Research, Society and Development, v. 11, n. 13, e519111335853, 2022
(CC BY 4.0) | ISSN 2525-3409 | DOI: http://dx.doi.org/10.33448/rsd-v11i13.35853

Influence of the addition of glass from long neck bottles in the properties of the reactive powder concrete

Influência da adição de vidro oriundo de garrafas do tipo *long neck* nas propriedades de concretos de pós reativos

Influencia de la adición de vidrio de botellas *long neck* en las propiedades del concretos de polvo reactivo

Received: 09/27/2022 | Revised: 10/06/2022 | Accepted: 10/08/2022 | Published: 10/14/2022

Igor Rafael Buttignol de Oliveira
ORCID: https://orcid.org/0000-0003-2565-2534
Universidade Federal de Alfenas, Brasil
E-mail: igor.oliveira@sou.unifal-mg.edu.br
Alan Rodrigo Sorce
ORCID: https://orcid.org/0000-0003-2370-9218
Universidade Federal de Alfenas, Brasil
E-mail: alan.sorce@sou.unifal-mg.edu.br
Marcos Vinicius Vieira Gaglieri
ORCID: https://orcid.org/0000-0001-6836-9080
Universidade Federal de Alfenas, Brasil
E-mail: marcos.gaglieri@sou.unifal-mg.edu.br
Fabia Castro Cassanjes
ORCID: https://orcid.org/0000-0002-8604-1203
Universidade Federal de Alfenas, Brasil
E-mail: fabia.cassanjes@unifal-mg.edu.br
Sylma Carvalho Maestrelli
ORCID: https://orcid.org/0000-0002-5037-4276
Universidade Federal de Alfenas, Brasil
E-mail: sylma.maestrelli@unifal-mg.edu.br

Abstract
This work presents an economical, technical, and environmentally correct solution for the disposal of long neck bottles (which cannot be bottled more than once), by replacing fine aggregates (sand) with residue of ground glass from long neck bottles in the production of reactive powder concrete (RCP). Using a reference formulation for RCP containing natural sand, this raw material was replaced in 12.5, 25, 50, 75 and 100 wt.% by glass residues, evaluating the physical and mechanical properties in the specimens at the ages of 7, 14, and 28 days. The ground glass was characterized by X-ray Fluorescence and DSC tests, indicating that it is a typical sodo-calcium glass, with a glass transition temperature equals to 560°C. Grain size distribution and optical microscopy assays of natural sand and ground glass indicated that the comminution let to the acquisition of glass with granulometry similar to that of natural sand, but with very different geometries and roughness. The replacement of natural sand by 100% of ground glass presented the best results of mechanical properties, reaching 85% of the mechanical strength value of the reference composition, with about 96MPa; this composition also presented the lowest water absorption value (3.94%) and the lowest void index (9.33%) among all compositions. The results indicated that the replacement of sand by powder from long neck bottles is potentially feasible, promoting an environmentally correct destination for this residue in the construction sector, bringing a reduction in environmental impact, and generating concrete within the technical standards required by the norm.
Keywords: Glass bottles; Reactive powder concrete; Mechanical strength; Reuse.

Resumo
Este trabalho apresenta uma solução econômica, técnica e ambientalmente correta para o descarte das garrafas *long neck* (que não podem ser envasadas mais de uma vez), a partir da substituição de agregados miúdos (areia) por resíduo de vidro moído de garrafas tipo *long neck* na produção de concreto de pós reativos (CPR). A partir de uma formulação referência para CPR contendo areia natural, esta foi substituída em 12,5, 25, 50, 75 e 100% em peso pelo resíduo de vidro, avaliando-se as propriedades físicas e mecânicas nos corpos de prova nas idades de cura de 7, 14, e 28. O vidro moído foi caracterizado por Fluorescência de Raios X e DSC, indicando que é um vidro sodo-cálcico, com temperatura de transição vítrea de 560°C. Ensaios de distribuição granulométrica e microscopia ótica para

caracterização e comparação da areia e vidro moído indicaram que com a cominuição obteve-se um vidro com granulometria semelhante à da areia, mas com diferentes geometrias e rugosidades. A substituição da areia por 100% de vidro moído apresentou as melhores propriedades mecânicas, atingindo 85% do valor da composição referência, aproximadamente 96 MPa; também apresentou o mais baixo valor de absorção de água (3,94%) e menor índice de vazios (9,33%) dentre as composições contendo substituição. Os resultados indicaram que a substituição da areia por pó de garrafas do tipo *long neck* é viável, promovendo uma destinação ambientalmente correta para esse resíduo na construção civil, trazendo redução do impacto ambiental e gerando um concreto dentro dos padrões exigido em norma.
Palavras-chave: Garrafas de vidro; Concretos de pós reativos; Resistência mecânica; Reuso.

Resumen
Este trabajo presenta una solución económica, técnica y ambientalmente correcta para el desecho de botellas *long neck* (que no se pueden llenar más de una vez), mediante la sustitución de áridos finos (arena) por residuos de vidrio triturado de botellas *long neck* en la producción de concretos de polvo reactivo (CPR). A partir de una formulación de referencia para CPR con arena, esta materia prima fue reemplazada en 12.5, 25, 50, 75 y 100% en peso por el residuo, evaluando las propiedades físicas y mecánicas en los especímenes en las edades de curación 7, 14, y 28. El vidrio molido fue caracterizado por Fluorescencia de Rayos X y DSC, indicando un vidrio sodocálcico típico, con una temperatura de transición vítrea de 560°C. Ensayos de distribución granulométrica y microscopía óptica para caracterizar y comparar arena y vidrio indicaron que com la trituración se obtenía un vidrio con granulometría similar a la de la arena, pero con diferentes geometrías y rugosidades. La sustitución de arena por vidrio al 100% mostró las mejores propiedades mecánicas, alcanzando 85% del valor de resistencia de la referencia, con 96 MPa; el valor de absorción de agua más bajo (3,94%) y la tasa de vacío más baja (9,33%) entre todas las composiciones. Los resultados indicaron que la sustitución de arena por polvo de botellas es viable, promoviendo un destino ambientalmente correcto para este residuo en la construcción civil, trayendo una reducción del impacto ambiental y generando un concreto dentro de los estándares técnicos exigidos en la norma.
Palabras clave: Botellas de vidrio; Concretos de polvo reactivo; Resistencia mecánica; Reutilizar.

1. Introduction

Concrete production has been undergoing a revolution with new dosing methodologies and additions of ultra-thin materials, aiming to leverage civil construction regarding technology and durability. In the near future, designing concrete structures with compressive strength lower than group I by ABNT NBR 8953 (ABNT, 2015), i.e., up to 50 MPa, will be uneconomical, especially when it comes to tall buildings, bridges and overpasses of large spans. The demands of civil construction have been requiring the development of new materials due to the need for greater load capacity, greater durability, lower cost, and with necessary characteristics for its application (Al-Quraishi et al., 2018).

The reactive powder concrete (RCP) is a new generation of concrete that belongs to the family of ultra-high-performance concretes. The term "reactive powder" reflects the meaning that all powder components in RCPs are chemically reactive (Dobiszewska et al., 2018; Li et al., 2022). The RCPs were originally developed with the aim of meeting specific requirements of prefabricated concrete structures exposed to aggressive environments. Later, due to its performance, the RCP was studied and designed to also meet specific military requirements (Eva et al., 2020).

RCP is a material that resembles steel, in terms of properties, but with lower cost and greater durability (Alexander & Beushausen, 2019; Luo et al., 2022). According to Vanderlei and Giongo (2006) "RCP was developed as an alternative to ultra-high-performance concrete (URPC) and even to steel, making it a high-tech material. Richard and Cheyrezy (1995), describes that the basic principle of reactive powder concrete is based on the production of a material with minimal defects, allowing it to support high stress values, combined with high durability.

According to Tokudome (2008), the basic composition of this type of concrete consists of the mixture of Portland cement, active silica, quartz powder, fine aggregate, water, superplasticizer additive and eventually metal fibers. According to Tafraoui, Escadeillas and Vidal (2016), the water/cement ratio required in the reactive powder concrete should be between 0.18 and 0.30, in order to achieve a high quality in the final product. Furthermore, in these concretes, the objective is to increase the efficiency of particle packaging and reduce the heterogeneity of the microstructure, minimizing the internal defects of the material such as porosity and micro fissures, which can be achieved through the use of fine and cementitious materials (Aldahdooh et al., 2013).

The mixture of the raw materials of the RCP aims to obtain a more homogeneous mass and an increase in compactness, optimized by refined granulometry with consequent improvement in the mechanical properties between paste and aggregate and in the ductility of the concrete. All this concern is based on two crucial points: the increase in the homogeneity of the mixture (which occurs with the removal and replacement of coarse aggregates by ultrafine particles) and the resulting formation of a much less porous microstructure, especially regarding the aggregate-paste interface (Wang et al., 2022; Velichko & Vatin, 2022; Qing-hua et al., 2022). According to Zdeb (2016), one of the most significant characteristics that improves the microstructure and distinguishes the reactive powder concrete from any other material based on high performance cement is the removal of the large aggregate, increasing the resistance in the matrix and homogeneity. According to Han, Zen…and Ou (2017) there are two main essential parameters that affect the values of compressive force in the RCP, in which they are: the selection of the appropriate materials and the proportion between them.

According to data from the United States Geological Suvery (2020) the world production of concrete reached levels higher than 4100 Mt (megatons) in 2019. Allied to this production, is the high global consumption of natural resources used in the manufacture of concrete, among which the use of natural sand stands out. The law No. 12,305 of August 2, 2010, which establishes the National Solid Waste Policy (Política Nacional de Resíduos Sólidos, 2010), and the Resolution CONAMA No. 307 (2002) strongly address issues involving waste recovery, reuse, and recycling. There are many advantages in applying the 3 Rs mentioned, such as the reduction in the consumption of non-renewable natural resources, when replaced by recycled waste (John & Agopyan, 2000), the reduction of the areas necessary for the landfill, due to the decrease in the volume of waste produced, in addition to the reducing of air pollution, and conservation of fauna and flora.

Glass is a non-equilibrium state and non-crystalline of condensed matter, which exhibits a vitreous transition. The glass structures are similar to those of their supercooled liquids (SCL) and spontaneously relax towards the State of SCL. Its final destination, for immensely long times, is crystallizing (Zanotto & Mauro, 2017). Although it is normally recyclable, there is a portion of the glasses that are not. According to the website Ecycle (2015), glass is a material that takes about 5,000 years to decomplant. With the reuse of glass, there is a reduction in the consumption of raw materials – which are taken from nature – and also from energy, since their shards use in their manufacture lower temperature and time for the melting process (Recicloteca, 2016). According to Araújo (1997), the manufacture of a ton of recycled glass prevents the extraction of a ton of sand. In addition, less than 32% of energy, 50% of water is spent, and air pollution inherent in the manufacturing process is reduced by 20%.

Studies by Reindl (1998) show that there are more than 60 forms of glass recycling. According to the Ambev (2016), for the manufacture of *long neck bottles*, approximately 65% of recycled vitreous material is used, which considerably reduces the consumption of natural raw material. Recycling materials arrive from wineries, bars, supermarkets, and partners of recycling cooperatives. The bottles used in the recycling process are returnable glass bottles of 600 ml and 1000 ml. Since they use high percentage of recycled waste in the manufacture of long neck bottles, they have their chemical composition modified. This modification was done to lower the manufacturing cost and make the bottles competitive in the market, however, the result compromises the strength of the packaging and does not allow its return to a second fill. Therefore, these bottles cannot be recycled as the other ones.

According to Cervieri Júnior, Teixeira Junior, Galinari, Rawet & Silveira (2014) report, in recent years Brazil has become the third largest producer and consumer of beer in the world. In 2012 alone, production was 14 billion liters. Although the packaging of beer in long neck bottles is lower, when compared to the others, this portion represents 420 million liters, resulting in approximately 1.4 billion units of these packages, which justifies a concern with its final disposal. To Righi, Köhler, Tabarelli, Kirchhof & Lima (2012), long neck glass bottles have been one of the most troubled wastes generated in the world, due to the ones being discarded soon after consumption, which generates and occupies space at the final destination, the landfills more frequently.

In civil construction, concrete production has the potential to absorb various types of waste. The addition of other residues in concrete in the form of fine or coarse aggregate has already been studied by several researchers. Some of these residues are added to improve the mechanical characteristics of concretes such as silica, mixtures of pozolanic materials, ash, basalt powder, slag, etc. (Babu & Prakash, 1995). Due to its high mechanical and durability properties, reactive powder concrete has been used in diverse areas such as construction, nuclear power, oil, marine and military structures and, with the increasing of the demand, its commercial production has also begun to be done in many countries such as Australia, Canada, China, France, South Korea, and the United States (Abid et al., 2017).

As examples of the use of glass in real scale, it is possible to highlight the example of Australia, which already uses ground glass from the garbage in concrete for construction, and from the U.S. state of New York that already presents recommendations for the use of this material in concrete (Sagoe-Crentsil et al., 2001). According to Idir, Cyr and Tagnit-Hamou (2010), the size of glass particles is an important parameter that must be controlled, because it influences the main properties of the cement matrix, since the incorporation of glass into this matrix can promote the alkali–silica reaction, which causes cracks in the matrix, influencing mechanical performance and durability. Wang, Shi…and Fang (2015) observed that when grinding the residue to equate its granulometric distribution with that of cement, the residue started to present the specific surface greater than that of the cement, due to the greater irregularity of the glass particle. Paiva, Silva, Labrincha and Ferreira (2006) and Matos and Sousa-Coutinho (2012) also observed this morphology of glass particles.

The purpose of this study was to investigate the applicability of glasses from long neck bottles in obtaining reactive powder concrete. Also, it aimed to investigate the similarities between the glass of long neck bottles and the sand normally used in the composition of the concrete mass, as well as the effect of adding different glass contents on the properties of a reactive powder concrete.

2. Methodology

The raw materials used in this research were: sand, glass powder, cement, microsilica and quartz powder. The sand used is of natural origin, coming from the region of Pirassununga, commercialized by the company Gato Neves building materials and it is in accordance with ABNT NBR 7211 (ABNT, 2009). The glass powder used was obtained by grinding long neck beer bottles. The bottles, previously selected of the same brand and amber color, underwent a process of labels removal and cleaning, being previously broken for later grinding using a ball mill until they reach the granulometry of the sand used. The cement used was the Portland Cement type "CP V – ARI", from the brand Cauê which meets the requirements of the standards ABNT NBR 5733 (ABNT, 1991). The microsilica used was provided by Tecnosil Indústria e Comércio de Materiais de Construção LTDA company. It has a specific mass of 2.22 g/cm^3, a specific surface area of 19.0 m^2/g, an average particle diameter of 0.20 µm, a volumetric density of 0.45 g/cm^3, and a spherical particle shape (data provided by the manufacturer). The quartz powder (from Brasilminas) has a specific weight of 2.65 g/cm^3 being an ultrafine material, mesh #1000 (4.66 µm).

Due to the substantial number of fine materials inherent to the formulation of reactive powder concrete, the cement mixture tends to become dry, causing a reduction in the workability of the product and a possible increase of the a/c factor (water/cement ratio) of the concrete. Therefore, to improve the fluidity of the material and optimize the mechanical properties of the concrete, a superplasticizer additive, Glenium 51™, was used, constituted of an aqueous solution based on polycarboxylato ether and having density of 1.055 g/cm^3. The superplasticizer was obtained as a donation from Master Builders Solutions, having been produced by BASF S/A. The water used in this research was available by the public supply network of the city of Poços de Caldas-MG and complies with the recommendations of ABNT NBR 15900-1 (2009), being considered suitable for use as a massing water for concrete and cementitious composites without the need for testing.

To transform the long neck bottles into smaller fractions it was necessary to make the use of a usual hammer, in order to reduce the initial size of the material, obtaining different particle sizes to facilitate the grinding process inside the ball mill, which consists of a stainless-steel cylinder containing forged steel spheres of different diameters and masses, where the material was grinded for 7 minutes at 55 rpm. This process was repeated several times, as the cylinder had no ability to grind all material at once. The granulometry assay was performed according to the specification standard: ABNT NBR 17054 (2022), which had as principles: to classify the sand and the glass from the long neck bottles according to their granulometric composition, build their granulometric curve and determine its maximum diameter and fineness modulus. The granulometric assay aimed to identify the geometric compatibility of the samples of the natural sand with those of the glass powder from long neck bottles to enable the replacement in the formulations as well as to optimize the packaging of particles with a more homogeneous distribution of materials in all particle size distributions. To perform the test, it was used the sample of sand previously dried in a greenhouse and glass powder from the long neck bottles. The equipment used were Mart-e scale, model AD3300 with accuracy of 0.01g of the mass of the test sample, Bertel sieves of the normal series, lid and bottom, of suspended sieves agitator from Solotest, brush with soft bristle. The entire standard procedure was repeated with the second sample collected for the performance of the counterproof.

Optical microscopy assays were performed using Zeiss benchtop optical microscope, model Scope A1. The test aimed to morphologically characterize the aggregates (sand and glass powder) according to their angularity and measurability and analyze the influence of the particle forms involved and the packaging of particles in concrete. X-ray fluorescence laboratory was performed in the laboratory of the industry Togni S/A Refractory Materials, located in the city of Poços de Caldas-MG, using the equipment Axios PW 4400/40 DY 1686. The pearls for analysis were made using lithium tetraborate ($Li_2B_4O_7$) 99.5% and lithium bromate (LiBr) 0.5% in a platinum-gold crucible, where the fundent and sample were homogenized. The pearls were placed in a previously heated muffle at 1200°C. A semiquantitative chemical analysis was performed. Tests were performed for two samples, one containing glass bottle material considered disposable (long neck) and the other with material from returnable bottles. The objective of the assay was to verify which type of glass belongs to the long neck packaging used to replace the sand in the reactive powder concrete. These samples were also submitted to the DSC (Differential Scanning Calorimetry) assay, using Netzsch equipment, model STA 449F3. The analyses were made in dynamic atmosphere of synthetic air, in aluminum crucibles with perforated lid with heating rate of 20°C/min.

The formulation used as a reference to produce the reactive powder concrete was developed by Professor Luiz Antônio dos Reis of the Pontifical Catholic University of Minas Gerais, Poços de Caldas, based on the particle packaging method adjusting the water/cement ratio, in addition to the content of the superplasticizer additive for workability adjustment. The maximum diameter (Dmax) of the aggregates was defined as 0.6mm referring to sieve number 30 in the mesh scale and the minimum diameter being the material retained until sieve number 200 in the mesh scale referring to 0.075mm. The a/c ratio (water/cement) was estimated according to the ABNT NBR 6118 (2014), standard and the Environmental Aggressiveness Class: aiming at the production of a sustainable, durable, and wide-applicability RCP, it was specified to meet Environmental Aggressiveness Class IV (strong, in an industrial environment or subject to tidal spatter). Therefore, the maximum water/cementitious materials ratio of 0.45 was adopted. The water/cement ratio was 0.30. For comparison reasons, table 1 presents some formulations used for the manufacture of Reactive Powder Concrete by authors who are reference in this type of concrete. The values of the dosages are unitary based on the initial amount of cement.

Table 1: Comparison of the reference formulation, Luiz dos Reis, with the literature.

Formulations Literature (in mass)						
Author	Cement	Sand	Quartz Powder	Microsilica	Deflocculant	Water
Reference, Luiz dos Reis	1	1.019	0.164	0.152	0.035	0.3
Richard and Cheyrezy, 1995	1	1.1	0.39	0.23	0.02	0.19
Bonneau, Poulin, Dugat and Tcin, 1996	1	1.432	0.298	0.326	0.027	0.28
Biz, 2001	1	1.43	0.3	0.32	0.01	0.29
Vanderlei and Giongo, 2006	1	1.101	0.235	0.246	0.02	0.216
Gusmão, 2017	1	1.01	0.241	0.252	0.03	0.19

Source: Authors (2022).

Five formulations of reactive powder concrete were produced and investigated: the first was used as a reference, consisting only of conventional raw materials (sand, micro silica, quartz powder, cement, and water) without the partial addition of glass powder from long neck bottles. The other formulations involved the partial replacement of 12.5; 25; 50; 75 and 100% by weight of the fine aggregate (sand) by the glass powder of the long neck bottles. The preparation of the cement paste was carried out in a mixer of the common mortar type, with a capacity of twenty liters, of constant speed, with naval propeller and rotational movement. After homogenizing the dry materials, the water and additive were gradually added, until a mixture with plastic aspect and desired fluidity was obtained, which occurred around approximately 5 minutes, and then the samples were molded for each formulation for later characterization. The molds used to produce the samples were made of PVC, rigid, inert, and non-absorbent material, according to ABNT NBR 5738 (2015), in cylindrical format with dimensions of 100mm in height and 50mm in diameter. The cure of concrete specimens was the cure by immersion in aqueous solution saturated with calcium hydroxide, at a temperature of 25 °C, where the pH values, which were between 11 and 13, were controlled with the aid of a measurer from Nova Instrumentos, model: NI PHM. Before performing the mechanical tests, the samples underwent a grinding process, as recommended by ABNT NBR 5738 (2015), in a cutting machine with Bel Air pneumatic actuator, maximum pressure of 1.03 MPa, at a speed of 400 rpm, with cutting disc and cooling of the blade by water.

The mechanical tests were carried out in the concrete laboratory of Polimix Concreto LTDA, located in the city of Poços de Caldas-MG, in a digital electrohydraulic concrete press from A.M.C, model 10014, with a maximum load capacity of 980.6 kN and load application speed control with precision of 0.098 kN. The samples were compressed at 7, 14 and 28 days from molding. The value of the mechanical strength adopted was an arithmetic mean of the compressive strength values of each sample. To obtain the results of compressive strength, it was necessary to adjust the results through Equation A, adopting the methodology standardized by the Brazilian standard ABNT NBR 5739 (2018).

$$fc=4.F/\pi.\ D \qquad \text{(Eq. A)}$$

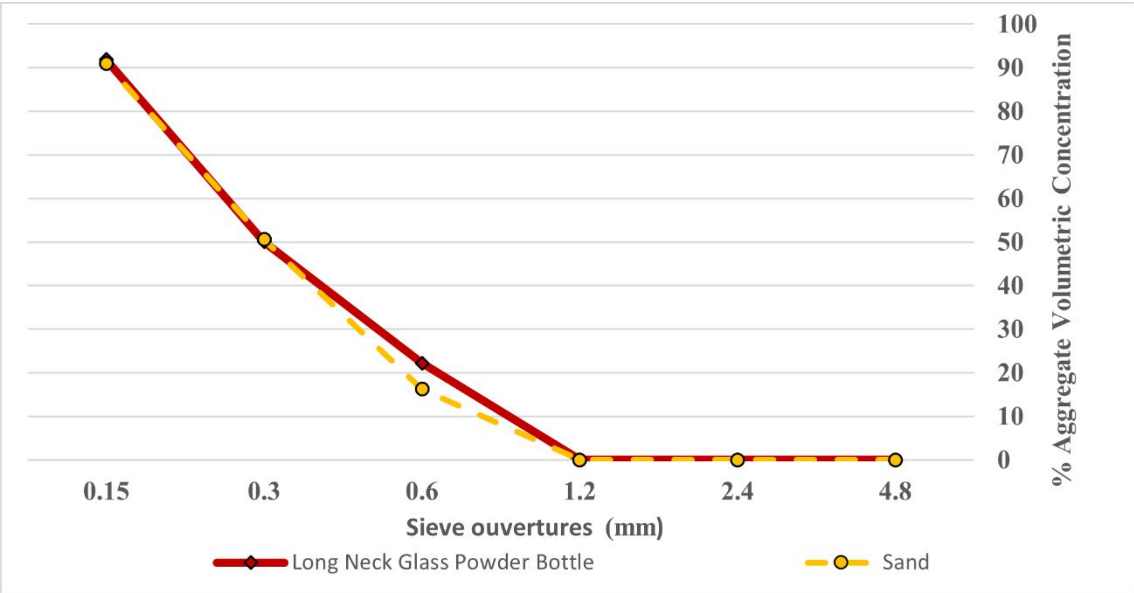
In which fc refers to the compressive strength in MPa; F, to the maximum n-break load, and D is the diameter of the sample in millimeters.

The absorption assay and void index of the specimens was carried out according to ABNT NBR 9778 (2005).

3. Results and Discussion

The granulometry tests (Figure 1) indicated that, for the glass powder from long neck bottles, the largest granulometric fraction (41.82% by mass retained with fineness modulus of 1.64) is in sieve #100, with a diameter of 0.15 mm, being characterized as a very fine material. The maximum aggregate in glass powder (0.6mm) represented 22.17% by mass of the sample. For sand, the largest particle size fraction (40.35% by mass retained with fineness modulus of 1.58) is in sieve #100 with a diameter of 0.15mm, being considered a very fine sand. The maximum aggregate in the sand (0.6mm) represented 16.24% by mass of the sample. Both the sand and the glass powder from the long neck bottles showed continuous granulometric distribution, being the distribution of the grains in the sand more homogeneous between the sieves from 30 to 100 mesh, both with particles of all diameters, from the maximum value (0.6mm) to the minimum value (0.075mm).

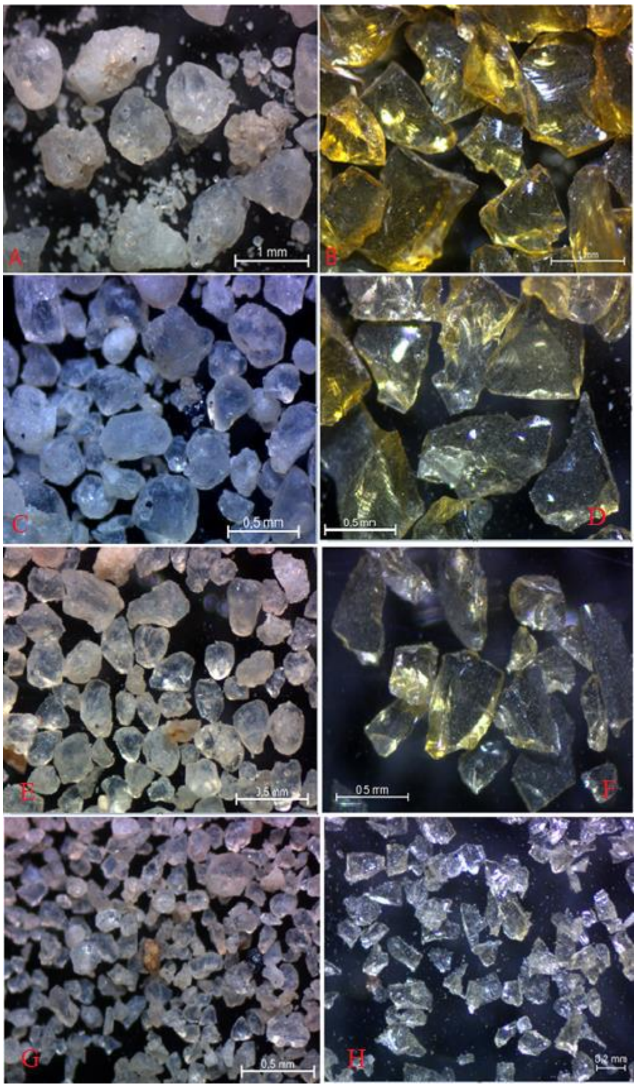
Figure 1: Granulometric distribution curve of ground glass and natural sand1, indicating that both materials are very similar and thin.



Source: Authors (2022).

Figure 2 shows the images referring to the optical microscopy assays of the natural sand and glass powder from the long neck bottles, according to the granulometric range used in the sieves 30, 50, 100 and 200 in the mesh scale. For the fine aggregates, the Brazilian standard ABNT NBR 7389 (2009) suggests the evaluation of the form by means of visual inspection, with the naked eye or with the aid of magnifying glass. According to this standard, each grain should be evaluated and compared with a standard chart that defines the degree of sphericity of the grains in high or low. After visual evaluation of the images of the grains analyzed in each sieve and comparing them with the classification of the norm, it can be concluded that the glass particles are angled and lamelar with low degree of sphericity, while the particles of the natural sand are sub-rounded with a high degree of sphericity. The observations were qualitative, making it possible to observe through the photos that the fine aggregate from the long neck bottles present the surface of the grains smoother than the fine aggregate of natural sand. Natural fine aggregate, such as sand, tend to be rounded due to the cumulative effect of collisions of their particles. The grinding process, as used in the present work to grind the glass from long neck bottles, produced angular particles in a sharp way. Aggregates with more spherical and rounded shapes, from the point of view of the final strength of the concrete, are preferable because they promote better packaging.

Figure 2: Images (reflected light) of the samples: (A) sand #30; (B) ground glass #30; (C): sand #50; (D): ground glass #50, (E): sand #100; (F): ground glass #100; (G): sand #200; (H): ground glass #200. The images prove that the glass particles are angled and lamelar with low degree of sphericity, while the particles of natural sand are subrounded with a high degree of sphericity.



Source: Authors (2022).

The chemical composition of the glass samples from long neck bottles, obtained via FRX assay, is shown in Table 2. The predominant presence of SiO_2, responsible for the vitreous network, as well as the presence of Na_2O and CaO were verified, indicating that it is a typical sodo-calcium glass. Other oxides appear in smaller quantities. These values are very close to those found in the literature (Aldahdooh et al., 2013; Shelby, 2020). The amber coloring, widely used in packaging, is due to sulfur oxide combined with iron oxide. Regarding beverage packaging, brown or amber glass plays a key role in preserving the contents of them, which might be damaged by the passage of ultraviolet radiation.

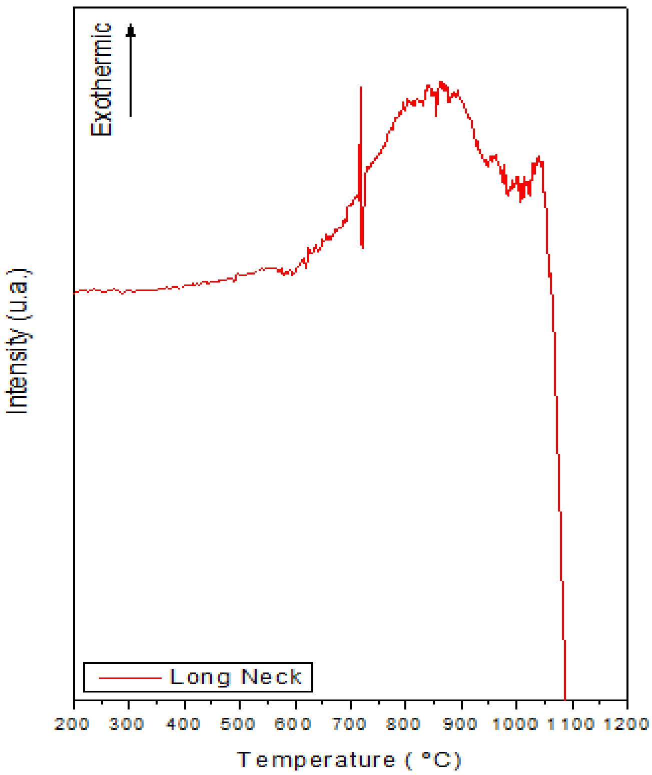
Table 2: FRX of the long neck glass samples, indicating that it is a typical sodo-calcium glass.

Determinations	***Long Neck* (%)**
Al_2O_3	2.06
SiO_2	70.90
TiO_2	0
Fe_2O_3	0.85
CaO	11.00
MgO	0.59
In_2O	14.00
K_2O	0.28
Cr_2O_3	0.03
P_2O_5	-
SO_3	0.06
CO_2	0.30

Source: Authors (2022).

Figure 3 shows the DSC curve obtained for the glass sample from the long neck bottles. By analyzing the curve, it was possible to determine the characteristic temperatures of the sample.

Figure 3: DSC test of the glass sample from long neck bottles, indicating crystallization peaks at different temperatures and baseline displacement and a glass transition temperature equal to 560□C.

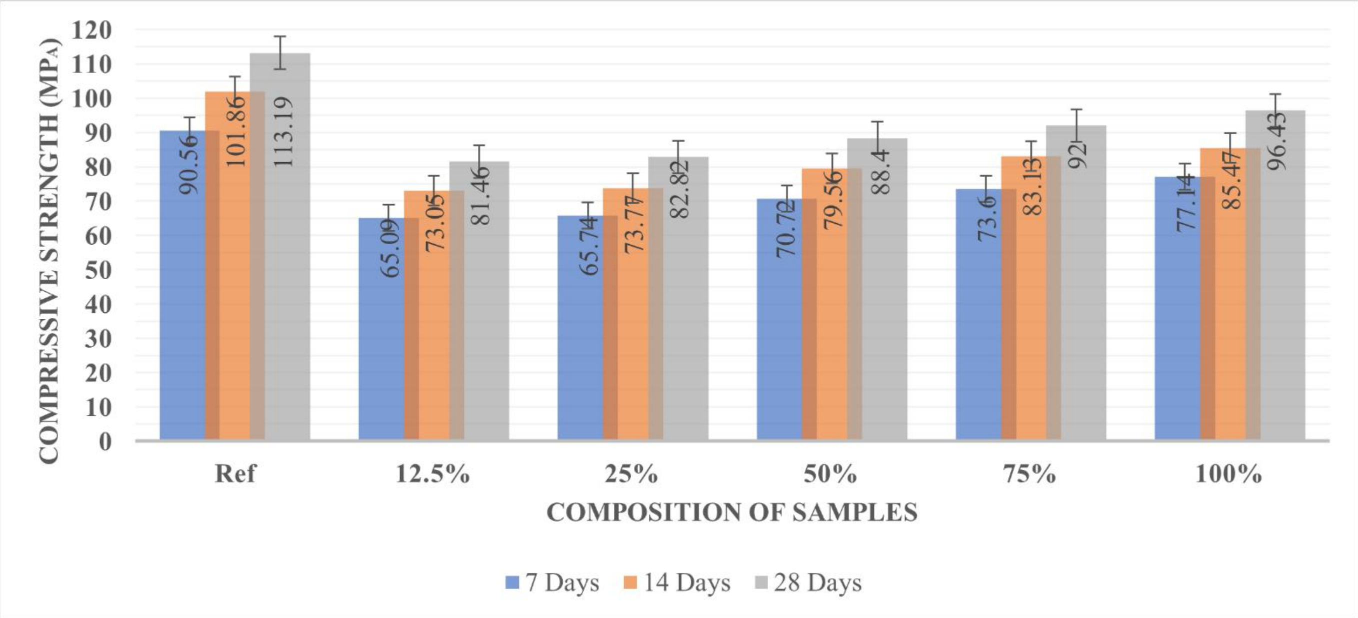


Source: Authors (2022).

For the long neck sample, it was observed a change in the baseline, occurring at 560°C, regarding the glass transition temperature (Tg). Soon after the occurrence of the Tg, the formation of a crystallization peak of the glass begins, which is extended, and the temperatures of the crystallization peak (Tp) occurs at 860ºC. It is also observed the formation of another crystallization peak, the starting crystallization temperature (Tc), which occurs around 1150ºC. However, it was not possible to fully observe the crystallization peak due to the limitations of the device since the temperature limit was 1100ºC.

The results of the compressive strength assay for the reference samples and for those with the addition of 12.5, 25, 50, 75 and 100% by weight of glass from long neck bottles, as well as the evolution of the resistances in 7, 14 and 28 days are shown in Figure 4. It was observed that the reference formulation presented superior performance to the other formulations studied, with an average value of 113.19 ± 1.25 MPa at 28 days.

Figure 4: Mechanical strength to average compression by breakage age for standard samples (reference) and with the addition of 12.5, 25, 50, 75 and 100% by glass weight from long neck bottles.

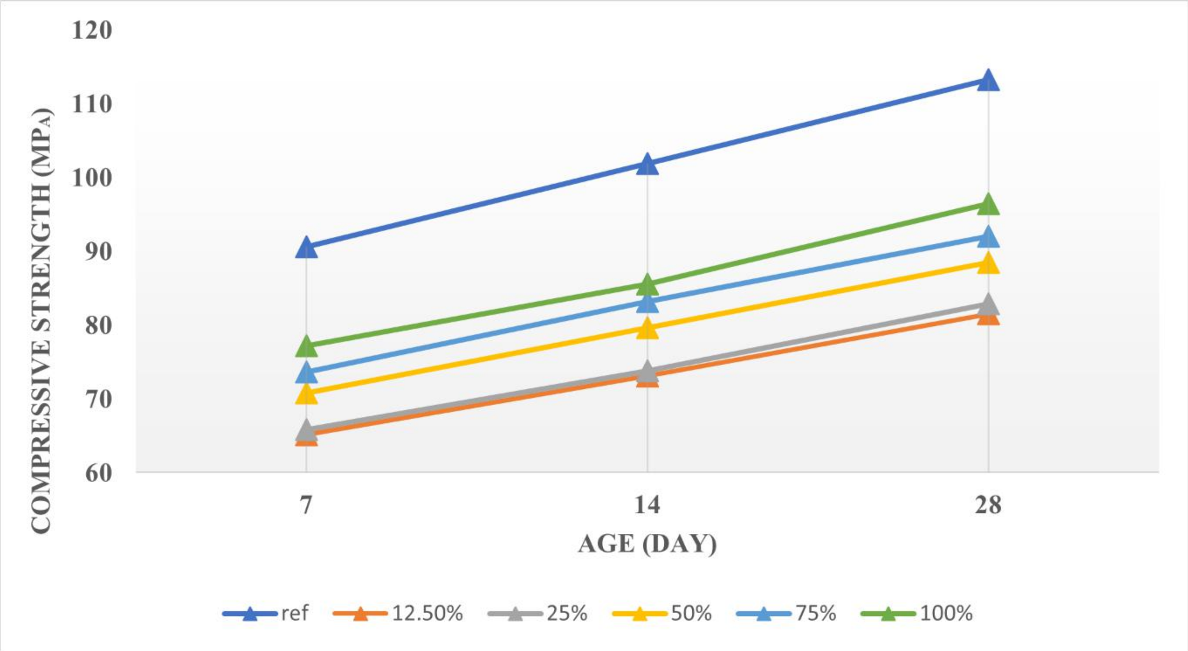


Source: Authors (2022).

The formulation with 100% replacement of sand by ground glass from long neck bottles was the formulation that presented the best compression strength values, in comparison to the other substitutions, reaching 85% of the reference composition value, with a value of 96.43 ± 0.81 MPa. The mechanical resistance at 28 days decreased as the replacement of sand by glass was lower. The formulations with 12.5% and 25% substitution presented the lowest values of mechanical resistance (about 72% of the mechanical resistance of the reference formulation), being very similar statistically. Overall, it was observed that the increase in the amount of recycled fine aggregates (glass powder) can cause a percentage increase in compressive strength. This increase in mechanical resistance (with the increase in the amount of glass powder replacing sand) occurred due to the presence of granulometric fractions that, when divided into minuscule fractions, began to present pozzolanic activity, that is, glass residue when in contact with water, began to react chemically with calcium hydroxide, forming compounds with cementitious properties. This pozzolanic reaction proved to be efficient for filling empty spaces, thus improving the strength and impermeability of the concrete. Regarding the reference formulation, in compressive strengths, the morphology of the grains of the natural sand was responsible for the higher mechanical resistances of the specimens made. The greatest mechanical resistance was due to the greater packaging of the grains and the greater adhesion between the phases of the microstructure, generating a concrete with less number of voids and consequently with higher mass density.

Regarding the evolution in the mechanical resistance of all formulations by age (7, 14 and 28 days), as shown in Figure 5, it is found that when the concrete was loaded in the early ages, the micro fissures tended to propagate more easily in the more porous areas towards other areas, following preferential rupture paths. However, over time, these voids were filled with hydration products and became a less porous and more resistant area. Overall, the strength of the concrete increased with age while the unhydrated particles of cement continued to form hydration products which caused a decrease in the total volume of pores, due to the hydration of the cement particles which occurred over time. Thus, calcium hydroxide and calcium silicate crystals began to fill the empty spaces previously occupied by the hydration water.

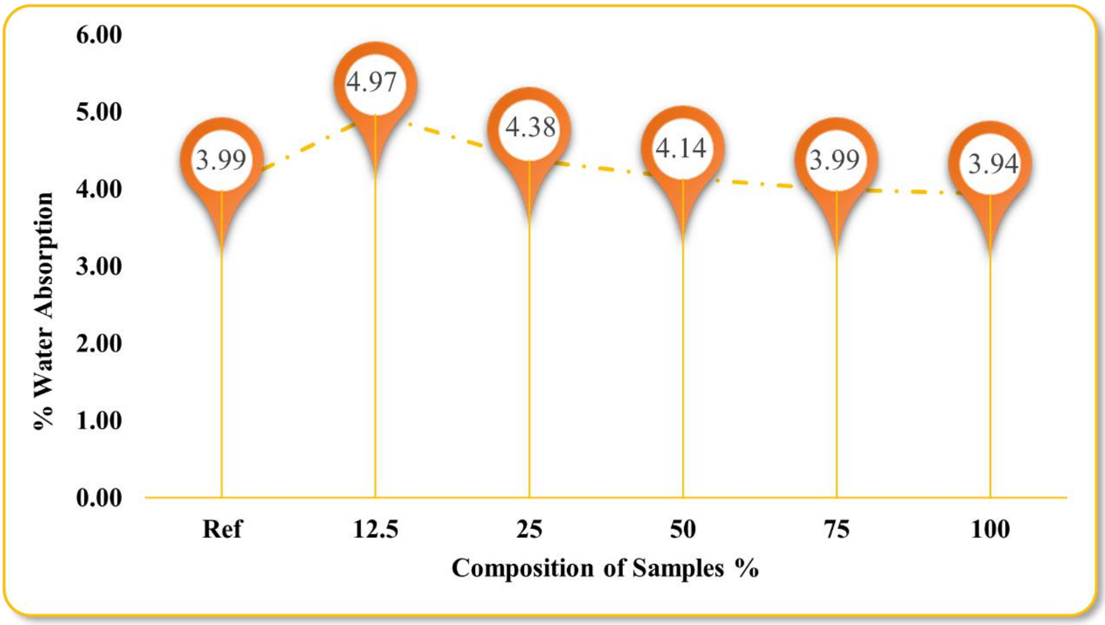
Figure 5: Evolution mechanical strength to compression by age for standard samples (reference) and with the addition of 12.5, 25, 50, 75 and 100% by weight of glass from long neck bottles.



Source: Authors (2022).

The water absorption measurements (Figure 6) indicated that the concrete with 100% substitution (of the natural sand by ground glass from the long neck bottles) obtained the lowest value, with 3.94% of water absorption, followed by the reference formulations and 75%, both with statistically equal absorption values of 3.99%. The formulation of 12.5% presented the highest absorption rates, 4.97, which can generate lower values in terms of mechanical properties and lower performance in use.

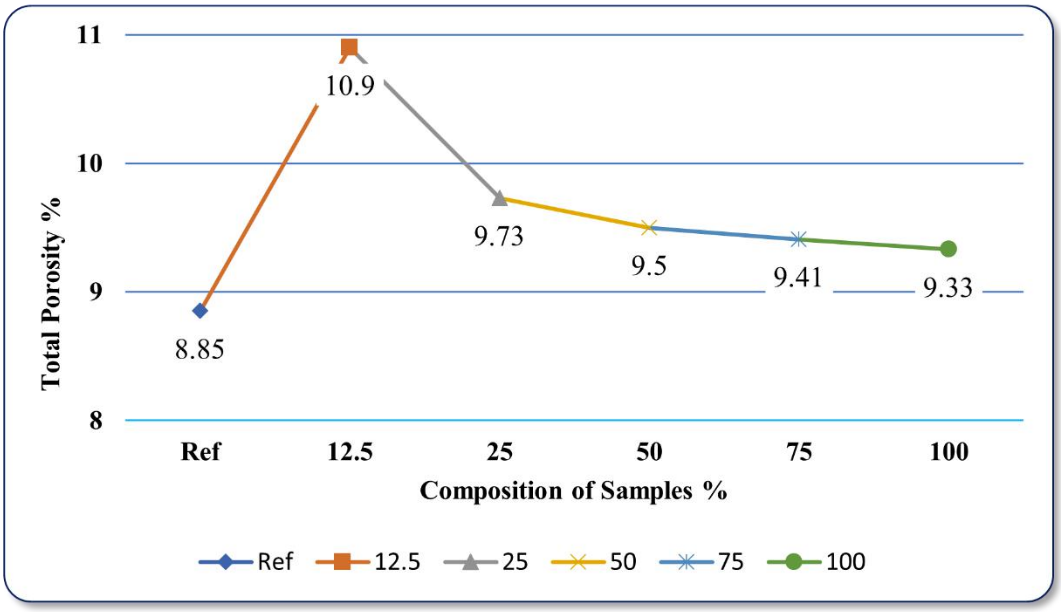
Figure 6: Results of the water absorption test (%) for standard samples (reference) and with the addition of 12.5, 25, 50, 75 and 100% by weight of glass from long neck bottles.



Source: Authors (2022).

When considering the empty index, Figure 7, the best results found were for the reference formulation, with 8.85% of voids, followed by the replacement of 100% and 75%, presenting values of 9.33% and 9.41% voids, respectively. The formulation of 12.5% presented the mean value of 10.9% voids, which corroborates the results obtained from water absorption.

Figure 7: Void Index Test for standard samples (reference) and with the addition of 12.5, 25, 50, 75 and 100% by glass weight from long neck bottles.



Source: Authors (2022).

It was observed a decrease in the values referring to the void index as the proportion of the replacement of ground glass by sand increased. The behavior of the volume of voids of the composition as a function of the relationship between the particles occurred as the percentage of fines in the composition increased. In a first stage, the volume of voids decreased, because the fines filled the voids of the thickest grains. However, when they reached a certain limit, the fines began to interfere in the accommodation of the thicker grains and the removal effect was predominant, raising the void index (figure7). The emptier in the granulometric composition, the smaller the packaging of the grains. Thus, it was possible to correlate the void index test with the results of mechanical resistance of the formulation. It was observed that the porosity exerts a negative influence on the compressive strength, since the pores reduced the area of the cross section and acted as stress concentrators, facilitating the onset of fissures and, with this, a possible fracture. The distribution of pore sizes and total porosity altered the mechanical properties of the concrete since the reduction of porosity allowed the increase of compression efforts.

The study of water absorption and the porosity of concrete worked as indicators of the durability of hardened concrete that is defined as its ability to resist the action of weather and chemical attacks, since water permeates the pores of the concrete, carrying with it substances that can produce the deterioration of concrete or, in the case of chloride ions, corrosion of the steel reinforcement. The values of void index and water absorption are within normal limits for mortars or concretes of reduced granulometry, as is the case of RPC. For the void index value, the formulations were within the expected when compared to studies related to concrete such as Silva (2003), which presented void index values for concrete in their samples of up to 16% in water absorption and 10% in void indexes in the mixtures.

4. Conclusion

The replacement of the natural aggregate (sand) by glass powder was feasible in all fractions of substitutions since both sand and glass powder have continuous granulometry, geometric compatibility and chemical similarity. The formulation with 100% replacement of sand by glass was the formulation that presented the best values of compressive strength when compared to the other substitutions, reaching 85% of the reference composition value reaching 96,43 ± 0,81 MPa. A decrease in void index and permeability was observed jointly with the gaining and increasing of the durability factor, as these factors decrease the occurrence of pathologies in concrete. The physical tests (water absorption and void index) showed that in relation to the void index, the reference concrete obtained the best result with 8.85% followed by the formulations of 100% and 75% with 9.33% and 9.41% respectively

The tests showed that the replacement of sand by the ground glass of the long neck bottles, in the proportions investigated, brought very promising results. It should be noted, however, that the use of this material requires further studies on its performance in specific applications through standards for technical specifications related to safety and durability, such as the thickness of the reinforcement cover, minimum dimensions for structural elements and the maximum crack opening. From an environmental point of view, the substitution of natural sand by glass powder from long neck bottles in reactive powder concrete proved to be a potentially interesting alternative for an adequate destination for this waste in the construction sector and, which is of fundamental importance for reducing the environmental impact, developing concrete that meets technical standards not altering their properties and not offering risks to the environment.

Acknowledgments

We thank the partner companies of this study: Togni Materiais Refratários S/A, Master Builders Solutions and Polimix Concreto LTDA, Professor Luiz Antônio dos Reis, of the Pontifícia Universidade Católica de Minas Gerais and engineer Bruno Cesar Lopes Coutinho (Polimix). We also thank FAPEMIG and CNPq for their financial and scientific support.

References

Abid, M., Hou, X., Zheng, W., & Hussain, R. R. (2017). High temperature and residual properties of reactive powder concrete – A review. *Construction and Building Materials*, *147*, 339–351. https://doi.org/10.1016/j.conbuildmat.2017.04.083

Al-Quraishi, H., Sahmi, N., & Ghalib, M. (2018). Bond Stresses between Reinforcing Bar and Reactive Powder Concrete. *Journal of Engineering*, *24*(11), 84–100. https://doi.org/10.31026/j.eng.2018.11.07

Aldahdooh, M. A. A., Bunnori, N. M., & Johari, M. A. M. (2013). Evaluation of ultra-high-performance-fiber reinforced concrete binder content using the response surface method. *Materials & Design (1980-2015)*, *52*, 957–965. https://doi.org/10.1016/j.matdes.2013.06.034

Alexander, M., & Beushausen, H. (2019). Durability, service life prediction, and modelling for reinforced concrete structures – review and critique. *Cement and Concrete Research*, *122*, 17–29. https://doi.org/10.1016/j.cemconres.2019.04.018

Ambev. (2016). *Sustainability report.* https://www.ambev.com.br/conteudo/uploads/2017/05/Ambev_Relat%C3%B3rio_Sustentabilidade_2016.pdf

Araújo, E.B. (1997). Glass: a brief history, characterization techniques and applications in technology, *Brazilian Journal of Physics Education,* 19 (3), 325–329. Retrieved from http://www.sbfisica.org.br/rbef/pdf/v19_325.pdf

Babu, K.G., & Prakash, P. V. S. (1995). Efficiency of silica fume in concrete. *Cement and Concrete Research*, *25*(6), 1273–1283. https://doi.org/10.1016/0008-8846(95)00120-2

Associação Brasileira de Normas Técnicas. (1991). *Portland cement of initial high strength* (ABNT NBR No.5733). https://www.abntcatalogo.com.br/norma.aspx?Q=NXhPMzRMNkVRU1BqTHFjZjFEMUZ1UElwT0FmU2FyR01QbnRPWHpoN0hsND0=

Associação Brasileira de Normas Técnicas. (2009). Aggregates - Petrographic analysis of aggregate for concrete Part 1: Fine aggregate (ABNT NBR No.7389). https://www.abntcatalogo.com.br/norma.aspx?Q=THhRZ0JoWWR5WkRTblpXNWlPd2YzZjk4SXYwTTJrWEN4dEdxQXhiRXJsdz0=

Associação Brasileira de Normas Técnicas. (2005). *Argamassa e concretos endurecidos- determinação da absorção de água, índice de vazios e massa específica* (ABNT NBR No. 9778). https://www.abntcatalogo.com.br/norma.aspx?Q=d3RSR1B4ZW54NkV0WHFLMTdUN2E2WjlDOHczS2VQMVVEalZjMGxJYSsvQT0=

Associação Brasileira de Normas Técnicas. (2018). *Concrete: Compression test of cylindrical specimens* (ABNT NBR No.5739). https://www.abntcatalogo.com.br/norma.aspx?Q=RXZ5VStweWJKaFJkSE16UEtuRTAyVEYvWHdONHplTXlqbVp5SlExQjg4TT0=

Associação Brasileira de Normas Técnicas. (2009). *Água para amassamento do concreto Parte 1: requisitos* (ABNT NBR No.15900-1). https://www.abntcatalogo.com.br/norma.aspx?Q=R2k2WVFFZkVjOFhMRVJHK25SamJ4bTdza1ZydHdXZTZaSE1sc3pwMHB0UT0=

Associação Brasileira de Normas Técnicas. (2009). *Aggregates for concrete: Specification* (ABNT NBR No.7211). https://www.abntcatalogo.com.br/norma.aspx?Q=NEZvK3NHUk5OZEVYdVM2T2t5SkZFNUtpcVgrZlZTZjhGeGx0TmVyK2tqZz0=#

Associação Brasileira de Normas Técnicas. (2014). *Design of concrete structures: Procedure* (ABNT NBR No.6118). https://www.abntcatalogo.com.br/norma.aspx?Q=U3JENHZueEVFaDVmUmFIUFFZd2Y5YlZQQ0hCTFEyN2RweTRIb0hMQjBNdz0=

Associação Brasileira de Normas Técnicas. (2015). *Concrete: Procedures for molding and curing specimens* (ABNT NBR No.5738). https://www.abntcatalogo.com.br/norma.aspx?Q=SEFrdzZmdi9vajRnUC95bmF2bm5lbkF2NUpJcno3ck1JK05QNDhZMHVPQT0=

Associação Brasileira de Normas Técnicas. (2022). *Aggregates: Determination of granulometric – test method* (ABNT NBR No. 17054). https://www.abntcatalogo.com.br/norma.aspx?Q=b0dsV0NuYlRZL1VCb2Z2OW5BWEVvUFY0YWorK3ZkT2Y2NHhEN2k3WVJOQT0=

Associação Brasileira de Normas Técnicas. (2015). *Concretos para fins estruturais – Classificação pela massa específica, por grupos de resistência e consistência* (ABNT NBR No.8953). https://www.abntcatalogo.com.br/norma.aspx?Q=QXhjajFQUFZ1bkRXVkNLQVVxNlBobDZ0T3RaUjIyWmEweTdWbWFSVzJwcz0=

Biz, C. E. (2001). *Reactive powder concrete* [Master's thesis, School of Engineering]. UNICAMP Campus Repository. https://core.ac.uk/download/pdf/296831426.pdf

Bonneau, O., Poulin Jr, C., Dugat, M., & Tcin, P-C. A. (1996). Reactive Powder Concretes: From Theory to Practice. *Concrete International*, *18*(4), 47–49. Retrieved from https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/1405

Cervieri Júnior, O., Teixeira Junior J. R., Galinari R., Rawet E. L., & Silveira C. T. J. (2014). *The beverage sector in Brazil.* BNDES. https://web.bndes.gov.br/bib/jspui/bitstream/1408/3462/1/BS%2040%20O%20setor%20de%20bebidas%20no%20Brasil_P.pdf

Dobiszewska, M., Schindler, A. K., & Pichór, W. (2018). Mechanical properties and interfacial transition zone microstructure of concrete with waste basalt powder addition. *Construction and Building Materials*, *177*, 222–229. https://doi.org/10.1016/j.conbuildmat.2018.05.133

Ecycle. (2015). *Are all types of glass recyclable?* https://www.ecycle.com.br/tipos-de-vidro/

Eva, Z., Kamila, H., Tereza, K., Patrik, S., Jiří, Š., & Ondřej, A. (2020). NDT Methods Suitable for Evaluation the Condition of Military Fortification Construction in the Field. *Applied Sciences*, 10(22), 8161. https://doi.org/10.3390/app10228161

Gusmão, A. C. (2017). *Use of reactive powders concrete as repair material: emphasis on adhesion resistance* [Master's thesis, Federal University of Viçosa], FUV Campus Repository. https://www.locus.ufv.br/bitstream/123456789/17686/1/texto%20completo.pdf

Han, B., Li, Z., Zhang, L., Zeng, S., Yu, X., Han, B., & Ou, J. (2017). Reactive powder concrete reinforced with nano SiO_2-coated TiO_2. *Construction and Building Materials*, *148*, 104–112. https://doi.org/10.1016/j.conbuildmat.2017.05.065

Idir, R., Cyr, M., & Tagnit-Hamou, A. (2010). Use of fine glass as ASR inhibitor in glass aggregate mortars. *Construction and Building Materials*, *24*(7), 1309–1312. https://doi.org/10.1016/j.conbuildmat.2009.12.030

John, V. M., & Agopyan, V. (2000). *Reciclagem de resíduos da construção*. In . São Paulo: Secretaria de Estado do Meio Ambiente / Cetesb.

Li, L., Zheng, Q., Wang, X., Han, B., & Ou, J. (2022). Modifying fatigue performance of reactive powder concrete through adding pozzolanic nanofillers. *International Journal of Fatigue*, *156*, 106681. https://doi.org/10.1016/j.ijfatigue.2021.106681

Luo, W., Wang, H., Li, X., Wang, X., Wu, Z., Zhang, Y., … Li, X. (2022). Mechanical Properties of Reactive Powder Concrete with Coal Gangue as Sand Replacement. *Materials*, *15*(5), 1807. https://doi.org/10.3390/ma15051807

Matos, A. M., & Sousa-Coutinho, J. (2012). Durability of mortar using waste glass powder as cement replacement. *Construction and Building Materials*, *36*, 205–215. https://doi.org/10.1016/j.conbuildmat.2012.04.027

Paiva, H., Silva, L. M., Labrincha, J. A., & Ferreira, V. M. (2006). Effects of a water-retaining agent on the rheological behaviour of a single-coat render mortar. *Cement and Concrete Research*, *36*(7), 1257–1262. https://doi.org/10.1016/j.cemconres.2006.02.018

Política nacional de resíduos sólidos [recurso eletrônico]. Brasil. [Lei n. 12.305, de 2 de agosto de 2010]. 2. ed. – Brasília: Câmara dos Deputados, Edições Câmara, 2012. 73 p. – (Série legislação; n. 81) Atualizada em 18/5/2012 Institui a Política Nacional de Resíduos Sólidos; altera a Lei nº 9.605, de 12 de fevereiro de 1998 e dá outras providências. ISBN 978-85-736-5972-6. http: //fld.com.br/catadores/pdf/politica_residuos_solidos.pdf

Qing-hua, L., Qing-hua, L., Xing, Y., GUO Kang-an, & XU Shi-lang. (2022). Experimental study on the interfacial shear strength between ultra-high toughness cementitious composites and reactive powder concrete. *工程力学*, *39*(8), 232–244. https://doi.org/10.6052/j.issn.1000-4750.2021.05.0355

Recycloteca. (2016). *Glass: history, composition, types, production and recycling*. https://www.recicloteca.org.br/material-reciclavel/vidro/

Reindl, J. (2003). *Reuse/recycling of glass cullet for non-container uses*. Retrieved from https://archive.epa.gov/wastes/conserve/tools/greenscapes/web/pdf/glass.pdf

Resolução CONAMA No.307, DE 5 DE JULHO DE 2002. (n.d.). Retrieved from https://cetesb.sp.gov.br/licenciamento/documentos/2002_Res_CONAMA_307.pdf

Richard, P., & Cheyrezy, M. (1995). Composition of reactive powder concretes. *Cement and Concrete Research*, *25*(7), 1501–1511. https://doi.org/10.1016/0008-8846(95)00144-2

Righi, D., Köhler, L., Tabarelli, A., Kirchhof, L., & Lima, R. (2012) Análise de concretos produzidos com vidro moído quando submetidos à elevadas temperaturas. *XXXV Jornadas Sul-Americanas de Engenharia Estrutura, Brazil,* 35, 1-13. https://docplayer.com.br/26947425-Analise-de-concretos-produzidos-com-vidro-moido-quando-submetidos-a-elevadas-temperaturas.html

Sagoe-Crentsil, K., Brown, T., & Taylor, A. (2001). *Recycled glass as sand replacement in premix concrete: Guide specification*. Ed.CSIRO. Retrieved from https://p2infohouse.org/ref/26/25900.pdf

Shelby, J.E. (2020) *Introduction to glass science and technology* (3rd ed.). Royal Society of Chemistry.

Silva, C. O. (2003). *Critical analysis of the requirements and quality criteria of the adhesive mortar* [Master's thesis, Polytechnic School of the University of São Paulo]. USP Campus Repository. https://teses.usp.br/teses/disponiveis/3/3146/tde-03112003-170246/publico/Dissertacaoargamassacolante.pdf

Tafraoui, A., Escadeillas, G., & Vidal, T. (2016). Durability of the ultra-high performances concrete containing metakaolin. *Construction and Building Materials*, *112*, 980–987. https://doi.org/10.1016/j.conbuildmat.2016.02.169

Tokudome, N. (2008, November 7). *High-performance concrete is already passed*. ITAMBE. https://www.cimentoitambe.com.br/massa-cinzenta/concreto-de-altodesempenho-ja-e-passado/

United States Geological Survey 2020. (2020). *Mineral Commodity Summaries*. https://doi.org/10.3133/mcs2020

Vanderlei, R. D.; & Giongo, J. S (2006). *Experimental analysis of reactive powder concrete: dosage and mechanical properties* [Doctoral dissertation, School of Engineering of São Carlos]. USP Campus Repository.

Velichko, E. G., & Vatin, N. I. (2022). Reactive Powder Concrete Microstructure and Particle Packing. *Materials*, *15*(6), 2220. https://doi.org/10.3390/ma15062220

Wang, D., Shi, C., Wu, Z., Xiao, J., Huang, Z., & Fang, Z. (2015). A review on ultra-high performance concrete: Part II. Hydration, microstructure and properties. *Construction and Building Materials*, *96*, 368–377. https://doi.org/10.1016/j.conbuildmat.2015.08.095

Wang, Y., Sun, Q., Ding, H., Leng, S., Cui, H., Xu, B., & Cui, H. (2022). Investigation of Interfacial Bonding Properties of Polyurethane Concrete and Cement Concrete/Steel Reinforcement. *Advances in Materials Science and Engineering*, *2022*, 1–28. https://doi.org/10.1155/2022/5644468

Zanotto, E. D., & Mauro, J. C. (2017). The glassy state of matter: Its definition and ultimate fate. *Journal of Non-Crystalline Solids*, *471*, 490–495. https://doi.org/10.1016/j.jnoncrysol.2017.05.019

Zdeb, T. (2017). An analysis of the steam curing and autoclaving process parameters for reactive powder concretes. *Construction and Building Materials*, *131*, 758–766. https://doi.org/10.1016/j.conbuildmat.2016.11.026