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Strengthening efficiency of nonstandard addition of fluidized bed ash in concrete

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ABSTRACT: The investigation of the influence of solid residue from hard coal combustion in circulating fluidized bed boilers on the strength of concrete was performed. The ash samples from power plant were collected regularly during 12 months to allow evaluation of variability of ash properties. Cementitious mixes were designed at the constant workability and batched using fluidized bed ash for partial replacement of Portland cement CEM I. The compressive strength of concrete at the age beyond 28 days was found to increase due to FBC ash addition for replacement of 20% of cement. The efficiency of fluidized bed ash as potential type II concrete additive was evaluated using Bolomey's and Feret's formulas for the compressive strength of concrete. The efficiency factors were established at the age of concrete up to 1 year.

1 INTRODUCTION

Solid residues from coal combustion in pulverized-fuel boilers are commonly used as cement and concrete additions – these are fly ashes conforming to the requirements of EN 450-1 or ASTM C618-03 standards. Coal combustion in fluidized bed boilers is increasingly used for electric power and heat generation in many countries, Oka (2004); such combustion process produces combustion by-products (ashes) of specific physical properties and chemical constitution. Due to significant addition of sorbent for dry flue gas desulfurization process and rather low temperature of combustion (about 850^0C) the ashes form fluidized bed combustion (FBC) are composed of fuel ash, unreacted and reacted sorbent used for desulfurization and unreacted coal/char, Havlica et al. (1998). Properties of FBC ash do not meet the requirements defined by EN 450-1 or ASTM C618-03 in order to be used for cement or concrete production. Accordingly, it has to be treated individually case-by-case in order to propose and accept a technology for its application/reuse, e.g. in civil engineering, on the basis of official technical approvals.

Good pozzolanic properties, and the presence of CaO_{free} and $CaSO_4$ in FBC ash may result in proper control of the hydration and production of stable and strong mineral microstructures. The preliminary potential for using FBC ash in concrete was revealed in Glinicki et al. (2004) and Zielinski (2007) - the steady strength and the adequate frost resistance was demonstrated for concrete containing up to 20% of FBC fly ash in the total mass of binder. Further investigation on durability of concrete revealed improved resistance to chloride migration/diffusion and reduced scaling resistance due to FBC ash additions up to 30% of binder mass, Jozwiak-Niedzwiedzka (2009), Malolepszy and Kolodziej (2009). To allow some quantitative understanding of the efficiency of such nonstandard additions in concrete it is necessary to define efficiency coefficients and provide tools for design of the compressive strength of concrete.

Following EN 206-1 for standard siliceous fly ash a single '*k*' coefficient is usually applied, although many factors like the composition of cement, the substitution rate, the fineness of the addition and the age of concrete induce a great variability of the efficiency coefficient, Cyr et al. (2000), Bentur (2007). Different European concepts for the application of additives to concrete type II were presented by Vollpracht and Brameshuber (2010) and the impact of additions using the *k*-efficiency factor concept was critically reviewed. In *k*-value approach the content of the additive (*a*) is multiplied with a *k*-value and the water to cement ratio (*w/c*) is replaced by $(w/c)_{eq} = w/(c + k \cdot a)$. The efficiency *k* factor concept is a simple tool to quantify the impact of addition and can serve as a friendly parameter for mix design, but it could be questionable when considering the fundamental aspects of the influence of additions on concrete performance, Bentur (2007). However, its applicability for nonstandard additions of coal combustion by-products from so called clean coal technology is largely unknown.

The objective of the current investigation is the evaluation of the efficiency factor of FBC ash in respect to the compressive strength of concrete. The tests were performed on concrete specimens at the age up to 1 year to provide experimental data for such evaluation of efficiency factor. The range of investigation included effects of actual variability of ash properties monitored by sampling of ash produced during several months of power generation.

2 EXPERIMENTAL

2.1 Materials and specimens

Experimental program included comparative tests of 24 concrete mixes of various cement content, in which a part of cement was replaced by FBC ash. The following materials were used for concrete manufacturing:

- ordinary Portland cement CEM I 32.5R in amount of 350 kg/m^3 and 300 kg/m^3,
- FBC ash from hard coal combustion in heat and electric power plant in Warsaw, captured by electrostatic precipitators and processed by so-called mechanical activation treatment, Glinicki et al. (2004),
- natural-type aggregate, i.e. gravel fraction from 2 to 16 mm and aggregate mix made from gravel fractions of 2-8 mm and 8-16 mm,
- complex water reducing-retarding chemical admixture, used at the constant rate of 0,4% of cement mass (or sum of cement mass and FBC ash mass),
- tap water.

The chemical composition of FBC ash determined using standard methods was as follows:

- SiO_2 content: from 25.8 to 40.9% (the average 35.6%),
- Al_2O_3 content: from 16.2 to 21.1% (the average 19.0%),
- CaO content: from 14.5 to 24.4% (the average 19.5%),
- SO_3 content: from 6.4 to 10.7% (the average 8.6%),
- LOI: from 5.6 to 10.2% (the average 7.3%).

FBC ash samples were collected several times during 12 months period. Detailed chemical analysis of randomly selected samples of FBC ash revealed the total ignition loss in temperature 975ºC of 10.1%, while on the basis of TGA-DTA method in a helium/air atmosphere the unburned carbon content was 5.9% only. Some loss on ignition can be attributed to the presence of calcium carbonates in FBC ash. The content of sulfurous acid anhydride SO_3 was 9.7% and free CaO content was 4.96%. The result of soundness test was positive: the expansion according to EN 196-3 was less than 1.0mm.

Concrete mixes were designed from selected materials using the assumption of constant slump. Each time a pair of concrete mixes was cast: without additive and with FBC ash. The FBC ash was used as a replacement of 20% of cement by weight. The proportions of concrete mixes are given in Tables 1-3; to show the mixes without addition and with FBC ash the lower indices “0” and “F” were introduced accordingly.

Concrete specimens for compressive strength testing were cast in the cubical moulds 150x150x150 mm. Laboratory batches of concrete (over 70 liter volume) were produced in a horizontal mixer and the mix was consolidated by vibration (5-7 seconds on a vibrating table). After 24 hours in moulds specimens were demoulded and cured in high humidity conditions RH > 90% at the temperature of 18-20 ºC until the age of testing.

2.2 Test methods

Standard methods were used to determine concrete mix properties:
- slump according to EN 12350-2,
- bulk density according to EN 12350-6,
- concrete mix temperature was checked about 10 minutes after end of mixing,
- air content according to EN 12350-7 in case of some mixes.

The compressive strength of concrete was determined according to EN 12390-3 at the selected age of concrete: 7, 28, 90 and 365 days. Each time three specimens were tested.

3 TEST RESULTS

The results of concrete mix tests and the average compressive strength of concrete are given in Tables 1-3. For determination of water-binder ratio *w/(c+fa)* the amount of water contained in admixture was included. To keep the equal slump of the mix with FBC ash it was necessary to increase the amount of water. The increased water demand for FBC ash mixes resulted in the increase of water-binder ratio *w/(c+fa)* by about 9%. This is due to angular shape of FBC ash particles and high porosity of grain surfaces. In contrast to common siliceous fly ash the grains of FBC ash are not spherical and the glassy phase is not present, Glinicki and Zielinski (2009).

Table 1. Concrete mix proportions, mix properties and the compressive strength of concrete –mix numbers from 7 to 26 (the lower indices “0” and “F” denote mixes without addition and with FBC ash respectively)

Basic ingredients of concrete mix [kg/m^3]		Concrete mix designation							
		7_0	**7_F**	**18_0**	**18_F**	**20_0**	**20_F**	**26_0**	**26_F**
Cement CEM I 32.5 R		349	288	362	291	359	284	341	277
FBC ash		-	72	-	73	-	72	-	69
Sand 0-2 mm		678	700	698	701	686	680	608	617
Gravel 2-16 mm		1096	1131	1116	1122	1112	1102	1184	1202
Water		145	166	171	188	178	187	174	183
Mix properties	Bulk density [kg/m^3]	2270	2359	2349	2377	2336	2326	2308	2349
	Slump [mm]	170	170	180	175	170	180	185	170
	Temperature [ºC]	9	8	8	8,5	10	10	14	14
	w/(c+fa)	0.418	0.464	0.475	0.519	0.498	0.528	0.513	0.531
Compressive strength [MPa]	3 days	-	-	26.6	15.6	-	-	-	-
	7 days	33.1	23.1	36.5	37.7	41.3	35.1	38.8	34.3
	28 days	42.2	45.7	47.8	46.2	52.6	43.4	45.3	47.6
	90 days	46.1	58.3	52.0	58.6	54.3	54.1	49.8	54.8
	365 days	52.9	61.1	-	-	60.0	58.4	55.3	59.2

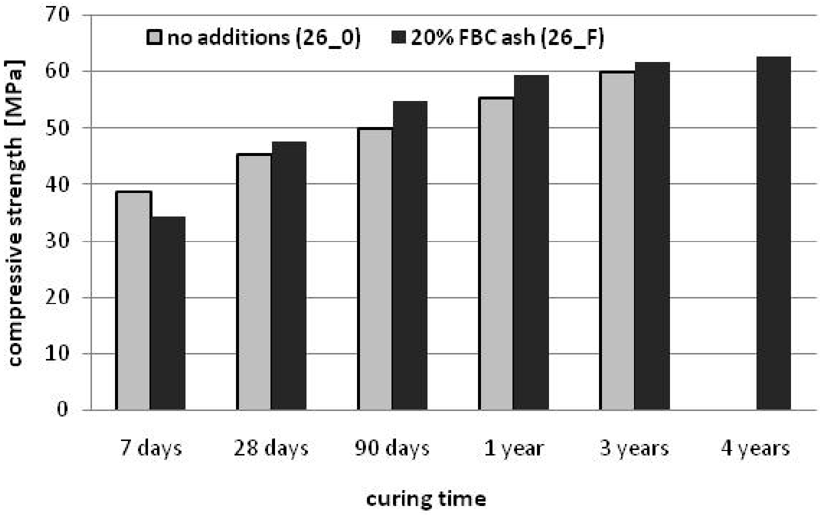
Table 2. Concrete mix proportions, mix properties and the compressive strength of concrete –mix numbers from 28 to 72; (a) – aggregate mixture obtained after mixing fraction 2-8 mm and 8-16 mm)

Basic ingredients of concrete mix [kg/m^3]		Concrete mix designation							
		28_0	**28_F**	**30_0**	**30_F**	**38_0**	**38_F**	**72_0**	**72_F**
Cement CEM I 32.5 R		344	279	348	282	340	270	346	275
FBC ash		-	70	-	71	-	68	-	69
Sand 0-2 mm		613	621	608	618	655	651	664	660
Gravel 2-16 mm [a)]		1193	1208	1189	1208	1166	1159	1180	1173
Water		175	185	169	185	192	200	186	187
Mix properties	Bulk density [kg/m^3]	2326	2364	2315	2365	2353	2349	2376	2365
	Slump [mm]	160	160	170	170	170	210	170	180
	Temperature [^{o}C]	13.5	13.5	10	10	9	9	22	21
	w/(c+fa)	0.511	0.533	0.488	0.527	0.565	0.595	0.538	0.547
Compressive strength [MPa]	7 days	43.5	33.0	40.0	33.0	-	-	34.3	33.1
	28 days	43.5	47.5	49.6	49.1	39.4	39.5	40.5	44.3
	90 days	46.9	56.0	52.2	56.7	43.0	49.0	48.3	51.7
	365 days	53.7	58.6	57.2	60.8	47.3	53.8	53.1	57.7

Table 3. Concrete mix proportions, mix properties and the compressive strength of concrete –mix numbers from 74 to 253; ; a) – aggregate mixture obtained after mixing fraction 2-8 mm and 8-16 mm, d) – mixture of amphibolites aggregate obtained by mixing fraction 2-6.3 mm and 8-16 mm)

Basic ingredients of concrete mix [kg/m^3]		Concrete mix designation							
		74_0	**74_F**	**153_0**	**153_F**	**244_0**	**244_F**	**253_0**	**253_F**
Cement CEM I 32.5 R		333	271	307	243	353	277	345	281
FBC ash		-	68	-	61	-	69 [e)]	-	70
Sand 0-2 mm		622	633	723	712	706	694	659	671
Gravel 2-16 mm		1166	1188	1232	1219	1250 [d)]	1227 [d)]	1153 [a)]	1173 [a)]
Water		172	194	149	167	175	182	146	148
Mix properties	Bulk density [kg/m^3]	2294	2355	2414	2405	2484	2450	2304	2344
	Slump [mm]	180	180	200	190	150	150	60	30
	Temperature [^{o}C]	21	21	11	11	13	14	15	14
	Air content [%]	-	-	2.8	1.8	2.0	2.2	-	-
	w/(c+fa)	0.520	0.575	0.492	0.556	0.496	0.527	0.426	0.425
Compressive strength [MPa]	7 days	35.4	29.8	27.9	15.9	41.0	39.0	41,9	32.7
	28 days	41.2	41.7	38.4	29.9	52.3	59.4	42,3	50.5
	90 days	44.5	48.1	45.1	39.8	59.4	67.3	55,8	59.5
	365 days	47.6	52.9	-	-	62.5	73.2	-	-

In the tables the lower indices "0" and "F" denote mixes without addition and with FBC ash respectively. The average compressive strength of concrete specimens tested at 28 days was within the range from 29.9 to 59.4 MPa while the coefficient of variation was not higher than 6%. The compressive strength of concrete without addition was found to grow faster in the early ages. The strength at the age of 7 days was about 85% of the 28-days strength, while for concrete containing FBC ash it was about 70%. At the age of 28 days the compressive strength of both types of concrete was almost identical, and in the long term the strength of concrete with FBC ash surpassed the strength of reference concrete by about 5-10%. For few series of specimens the compressive strength data was available up to the age of 4 years and that was used to illustrate the effect of age on the compressive strength of concrete with and without fluidized bed ash additive (Fig. 1).



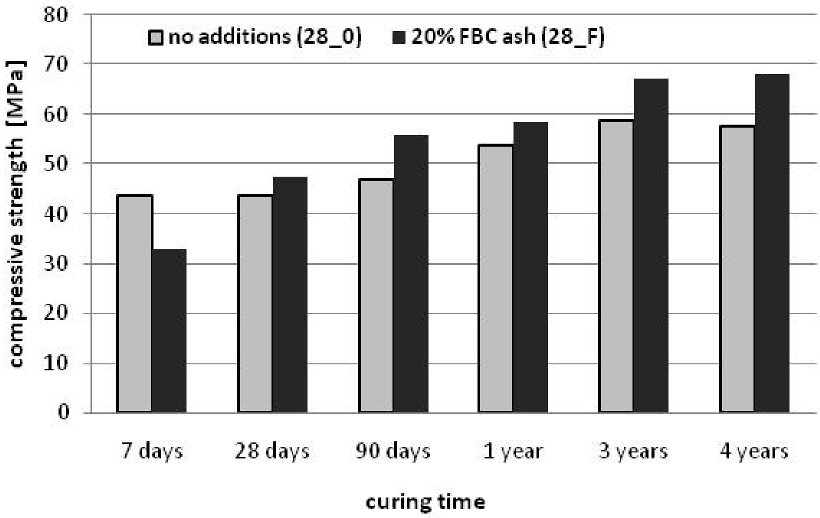


Figure 1. The effect of age on the compressive strength of concrete with and without fluidized bed ash additive (examples selected from Tables 1 and 2- the experimental data included the strength after 3 and 4 years that were not available for other series).

4 ASSESMENT OF THE EFFICIENCY OF THE ADDITION

To assess the influence of additions on the compressive strength of concrete the well known Bolomey's and Feret's formulas were used, Kasperkiewicz (1998). Instead of one *k*-factor two distinct efficiency factors are introduced. Simple Bolomey's formula describes the proportionality of the concrete strength to cement-water ratio *c/w*. On this basis the proportion of strength of reference concrete f_c and concrete with addition f_{cfa} can be expressed as the ratio of adequate binder-to-water ratio. For concrete with addition of FBC ash the (*c/w*) ratio should be replaced by an equivalent binder-to-water ratio $(b/w)_{\mathrm{fa}}$, assuming the equivalent binder mass *b* in the following way:

$$b = c_{fa} + \beta \cdot a_{fa} = c \cdot (0.8 + 0.2 \cdot \beta) \tag{1}$$

where c – mass of cement in the reference concrete, $c = c_{fa} + a_{fa}$,
c_{fa}, a_{fa} – mass of cement and mass of fluidized bed ash in concrete mix containing FBC ash,
β – efficiency factor of fluidized bed ash in relation to cement.

Numerical coefficients 0.8 and 0.2 result from 20% cement replacement by fluidized bed ash. Water content in reference concrete and concrete with fluidized bed ash is denoted by w and w_{fa} respectively. And therefore the ratio of concrete strengths is described by the following formula:

$$\frac{f_{cfa}}{f_c} = \frac{\frac{b}{w_{fa}}}{\frac{c}{w}} = \frac{\frac{0.8 + 0.2 \cdot \beta}{w_{fa}}}{\frac{1}{w}} \tag{2}$$

from which the efficiency factor β may be calculated.

In Feret's formula the compressive strength is proportional to the square of the fraction of cement volume over the total volume of cement, water and air voids. Denoting the efficiency factor of fluidized bed ash in relation to cement as α, the equivalent binder mass b is given by a following formula:

$$b = c_{fa} + \alpha \cdot a_{fa} = c \cdot (0.8 + 0.2 \cdot \alpha) \tag{3}$$

where numerical coefficients correspond to 20% cement mass replacement by fluidized bed ash. Assuming previously introduced symbols, Feret's formula for the compressive strength of concrete with and without FBC ash yields the following formulas:

$$\sqrt{\frac{f_c}{A}} = \frac{\frac{c}{3.1}}{\frac{c}{3.1} + w + 20}; \quad \sqrt{\frac{f_{cfa}}{A}} = \frac{\frac{0.8c}{3.1} + \frac{\alpha \cdot 0.2c}{2.6}}{\frac{0.8 \cdot c}{3.1} + \frac{\alpha \cdot 0.2c}{2.6} + w_{fa} + 20} \tag{4}$$

For derivation of these formulas a constant air void content of 2% was assumed for concrete mixes (i.e. 20 dm^3/m^3). The meaning of other parameters is:

- A – a coefficient used for global description of aggregate quality, cement strength and additional influencing factors, in MPa;
- 3.1 – density of cement in kg/dm^3,
- 2.6 – density of FBC ash in kg/dm^3.

There are two unknown variables in the set of two equations (4), so the equations can be solved for unknown A and unknown efficiency factor α.

After introducing the experimental data as the parameters of concrete mix composition and experimentally determined concrete compressive strength the formulas (2) and (4) yielded the efficiency factor β according to Bolomey's formula and the efficiency factor α according to Feret's formula, respectively. Calculated efficiency factors for the compressive strength of concrete at the age up to 90 days were in the following range: β from 0.95 to 3.24 and α from 0.85 to 2.46 (in each case $\beta > \alpha$). Average values of efficiency factors determined for the same age of concrete up to 1 year fell in a fairly narrow range: β from 1.8 to 2.0 and α from 1.4 to 1.5, in spite of expected variability of FBC ash properties during 12 months of sampling. A tendency of decreasing standard deviation β and α factors with increasing the age of concrete was found. Calculated values of coefficient A used in Feret's formula were 358±38 MPa and 404±38 MPa for concrete age of 90 and 365 days, respectively.

To estimate the characteristic value of efficiency factor the scatter of experimental data should be taken into account, although some authors use average values only, Papadakis and Tsimas (2002). Considering the scatter of data a conservative estimation of the characteristic efficiency factor equal to 1.0 is proposed both for β and α for concrete age of at least 90 days. For 28-day compressive strength an estimated characteristic efficiency factor is slightly lower, i.e. 0.8 or 0.9 respectively, depending on the formula used to design the compressive strength of concrete containing nonstandard FBC ash addition. FBC ashes are chemically active and readily react with water; the chemical reactivity of the ashes is largely due to the large content of unreacted lime from the calcinations of excess limestone sorbent, Bulewicz (2008). Therefore, because of both hydraulic and pozzolanic activity, such high efficiency factor for FBC ash can be justified.

5 CONCLUSIONS

Performed experimental investigation resulted in the following conclusions.

-An increased water demand was observed for concrete mixtures containing FBC ash used to replace 20% of cement mass in mix. An average increase of water-binder ratio $w/(c+fa)$ by about 9% was needed to keep the same consistency of the mix.

-The compressive strength of concrete containing FBC ash used to replace 20% of cement mass was increased by 10-15% in comparison to reference mixes at the age of 28 days and beyond.

-Average FBC efficiency factor calculated using Bolomey's formula and Feret's formula for the same age of concrete up to 1 year was from 1.8 to 2.0 and from 1.4 to 1.5, respectively, in spite of expected variability of FBC ash properties.

- A characteristic efficiency factor of 1.0 corresponds to a conservative estimation of the effectiveness of FBC ash in relation to the cement in regard to the long-term concrete compressive strength.

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