Fine-ground ceramics as an alternative binder in high performance concrete

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Abstract

The ceramic industry often produces calcined clays that result from burning illite-group clays, which are commonly used in the production of red-clay ceramic products. A portion of these products (which amounts up to 2% depending on producer and country) is discarded as scrap, and thus constitutes industrial waste. The residues of ceramic bricks and floor and roof tiles ground to a suitable fineness can become active pozzolans. So, they have the potential to be used in mortar and concrete. In this paper, mechanical properties and heat and water transport parameters of high performance concrete containing fine-ground ceramics as a partial replacement of Portland cement are studied and compared with reference high performance concrete. The experimental results show that the replacement of Portland cement in the amount of 20% by mass is the most suitable solution. In comparison with reference high performance concrete the mechanical properties of concrete where up to 20% of cement is replaced by fine-ground ceramics are similar or slightly worse, and water transport properties are still acceptable from the durability point of view.

Keywords: high performance concrete, fine-ground ceramics, mechanical properties, water transport properties, thermal properties.

1 Introduction

Many industrial byproducts possessing pozzolanic properties are produced in large amounts worldwide, and despite the current trends of environmental protection and sustainable construction, their production volume still greatly

WIT Transactions on The Built Environment, Vol 112, © 2010 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/HPSM100091

exceeds their industrial reuse. Therefore, there are compelling reasons to extend the practice of partial replacement of cement in concrete and mortar with waste materials or at least with more environmentally friendly materials from the point of view of CO_2 production, which have pozzolanic properties. One possible source for such a pozzolan is calcined clay [1].

The ceramic industry often produces calcined clays that result from burning illite-group clays, which are commonly used in the production of red-clay ceramic products. A portion of these products (which amounts up to 2% depending on producer and country) is discarded as scrap, and thus constitutes industrial waste. The residues of ceramic bricks and floor and roof tiles ground to a suitable fineness can become active pozzolans [2–4]. Therefore, waste ceramic materials may have the potential to become a cheaper but almost equivalent alternative to metakaolin as a supplementary binder in mortar and concrete.

In this paper, fine-ground ceramics is used as an alternative binder in high performance concrete (HPC), replacing Portland cement in the amount of up to 60% of mass.

2 Materials and samples

The high performance concrete mixtures presented in Table 1 were prepared with Portland cement CEM I 42.5 R as the main binder. The chemical composition of cement is shown in Table 2; its specific surface area was 341 m^2/kg. A part of cement was replaced by fine-ground ceramics with the chemical composition shown in Table 3. Its specific surface area was 582 m^2/kg.

The measurement of material parameters of hardened concrete mixes was done after 28 days of standard curing. It took place in a conditioned laboratory at the temperature of 22±1°C and 25-30% relative humidity. The following specimens were used in the experiments: basic physical properties - 6 specimens 50 x 50 x 25 mm, bending strength - 3 specimens 100 x 100 x 400 mm, compressive strength – 3 specimens 150 x 150 x 150 mm, water transport

Table 1: Composition of the studied concretes.

Component	Composition [kgm^{-3}]				
	RC	RC10	RC20	RC40	RC60
CEM I 42.5 R	484.0	435.6	387.2	304.8	193.6
fine-ground ceramics	-	48.4 (10%)	96.8 (20%)	179.2 (40%)	290.4 (60%)
aggregates 0-4 mm	812	812	812	812	812
aggregates 8-16 mm	910	910	910	910	910
plasticizer Mapei Dynamon SX	5.3	5.3	5.3	5.3	5.3
water	160	160	160	160	160

Table 2: Chemical composition of cement.

Component	Amount [%]
SiO_2	21.89
Al_2O_3	5.60
Fe_2O_3	3.75
CaO	62.33
MgO	1.04
K_2O	0.92
Na_2O	0.11
TiO_2	0.30
P_2O_5	0.17
SO_3	2.88

Table 3: Chemical composition of fine-ground ceramics.

Component	Amount [%]
SiO_2	63.45
Al_2O_3	13.98
Fe_2O_3	5.39
TiO_2	0.77
CaO	8.18
K_2O	2.43
Na_2O	0.90
SO_3	0.10

properties - 5 specimens 50 x 50 x 20 mm, thermal properties - 3 specimens 70 x 70 x 70 mm.

3 Experimental methods

3.1 Compressive and bending strength

The measurement of compressive and bending strength was done by the electromechanical testing device VEB WPM Leipzig 3000 kN having a stiff loading frame with the capacity of 3000 kN. The tests were performed according to ČSN EN 12390-3 [5].

3.2 Basic physical parameters

Among the basic properties, the bulk density, matrix density and open porosity were measured using the gravimetric method and water vacuum saturation method [6]. Each sample was dried in a drier to remove majority of the physically bound water. After that, the samples were placed into the desiccator with deaired water. During three hours, air was evacuated with vacuum pump from the desiccator. The specimen was then kept under water not less than 24 hours.

3.3 Water transport properties

The water sorptivity was measured using a standard experimental setup [7]. The specimen was water and vapour-proof insulated on four lateral sides and the face side was immersed 1-2 mm in the water. Constant water level in tank was achieved by a Mariotte bottle with two capillary tubes. One of them, inside diameter 2 mm, was ducked under the water level, second one, inside diameter 5 mm, was above water level. The automatic balance allowed for recording the increase of mass. The water absorption coefficient A [$kgm^{-2}s^{-1/2}$] was calculated using the formula

$$i = A \cdot \sqrt{t} \tag{1}$$

where i [kg/m^2] is the cumulative water absorption, t is the time from the beginning of the suction experiment. The water absorption coefficient was then used for the calculation of the apparent moisture diffusivity in the form [8]

$$\kappa_{app} \approx \left(\frac{A}{w_c - w_0} \right)^2 \tag{2}$$

where w_c is the saturated moisture content [kgm^{-3}] and w_0 the initial moisture content [kgm^{-3}].

3.4 Thermal properties

Thermal conductivity λ [$W\ m^{-1}\ K^{-1}$] and specific heat capacity c [$J\ kg^{-1}\ K^{-1}$], were measured using the commercial device ISOMET 2104 (Applied Precision, Ltd.). The measurement is based on analysis of the temperature response of the analyzed material to heat flow impulses. The heat flow is induced by electrical heating using a resistor heater having a direct thermal contact with the surface of the sample.

4 Experimental results and discussion

4.1 Compressive and bending strength

Table 4 shows the mechanical properties of five studied concretes. The replacement of Portland cement by find-ground ceramics up to 20% of mass did not lead to any significant decrease in compressive strength; the decrease of bending strength was lower than 15% which was still acceptable. For the replacement level higher than 20% of the mass of cement, the compressive strength was affected to a much higher extent than the bending strength. For RC60 the compressive strength was three times lower as compared with the reference concrete mixture but the bending strength was only 30% lower. In any case, as for the mechanical properties, the concretes with 40% of fine-ground ceramics and more did not meet the basic criteria to be considered high performance materials.

A comparison with similar HPC containing metakaolin [9] showed that for the same amount of Portland cement replacement the compressive strength of HPC with fine-ground ceramics was 5% lower and bending strength 35% lower. However, also the mechanical properties of reference HPC from [9] were better than RC in this paper so that this comparison did not present a convincing argument that metakaolin as cement replacement was a more successful solution than the application of fine-ground ceramics.

4.2 Basic physical parameters

The bulk density of the analyzed concretes (Table 5) decreased with the increasing amount of fine-ground ceramics; the open porosity increased in the corresponding way. The values of matrix density were almost the same (within a 3% limit) for all studied concretes. For up to 20% replacement of Portland cement the obtained results were very similar with metakaolin concrete from [9].

Table 4: Mechanical properties of the studied concretes.

Material	Strength [MPa]	
	Compressive	Bending
RC	62.0	8.44
RC10	65.7	7.69
RC20	60.2	7.11
RC40	42.6	6.55
RC60	22.5	5.69

Table 5: Basic physical properties of the studied concretes.

Material	ρ_b	ρ_{mat}	ψ
	[kg m^{-3}]	[kg m^{-3}]	[%]
RC	2400	2690	10.7
RC10	2370	2710	12.6
RC20	2310	2630	13.0
RC40	2270	2660	14.0
RC60	2270	2650	14.5

Table 6: Water transport properties of the studied concretes.

Material	A	κ
	[kg m^{-2}s$^{-1/2}$]	[m^2 s^{-1}]
RC	0.0041	1.321E-09
RC10	0.0067	3.794E-09
RC20	0.0077	3.825E-09
RC40	0.0101	6.225E-09
RC60	0.0104	5.212E-09

4.3 Water transport properties

The results of water sorptivity measurements are presented in Table 6. They were in a very good qualitative agreement with the open porosity data (Table 5). The liquid water transport parameters systematically increased with the increasing amount of fine-ground ceramics in the mix. This is a negative trend, in general. However, in a comparison with common HPC containing silica fume [10] the values of water sorptivity of concretes with fine-ground ceramics were for up to 20% replacement of Portland cement lower. HPC containing metakaolin [9] with the same level of Portland cement replacement had the water sorptivity effectively the same as HPC with fine-ground ceramics in this paper (the difference was within a 5% limit which was within the error range of the measuring method). Therefore, similarly as with the mechanical parameters, RC20 appeared as the most suitable mix design.

4.4 Thermal properties

The values of thermal conductivity of studied concretes in dry state (Table 7) were in a basic qualitative agreement with open porosity results (Table 5); the

Table 7: Thermal properties of the studied concretes in dry state.

Material	λ [$Wm^{-1}K^{-1}$]	c [$Jkg^{-1}K^{-1}$]
RC	1.69	691
RC10	1.53	678
RC20	1.57	705
RC40	1.53	783
RC60	1.41	768

thermal conductivity decreased with the increasing amount of replacement of Portland cement by fine-ground ceramics. The values of specific heat capacity increased with the increasing amount of fine-ground ceramics; the maximum difference was 13%, as compared with the reference HPC. The obtained data were in basic agreement with previous measurements of thermal properties of HPC [10–12].

5 Conclusions

Experimental results presented in this paper confirmed that find-ground ceramics can be considered an environmental friendly binder with a potential to replace a part of Portland cement in concrete in building industry. However, it was shown that although it was desirable from both environmental and economical point of view to use its highest possible amounts in concrete production, the extent of Portland cement replacement which could be chosen in preparation of high performance concrete mixes had certain limitations.

The main limiting parameter for using higher amounts of fine-ground ceramics in HPC was found the compressive strength. For higher replacement levels than 20% of mass of cement the compressive strength decreased very fast and the produced concrete lost its high performance character. The water transport parameters increased with increasing amount of fine-ground ceramics in the mix but the increase was not that steep as the decrease in compressive strength. For 20% Portland cement replacement the water sorptivity was still relatively low and quite acceptable from the point of view of concrete durability. Therefore, concrete with the replacement of Portland cement by fine-ground ceramics in the amount of 20% by mass was the most suitable solution among the mixes analyzed in this paper.

Acknowledgement

This research has been supported by the Czech Science Foundation, under grant No P104/10/0355.

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