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THE PROPERTIES OF MASS CONCRETE WITH CFBC FLY ASH-SLAG BINDER

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The manuscript presents the research results concerning the properties of concrete with non-clinker, low-emission binder composed of by-products from metallurgy and power industry: ground granulated blast furnace slag and fly ash from circular fluidized-bed combustion of brown coal. The binder was added in five proportions. The consistency and air content of the concrete mix were measured, as well as the temperature of the concrete mix during hardening. The compressive strength of the hardened concrete was investigated in three periods of samples' curing: after 28, 90 and 360 days. Also the penetration depth of water under pressure and freeze and thaw resistance of concrete samples were investigated. The results confirm the possibility of application of slag-CFBC fly ash binder for mass concrete due to low temperature during hardening. The obtained results of the compressive strength and penetration depth of water under pressure reveal the influence of changing the proportion of the binder ingredients, as well as the sample damage during testing the freeze/thaw resistance. The CFBC fly ash-slag binder can be used for mass concrete, hydrotechnical concretes in particular, but excluding the zones exposed to frost.

Keywords: CFBC fly ash-slag binder, low-emission binder, mass concrete, circular economy

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1. INTRODUCTION

The search for binders that are alternative to ordinary Portland cement arises from the fact that it is an energy-consuming and costly material. Intensive exploitation of non-renewable natural resources and CO_2 emissions associated with cement production encourage to use low-emission binders, as per the principles of the new economy model – circular economy (CE). The CE model is a loop wherein waste generated in the course of one of the economic processes becomes a resource within another process (does not end up in a landfill). This leads to minimizing natural resource mining, increasing the utilization of recyclable resources and limiting CO_2 emissions. Recyclable materials and industrial process waste can be successfully used in various engineering branches, among others, construction or geotechnics [1, 8, 10, 11, 17].

Research centres in Poland and worldwide have been working on the possibility of maximizing the use of fly ashes for the production of cement and concrete. Siliceous fly ash and ground granulated blast furnace slag are widely used in the cement industry as the main component or type 2 additive for concrete. Fluidized bed combustion fly ash has limited applicability due to its high water demand and developed grain specific surface. These features significantly reduce the workability of the concrete mix. Whereas the content of active calcium components (i.a. anhydrite and calcium oxide) gives it pozzolanic and hydraulic properties. The combination of this type of ash with ground granulated blast furnace slag provides a low-emission binder, without the addition of Portland cement, which is characterized by low hardening heat [3]. This feature indicates a potential applicability of the slag and fly ash binder in terms of mass concrete, which can experience damage resulting from exothermic reactions occurring during hydration. Hydrotechnical concrete, used to erect dams – which operate in various exposure conditions, i.a., under the action of pressurized water or with a variable water table position – is a particular type of mass concrete. Variable exposure conditions lead to the zoning of concrete within a hydrotechnical structure, due to various requirements [18].

2. EXPERIMENTS

2.1. MATERIALS

A slag and fly ash binder was created by mixing ground granulated blast furnace slag with circular fluidized-bed brown coal combustion fly ash. Blast furnace slag, ground to a suitable specific surface, is a hydraulic additive, which is commonly used for cement or concrete production, partially replacing Portland clinker. Blastfurnace cement, which contains from 35% to 95% of blast furnace slag, is used when the conditions require low hydration heat and higher chemical resistance of the binder and maintaining the design concrete strength class. Blast furnace slag is a material with latent hydraulic properties, as well as a high content of the glassy phase (up to 95%), which was confirmed in studies [3]. Slag binding reaction is activated by adding basic or weak acidic compounds, as well as by applying elevated pressure and temperature or grinding.

The circular fluidized-bed coal combustion process enables limiting sulphur oxide and nitrogen oxide emissions to the atmosphere, and to decrease the unit heat consumption, which is why electricity generation is cheaper relative to power produced in the course of conventional coal combustion [9]. The fly ash formed as a result of this process exhibits pozzolanic and hydraulic properties, and is also characterized by developed specific surface of the grains, high water demand and high pH. Due to the large variability of the chemical composition, this type of ash is not approved for use in cement or concrete production, and can only be applied as a secondary additive in cement (max. 5%). The main field of application includes filling post-mining workings, ground stabilization and reclamation, road construction or neutralization of acidic industrial wastewater [6].

Circular fluidized-bed brown coal combustion fly ash (CFBC fly ash), which is used in composites based on blastfurnace cement (CEM III) and Portland cement (CEM I), favourably affects their properties. This was demonstrated in the publication [16], which reviews the results of compressive strength tests involving cement and ash slurries with variable water to binder ratios. The publication [20] showed that adding fly ash resulted in increased tightness and strength of hardening slurries with ordinary Portland cement and blast furnace cement.

Fly ash used to activate the blast furnace slag binding reaction primarily contains calcium oxides (21.1%), silicon oxides (34.9%) and aluminium oxides (23.1%). The content of free calcium oxides is 7.0%, while 13.9% for reactive calcium oxide. The content of reactive silica is 19.5%, sulphur oxide 5.7% and chlorides 0.04%. Studying the phase composition of the fly ash has shown the presence of aluminate and silicate phases, amorphous silica and crystalline compounds, as well as anhydrite, calcium carbonate and calcium hydroxide [3].

Table 1 shows the physical properties of fly ash and blast furnace slag.

Table 1. The physical properties of CFBC fly ash and slag [2]

Property	CFBC fly ash	Slag
Density, [kg/m^3]	2440	2900
Fineness (sieve mesh size 0,045 mm), [% of mass]	28.2	2.3
Blaine's specific surface, [cm^2/g]	4690	3150
Water demand, [%]	125.4	-

The test results for slag and fly ash pastes, at the early and later curing periods (after 2, 28 and 90 days) were shown in the publications [3, 19]. After mixing with water, the slag and fly ash binders undergoes hydration processes, with forming phases characteristic for cement composites (hydrated silicates and calcium aluminosilicates, ettringite). The outcome of ongoing processes is obtaining a certain strength level. From the perspective of using this binder in mass concrete, its low hardening heat is an extremely important feature. The amount of heat released in the course of binder hydration satisfies the requirements of the standard for common-use cements with a low hydration heat (LH $\leq$ 270 J/g) and special cements with a very low hydration heat (VLH $\leq$ 220 J/g) [3].

Common aggregate, which satisfies the relevant standards covering the content of ash, chemical compounds and organic impurities, grain shape, alkaline reactivity and resistance, was used to produce the mass concrete. The aggregate mix was engineered using 0/2 mm sand (30% of mass), 2/8 mm gravel (20% of mass), 8/16 gravel (20% of mass) and 16/32 mm gravel (30% of mass). The resultant fine aggregate content (0/2 mm) was 31%, and the content of grains over 32 mm – ca. 3% [2].

Due to the high water demand of fly ash, a liquefying admixture – superplasticizer based on PCE Polycarboxylate Polyether was used, which was intended for special concrete, including hydrotechnical concrete.

2.2. SAMPLE PREPARATION

Concrete samples were prepared in the shape of cubes with 15 cm side, through mechanical mixing of ingredients (water, binder, aggregate, admixture). Five concrete recipes, with variable proportions of binder components (slag and fly ash) and a fixed water to binder ration, equal to 0.5, were executed. The content of tested concrete samples varied in terms of binder component dosage – blast furnace slag and CFBC fly ash, which is shown in Table 2.

Table 2. Dosage of concrete components in 1 m^3 of concrete [2]

Sample	**1**	**2**	**3**	**4**	**5**
Water, [kg]	150				
GGBFS, [kg]	210	180	150	120	90
CFBC fly ash, [kg]	90	120	150	180	210
Sand, [kg]	585				
Gravel 2/8 mm, [kg]	390				
Gravel 8/16 mm, [kg]	390				
Gravel 16/32 mm, [kg]	585				
Admixture SikaViscoCrete V600, [kg]	3.0				

2.3. TEST METHODS

The following laboratory tests of the properties were conducted:

- concrete mix:
  - consistency – tested with two methods, namely, slump test as per PN-EN 12350-2 [12] and flow table test as per PN-EN 12350-5 [13] within 30 minutes from mixing of the ingredients,
  - air content,
  - hardening temperature recorded by the SemAment (by Sika) semiadiabatic calorimeter, using 3 kg concrete mix samples,
- hardened concrete:
  - compressive strength as per standard PN-EN 12390-3 [14] (tested on three samples curing in tap water with a temp. of 20±1°C),
  - waterproofness according to the water penetration depth criteria as per standard PN-EN 12390-8 [15] (tested on six samples after 90 days of curing in tap water with a temp. of 20±1°C),
  - freeze/thaw resistance using the basic method as per the recommendation of a hydrotechnical standard [4], which involves cyclic freezing of samples at an ambient temperature of -18°C and thawing in tap water, at a temp. of +20°C; 12 samples for each

recipe were prepared, and after 90 days of curing in tap water six samples were tested for freeze/thaw resistance, and the other 6 (control samples) were left in water; after a dedicated number of alternative freezing and thawing cycles, the tested samples were removed from the chamber, dried, weighed and, together with the control samples, tested for tensile strength at splitting; the mass decrease and relative decrease of the destructive force were determined for each sample.

3. RESULTS AND DISCUSSION

3.1. CONCRETE MIX PROPERTIES

3.1.1. CONSISTENCY CLASS AND AIR CONTENT

The ability of a concrete mix to flow – its consistency – depends on its composition. The more binder in a mix, the lower the consistency. Adding water, besides increased mix fluidity, results in decreasing the target strength of the concrete. The initial testing involved the preparation of a concrete mix with a slag and fly ash binder, without a plasticizing admixture. This led to obtaining a dry and non-workable mix, which results from the presence of fly ash with a high water demand (Fig. 1). In order to guarantee a high consistency of the concrete mix and to improve its workability, the fly ash was subjected to mechanical activation causing the separation of ash grain conglomerates and refreshing their surface without changing their size. The mix was also supplemented with a liquefying admixture in the amount of 1% of the binder mass. The concrete mix consistency test results are shown in Fig. 2.

Fig. 1. Concrete mix without (left) and with (right) a superplasticizer

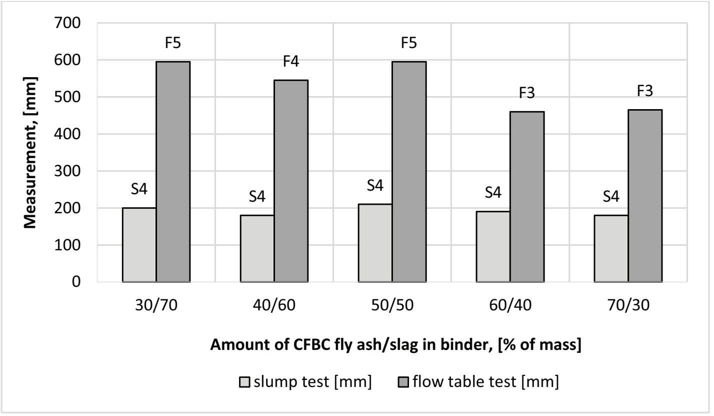

Fig. 2. Consistency class of concrete mixes tested with the slump test and flow table test (measured within 30 minutes from mixing)

Air content in the concrete mix was tested as per standard PN-EN 12350-2 [12]. This parameter depends on the method of mixing and compacting of the concrete mix. No air entraining admixture was used for the concrete. The air content in tested concrete mix recipes varied from 0.9% to 1.2%, which means a correct design and execution.

3.1.2. TEMPERATURE OF HARDENING CONCRETE MIX

Thermal processes ongoing within a hydrating binder cause damage, especially in mass concrete structures. Due to heat exchange with the environment, the external surface of a block is cooled down faster than its inside, and temperature differences can be destructive to young concrete. A temperature measurement in the course of slag and fly ash binder curing within a concrete mix is shown in Fig. 3. The maximum curing temperature of 26°C was achieved by mix No. 5, one with the highest ash content (70% of the binder mass), and the minimum temperature – 24.1°C – mix No. 1, one with the lowest ash content (30% of the binder mass). The graph also shows the temperature of a concrete mix (curve A) made of CEM I 42.R Portland cement binder, with 10% of its mass replaced with CFBC fly ash addition (water to binder ration of 0.5) [7]. Due to the used cement with high early strength, one can observe a significant increase of temperature within approximately 12h of curing. Whereas the highest temperature in the case of mixes with slag and fly ash binder was recorded after approximately 24h of curing.

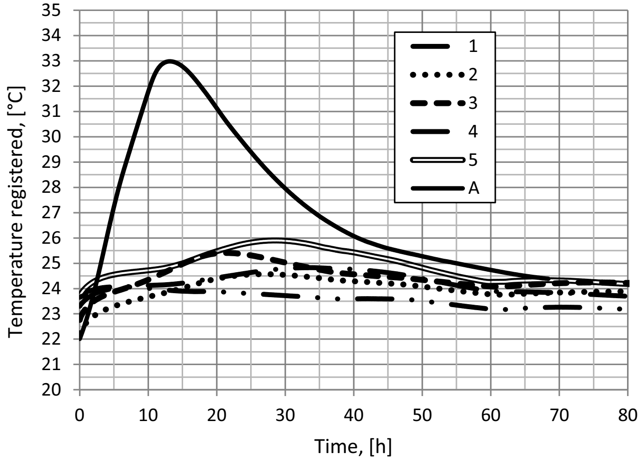

Fig. 3. Temperature registered during concrete curing over time [2, 7]

Given the above, a simulation of temperature development within a 3x3x3 m concrete block was developed for recipe No. 5, with the assumptions of formwork as the environment and an air temperature of +20°C (Fig. 4). When analysing the heat map, it can be concluded that a slag and fly ash binder presents low heat of hardening, and the temperature increase during hydration does not pose a threat to the block element. It is particularly important in the case of hydrotechnical concrete structures operating under the water pressure, where any material discontinuities constitute a potential filtration route.

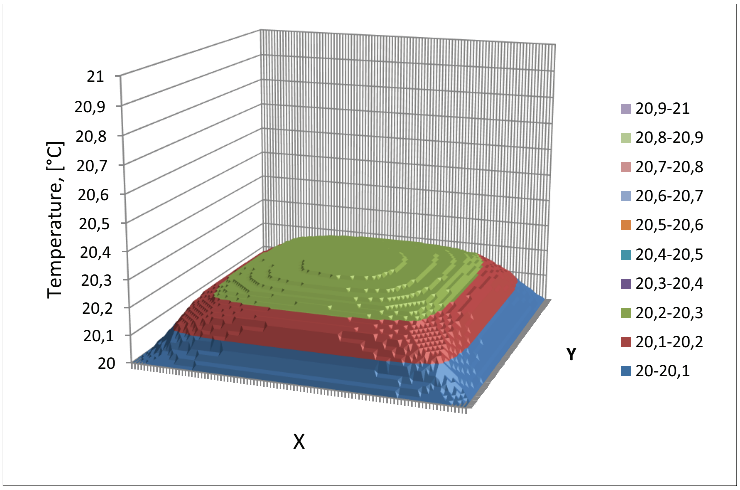

Fig. 4. Simulation of temperature development (temperature map) within a 3x3x3 m concrete block

3.2. CURED CONCRETE PROPERTIES

3.2.1. COMPRESSIVE STRENGTH

Increasing compressive strength during curing can be observed in the case of all considered recipes for concrete with a slag and fly ash binder (Fig. 5). It can be seen that this parameter increases with growing amount of CFBC fly ash in the binder. This indicates a greater degree of conversion in binder components and confirms the role of fly ash in activating the reaction of blast furnace slag binding and hardening. This tendency was observed when studying slag and fly ash pastes [19].

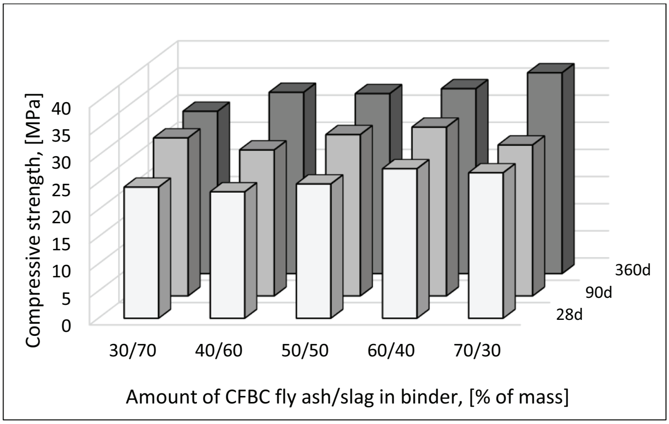

Fig. 5. Compressive strength of concrete samples [2]

3.2.2. DEPTH OF PENETRATION OF WATER UNDER PRESSURE

The concrete watertightness test, as per the criterion of the depth of water penetration into a sample were conducted as per the standard PN-EN 12390-8 [15]. The results are shown in Table 3. When analysing the obtained values, it can be observed that the samples are characterized by material heterogeneity, as evidenced by the high differences between the maximum and minimum values of the penetration depth of water under pressure. Furthermore, the tendency observed when testing strength that the more fly ash in the binder, the higher conversion degree of slag and lower water penetration depth is confirmed. The standard [15] does not stipulate the limit values for the penetration depth of water under pressure. However, they can be found in the German DIN 1045 standard [5] (national supplement to the European Standard EN 206), which stipulates that the maximum water penetration depth is 50 mm, and the average for a test involving a minimum of three samples cannot be higher than 20 mm. It can be concluded that the tested concrete samples do not satisfy the criterion formulated for waterproof concrete.

Table 3. Depth of penetration of water under pressure in concrete samples [2]

Sample		1	2	3	4	5	Max. depth acc. to [5]	Average of 3 samples acc. to [5]
d, [mm]	min.	120	80	70	70	84	50	20
	max.	200*	135	111	100	105		

*water filtered through two samples (out of the six tested), after 24h and 36h, respectively

3.2.3. FREEZE/THAW RESISTANCE

The samples were evaluated for freeze/thaw resistance by analysing the measurement results involving mass change and destructive (splitting) force decrease, after a specified number of freezing/thawing cycles, as well as when conducting the macroscopic evaluation of samples. The samples 1, 2 and 3 experienced a slight mass increase in the course of the test, which results from progressive cracking and the penetration of additional amounts of water into the samples. A significant loss of sample mass after approximately 80 freezing/thawing cycles was observed, which was caused by their developing degradation. A clear tendency of the samples to lose mass as a result of increasing fly ash content in the binder was not observed. The relative decrease of the destructive force, which exceeded 25%, leads to the conclusion that none of the samples achieved the assumed frost-resistance grade. The destruction plane in the sample was visually inspected after testing the tensile strength at splitting. It was observed that husking of the aggregate resulting from weakened paste in the zone of the interface with aggregate occurred with increasing dosage of fly ash in the binder and the number of freezing/thawing cycles. Hairline cracking, decrements at sample corners and edges, as well as exposed aggregate were observed in the course of conducting a macroscopic assessment of the sample outer surface condition. The trowelled surface was subjected to gradual scaling as the test progressed. Sample degradation was greater the more CFBC fly ash the binder contained (Fig. 6).

Fig. 6. Sample degradation after 100 freezing/thawing cycles: sample as per recipe No. 1 (left), sample as per recipe No. 3 (centre), sample as per recipe No. 5 (right)

4. CONCLUSIONS

A concrete mix with a slag and CFBC fly ash binder is non-workable without a plasticizing admixture. This is due to the high water demand of the used fly ash grains from circular fluidized-bed brown coal combustion. Whereas a slag and fly ash binder does not cause adverse thermal effects within the concrete during the curing process. In the case of hardened concrete with slag and fly ash binder, the outcome of changing the proportion of the binder ingredients translates to the compressive strength of the concrete (the higher CFBC fly ash to slag ratio in the binder the higher the strength), water penetration depth under pressure (this parameter decreases with increasing amount of CFBC fly ash in the binder) and sample damage when testing freeze/thaw resistance.

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WŁAŚCIWOŚCI BETONU MASYWNEGO ZE SPOIWEM ŻUŻLOWO-POPIOŁOWYM

Słowa kluczowe*: spoiwo żużlowo-popiołowe, spoiwo niskoemisyjne, beton masywny, gospodarka obiegu zamkniętego*

STRESZCZENIE

W artykule przedstawiono wyniki badań betonu wykonanego z udziałem niskoemisyjnego, bezklinkierowego spoiwa, powstałego przez zmieszanie mielonego granulowanego żużla wielkopiecowego i popiołu lotnego z fluidalnego spalania węgla brunatnego (w pięciu proporcjach dozowania składników spoiwa, przy stałym w/s=0,5). W celu ustalenia wpływu spoiwa żużlowo-popiołowego na właściwości mieszanki betonowej wykonano badania konsystencji mieszanki metodami stożka opadowego wg PN-EN 12350-2 [12] i stolika rozpływowego wg PN-EN 12350-5 [13], badania zawartości powietrza i zmian temperatury mieszanki podczas twardnienia. Wykonanie mieszanki betonowej bez dodatku domieszki upłynniającej jest niezwykle trudne ze względu na wysoką wodożądności i rozwiniętą powierzchnię właściwą ziaren zastosowanego popiołu lotnego. Dodatek domieszki umożliwił uzyskanie konsystencji S4 wg [12] i F3÷F5 wg [13]. Zawartość powietrza w mieszance wyniosła 0,9÷1,2%. Zmierzona temperatura twardnienia betonu wykonanego według pięciu receptur wskazuje na możliwość wykorzystania do wykonania betonu masywnego (maksymalna temperatura twardnienia 26°C).

Przedstawiono również badania betonu stwardniałego: wytrzymałość na ściskanie w trzech terminach dojrzewania (po 28, 90 i 360 dniach), wodoszczelność i mrozoodporność. W przypadku wszystkich rozpatrywanych receptur betonu ze spoiwem żużlowo-popiołowym obserwuje się wzrost wytrzymałości na ściskanie w czasie dojrzewania. Można zauważyć, że parametr ten jest wyższy w miarę wzrostu ilości popiołu lotnego z fluidalnego spalania węgla brunatnego w spoiwie. Wskazuje to na większy stopień przereagowania składników spoiwa i potwierdza rolę popiołu lotnego w aktywacji reakcji wiązania i twardnienia żużla wielkopiecowego.

Badania wodoszczelności betonu według kryterium głębokości penetracji wody pod ciśnieniem w próbkę, wykonane zgodnie z normą PN-EN 12390-8 [15], wykazały, że próbki charakteryzują się niejednorodnością materiału, o czym świadczą duże różnice między wartością maksymalną a minimalną głębokości wniknięcia wody. Potwierdzono tendencję zaobserwowaną podczas badania wytrzymałości, że im więcej popiołu lotnego w składzie spoiwie tym wyższy stopień przereagowania żużla i mniejsza głębokość wnikania wody.

Oceny stopnia mrozoodporności badanych próbek dokonano analizując wyniki pomiarów zmiany masy i spadku siły niszczącej (rozłupującej) próbki po określonej liczbie cykli zamrażania/rozmrażania, a także dokonując oceny makroskopowej próbek. Niektóre próbki doznały wzrostu masy podczas badania, wynikającego z wnikania dodatkowej ilości wody w powstałe w próbkach spękania. Zaobserwowano znaczny ubytek masy próbek po około 80 cyklach zamrażania/rozmrażania spowodowany ich postępującą degradacją. Nie zaobserwowano jednoznacznej tendencji próbek do utraty masy w związku ze wzrostem ilości popiołu lotnego w spoiwie. Analizując względny spadek siły niszczącej (powyżej 25%) należy stwierdzić, że żadna z próbek nie uzyskała założonego stopnia mrozoodporności. Oględziny płaszczyzny zniszczenia w próbkach wykazały osłabienie zaczynu w strefie styku z kruszywem skutkujące wyłuskaniem kruszywa podczas badania wytrzymałości. Zaobserwowano spękania włosowate, ubytki w narożach i na krawędziach próbek oraz odsłonięcie kruszywa.

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