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Lightweight self-compacting concrete with sintered fly ash aggregate*

Key words: light-weight self-compacting concrete, sintered fly ash aggregate, flowability, passing ability, compressive strength

Introduction

The development of new types of high performance concretes, such as self-compacting concrete (SCC) or lightweight concrete (LWC) responds to some requirements of the construction industry. Lightweight concrete has been used for a number of applications and is known for its good performance and durability. In structural applications the dead load of a concrete structure is important since it represents a large portion of the total load. Due to the reduced weight LWCs have other advantages compared to normal-weight concrete, such as good fire resistance and improved heat insulation. Only lightweight aggregates (LWA) or combination of LWA with natural aggregates are used for these concretes. Lightweight aggregates such as sintered expanding clays, expanded slate, expanded high-grade shale, sintered fly ash, clayey diatomite, pumice, perlite, bottom ash, blast furnace slag aggregate etc. have been successfully used in the production of LWCs (Lo & Cui, 2004; Bogas, de Brito & Figueiredo, 2015; Domagała, 2015; Aslam, Shafigh, Jumaat & Lachemi, 2016; Stamatakis et al. 2016). These aggregates vary in terms of bulk density and mechanical properties, and therefore have different applications – from insulating concretes to structural concretes, even high strength LWC (Kaszyńska, 2009). Among all these LWAs, sintered fly ash aggregate is the best for the use in structural applications (Nadesan & Dinakar, 2017).

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Self-compacting concrete (SCC) does not require vibration for placing and compaction. It is able to flow under its own weight, completely filling formwork and achieving full compaction, even in the presence of congested reinforcement, without segregation of material constituents (EFNARC, 2005). Lightweight aggregate self-compacting concrete (LWASCC) combines the properties of SCC, such as the filling and passing ability and segregation resistance, with the advantages of a structural lightweight aggregate concrete (LWAC), such as reduced dead loads and formwork pressure, high insulation capacity, improved durability, resistance against fire and chemical attack. Self-compacting concretes use their own weight for flowing. Structural LWASCC must satisfy all requirements in fresh state while having a low density. When LWA is used there is no sufficient dynamic energy of the mixture during flow, and compared to the concretes with natural aggregate, the flow is slightly slower especially through reinforcement (Maghsoudi, Mohamadpour & Maghsoudi, 2011; Papanicolaou & Kaffetzakis, 2011). It is therefore very important to balance out the composition of concrete to produce an easily pourable concrete in a fresh state and a high-quality and compact concrete in a hardened state (Juradin, Baloević & Harapin, 2012). Moreover, some unfavorable properties of LWAs such as high porosity, high water absorption and tendency to buoyancy are additional factors that should be taken into account during mix proportioning.

Fresh concrete is combined of fine and coarse aggregates suspended in a matrix of binder paste. Viscosity of the mortar and the volumetric fraction of the aggregates control the flow behavior. LWASCC shows specific features which result from using the LWA. Ensuring the mix flowability and the low density of hardened concrete without segregation is the typical problem. Because of the significant difference between bulk densities of LWA and the surrounding cement matrix, coarse aggregate particles tend to float to the surface when the cement paste has not sufficient viscosity. These concretes show even greater tendency to segregation than the normal weight SCC.

High dynamics of water absorption by LWA, due to its porous structure, is a significant problem and so it is difficult to estimate the required water volume. Various treatments may be applied to avoid the adverse effect of water to cement ratio reduction in structural LWAC as a result of water absorption by the LWA. Preliminary saturation of the aggregate with water is the most often used method. This is especially favorable for lightweight high-quality concretes, where there is a danger of autogenic shrinkage due to low w/c ratio. Initial saturated LWAs may also serve as reservoirs for self-curing water in concrete (Rajamanickam & Vaiyapuri, 2016). Coating of LWA with thin cement paste (cement milk) is another pre-treatment procedure. This treatment causes decrease of water absorption by the aggregate and slightly increases density of aggregate grains (Mechtcherine, Haist, Hewener & Mueller, 2002).

Use of processed LWAs contribute to the sustainable development by waste utilization. The utilization of coal fly ash (FA), which is a waste product from coal thermal power stations, is a major environmental problem in many countries, including Poland. Coal fly ash is used in a range of applications, particularly as a substitute for cement in concrete, but large amount remains unused and thus requires disposal. Coal fly ash based processed lightweight aggregate offers potential for utilization of once deposited fly ash as well as wastes from current production.

The article presents the results of research assessing the possibility of making LWASCC from the locally produced sintered fly ash aggregate CERTYD. Two methods of preliminary LWA preparation were applied: pre-soaking with water and coating with a film of cement paste. Not only coarse fractions of CERTYD were used, but fine and coarse light-weight sand as well.

Materials and mix design

Portland cement CEM I 42.5 R conforming to the standard PN-EN 197--1:2012 was used in the research. Cement properties, provided by the manufacturer, are given in Table 1. Two cementicious additions were used: siliceous fly ash (FA) and zeolite (Z). Declared FA properties comply with the requirements of PN-EN 450-1:2012 for loss on ignition Category A and fineness Category N. Natural zeolite (Zeobau50) is a rock from the group of aluminosilicate minerals. Its basic component is hydrated alkaline aluminosilicate (clinoptilolite).

Postglacial sand was used as a natural fine aggregate. Sand 0/4 mm was used in one batch. The rest mixes contained sand 0/2 mm with grading given in Figure 1.

TABLE 1. Properties of CEM I 42.5R (manufacturer analysis)

Properties	Average
Specific surface (Blaine) [$cm^2 \cdot g^{-1}$]	4 232
Initial set [min]	170
Final set [min]	223
Soundness [mm]	1.0
two-day compressive strength [MPa]	27.7
28-day compressive strength [MPa]	59.0
SO_3 content [%]	3.12
Cl^- content [%]	0.05
Insoluble residue [%]	0.46
Loss on ignition [%]	3.55

Sintered fly ash aggregate CERTYD was used as LWA. It is produced by high-temperature sintering (1,000–1,200°C) of anthropogenic minerals under controlled conditions in the uniquely designed rotary furnace (Łuczaj & Urbańska, 2015). The main raw material for its production is fly ash from the combustion of hard coal in fine coal boilers of the Białystok Power Station. CERTYD characteristics and properties comply with the standard PN-EN 13055:2016-07. The bulk density, depending on the product fraction, is in the range 600–750 $kg \cdot m^{-3}$, bulk crushing resistance of coarse aggregate 6–10 MPa and 24-hour water absorption 16–17%. The coarse aggregate grains are rough in texture, partially rounded and partially crushed in shape with an interior cellular structure (Fig. 2). The lightweight sand (0/0.5 and 1/4 mm) is obtained by crushing bigger grains. Because of the porous structure the dry grains absorb water very fast and may disturb the workability of the mixture. Therefore, a pre-wetting with extra water (EW) or extra thin cement paste (EP)

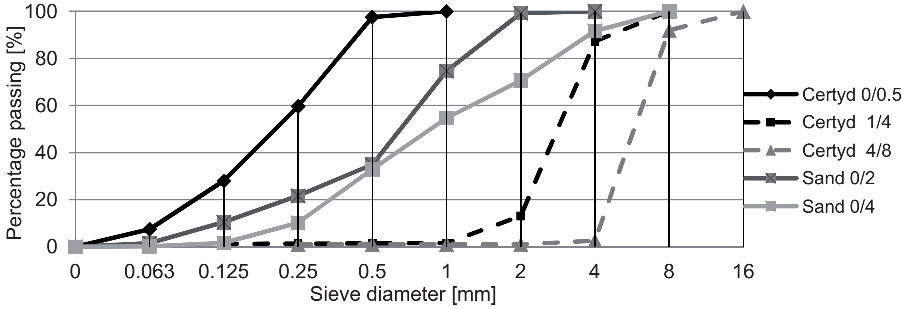

FIGURE 1. Grading analysis of CERTYD aggregate and natural sand 0/2 mm

FIGURE 2. CERTYD aggregate fractions 1/4 and 4/8 mm

with w/c = 3.0 was applied to limit mixing water absorption. CERTYD aggregate water absorption during 15 min was tested prior to the concrete preparation to determine amount of water needed for pre-wetting. On this basis the EW was accepted as 10% by LWA mass. Extra thin cement paste for initial impregnation was assumed as 150% of EW – 15% by CERTYD mass.

High range water reducing admixture (superplasticizer SP) produced on the basis of stabilized polycarboxylates was used in all concrete series.

Regarding concrete mix design, the mix proportions of LWASCC were determined through preliminary tests described in (EFNARC, 2005). The sequence of mixing the constituent materials was as follows: EW or EP (depending on the impregnation method) was mixed with CERTYD and left for 15 min, then natural sand, cement and mineral additions were added and mixed for 30 s, and finally the mixing water with SP was added and mixing was continued for 3 min. Based on the 11 trial and error mixes results on fresh concrete, 6 mixes met SCC requirements (EFNARC, 2005). Mixture proportions are shown in Table 2. The first composition (FA_1_EP) contains only natural sand as the fine aggregate. In the subsequent mixes natural sand was partially substituted by light-weight fine sand (FA_2 and FAZ_2) or light-weight fine and coarse sand (FAZ_3). In the names of the particular series FA stands for fly ash and Z for zeolite as mineral addition, EW for extra water and EP for extra paste as pre-soaking materials.

TABLE 2. Mixture compositions per 1 m^3

Component	FA_1_EP	FA_2_EP	FA_2_EW	FAZ_2_EW	FAZ_3_EP	FAZ_3_EW
Water/binder	0.315	0.31	0.31	0.30	0.30	0.30
Binder [kg]	560	560	560	575	575	575
Cement	381	381	381	381	381	381
Fly ash	179	179	179	179	179	179
Zeolite	0.0	0.0	0.0	15.0	15.0	15.0
Water [dm^3]	176.4	173.6	173.6	173.6	173.6	173.6
Sand 0/2 [kg]	–	600	600	600	490	490
Sand 0/4 [kg]	800	–	–	–	–	–
CERTYD 0/0.5 [kg]	–	100	100	100	80	80
CERTYD 1/4 [kg]	–	–	–	–	80	80
CERTYD 4/8 [kg]	490	490	490	490	490	490
SP [kg]	9.02	11.2	11.2	11.5	11.5	13.7
EW [kg]	–	–	59.0	59.01		65.0
EP [kg]	63.7	88.5	–	–	97.5	–

Test methods

Self-consolidating concrete should satisfy flowability, filling ability and segregation resistance ability in its fresh state. In this research the recommendations given in EFNARC (2005) were applied to assess the properties of LWASCC in the fresh state. Immediately after mixing the following properties of fresh LWASCC were evaluated: slump-flow, time required to reach 500 mm of slump-flow T_{500} and passing ability (confined flowability) using L-box (H_2/H_1). The tests were repeated after 60 min (slump-flow and T_{500}) and 80 min (L-box). The visual stability index (VSI) was used to assess the degree of segregation of mixtures. After slump-flow test, visual inspection of the concrete mixture is made by observing the distribution of the coarse aggregate within the concrete mass, the distribution of the mortar fraction particularly along the perimeter, and the bleeding characteristics. There are four classes of stability, determined on the basis of a visual assessment (ACI 237R-07:2007; Gołaszewski & Szwabowski, 2011).

All SCC specimens were cast without hand compaction or mechanical vibration into cubic molds of 100 mm for compressive strength and cubes of 150 mm for split tensile strength. After casting, the specimens were covered with plastic sheets and left at room temperature for 24 h. They were then demoulded and transferred to the water tanks (20 ±1°C) until testing. The compressive strength was determined after 2, 7 and 28 days. After 28-day splitting tensile strength was tested and specimens were oven dried for bulk density and water absorption measurements.

Results and discussion

Properties of fresh LWASCC with CERTYD aggregate are presented in Table 3. Based on VSI all mixtures were classified as class 0 (highly stable) or 1 (stable). The image of FA_2_EP mixture (class 0) is presented in Figure 3a. The uniformity of LWA distribution was confirmed after splitting (Fig. 3b). It is evident from the results that all mixtures are in conformity with (EFNARC, 2005), however FAZ_3_EP mix is not suitable for reinforced structures, because $H_2/H_1 < 0.80$ in L-box test. After 1 h mixes with higher replacement of natural sand by CERTYD sand (FAZ_3_EP and FAZ_3_EW) lost self-compacting ability. The values of T_{500} are much higher than usually obtained for normal-weight SCC. This may be contributed to the lower density of aggregate and thus low dynamic energy of the mixtures. With the increase of the flow time the mixtures are more likely to exhibit thixotropic effects, which may be helpful in limiting the formwork pressure or improving segregation resistance. Negative effects may be lower quality of surface finish (blow holes) and sensitivity to stoppages or delays between successive lifts (EFNARC, 2005).

It is evident from the result obtained for FA_2_EW and FAZ_2_EW that the increase of powder contents by adding zeolite, which resulted in the increase of paste contents, improved the properties of concrete in the fresh state: slump-flow increased and mixture retained its flowability after 60 min, T_{500} time was shorter at 10- and 60-minute test. When natural sand was partially substituted by fine CERTYD sand (FA_1_EP *versus* FA_2_EP) slump-flow increased, especially after 60 min, and passing ability improved. These results are in accordance with other authors' studies (Juradin et al., 2012).

TABLE 3. Properties of fresh concretes; slump flow and T_{500} were tested after 10 and 60 min, L-box test was performed after 15 and 80 min

Mix ID	Time of testing [min]	Slump-flow [mm]	T_{500} [s]	L-box H_2/H_1 [-]	Bulk density [kg·dm^{-3}]
FA_1_EP	10/15	770	8.4	0.88	2 058
	60/80	715	25.0	0.88	
FA_2_EP	10/15	775	8.6	0.98	1 945
	60/80	770	16.4	1.00	
FA_2_EW	10/15	750	19.4	0.81	1 964
	60/80	725	24.0	0.94	
FAZ_2_EW	10/15	790	15.0	0.93	1 978
	60/80	785	15.4	0.95	
FAZ_3_EP	10/15	735	9.6	0.68	1 872
	60/80	400	–	–	
FAZ_3_EW	10/15	750	17.9	0.93	1 908
	60/80	–	–	–	

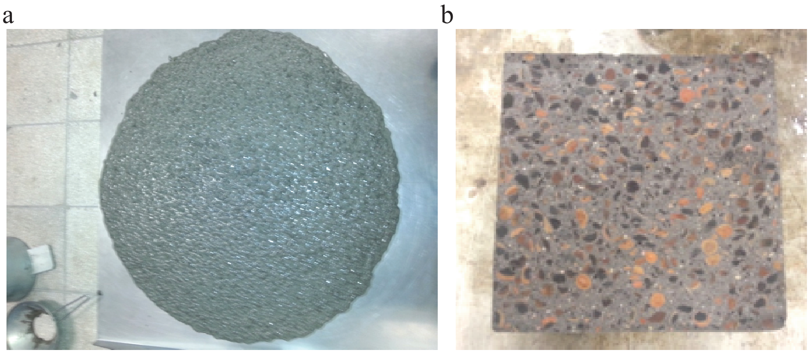

FIGURE 3. a – slump flow of FA_2_EP mixture; b – aggregate distribution in cube 150 mm after splitting, FA_2_EP

Figure 4 compares how aggregate preparation affected workability of individual mixes up to 60 min. The better results were obtained when aggregate was coated with cement paste (FA_2_EP and FAZ_3_EP) – the slump-flow loss was lower and the T_{500} time was shorter. Partial substitution of natural sand by fine CERTYD sand alone proved to be more effective than using fine and coarse light-weight sand. Mixes containing 1/4 mm LW sand did not exhibit self-compacting properties after 60 min.

The hardened concrete properties are listed in Table 4. Bulk densities of all concretes were in the range 1,816–1,957 kg·m^{-3}, thus they can be qualified to density class D2.0. The development of compressive strength gain is presented in Figure 5. The ultimate strength tested on 100 mm cubes ranged from 58.8 to 71.7 MPa. The highest compressive strength, regardless the age of specimens, was achieved by FA_1_EP concrete, where only coarse LWA was used. Considering aggregate preparation, it is evident that compressive strength at 28 days is slightly higher when water was used for pre-wetting, though at earlier terms (2 and 7 days) the situation is opposite and favors paste impregnation. This increase in strength may be due to the internal self-curing of concrete resulting from the pre-saturation of CERTYD

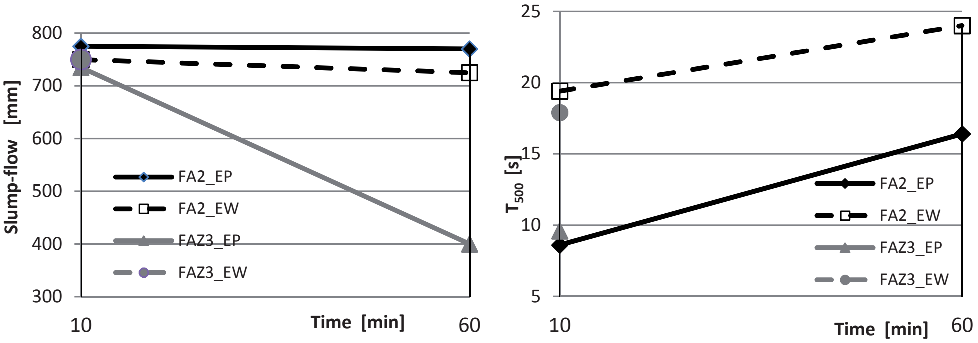

FIGURE 4. Influence of pre-wetting method on slump-flow and T_{500}

TABLE 4. Properties of hardened concretes

Mix ID	Time of testing [days]	Compressive strength [MPa]		Splitting tensile strength [MPa]	Water absorption [%]	Oven dry bulk density [kg·dm^{-3}]
		mean	*SD*			
FA_1_EP	2	39.7	1.4	–	3.47	1 940
	7	51.2	1.2	–		
	28	71.7	6.2	2.92		
FA_2_EP	2	33.2	2.0	–	4.88	1 848
	7	47.5	2.2	–		
	28	58.8	2.7	3.45		
FA_2_EW	2	33.6	1.7	–	6.04	1 874
	7	48.1	5.1	–		
	28	63.4	1.9	4.01		
FAZ_2_EW	2	28.8	1.1	–	4.75	1 957
	7	50.3	4.5	–		
	28	66.7	5.5	3.46		
FAZ_3_EP	2	34.8	1.5	–	5.78	1 847
	7	49.1	2.2	–		
	28	61.3	3.3	3.65		
FAZ_3_EW	2	28.4	0.6	–	6.34	1 816
	7	47.9	3.2	–		
	28	62.5	4.2	2.53		

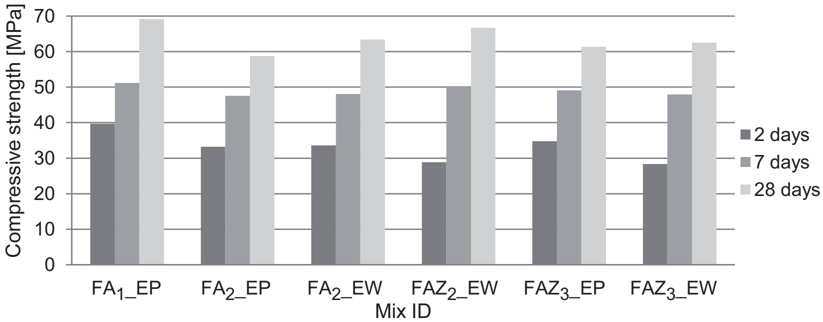

FIGURE 5. Compressive strength development of LWASCC

aggregate (Rajamanickam & Vaiyapuri, 2016). The additional pozzolanic reaction resulting from zeolite incorporation caused strength increase after 7 and 28 days (FA_2_EW compared to FAZ_2_EW). The splitting tensile strength ranged from 2.53 to 4.01 MPa, but no tendency considering aggregate preparation or type of fine aggregate can be determined.

Water absorption of the tested LWASCC was in the range 3.5–6.3%, which is comparable with normal-weight concrete properties. Lower absorption was achieved when paste impregnation was applied, because the thin film of cement paste protected porous aggregate grains from water penetration.

Conclusions

It is possible to produce structural LWASCC with CERTYD sintered fly ash aggregate. All concretes maintained air dry density below 2,000 kg·m^{-3} and compressive strength ranged from 58.8 to 71.7 MPa. Partial replacement of natural sand by fine CERTYD sand (0/0.5 mm) improved filling and passing abilities of fresh concrete, also reduced slightly the bulk density. However, it resulted in compressive strength loss by 12–18%. In terms of both fresh and hardened concrete properties, it is more favorable to use only fine CERTYD sand as substitution of natural sand. Considering fresh concrete properties, paste impregnation of LW aggregate is more efficient than saturation with water.

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Summary

Lightweight self-compacting concrete with sintered fly ash aggregate. The article presents the results of research assessing the possibility of making LWSCC from the locally produced sintered fly ash aggregate CERTYD. Two methods of preliminary LWA preparation were applied: pre-soaking with water and coating with a film of cement paste. The following properties of fresh LWSCC were evaluated: slump-flow, time T_{500} and passing ability using L-box. Partial replacement of natural sand by fine LW sand (0/0.5 mm) improved filling and passing abilities of fresh concrete, reduced slightly the bulk density, but it resulted in compressive strength loss by 12–18%. In terms of both fresh and hardened concrete properties it is more favorable to use only fine LW sand as natural sand replacement. Considering fresh concrete properties paste impregnation of LW aggregate is more efficient than saturation with water.

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