Cement & Concrete Composites 34 (2012) 55–61

Contents lists available at SciVerse ScienceDirect

Cement & Concrete Composites

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

Properties of high performance concrete containing fine-ground ceramics as supplementary cementitious material

Eva Vejmelková [a], Martin Keppert [a], Pavla Rovnaníková [b], Michal Ondráček [c], Zbyněk Keršner [d], Robert Černý [a,*]

[a] Department of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7, 166 29 Prague 6, Czech Republic
[b] Institute of Chemistry, Faculty of Civil Engineering, Brno University of Technology, Žižkova 17, 602 00 Brno, Czech Republic
[c] Institute of Technology of Building Materials and Components, Faculty of Civil Engineering, Brno University of Technology, Veveří 95, 602 00 Brno, Czech Republic
[d] Institute of Structural Mechanics, Faculty of Civil Engineering, Brno University of Technology, Veveří 95, 602 00 Brno, Czech Republic

ARTICLE INFO

Article history:
Received 22 September 2010
Received in revised form 26 September 2011
Accepted 27 September 2011
Available online 2 October 2011

Keywords:
High performance concrete
Fine-ground ceramics
Mechanical properties
Fracture-mechanics properties
Durability properties
Hydric properties
Thermal properties

ABSTRACT

This paper presents experimental work regarding the basic physical characteristics, mechanical and fracture-mechanics properties, durability characteristics, hydric and thermal properties of high performance concrete (HPC) with up to 60% of Portland cement replaced by fine-ground ceramics. Experimental results show that the amount of the ceramics in the mix is limited mainly by the resistance against de-icing salts which is found satisfactory only up to the cement replacement level of 10%. The mechanical and water transport properties are not significantly impaired by ceramic additions of up to 20%, whereas the effective fracture toughness, specific fracture energy, and chemical resistance (to $MgCl_2$, NH_4Cl, Na_2SO_4, HCl) are effectively maintained up to 40%. The frost resistance, water vapor transport and storage parameters and thermal properties are not significantly impaired even up to a 60% replacement level.

1. Introduction

Clay minerals become highly reactive when they are incinerated at temperatures between 600 and 900 °C and then ground to cement fineness [1]. They are mainly formed by siliceous and aluminous compounds. The loss of water due to thermal treatments causes destruction of their crystalline structure, and they are converted into unstable amorphous state [2]. If they are then mixed with calcium hydroxide and water they undergo pozzolanic reaction and form compounds with enhanced strength and durability.

The utilization of calcined clay in the form of metakaolin as a pozzolanic addition for mortar and concrete was widely studied within the last several decades. The preference of metakaolin to other types of calcined clays adopted by many investigators had the apparent reason that clays from the kaolinite group presented after calcination the highest pozzolanic activity as compared for instance with the illite or montmorillonite clay groups [3,4].

Waste ceramic materials may become a cheaper but almost equivalent alternative to metakaolin as supplementary binder in concrete. 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, thus constitutes industrial waste. The residues of ceramic bricks and floor and roof tiles ground to a suitable fineness can though become active pozzolans [5–7]. So, they have a potential to be used in mortar and concrete.

The effect of ground waste ceramics as partial cement replacement on the properties of concrete or mortar was investigated far less often than in the case of metakaolin. However, the number of publications increased fast during the last few years. As it is usual also with other types of cementitious composites, the most references were concentrated on mechanical properties. To give only couple of examples, O'Farrell et al. [8,9] studied the effect of waste clay brick in the amount of up to 30% of cement on the compressive strength of mortars and found a decrease in early strengths up to 28 days but increase in 90-days strengths, Lavat et al. [6] observed decrease in early strengths, Toledo Filho et al. [7] and Goncalves et al. [10] measured a slight increase in compressive strengths for the cement replacement by waste brick powder up to 10–20%.

Water and salt transport properties were investigated less often. Toledo Filho et al. [7] and Goncalves et al. [10] measured sorptivity of cement mortars modified with ground brick and

---

[*] Corresponding author. Tel.: +420 224355044; fax: +420 224354446.
E-mail address: cernyr@fsv.cvut.cz (R. Černý).

0958-9465/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconcomp.2011.09.018

realized that sorptivity decreases with the increasing amount of ground brick. A decrease in water- and water vapor permeability of mortars containing fine ceramics was reported by Silva et al. [11]. Goncalves et al. [10] and Bektas et al. [12] observed a decrease in chloride ion penetration with the increasing amount of ground brick in cement mortars. Pacheco-Torgal and Jalali [13] reported a decrease of water permeability and chloride ion diffusion in concrete with 20% of ground ceramics as Portland cement replacement.

Durability properties were studied very rarely. O'Farrell et al. [9,14] reported increased sulfate resistance as a result of partial replacement of cement by ground brick. Measurements of fracture-mechanics properties or thermal properties of cementitious materials containing ground brick as partial cement replacement were not found at all in common reference sources.

It should be noted that the references mentioned above were concerned mostly with mortars. The use of ground ceramics as partial cement replacement in concrete was reported only lately [13]. References describing investigations of concrete with crushed brick as partial replacement of aggregates were more frequent [13,15–20]. However, in either case the research work was aimed at concretes and mortars with lower compressive strengths, typically up to 50 MPa; not any experimental investigations dealing with high performance concretes containing ground brick as binder or crushed brick as aggregates were found in common databases.

In this paper, high performance concrete (HPC) mixes containing fine-ground ceramics as Portland cement replacement in a wide range are investigated. A representative set of parameters including basic material characteristics, mechanical and fracture-mechanics properties, durability characteristics, hydric and thermal properties is determined and compared with the parameters of reference Portland cement concrete.

2. Experimental methods

2.1. Basic characteristics and mechanical properties

As fundamental physical material characteristics, bulk density ρ_b (kg m^{-3}), open porosity (vol.%) and matrix density ρ_{mat} (kg m^{-3}) were determined using the water vacuum saturation method [21]. Characterization of the pore structure was performed by mercury intrusion porosimetry. The experiments were carried out using the instruments Pascal 140 and 440 (Thermo Scientific).

The compressive strength was tested according to the standard ČSN EN 12390-3 [22] using a 3000 kN hydraulic testing device. The effective fracture toughness was measured using the Effective Crack Model [23]. A three-point bending test [24] of a specimen having a central edge notch with a depth of about 1/3 of the depth of the specimen was used in the experiment. The loaded span was equal to 300 mm. A continuous record of the load–deflection (*F*–*d*) diagram was used for the calculation of effective fracture toughness. An estimate of fracture energy was obtained from the *F*–*d* diagram according to the RILEM method (work-of-fracture) [25].

2.2. Durability properties

Frost resistance tests were carried out according to ČSN 73 1322/Z1:1968 [26]. The frost resistance coefficient *K* was determined as the ratio of bending or compressive strength of specimens subjected to 100 freezing and thawing cycles to the strength of reference specimens which did not undergo the frost resistance test. The resistance of studied concrete against de-icing salts was measured according to ČSN 731326/Z1:1984 [27]. The mass loss due to spalling of particles on the surface was measured after every 25 cycles.

Table 1
Corrosion environments used in the tests.

Environment	Concentration
Air	–
Distilled water	–
$MgCl_2$ (g L^{-1})	17.76
NH_4Cl (g L^{-1})	2.97
Na_2SO_4 (g L^{-1})	14.79
HCl (mol/L)	10^{-3}
CO_2 (vol.%)	65 ± 5

The chemical resistance in various environments (Table 1) was tested according to the procedure developed at the Brno University of Technology [28]. The coefficient of chemical resistance K_{cr} was determined as the ratio of the compressive strength after 60 days in a particular environment and compressive strength after 60 days in laboratory conditions. All the specimens were water-leached after the compressive-strength test and the pH value was determined by potentiometry. X-ray Diffraction (XRD) analysis in the range of Θ-angle of 5–80° (Bruker D8 Advance device, CuK$_\alpha$ radiation, 0.154184 nm) was done as well to test the possible appearance of new phases.

2.3. Hydric and thermal properties

The dry-cup method was employed in the measurement of water vapor transport properties [21]. The water vapor diffusion permeability δ, water vapor diffusion coefficient *D* and water vapor diffusion resistance factor μ were the investigated parameters. Water adsorption and desorption isotherms were determined using the desiccators method [21]. The liquid water transport was characterized by the determination of water absorption coefficient *A* and apparent moisture diffusivity κ which were measured using a free water intake experiment [29,30].

The thermal conductivity λ, specific heat capacity *c* and thermal diffusivity *a* were measured using the commercial device Isomet 2104 (Applied Precision, Ltd.). The measurement is based on the analysis of the temperature response of the analyzed material to heat flow impulses.

3. Materials and samples

The high performance concrete mixes were prepared with Portland cement CEM I 42.5 R as the main binder. The chemical composition of cement is shown in Table 2. It was determined by X-ray fluorescence analysis; an X-ray spectrometer S4 Pioneer was used. To determine the loss on ignition the sample was burnt for one hour at 1000 °C. The specific surface area of cement was 341 m^2/kg. A part of cement (10–60% by mass) was replaced by fine-ground ceramics (a waste material from different brick kilns) with the chemical composition shown in Table 3. Its density was

Table 2
Chemical composition of cement.

Component	Amount (%)
SiO_2	18.89
Al_2O_3	4.24
Fe_2O_3	3.83
CaO	62.37
MgO	0.99
SO_3	2.31
Not identified	3.81
Loss on ignition	1.52

Table 3
Chemical composition of fine-ground ceramics.

Component	Amount (%)
SiO_2	63.45
Al_2O_3	13.98
Fe_2O_3	5.39
CaO	8.18
TiO_2	0.77
K_2O	2.43
Na_2O	0.90
SO_3	0.10
Loss on ignition	1.13

Table 4
Composition of studied concretes.

Component	Composition ($kg\ m^{-3}$)				
	CR	CB10	CB20	CB40	CB60
CEM I 42.5 R	484.0	435.6	387.2	304.8	193.6
Fine-ground ceramics	0	48.4	96.8	179.2	290.4
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 5
Properties of fresh mixtures.

Material	Slump (mm)	Bulk density ($kg\ m^{-3}$)
CR	180	2410
CB10	210	2400
CB20	210	2380
CB40	180	2394
CB60	150	2370

Table 6
Basic physical properties.

Material	Bulk density ($kg\ m^{-3}$)	Matrix density ($kg\ m^{-3}$)	Open porosity (%)
CR	2430	2740	11.2
CB10	2420	2730	11.4
CB20	2370	2720	12.8
CB40	2330	2700	13.9
CB60	2310	2730	15.5

2722 kg/m^3, the specific surface area 336 m^2/kg. Crushed granodiorite was used as coarse aggregate (Olbramovice, 2640 kg/m^3), sedimentary river psefites as fine aggregate (Žabčice, 2580 kg/m^3). The design of the concrete mixes was done according to ČSN EN 206-1. The equation of absolute volumes was used; the volume of each component was calculated to give a total sum of 1 m^3, taking into account 2% of the air. The composition of the studied HPC mixes is presented in Table 4, the properties of fresh mixtures are given in Table 5. The addition of lower amounts of ceramics led to a slight increase of slump values but for its content higher than 20% of cement mass the slump decreased. The bulk density of fresh mixtures decreased with the increasing amount of ceramics but the differences remained only within a 1–2% margin.

The measurement of material parameters was done (unless stated otherwise) after 28 days of standard curing in a conditioned laboratory at the temperature of 22 ± 1 °C and 25–30% relative humidity. The following specimens' sizes were used in the experiments: basic physical properties – 50 × 50 × 25 mm, compressive strength – 150 × 150 × 150 mm, fracture-mechanics properties – 100 × 100 × 400 mm, freeze/thaw resistance, de-icing salts resistance – 100 × 100 × 400 mm, chemical resistance – 100 × 100 × 50 mm, water vapor transport properties, sorption isotherms, water transport properties – 50 × 50 × 20 mm, thermal properties – 70 × 70 × 70 mm.

4. Experimental results and discussion

4.1. Basic characteristics and mechanical properties

The bulk density decreased with the increasing amount of ceramics in the mix (Table 6); the difference between the limiting cases of CR and CB60 was 5%. The open porosity increased in a corresponding way. This indicated the possible durability problems for mixes with higher Portland cement replacement.

The pore distribution of all mixes (Fig. 1) exhibited a major peak between 0.01 μm and 0.1 μm. This peak was for CB10 and CB20 lower than for the reference mix CR and decreasing with increasing ceramics amount, for CB40 and CB60 an opposite trend was observed. For CB10–CB60, another peak started to build up between 0.1 μm and 1 μm. This implied a possibility of enhanced water transport. Table 7 presents the pore size distribution according to IUPAC classification where the volumes and percentages of macropores and mesopores are given; the amount of micropores is not included because the applied MIP method did not make it possible to identify micropores with $d < 2$ nm. For all materials the percentage of macropores was higher than mesopores. The specific volume of macropores increased with the increasing content of fine-ground ceramics in the mix but for mesopores it was similar for CR, CB10, and CB20 and only for higher cement replacement levels it began to increase.

The porosity of HPC mixes in Table 6 was higher than the values reported in [7] for mortars with similar compressive strength; the differences also increased with the increasing amount of fine-ground ceramics. This was probably related to the lower cement/aggregate ratio (1:3.5 against 1:1.5 in [7]) and to the high amount of coarse aggregates of the mixes used in this paper. On the other hand, the porosity of 30–35 MPa concrete produced using a blended binder with 20% of ground ceramics, which was studied in [13], was significantly higher than for CR and CB20, by 30–40%. This was apparently due to the water/cement ratio of 0.6.

The compressive strength of CR and CB10 exceeded 60 MPa (which can be considered a lower limit for HPC) already after 7 days (Table 8) and did not increase further until 28 days. Among the other mixes, CB20 achieved 60 MPa after 28 days, with a substantial increase between 7 and 28 days, which was still satisfactory. However, the compressive strengths of CB40 and CB60 were well below the desired values. The reference concrete CR achieved the highest effective fracture toughness K_{Ic}^{e} and specific fracture

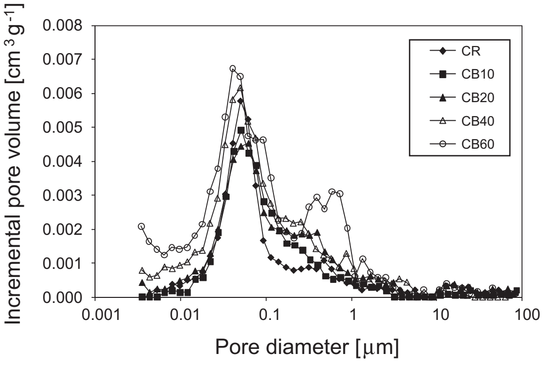

Fig. 1. Pore size distribution.

Table 7
Pore size distribution according to IUPAC classification.

Material	Macropores $d > 50$ nm		Mesopores $50\ \text{nm} > d > 2$ nm	
	$cm^3\ g^{-1}$	%	$cm^3\ g^{-1}$	%
CR	0.&	62	0.016	38
CB10	0.029	67	0.014	33
CB20	0.036	68	0.017	32
CB40	0.041	60	0.027	40
CB60	0.051	57	0.038	43

Table 8
Compressive strength (MPa).

Material	7 days	28 days
CR	63.3	62.0
CB10	65.2	65.7
CB20	47.8	60.2
CB40	37.9	42.6
CB60	21.3	22.5

Table 9
Fracture-mechanics properties.

Material	Effective fracture toughness (MPa $m^{1/2}$)	Specific fracture energy (J m^{-2})
CR	1.71	287
CB10	1.58	278
CB20	1.50	253
CB40	1.59	238
CB60	1.16	199

energy G_F (Table 9). Both K_{Ic}^{e} and G_F decreased with the increasing amount of ceramics in the mix. For CB40 K_{Ic}^{e} was reduced by 7%, G_F by 17% as compared with CR, so that their values were still relatively high. However, for CB60 the decrease was already 32% for K_{Ic}^{e} and 31% for G_F which seems to be too much.

The decrease in compressive strength with the increasing amount of ground waste clay bricks was also observed in [7,9] where mortars with similar compressive strength as the concretes in this paper were investigated. The 28-days strength determined in [9] decreased significantly faster for the Portland cement replacement up to 20% (by 15%, as compared with the 3% of the concrete mixes studied in this paper). On the other hand, the results obtained in [7] showed a similar trend to our HPC mixes up to the 40% replacement level.

The measurement of fracture-mechanics properties of concretes containing ground ceramics as supplementary binder was not reported to date. The values of the specific fracture energy and fracture toughness were significantly higher than those commonly obtained for normal concrete or high strength concrete. The main reason was, apparently, the low water to cement ratio of the mixes investigated in this paper. A comparison with a similar mix BM containing 10% of metakaolin (the cement, aggregates and plasticizer of the same types and quantities as in the mixes designed in this paper, the amount of water 142 kg/m^3, the slump 130 mm) [31] showed that the effective fracture toughness of CB10 exceeded BM by 7%, the specific fracture energy by 16%. As the compressive strength of CB10 was only 5% lower than BM which was partially due to the slightly higher water/binder ratio, it seems that – at least from the point of view of mechanical properties – fine-ground ceramics in lower replacement amount may be considered a viable alternative to metakaolin as supplementary cementitious material in concrete.

4.2. Durability properties

The frost resistance of all studied concrete mixes was excellent (Table 10) and well exceeded the limit of $K = 0.75$ which according to the standard [26] makes possible to classify a concrete mix as frost resistant. On the other hand, the resistance against de-icing salts (Fig. 2) was poor for mixes with higher Portland cement replacement level. For CB60 and CB40 the loss of mass exceeded the standard limit of 1000 g/m^2 [27] already after 25 cycles, for CB20 it was after 75 cycles. Only CB10 as the best performing mix and the reference CR met the requirements of the standard. The probable reason why the de-icing salt resistance of the analyzed materials was much worse than their frost resistance was the higher severity of the former test. The combination of the ice formation and chloride binding in the pore system induced by the repeated exposure to the NaCl solution could result in a faster destruction of the finer pores. As the volume of the smallest pores under 0.01 μm increased with the increasing amount of fine-ground ceramics in the mix (Fig. 1), the materials with higher ceramics content were damaged in a more significant way.

The chemical resistance of CB10, CB20 and CB40 (Fig. 3) was for all studied environments (except for CO_2) better than for the reference mix CR. The highest differences in K_{cr} (as compared to CR) were observed for Na_2SO_4, HCl, and distilled water. The performance of CB60 was significantly worse, in some cases (HCl, $MgCl_2$) even in a comparison with CR. Adopting for the chemical resistance a similar criterion for satisfactory performance as for the frost resistance, i.e., $K_{cr} > 0.75$, it could be concluded that all materials (except for CR in Na_2SO_4) exhibited good chemical resistance in all chosen environments.

The pH values of water leaches of specimens submerged for 60 days in various environments are presented in Fig. 4. The alkalinity of most leaches decreased with the increasing amount of fine-ground ceramics in the mix, only in $MgCl_2$, Na_2SO_4, and HCl the water leach of CB10 had slightly higher pH than CR. In most cases, the pH values were higher than 11; the only exception was CB40 and CB60 in CO_2 where pH decreased under 10. Such substantial decrease in pH might indicate a higher carbonation extent which was not expected in materials where relatively high

Table 10
Frost resistance.

Material	Frost resistance coefficient K	
	As the ratio of compressive strengths (–)	As the ratio of bending strengths (–)
CR	0.96	0.87
CB10	1.00	1.00
CB20	1.00	1.00
CB40	1.00	1.00
CB60	0.95	1.00

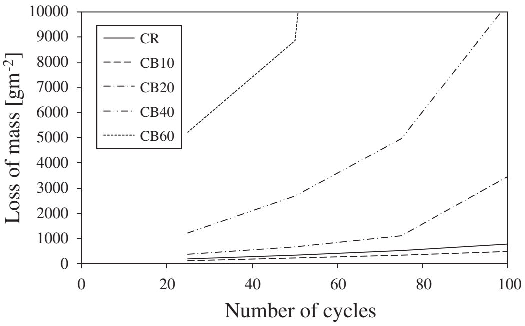

Fig. 2. Loss of mass due to the de-icing salts action.

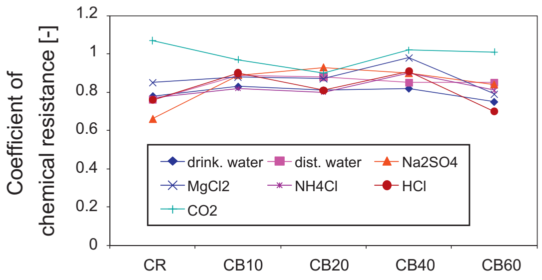

Fig. 3. Coefficient of chemical resistance K_{cr} in various environments.

amount of Portland cement was substituted by fine-ground ceramics having much lower content of CaO (Table 3). The probable reason was the higher porosity of CB40 and CB60 which made the contact of CO_2 with the interior of the tested specimens easier than for the remaining mixes.

The results of XRD analysis of specimens submerged into the environments listed in Table 1 did not show any new phases for all mixes and all environments. This means that all materials were relatively compact; the chemical substances could react just on the surface and could not penetrate deeper into the porous structure. A characteristic example of XRD analysis (for one of CB20 specimens) is presented in Fig. 5.

The results of sulfate resistance experiments performed in this paper were in a qualitative agreement with the results obtained for mortars with Portland cement replacement level up to 40% in [7] and up to 30% in [9].

In a comparison with the metakaolin concrete BM studied in [31], the frost resistance of CB10 was the same (excellent), the loss of mass in the de-icing salt resistance test slightly higher, and the coefficient of chemical resistance K_{cr} for the environments listed in Table 1 almost the same, within the error range of the experimental method. Therefore, also from the durability point of view the fine-ground ceramics at lower replacement levels may serve as a supplementary cementitious material alternative to metakaolin in concrete.

4.3. Hydric and thermal properties

The water vapor transport parameters of all analyzed mixes (Table 11) were very similar. The maximum difference was within a 10% limit which was on the edge of the error range of the measuring method. Also the adsorption and desorption isotherms (Fig. 6) of all materials did not exhibit much difference, except for CB60, which had slightly lower maximum hygroscopic moisture content than other materials and also the moisture contents on its desorption isotherms were lower. The probable reason could be a different topology of the pore space of CB60 which had significantly higher open porosity than the other mixes and could possibly contain lower volume of "bottleneck" pores (pores separated by a narrow passage).

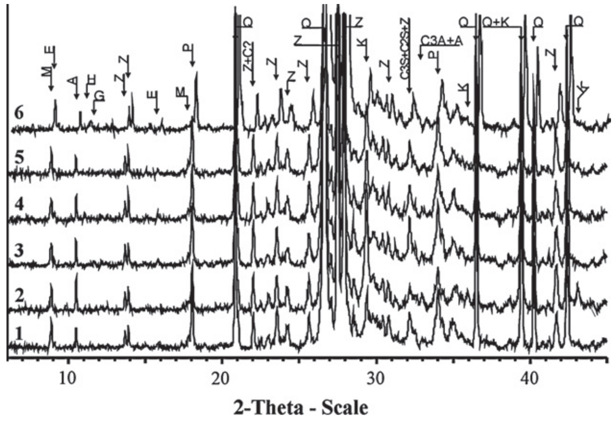

Fig. 5. Example of X-ray diffraction analysis (one of CB20 specimens). 1 – distilled water, 2 – CO_2, 3 – Na_2SO_4, 4 – NH_4Cl, 5 – HCl, 6 – $MgCl_2$. M-muscovite; E-ettringite, A-hornblende; H-hydrokalumite; G-gypsum; Z- feldspars, P-portlandite; Q-quartz; C-cristobalite; K-calcite; C_3S, C_2S, C_3A-clinker minerals.

Table 11
Water vapor transport properties in dry-cup arrangement.

Material	Water vapor diffusion permeability (10^{-11} s)	Water vapor diffusion coefficient (10^{-6} m^2 s^{-1})	Water vapor diffusion resistance factor (–)
CR	1.13	1.55	14.94
CB10	0.99	1.36	17.07
CB20	1.00	1.38	17.08
CB40	1.05	1.45	16.14
CB60	1.00	1.38	16.95

The liquid water transport parameters (Table 12) systematically increased with the increasing amount of fine-ground ceramics in the mix. This was in a good qualitative agreement with the open porosity data (Tables 6 and 7) but contradictory to the results obtained in [7] for mortars of similar compressive strength where water sorptivity was found to decrease with the increasing amount of ground brick up to 40% of mass of cement. This was clearly related to the differences in porosity analyzed above.

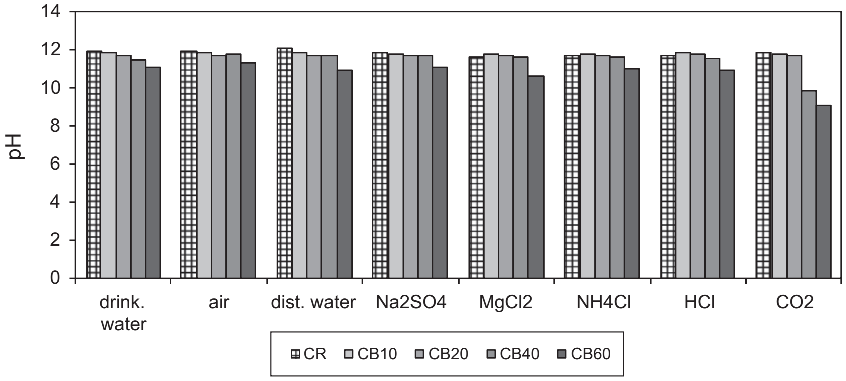

Fig. 4. Measured pH values of water leaches of concrete specimens submerged for 60 days in various environments.

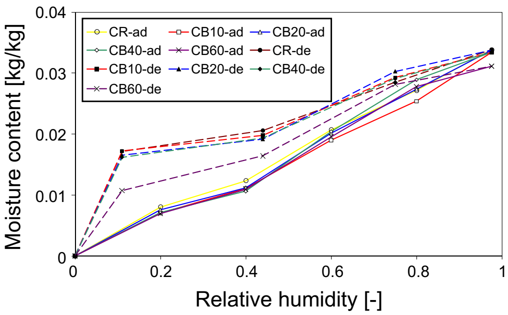

Fig. 6. Adsorption and desorption isotherms.

Table 12
Water transport properties.

Material	Water absorption coefficient (kg m^{-2} s$^{-1/2}$)	Apparent moisture diffusivity (10^{-9} m^2 s^{-1})
CR	0.0041	1.32
CB10	0.0067	3.79
CB20	0.0077	3.82
CB40	0.0101	6.22
CB60	0.0104	5.21

Table 13
Thermal properties in dry state.

Material	Thermal conductivity (W m^{-1} K^{-1})	Specific heat capacity (J kg^{-1} K^{-1})	Thermal diffusivity (10^{-6} m^2 s^{-1})
CR	1.69	691	1.006
CB10	1.53	678	0.937
CB20	1.57	705	0.944
CB40	1.53	783	0.842
CB60	1.41	768	0.797

In a comparison with common HPC containing silica fume [32] the values of water sorptivity of CR, CB10 and CB20 were lower, but for the remaining mixes they were higher. HPC containing metakaolin [31] 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).

The values of thermal conductivity of studied concretes in dry state (Table 13) were in a qualitative agreement with open porosity results (Table 6); the thermal conductivity decreased with the increasing amount of Portland-cement replacement 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 thermal diffusivity data followed the same trend as the thermal conductivity.

The thermal properties of HPC are a topic which was investigated relatively rarely, so there was a limited possibility for direct comparison with data published by other investigators. The obtained data agreed with our previous measurements reported in [32–34] for HPC with silica fume as supplementary cementitious material.

5. Conclusions

High performance concrete mixes containing fine-ground ceramics as Portland-cement replacement in an amount of up to 60% of mass were studied in the paper. Experimental results showed that fine-ground ceramics can be successfully used as supplementary cementitious material in producing high performance concrete. The main findings can be summarized as follows:

- The bulk density of analyzed HPC mixes decreased with the increasing amount of fine ground ceramics in the mix and the open porosity increased in a corresponding way. This indicated possible problems with both mechanical properties and durability for mixes with higher Portland cement replacement.
- The compressive strength decreased very fast for the replacement levels higher than 20%; the produced concrete lost its high performance character. On the other hand, the effective fracture toughness and specific fracture energy decreased only slowly up to 40%.
- The limit of the amount of fine ground ceramics from the point of view of liquid water transport parameters was 20% as well. The water absorption coefficient of CB20 was still relatively low, indicating concrete durability on satisfactory level.
- The frost resistance of all studied concrete mixes was excellent. They also exhibited good chemical resistance in all environments listed in Table 1. Up to 40% replacement level the mixes with fine ground ceramics performed even better than the reference mix. However, from the point of view of the resistance against de-icing salts only the mixes containing up to 10% of fine-ground ceramics were found satisfactory.
- The water vapor transport parameters of all analyzed mixes were very similar. Also, the adsorption and desorption isotherms did not exhibit much difference.
- Thermal conductivity of studied concretes in dry state decreased with the increasing amount of replacement of Portland cement by fine-ground ceramics. This was in a qualitative agreement with the open porosity.
- A comparison of the HPC mix with 10% of fine ground ceramics as Portland cement replacement with a similar mix containing 10% of metakaolin [31] showed that: its compressive strength was only slightly lower, both effective fracture toughness and specific fracture energy were slightly higher, the frost resistance was the same (excellent), the loss of mass in the de-icing salt resistance test was slightly higher, and the coefficient of chemical resistance for the environments listed in Table 1 was almost the same. Therefore, fine-ground ceramics at lower Portland cement replacement levels may be considered a viable alternative to metakaolin as supplementary cementitious material in concrete. This may have interesting economical consequences as the price of waste ceramics (including its grinding) is about two times lower than the price of metakaolin on common markets.

Acknowledgement

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

References

[1] Baronio G, Binda L. Study of the pozzolanicity of some bricks and clays. Constr Build Mater 1997;11:41–6.
[2] Murat M. Hydration reaction and hardening of calcined clays and related minerals: II. Influence of mineralogical properties of the raw-kaolinite on the reactivity of metakaolinite. Cement Concrete Res 1983;13:511–8.

[3] Ambroise J, Murat M, Pera J. Hydration reaction and hardening of calcined clays and related minerals. V – extension of the research and general conclusions. Cement Concrete Res 1985;15:261–8.

[4] He C, Osbaeck B, Makovicky E. Pozzolanic reactions of six principal clay minerals activation, reactivity assessments and technological effects. Cement Concrete Res 1995;25:1691–702.

[5] Gonçalves JP. Use of ceramic industry residuals in concrete. REM-Revista Escola de Minas 2007;60:639–44.

[6] Lavat AE, Trezza MA, Poggi M. Characterization of ceramic roof tile wastes as pozzolanic admixture. Waste Manage 2009;29:1666–74.

[7] Toledo Filho RD, Gonçalves JP, Americano BB, Fairbairn EMR. Potential for use of crushed waste calcined-clay brick as a supplementary cementitious material in Brazil. Cement Concrete Res 2007;37:1357–65.

[8] O'Farrell M, Wild S, Sabir BB. Pore size distribution and compressive strength of waste clay brick mortar. Cement Concrete Compos 2001;23:81–91.

[9] O'Farrell M, Sabir BB, Wild S. Strength and chemical resistance of mortars containing brick manufacturing clays subjected to different treatments. Cement Concrete Compos 2006;28:790–9.

[10] Gonçalves JP, Taveres LM, Toledo Filho RD, Fairbairn EMR. Performance evaluation of cement mortars modified with metakaolin or ground brick. Constr Build Mater 2009;23:1971–9.

[11] Silva J, De Brito J, Veiga R. Incorporation of fine ceramics in mortars. Constr Build Mater 2009;23:556–64.

[12] Bektas F, Turanli L, Wang K, Ceylan H. Comparative performance of ground clay brick in mitigation of alkali–silica reaction. J Mater Civil Eng 2007;19:1070–8.

[13] Pacheco-Torgal F, Jalali S. Reusing ceramic wastes in concrete. Constr Build Mater 2010;24:832–8.

[14] O'Farrell M, Wild S, Sabir BB. Resistance to chemical attack of ground brick-PC mortar. Part I. Sodium sulphate solution. Cement Concrete Res 1999;29:1781–90.

[15] Corinaldesi V, Giuggiolini M, Moriconi G. Use of rubble from building demolition in mortars. Waste Manage 2002;22:893–9.

[16] Poon CS, Chan D. The use of recycled aggregate in concrete in Hong Kong. Resour, Conserv Recy 2007;50:293–305.

[17] Debieb F, Kenai S. The use of coarse and fine crushed bricks as aggregate in concrete. Constr Build Mater 2008;22:886–93.

[18] Cachim PB. Mechanical properties of brick aggregate concrete. Constr Build Mater 2009;23:1292–7.

[19] Cabral AEB, Schalch V, Dal Molin DCC, Ribeiro JLD. Mechanical properties modeling of recycled aggregate concrete. Constr Build Mater 2010;24:421–30.

[20] Torkittikul P, Chaipanich A. Utilization of ceramic waste as fine aggregate within Portland cement and fly ash concretes. Cement Concrete Compos 2010;32:440–9.

[21] Roels S, Carmeliet J, Hens H, Adan O, Brocken H, Černý R, et al. Interlaboratory comparison of hygric properties of porous building materials. J Therm Envelope Build Sci 2004;27:307–25.

[22] ČSN EN 12390-3 Testing of hardened concrete – Part 3: compressive strength. Prague: Czech Standardization Institute; 2002.

[23] Karihaloo BL. Fracture mechanics of concrete. New York: Longman Scientific & Technical; 1995.

[24] ČSN EN 12390-5 Testing of hardened concrete – Part 5: bending strength. Prague: Czech Standardization Institute; 2007.

[25] RILEM TC 50-FMC Fracture mechanics of concrete, determination of the fracture energy of mortar and concrete by means of three-point bend tests on notched beams. Mater Struct 1985;18: 285–90.

[26] ČSN 73 1322/Z1:1968, Concrete testing – Hardened concrete – Frost resistance. Prague: Czech Standardization Institute; 2003.

[27] ČSN 731326/Z1:1984. Determination of the resistance of the surface of concrete against water and de-icing salts. Prague: Czech Standardization Institute; 2003.

[28] Vejmelková E, Pavlíková M, Keršner Z, Rovnaníková P, Ondráček M, Sedlmajer M, et al. High performance concrete containing lower slag amount: a complex view of mechanical and durability properties. Constr Build Mater 2009;23:2237–45.

[29] Kumaran MK. Moisture diffusivity of building materials from water absorption measurements. J Therm Envelope Build Sci 1999;22:349–55.

[30] Vejmelková E, Pavlíková M, Jerman M, Černý R. Free water intake as means of material characterization. J Build Phys 2009;33:29–44.

[31] Vejmelková E, Pavlíková M, Keppert M, Keršner Z, Rovnaníková P, Ondráček M, et al. High performance concrete with Czech Metakaolin: experimental analysis of strength, toughness and durability characteristics. Constr Build Mater 2010;24:1404–11.

[32] Vejmelková E, Padevět P, Černý R. Effect of cracks on hygric and thermal characteristics of concrete. Bauphysik 2008;30:438–44.

[33] Toman J, Černý R. Thermal conductivity of high performance concrete in wide temperature and moisture ranges. Acta Polytech 2001;41:8–10.

[34] Toman J, Černý R. Temperature and moisture dependence of the specific heat of high performance concrete. Acta Polytech 2001;41:5–7.