Proceedings of the Creative Construction Conference (2023)
Edited by: Miroslaw J. Skibniewski & Miklos Hajdu
https://doi.org/10.3311/CCC2023-016

Keszthely, Hungary
20-23 June 2023

IMPACT OF FLUIDIZED BED FLY ASH ON STRENGTH DEVELOPMENT OF SELF-COMPACTING CONCRETE

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Abstract

The use of self-compacting concrete (SCC) instead of traditional vibrated concrete has many advantages, which are most evident through the increased efficiency of SCC concrete under the influence of the environment. However, its use requires careful planning of concrete works and careful optimization of concrete mix design. SCC usually includes large amount of fine particles which ensure cohesiveness of the mixture and provide enough excess paste which is necessary for achieving adequate flow properties. When pulverized coal fly ash is used as a fine mineral additive, its spherical particles reduce water demand, and slow pozzolanic reactions reduce permeability and this leads to increased durability. Nowadays, pulverized coal combustion technology is being replaced by combustion in a circulating fluidized bed, which is characterized by lower energy consumption. Circulating fluidized bed fly ash particles are irregularly shaped and differ in chemical composition from pulverized coal fly ash. In this paper the possibility of designing SCC with the addition of circulating fluidized bed fly ash is being investigated. SCC mixes with different amounts of fly ash were designed and its properties in the fresh state were tested using slump-flow, J-ring and L-box measurements. Compressive strength was tested in the period from 2 days to 90 days to evaluate the effect of circulating fluidized bed fly ash on strength development.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2023.

Keywords: fly ash, limestone quarry dust, supplementary cementitious materials, self-compacting concrete

1. Introduction

Pulverized coal fly ash has gained considerable importance as a supplementary cementitious material due to its pozzolanic properties, but also due to the improved workability of concrete attributed to the spherical shape and plain surface of ash particles. Nowadays, circulating fluidized bed combustion technology is being more widely accepted as a method for production of heat and electrical energy because it is more energy efficient. In conventional pulverized coal-fired boilers, combustion takes place at temperatures between 1150 °C and 1750 °C which results in the melting of the majority of the minerals contained in the coal which is crucial for the formation of spherical particles [1]. In fluidized bed combustion the temperature of combustion is below the melting point (up to 900 °C). Because of lower temperature of combustion and interaction of coal with bed material, fluidized bed fly ash is more crystalline and irregularly shaped [2].

Utilization of fluidized bed fly ash in building materials has been widely investigated during the last decade [3,4]. It was shown that these ashes compared to pulverized coal fly ash poses self-cementitious properties [3,4,5]. Increasing the content of fluidized bed fly ash usually increases the water demand of the mix [6,7]. When used as a cement replacement, especially at higher replacement ratios it decreases strength but at lower dosages strength could also increase which is attributed to the denser microstructure [3,4,7]. The filling effects are also used to explain reduced permeability and improved durability of concrete made with fluidized bed fly ash [8,9,10].

The application of fluidized bed fly ash is currently outside the scope of the standard for fly ash for concrete (EN 450-1:2012). It may be used as a supplementary cementitious material however, its performance as concrete pozzolan is not yet well established [1], probably due to its high variation in chemical composition depending on the source of fuel [3]. In this work possibility of producing SCC with circulating fluidized bed fly ash is being investigated. Mixes with different amount of fly ash used as a cement replacement and/or filler were tested using standardized methods for SCC. Besides fresh concrete properties impact of fly ash on compressive strength development has been evaluated.

2. Materials and methods

2.1. Characterization of component materials

Cement used was Portland cement type CEM I 52,5 N (CEM I) according to classification in European standard EN 197-1:2011. Limestone quarry dust (LQD) originated from the same quarry as the aggregate used in this work. LQD is a by-product generated during mining and crushing processes of aggregate production. The problem of generation of excess amounts of LQD is often present at aggregate crushing facilities. It is usually possible to influence the amount of LQD generated by optimization of crushing technology [11]. LQD requires adequate handling and storage in order to reduce the pollution of the surrounding areas by small airborne particles. LQD had more than 85 % of particles passing the 0,063 mm sieve (Fig. 1.) as determined by air jet sieving method (EN 933-10:2009) and in this work it was used as filler for design of SCC. Fly ash (FA) originated from thermal power plant Stanari located in the central part of Bosnia and Hercegovina. Power plant uses lignite coal as a fuel which is incinerated at ≈ 850 °C using circulating fluidized bed combustion technology. Chemical and physical properties of this FA have already been presented in [12]. Pozzolanic oxide content (SiO_2+Al_2O_3+Fe_2O_3) of FA is 78,85 % [12] which indicates its potential to serve as a cement replacement material. It also has finer particles than cement with median particle size of 18,8 µm (Table 1). The particle size distribution (PSD) of powder materials (CEM I, LQD and FA) is shown in Fig. 1. The PSD of CEM I and FA was analysed by a laser diffraction method using a dry measurement (Shimadzu SALD 3101 Instrument) while the PSD of LQD was analysed by air-jet sieving method. Density of powder materials was determined according to standard ASTM C188-17 (Table 1).

Water demand of powder represents the minimum amount of water necessary to mix with powder to form a cohesive paste. At this state bonds between solid particles are strongest and maximum packing density is achieved [13,14]. Water demand and packing density are both simple to measure and can be used to qualitatively estimate effects of adding mineral admixtures on density and workability of the concrete. Different methods have been proposed for evaluation of water demand of powders [15]. In this work minimum water requirement was determined by combined use of standard consistency test (EN 196-3), mini-slump test [16] and visual observation. It was determined that the water requirement of FA is approximately three times of that of CEM I or LQD (Table 1). Packing density of each powder was determined by measuring mass of the sample compacted in the cylinder mould with a volume of 70 cm^3 and then volume of solid particles is calculated from known data about water/powder ratio and densities of water and powder. It was determined that LQD had the highest packing density and the lowest packing density was measured for FA (Table 1).

Aggregate used was crushed limestone. Three size fractions 0/4 mm, 4/8 mm and 8/16 mm were used for making concrete. Particle size distribution of aggregate is presented in Fig.1. Water absorption was 0,6 %, 0,4 % and 0,3 % for fractions 0/4 mm, 4/8 mm and 8/16 mm respectively. The average density of aggregate was 2,68 kg/dm^3. Superplasticizer used was MasterEase 7007 from Master Builders.

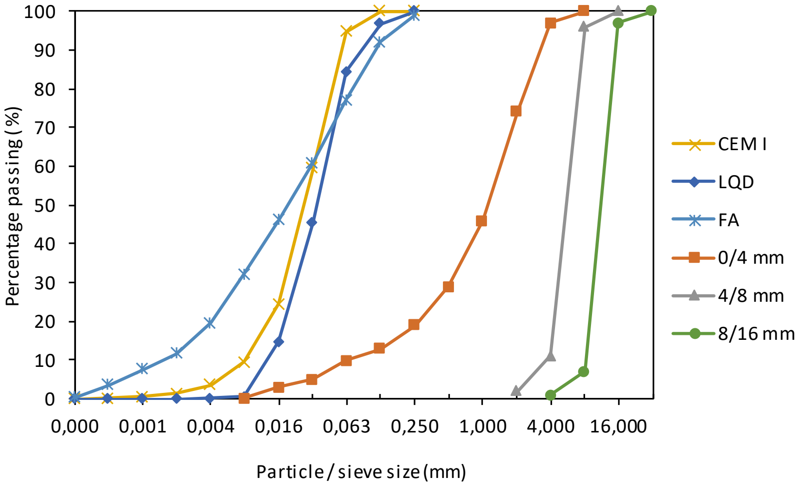

Fig. 1. Particle size distributions of powders and aggregates

Table 1. Physical properties of cement, limestone quarry dust and fly ash

Property	CEM I 52,5 N	Limestone quarry dust	Fly ash
Median, d_{50} (µm)	26,5	33,7	18,8
Density (g/cm^3)	3,01	2,72	2,39
Water requirement (-)	0,28	0,22	0,75
Wet packing density (-)	0,577	0,647	0,385

2.2. Concrete mix design and testing methods

One of the goals of this work was to design mixes that will have reduced cement content by replacing it with FA while meeting the requirements for SCC. Another goal was to maximize the use of both LQD and FA since considerable quantities of both materials are currently being landfilled. Concrete mix compositions are given in Table 2. Mixes M1-M8 are designed with the same powder content (CEM I+LQD+FA) of 580 kg per 1 m^3. Both CEM I and FA were treated as binder and mixes were designed with water/binder (w/b) ratio of 0,4, 0,45 and 0,5. Mix M1 has been selected as reference and was made without FA. In mixes M2 and M3 CEM I have been partially replaced with LQD. Mixes M4 and M5 were made with w/b ratio of 0,4. In mix M4 50 % of LQD was replaced with FA while in mix M5 cement was also partially replaced with FA. Mixes M6-M8 were made with w/b ratio 0,45 and different amounts of CEM I replaced by FA. Mix M9 has been designed with powder content of 315 kg per 1 m^3 with an aim to maximally reduce cement content while maintaining SCC properties. To avoid segregation in mix M9 aggregate particle size distribution has been modified compared to mixes M1-M8 by increasing the percentage of 0/4 mm aggregate fraction. Quantity of superplasticizer in mixes was adjusted to achieve adequate flowability required for SCC.

The mixing of the concrete was performed in a compulsory mixer with a capacity of 75 litres. Before mixing, all constituents were conditioned in a laboratory for approximately 1 day to equilibrate temperature differences between constituents. The mixing procedure similar to that described in [17] was followed. Fine and coarse aggregates were first homogenized in a mixer and shortly after about one third of the mixing water was added and mixed for 30 seconds. Then cement and mineral additive were added and mixed for another 30 seconds and the second third of water was added and mixed for one minute. The superplasticizer dissolved in remaining water was introduced into mixer and mixed for another two minutes and then left for a two-minute rest. Concrete was then mixed for additional two minutes to complete the mixing sequence.

In the fresh state temperature and density of concrete were measured. Density was measured using pressure method on a sample with volume of 8 litres. Standardized tests for self-compacting concrete were used to evaluate flowability, viscosity, passing ability and segregation resistance. Flowability was evaluated by slump-flow test according to standard EN 12350-8:2019, viscosity was evaluated by measuring t_{500} time in slump-flow test and by V-funnel test described in EN 12350-9:2010. Passing ability was evaluated by L-box test with 3 bars (EN 12350-10:2010) and by J-ring with 12 bars (EN 12350-12:2010). Segregation resistance was evaluated by sieve segregation test (EN 12350-11:2010).

Table 2. Concrete mix composition (quantities per 1 m^3 of concrete).

Mix Designation	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**
CEM I (kg)	400	355	320	400	350	400	350	300	234
Water (kg)	160	160	160	196	196	221	221	221	200
Superplasticizer (kg)	8,5	10,3	11,0	12,0	13,8	10,2	9,8	9,8	4,7
LQD (kg)	180	225	260	90	90	90	90	90	-
FA (kg)	-	-	-	90	140	90	140	190	81
CEM I+LQD+FA (kg)	580	580	580	580	580	580	580	580	315
Water/cement ratio	0,40	0,45	0,50	0,49	0,56	0,55	0,63	0,74	0,85
Water/binder ratio	0,40	0,45	0,50	0,40	0,40	0,45	0,45	0,45	0,63
Water/powder ratio	0,28	0,28	0,28	0,34	0,34	0,38	0,38	0,38	0,63
Aggregate 0-4 mm (kg)	941	941	941	877	872	843	838	833	1248
Aggregate 4-8 mm (kg)	342	342	342	319	317	307	305	303	249
Aggregate 8-16 mm (kg)	428	428	428	399	397	383	381	378	341

The concrete compressive strength was tested on concrete cubes with a side length of 150 mm at 2, 7, 28 and 90 days of age according to standardized procedure (EN 12390-3:2019). All specimens were cast without compaction and vibration. After casting, the specimens were kept covered in the laboratory for 24 h until demoulding to reduce water evaporation. Then, the specimens were placed in a water bath at temperature of 20 ± 2 °C.

3. Results and discussion

3.1. Fresh concrete properties

Results of fresh concrete properties are presented in Table 3. Temperature of fresh concrete varied between 23,5 °C and 28,7 °C. These variations are partly caused by initial temperature differences in the constituents between mixes due to variation of air temperature in the laboratory. It can also be seen that mixes M6-M8 made with highest water content had lowest initial temperature which indicates that these temperature variations are also caused by increased heat capacity of these mixes. Increased water content in mixes M4-M8 is also the main reason for reduced fresh concrete density.

Replacing CEM I with LQD led to increased water demand. As presented in Table 1 LQD has lower water demand and higher packing density than CEM I. Therefore, increased water demand could be explained by increased packing density of concrete which also led to increased cohesiveness of the mix. This is supported by increased density and compressive strength of mix M2. The same effect is not apparent in mix M3 because there is 80 kg/m^3 less binder compared to mix M1 and density of LQD is lower than that of cement (Table 1). Segregation resistance measurement shows that replacing CEM I with LQD increased likelihood of segregation (class SR1, see Table 4).

In mixes containing FA it was impossible to achieve adequate flowability of concrete without increasing water content. This is the reason why mixes M4 and M5 were designed with increased amount of water compared to reference mix. Both mixes had increased passing ability as determined by J-ring and L-box test and had good segregation resistance (Table 3 and Table 4). Increasing the amount of FA required further increase in the dosage of the superplasticizer. During trials there was also an attempt to produce mix with 190 kg/m^3 of FA and 196 kg/m^3 of water but it was impossible to achieve required workability regardless of the dosage of the superplasticizer.

Further increase of water content in mixes M6-M8 enabled reduction of the superplasticizer dosage while maintaining good segregation resistance and passing ability. All mixes made with powder content of 580 kg/m^3 containing FA had very good passing ability according to J-Ring test results (Table 3 and Table 4).

Mix M9 could be classified as eco-concrete because it was made with very low cement and powder content [16,18]. Mix M9 had low viscosity and good segregation resistance while its passing ability was lower compared to mixes with high powder content containing FA (Table 3, Table 4).

Table 3: Properties of fresh concrete

Mix Designation	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**
Temperature (°C)	27,2	28,7	27,0	26,0	25,5	23,5	24,8	25,0	28,0
Fresh density (kg/m^3)	2420	2430	2410	2350	2365	2343	2310	2310	2360
Slump flow, SF (mm)	690	620	680	700	700	740	630	650	720
SF t_{500} (s)	2,5	2,0	2,3	2,0	3,5	1,0	2,4	2,3	1,1
V-funnel (s)	13,5	13,0	11,5	10,5	15,5	5,0	10,0	13,0	4,7
J-ring - 12 PJ (mm)	17	12	9	9	9	3	6	8	14
J-ring SF (mm)	690	680	700	760	760	770	640	660	690
L-box PL2 (-)	0,84	0,82	0,88	0,94	0,93	1,00	0,86	0,89	0,83
GTM SR (%)	7	19	19	12	12	13	6	7	5

Table 4: Categorization of SCC according to EN 206:2021:2013+A2:2021

Mix Designation	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**
Flowability - Slump flow, SF (mm)	SF2	SF1	SF2	SF2	SF2	SF2	SF1	SF1	SF2
Viscosity -SF t_{500} (s)	VS2	VS1	VS2	VS1	VS2	VS1	VS2	VS2	VS1
Viscosity - V-funnel (s)	VF2	VF2	VF2	VF2	VF2	VF1	VF2	VF2	VF1
Passing ability - J-ring - 12 PJ (mm)	×	×	PJ1	PJ1	PJ1	PJ1	PJ1	PJ1	×
Passing ability L-box PL2 (-)	PA2	PA2	PA2	PA2	PA2	PA2	PA2	PA2	PA2
Segregation resistance - GTM SR (%)	SR2	SR1	SR1	SR2	SR2	SR2	SR2	SR2	SR2

3.2. Compressive strength

Compressive strength test results are presented in Fig. 2. Compressive strength results in Fig. 2 represent average strength obtained on three specimens. Based on the 28-day strength mixes M1, M2, M4 and M5 could be classified as high strength concrete according to the European standard EN 206:2021. Mixes M1, M4 and M5 are made with w/b ratio of 0,4 and mix M2 had w/b ratio 0,45. Mix M2 also has the highest 90-day compressive strength of 90,7 MPa. As already mentioned, this supports the conclusion that, although cement content is reduced improved packing density led to the higher compressive strength of mix M2. Mixes M3, M6, M7 and M8 fulfil requirements for concrete strength class C50/60 and mix M9 can be classified as C30/37 strength class according to EN 206:2021.

Estimation of the potential reactivity of FA is usually based on its chemical composition. The contribution of pozzolanic reactions to strength becomes significant after 7 or 28 days of hydration [19]. All mixes with FA (M4-M9) had strength increase in the period from 28-90 days approximately equal to mixes made without FA. However, compressive strength of mixes M6-M8 shows that reduction of the cement content of 100 kg/m³ and replacing it with FA had a very little effect on compressive strength. In fact, highest 90 day compressive was determined on samples from mix M8 which had the highest replacement of CEM I with FA. Replacing 50 kg/m³ of CEM I with FA in mix M5 compared to mix M4 resulted in slower initial strength development but in the period between 7-28 days faster strength development was measured in mix M5. This shows that FA had significant contribution to compressive strength of concrete which could be attributed to the pozzolanic activity of FA.

In Fig. 3 linear regression results are given for correlation of 28-day compressive strength with w/c and w/b ratio. Based on coefficients of determination R^2 there is a higher level of correlation between compressive strength and w/b ratio (R^2=0,89) then between compressive strength and w/c ratio (R^2=0,72). This also shows that FA had a large contribution to compressive strength of concrete mixes analysed in this research.

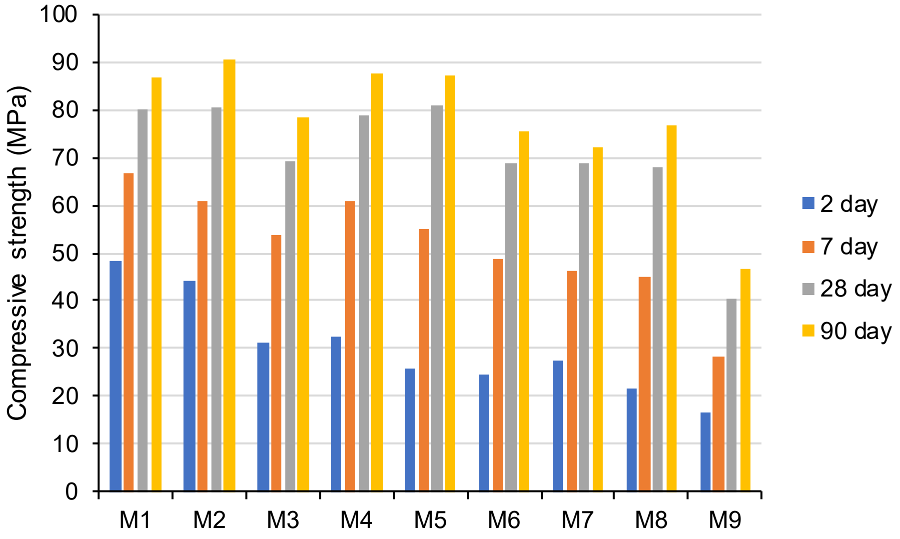

Fig. 2. Compressive strength development

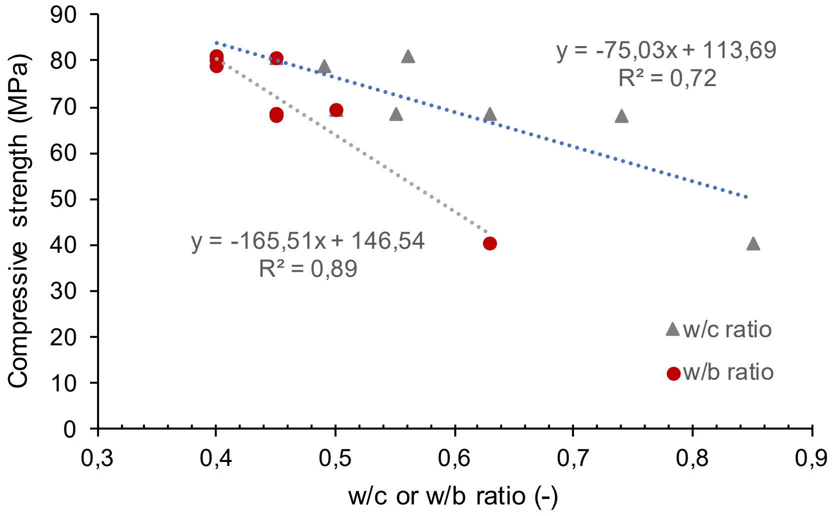

Fig. 3. Correlation of 28-day compressive strength with w/c ratio and w/b ratio

4. Conclusions

Addition of circulating fluidized bed fly ash in concrete as a cement replacement and a filler in SCC concrete resulted in increased water demand. Characterisation of powder materials showed that the water requirement of FA is approximately three times of that of CEM I or LQD. Increased water demand can be attributed to the irregular shape of FA particles and to the increased fineness compared to CEM I and LQD. Adjusting the water content and the amount of superplasticizer in the mix enabled production of SCC with adequate flowability. Incorporation of FA contributed to the increased passing ability of SCC as determined by J-ring test.

Replacing up to 100 kg/m^3 of CEM I with FA didn't reduce 28-day or 90-day compressive strength, although somewhat lower strengths were present at 2 and 7 days. This could be related to the slow pozzolanic reactions of FA.

SCC with very low amount of cement (234 kg/m^3) and the total powder content of 315 kg/m^3 was achieved with 28-day compressive strength of 40 MPa. For higher strength mixes with larger amount of powder further investigation should try to reduce the superplasticizer dosage necessary achieve targeted fresh and hardened concrete properties.

Acknowledgements

This research is supported by project entitled ''Concrete development for sustainable construction in the marine environment'' (KK.01.2.1.02.0093), funded by the European Regional Development Fund.

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