Research Article

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Cements with calcareous fly ash as component of low clinker eco-self compacting concrete

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Abstract: The main goal of the presented research was to verify the possibility of obtaining ecological self-compacting concrete of low hardening temperature, containing different types of cements with calcareous fly ash W as main component and the influence of these cements on basic properties of fresh and hardened concrete. Cements CEM II containing calcareous fly ash W make it possible to obtain self-compacting concrete (SCC) with similar initial flowability to analogous mixtures with reference cement CEM I and CEM III/B, and slightly higher, but still acceptable, flowability loss. Properties of hardened concretes with these cements are similar in comparison to CEM I and CEM III concretes. By using cement non-standard, new generation multi-component cement CEM “X”/A (S-W), self-compacting concrete was obtained with good workability and properties in hardened state.

Keywords: calcareous fly ash, self-compacting concrete

1 Introduction

Eco-concrete is defined as a concrete which uses waste materials as at least one of its components, its production process does not lead to environmental destruction, and it has high performance and life cycle sustainability (*Fib Bulletin No. 67: Guidelines for green concrete structures*, 2012). The eco-concrete is characterised by the optimization of use of materials and mix design, which especially includes: minimization of cement and clinker content through its substitution with mineral additives; enhanced workability of fresh concrete, best by using self-compacting concrete (SCC), enhanced durability and service life, and last but

not least, acceptable cost, obtained by usage of commonly and locally available low cost materials and technologies. (Suhendro, 2014)

Thermal effects associated with cement hydration are of particular importance for concrete durability (Neville & Brooks, 2010). They can cause cracking in the whole volume of concrete element lowering its durability and shortening its service life-time. The problem is especially important in the case of SCC which is usually characterized by high cement content. Thus, composition concept of eco-SCC with low hydration heat was developed and presented in (Gołaszewski & Cygan, 2017a) (Gołaszewski & Cygan, 2017b).

One of mineral admixtures which could be used in eco-concrete is calcareous fly ash W (CFA-W). CFA-W can be the main constituent of cement (EN 197-1:2002, EN 2012-1:2012), however its use is limited due to significant changeability of its chemical composition and physical properties, a high content of free calcium and sulphur compounds which are potentially detrimental to the durability and shrinkage of concrete and its high water demand which negatively affects workability, as seen in (Dziuk et. al. 2013; Felekoğlu, Türkel, & Kalyoncu, 2009; Giergiczny, Synowiec, & Żak, 2013; Gołaszewski, Kostrzanowska, Ponikiewski, & Antonowicz, 2013; Tsimas & Moutsatsou-Tsima, 2005). However, many studies such as (Czopowski, Łaźniewska - Piekarczyk, Rubińska-Jończy, & Szwabowski, 2013; Dąbrowska & Giergiczny, 2013; Gibas, Glinicki, & Nowowiejski, 2013) show no negative influence of CFA-W on properties of hardened concrete and that negative influence of CFA-W on the workability of fresh concrete may be lower when it is used as a main constituent of cement, as seen in (Czopowski i in., 2013; Dziuk i in., 2013; Gołaszewski i in., 2013). Moreover, CFA-W has pozzolanic and hydraulic properties, due to the high content of active silica, mostly in amorphous phase; hydration mechanisms of CFA-W were presented in (Giergiczny, Garbacz, & Ostrowski, 2013).

The main goal of the presented research was to verify the possibility of obtaining eco-SCC containing different types of cements with CFA-W as a main component. The scope of application of eco-SCC covers all types of

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construction, but it is especially dedicated for to semi-massive and massive constructions. Therefore, the influence of CFA-W addition to cement for SCC was analysed, both in terms of possibility of obtaining SCC concrete, and its thermal characteristics.

2 Materials and methods.

Influence of 7 types of cements containing CFA-W as a main component on properties of fresh and hardened self-compacting concrete was investigated. Properties of these cements, produced by the Institute of Ceramics and Building Materials in Cracow, are presented in details in Table 1. Cements were obtained by intergrinding the constituents. As data in Table 1 indicate, properties of cements containing CFA-W meet the requirements for common cements according to EN 197-1. The properties of SCC with CFA-W cements were compared to concretes with CEM I and CEM III/B cements.

Concrete composition is presented in Table 2. Concretes were designed according to the concept of eco-SCC with low hydration heat, first of all aiming at minimization of cement content, and thereby clinker content in concrete. Flowability of all eco-SCCs was designed for slump flow diameter $650 \text{ mm} \pm 40 \text{ mm}$ (flow class SF1 - SF2, according to EN 12350-8:2010) by appropriately choosing the amount of superplasticizer (SP). Polycarboxylic-ether-based SP was selected on the basis of preliminary tests as giving optimal balance between high fluidity and stability of the fresh concrete. Natural aggregate was used with maximum grain diameter of 16 mm, with 45 % of fine fraction ($<2 \text{ mm}$).

The scope of the research included the following properties and tests:

- Consistency and flow time T_{500} of concrete was tested using slump-flow test (EN 12350-8). The stability of SCC was evaluated with the Visual Stability Index (VSI; ACI 237 R-07). Measurements were performed 5 and 60 min after the end of mixing. The air content in the concrete mix was determined according to EN 12350-7, 5 min after the end of mixing.
- Development of concrete hardening temperature was tested using 250 mm cubic samples insulated using styrofoam coating of thickness 100 mm and thermal conduction coefficient $0.044 \text{ W/m}\cdot\text{K}$ (Fig. 1). Temperature of concrete was measured in the middle of a cube, with a temperature probe inserted into concrete at the time of concreting. External temperature during the test was 20°C .

Figure 1: Methods of testing development of concrete hardening temperature and setting time.

- Setting time of concrete was tested using Schleibinger Vikasonik ultrasonic system (Fig. 1). Transmitter and receiver were placed on the sides of cubic sample tested for of concrete hardening temperature development.
- Hydration heat of cements was measured using isometric calorimeter TamAir. Measurement was held during 72 hours at a temperature 20°C .
- Compressive strength after 1, 7 and 28 days was tested according to PN-EN 12390-3, samples were cured according to PN-EN 12390-2.

Six samples were tested for each concrete, and average value was used in the analysis.

3 Test results and discussion.

Obtained results are compiled in Tables 3 and 4.

Flowability loss increases with the increase of content of CFA-W in cement. Negative impact of CFA-W on consistency can be linked to its high water demand (Gołaszewski i in., 2013). If the content of CFA-W in cement is on level 15% (B2, B3, B4, B5) the flowability loss is clear, but the fresh SCC keeps fluidity within class SF1 limits. If the content of CFA-W is between 24 - 50% (B6, B7) the fluidity loss is so high that fresh SCC fluidity is out of SF1 limits, however slump flow diameter remains over 520 mm. In case of fresh SCC with CEM „X”/A (S-W) (B8) slump flow after 60 min remains at the SF1 class limit. Obtained flowability allows to use all the cements with CFA-W for SCC for formation of horizontal and vertical elements with regular reinforcement.

All tested fresh SCC were stable, segregation resistant, not exhibiting bleeding (VSI0), and were characterized by the air-content of 1,5 - 3,5%. Air content of fresh concretes with CFA-W cements is insignificantly higher (by about 1 - 1,5%) than of reference concretes B0 and B1. It is probably due to higher viscosity of fresh SCC with CFA-W cements,

Table 1: Cement properties

Parameters		Cement								
		CEM I	CEM III/B	CEM II/A-W	CEM II/B-M (V-W)	CEM II/B-M (S-W)	CEM II/B-M (LL-W)	CEM IV/B-W	CEM IV/B (V-W)	CEM „X”/A-W ¹
Constituent, % mass	Clinker	94.5		81.1	66.7	64.7	66.0	45.8	48.0	47.9
	Fly ash W	-		14.3	14.3	15.3	14.0	50.0	24.0	23.9
	Fly ash V	-			14.3				24.0	
	Slag S	-	70			15.3				23.9
	Limestone LL	-					14.0			
	Gypsum	5.5		4.6	4.7	4.7	6.0	4.2	4.0	4.3
Components, % mass	LOI	1.92	0.86	2.28	2.05	1.92	6.10	2.30	2.24	2.14
	SiO ₂	20.35		24.37	26.47	24.49	19.60	25.97	29.51	26.94
	Al ₂ O ₃	4.48		6.90	9.52	6.99	6.15	11.54	12.68	8.98
	Fe ₂ O ₃	2.06		2.46	3.28	2.44	2.30	3.76	4.16	2.93
	CaO	66.56		58.27	52.42	57.91	60.68	50.28	44.10	52.02
	MgO	0.93		0.98	1.35	1.77	1.03	1.39	1.67	2.28
	K ₂ O	0.54		0.53	0.61	0.19	0.14	0.15	0.94	0.53
	Na ₂ O	0.24	0.70	0.26	0.34	0.30	0.22	0.28	0.44	0.26
	SO ₃	2.82	1.95	3.01	3.16		3.11	3.30	3.19	3.33
Surface, cm ² /g		3830	5290	4190	4130	4230	4430	4200	4130	3810
Setting time, min		152	204	173	204	197	232	213	356	252
Compressive strength, MPa	2 d	27.5		23.5	20.4	17.1	18.0	11.6	12.0	11.7
	7 d	48.7	26.9	40.9	35.6	34.5	36.0	22.3	23.2	
	28 d	56.3	55.3	50.1	47.4	49.8	45.6	37.7	37.7	40.3
Water demand, %		26,5	31.9	27.6	28.6	29.2	27.2	34.6	30.8	29.8
Flow diameter, cm		18,0		16.4	14.9	12.9		17.0	16.0	15.6
Shrinkage after 28 days, %		0,33		-0.40	-0.46	-0.42	-0.31	-0.28	-0.44	-0.36
Hydration heat after 72h, J/g		287,3	225	287.8	258.3	276.5	264.9	239.6	238.8	222.1

which impedes their ability to remove air from the fresh concrete.

The use of cements with CFA-W delays the setting time of concrete in relation to concrete with CEM I cement, and the delay amounts from 50% to even 200% (from 3h to 13 h) (Table 4). The longest delay was observed for concretes B5, B7 and B8 (cements CEM II/B-M (LL-W), CEM IV/B (V-W) and CEM „X”/A (S-W) respectively). Due to higher specific surface, and despite a large amount of slag, that cement does not delay setting time of concrete as much as cements with CFA-W.

The highest amount of generated heat during the cement hydration process obviously characterized B0 sam-

ples (CEM I and SP). The other samples are characterized by lower hydration heat and kinetics of its generation, and the amount of generated heat is mainly dependent on the amount of clinker in cement and cement specific surface area. Obtained results clearly show the influence of CFA-W on the reduction of hydration heat of cement and thus maximal temperature of concrete (Fig. 3). However, the crucial factor seems to be the amount of SP content in concrete. It increases significantly in proportion to the amount of CFA-W in cement contributing significantly to slowing down of the process of hydration. Taking under consideration the resistance of concrete to thermal cracking, moment of maximum temperature should be as late as possi-

Table 2: Composition of concrete

Material	B0	B1	B2	B3	B4	B5	B6	B7	B8
	CEM I	CEM III/B	CEM II/A-W	CEM II/B-M (V-W)	CEM II/B-M (S-W)	CEM II/B-M (LL-W)	CEM IV/B-W	CEM IV/B (V-W)	CEM „X” (S-W) ¹
Cement, kg/m ³	306								
Sand 0-4 mm, kg/m ³	969	969	961	932	944	935	917	938	940
Coarse aggregates 4-11 mm, kg/m ³	363	363	360	349	354	350	343	351	352
Coarse aggregates 8-16 mm, kg/m ³	451	451	448	434	439	436	426	436	436
Water, kg/m ³	193								
SP, kg/m ³	2.90	2.90	4.69	4.39	5.75	4.68	8.07	4.81	4.47
SP, % of cement mass	0.94	0.94	1.53	1.43	1.88	1.53	2.64	1.57	1.46
w/c	0.63								
w/c _{eff}	0.54								
w/p _{eff}	0.45								
Volume of cement paste, dm ³	294	294	297	294	296	299	301	297	297
Clinker content, kg/m ³	289	92	248	204	198	202	140	147	147

Table 3: Heat of hydration of cements with of SP (w/c = 0.54, SP content see Table 2)

Sample	Cement	Hydration heat (J/g) at time					
		1 h	12 h	24 h	36 h	48 h	72 h
B0	CEM I	11.81	49.92	137.59	193.30	223.92	261.30
B1	CEM III/B	3.21	9.39	11.35	22.7	32.52	94.03
B2	CEM II/A-W	21.50	32.07	52.42	135.75	194.12	250.65
B3	CEM II/B-M (V-W)	19.27	27.21	34.62	62.04	125.73	220.16
B4	CEM II/B-M (S-W)	4.86	10.45	14.56	22.23	37.14	102.31
B5	CEM II/B-M (LL-W)	12.84	21.19	35.45	69.94	136.11	179.55
B6	CEM IV/B-W	14.08	22.88	25.95	30.37	37.76	99.25
B7	CEM IV/B (V-W)	5.08	14.82	21.60	33.09	62.92	132.88
B8	CEM „X” (S-W)	16.42	20.93	26.74	53.56	92.17	158.96

ble. In respect to concrete with CEM I, the moment of obtaining maximum temperature by concretes with cements with CFA-W is significantly delayed.

Results of compressive strength tests are shown in Fig. 4. As it could be expected after analysing the setting times results, the early compressive strength of cements with CFA-W is low. After 28 days, compressive strength of concretes with cements CEM II/A-W and CEM II/B-M (B2, B3, B4, B5) is comparable to compressive strength of ref-

erence concrete with CEM III/B (B1), while compressive strength of concretes with CEM IV/B and CEM „X”/A (S-W) (B6, B7, B8) is visibly lower. All concretes with cements CEM II containing CFA-W have a class C30/37 or higher, concretes with cements CEM IV and CEM „X” have a class C25/30. Keeping in mind that clinker content in CEM II/B-M is ~200 kg/m³ and in cements CEM IV/B and CEM X is ~140 kg/m³ of clinker, obtained compressive strengths of concretes are satisfactory.

Table 4: Properties of SCC

Property		B0	B1	B2	B3	B4	B5	B6	B7	B8
		CEM I	CEM III/B	CEM II/A-W	CEM II/B-M	CEM II/B-M	CEM II/B-M	CEM IV/B-W	CEM IV/B (V-W)	CEM „X” (S-W)
Slump flow diameter, mm	after 5 min	675	680	630	665	655	640	630	620	640
	after 60 min	640	670	560	610	620	610	540	520	570
Flow time T_{500} , s	after 5 min	3	2.7	2.8	2.4	2.2	2.2	3.2	3	2.8
	after 60 min	2.4	2.9	2.9	3.2	3	3.1	-	-	3.4
VSI index	after 5 min	VSI0	VSI0	VSI0	VSI0	VSI0	VSI0	VSI0	VSI0	VSI0
	after 60 min	VSI0	VSI0	VSI0	VSI0	VSI0	VSI0	VSI0	VSI0	VSI0
Air content, %		2,2	1.9	2.2	3.2	2.8	2.4	3.4	2.4	2.9
Setting time of concrete, h		6.33	10.07	9.70	10.9	11.43	16.60	11.07	19.08	17.87
Maximal temperature, °C		52,6	34,8	49,3	44,2	37,9	42	38,6	39,2	40,0
Time of max.temperature, h		17.93	39.92	24.5	29.9	32.16	44.25	32.4	34.4	36.37
Compressive strength, MPa	after 1 day	6.9	2.27	4.3	3.5	2.9	2.7	3.2	2.4	2.4
	after 7 days	37.4	25.4	30.8	28.1	22.7	23.9	15.4	19.6	18
	after 28 days	54.2	41.4	43.1	42.3	39.8	42.6	33.2	34.8	33.1

Figure 2: The influence of the cement type on slump flow and flow time of the fresh SCC.

Figure 3: The influence of cement type on maximal temperature and time of obtaining maximal temperature of SCC.

Figure 4: The influence of cement type on compressive strength of self-compacting concrete.

4 Conclusions

The conducted research allows to formulate the following conclusions:

1. It was proven that by using CFA-W cements and by optimizing concrete composition it is possible to obtain SCC of acceptable flowability, low hydration heat, prolonged setting time and good 28 days strength.
2. Cements CEM II/A-W, CEM II/B-M make it possible to obtain SCC with similar initial flowability to analogous mixtures with reference cement CEM I and CEM III/B, and slightly higher, but still acceptable, flowability loss. Properties of hardened concretes with those cements are at least not worse than those of concretes based on cements with CEM III/B of the same class but lower compressive strength in comparison to CEM I.
3. SCC with CFA-W cements CEM IV/B-W and CEM IV/B (V-W) are characterized by high flowability loss and their properties in hardened state are in general worse than CEM I, CEM III/B, CEM II/A-W and CEM II/B-M concretes. While it makes them more difficult to use, it does not exclude their use in eco-SCC.
4. The results confirm the possibility of successfully using the new generation multi-component cement. By using cement CEM "X"/A (S-W), self-compacting concrete was obtained with acceptable workability, low hardening temperature and good properties in hardened state.
5. Results indicate that cements with CFA-W can be used to obtain eco-SCC concrete.

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materials and concretes made with high – calcium fly ashes.

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