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Influence of fired clay brick waste additions on the durability of mortars

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ABSTRACT

The use of metakaolin is known to help improve properties of Portland cement-based mortars. The presumed similarities between the characteristics of metakaolin and those of a powdered (<45 μm) fired clay brick clean waste (CBW) led to the investigation of the effect on the durability of mortars of partial replacement (10, 25 and 40 wt.%) of Portland cement by CBW. Properties such as 28 and 90 days-compressive strength, water absorption, apparent porosity, absorption by capillarity, chloride retention, carbonation depth and sulphate resistance were evaluated. The CBW-containing cured mortars showed improved strength and density, as the result of combined physical and pozzolanic pore filling effect of added CBW. However, CBW-free mortar exhibited larger spreading and, being more porous, higher sulphate resistance and ability to absorb chlorides. Optimum performance was found for the 40 wt.% CBW mortar whose compressive strength can be up to 130% higher than that of the CBW-free mortar.

1. Introduction

Along with the reduction of production costs and the increasing scarcity of natural resources, the quest for sustainable development has intensified the study of the reuse of waste materials in order to minimize environmental impacts. In Brazil, the ceramic bricks industry generates a significant amount of rejected non-conform (not marketable) bricks primarily due to lack of raw materials homogeneity and processing difficulties, which result in cracks and breakages. Discarded waste bricks are not reused in the process due to changes imparted to the plasticity of the raw clay mixture. However, upon firing at temperatures between 500 and 900 °C, the dehydroxylation that occurs in clay minerals (formation of metakaolin, an amorphous material with strong reactivity) results in pozzolanic activity (capability of reacting with calcium hydroxide and water to form cementitious compounds). Thus, powdered clay brick waste (CBW) might be used in cement based materials, with environmental benefits from the reduction of both the amount of discarded wastes and the CO_2 emissions by cement industries [1].

The effect of metakaolin as partial replacement for Portland cement in mortars depends on the physical, chemical and microstructural characteristics of the material and the composition of the mortars. Moreover, the properties of metakaolin are affected by the characteristics of the original clay minerals (particle size, mineralogy, crystallinity, structural order and disorder) and the heat treatment conditions used [2].

A large variety of clays have been used as pozzolanic materials in mortars and concrete as partial substitute of Portland cement. They generally contain significant amounts of kaolinite ($Al_2O_3{\cdot}2SiO_2{\cdot}2H_2O$) that are transformed into metakaolinite upon calcination [3]. The faster reactions between amorphous silica and alumina from metakaolin with lime released from the cement lead to the formation of larger amounts of CSH and C_4AH_{13}, which promote several properties of the final mortar or concrete, namely high ultimate strength and low permeability [4]. The use of metakaolin and other pozzolanic materials, such as fly ash, silica fume, slag, rice husk ash, fired clay bricks and natural pozzolans, has also been shown to refine the pore structure, which results in reduced ionic mobility, consumption of calcium hydroxide and entrapment of alkalis in silica-rich hydration products, thus helping to suppress the deleterious expansion that results from alkali–silica reactions or exposure to chlorides and sulphates [5–8]. Nevertheless, the use of metakaolin as partial replacement for Portland cement seems to be more effective in reducing the carbonation depth than fly ash or silica fume additions [6].

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Although the reuse potential of a variety of ceramic-related industrial wastes, namely sludges, fired clays and demolition waste, has been investigated, these had been subjected to firing temperatures up to 1100 °C at some stage of their former processing [6–11] and they generally require waste collection and conditioning operations that might be rather elaborate. On the contrary, rejected low temperature fired clay bricks, straight from the production line, constitute a clean and ready to use waste material, whose effect on concrete or the durability of mortars has not been investigated. Given the similarities to construction and demolition waste, preliminary work was carried out with such a clay brick waste (CBW) in concrete applications. The results suggested that replacement of 23–30% of Portland cement could be achieved with no significant harm to technological properties. Therefore, since the changes introduced by CBW might be easier to understand in mortars, the purpose of this work is to assess the effects on typical fresh and hardened mortar properties of partial replacement of Portland cement by CBW up to 40 wt.%, so that application-optimized mortar formulations might be designed.

2. Experimental

In the typical construction mortars prepared in this work, Portland cement CP II–Z–32 (Brazilian Portland Cement Society) was used as binder. According to the supplier [12], it has a particle size <41 μm, BET (Brunauer–Emmett–Teller) specific surface area (SSA) of 0.37 m^2/g (Blaine fineness) and the chemical composition shown in Table 1. The clay brick waste (CBW) was obtained from industrially fired bricks discarded by the ceramic industry due to presence of cracks, irregular dimensions or other imperfections. In the regular production process, firing is carried out in a continuous furnace at 700 °C for 24 h. Those bricks discarded at the end of the firing cycle were ball-milled and sieved through 45 μm to obtain the CBW fine powder. Quartz sand with particle sizes ranging from 150 to 2360 μm (average 510 μm) was used as aggregate and hydrated lime CH-III (Brazilian Association for Technical Standards) with 75% of the particles <75 μm. The CBW characterization included the determination of the BET specific surface area (Gemini V2.00 surface analyzer), the particle size distribution (laser diffraction, CILAS 1064), the chemical analysis (X-ray fluorescence, Philips PW 2400) and the identification of crystalline phases (X-ray diffraction, Shimadzu XRD 6000, using the Cu Kα radiation). The unfired clay used in the bricks manufacture was also characterized in terms of mineralogy by X-ray diffraction (XRD) and by Fourier Transform Infra Red spectroscopy (FTIR, Perkin–Elmer Spectrum One, 4000–560 cm^{-1} wave length range).

Various mortars were prepared (based on constant 2.5×10^3 cm^3 total volume) in which the Portland cement was replaced with CBW up to 40 wt.% (Table 2). The water to cement weight ratio (*W*/*C*) used in the CBW-free mortar was kept constant in the other mortars (for this purpose, the added CBW was included in the cement content). This strategy was adopted because the use of varying *W*/*C* ratios to maintain the workability conceals the real effect of mineral additions on the fresh and hardened properties [13].

The flow (spreading) tests and the preparation of specimens, with $40 \times 40 \times 160$ mm^3, followed the Brazilian standard NBR 13276 [14]. The specimens were cured for 28 and 90 days in water saturated with calcium hydroxide at ambient conditions (23 °C, 65–80% relative humidity) and dried before testing. The natural carbonation tests were carried out on specimens cured in air and the carbonation depth was measured by visual analysis of photographs [15]. The retained chloride tests followed the procedure described in the literature [16], by 24 h immersion (of dried 90 days aged specimens) in a sodium chloride saturated solution (1 kg of sodium chloride in 2.78 dm^3 water) followed by drying (90 ± 5 °C) until constant weight. The retained chloride was determined as the difference between specimen weights before chloride saturation and after drying. The sulphates resistance test also followed the procedure described in the literature [16,17], using dried 90 days aged specimens and successive 2 h immersion cycles in a sodium sulphate decahydrate solution at 6.17% (65.8 g of sodium sulphate decahydrate in 1 dm^3 of water). After each immersion, specimens were dried at 90 ± 5 °C for 21.5 h and then cooled for about 30 min. The solution pH (measured with a paper strip colour indicator) remained constant at about 10. Several other properties (compressive strength [18], apparent porosity and water absorption [19] and water absorption coefficient by capillarity [20]) were measured following standard procedures as indicated in Table 3.

The microstructure of CBW particles was observed by Scanning Electron Microscopy (SEM, Hitachi SU-70) after carbon coating. Qualitative elemental analysis was carried out by Energy-dispersive X-ray spectroscopy (EDS) on selected areas. The microstructure of cured mortars was observed by SEM (Jeol

Table 1
Chemical composition of CBW, as determined by X-ray fluorescence.

	Chemical composition (wt.%)	
	CP II–Z–32	CBW
Al_2O_3	6.77	21.21
CaO	52.79	0.21
Fe_2O_3	3.15	6.22
MgO	4.15	0.48
MnO	–	0.06
P_2O_5	–	0.09
SiO_2	22.41	66.72
TiO_2	–	1.37
SO_3	2.79	–
$(K_2O + Na_2O)$[a]	0.78	0.85
Loss on ignition	5.00	2.78

[a] Alkali equivalent, which can form expansive compounds.

Table 2
Fresh mortars formulations (based on constant 2.5×10^3 cm^3 total volume) and corresponding flow index (spreading).

Formulation	Mixture components[a] (g)					Flow index (mm)
	PC	CBW	Lime	Sand	Water	
0	394	–	409	3305	986	267.0 ± 1.3
10	344	38	418	3381	955 (1047[b])	246.3 ± 1.5
25	272	90	433	3504	907 (1109[b])	208.7 ± 1.1
40	205	136	450	3636	854 (1124[b])	172.0 ± 0.6

[a] To produce nine $40 \times 40 \times 160$ mm^3 specimens.
[b] Amount of water to produce mortars with similar flow index as CBW-free mortar.

Table 3
Experimental program and test methods.

Studied properties	Curing time (days)	Samples per test	Standard test method
Consistency index	0	3	NBR 13276 [13]
Carbonation	28, 90	1	RILEM CPC-18 [14]
Attack by sulphates	90	2	ASTM C 1012 [16], Rodrigues, 2004 [15]
Retained chlorides	90	2	Rodrigues, 2004 [15]
Compressive strength	28, 90	4	NBR 13279 [17]
Apparent porosity and water absorption	90	2	NBR 9778 [18]
Water absorption coefficient by capillarity	90	2	NBR 15259 [19]