Construction and Building Materials 175 (2018) 508–518

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Rheological behavior of Portland cement pastes and self-compacting concretes containing porcelain polishing residue

Paulo Ricardo de Matos [a,*], Alexandre Lima de Oliveira [b], Fernando Pelisser [a], Luiz Roberto Prudêncio Jr [a]

[a] Department of Civil Engineering, Federal University of Santa Catarina (UFSC), Brazil
[b] Department of Civil Engineering, Federal Institute of Santa Catarina (IFSC), Brazil

HIGHLIGHTS

- Replacing the cement by PPR increased the viscosity and yield stress of the pastes.
- SCCs with up to 20% PPR showed properties similar to those of the reference.
- Pastes/concretes containing limestone showed lower viscosities and yield stresses.

ARTICLE INFO

Article history:
Received 21 December 2017
Received in revised form 17 April 2018
Accepted 25 April 2018

Keywords:
Self-compacting concrete
Cement paste
Rheology
Porcelain polishing residue
Limestone powder
Workability

ABSTRACT

Brazil is the second largest producer of ceramic tiles in the world, generating 60,000 tons of porcelain polishing residue (PPR) annually. This material presents high pozzolanic activity, with great potential for use as a supplementary cementitious material. In this work, cement pastes and self-compacting concretes (SCCs) with different replacement levels of Portland cement by two PPRs and a limestone powder were prepared. The flow behavior of the mixtures was evaluated by paste and concrete rheometry and concrete workability tests. The results showed that the replacement by either PPR increased the plastic viscosity and yield stress of pastes. In the SCCs, replacement of the cement by up to 20% of PPR resulted in mixtures with similar rheological properties and better passing abilities compared with the reference paste (no replacement). Higher contents led to considerable increases in the viscosity and significant reductions in the passing ability of the SCCs. The replacement of cement by limestone powder led to reduction in viscosity and yield stress, both in pastes and concretes. The slump flow and T_{500} did not show good correlations with the rheological parameters of the SCCs, while V-Funnel time and J-Ring/slump flow ratio adequately evaluated the viscosity and passing ability of the mixtures, respectively.

1. Introduction

Self-compacting concrete (SCC) is a highly flowable concrete that can spread into place under its own weight and achieve good consolidation in the absence of vibration without exhibiting defects due to segregation and bleeding [1]. To achieve such stability, this type of concrete needs high fines content, often leading to high cement consumption [2–4]. Supplementary cementitious materials (SCM) can supply this demand of fines, reducing costs and improving the concrete properties in fresh and hardened state. Limestone powder (crystalline $CaCO_3$) is widely used in SCC because it is widely available and it has the ability to improve the cohesion and fluidity of the mixtures [1,5,6].

The use of SCM in concretes, which do not require additional clinker processes, leads to significant reductions in CO_2 emissions per ton of cementitious material [7]. Aiming to produce sustainable concretes, some researchers were able to produce satisfactory mixtures with a percentage of Portland cement replaced by fly ash, limestone and/or slag of up to 75% [6,8,9], while achieving resistances of the order of 120 MPa and binder intensity index [10] (kg of cement/MPa.m^3) of 2.7, well below the mean of 5.0 for high performance concrete [11]. Since most SCM are industrial byproducts – slag is a byproduct of pig iron production, fume silica of iron silicon production and fly ash from coal combustion [7] –, the use of such materials in concrete is a great solution from an environmental point of view.

Brazil is the world's second largest ceramic tile manufacturer with a production of 899 mi m^2/year, 68% of which corresponds to porcelain tiles [12]. During the production process, the polishing step removes roughly 1 mm from the tile surface, generating

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* Corresponding author.
E-mail addresses: paulorm.matos@gmail.com, paulo.r.matos@posgrad.ufsc.br (P.R.d. Matos).

https://doi.org/10.1016/j.conbuildmat.2018.04.212
0950-0618/

porcelain polishing residue (PPR). About 100 g of residue are generated per m^2 of porcelain tile produced [13,14]. The polishing operation is performed by water cooled machines using silicon carbide (SiC), magnesium-based (MgOHCl) and/or diamond abrasive tools. A water suspension is formed by the water and the particles from the porcelain tile, in addition to a small portion from the abrasive tools. After removing the residual water, this material is generally disposed in landfill sites [15–17]. Due to its high fineness and pozzolanic activity, this material has great potential for use in SCC, given that it reduces the consumption of cement and improves the rheological properties of the mixtures.

Rheology is the science that studies the flow of materials under mechanical stresses. In cement-based materials, two properties stands out: yield stress, related to the energy required to start the flow, and viscosity, related to the flow velocity [18]. In concrete, the paste represents only 30–40% of the total volume. Although, the flow properties of the system are directly ruled by this phase, since they are responsible for involving the aggregates and filling the voids between them, and promoting the relative movement between these particles [3,19,20]. However, it is very difficult to predict the flow behavior of concrete by the behavior of the paste alone, since this system can be composed of particles ranging from a few nm to 20 mm [21]. Moreover, the presence of aggregates increases the internal shear and the dispersion of the particles, and may even alter the hydration kinetics of the cement [22]. Therefore, in this work, the rheological properties of both pastes and SCC were evaluated.

1.1. Research significance

In Brazil, approximately 60,000 tons of PPR are generated annually [12,14]. The disposal of this residue in landfills, the most common destination for PPR, leads to environmental impacts and high costs for industry. Nandi et al. [14] estimated transportation and material disposal costs of US$ 120 per ton of residue. Thus, the search for a suitable destination for PPR is justified. According to Pelisser et al. [23], this material can enhance the kinetics of Portland cement hydration and improve the dispersion of the binder matrix, acting as nucleation sites due to its high fineness ($D_{50} \sim$ 7–10 μm). Moreover, it presents great pozzolanic potential due to the high levels of amorphous silica and alumina ($SiO_2 + Al_2O_3 >$ 80% and up to 90% amorphous). Some authors have studied the use of PPR in Portland cement based materials. Andreola et al. [16] successfully produced a pozzolanic cement CEM II by EN 197-1 [24], composed of 75% Portland cement + 25% PPR. Bignozzi and Bonduà [25] and Bignozzi and Saccani [26] respectively investigated the corrosion resistance and the alkali silica reaction in mortars prepared with the cement proposed by Andreola et al. Wattanasiriwech et al. [27] and Penteado et al. [28] fabricated paving blocks containing PPR. Additionally, some works have confirmed the high pozzolanic activity of PPR in pastes and mortars [13,15,23].

The existing researches emphasizes the hardened state properties (compressive strength, pozzolanic activity, and durability), presenting very limited characterizations in the fresh state. In fact, there are no reports of the evaluation of Portland cement based materials containing PPR by rheometry; moreover, there is no research regarding the use of PPR in SCC. Thus, this work aimed to evaluate the influence of the presence and content of different PPR on fresh state properties of pastes and SCCs through rheometry and workability tests.

2. Experimental program

2.1. Materials

A Portland cement classified as Type III by ASTM C150 [29], CEM I by EN 197-1 [24] and CPV-ARI by ABNT NBR 5733 [30] was used in all the mixtures. The chemical composition and physical properties of the cements are shown in Table 1. Two sources of PPR were used, one from Criciúma, SC (referred to as PPR-C), and one from Tijucas, SC (referred to as PPR-T). Samples of 100 kg were collected from each source, and were dried at 105 °C for 24 h, manually crushed and homogenized. A limestone powder (L) was also used to compare the performance of PPR with a fine material widely employed in SCC [1,31]. The chemical composition and physical properties of both PPRs and limestone are presented in Table 1. Fig. 1 show the particle size distribution of the cement, PPRs and limestone powder, measured using Microtrac S3500 Particle Size Analyzer (laser diffraction method with dry suspension). In the concretes, a polycarboxylate-based superplasticizer with a specific gravity of 1.09 g/cm^3 and solid content of 39.0% was used. In order to check the compatibility of SP – cement – PPR, the mixtures were previously tested on a smaller scale.

Table 1
Chemical and physical characteristics of Portland cement (PC), porcelain polishing residues (PPRs) and limestone (L).

	PC	PPR-C	PPR-T	L
Chemical composition (%)				
SiO_2	18.69	68.56	67.23	0.85
Al_2O_3	4.25	19.14	19.93	0.31
Fe_2O_3	2.96	1.21	1.27	0.22
CaO	60.12	2.02	2.33	54.03
K_2O	0.67*	1.38	1.97	0.02
Na_2O		1.23	1.76	–
MgO	4.08	2.91	2.22	1.91
P_2O_5	–	0.36	0.53	–
TiO_2	–	0.29	0.46	–
SO_3	3.23	–	–	–
LOI	3.24	2.83	2.25	42.20
IR	0.70	–	–	–
Free CaO	0.59	–	–	–
Physical properties				
Specific Gravity (g/cm^3)	3.12	2.48	2.48	2.80
Blaine (m^2/kg)	447.4	–	–	–
B.E.T. (m^2/g)	–	14.69	12.81	–
D_{50}	15.19	8.53	9.66	38.09
% Amorphous	–	86.5	88.4	–

* Na_2O equivalente: $Na_2O + 0.64\ K_2O$; LOI: loss on ignition; IR: insoluble residue.