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Effects of windshield waste glass on the properties of structural repair mortars

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ABSTRACT

The use of waste glass incorporated into construction materials has been the focus of several studies. Its utilization in cementitious matrices as a cement surrogate has been the most suitable application because of its potential pozzolanic properties. In this study, the influence of varying the amount of cement replaced by waste glass on several mechanical properties considered essential to ensuring the performance of mortars in structural repair, such as compressive strength, modulus of elasticity, linear shrinkage and tensile bond strength, was analyzed. Additionally, the influence of waste glass on water absorption by capillarity and the microstructure of these mortars were also assessed. The results indicate the potential use of this waste material for cement mortars. The 5% replacement rate showed the best results.

1. Introduction

The construction industry is a major consumer of natural resources and a significant waste generator. New alternatives have arisen to minimize these impacts, including the reuse of waste incorporated into construction materials, which has been suggested as an appropriate way to preserve natural raw materials, save energy, reduce pollutant emissions and eliminate landfill costs [1,2].

Among the various wastes generated in Brazil, waste glass stands out. In 2011, an estimated 3 million tons of glass was produced, half of which was flat glass, which is mainly used by the construction and automotive industries. Automobile production consumed 10% of the flat glass produced, using this glass in laminated glass windshields, among other purposes [3]. Laminated glass windshields consist of two or more flat glass layers joined by an organic polymer called polyvinyl butyral (PVB) [4], and the reuse of waste automotive glass after its useful life is limited due to the difficulty of completely separating the PVB from the glass. Hence, waste automotive glass is generally disposed of in landfills.

Several studies have been conducted using waste glass incorporated into concrete and mortar as a partial substitute for either the fine aggregate [5–11] or the cementitious material [12–18,20] in an attempt to take the advantage of the pozollanic nature of the residue. Idir et al. [12] studied the pozollanic behavior of glass residue. The authors evaluated the relationship between the waste pozollanic behavior as a function of the particles grain size. They conclude that particles with grain size greater than 0.1 mm showed small pozzolanic activity. However, for particles with grain size smaller than 0.08 mm the pozollanic characteristics were increased being even higher for materials with grain size smaller than 0.04 mm, which confirms the smaller the grain size of the glass waste the greater the pozollanic index. Those results were also stated by other researches [14,17–19] as presented in Table 1.

These uses confirm the pozzolanic potential shown by this waste when used at a grain size below 0.075 mm. This behavior arises due to the significant amount of amorphous silica in the composition of waste glass. At this grain size, waste glass inhibits the alkali-silica reaction, and in mortars with up to 20% of the cement replaced by waste glass, the expansion caused by the reaction is reduced with increasing replacement degree [14,18].

The studies conducted to evaluate the mechanical performance of cementitious matrices with waste glass, concrete and mortar with up to 20% replacement show results above the reference value for compressive strength [7,10,11,14]. The dynamic modulus of elasticity displayed no significant differences in the results with respect to the variation in the substitute content in the mortars [11,14]. This variation affects the linear shrinkage of the mortars, and the drying shrinkage is reduced with increasing replacement level [9,11,16].

The ability of the mortar to bond to the substrate is directly linked to the other mechanical properties mentioned above. Thus, when evaluating this capacity, Penacho [10] found higher values of

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Table 1
Studies about pozollanic activity index as a function of particles grain size.

Authors	Glass waste grain size	Pozollanic activity index at 28 days (%)
Paiva et al. [14]	5 μm	104
Khmiri et al. [17]	⩽40 μm	85
Matos and Souza-Coutinho [18]	⩽75 μm	90
Pereira-de-Oliveira et al. [19]	⩽75 μm	85
Idir et al. [12]	⩽80 μm and ⩽41 μm	>90

bond strength in mortars with 20% of the cement replaced by waste glass.

Due to these characteristics, finely milled waste glass can be considered a pozzolanic addition [19] that also acts as a filler, reduces porosity and permeability and yields denser mortars than the reference materials, thus increasing the durability [11,18]. Further, there is significant potential for the use of waste glass as a partial substitute for materials such as active silica and fly ash [17,19].

Structural repair mortars based on Portland cement with active silica are widely used in surface repair systems [21]. The compatibility of the physical properties of the mortars with the substrate to which they will be applied is essential, so that a perfect interaction is achieved between these materials [22].

Although there are many studies referring to the use of waste glass in cement systems, the use of this material for structural repair mortars are not many. To contribute in this subject, this study intends to evaluate the effects of windshield waste glass on the properties of structural repair mortars by replacing part of the cement by different percentages (0%, 5%, 10%, 15% and 20%) of glass waste. Several mechanical properties such as compressive strength, dynamic modulus of elasticity, linear shrinkage and tensile bond strength were evaluated. The permeability of the mortar materials based on capillary water absorption testing is also assessed. Moreover, the studied mortars microstructure is investigated using scanning electron microscopy to understand the influence of the elements present in the microstructure with respect to the strength, dimensional stability and durability of the studied mortars.

2. Materials and methods

2.1. Materials

Portland-type cement with high-early-strength strength (Brazilian type CPV-ARI) with a Blaine specific surface area of 477 m^2/kg and a specific gravity of 3.05 was used to prepare the mortar in accordance with the Brazilian standard NBR 5733 [23]. Quartzose sand extracted from natural deposits was used as fine aggregates, classified according to the Brazilian standard NBR 7211 [24] within the optimal range, with a fineness modulus equal to 2.71, a characteristic maximum dimension of 2.36 mm and a specific mass of 2.62 g/cm^3.

The waste glass used in this study as a partial cement surrogate originated from vehicle windshields and was provided by a glass recycling plant located in the São Paulo state of Brazil, where this material is milled and sold to packaging industries or is intended for disposal in landfills because the waste glass resulting from this process is contaminated with a small amount of PVB. This waste glass was milled in the laboratory for 40 s in fractions of 50 g using a ring roller mill, which resulted in 98% of particles smaller than 75 μm. Fig. 1 shows the distribution of the waste glass particles and cement used in this study. The physical and chemical characteristics of the waste and cement are shown in Table 2.

The high content of loss-on-ignition of the waste glass (three times the value found for cement) was due to the amount of PVB, which is an organic material that was still present in the waste. Further, according to the Brazilian standard NBR 12653 [25], the high content of reactive silica present in the waste glass satisfies the basic chemical requirement for a pozzolan. However, this material does not meet the alkali content requirement due the high percentage of Na_2O. X-ray diffraction was carried out using an XDR 6000 device. The results showed that this residue is predominantly in the amorphous state (Fig. 2).

The pozzolanicity of this residue was confirmed with the pozzolanic activity index of the cement at 28 days, yielding the value of 86.36%. The minimum established by the Brazilian standard NBR 12653 [25] for pozzolanic materials is 75%.

The use of a concentrated natural resin-based and chloride-free plasticizer additive was necessary to ensure mortar workability and achieve the preset consistency index of 200 ± 10 mm.

2.2. Sample preparation and test methods

Mortars were produced with a water/cement ratio of 0.4 and a binder/aggregate ratio of 1:3 by mass, designed to achieve a value of 30 MPa, which is a very common average compressive strength in conventional concrete structures in Brazil. The materials proportions, according to the content of the cement surrogate by waste glass, are described in Table 3. The mortars were prepared according to Brazilian standard NBR 7215 [26]. Table 4 shows the required steps for mixing the mortar components.

Tests to determine the flow of hydraulic cement mortar was also performed to guarantee mortar workability in accordance to the Brazilian standard NBR 13276 [27].

Because there are no standards in Brazil for evaluating the properties of structural repair mortar, the test methodology proposed by Mattos [21], who compared industrialized repair mortars with repair mortars using active silica produced in the laboratory, was selected. For the compressive strength, the dynamic modulus of elasticity and the capillary water absorption test, cylindrical test specimens of 50 × 100 mm were molded and cured by immersion in lime-saturated water. The axial compressive strength tests were conducted at 7, 28, 63 and 270 days in accordance with Brazilian standard NBR 5739 [28]. The determinations of the dynamic elasticity modulus were performed at 28, 63 and 270 days, using an ultrasonic pulse velocity measurer according to ASTM E494 [29]. Water absorption by capillarity was observed in the mortar after 63 days of aging, according to the methodology described in Brazilian standard NBR 9779 [30].

Mortar linear shrinkage tests were performed on prismatic test specimens measuring 25 × 25 × 285 mm, cured under ambient conditions, at ages determined by Brazilian standard NBR 15261 [31]. The mortars were protected against evaporation for the first 48 h after molding, when unmolded, and during the initial measurements.

The tensile bond strength was determined on the seventh day after mortar application onto the standard substrate, only for the mortars with 0%, 10% and 20% replacement levels of cement by waste glass, using prismatic test specimens measuring 100 × 100 × 15 mm, according to Brazilian standard NBR 13528 [32]. For this test procedure, three reinforced concrete substrates were produced and cured in ambient temperature for 28 days prior to the mortar application. After curing, mortars were applied to the substrates and left for three days in laboratory. After three days, it was made a cut in the mortar-substrate region to delimitate the testing area and 100 × 100 mm metallic ingots were fixed in the mortars using epoxy. The tensile bond strength tests were then performed after 7 days of the mortar application to the concrete substrate applying a constant loading rate of 250 N/s.