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Influence of biomass fly ash blended with bituminous coal fly ash on the properties of concrete

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Abstract: There is a growing concern over the insufficient utilization of by-products from biomass combustion in Poland. Moreover, the concrete industry faces the threat of inadequate supplies of good quality coal fly ash. One way of enhancing the utility of biomass fly ash is blending it with coal fly ash. The aim of this study is to assess the influence of blending biomass fly ash with coal fly ash on the properties of concrete. A 20% replacement of blended fly-ash enhanced the 90-days compressive strength results of concrete by 10% when compared to the results of specimens with the same amount of non-blended biomass fly ash.

Keywords: cement, fly ash, biomass, concrete

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Introduction

The importance of renewable energy sources is growing in the Polish energy industry. In 2015 almost 10% of energy produced in Poland was obtained from firing solid biomass, mainly wood and forestry biomass (Główny Urząd Statystyczny, 2017a). This situation provides a new challenge for the economy to utilize the by-products of biomass firing that are currently unfit for reuse in many industries.

Usage of coal fly ash in the construction industry has a long tradition dating back to the 1970's. The efficiency of its utilization is high – in 2016 86.7% of coal fly ash produced in Poland was recycled, 11.3% neutralized, and 2% temporally stored (Główny Urząd Statystyczny, 2017b). However, there is growing concern about the availability of good quality fly ash for the concrete and cement industry (Lelusz, 2012).

The PN-EN 450-1 standard currently allows conventional combustion coal fly ash and co-combustion fly ash as a concrete additive (PN-EN 450-1:2012). The chemical and physical properties of biomass fly ash varies and are dependent on the source of biomass and its combustion conditions (Vassilev et al., 2012; Jaworek et al., 2013). Even though, in many cases, the properties of biomass fly ash can be similar to type C fly ash (Wang et al., 2008).

An addition of 20% binder's mass (b.m.) of biomass fly ash can retard and diminish the thermal hydration peak of cement binder (Rajamma et al., 2009; Lelusz, 2016). A 20% b.m. addition of biomass fly ash can decrease the flow of cement mortar by up to 15% (Rajamma et al., 2015; Popławski & Lelusz, 2018). There are mixed reports on the pozzolanic properties of biomass fly ashes. The mechanical properties of cement composites can be enhanced with a 10-20% b.m. addition of woody fly-ash (Rajamma et al., 2009; Teixeira et al., 2019).

To improve its properties fly ash can be activated by either chemical, physical or mechanical means (Doudart de la Grée et al., 2016). The utility of biomass fly ash for usage in cement composites can be enhanced by blending it with coal fly ash (Wang et al., 2008).

The aim of this study was to assess the influence of biomass fly ash, coal fly ash and biomass fly ash blended with coal fly ash on the density of fresh mixture, compressive strength, density, depth of penetration of water under pressure, and water absorption of hardened concrete.

1. Materials, experiment design and test methods

1.1. Materials

Commercial CEM I 42.5R cement that conformed to the requirements of the PN-EN 197-1 standard was used as a binder (PN-EN 197-1:2012). The biomass fly ash was taken from fluidized bed combustion (750°C) of woody material, while coal fly ash was taken from conventional combustion (1150°C). Both fly ashes came from the local combined heat and power plant. Their grain size distributions are presented in Table 1 and their properties in Table 2. Natural sand and aggregate with a maximum diameter of 16 mm was used. Tap water was used for mixing.

Table 1. Grain size distributions of fly ashes (*own research*)

Fly ash	2-1 mm	1-0.5 mm	0.5-0.25 mm	0.25-0.125 mm	0.125-0.63 mm	0.63-0.045 mm	< 0.045 mm
Biomass fly ash	0.0%	0.2%	31.7%	31.2%	10.5%	9.9%	16.5%
Coal fly ash	0.0%	0.0%	0.0%	0.6%	17.4%	12.3%	69.7%

Table 2. Properties of fly ashes (*own research*)

Property	PN-EN 450-1 requirements	Biomass fly ash	Coal fly ash
SiO_2 content	≥ 25%	25.0%	27.2%
Loss on ignition	≤ 9%	3.6%	12.4%
Fineness	≤ 40%	71.6%	29.3%
Pozzolanic activity index after 28 days	≥ 75%	71.0%	72.8%
Pozzolanic activity index after 90 days	≥ 85%	79.3%	96.4%

1.2. Mixture composition and specimen preparation

9 series of specimens with different amounts of either biomass fly ash (FA(B)), biomass fly ash blended with coal fly ash (FA(M)) or with only coal fly ash (FA(C)) were prepared. The replacement rate of cement by fly ash in the binder was either 20, 40 or 60% of binder's mass (b.m.). The amount of binder in 1 m^3 of mixture was 360 kg. Water to binder ratio (w/b) was 0.35. Control specimens (CEM I) without additives were prepared. The proportions of concrete mixtures are presented in Table 3. The specimens were cast in molds and compacted by vibration. They were demolded after 24 h, and stored in tap water at 20±2°C until the test date.

Table 3. Proportions of concrete mixtures (*own research*)

Series code	The proportions for 1 m^3 of concrete mix [kg]								
	Cement	Fly ash		Sand	Aggregate			Water	Super-plasticizer
		Biomass	Coal		2-4 mm	4-8 mm	8-16 mm		
FA(B)-20%	288	72	0	690	196	292	782	125	2.88
FA(B)-40%	216	144	0	690	196	292	782	125	2.88
FA(B)-60%	144	216	0	690	196	292	782	125	2.88
FA(M)-20%	288	36	36	690	196	292	782	125	2.88
FA(M)-40%	216	72	72	690	196	292	782	125	2.88
FA(M)-60%	144	108	108	690	196	292	782	125	2.88
FA(C)-20%	288	0	72	690	196	292	782	125	2.88
FA(C)-40%	216	0	144	690	196	292	782	125	2.88
FA(C)-60%	144	0	216	690	196	292	782	125	2.88
CEM I	360	0	0	690	196	292	782	125	2.88

1.3. Test methods

The fresh density was measured directly after compaction on three 100 x 100 x x 100 mm specimens for each series. Compressive strength was tested after 7, 28, and 90 days from mixing on three 100 x 100 x 100 mm specimens for each test date for each series. The compressive strength tests were performed in accordance with the PN-EN 12390-3 standard (PN-EN 12390-3:2019-07) and multiplied by 0.9 coefficient to the standard compressive strength value for data presentation and compressive strength class evaluation in accordance with the PN-EN 206 standard (PN-EN 206+A1:2016-12). Other tests were performed after 28 days. The water absorption was calculated as an amount of absorbed water mass compared to the mass of a specimen dried to constant weight, and expressed as a percentage value. Three 100 x 100 x 100 mm specimens from each series were used. The depth of penetration of water under pressure test were performed in accordance with the PN-EN 12390-8 standard (PN-EN 12390-8:2019-08) on three 150 x 150 x 150 mm specimens from each series. Statistical validation was carried out via ANOVA analysis in the Statistica software.

2. Results analysis

2.1. Fresh mixture density

While the difference in the type of fly ash and in the amount of fly ash were found statistically significant, the differences in fresh density values were small between series. The amount of fly ash in the binder marginally influenced the density of the fresh concrete mixture. With the increase of the replacement of cement by fly ashes, the density slightly decreased. The most noticeable difference between the lowest (20% b.m.) and the highest (60% b.m.) fly ash replacement rate was observed in the group of FA(C) specimens (Table 4).

Table 4. Fresh density test results and mean 28-days compressive strength values for each series with their compressive strength classes (*own research*)

Series code	Fresh density [g/cm^3]	Mean 28-days standard compressive strength [MPa]	Compressive strength class
FA(B)-20%	1.92	54.0	C40/50
FA(B)-40%	1.88	45.9	C30/37
FA(B)-60%	1.88	27.1	C16/20
FA(M)-20%	1.90	60.7	C45/55
FA(M)-40%	1.86	47.3	C30/37
FA(M)-60%	1.85	34.5	C25/30
FA(C)-20%	1.89	53.0	C35/45
FA(C)-40%	1.83	41.7	C30/37
FA(C)-60%	1.80	19.3	C12/15
CEM I	1.94	67.7	C50/60

The density of fly ash is lower than the density of cement, thus the density of fresh concrete may be affected by the increase in replacement of cement by fly ash. The coal fly ash had a finer grain size distribution than the biomass fly ash. It also had substantially higher loss on ignition value which could be attributed to a higher amount of porous unburned coal particles in the fly ash. Both parameters can decrease the workability of the concrete, especially with high replacement rates.

2.2. Compressive strength

The difference in the type and amount of fly ash and their interaction were found to be statistically significant for 7-days, 28-days and 90-days compressive strength results. With the increase in the replacement of cement by any type of fly ash the compressive strength of the concrete decreased. The type of fly ash influenced the replacement rate. In the case of the series with 20% b.m. replacement rate, specimens with blended fly ash FA(M) obtained higher compressive strength results compared to non-blended biomass fly ash FA(B) specimens at any given test date (Fig. 1a). The 28-days compressive strength of specimens with blended fly ash FA(M) were 12% higher than either the coal fly ash FA(C) or the biomass fly ash FA(B) specimens' results. The 90-days compressive strength results of FA(M)-20% specimens were about 7% lower than the result of the control specimens (CEM I) and 10% higher than the result of non-blended biomass fly ash FA(B)-20% specimens (Fig. 1d). The results of the series with 40% b.m. replacement rate of different types fly ash were more comparable to each other, with 90-days compressive strengths results around 60 MPa (Fig. 1b). In the case of 60% b.m. replacement rate of cement by fly ash, the 28-days compressive strength result of FA(M)-60% specimens was 72% higher than FA(C)-60% specimens' and 26% higher than FA(B)-60% specimens' result (Fig. 1c) which was also noticeable in the difference between compressive strength classes (Table 4). The 90-days compressive strength result of blended fly ash specimens were about 24% higher than the coal fly ash specimens' results.

The biomass fly ash and the coal fly ash exhibit different values of some key properties. While the amount of SiO_2 were comparable, the loss on ignition percentages were different (Table 2). Moreover, high levels of unburned carbon may negatively affect the pozzolanic activity index (Ferreira et al., 2016). The 28-days pozzolanic activity index of the coal fly ash might have met the 75% PN EN 450-1 threshold with a lower loss on ignition value. The 90-days pozzolanic indexes of both fly ashes clearly show pozzolanic properties of the coal fly ash and non-pozzolanic nature of the biomass fly ash. The grain size distribution of the biomass fly ash was coarser than the coal fly ash's (Table 1). The blending of the biomass fly ash with the finer coal fly ash might have resulted in a better packaging of fine particles in the concrete. That filler effect might explain higher 7-days and 28-days compressive strength results of the concrete specimens with 20% b.m. replacement rate of blended fly ash (FA(M)) in comparison to the results of the specimens with other fly ashes (Fig. 1a).

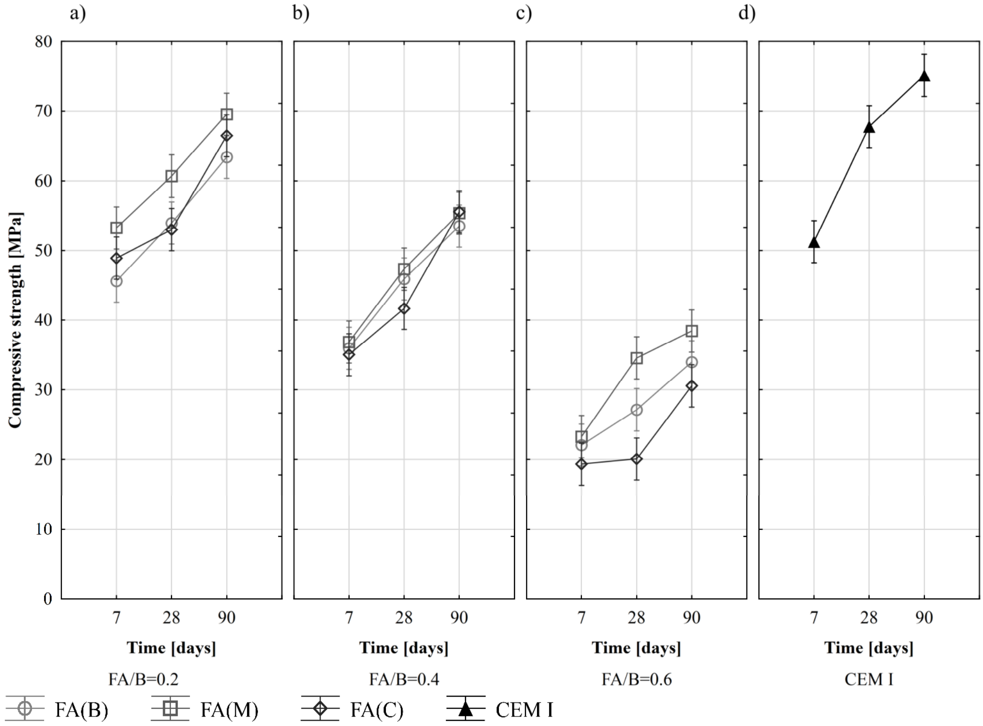

Fig. 1. Effect of biomass FA(B), blended FA(M) and coal FA(C) fly ash replacement at: a) 20% b.m., b) 40% b.m., and c) 60% b.m. replacement rate on compressive strength results; d) the compressive strength results of the control series (with ANOVA least mean values for all factors) (*own research*)

The 90-days compressive strength results of FA(M) specimens could be attributed to the pozzolanic reaction. With the increasing replacement rate of cement by the coal fly ash, the negative influence of the amount of unburned carbon on compressive strengths development was more evident, thus the results of FA(C)-60% specimens (Fig. 1c) and its compressive strength class (Table 4) were affected.

2.3. Density, water absorption and water penetration

The difference in the type and amount of fly ash and their interaction were found statistically significant, but their influence was hardly observable (Table 5). The results of specimens with 20% b.m. replacement rate of cement by any type of fly ash (water absorption around 3.7%) were similar to the result of CEM I specimens (3.5%). The result of FA(C)-60% specimens (4.9%) was noticeably higher than the result of the control specimens. No statistical influence and no clear influence of the replacement rate on depth of penetration of water was observed. A difference between the results of blended fly ash FA(M) specimens and non-blended biomass and coal fly ash specimens was observed. The difference in the type and amount of fly ash and their interaction were found statistically significant, but the change in either replacement rate of fly ash or in the type of fly ash marginally affected the density of concrete. The FA(C)-60% specimens had the lowest density result (Table 5). The results of other specimens were around 2.3 g/cm^3.

The lowest density result and the highest water absorption result were obtained on FA(C)-60% specimens which could be attributed to the high loss on ignition value. FA(M) specimens with the same replacement rate value obtained similar density and water absorption results to control specimens probably by mitigating the influence of unburned carbon in the coal fly ash. The lower than CEM I specimens' depth of penetration of water results for FA(M) specimens could be attributed to the better filler effect of blended fly ash.

Table 5. Density, water penetration and water absorption test results (*own research*)

Series code	Water absorption [%]	Water penetration [cm]	Density [g/cm^3]
FA(B)-20%	3.72	7.3	2.36
FA(B)-40%	3.49	9.8	2.34
FA(B)-60%	3.79	5.8	2.31
FA(M)-20%	3.73	5.5	2.33
FA(M)-40%	4.12	5.3	2.29
FA(M)-60%	3.80	6.0	2.27
FA(C)-20%	3.72	7.0	2.32
FA(C)-40%	3.93	6.3	2.27
FA(C)-60%	4.85	10.0	2.20
CEM I	3.47	6.0	2.36

Conclusions

The change in the type of fly ash did not affect fresh density results. The FA(C)-60% specimens had the lowest result. The FA(M) specimens performed as good or better than FA(B) and FA(C) specimens. The 90-days test result of the FA(M)-20% specimens were about 7% lower than the result of the control specimens and 10% higher than the result of specimens with the FA(B) fly ash at the same replacement rate. The specimens with any fly ash replacement had similar results of water absorption and density tests to the result of the control specimens. The results of FA(M) specimens were lower in the depth of penetration of water under pressure tests than the result of CEM I specimens.

The blending of fly ash enabled more effective utilization of fly ashes' unique properties. It might be considered a suitable route for property stabilization of biomass fly ash.

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