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Effectiveness of ceramic tile polishing residues as supplementary cementitious materials for cement mortars

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ABSTRACT

The sludge coming from the polishing process of ceramic tiles, particularly 'porcellanato' and 'monoporosa', results in a large amount of waste that requires disposal in controlled landfills. Consequently, the financial and environmental costs of landfilling are very high. However, the 'porcellanato' and 'monoporosa' polishing residues could be used as supplementary cementitious material (SCM) instead of being disposed or landfilled. Therefore, in this study, the synergistic effect of 'porcellanato' and 'monoporosa' polishing residues (MixPR) as supplementary cementitious materials was reported. The physical and chemical characteristics of MixPR were determined by laser diffraction (particle size), X ray fluorescence (chemical composition) and X ray diffraction (mineral composition). The variability of the characteristics of the studied MixPR was evaluated over a period of three months at the source. Mortar compositions were studied replacing the cement content by MixPR (0, 10, 20, 25, 30 and 40% mass fractions). The mortars were characterized by their consistency index (flow-table), compressive strength, pozzolanic activity index, thermal behavior (calorimetry) and autogenous shrinkage. As a result, the mortar compositions using MixPR maintain their plasticity and show a high rate of pozzolanic activity index, reaching 111%. The compressive strength at 120 days of curing was 41.5 MPa when using 25% MixPR, as compared to 40.0 MPa when no MixPR was used (0% addition). At early ages (28 days) the use of 25% MixPR reduces the compressive strength by 10–15% due to the slow nature of the pozzolanic activity caused by the residue. The results show an improvement of the efficiency index (given in kg m^{-3} MPa^{-1}) when using MixPR due to the reduction on cement consumption by 30%, reducing therefore the CO_2 emissions.

1. Introduction

Ceramic polishing residues (PR) can be used for the manufacturing of several products, including ceramic tiles [1–3]. However, studies on the reuse of ceramic polishing residues in cement-based materials are scarce [4–6]. The polishing residue, called PPR if coming from 'porcellanato' tiles or MPR if coming from 'monoporosa' tiles, is a common waste from the ceramic industry, being, usually, landfilled. In the polishing process almost 1 mm of the tile surface is removed by the action of SiC and/or diamond tools that are fixed on water-cooled machines. As a result, a water suspension formed by a mixture of the abraded tool with the abraded ceramic surface is formed, that is called polishing residue. This sludge is processed in effluent treatment plants. There are large amounts of this sludge with relatively similar characteristics piled up in ceramic tile industries [1–3].

According to the NBR 10,004/2004 Brazilian Standard, both sludge ('monoporosa' and 'porcellanato' polishing residues) are classified as 'non-inert Class IIA residue' due to their pH after solubilization tests (pH = 13.8 for the mix). Therefore, the sludge must be adequately disposed on controlled landfills or adequately used as filler for cementitious materials [4–6].

Polishing residues, along with their filler effect [6-8], can maximize the hydration process in Portland cement due to the high amount of amorphous silica and alumina, that promotes the pozzolanic reaction. During hydration, the residue can act as nucleation centers owing to its small particle size after polishing.

Tests performed by Rambaldi et al. on cement mortars using 10% and 20% polishing residue (mass fractions) showed that the compressive strength at 56 days age increased by 50% [1]. At the same study, thermogravimetric (TG) results showed that portlandite was consumed by silica, which is part of the waste composition, in order to form C-S-H, presenting, therefore, pozzolanic action. The pozzolanic effect presented by polishing residues enables its use as supplementary cementitious materials (SCM) because the polishing residue (PR) improves cement performance due to the reduction in

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cement consumption, reducing, therefore, the environmental impacts caused by carbon dioxide emissions caused by Portland cement production [1,4].

Another important issue when using Portland cement for the production of more efficient materials, such as high-performance concrete, is the phenomenon of retraction, caused by the autogenous shrinkage. Retraction (or shrinkage) can lead to cracking of hydrated cement matrix and the early deterioration of concrete structures. The effect of PR addition on the autogenous shrinkage of cement pastes can be caused by four phenomena [9]: (i) cement dilution by PR, with less cement generating less shrinkage; (ii) heterogeneous nucleation of hydrates on the surface of PR particles, accelerating cement hydration and, consequently, increasing shrinkage; (iii) pozzolanic reaction of PR with CH produced by cement and; (iv) increase of capillary tension, due to the refinement of pore size distribution, leading to an increase in autogenous shrinkage.

Andreola et al. [4] showed in their study on polishing residues as supplementary cementitious material that the use of PR has resulted in an increase in compressive strength and a reduction in porosity. For them, there was chemical activity between the residue and portlandite (calcium hydroxide). The chemical composition of the sludge studied by Andreola et al. [4] is similar to the sludge studied in this work. In their study, the compressive strengths were 63.2, 56.8 and 53.3 MPa for the compositions using no residue (0% PPR), 25% 'porcellanato' residue and 25% glazed residue, respectively. For 'porcellanato' residue and glazed residues, respectively, the pozzolanic activity indices were 89.9 and 84.3 at 28 days, and 101.4 and 88.0 at 90 days. The replacement of 25% cement by PR outperformed the pure cement, showing the synergistic effect of mixing cement with PR, and leading to the improvement of permeability and durability of the products. The water/cement ratio was 0.50.

The results of Pelisser et al. [6] corroborate this behavior. The use of PPR as addition to cement resulted in an increase in compressive strength, from 27.2 MPa for 0% PPR to 41.2 MPa for 20% PPR addition after 56 days. Considering that, for the reference mortar, 17 kg of cement are needed to obtain 1 MPa of strength with a cement consumption of 456 kg/m^3, the increase in compressive strength would save, in theory, about 238 kg of cement per cubic meter of mortar. In this case, the performance index of cement consumption would decrease from 16.7 kg/MPa for 0% PPR addition to 10.4 kg MPa for 20% PPR addition. For both examples, the cement yield is higher than 40%.

Wattanasiriwech et al. [5] studied the use of polishing residues for the production of paving blocks. The results showed that the use of 20% cement in the composition could result in a compressive resistance of 35 MPa after 28 days age.

'Monoporosa' is another common polishing residue, which has not been extensively studied for application as SCM in Portland cement products. For some ceramic tile industries, the amount of 'monoporosa' polishing residue is higher than that of 'porcellanato' polishing residue. As our previous study [6] showed the effect of 'porcellanato' sludge as supplementary cementitious materials (SCM), studying the effect of 'monoporosa' as SCM is important in order to compare the feasibility of using both residues in cement products. Furthermore, to date there are no studies on the variability of the properties of both residues over time for use as SCM.

Therefore, the aim of this work was to study the effect and variability over time of production of PPR ('porcellanato' polishing residue) and MPR ('monoporosa' polishing residue) as supplementary cementitious materials (SCM). In order to evaluate the variability in their physical–chemical characteristics in batch production, both residues were collected in a period of three months from a company specialized in polishing ceramic tiles located at Criciúma city, Santa Catarina state, Brazil. The residues were characterized by XRF, XRD and PSD and a mixture of them was added to mortar compositions to determine their effectiveness as SCM.

2. Materials and methods

CP V ARI Portland cement (equivalent to CEM I 52.5 cement according to EN 197–1 [10] standard) and Brazilian standard sand (NBR 7215 standard, mixing the four particle sizes [11]) were used for the composition of all cement pastes and mortars developed in this study.

The 'porcellanato' and 'monoporosa' polishing residues were collected during eight weeks in order to evaluate the variability of the residue. The samples were collected from a company specialized in polishing and lapping ceramic tiles (wall and floor tiles), located at Criciúma, southern of Santa Catarina state, Brazil. The water used in the processing (polishing and lapping) lines, cleaning and cooling equipment is drained by gravity into channels to the wastewater treatment system. Any residue coming from 'porcellanato' or monoporosa tiles share the same circuit pipes to the treatment system, preventing the separation of both before the filter press system.

Also, there is a great daily or even weekly variation in the production of both residues; sometimes the production lines produce more 'monoporosa' residue, sometimes more 'porcellanato' tile residue. Due to the change in volume coming from both residues, a schedule of collections (eight weeks) was drawn up on the same day of the week, in order to well represent the variation in output and to determine if there were significant differences on both residues. The samples were identified as 'porcellanato' polishing residue (PPR) and 'monoporosa' polishing residue (MPR) due to the company having processed more 'porcellanato' tiles or 'monoporosa' tiles.

The residues were characterized by X-ray diffraction (XRD, CuKα, $\lambda = 1.5418$ Å, 10° to 80° (2θ) in 2°/min reading time), laser diffraction and X-ray fluorescence (by WDS) techniques in order to determine their mineralogical, particle size distribution and chemical characteristics. No significant differences could be observed between the PPR and MPR samples, as shown in Table 1. Therefore, both residues were mixed together to study their effect on cementitious materials, and the residue was called only PR (polishing residue) and assigned as MixPR for analysis. After mixing, the average particle size was determined to be 13.7 μm.

The mortars were produced in 1:3:0.6 ratio (cement: sand: water/binder ratio) with cement replacement by MixPR at 0, 10, 20, 25, 30 and 40 wt.% concentrations. The replacement was performed in relation to the cement mass, because the bulk density of both materials is close. The plasticity (determined by the flow-table method, according to EN 1015 [12] standard) was kept constant at 27 ± 2 cm.

To characterize the cement/residue compositions, compressive strength, pozzolanic activity, differential thermal analysis and isothermal calorimetry tests were performed:

i) Compressive strength tests according to ASTM 1231 standard [13] at 2, 7, 28, 100 and 120 days of age. Additionally, strength tests (at 28 days) using limestone filler ($D_{50} = 29.47$ μm) in place of the MixPR were performed;

ii) Pozzolanic activity index (PAI) according to ASTM C 311 standard [14], considering PAI = 75%. The pozzolanic activity index was determined using Eq. (1) [14]:

$$\mathrm{BI} = \frac{\text{cement cons.}}{\text{Strength}} \qquad (1)$$

where: BI is the efficiency index or binder index; cement cons. is the cement consumption (kg/m^3); and strength is the performance indicator, in this case, the strength of the samples (MPa).

iii) Thermal analysis in samples containing 0, 20, 25 and 40 wt.% MixPR at 28 days age (Q600 SDT, TA Instruments, 10 °C/min heating rate, 20–800 °C, 100 ml/min N_2 flow, platinum crucible, 15 mg sample). The amount of calcium hydroxide was calculated considering Eq. (2) (Silva et al. [15])

$$\mathrm{CH} = \mathrm{pmCH}\ \mathrm{x}\, \frac{\mathrm{mmCa(CH)_2}}{\mathrm{mmH_2O}} \qquad (2)$$