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Pozzolanic effect of porcelain polishing residue in Portland cement

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ABSTRACT

Ceramic tiling is used on a large scale by the construction industry. The production process of tiles produces porcelain polishing residues (PPR), one of the main residues in the sludge, with loss rates above 1%. Since it is a residue that is impure for reuse in the process, it ends up being discarded in landfills. However, considering its characteristics, its fineness and chemical composition, its potential as a pozzolanic material was evaluated for use in the manufacture of cement-based construction materials in order to improve their yield. Tests were conducted on mortar and cement pastes using substitutions of 5%, 10% and 20% cement by PPR. The results of compressive strength (at 84 days) determined for the mortars showed an increase of 18%, with reduced cement consumption per MPa/m^3 for mortar of 11.5 kg MPa^{-1} m^{-3} at 0% and 7.5 kg MPa^{-1} m^{-3} at 20% residue content. Thermogravimetric analysis revealed that the portlandite formed by cement was consumed by the silica present in the residue, forming calcium silicate hydrate (C–S–H), which characterizes a pozzolanic reaction. This effect contributed to the study and to the applications of supplementary cementitious materials, while optimizing the use of Portland cement and reducing the environmental impact of carbon dioxide emissions originating from its production.

1. Introduction

Sustainability in construction is currently a major concern, given the important environmental, social and economic impacts of this industry, and cement consumption should be one of the principal considerations when manufacturing materials. The ecological footprint of the cement industry determines the reduction in consumption of clinker to minimize the environmental impacts of carbon dioxide emissions (Marland et al., 2008; Schneider et al., 2011; Yang et al., 2014), it can be currently considered a social problem and also economic. It is expected that the production of cement – 4 Mt last year – will double by 2050 (Cement Technology Roadmap, 2009), and with it, the cost to mitigate its environmental impact will also increase (Schneider, 2014). On the another hand, ceramic waste arising from the polishing process of porcelain tiles generates large amounts of waste that require disposal and water treatment of the solid part in controlled landfills at substantial financial and environmental cost.

The synergistic effect of porcelain polishing residue (PPR) as supplementary cementitious materials (SCM) has been reported, enhancing the effect of Portland cement in cementitious materials. Besides its filler effect (Wild et al., 1996; Pelisser et al., 2012), PPR can maximize hydration in Portland cement because it contains high amounts of amorphous silica and alumina, which promote the pozzolanic reaction (Mehta and Monteiro, 2006). During hydration, the residue can act as nucleation centers due to its small particle size after polishing, thus reducing permeability and consequently increasing the durability of cement-based materials.

Tests were conducted on cement pastes and mortars using 10% and 20% (mass) additions of PPR (Pelisser et al., 2012). The compressive strength results on mortars at 56 days age showed a 50% increase in strength. Thermogravimetric (TG) results showed that portlandite was consumed by the silica present in the residue in order to form C–S–H, thus characterizing a pozzolanic action. This feature improves cement performance, assisting in the research and application of supplementary cementitious materials (SCM) and the use of Portland cement, increasing the efficiency ratio of cement consumption – Binder index (*bi*) (Damineli et al., 2010).

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The residue derived from the polishing step in the manufacture of ceramic tiles is a common waste in many companies that use polishing and grinding operations to produce ceramic tiles, particularly porcelain tiles. In the polishing operation, silicon carbide and diamond abrasives are used in automated machines refrigerated with water, and roughly 1 mm of the tile surface is removed. Therefore, the polishing residue is composed of a mixture of both the abrasive tools and the ceramic tile, which is then processed in effluent treatment plants. The ceramic tile industry is a significant source of this type of residue, and most residues show similar characteristics. Locally, ceramic tile companies in southern Santa Catarina State, Brazil, produce an estimated one thousand ton of residue each week.

It is increasingly important that the current development of mortars and concretes ensures that they are economic, structurally durable and sustainable. The search for more efficient materials is constantly evolving, to improve the cost/benefit ratio and to address the ongoing concern with reusing materials, including solid residues, from other segments of the industry in order to reduce the overall environmental impact (Shi et al., 2011; Novais et al., 2015).

In this context, PPR from the tile production process was obtained from a ceramic tile company in southern Santa Catarina State, Brazil. Previous analyses have shown that tests involving cement pastes and mortars adding 10% and 20% (mass of cement) result in significant increases in compressive strength in mortars, greater than 50% – up to 56 days (Pelisser et al., 2012). The results of thermogravimetric analysis (TGA) show that portlandite formed by the cement is consumed by the silica present in the residue in order to form calcium silicate hydrate; this characterizes a pozzolanic reaction. To establish greater industry credibility, in this study, we evaluated the pozzolanic activity index considering technical standards ASTM C 311 (1996), using two types of cement, and determined the strength of the products up to 84 days.

2. Materials and methods

Eight mixtures of cement, sand and water (1:3:0.60 – by mass) were fabricated substituting 0% (reference mix), 5%, 10% and 20% cement with PPR, using two types of cement: Brazilian type CPII-Z32 and CPV Portland cements (equivalent to ASTM type MH-II standard and ASTM type III – high early strength). Standard sand (NBR 7215, 1996) was used, mixing the sand in four particle sizes (main diameters of 0.15–0.3 mm, 0.3–0.6 mm, 0.6–1.2 mm and 1.2–2.4 mm). The PPR was dried at 60 °C, characterized by chemical analysis (X-ray fluorescence, PW-2400/Philips; fused sample), and particle size distribution analysis (laser diffraction, 1064/Cillas; 0.04–500 μm) for the purpose of classifying it as a pozzolanic material in accordance with the ASTM C618 (2005) standard. The consistency index for all mixtures was maintained constant at 27 ± 2 cm (Flow-Table Test, EN 1015-3, 2007).

The following characterization tests were performed:

i) The mortar mixtures were characterized for compressive strength (ASTM C 1231, 2010), at 28 and 84 days. Compressive strength testing was conducted in a universal testing machine (EMIC/PC 200I, 0.5 MPa/s) on three specimens measuring 5 × 10 cm (diameter × length) and the mortar compressive strength results were analyzed by Analysis of Variance (ANOVA). The pozzolanic activity index was determined according to the norm ASTM C 311 (1996), following the substitution of 20% cement by PPR, which was calculated as the percentage ratio between the mean compressive strength of mortar with the substitution and the mean compressive strength of the reference mortar.

ii) Calorimetry tests were conducted at 22 °C in a calorimeter (TA Instruments – TAM) under atmospheric air. The cement pastes (w/c = 0.40 – water/cement ratio) were mixed before testing (11 ± 0.1 g sample mass).

iii) Thermogravimetric analysis (TGA) was performed in a thermal analyzer (TA Instruments SDT Q600). The samples were cured for 84 days and dried at 50 °C for 10 min to prevent moisture changes in the samples; then the temperature was raised to 800 °C at a heating rate of 10 °C/min and 100 mL/min N_2 flow using a platinum crucible. Previously, the samples were ground in a micro-mill with an agate mortar and sieved through a 75 μm mesh, then maintained in a vacuum oven (50 °C) prior to analysis.

Using the TGA results, the amount of calcium hydroxide (CH) was calculated due to the mass loss that occurs during the decomposition of the water released in the thermal decomposition of PMCH (calcium hydroxide mass loss) phase, using equation (1) (Silva et al., 2002):

$$CH = PMCH(\%) \times \left[mmCa(OH)_2 / mmH_2O\right] \quad (1)$$

where $mmCa(OH)_2$ is the molar mass of calcium hydroxide and mmH_2O is the molar mass of water.

3. Results and discussion

Based on the chemical analysis and the average particle size of polishing residue (PPR; Table 2), where the sum of $SiO_2 + Al_2O_3 + Fe_2O_3$ was equal to 84 wt% and the average diameter was 10.1 μm (Table 2), it is reasonable to conclude that PPR can be classified as a pozzolanic material in accordance with the ASTM C618 (2005) standard. The standard recommends that the sum of $SiO_2 + Al_2O_3 + Fe_2O_3$ should be at least 70 wt% for a particle size with an equivalent diameter of less than 45 μm. However, high alkali content (Na_2O and K_2O) is not recommended for concretes due to harmful alkali-silica reactions in the presence of amorphous silica. The cement chemical analysis showed a typical Portland cement composition, with silica and calcium oxide as the main components (Table 1) and the average diameter was 12.1 μm and 16.9 μm for cement types CP-V and CP-IIZ, respectively (Table 2). The particle size distributions of Portland cement and the PPR residue were similar, particularly for the CP-V type.

The results of compressive strength at 28 days showed that substituting cement for PPR did not alter the mechanical behavior of the mortars (Fig. 1). At 84 days, a 10% increase in compressive strength was determined for CPII-Z cement and 18% for CP-V cement using the maximum substitution of 20% cement by PPR. At this concentration, we calculated the pozzolanic activity index, in accordance with the norm ASTM C-311 (1996), which showed the excellent performance of PPR (Table 3), with indices close to 1.0 at 28 days and reaching 1.18 at 84 days. At this age, the composition presented the highest pozzolanic activity and showed that CP-IIZ cement presents a stable increase in strength following 10% PPR substitution, while CP-V cement showed a slight increase with 20% substitution. This is due to the greater purity of the latter, i.e. CPII-Z cement fabrication includes mineral additions from 6% to 14%, while in CP-V cement, additives are limited to 5%. The pozzolanic activity indices determined by Andreola et al. (2010) were 89.9% at 28 days and to 101.4% at 90 days, indicating a slight reduction in compressive strength at 28 days due to substitution; in their study, 25% of cement was replaced by PPR and a proportional net gain in yield occurred at both ages.

The increase in strength, which became greater over time in relation to the reference composition, is characteristic of pozzolanic