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Strength and Permeability of Concrete with CEM II and "CEM V" Cements Containing High Calcium Fly Ash

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ABSTRACT

The use of high calcium fly ash from brown coal combustion in Belchatow Power Plant in Poland as one of major components of common cements was studied. The strength and the permeability of concrete made with blended cements CEM II and "CEM V" was investigated at two assumed w/c ratios 0.45 and 0.55. The range of investigation included also ternary cements blended with siliceous fly ash and blast furnace slag. Blended cements were manufactured by joint grinding of clinker and additions to achieve the target specific surface of 3800 cm^2/g (Blaine); the rate strength development of cements f_{c2}/f_{c28} was "medium". Experimental tests were performed on concrete specimens to determine strength and permeability properties adequate for general application range. The influence of new blended cements containing calcium fly ash on the development of compressive strength up to 90 days, the depth of water penetration and the coefficient of air permeability was determined.

Keywords. air permeability, blended cement, calcareous fly ash, ternary cement, water penetration

INTRODUCTION

Fly ash is a common component of blended cements and concrete mixtures produced in numerous countries; its use provides a significant improvement in concrete technology due to improved environmental profile, reduced costs and beneficial material properties attained both in fresh mix and in hardened concrete. This is a valid statement for siliceous fly ash, mainly consisting of spherical and amorphous grains, conforming to BS-EN 450-1, ASTM C618 class F or other similar technical standards. The use of high-calcium fly ash in concrete is not so common, although it has been studied at least for three decades (Diamond and Olek, 1988). Up to a certain level of cement replacement with high-calcium fly ash conforming to ASTM C618 class C, strength properties of concrete are either better than or comparable to concrete without fly ash (Naik and Singh, 1995). More recent investigations performed in European countries (Papadakis and Tsimas, 2005), (Yildirim et al., 2011), (Gibas et al., 2013) demonstrated also adequate strength and durability characteristics of concrete containing high calcium fly ash used as an active addition to concrete mix. Because of high content of active CaO this type of fly ash usually exhibits strong hydraulic properties. However its performance in cementitious systems is variable and does differ from siliceous fly ash due to significantly lower content of glassy phase, increased content of SO_3 and diversified shape of grains, commonly irregular and porous.

It was suggested by Naik and Singh (1995) that future research efforts should be undertaken for the use of high-lime fly ash in pre-blending it with Portland cement to create a new generation of blended cements for wide use in high-quality concrete. This is feasible according to European common cement standard BS-EN 197-1 but it has not been done at a large scale. Among numerous types of standard blended cements an adequate definition of CEM II and CEM IV types containing high calcium fly ash is included. Possible use of high-calcium fly ashes in the composition of cement could result in a number of environmental and technical benefits, including a more consistent properties of binders.

The objective of the investigation is to study the principal properties of concrete made with new blended cements containing high calcium fly ash available in Poland in large quantities.

EXPERIMENTAL

Materials. Experimental tests were performed on concrete made using new blended cements containing high calcium fly ash from Belchatow Power Plant in Poland. After monitoring the composition and properties of ash during 18 months a representative lot (Table 1 and 2) was selected for further use. The content of MgO, SO_3, CaO_{free} is moderate and the loss on ignition is low. Physical properties are representative for rather coarse ash in comparison to these used in North America. Since the content of CaO >15% the strength of the fly ash binder should attain the compressive strength of 10 MPa following BS-EN 197-1. For various lots of high calcium fly ash the compressive strength was between 2 and 5 MPa, not even close to 10 MPa. Considering the high content of active silica, this type of ash has both pozzolanic and self-hardening properties; the case when both reactive CaO and SiO_2 are greater than 15% and 25% respectively seems not to be covered by the standard classification according to BS-EN 197-1. Nevertheless, multicomponent cements were manufactured by grinding Portland cement clinker together with gypsum, high calcium fly ash (W) and selected mineral additives (Table 3). Properties of siliceous fly ash (V) and ground granulated blastfurnace slag (S) were in compliance with European standard requirements.

Table 1. Chemical composition of high calcium fly ash

LOI	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	CaO_{free}
2.12	40.88	19.00	4.25	25.97	1.73	3.94	0.14	0.13	1.07

Table 2. Physical properties of high calcium fly ash

Specific gravity g/cm^3	Fineness %	Surface area (Blaine), cm^2/g	Grain size $d_{(0.9)}$ *) μm
2.60	46.3	2400	23.5

*) laser diffraction particle size analysis

Mix design and specimens. Concrete mixes were designed using natural sand 0-2mm, crushed amphibolite aggregate 2-8 mm and crushed granodiorite aggregate 8-16 mm with w/c ratios 0.45 and 0.55. The assumed slump was between 140-170 mm. The amount of superplasticizer (HRWR) was adjusted to maintain the target slump. The composition of prepared concrete mixes is shown in Table 4.

Table 3. The composition and physical properties of blended cements containing high calcium fly ash W *)

Type of cement	Main constituents, %				Properties		
	Cement clinker	Fly ash		Slag S	Specific gravity, g/cm^3	Surface area (Blaine), cm^2/g	SO_3 content, %
		W	V				
CEM I	94.5	-	-	-	3.10	3850	2.82
CEM II/A-W	80.9	14.3	-	-	3.05	3840	3.11
CEM II/B-W	67.4	28.9	-	-	2.98	3750	3.13
CEM II/B-M (V-W)	66.6	14.3	14.3	-	2.93	3750	3.13
CEM II/B-M (S-W)	66.6	14.3	-	14.3	3.03	3720	3.33
"CEM V/A (S-W)"**)	47.9	23.9	-	23.9	2.97	3800	3.33

*) data obtained at Institute of Ceramics and Building Materials, Krakow
**) not defined in BS-EN 197-1, therefore written here between quotation marks

Table 4. Concrete mix design [kg/m³]

Series designation	Cement	Sand	Crushed amphibolite	Crushed granodiorite	HRWR	Water
CEM I/0.45	336	606	667	629	0.88	153
CEM II/A-W/0.45	336	605	666	628	1.66	152
CEM II/B-W/0.45	336	605	666	628	2.09	153
CEM II/B-M(V-W)/0.45	336	604	665	628	1.64	154
CEM II/B-M(S-W)/0.45	340	612	674	637	1.36	155
CEM V/A (S-W)/0.45	337	606	667	628	1.79	153
CEM I/0.55	313	617	661	636	0	172
CEM II/A-W/0.55	313	615	659	634	0.35	172
CEM II/B-W/0.55	312	615	659	634	0.70	172
CEM II/B-M(V-W)/0.55	312	614	658	633	0.56	172
CEM II/B-M(S-W)/0.55	313	617	661	637	0.50	172
CEM V/A (S-W)/0.55	312	615	659	634	0.50	172

Standard 150mm cube specimens were cast for compressive strength testing and water penetration testing. Square slabs 500x500x100mm were cast for air permeability testing. The specimens were subjected to standard moist curing conditions in a climatic chamber at temperature of 20 °C and relative humidity of 95%. Slabs for air permeability testing were removed from the moist chamber at the age of 21 days and stored in dry laboratory conditions at RH of 50-60% and temperature of 20-22°C until testing.

Test methods. The following test methods were applied according to European standard procedures: the consistency by slump, the compressive strength on cube specimens, the depth of water penetration. Torrent air permeability testing was performed following Swiss standard procedure (Torrent et al., 2007).

TEST RESULTS

The influence of cement type on the compressive strength development up to 90 days is shown in Fig.1. The 2 day strength of concrete was found to decrease down to 45% with decreasing clinker factor for w/c=0.55 but for the lower w/c the strength decrease by 22-38% was recorded. At the age of 28 days the differences in strength due to changing cement type were diminished: a decrease by not more than 30% or even an increase by 12-16% was found for w/c=0.55 and 0.45 respectively. As it could be expected the 90 day strength of concrete with blended cements was equal or somewhat (up to 15-18%) higher than the strength of reference concrete. Only for w/c=0.55 the strength of concrete containing two types of ternary cement was lower by about 13%.

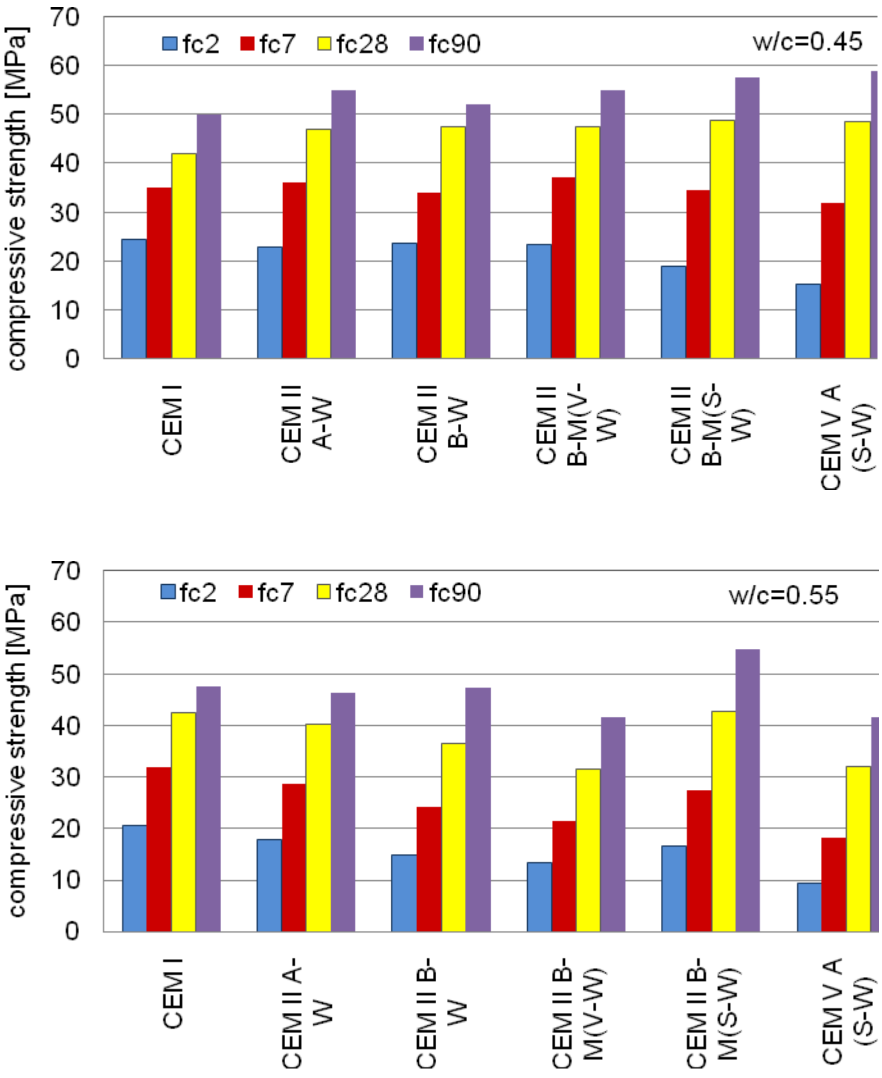

Figure 1. The development of compressive strength of concrete in time

Results of tests of water penetration into concrete specimens are shown in Fig.2. For w/c=0.55 the influence of cement type on the depth of water penetration was quite similar as for the 28 day strength (a mirror reflection). In two cases of concrete with the lowest 28 day strength the penetration of water across the whole depth of 150mm specimens was recorded. For the lower w/c ratio the penetration depth was from 11 to 54mm; the performance of concrete with CEM II A-W, B-W and B-M(V-W) cements was comparable or slightly superior than the reference CEM I concrete. The increased water penetration in concrete with CEM II B-M(S-W) and "CEM V/A(S-W)" cements can be associated with much incomplete hydration at the age of 28 days.

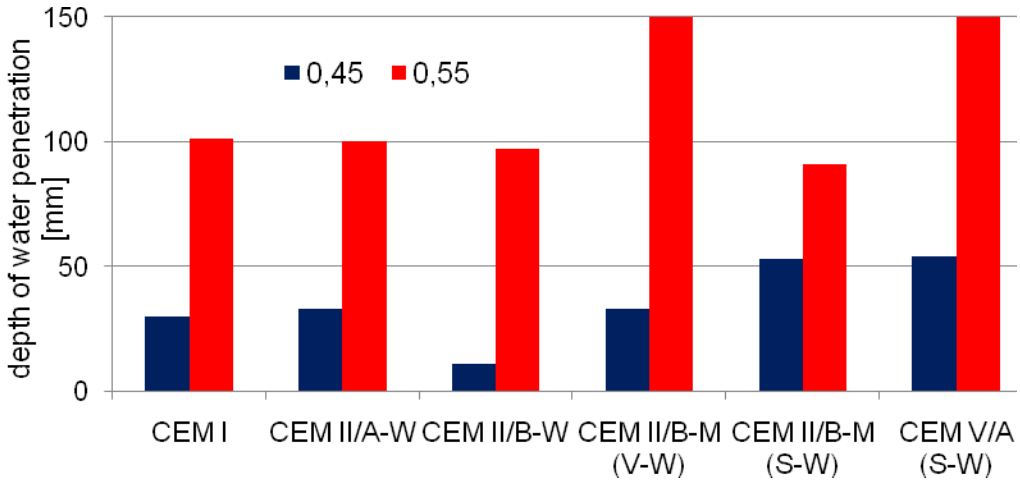

Figure 2. The depth of water penetration under pressure up to 1.2 MPa

The influence of cement type and w/c on the coefficient of air permeability kT is shown in Fig. 3. The average values of 5 tests at different locations over the slab surface are given. Because of assumed storage conditions the later age of concrete is manifested by progressive drying of specimens and therefore some increase of kT is found at the age of 60 days in relation to 28 day results. Similar effects of moisture on the results measured with the Torrent method ware observed by Romer (2005) and Denarie et al, (2005). The measurements of concrete surface humidity using Wenner probe nor Tramex CME4 did not reveal significant changes in time so the results at the age of 60 days were assumed as representative. Referring to the air permeability classification (Torrent et al., 2007) the performance of concrete at w/c=0.45 can be classified as "low permeability" since kT is within the limits $0.04\text{-}0.1\cdot 10^{-16}$ m^2 regardless of the type of cement. For w/c=0.55 there is a significant influence of cement type on kT. The use of CEM II A-W and B-W cements resulted in a reduction of air permeability coefficient by 53-77% in comparison to the reference CEM I concrete. The use of CEM II B-M(S-W) was also beneficial – a reduction of kT by 23% was found. The increase of air permeability coefficient by about 160% in comparison to the reference concrete was found for concrete containing CEM II B-M(V-W) and "CEM V/A(S-W)" cement. The performance of concrete at w/c=0.55 can be classified as "medium permeability" except the cases of CEM II A-W and B-W cements classified as "low permeability".

DISCUSSION

The obtained results revealed quite adequate strength and permeability properties for general construction purposes. It should be noted that to maintain the mix consistency for blended cements it was necessary to increase a superplasticizer content, particularly for CEM II B-W cement. The increased water demand of high calcium fly ash blended cements was a reason to omit CEM IV type cements with the increased content of ash W (Golaszewski et al., 2011). Instead, the ternary combinations V-W and S-W were included and the water demand in such cases was found to increase moderately even for a highly reduced clinker content down to 48%.

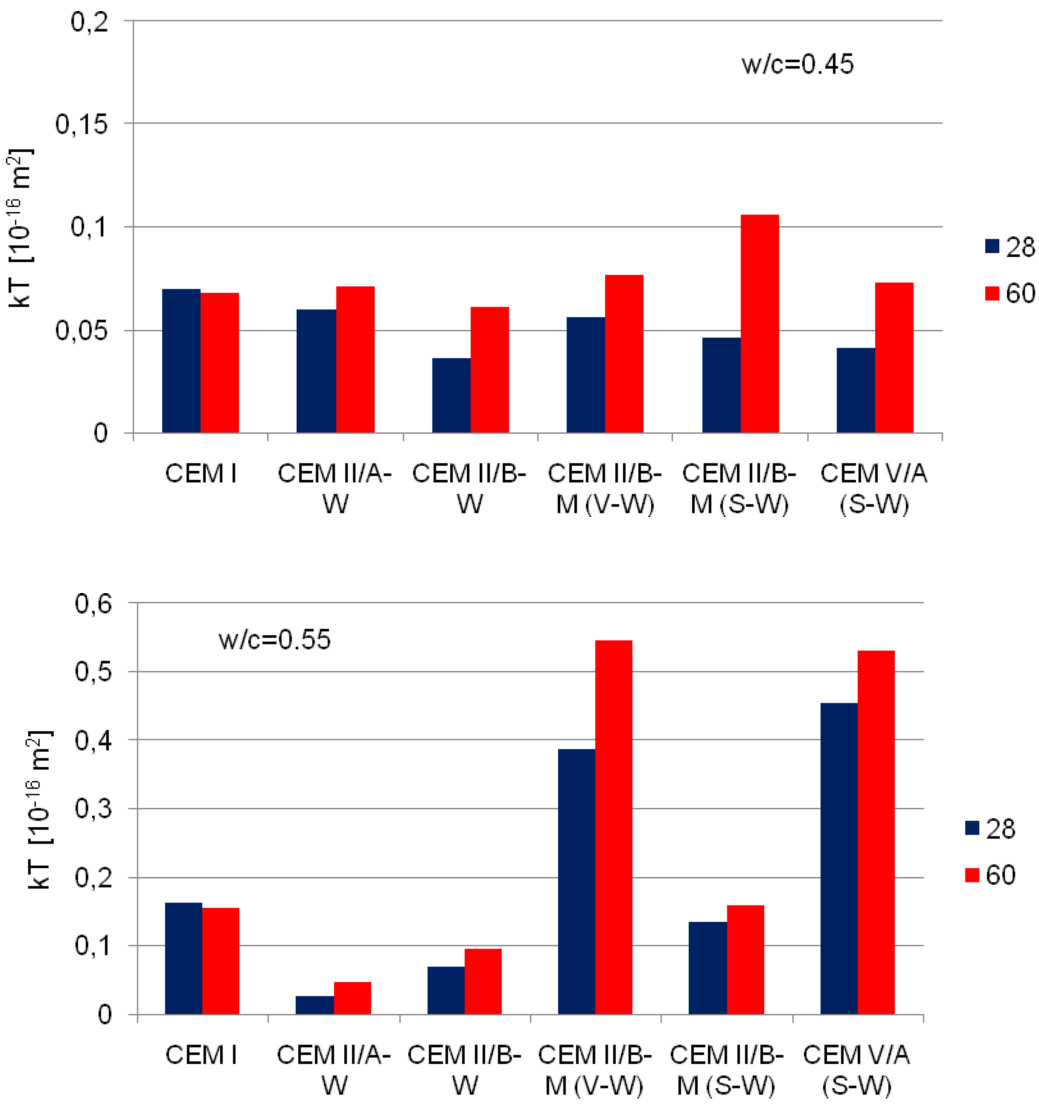

Figure 3. The air permeability coefficient of concrete at the age of 28 or 60 days

The adverse effects of clinker substitution on the early strength of concrete were quite moderate, except the case of the low clinker content of 48%. Ternary combinations including high calcium fly ash and silica fume are known to be effective also at the age of 7 days onward (Radlinski and Olek, 2012). Stable positive effects on the compressive strength at the latter age were observed as in the case of using high calcium fly ash as an additive to concrete mix (Naik et al., 1995). Water penetration tests performed at rather high water pressure revealed quite similar material characteristics as the strength data. As far as the air permeability is concerned the outstanding performance of concrete with CEM II/A-W and CEM II/B-W should be noticed. Such effects observed for W cements were much better than using unprocessed high calcium fly ash as an additive to concrete mix (Jozwiak-Niedzwiedzka et al., 2011, Glinicki et al., 2010). The low air permeability of such concrete is a promising indication for a proper resistance to carbonation. It is contradicting to an observation of increasing carbonation coefficient along with the increase in fly ash content, reported by (Khunthongkeaw et al., 2006) and others. Since the resistance to carbonation is of primary importance for durability design of structural concrete, this feature requires some more detailed investigation before establishing the range of applications for new blended cements.

CONCLUSIONS

The following conclusions can be drawn.

1. New blended cements CEM II and „CEM V" containing high calcium fly ash from Belchatow power plant exhibited a higher water demand that could be compensated with a moderate increase of superplasticizer added to concrete mix. Ternary combinations with siliceous fly ash or blastfurnace slag were less water demanding than addition of high calcium fly ash only.
2. The compressive strength of concrete made with blended cements at 2 days decreased with reduced clinker factor down to 45% for w/c=0.55 and by 22-38% for w/c=0.45. At the age of 28 days the differences in strength due to changing cement type were diminished: a decrease by not more than 30% and an increase by 12-16% was found for w/c=0.55 and 0.45 respectively.
3. The influence of blended cement type on the depth of water penetration under pressure of 1.2 MPa was found to follow inversely the trend for the compressive strength at 28 days at w/c=0.55. For w/c=0.45 the penetration depth was from 11 to 54mm, comparable or lower for concrete with CEM II A-W, CEM II B-W and CEM II B-M(V-W) than with CEM I.
4. The use of CEM II A-W, CEM II B-W and CEM II B-M(S-W) cements resulted in a reduction of air permeability coefficient of concrete by 53%, 77% and 23% respectively, for w/c=0.55. For w/c=0.45 the coefficient kT was within the limits $0.04\text{-}0.1 \cdot 10^{-16}$ m^2 (low air permeability) regardless of the type of cement.

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