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RESEARCH ARTICLE

Durability analysis of partial replacement of ordinary Portland cement by white glass waste concrete

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Abstract

Concrete consists of cement, water, fine aggregate, coarse aggregate, and air. The cement manufacturing process is responsible for a large carbon dioxide emission. Therefore, several research have been conducted to find advantageous substitute materials, even if only partially. Waste glass emerges as an alternative because it is a non-biodegradable inert material, with a high recycling rate and low cost. Several studies on recycled glass as a partial substitute for cement in concrete have already been conducted in terms of workability, strength, and properties, but few have reviewed the durability properties of concrete incorporating glass waste. It is a fact that durability is of great importance for the performance of concrete, because compromising it can lead to the emergence of pathologies. This article aims to carry out a study on the durability of concrete with the replacement of cement by glass waste, to verify its performance in relation to conventional concrete, identifying the advantages that attest to its use in civil construction as an alternative to concrete to be used in buildings, whether in new constructions or in the process of rehabilitation or maintenance.

Keywords Concrete · Cement · Waste glass · Durability

1 Introduction

Concrete is a composite material consisting of cement, water, fine aggregate (sand), coarse aggregate (stone or gravel) and air. It is considered the world's main building material and its worldwide consumption is estimated at 1.7 tons for every living human being [7]. Ordinary Portland cement, or hydraulic cement, is the key component of a country's construction industry and is made primarily of very fine ground clinker, which is composed of hydraulically active calcium and silicate minerals formed by the high temperature burning of limestone and other materials in a kiln. The adjective "hydraulic" refers to the ability of cement to consolidate (stiffen and hold a shape) and harden in the presence of a lot of water [26].

In its manufacturing process, cement is responsible for the emission of various gases, especially carbon dioxide (CO_2). 7 to 8% of all CO_2 emissions (approximately 1.4 billion tons/year) are due to the production of ordinary Portland cement [15, 17]. Data indicate that for every ton of clinker produced 870 kg of CO_2 are released into the atmosphere [23]. In addition, it is observed that the production of 1 ton of cement consumes around 1.6 tons of natural resources [13].

In this context, the scientific community has conducted much research to find advantageous materials as a substitute, even partially, for cement. Among the studies, the most usual waste mineral additions are blast furnace slag, fly ash, silica fume and rice husk ash. More recent research has shown the pozzolanic potential of sugarcane bagasse ash and vitreous waste [24].

The global supply of waste glass accounts for approximately 3% (130 million tons) of total cement consumption [12]. In the United States, for example, glass recycling accounts for only 2.99 million tons of glass against glass

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production of around 11.5 million tons [21]. On the other hand, Brazil produces an average of 980,000 tons of glass in the form of packaging and recycles 47% of that volume [14]. Impurities, type, color, and lack of sorting facilities hinder reuse and usually end up in stockpiles or landfills [3, 8].

Therefore, glass waste management can be considered as one of the main challenges faced by researchers and scientists worldwide due to the lack of open areas and landfills, the low recycling rate, and the absence of sufficient open area spaces [20, 27]. When glass is incorporated into concrete, it is cleaned of dirt and impurities, crushed in specific machines, and ground into different sizes of coarse, fine, and powdered glass particles. The use in concrete manufacturing is a favorable practice that can assist in absorbing a considerable amount of glass waste [18].

Previous studies have investigated the effect of glass addition, mixed with pozzolanic material, on concrete durability. Most have indicated improved concrete properties as a function of fineness and replacement level. Glass can be added in crushed or powdered form along with plasticizer additives or without the addition of any of the alternative materials in concrete [25]. However, the addition of this alternative material needs to be thoroughly reviewed to justify and emphasize the effectiveness of using recycled glass as a partial replacement for cement. The addition of glass to concrete leads to some strength and durability properties and it is possible to add it by partially replacing any of the ingredients in any form of glass [1].

Several studies on recycled glass as a partial replacement for cement in concrete have been reported in terms of workability, strength, and properties. However, few have reviewed the durability properties of concrete incorporating waste glass as a partial replacement to cement. Durability is of great importance for concrete performance, as it is not specified only by its fresh or mechanical properties. Thus, this paper aims to conduct a study on the durability of concrete with cement replacement by waste glass in the proportions of 10 and 20%, to verify the performance compared to conventional concrete, identifying the advantages that attest to the use of this material in civil construction, thus avoiding the emergence of pathological problems in concrete.

2 Methodology

The analysis procedure for the durability of concrete with partial replacement of cement by glass talc started with the dosage of mixtures to obtain concrete with 30 and 40 MPa compressive strength. With this, reference concrete and concrete with partial replacement of 10 and 20% in relation to the mass of cement were produced. Water penetration under pressure, chloride migration and electrical resistivity tests were performed to evaluate the durability properties of the concrete. For all tests, it was necessary to rectify the specimens so that the lower and upper surfaces were regular.

2.1 Mix design and procedure

Glass waste is a non-biodegradable inert material, with high recycling rate and low cost. It is observed in its composition a large amount of silica oxide, which can present pozzolanic characteristics, which in turn bring positive results regarding the mechanical properties of concrete [9], favoring its durability. Table 1 shows the composition of the glass talc used in this work.

The ordinary Portland cement and the white waste glass used, presented, specific masses equal to 2.90 and 2.59 g/cm^3, respectively and have the granulometric curve shown in Fig. 1, performed through a laser granulometry. For the waste glass, the diameter at 10% (D10) is 5.45 µm, diameter at 50% (D50) is 21.52 µm, diameter at 98% (D98) is 116.32 µm, and average diameter is 32.60 µm. As for the Portland cement used, there is a D10 of 4.04 µm, diameter at 50% (D50) of 12.46 µm, diameter at 98% (D98) of 70.87 µm and average diameter of 18.84 µm. As fine aggregates were used the river sand with maximum diameter of the aggregate of 4.75 mm and artificial gravel dust with DMC of 4.75 mm, and as coarse aggregates, there is the gravel 0 with DMC of 9.5 mm and gravel 1 with DMC of 19 mm.

The Portland cement, sands and gravel were collected at the Apodi Distribution Center in the city of Fortaleza—Brazil. The white waste glass was supplied by Eco Engenharia e Distribuição, being the result of a grinding process of windshield glass sent for recycling.

The mixtures considered for this work were 30 and 40 MPa, which were molded in three types: the reference (RC), without partial replacement of ordinary Portland cement by white glass talc, and the 10% (CG10) and 20% (CG20), both with partial replacement of white glass talc in relation to the cement. The materials used were ordinary Portland cement type CP-V, white glass talc, natural river sand and artificial stone powder sand, crushed stones 0 and 1, polyfunctional additive and water, as shown in Table 2. After concrete production, the specimens were molded according to NBR 7215 and submitted to wet curing for 28 days to perform the durability tests.

Table 1 Oxides compositions of the white waste glass

Oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	PF	Cr_2O_3
%	65.17	0.92	1.28	10.38	3.58	0.29	16.60	0.23	1.34	0.05

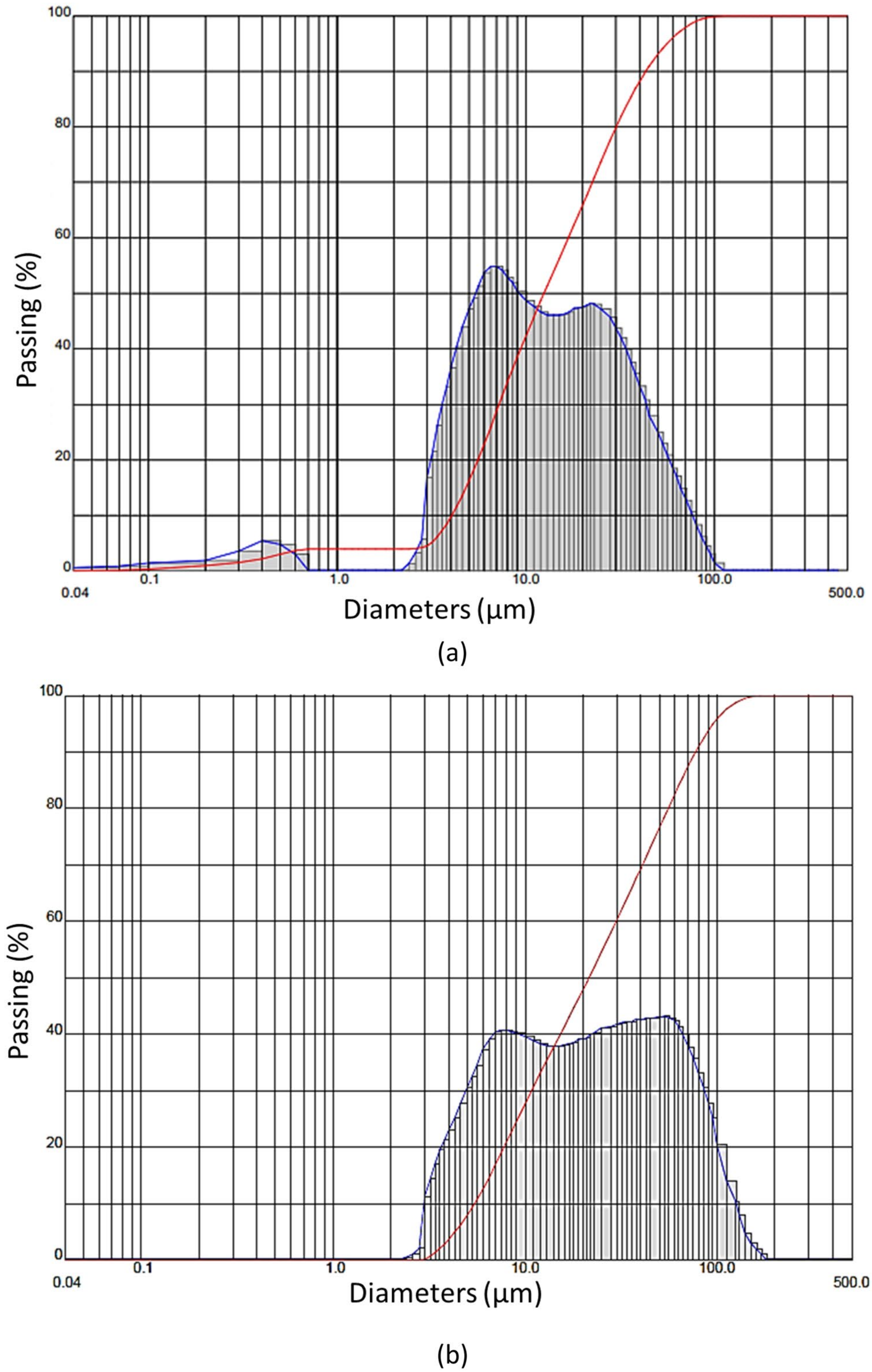

Fig. 1 Granulometry of the **a** cement **b** glass waste

The production methodology of the concretes was performed in the free fall concrete mixer following these steps: (i) 1-min mixing of coarse aggregates with 10% water; (ii) addition of homogenized binders and 80% of water and mixing for 4 min; (iii) addition of fine aggregates and mixing for 4 min; (iv) addition of the remaining 10% water and mixing for 2 min.

Table 2 Formulation of the used concretes

TRAÇO	Fck (Mpa)	CP-V (kg/m^3)	Glass powder (kg/m^3)	Natural sand (kg/m^3)	Artificial sand (kg/m^3)	Gravel 0 (kg/m^3)	Gravel 1 (kg/m^3)	SP (kg/m^3)	Water (kg/m^3)
Reference concrete (RC—30)	30	10.72	–	14.62	9.75	6.70	26.78	0.08	6.43
Reference concrete (RC—40)	40	13.76	–	12.89	8.57	6.69	26,79	0.11	6.67
Concrete with glass—10% (CG10-30)	30	9.65	0.96	14.62	9.75	6.70	26.78	0.08	6.43
Concrete with glass—10% (CG10-40)	40	12.38	1.23	12.89	8.57	6.69	26.79	0.11	6.67
Concrete with glass—20% (CG20-30)	30	8.58	1.92	14.62	9.75	6.70	26.78	0.08	6.43
Concrete with glass—20% (CG20-40)	40	9.90	2.46	12.89	8.57	6.69	26.79	0.11	6.67

2.2 Pressure water penetration test

The test was performed based on the standard NBR 10787 [6]—Hardened concrete—determination of water penetration under pressure. The experimental procedure aims to analyze the depth of water penetration at a controlled pressure. The test consists in using three specimens with dimensions of 10 cm in diameter and 20 cm in height, previously air dried for a period of 24 h before the start of the test after 28 days of wet curing (Fig. 2).

After positioning the specimens in the equipment, the register is opened for water intake, allowing it to fill the entire volume of the reservoir and pipes. After this procedure, the water admission valve for the specimens is opened. Initially and for a period of 48 h, a pressure of 0.1 MPa is applied. After this, the pressure is increased to 0.3 MPa for 24 h. Finally, the pressure is increased to 0.7 MPa for the final 24 h.

After these steps, all the confined pressure is released so that the specimens are removed from the assembly. Immediately after this procedure, they are broken in half, orthogonally to the face where the pressure was applied, and the depth of water penetration is measured.

2.3 Chloride migration test

An apparatus suggested by Andrade [4] and developed by Ribeiro [22], based on ASTM C 1202:19 ("Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration") was used. The test is

Fig. 2 Pressure water penetration test

composed of two chambers: one with a 3% Sodium Chloride solution and the other with 0.3 N sodium hydroxide. Two specimens are sawed, resulting in a total of 4 specimens of 10 cm in diameter and 5 cm in height for the test. The chloride flux is accelerated by means of an electric field, with a potential difference of 60 V, applied between the two chambers of the diffusion cell, with the help of two metallic electrodes as shown in Fig. 3. The test was performed after 28 days of wet curing by measuring the current intensity in Coulombs every 30 min, for 6 h. The objective is to calculate a charge in Coulomb associated with the migration of these chlorides through the specimen.

To obtain the results, the current intensity was measured, in Coulombs, every 30 min and during a total period of 6 h of testing. Using the equipment, it is possible to obtain chloride ion penetrability parameters based on the passing charge obtained in the test. The formula for obtaining the passing load is given by:

$$Q = 900 * (I_0 + 2I_{30} + 2I_{60} + \cdots + 2I_{300} + 2I_{330} + I_{360}) \quad (1)$$

where: Q is the passing load, I_t are the current (amperes) at t min after voltage is applied.

However, a correction must be made to the value of Q because the result of the load passing through the equipment is given for a PC with dimensions 9.5 × 5 cm and not the one with dimensions 10 × 5 cm, which was used. Thus, the correction equation is given by:

$$Q_s = Q_x * \left(\frac{95}{Q}\right)^2 \quad (2)$$

where: Q is the average passing load, Qx is passing load for 95 mm PC and Qs is corrected passing load for 100 mm PC.

The test assumes a direct relationship between the amount of through charge and chloride flow, therefore, a large amount of through charge represents a large "permeability" of concrete to chlorides [4]. Thus, with the passing load it is possible to measure, according to Table 3, the penetration rate of chlorides. The test readings are shown in the results item.

2.4 Electrical resistivity test

According to Halliday et al. [10], the electrical resistivity can be considered as the difficulty of electric current passing through an object, obtained by multiplying the ratio between the voltage that is applied and the current that results with a cell constant. The electrical resistivity is seen as one of the main parameters to evaluate the corrosion of reinforcement embedded in concrete [11].

For the evaluation of the concretes CR, CG10 and CG20, 4 specimens of each were used after 28 days of wet curing. To obtain the electrical resistivity indicator, it was followed with the guidelines of NBR 9204:2012 [5], being necessary that the upper and lower surfaces of the specimens had a good contact surface, which was obtained after the rectification process. After rectification, the measurements of the new dimensions of the specimens (diameter and height) were performed. The resistivity measuring principle consisted in applying a potential difference between two or more electrodes, positioned on opposite sides or on the same side of the specimen, aligned and pressed against the surface. Thus, the relationship between the applied voltage and the measured current provides the resistance of the current flow,

Table 3 Chloride ion penetration as a function of the passing charge

Through charge (Coulombs)	Penetration of chloride ions (Cl^-)
> 4000	Alta
2.000–4.000	Moderada
1.000–2.000	Baixa
1.00–1.000	Muito baixa
< 100	Insignificante

Adapted ASTM C1202 [2]

Fig. 3 Chloride migration test

in accordance with Ohm's law. For the analysis, the Resipod equipment from Proceq SA was used (Fig. 4).

The electrical resistivity (ρ) is determined by multiplying the resistance (R) by a correction factor, called cell constant (K), and depends on the dimensions of the specimen in which the resistivity measurements were taken, being the ratio of the section area by the length of the specimen [22]. By the description we have that:

$$\rho = K * Rcorrigido \quad (3)$$

where: ρ is the electrical resistivity (kΩ.cm); K is the cell constant (cm); R is the Resipod device reading (kΩ) and Rcorrigido = R/2πa (kΩ). The obtained values were compared to the evaluation criteria according to Table 4.

Table 4 Criteria for evaluating electrical resistivity

Concrete resistivity (kΩ cm)	Risk of corrosion
> 20	Negligible
10–20	Low probability
5–10	High probability
< 5	Very high probability

Adapted CEB, 1989

3 Experimental results

3.1 Penetration of water under pressure

The average of the maximum penetration of water under pressure is shown in Fig. 5a. Figure 5b shows the rupture of two specimens, which were performed orthogonal to the face where the pressure was applied. It was observed that the highest average of water penetration is 65 mm in the CG20-40 concrete. For the 30 MPa concrete, similar average values of water penetration under pressure were observed, ranging between 32.67 and 36.67. For concretes of 40 MPa, it was observed that the higher the percentage of glass, higher the water penetration. This fact may be related to the grain sizes of the glass waste, which are larger than those of the cement, reducing the filler effect.

Despite the variation in water penetration values, according to Neville and Brooks [19], the values found are considered low, except for CG20-40. Neville and Brooks [19] argues that a concrete in which the penetration measurement of less than 50 mm is obtained is classified as "impermeable", and if less than 30 mm, it is classified as "impermeable under aggressive conditions". However, it is important to note that concrete permeability can be influenced by many factors, such as: compaction, curing, differences in material homogeneity, among others [6]. This fact is positive in relation to the durability of concrete with glass, since it showed low ability to be traversed by fluid even under pressure, which can avoid the action of external agents harmful to the material.

3.2 Chloride migration

From the electric current data over time, the average passing charges for each type of concrete were calculated and are presented in Fig. 6. For the 30 MPa concrete the glass replacement caused an increase in the current, and the consequent higher passage of chloride ions. For the 40 MPa concretes, the same occurred, except for CG20-40, which presented the lowest average passing load, representing the lowest passage of chloride ions. Even with the differences, all concrete fits into the same classification, although in most cases, mixtures with glass presented higher values of chloride penetration. It is then observed, after data correction, that all concretes are classified as moderate with respect to chloride ion penetration (Table 3), in accordance with the average passing load limits established in the test standard (2000 C < Q < 4000 C).

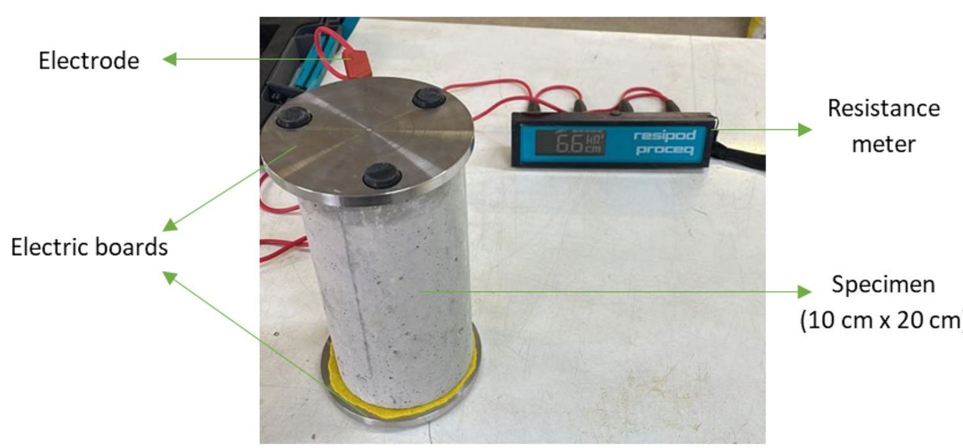

Fig. 4 Electrical resistivity test

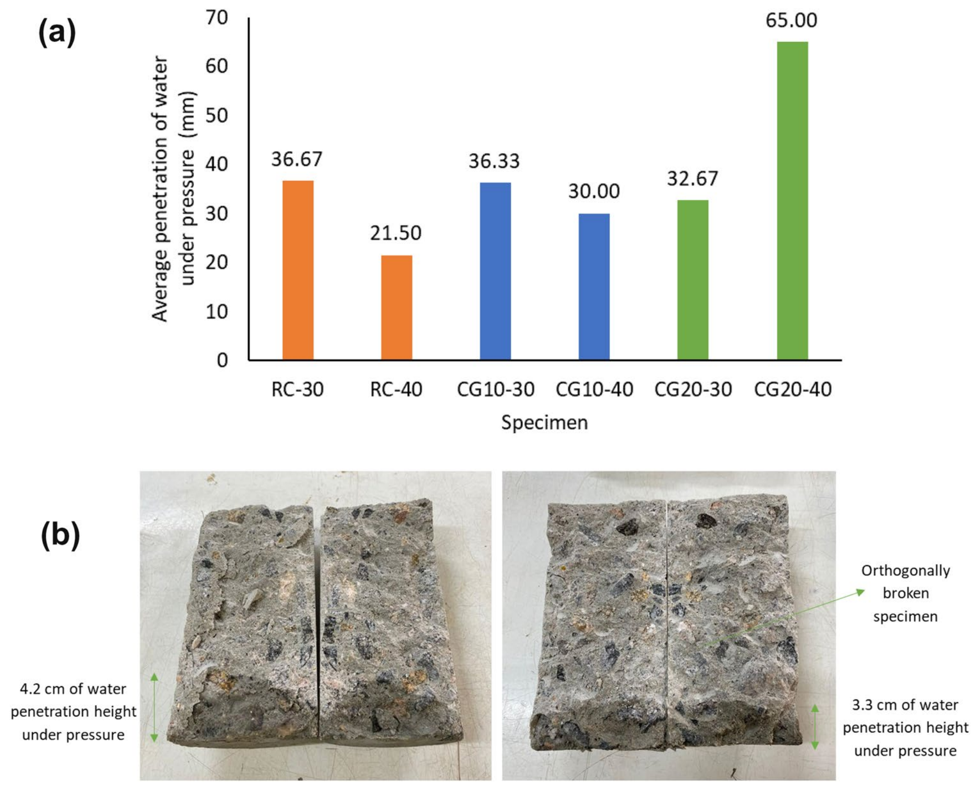

Fig. 5 Results of the pressurized water penetration test: **a** the penetration depth of the test and **b** the specimens after the pressurized water penetration test

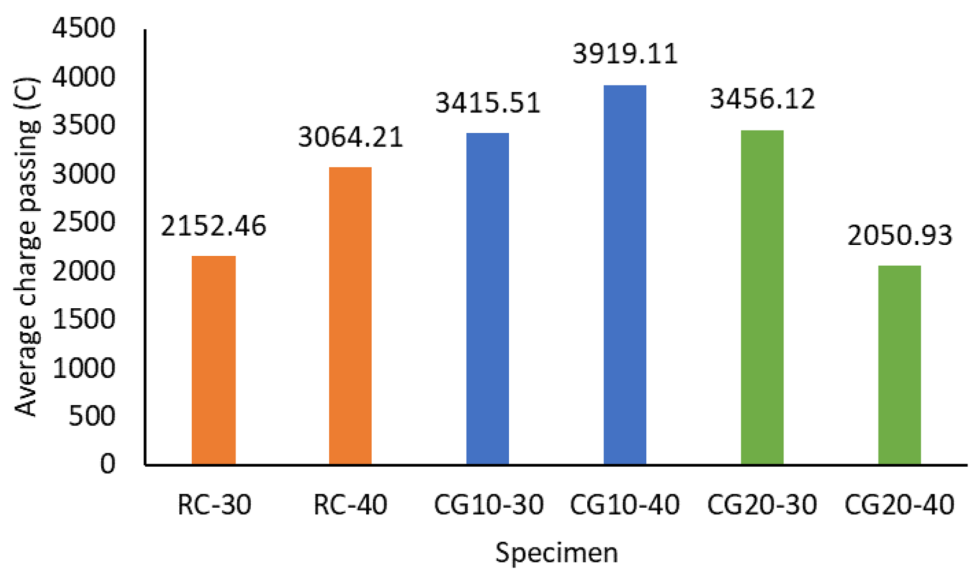

Fig. 6 Chloride migration test results

3.3 Electrical resistivity

Figure 7 shows the electrical resistivity values of the studied concretes. The use of white waste glass in the 30 MPa concrete favored an increase in electrical resistivity. For the 40 MPa concretes, the inverse occurred with the percentage increase of glass substitution. The concretes RC-40, CG10-30 and CG20-30 were classified as low probability of corrosion risk and concretes RC-30, CG10-40, and CG20-40 as high probability of corrosion risk, according to Table 4. In accordance with Medeiros Júnior et al. [16], it is related to concrete permeability and its resistance to the penetration of aggressive agents (CO_2 and chlorides). Despite the different classifications, the electrical resistivity test did not demonstrate significant differences between the studied materials.

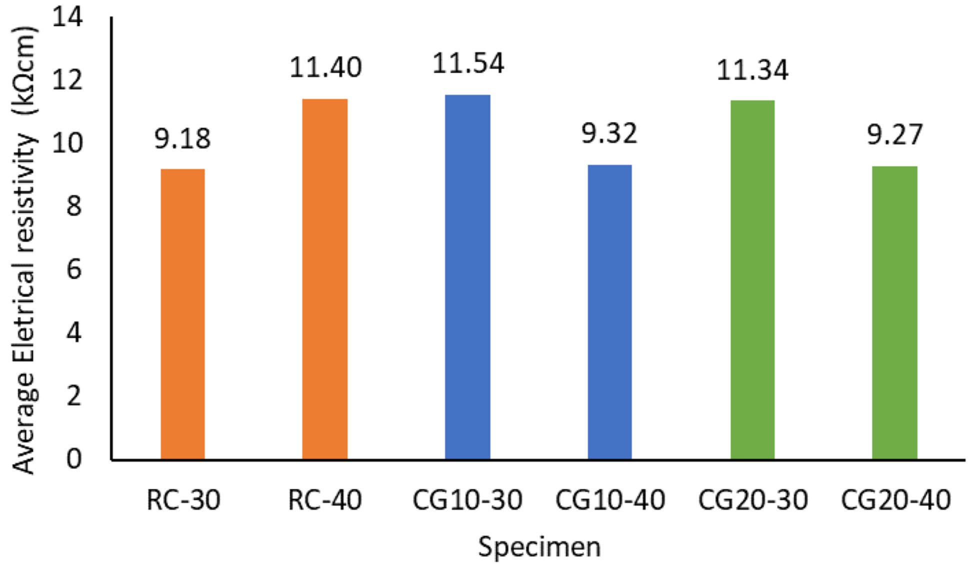

Fig. 7 Electrical resistivity test results

4 Conclusions

This research aimed to contribute to the durability analysis of concrete with alternative materials, to predict future pathological manifestations in buildings. In the case of the white waste glass in this research, it sought to validate its use in concrete, from the analysis of the changes in properties obtained as a result of the replacement of Portland cement by the glassy residue.

From the results of the experimental tests, for the water penetration under pressure test, it can be concluded that from a certain value of cement replacement by glass waste, with its current granulometry, a more porous concrete is obtained. Regarding the chloride migration test, it can be concluded that there were no significant differences among the concretes under study and that all of them fit the same classification concerning chloride ion penetrability, although in the majority, mixtures with glass waste have presented higher chloride penetration values. For the electrical resistivity tests, it was found that the results of the concretes were classified with low probability of corrosion risk for some concretes such as RC-40, CG10-30 and CG20-30, and high probability of corrosion for concretes RC-30, CG10-40, and CG20-40, with no great differences in classification among the concretes.

Despite having shown, in general, inferior results when compared to Portland cement concrete, the concrete with replacement by white glass waste presented a positive performance regarding durability, since it has low porosity and low capacity to be crossed by fluid even under pressure, preventing the action of external agents harmful to the material. Thus, the material can be considered a viable option for use mainly in environments that have lower or moderate classes of environmental aggressiveness.

Given all the above, it can be affirmed that white glass waste is a viable alternative as a partial replacement for Portland cement. The main advantage in civil construction is the production of a more sustainable concrete, with a smaller amount of cement use, thus reducing costs with the purchase of Portland cement. In addition, the tests point to the viability of it uses in construction or maintenance of buildings that are mainly in environments with weaker or moderate environmental aggressiveness class, as indicated in the NBR 6118:2014. This fact demonstrates that concrete with the partial replacement of cement by white glass waste can provide an alternative to the construction and rehabilitation processes of buildings.

For future research, it is suggested the use of waste glass in smaller maximum diameters, as well as the evaluation in percentages between 10 and 20% to obtain an optimum percentage for use of the material to improve its filler effect and its durability properties, avoiding future pathological manifestations.

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Author contributions MJSF, MLDS, VCPV wrote the article, performed tests and made revisions, as well as figures and tables. AEBC performed a review of the article.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Ali EE, Al-Tersawy SH (2012) Vidro Reciclado como Substituto Parcial de Agregado Fino em Concreto Autocompactável. Constr Construir Mate 35:785–791
2. American Society For Testing and Materials (2019) C1202: standard test method for electrical indication of concrete's ability to resist chloride ion penetration. West Conshohocken
3. Amin M, Zeyad AM, Tayeh BA, Agwa IS (2022) Efeito do ferrosilício e da sílica ativa nas características mecânicas, de durabilidade e microestrutura do concreto de ultra alto desempenho. Constr. Construir. Mate., 320, Artigo 126233.
4. Andrade C (1993) Calculation of chloride diffusion coefficients in concrete from ionic migration measurements. Cem Concr Res 23(3):724–742
5. Associação brasileira de normas técnicas (2012) NBR 9204: Concreto endurecido – Determinação da resistividade elétrico-volumétrica. Rio de Janeiro
6. Associação brasileira de normas técnicas (2011) NBR 10787: Concreto endurecido—Determinação da penetração de água sob pressão, Rio de Janeiro.
7. Diab AM, Awad AEM, Elyamany HE, Abd Elmoaty AEM (2012) Guidelines in compressive strength assessment of concrete modified with silica fume due to magnesium sulfate attack. Constr Build Mater 36(Nov):311–318
8. Dong W, Li W, Tao Z (2021) Uma revisão abrangente sobre o desempenho de concretos cimentícios e geopoliméricos com resíduos de vidro reciclado como pó, areia ou caco de vidro. Recurso Conserva Reciclar 172:105664
9. Gomes CC (2012) Propriedades mecânicas do concreto com adição de vidro reciclado
10. Halliday D, Resnick R, Walker J (2009) Fundamentos de Física, volume 3: eletromagnetismo. Jearl Walker: tradução e revisão técnica. Ronaldo Sérgio de Biasi. LTC, Rio de Janeiro, p 395
11. Hornbostel K, Larsen CK, Geiker MR (2013) Relationship between concrete resistivity and corrosion rate—a literature review. Cem Concr Compos 39:60–72
12. Islam GMS, Rahman MH, Kazi N (2017) Waste glass powder as partial replacement of cement for sustainable concrete practice. Int J Sustain Built Environ 6:37–44. https://doi.org/10.1016/j.ijsbe.2016.10.005
13. Jennings HM, Bullard JW (2011) From electrons to infraestructure: engineering concrete from the bottom up. Cem Concr Res 41:727–735
14. Miranda EJP Jr, Bezerra HD, Politi FS, Paiva AE (2014) Increasing the compressive strength of portland cement concrete using flat glass powder. Mater Res 17:45-50. https://doi.org/10.1590/S1516-14392014005000058
15. Malhotra VM (2002) Introduction: sustainable development and concrete technology. Concr Int 24(7):22
16. Medeiros Junior RA, Lima MG (2015) Variação da resistividade elétrica do concreto com o formato de corpos de prova para diferentes tipos de cimento. Revista de Engenharia e Cimento. 2015
17. Miller SA, Horvath A, Monteiro PJM (2016) Readily implementable techniques can cut annual CO_2 emissions from the production of concrete by over 20%. Environ Res Lett 11:074029
18. Nassar RUD, Soroushian P, Sufyan-Ud-Din M (2021) Desempenho de Campo de Longo Prazo do Concreto Produzido com Resíduos de Vidro em Pó como Substituição Parcial do Cimento. Estudo de Caso Constr Mate 15:e00745
19. Neville AM, Brooks JJ (1997) Concrete technology: update. 2. rev. Singapura, 1997
20. Pereira-de-Oliveira LA, Castro-Gomes JP, Santos PM (2012) Potencial atividade pozolânica de resíduos de vidro e cerâmica vermelha como componentes de argamassas cimentícias. Constr Construir Mate 31:197–203
21. Rashidian-Dezfouli H, Afshinnia K, Rao P (2018) Efficiency of ground glass fiber as a cementitious material, in mitigation of alkali-silica reaction of glass aggregate in mortars and concrete. J Build Eng 15(July):171–180
22. Ribeiro DV (2010) Influência da adição da lama vermelha nas propriedades e na corrosibilidade do concreto armado. Tese (Doutorado). Programa de Pós-Graduação em Ciência e Engenharia de Materiais. São Carlos, p 224
23. Ruiz-Santaquiteria C, Fernandez-Jimenez A, Palomo A (2009) Cementos de bajo impacto ambiental: activación alcalina de aluminosilicatos. In: X Congreso Latinoamericano de Patología Y XII Congreso de Calidad En la Construcción. CONPAT 2009. Valparaíso, Chile. Anais, 2009
24. Sales FA (2014) Estudo da atividade pozolânica de micropartículas de vidro soda-cal, incolor e âmbar, e sua influência no desempenho de compostos de cimento Portland
25. Singh B, Jain R (2018) Avanços em Agricultura e Ciências Naturais para Agricultura Sustentável (12 e 13 de outubro de 2018) Uso de Resíduos de Vidro em Concreto: Uma Revisão. J Pharmacogn Fitoquímica 5:96–99
26. Van Oss HG, Padovani AC (2002) Cement manufacture and the environment: Part I: Chemistry and technology. J Ind Ecol 6:89–105. https://doi.org/10.1162/108819802320971650
27. Zhang T, Gao P, Wei J, Yu Q (2013) Eficácia de métodos novos e tradicionais para incorporar resíduos industriais em materiais cimentícios—uma visão geral. Recurso Conserva Reciclar 74:134–143