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Modification of the properties of concrete by a new pozzolan A waste catalyst from the catalytic process in a fluidized bed

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Abstract

The zeolitic waste material studied (fluidized bed cracking catalyst, FBCC) is characterised by a content of more than 90 wt.% of SiO_2 and Al_2O_3, a mean grain size within 20–80 μm, and a specific surface above 100 m^2/g. Its chemical composition makes it similar to some fly ashes and metakaolin. The present work was devoted to the study of the mechanism of interaction of FBCC with Portland cement and of the pozzolanic activity. Concretes were made with FBCC additions of 10% and 20% (relative to the mass of cement) used as a substitute for the sand aggregate fraction, and the following properties of the concretes were determined under nonaggressive conditions: compressive strength, porosity, water absorption, frost resistance, and steel passivation ability. It has been found that FBCC has pozzolanic properties, and its pozzolanic activity depends on its grain size. FBCC favourably modifies the porous structure of the concretes, increases their compressive strength, density, and frost resistance, and reduces water absorption. The effectiveness of FBCC increases under conditions of strong dispersion. FBCC does not deteriorate the steel passivation ability of concrete when used as a 10% additive, but at a content of 20 wt.%, it can make difficult the formation of a passive layer that conforms to the Polish standards. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Waste catalyst; Pozzolan; Concrete

1. Introduction

The waste fluidized bed cracking catalyst (FBCC) from the petrochemical industry is a zeolite material containing more than 50% SiO_2 and about 40% Al_2O_3. Its chemical composition is similar to that of many pozzolans, such as fly ashes from combustion of certain sorts of brown coal [1] or metakaolin [2,3], which are increasingly used for the modification of Portland cement mortars and concretes. Recently, some papers have been published on the use of industrial wastes of this kind for the modification of cement-based materials [4–6]. Pozzolanic materials added to concretes participate in the process of hydration of cement by the formation of additional amounts of C-S-H gel in reaction with $Ca(OH)_2$, as well as by the modification of the transition zone between the aggregate and the paste [7]. However, in cases where the additive contains considerable amounts of Al_2O_3, the formation of hydrous silicates in cement is accompanied by the formation of hydrous calcium aluminates [8]. Hence, the favourable changes in the structure of the materials lead to increases in their mechanical strength and decreases in their permeability [4–6].

If the zeolitic pozzolan is used in a cement mortar as a substitute of the finest fraction of the aggregate, the pozzolanic reaction is not constrained by limited amounts of calcium hydroxide liberated during the hydration of cement, and the increase of mechanical strength is higher than that observed in cases where the pozzolan is added as a substitute for a part of cement [4]. In the case of reinforced concretes, the use of a pozzolan may be of substantial importance for retaining their passivity to the reinforcing steel. On one hand, an excessive depletion of $Ca(OH)_2$ can occur and, on the other hand, unreacted pozzolan can form clusters at the steel surface, thus leading to local decreases of pH and worsening the conditions of corrosion protection [9]. The additive also modifies the microstructure of the material thus altering the conditions of oxygen diffusion.

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The aim of this work was to determine the function of FBCC in the cement hydration process and to evaluate the effect of FBCC on the technological properties of the concrete kept under nonaggressive conditions, including its mechanical strength, water absorption, porosity, frost resistance, and passivation of the reinforcing steel.

2. Materials and methods

2.1. Materials

Experimental work was performed using Portland cement (CEM I 32.5R) with the following oxide contents, in wt.%: CaO, 64.1 ± 0.1; SiO_2, 20.5 ± 1.3; Al_2O_3, 4.8 ± 0.2; Fe_2O_3, 2.25 ± 0.05; SO_3, 3.05 ± 0.15; standard sand; natural coarse aggregate; natural fine aggregate; and plasticising admixtures (plasticiser and superplasticiser). Two kinds of FBCC taken from the Fluidized Bed Catalytic Cracking installation were used: FBCC D, a fine-grained waste material from cleaning the electrostatic precipitators, and FBCC G, a coarser-grained waste material withdrawn from the installation because of excessive decrease of the catalytic properties (Table 1).

2.2. Preparation of pastes, mortars, and concretes

The pastes were prepared with constant ratio of water/(cement + FBCC D) = 0.5. The levels of FBCC D used were 5, 10, 15, 20, or 25 wt.% of the binder. The pastes were poured into triple moulds of dimensions 4 × 4 × 16 cm, compacted in two layers and vibrated at 60 shocks/layer. After 24 h, the samples were taken out of the moulds and cured in water for 3 months.

In order to determine the pozzolanic activity of FBCC, a control mortar without the additive and mortars with FBCC were prepared. The control mortar was prepared using the ratio of water/cement = 0.5 and sand/cement = 3. The mortars containing 25% replacement of cement with FBCC D or FBCC G were prepared using the ratio of sand/(cement + FBCC) = 3 and extra water was added in order to obtain the consistence identical with that of the mortar containing no pozzolan. The consistence was determined from the flow of a portion of the mortar on a plane horizontal surface by measuring the diameter of the resultant cake in two perpendicular directions [11]. The ratio of water/(cement + FBCC) was 0.518 in the mortar with FBCC D and 0.556 in that containing FBCC G additive. The mortars were poured into moulds of dimensions 4 × 4 × 16 cm conforming to the standard PN-EN 196-1 [12] and PN-85/B-04500 [13], compacted in a manner identical to that applied during the preparation of the pastes and cured in water for 3 months.

For the purposes of electrochemical studies, some mortars were prepared containing FBCC D in amounts of 10 or 20 wt.% of cement, either replacing a part of cement (water/(cement + FBCC D) = 0.5, sand/(cement + FBCC D) = 3) or replacing a part of the sand (water/cement = 0.5, (sand + FBCC D)/cement = 3, a superplasticiser was added in an amount identical to that applied in the concretes). The compositions of the mortars are given in Table 2. Samples of reinforced mortars were compacted in cylindrical moulds 46 mm in diameter and 100 mm in length containing a mechanically cleaned and degreased insert of reinforcing steel 6 mm in diameter with 1160 mm^2 of active surface. The mortars were compacted in two layers. The demoulded cylinders were cured in water for 28 days [14].

The concrete samples were prepared using the ratio of water/cement = 0.55. Either FBCC D or FBCC G were added in amounts 10 or 20 wt.% of cement as a volume substitute of the part of aggregate sand fraction. The composition of the concrete mixtures, conforming to the patent application [15] is given in Table 3. The concrete

Table 1
Chemical composition, physical properties, and pozzolanic activity of FBCC, and the properties of other pozzolanic additives used in concretes, as required by the ITB Instruction [10] and the ASTM C 618-97 [11]

Property		FBBC D	FBCC G	According to Ref. [10]	Class mineral additive according to Ref. [11]		
				Fly ash	N	F	C
Chemical composition $SiO_2 + Al_2O_3 + Fe_2O_3$, min. %		93.1	95.8	active SiO_2, min. 25%	70.0	70.0	50.0
Grain size[a], max. %		28	92	40	34	34	34
Average grain diameter, μm		21	76	not specified			
Specific surface, m^2/g		105	127	not specified			
Pozzolanic activity, min. %	28 days	119[b]	83[b]	75	75	75	75
	90 days	107[b]	82[b]	85			
Extra water volume/100 g of FBCC added in order to obtain the consistence identical with that of the mortar containing no additive, cm^3		7.1	22.2	not specified			
pH of FBCC in water, FBCC/water = 1/10 (g)		4.0	5.55	not specified			

[a] Residue on a 45-μm sieve. The results of granulometric analysis of FBCC given in the table are the residues retained on a 40-μm sieve.
[b] The determination was performed conforming to recommendation [10].

Table 2
Compositions of mortars containing FBCC D added in place of a part of cement and in place of a part of sand (for reinforced mortars used to electrochemical researchers)

Added FBCC D	Content of FBCC D, %	Cement, g	FBCC D, g	Sand, g	Water, cm^3	Chemical admixtures, cm^3
Replaces a part of cement	0	450	0	1350	225	not added
	10	409.1	40.9			
	20	375	75			
Replaces a part of sand	0	450	0	1350	225	2.30
	10		45	1305		4.14
	20		90	1260		5.99

mixtures were prepared in such a manner as to conform, as much as possible, to the conditions of commercial production of concrete. The addition of superplasticiser was optimized basing it on the consistence measurements conforming to ISO 9812 [16]. Concrete was compacted by vibration in 150-mm (type B) or 100-mm (type C) cube moulds [17], and after 4–6 h, it was wetted and covered with a polyethylene foil. The process of curing proceeded as follows: for 2 days, the samples were moistened with water whilst being kept in their moulds covered with a polyethylene foil, then they were kept for 12 days in a tent under conditions of high humidity ($\geq$95%), and, finally, they were stored in air at a humidity of 55–75% and at mean temperature about 18 °C.

2.3. Investigation methods

The mechanism of interaction of cement with FBCC was evaluated for 3-month-old cement pastes with the aid of thermal analysis. Samples for measurements were taken from the middle parts of the paste specimens. Thermogravimetric curves were recorded for 150-mg samples of the pastes in air in the temperature range 50–1000 °C using a Derivatograph C Analyser (Hungary). The $Ca(OH)_2$ contents of the pastes were evaluated from the loss in mass at temperatures of about 500 °C where calcium hydroxide decomposes. The results were referred to the mass of the sample ignited at 1000 °C. The results were also compared with the "theoretical" contents of $Ca(OH)_2$ in the sample calculated on the assumption that the additive used does not affect the hydration processes, but it substitutes a part of the cement in the pastes.

The X-ray diffraction studies were performed with the use of an HZG-4C diffractometer using CuK_α radiation.

The pozzolanic activity of FBCC was determined according to the ITB Instruction No. 328 for fly ashes [10], which is based on compressive strengths of 28- and 90-day cured samples of mortars containing 25% additions of FBCC D and FBCC G used as cement substitute relative to that of mortars without the pozzolans. The compressive strength of the mortars was measured for three specimens, on testing machine type ZD 10/90 having a maximum load of 100 kN, using a loading rate recommended in the standard procedures [12,13].

Concrete compressive strength was measured after 3, 28, 90, and 330 days of curing. The measurements of strength were determined for at least three samples using testing machine DP 1600, with a range of 0–1600 kN and a precision of 0.1 kN.

The porosity determinations of 3-month-old concretes were carried out by the Hg porosimetry method using an AUTOPORE apparatus produced by Micrometrics and concrete samples weighing 3 ± 0.5 g. The measuring range of the apparatus was 0.003–200 μm. The samples to be measured were dried under high vacuum at room temperature just before the measurement.

Measurements of water absorption and apparent density of the concretes were performed on type C samples according to PN-88/B-06250 [17].

The freeze–thaw resistance of 28-day-old samples of concrete was determined according to the Polish Standard [17] for type C samples using 200 cycles: freezing to − 20 °C within 4–5 h/thawing to + 20 °C within 3–4 h. The parameters used to indicate frost resistance were the change in compressive strength and in mass of the samples relative to those of equivalent samples kept in water for the same period in temperature 18 °C.

Table 3
Compositions of concrete mixtures containing FBCC D and FBCC G (the latter values are given in parentheses)

	Composition of concrete mixture per cubic meter				
Content of FBCC, %	Cement, kg	FBCC, kg	Water, dm^3	Aggregate, kg	Chemical admixtures, cm^3/kg of cement
0	300 (315)	0	165 (171)	1903 (1868)	5.1 (4.2)[a]
10	300 (315)	30 (31.5)	165 (171)	1870 (1833)	9.2 (7.7)[a]
20	300 (315)	60 (63)	165 (171)	1836 (1798)	13.3 (11.2)[a]

[a] The more effective plasticising admixtures were used.

The ability to passivate reinforcing steel was determined by the current–voltage polarization method using an ATLAS 9131 instrument conforming to PN-86/B-01810 [14]. Two separate procedures were adopted. These were for the following.

• Mechanically cleaned and degreased samples of reinforcing steel 6 mm in diameter (identical to the steel inserts in reinforced mortars) in aqueous extracts of concretes, aged > 28 days, prepared from 3 parts of powdered concrete and 10 parts (by weight) of distilled water. The measurements were performed after 24-h passivation of the steel in the concrete extract, with free access of air. A saturated calomel electrode (SCE) was used as the reference electrode, and platinum wire gauze was used as a supplementary electrode.

• Twenty-eight-day-old samples of reinforced mortars, using a SCE as the reference electrode and a piece of stainless steel tube as the supplementary electrode. This study was carried out because of the fact that FBCC present in the mortars can alter the conditions of oxygen diffusion and that the clusters of unreacted zeolite remaining inside the bulk of the hardened mortar might worsen the quality of the passivating layer on the steel surface.

The polarization curve was recorded starting from a potential lower by 50 mV than the corrosion potential of the steel used (E_C — corrosion potential of the steel) and the rate of change of potential was 25 mV/min. The degree of passivation relative to the requirements of the standard [14] was estimated in terms of E_C, density of the passivation current, and the depassivation potential, E_D.

3. Results and discussion

3.1. General characteristics of FBCC and its role in the hydration process

The spent catalyst from catalytic cracking in a fluidized bed is a zeolitic fine-grained material (more than 90 wt.% of $SiO_2 + Al_2O_3$), of specific surface > 100 m^2/g, colour white-grey to grey.

As mentioned above, the properties of the concrete were studied as a function of FBCC collected from different points of the installation. The physico-chemical properties of these materials and their comparison with those of pozzolan additives are presented in Table 1. The essential differences between the two kinds of FBCC are connected with their particle size: the mean particle size of the FBCC D is 21 μm, and that of FBCC G is 76 μm. The latter is also characterised by a slightly higher specific surface and water absorption, which may be accounted for by its higher porosity. As might be expected, these properties influence the mechanism of interaction between FBCC and cement, the properties of the concrete mixtures and, consequently, the utility features of the cement composites obtained. Owing to the high degree of dispersion and highly developed specific surface, FBCC reduces the workability of concrete mixtures, thus demanding increased amounts of mix water or use of plasticisers. The increase in water demand is higher in case of FBCC G than in case of FBCC D.

The mechanism of FBCC interaction in the cement system is a compound of several factors. As a fine-grained material, FBCC can provide a nucleation centre for the precipitating products of cement hydration, hence, it can influence the rate of the hydration processes. The zeolitic structure of FBCC is of considerable importance here. Zeolites are porous ion exchangers, which, in a strongly alkaline medium of hydrating cement, can undergo pozzolanic reaction accompanied by the decay of their aluminosilicate skeleton [18]. This process leads to formation of a C-S-H phase and hydrous aluminates. It is generally accepted that zeolites are at least as reactive as vitreous pozzolans [18], or even more reactive [7] owing to their high porosity and the possibility of exchanging intercluster ions. The process of binding calcium hydroxide from the liquid phase proceeds rapidly and the pozzolan undergoes conversion to an aluminosilicate gel. In the point of view of some authors [4], the skeletal structure of the spent cracking catalysts may possess a large number of acidic sites suitable for realization of the pozzolanic reaction.

Such behaviour by FBCC in the cement system is confirmed by the current results of thermogravimetric studies, in which the amount of $Ca(OH)_2$ was evaluated in 3-month-old pastes as a function of the content of the FBCC D used. In pastes containing FBCC D additions, the decrease of $Ca(OH)_2$ content is greater (as compared with the control paste) than the percent reduction in the amount of cement as a result of the partial replacement of cement by FBCC D (Fig. 1). This provides clear evidence of the pozzolanic properties of FBCC.

The results are confirmed by the X-ray diffraction studies (Fig. 2). The crystallinity of the cement paste samples studied was very low, and it was difficult to give a detailed interpretation of the diffraction patterns recorded. Crystalline $Ca(OH)_2$ was one of the easiest detectable components of the hardened paste. A distinct decrease of intensity of the peaks characteristic of $Ca(OH)_2$ was observed in for example the paste containing 20 wt.% of FBCC D as compared with the control paste, which can be accounted for by a smaller content of $Ca(OH)_2$.

The pozzolanic properties of FBCC and their dependence on the grain size have also been confirmed in the studies of pozzolanic activity. The results obtained (see Table 1) point to a high activity for FBCC D, which exceeds the requirements imposed by the ITB Instruction No. 328 for fly ashes, and to a lesser activity for FBCC G. Taking into account the slight differences in the chemical composition of the FBCC studied and the higher specific surface of the FBCC G, it seems reasonable to state, with a high degree of probability, that the mean grain diameter is

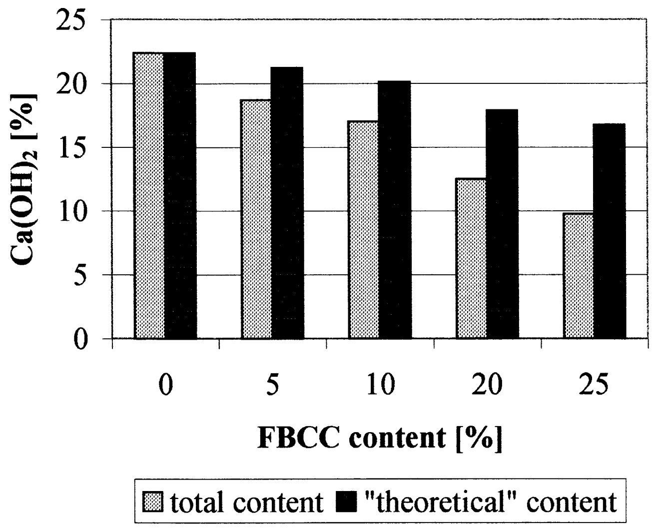

Fig. 1. Total contents of $Ca(OH)_2$ in 3-month-old cement pastes containing different levels of FBCC D as compared with the "theoretical" content of $Ca(OH)_2$ resulting from the substitution of part of the cement by the additive.

decisive for the process of pozzolanic reaction. It is probably connected also with the easier access of $Ca(OH)_2$ to the active sites on the surface of the finer product. In the case of the FBCC G, the more developed specific surface does not compensate for the smaller outer surface of the material grains, since the hydration products can clog the entries to the zeolite channels and the inner acidic centres will remain unused. Similar conclusions have also been drawn by other authors [4].

On the other hand, the low strength of mortars containing 25% FBCC G may also arise from the high demand of mix water (higher than that for FBCC D), which involves an increase of the water/binder ratio (up to 0.556) and hence in the porosity of the mortars.

The effect of the FBCC grain size on its activity in the cement system is also reflected in the results of calorimetric studies [19], which show that the finer material exhibits a higher activity in the cement system, as compared with the FBCC G.

3.2. *Effect of the presence of FBCC on the properties of concretes*

3.2.1. *Compressive strength*

The results of compressive strength measurements of concretes, which were kept in air for up to 1 year and in which a part of aggregate was replaced by FBCC, are given in Fig. 3. The results show the following.

• That FBCC D or FBCC G added in amounts up to 20 wt.% of cement, used along with a superplasticiser have a favourable effect on the strength of concrete. The increase of compressive strength is particularly evident in the first 28 days of curing. Thus, FBCC enhances the early strength of concrete and this is confirmed by the results of other authors

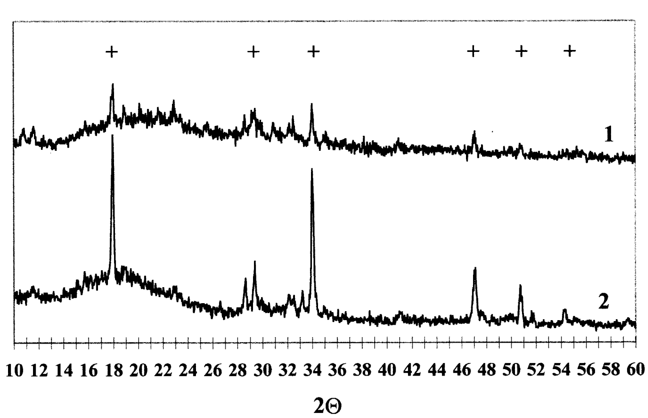

Fig. 2. X-ray diffraction patterns of 3-month-old cement pastes containing 20% addition of FBCC D (1) and without additive (2). The peaks due to $Ca(OH)_2$ are marked with (+).

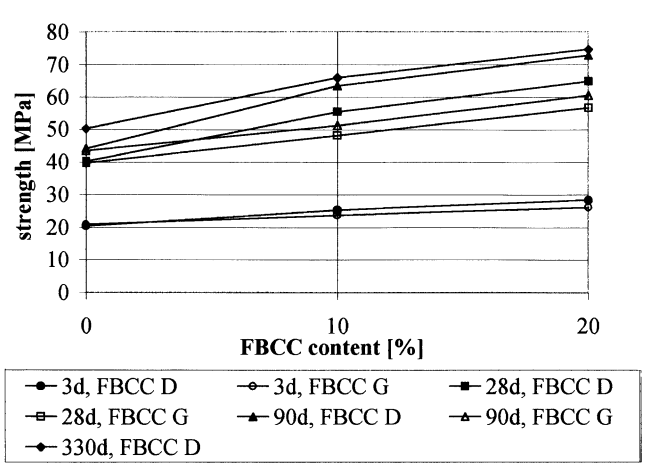

Fig. 3. Effect of the type and amount of FBCC on the strength of concretes.

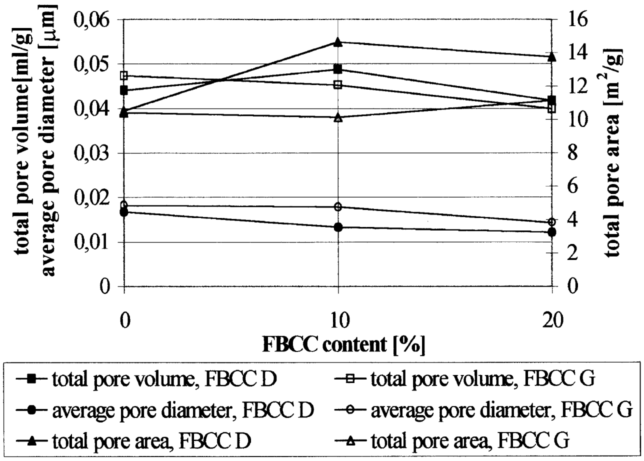

Fig. 4. Effect of the type and amount of FBCC on the pore structure of 3-month-old concretes.

[4] who studied the strength of mortars in which FBCC was added as a substitute of a part of the cement or sand.

• That the strength of concrete exhibits a higher increase in the presence of FBCC D. For example, a concrete containing 20% FBCC D has a compressive strength of 72.8 MPa after 3 months and 75 MPa after 11 months (despite of the high water/cement ratio = 0.55); under identical conditions a concrete with FBCC G had after a 3-month curing period a strength of only 60.5 MPa. In case of FBCC D the increase in strength, relative to the control concrete, was higher after the addition of the first 10% of additive (increase of 44%), than after the addition of further 10% (total increase of 65%). For FBCC G, the respective increments of compressive strength relative to the control concrete were 18% and 39%. The effect of a 20% addition of the less active FBCC G was comparable with that of a 10% addition of FBCC D.

3.2.2. Tightness and apparent density

The effect of FBCC on the tightness parameters of concrete is presented as:

the effect of FBCC D and FBCC G on the pore structure of concrete (Fig. 4),
the effect of FBCC D (Fig. 5A) and FBCC G (Fig. 5B) contents on distribution of pore size in concrete, and
the effect of FBCC D and FBCC G on the density and water absorption of concrete (Fig. 6).

According to the range of pore diameters of the concretes given in literature [20,21], it is possible to state the following.

• That the use of FBCC in amounts of up to 20 wt.% of cement as a substitute for a part of aggregate, irrespective of its grain size, results in a decrease of mean pore diameter, as compared with the control concrete, which may be accounted for by formation of extra amounts of the C-S-H phase of high specific surface. The pozzolanic and the pore refining effects

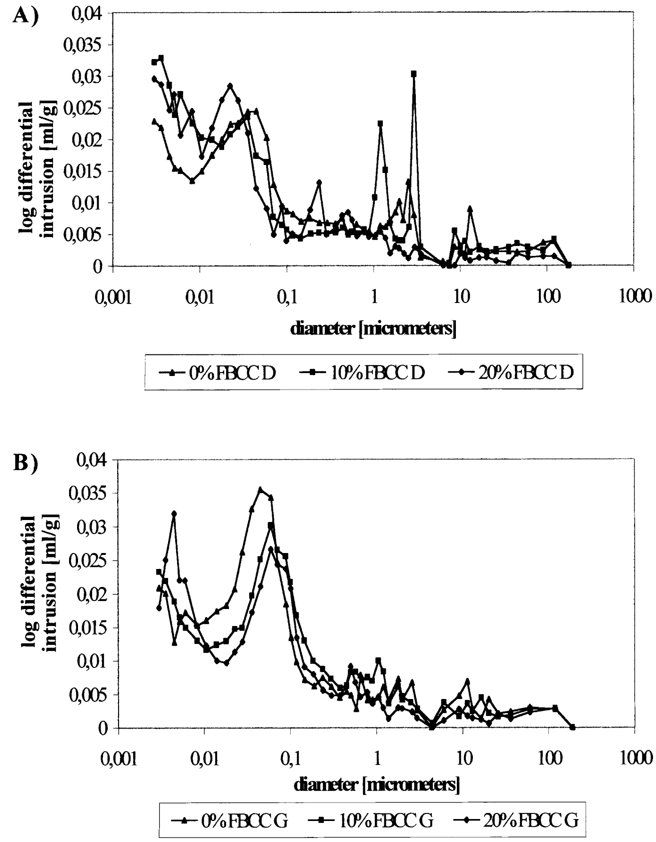

Fig. 5. Differential pore distribution in 3-month-old concretes containing different amounts of FBCC D (A) and FBCC G (B).

are stronger in the case of FBCC D, which gives a more pronounced increase of specific pore surface. This fact may be accounted for by the higher pozzolanic activity of this additive (Fig. 4). Probably, the high early strength of concretes dosed with FBCC is due to the mechanism of filling the pores with the secondary C-S-H phase.

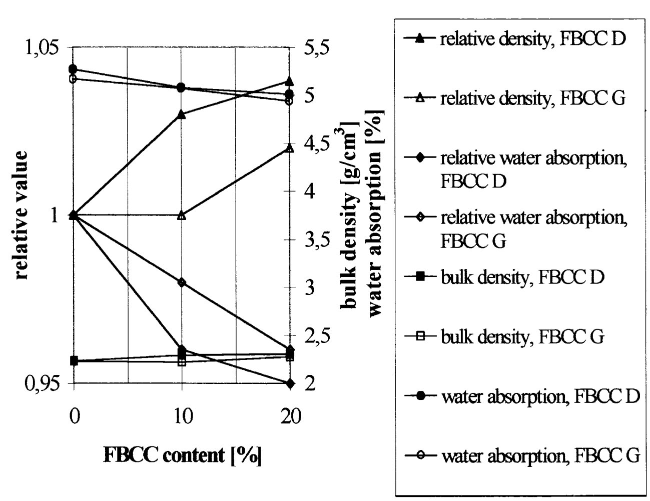

Fig. 6. Effect of the type and amount of FBCC on absolute and relative physical properties of 3-month-old concretes.

• That an analysis of the pore size distribution indicates that the addition of up to 20% of FBCC, irrespective of its grain size, results in an increase of the total volume of fine pores with pore diameter < 0.01 μm. No substantial difference is observed in the concrete pore structure in the mean pore diameter range 0.01–0.05 μm, between the control concrete, and concrete with 10% addition of FBCC D, whereas a 20% addition of FBCC D results in an increase of the volume of these pores, with a shift of the dominant pore diameter towards the fine pores (Fig. 5A). In the case of concretes containing FBCC G, a decrease of pore volume with respect to control samples was observed irrespective of the amount of the additive used (Fig. 5B).

The results of porosity studies suggest a somewhat different mechanism in modifying the pore structure when 10% FBCC is used to replace a part of aggregate, as opposed to 20%. It is suggested that 10% addition influences the concrete structure mainly due to the pozzolanic reaction, whereas the addition of greater amounts (e.g., 20 wt.%) results in the unreacted excess acting as a nonactive filler (Fig. 4).

Studies of the apparent density and water absorption of the concretes show that an increase in the content of FBCC replacing a part of the aggregate contributes to a slight increase in apparent density and decrease in water absorption. The changes are more readily apparent when expressed in relation to the control sample (Fig. 6). The results confirm those obtained in the measurements of porosity.

3.2.3. Frost resistance

The results of the frost resistance studies of a concrete containing 20% FBCC D and of the control concrete are shown in Table 4. The results show that the more compact structure of the concrete containing FBCC is much more resistant to frost than that of control concrete.

3.2.4. Passivation of reinforcing steel

The effect of FBCC on the passivating properties of concretes as regards the reinforcing steel are shown in Fig. 7 (aqueous extracts of concretes more than 28 days old) and in Fig. 8 (28-day reinforced mortars). The following conclusions may be made.

• Steel is very well passivated in aqueous extracts of concretes containing FBCC D and FBCC G, as evidenced by low passivation current densities, lower than required by the standard [14] and high values of the corrosion potential, E_C. Better passivating effects were achieved with concretes containing the FBCC D additive. Also, the steel depassivation potential, E_D, in the extracts of the concretes studied remained in the range 450–700 mV required by the standard.

• The steel embedded in mortars dosed with FBCC D used as a substitute for a part of the cement was very well passivated in the whole range of concentrations studied, whereas the steel embedded in mortars dosed with FBCC D used as a substitute for a part of the sand was passivated (i.e., conformed with the standard) only in cases where a 10% content of FBCC was applied. The presence of 20% additions resulted in the loss of steel depassivation in the

Table 4
Changes in strength and in mass of concretes following 200 cycles of freezing–thawing relative to the equivalent concrete (kept for the same time in water at a temperature of about 18 °C and not subject to freezing)

Parameter	0% FBCC D	20% FBCC D
Decrease of strength, %	5.52	0.65
Loss in mass, %	0.29	0.09

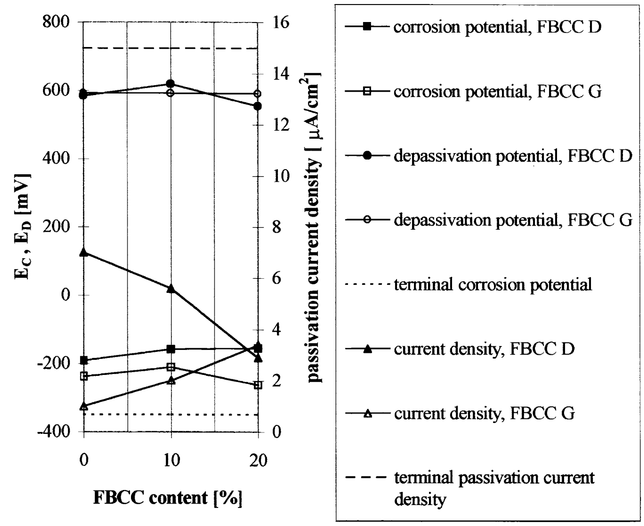

Fig. 7. Effect of the type and amount of FBCC added to the concrete mixtures on the current–potential properties of reinforcing steel in aqueous extracts of more than 28-day-old concretes. E_C — corrosion potential; E_D — depassivation potential.

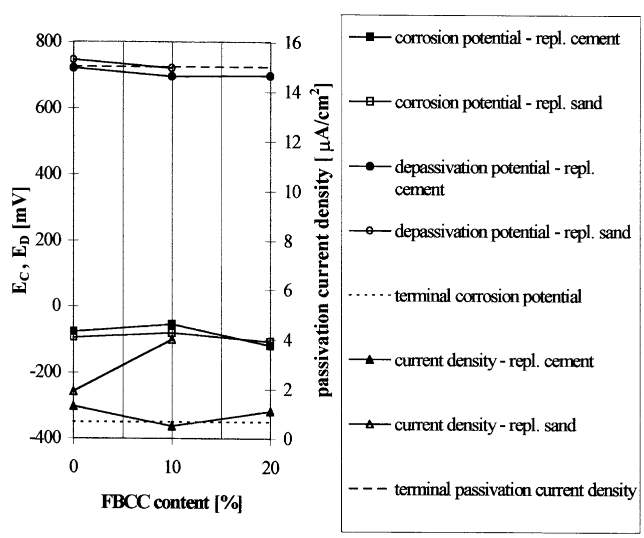

Fig. 8. Effect of the amount of FBCC D added as a partial substitute for cement or sand on the current–potential properties of reinforcing steel coated with a layer of 28-day-old mortar and stored in water. Notation as in Fig. 7.

potential range 450–700 mV required by the standards [14], despite low values of anode current density. Such an effect may be accounted for by retardation of the anodic process — oxygen release — owing to diffusion limiting reasons (high gas tightness and resistance of the mortar) rather than to the alkalinity of the pore solution. Extracts of the concrete in which FBCC was used as a substitute for fine aggregate had a pH above 12.

4. Conclusions

(1) FBCC, a waste catalyst from catalytic cracking in a fluidized bed, reacts with Portland cement during the hydration process leading to a decrease of $Ca(OH)_2$ content in hardened cement paste and to formation of secondary C-S-H phase. Hence, it can be used as a pozzolanic additive for concrete.

(2) The pozzolanic activity of FBCC depends on the average diameter. Coarser fractions of FBCC have lower pozzolanic activities, but they can be used as good fine-grained fillers for concrete.

(3) FBCC improves the strength of concrete. The most rapid rate of strength gain for concrete dosed with FBCC was observed during the first 28 days of hydration. Higher effectiveness was observed for finer fractions of the additive.

(4) FBCC makes the concrete microstructure more compact, increases its density, reduces water absorption, and improves frost resistance.

(5) FBCC does not worsen the passivation of steel in reinforced concrete. However, excessive gas tightness of concrete can result in difficulty in obtaining a passive layer, which conforms to the Polish standards—depassivated in the potential range 450–700 mV.

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