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Potential for use of crushed waste calcined-clay brick as a supplementary cementitious material in Brazil

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Abstract

The Brazilian ceramic industry generates large amounts of calcined-clay waste. This paper examines the factors that influence its potential for use as a partial replacement of Portland cement. Superplasticized mortars of equal workability containing ground crushed waste calcined-clay brick (GCWCCB) in the proportions of 10, 20, 30 and 40% as a cement replacement were analyzed through mechanical tests, pore structure characterization and durability tests. The results indicated the optimal percentages of substitution lies between 10% to 20%. The potential reduction of CO_2 emissions could be as high as 10% of current Brazilian cement industry emissions if this approach were to be fully implemented, and it could be eligible for "Clean Development Mechanism" credits under Kyoto protocol.

Keywords: Calcined clay (D); Microstructure (B); Mechanical properties (C); Durability (C); CO_2 emissions (E)

1. Introduction

The changes in the earth's climate and the potential impact on human life have been debated over the past decades. The Third Assessment Report of the Intergovernmental Panel on Climate Change [1] expresses the scientific consensus that most of the global warming observed over the last fifty years is caused by anthropogenic emissions of greenhouse gases (GHG). The question now addressed is how to achieve a level of GHG concentration in the atmosphere that is not dangerous to humanity.

The Convention on Climate Change held in Rio de Janeiro, Brazil, in 1992 stated that GHG concentrations in the atmosphere should be stabilized at a level that would prevent dangerous anthropogenic interference with the climate system. A further step, in terms of quantitative targets, was established during the 3rd Conference of the Parties held in Kyoto, Japan, in 1997. It was agreed that the developed countries should reduce the annual emissions of GHG to a level 5.2% lower than that observed in 1990 during the first commitment period, which runs from 2008 to 2012.

It is necessary, however, to define an effective policy for reducing these emissions. The Rio de Janeiro Convention recognized that developed countries should lead this process. In Kyoto, some flexible mechanisms were conceived to help developed countries to accomplish their reduction commitments. One of the mechanisms is called Clean Development Mechanism (CDM). According to the CDM, a project that reduces greenhouse gases emissions in a non-industrialized country may result in Certified Emission Reductions (CER) that can be acquired by industrialized countries to achieve their reduction commitments. The Kyoto Protocol entered into force in February 2005. In January 2006 there were globally 77 project activities registered, 66 requesting to be registered and 48 methodologies approved [2]. Nevertheless only one of these methodologies concerned the blend in cement production [3] and there were no projects which covered cement blend registered yet. In this regard there is an important potential for sustainable cement in Brazil.

Quoting IPCC-TAR (Intergovernmental Panel on Climate Change — Third Assessment Report) [1], the most recent

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general report for policy makers, the world emissions of carbon dioxide from fossil fuel combustion and industrial process in 2000 reached 25 billion tonnes. Cement production is responsible for about 5% of this quantity [4]. Concrete is the prime material for infrastructural facilities worldwide and will remain so for the foreseeable 21st century [5]. The challenge is, therefore, to develop sustainable solutions based on green cementitious materials. These materials put a smaller demand on precious raw materials and energy and reduced GHG emissions are associated with their production.

There are three main steps in cement manufacture: (i) preparing, proportioning and processing the raw materials for the kiln feed, (ii) burning the processed raw material in the kiln to produce clinker, and (iii) grinding and blending clinker with other complementary materials to make cement. Within the framework of these industrial processes, several factors that affect the GHG emissions can be distinguished: (i) the properties of the raw materials; (ii) the type of fuels employed; (iii) the GHG intensity of electricity used; (iv) the manufacturing process used, and (v) the type of cement that is produced and in particular its clinker content, clinker being the most GHG-intensive component of cement [4].

Several waste materials can be used in blended cements or directly as addition in concrete [6–12]. However, in Brazil, due to a particular energy matrix based on hydroelectricity, the most widely studied pozzolan, fly ash, is not largely available [13]. In this way, the Civil Engineering Department of the Federal University of Rio de Janeiro has an ongoing program dealing with the use of calcined-clay brick, metakaolin, rice husk ash, sugarcane bagasse ash and sludge ash from sewage treatment plant as clinker replacement materials.

It should be emphasized that, although Brazil is the ninth largest economy in the world, it is a developing country, with enormous needs in infrastructure that will demand for cement based materials applications. Therefore, it is worthy to search for new mineral admixtures that can respond to development needs without degrading the environment.

In this paper we discuss the potentialities of using large volumes of ground crushed waste calcined-clay brick (GCWCCB) as a partial replacement of clinker. Calcined soils, in the form of crushed pottery fragments, were the first artificial pozzolans, and formed when mixed with lime the first man-made hydraulic cement about 3600 years ago [14]. Clay minerals become highly reactive when they are incinerated at temperatures between 600–900 °C and then ground to cement fineness or finer. These pozzolans are predominantly composed of silica and alumina. The thermal treatment transforms the crystalline network of silica and alumina into a disordered unstable amorphous state. As a result, the pozzolan can react when combined with lime and water to form insoluble products. Hence, the residues of clay bricks and tiles ground to a suitable fineness can become active pozzolans if the original clay and the firing process provides the necessary conditions [7,15,16].

Aiming the use of GCWCCB as cement replacement material an experimental investigation was carried out with superplasticized mortar mixes of equal workability. The amount of cement replacement ranged from 10 to 40% (by weight). The influence of the partial replacement of Portland cement on the mechanical properties of two mortar mixes of proportions by weight of 1.0 Portland cement: 1.5 sand and water/cement ratios of 0.4 and 0.5, respectively, were evaluated. Sorptivity, water absorption capacity, chloride ion penetration, and resistance to sulfate attack tests, as well as pore size distribution analysis were carried out on uniformly prepared specimens to provide information on the durability of the mixes.

In what concerns the use of GCWCCB as a clinker replacement material, it is worthy to investigate the potential of CDM projects that may help to reduce the costs of implementation of the clinker replacement program. Hence, we present a systematic calculation of CO_2 emissions associated with Portland cement production in Brazil, indicating the potential of GCWCCB to reduce these emissions.

2. Experimental program

2.1. Materials

We used a Portland cement, class CPII-F32 under Brazilian standards [17] (defined as containing: $85\% < \text{clinker} \leq 91\%$; $3\% < \text{gypsum} < 5\%$; $6\% < \text{filler} < 10\%$, by mass), and giving 32 MPa compressive strength at 28 days in the standard test. Its main chemical and physical characteristics are presented in Table 1. The sand used was natural sand with fineness modulus of 2.37 and density of 2.64 g/cm^3. A naphthalene sulphonate formaldehyde-based superplasticizer (SP) with a total solids content of 44.5% was used to correct the workability of the blended mixes. Tap water was used in all mixes.

The waste material used to produce GCWCCB consisted of crushed fragments of fired clay bricks that had been calcined at 850 °C. These fragments, whose diameters vary from 3 mm to 10 mm, were finely ground in a vibratory mill. Fig. 1 displays the granulometric curves of GCWCCB and of the Portland cement.

If the replacement material has its grains finer than cement (e.g., silica fume), the packing density of the mix has a tendency to be improved. In what concerns GCWCCB, the grading curves of Fig. 1 do not display a clear difference between its granulometry and the one of cement, even though GCWCCB had a larger amount of fine particles. To investigate if the

Table 1
Physical and chemical properties of the Portland cement and the ground brick

	CP II F 32	Calcined-clay brick
Specific gravity (g/cm^3)	3.10	2.65
BET surface area (m^2/kg)	–	1899
% passing on 45 mm mesh	80	62
Chemical properties (wt.%)		
SiO_2	19.98	63.89
Fe_2O_3	3.12	7.73
Al_2O_3	3.70	25.49
CaO	62.80	0.29
MgO	3.10	0.04
Na_2O	0.07	Traces
K_2O	0.80	0.95
Insoluble residue (%)	1.50	Traces

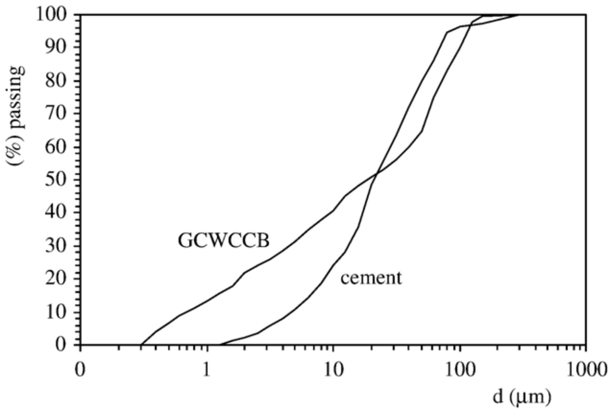

Fig. 1. Grading curve of Portland cement and calcined-clay brick.

replacement of cement by GCWCCB could have a strong effect on the packing density of the mix it was used the framework of the Compressive Packing Model-CPM [18]. This model quantifies the intrinsic packing of an individual category of grains by means of a parameter called the virtual packing density ($0<\beta\leq 1$). This parameter represents the volume of grains contained in a unitary volume, compacted with an ideal compaction energy that would correspond to a maximum virtual packing. The value of the virtual packing density of both cementitious materials was determined by the water demand experimental procedure [18] and it was found that the Portland cement had $\beta=0.63$, and GCWCCB $\beta=0.60$. Using these two parameters, the densities and the grading curves of the materials as input parameters in the CPM model, it was found that the binary mixtures of OPC and GCWCCB, for the level of cement replacement used in this study, presented nearly the same packing density. A maximum difference of about 1% was observed for the mix containing 40% of GCWCCB. A detailed analysis of the packing characteristics of the materials used in the present research, within the framework of CPM, can be found in [16].

The BET surface area of GCWCCB was 1899 m^2/kg. The physical and chemical characteristics of the calcined clay are also presented in Table 1. X-ray diffraction results are presented in Fig. 2 The results have shown that the pozzolan meets the specification requirements of ASTM 618 C [19] for Portland cement mineral additives. The diffractometric analysis reveals the presence of amorphous material, quartz, hematite, sillimanite, microcline and illite in the pozzolan. Using the Rietveld method it was found that the amount of amorphous materials was about 61% whereas the content of quartz, hematite, sillimanite, microcline and illite were, respectively, about 27%, 5%, 2%, 2% and 1.5%.

2.2. Mix proportions

We produced ten different mortar mixes, with the proportions by weight of 1 cementitious material: 1.5 sand. The mixes were named M*i*B*g*, where: *i* stands for the water/cement (*w*/*c*) ratio, $i=1$ corresponds to $w/c=0.40$, $i=2$ corresponds to $w/c=0.50$; and *g* stands for the percentage (by weight) of Portland cement replaced by GCWCCB. Therefore, the experimental program encompassed the control mixes, M1B0 and M2B0, and the mixes M1B10, M2B10, M1B20 M2B20,

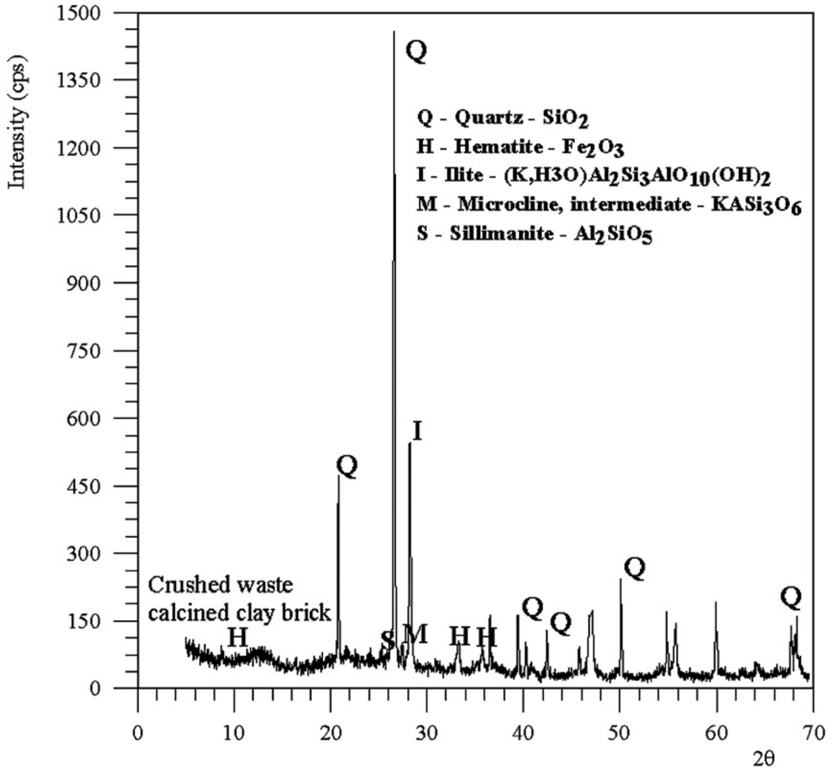

Fig. 2. X-ray diffraction of the calcined-clay brick.

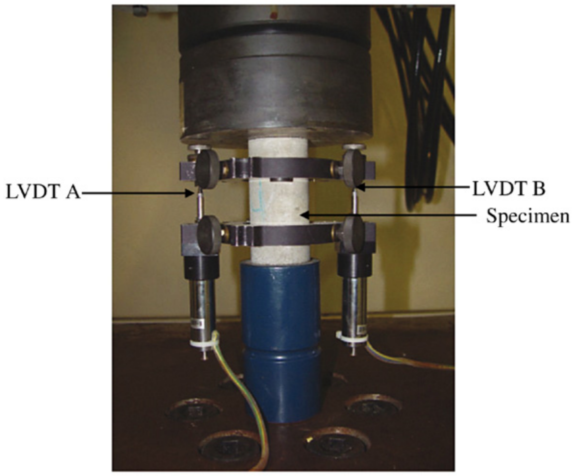

Fig. 3. Uniaxial compression testing set-up.

M1B30, M2B30, M1B40 and M2B40. Mixing was performed in a bench mounted mixer. The sand was firstly added, followed by a previously blended mix of cement and GCWCCB. After mixing for about 2 min, water was slowly added and the mixing process was continued for a total period of 5 min. Superplasticizer was added to mixes containing 20, 30 and 40% of GCWCCB in order to obtain the same workability for all mixes, measured by the flow-table test. The superplasticizer content (SP dry extract/mass of binder in %) for the mixes M1B20, M1B30 and M2B20 was 0.20% whereas for the mixtures M1B40, M2B30 and M2B40 it was 0.3%.

2.3. Specimen preparation, curing and testing

For each mix, twelve specimens 50 mm in diameter and 100 mm in length were cast in steel moulds and compacted by external vibration. Four specimens were tested under compression at the age of 28 days to obtain the stress–strain curve until failure. Four other specimens were used to determine the total porosity by means of the water absorption capacity tests, and the remaining specimens were used for the sorptivity tests.

After casting, the moulds containing the specimens were covered with a damp cloth and a polythene sheet to prevent water loss and after 24 h the specimens were demoulded and water-cured at 24°C for 28 days.

The uniaxial compression tests were carried out in a 1000 kN Shimadzu testing machine at a loading rate of 0.01 mm/min. The test set-up is shown in Fig. 3.

The water absorption capacity test and the sorptivity test, based on the direct gravimetric method, were executed in accordance with the Brazilian standards NBR 9779 [20] and NBR 9778 [21], respectively, were performed after 28 days curing.

Only selected mixes were used to the chloride ion penetration and sulphate attack tests and to conduct the pore size distribution measurements. These were the control mix M2B0, and the mixes M2B10, M2B20. These mixes have been chosen for two reasons: (i) the greater the water to cement ratio, the

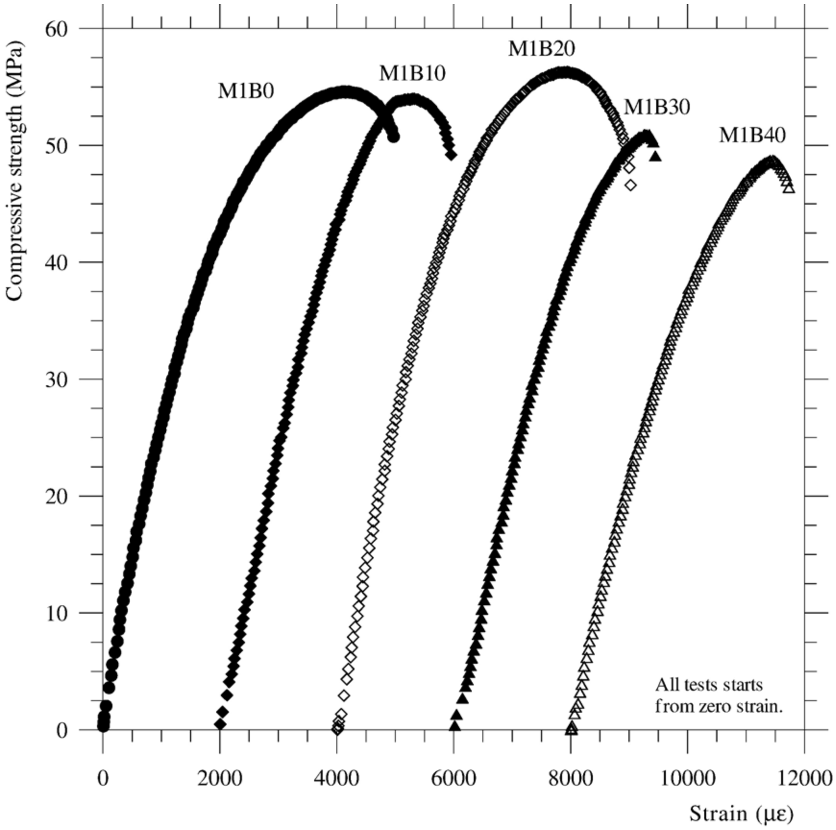

Fig. 4. Stress–strain curves for the mortar mixtures M1B0, M1B10, M1B20, M1B30 and M1B40.

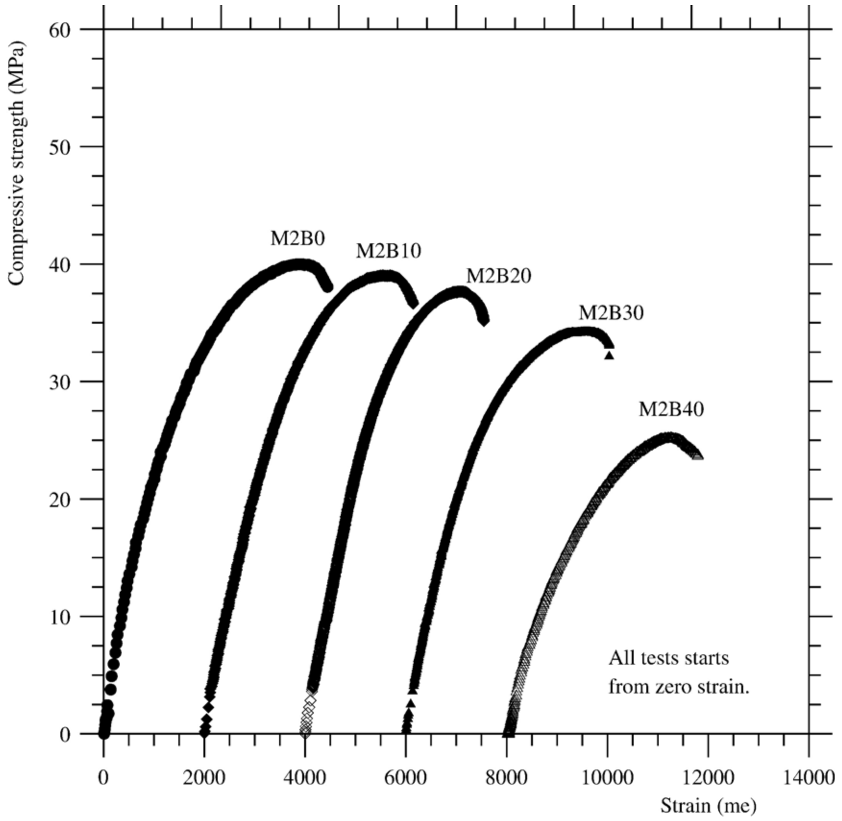

Fig. 5. Stress–strain curves for the mortar mixtures M2B0, M2B10, M2B20, M2B30 and M2B40.

greater the porosity and the permeability, and consequently the greater the sensibility of the samples to external attacks; (ii) the mixes containing 10% and 20% of GCWCCB as cement replacement were found to be the more appropriate since there was no significant reduction in the compressive strength of these mixtures when compared with the reference OPC mortar (see Section 3). For each of these mixes two cylindrical specimens of 100 mm in diameter × 200 mm in length were cast for the chloride ion penetration tests. A disk of 100 mm in diameter × 50 mm thickness was cut from the central part of each cylinder and tested according to ASTM 1202 [22] after 28 days of curing. Samples from the extremities of the cylinders were taken and used to conduct the pore size distribution measurements using the mercury intrusion porosimetry (MIP) technique. Additionally, three cylinders of 100 mm in diameter × 200 mm in length were cast for each mix to study the resistance of the selected mortars to the attack of magnesium sulphate. From the central part of each cylinder it was taken 5 disks of 100 mm in diameter × 25.5 mm thickness to evaluate the indirect tension strength of the mortars after 28 days of cure in deionised water and after 100 and 200 days of exposition to a 5% MgS solution.

3. Results and discussion

3.1. Stress–strain behavior

Typical compressive stress–strain curves for the ten mortar mixes are presented in Figs. 4 and 5. The mean and the coefficient of variation (CV) of the compressive strength (f_c) and modulus of elasticity (E) are given in Table 2 together with relative strength (RS) and rigidity (RR) defined as, respectively,

Table 2
Compressive strength, relative strength, elastic modulus, relative rigidity, porosity and water sorptivity of mortar mixes

MIX	f_c — CV (MPa) — (%)	Relative strength	E — CV. (GPa) — (%)	Relative rigidity	Porosity — CV (%) — (%)	Sorptivity — CV. (cm/h$^{1/2}$) — (%)
M1B0	55.09 — 0.70	1.00	26.62 — 1.16	1.00	10.10 — 1.04	0.09 — 3.66
M1B10	55.19 — 1.00	1.00	26.86 — 5.50	1.01	9.88 — 3.59	0.07 — 5.06
M1B20	56.76 — 0.83	1.03	27.14 — 1.95	1.02	10.99 — 0.18	0.06 — 4.23
M1B30	49.41 — 3.15	0.90	25.02 — 4.62	0.94	10.96 — 2.53	0.05 — 5.35
M1B40	47.70 — 2.17	0.87	24.79 — 4.76	0.93	10.55 — 1.96	0.05 — 5.25
M2B0	40.92 — 2,44	1.00	24.64 — 1.50	1.00	12.94 — 1.8	0.22 — 2.67
M2B10	39.77 — 1.77	0.97	23.84 — 1.42	0.97	13.37 — 1.01	0.18 — 2.18
M2B20	38.09 — 1.08	0.93	23.39 — 1.39	0.95	14.67 — 3.26	0.16 — 3.13
M2B30	32.97 — 4.35	0.81	22.88 — 4.77	0.93	14.31 — 0.42	0.12 — 8.36
M2B40	26.50 — 4.78	0.65	22.34 — 2.53	0.91	13.61 — 7.45	0.12 — 3.92

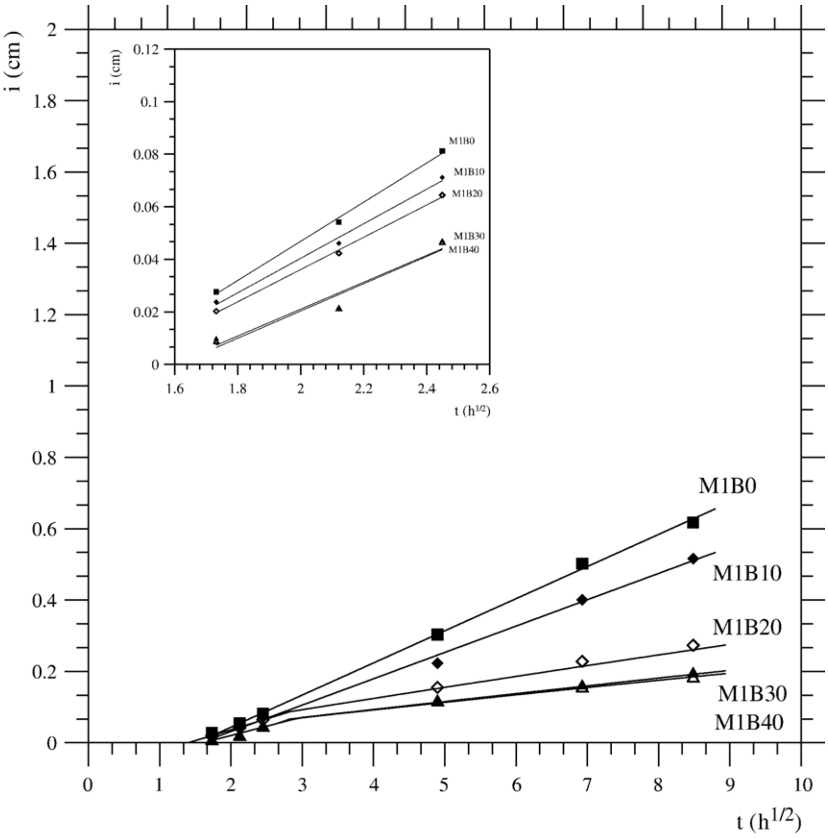

Fig. 6. Sorptivity plots (i versus $t^{1/2}$) for the mortar mixes M1B0, M1B10, M1B20, M1B30 and M1B40.

the ratio of the strength and elastic modulus of GCWCCB mortars to the strength and elastic modulus of the control mortars. For mortars of the series M1 with up to 20% cement replacement, almost no differences were observed in compressive strength or elastic modulus. Mortars of the series M2 containing until 20% of cement replacement show a slight decrease in the values of these properties. Mortars containing higher contents of GCWCCB presented, however, significantly lower strengths and elastic moduli than the control mortars. This behavior was more pronounced for the mortar mixes of series M2 with higher w/c ratios. Therefore, we can conclude that the optimum replacement level of Portland cement by GCWCCB probably lies between 10 and 20% at $w/c = 0.40$. Regarding the strain at peak stress, no significant differences were observed for all levels of replacement and w/c ratio studied (see, as an example, the stress–strain curves in Figs. 4 and 5).

In what concerns the evolution of the compressive strength with time of cement based material containing GCWCCB, a further research have been carried out by [16] using normal and high strength concrete mixtures containing 20% of cement replacement by GCWCCB. The results indicated that the relative compressive strength at an age a ($\mathrm{RCS}_a = \mathrm{fc}_a / \mathrm{fcref}_a$), defined as the relation between the compressive strength at a certain age a (fc_a) and the strength of a reference concrete at the same age (fcref_a), increases for later ages ($\mathrm{RCS}_{28} = 1.00$; $\mathrm{RCS}_{90} = 1.05$; $\mathrm{RCS}_{180} = 1.07$). These results are in accordance with others found in the literature [23,24].

3.2. Porosity, sorptivity and pore size distribution

The values of open porosity measured by the water saturation method (gravimetric technique) are presented in Table 2. For the specimens of series M1 it was observed both increases and decreases in the mean values of the total porosity due to the replacement of Portland cement by GCWCCB. For example, a small reduction of 2%, and increase of 4%, in the porosity was measured for the mixes M1B10 and M1B40, relatively to the control mix M1B0. For the mixes M1B20 and M1B30, the increase in porosity reached 9%. In what concerns series M2, the increase in total porosity ranged from 3% to 13%. Comparing the porosity of the two series of mortars, it can be verified that, as expected, the mixes of series M2 showed porosity values 28% to 35% higher than those observed for the mixes of series M1.

The results of the sorptivity tests are presented in Figs. 6 and 7. In all cases, the water penetration depth (i) versus $t^{1/2}$ could be modeled by a bi-linear form. Values of water sorptivity determined from the gradients of these plots during the initial water exposure [25] are presented in Table 2. The results indicate that the sorptivity of both series M1 and M2 reduces the greater is the percentage of GCWCCB. This behavior may be related to a refinement in the pore structure of the control mixes produced by both filer and pozzolanic effect of GCWCCB.

The results of mercury pore size distribution obtained for the mixes M2B0, M2B10 and M2B20, displayed in Fig. 8, indicate

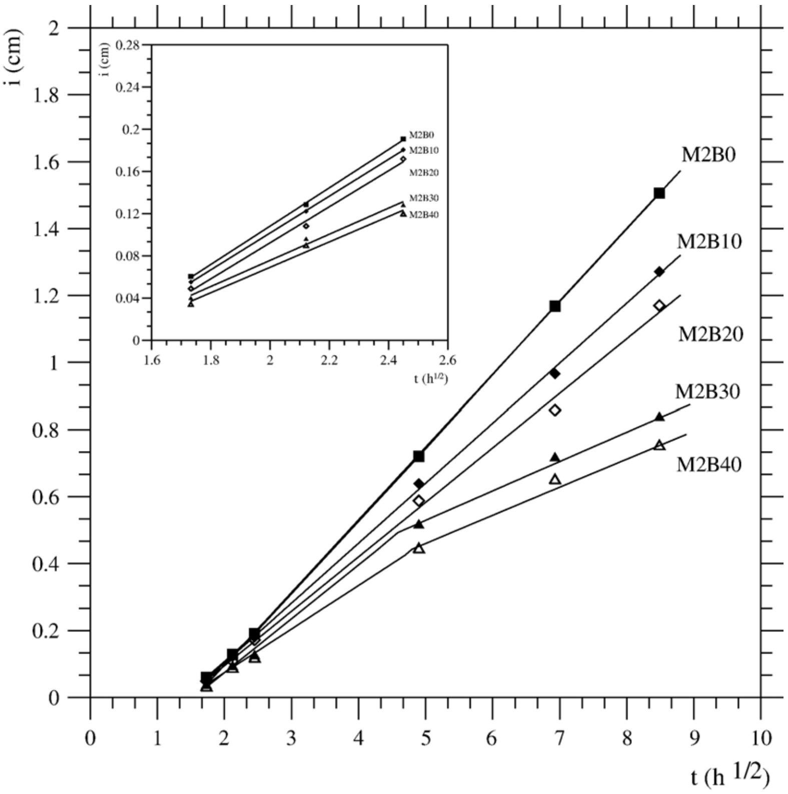

Fig. 7. Sorptivity plots (i versus $t^{1/2}$) for the mortar mixes M2B0, M2B10, M2B20, M2B30 and M2B40.

that the pore structure is refined when Portland cement is replaced by GCWCCB. We took the percentage of the total volume of pores that have diameter less than 0.1 μm as a measure of pore refinement [26]. This percentage was found to be 51.2%, 57.2% and 83.3%, respectively, for mixes M2B0, M2B10 and M2B20.

3.3. Chloride ion penetration and sulfate resistance.

The use of GCWCCB reduced significantly the rate of chloride ion penetration of the mortars. For example, the charge passed through mix M2B0 was reduced from 13500 C to, respectively, 8250 C and 2000 C when 10% and 20% of Portland cement was replaced by GCWCCB. This behavior may be associated with pore refinement promoted by the replacement material that created difficulties to the ionic transport inside the mixes.

Regarding the sulfate resistance of the mortars mixes, the results presented in Table 3 indicate that after 100 days the specimens exposed to magnesium sulfate presents nearly the same strength of those cured in deionized water for the same period. This behavior has changed in the later stage of curing/exposure. The tensile strength loss is less pronounced, however, to the specimens containing GCWCCB. For example,

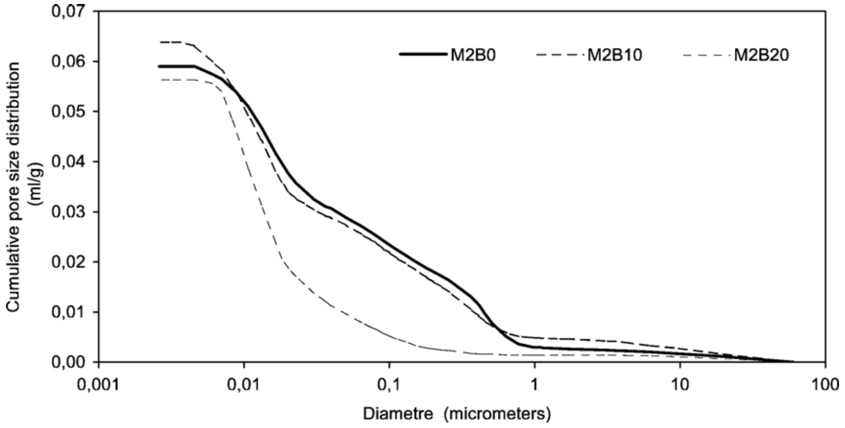

Fig. 8. Pore size distribution of the mixes M2B0, M2B10 and M2B20.

Table 3
Values of tensile strength (f_t), coefficient of variation (CV) and relative strength for the mortar mixes immersed in deionised water (f_{tw}) and in a 5% MgS solution ($f_{t\ 5\%MgS}$)

Time of immersion (days)	Mix	Tensile strength (MPa) — (CV (%))		
		f_{tw}	$f_{t\ 5\%MgS}$	$f_{t\ 5\%MgS}/f_{tw}$
Prior to immersion [a]	M2B0	3.33 — (3.03)	–	–
	M2B10	3.22 — (2.02)	–	–
	M2B20	3.03 — (3.26)	–	–
100	M2B0	4.03 — (1.19)	3.92 — (0.12)	0.97
	M2B10	4.07 — (2.10)	4.28 — (1.25)	1.05
	M2B20	3.53 — (3.66)	3.52 — (2.39)	1.00
200	M2B0	4.33 — (5.15)	3.83 — (0.84)	0.88
	M2B10	4.17 — (8.20)	4.04 — (2.33)	0.97
	M2B20	3.70 — (3.65)	3.43 — (0.44)	0.93

[a] Values of tensile strength of the specimens cured in water at 24 °C for 28 days.

a strength loss of about 12% is observed for the control specimens exposed to the sulfate solution at the age of 200 days, whereas for the same period of exposition the specimens of mixes M2B10 and M2B20 presented strength loss of 3% and 5%, respectively. According to [24] and [27], that observed the same trend in their studies when using GCWCCB as cement replacement, the mechanisms that can explain the improvement in the durability of these cementitious systems are: (i) the reduction of the content of calcium hydroxide in the matrix; (ii) the reduction the compounds of C_3A that causes the ettringite formation, thanks to cement substitution; (iii) the formation of additional hydrates, which can reduce the permeability and increase the densification of the materials making more difficult the penetration of aggressive agents.

3.4. CO_2 emissions associated with Portland cement production in Brazil

The developments presented in this section are based on the methodology for the estimation of CO_2 emissions of the Intergovernmental Panel on Climate Change [28,29], which considers two main sources of emissions associated with Portland cement production: (i) calcination of limestone; and (ii) energy consumption.

The amount of CO_2 emissions due to calcination of limestone (E_{Cal}) can be estimated based on the amount of cement production, clinker to cement ratio and calcium oxide to clinker ratio as described in Eq. (1):

$$E_{Cal} = (K_c \cdot CaO_{clinker} \cdot Clinker_{cement}) \cdot CP \tag{1}$$

where:

K_c is a constant equal to 0.785 (g/mol of CO_2)/(g/mol of CaO); $CaO_{clinker}$ is the calcium oxide to clinker ratio, $Clinker_{cement}$ is the clinker to cement ratio; and CP is the cement production.

Taking the averaging values for the Brazilian cement production of $CaO_{clinker}=0.632$ [12] and $Clinker_{cement}=0.80$ [4], and applying Eq. (1) to the 34 million tonnes of cement produced in Brazil in 2003, a total emission of 13.5 million tonnes of CO_2 is found for the calcination process.

To compute the emissions originated from energy combustion in the cement sector (E_{Com}), it should be considered the amount of CO_2 emissions related with the combustion process. This depends on the content of carbon present in the used fossil fuels used for cement production. According to the IPCC procedures, and with the data obtained from the Brazilian Energy Balance [30], it was found the emission of 9.2 million tonnes of CO_2 due to combustion for Brazilian cement production.

Therefore, the total CO_2 emissions from the cement industry in Brazil in 2003 were 22.7 million tonnes of CO_2 leading to a total emission factor of 0.67 tonnes of CO_2 per tonne of cement. This emission factor is significantly lower than the value of 1.0 currently used in the literature (see, for instance, [31]). The main reasons to explain this difference are: (a) in Brazil the main source of electricity is hydroelectricity (95%) with no relevant CO_2 emissions [32]. (b) 20% of the fuel consumption in the cement sector in 2003 came from renewable sources with neutral CO_2 emissions [30]; (c) the clinker to cement ratio of the Brazilian cement is, in average, 0.8, whereas the nominal clinker to cement ratio of Portland cement, generally used to compute the emissions in the sector is 0.95 [4].

3.5. Emissions avoided replacing Portland cement by GCWCCB.

The results obtained with the experimental program presented in this paper, indicated that GCWCCB can be used as cement replacement material with optimal percentages varying from 10% to 20%. Since the quantity of available residues of calcined-clay brick was estimated to be equivalent to 10% of the Brazilian production in 2003, it is evident that the substitution of 3.4 million tonnes of cement by GCWCCB, would correspond to a reduction of 2.3 million tonnes of CO_2 emissions, considering the emission factor of 0.67 calculated above. It should be pointed out that the only emission that would intervene in the CO_2 balance would be the emissions originated by grinding of GCWCCB, but as it was stated in the previous section, grinding, in Brazil, uses hydroelectricity with no relevant CO_2 emissions.

4. Conclusions

The following conclusions may be drawn from this study:

1. The addition of GCWCCB had almost no influence on the compressive strength and elastic modulus until the percentage of 20% cement replacement. Mortars containing high content of GCWCCB (30 and 40% of replacement) presented, however, strength and elastic modulus lower than the control mixes. This behavior was more noticeable for the mortar mixes with higher *w*/*c* ratio.
2. The addition of GCWCCB reduced the sorptivity of the mixes. This behavior may be related with a refinement in the pore structure. Mercury pore size distribution indicated an

increase in the percentage of the total pore volume of pores having diameters less than 0.1 mm when 10% and 20% of cement is replaced by GCWCCB.

3. The use of GCWCCB reduced the chloride ion penetration and the tensile strength loss of the control mortars exposed to a 5% magnesium sulfate solution at the age of 200 days.
4. Brazilian CO_2 emissions due to cement production, for the year 2003, have been estimated as 23.6 million tonnes, and the replacement of cement by GCWCCB would reduce 2.3 million tonnes of these emissions. This reduction can be eligible under the Clean Development Mechanism (CDM) established by the Kyoto protocol, and generate credits that will help the implementation of the substitution projects in large scale.
5. In addition to the reduction of CO_2 emissions, the substitution of cement by GCWCCB would have an additional positive environmental impact because it would permit the recycling of a by-product of the ceramic industry that otherwise would remain in the environment as a waste product.

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