Impact of separated bottom ashes on the parameters of concrete mix and hardened concrete

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Abstract. Polish energy industry is based primarily on the combustion of coal in conventional boilers and increasingly in fluidised bed boilers. As a result of combustion, by-products are formed, such as fly and bottom ashes. In the case of fly ashes, a number of methods of utilising them have already been developed, e.g. for the production of cement, concrete and in other industries. With regard to bottom ashes, whose properties differ significantly from those of fly ashes, methods are still being researched for the possibility of their industrial application. Similarly to fly ashes, it seems reasonable to move in the direction of bottom ashes being used in the wider construction industry, including for the production of concrete.

This paper analyses the impact of the addition of bottom ashes obtained from hard coal combustion in conventional and fluidised bed boilers on the properties of fresh and hardened concrete. A concrete mix composition was developed by an experimental method, which was then modified with the use of bottom ashes. The impact of the substitution of cement and aggregates with bottom ash on the concrete properties was examined. For all the obtained series of concretes, tests were performed for the consistency of the fresh concrete using the concrete slump test, the compressive strength and tensile strength of the concrete after 3, 7 and 28 days of maturing and their absorption. The experiments have shown significant declines in the strength parameters of the concretes being analysed in the case of the substitution of cement with separated bottom ash. However, substituting relevant aggregate fractions with separated bottom ash resulted in an increase in both the compressive strength and the tensile strength in the analysed concretes.

1 Introduction

As a result of coal combustion, residues in the form of ash, soot and slag are produced. Ash is solid particles transported by gases and can be divided into two types: bottom ash and fly ash, with the latter being captured on electrostatic filters and bag filters. Ash consists primarily of oxides: silicon, aluminium, iron, calcium, magnesium, sodium, potassium, titanium and manganese oxides [1]. Their characteristics and quantity depends on both the properties of coal being burned, i.e. coal granulation, its caking properties, moisture content, and the combustion process technique and parameters, including the type of furnace, combustion temperature, thermal intensity of the combustion chamber, the air and flue gas flow parameters. It should be emphasised that the properties of ashes from conventional pulverised coal boilers [1] differ significantly from those of the ashes from fluidised bed boilers, which are characterized by e.g. the lack or negligible amount of glaze and unburned carbonaceous substance.

Polish energy sector is based primarily on coal and the signs are that this situation will not change any time soon [2]. Thus it seems important to develop comprehensive programmes for the management of combustion by-products produced during the production of energy in Poland. In the case of fly ashes, a number of methods of utilising them have already been developed, e.g. for the production of cement, concrete and in other industries [3]. With regard to bottom ashes, methods are being researched for the possibility of their industrial application. Similarly to fly ashes, it seems reasonable to move in the direction of bottom ashes being used in the wider construction industry. Currently, in the literature can be found some ideas for its application, e.g. in concrete technology in order to improve workability [4], durability [4,5] or sound absorption [6]. Also, as an aggregate in lightweight fly ash geopolymer concrete [7], as well as to improve the workability of high-strength mortar [8]. Nevertheless, because of the significant need to develop methods for utilization of bottom ashes, research work has been conducted to asses the impact of the addition of bottom ashes obtained from hard coal combustion in conventional and fluidised bed boilers on the properties of concrete mix and hardened concrete, the results of which are presented in this paper.

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DOI: 10.1051/e3sconf/20161000099

2 Characteristics of the used bottom ashes

The tests were conducted on the energy waste resulting from the combustion of coal in a fluidised bed boiler (PDF) and pulverised coal boiler (PDP), which were separated using a sieve with 0.63 mm mesh size. Particle size composition curves for the used ashes are shown in figure 1.

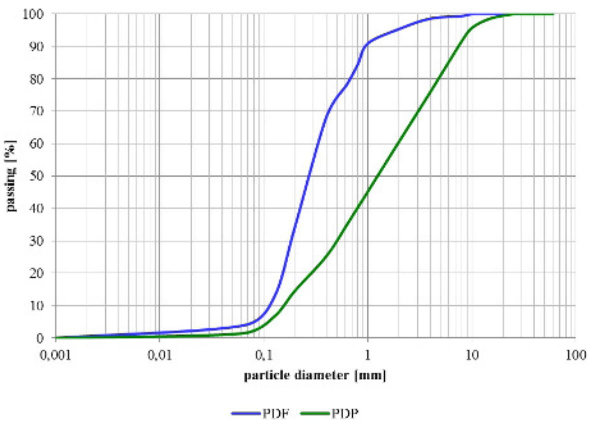

Figure 1. Particle size composition curves of bottom ashes.

The bottom ashes were characterised by a particle diameters of up to 10 mm for the bottom ash from the fluidised bed boiler (PDF) and 25 mm for the bottom ash from the pulverised coal boiler (PDP). The content of fractions below 0.63 mm in the bottom ashes was:

- for PDF: 78.3%
- for PDP: 35.0%

The significant differences in the particle size composition of the bottom ashes resulted from the coal combustion technology used in the boilers and the method of collecting this waste from the bottom of the furnace. The PDF ash contained mainly dust and sand fractions (74.2% and 21.1% respectively) and the bottom ash from the pulverised coal boiler was characterised by a larger particle diameters and contained dust fraction (29.8%), sand fraction (30.9%) and gravel fraction (39.3%).

The average density of the fluidised bed bottom ash (PDF) was 2.68 g/cm^3. The bottom ash from the pulverised coal boiler was characterised by lower density of 2.27 g/cm^3.

Figures 2 and 3 shows the content of the main chemical ingredients in the analysed ashes by particle size.

The chemical composition of the PDF ash did not differ from the other bottom ashes produced in fluidised bed boilers. A characteristic feature of the tested material was high CaO and SO_3 content, resulting from the process of flue gas desulphurisation. This is associated, in particular, with the addition of calcium sorbent into the boiler, the penetration of desulphurisation products into bottom ash and the residues of unreacted calcium sorbent. A high SiO_2 content in the bottom ashes results from the presence of quartz sand used as a fluidised bed material.

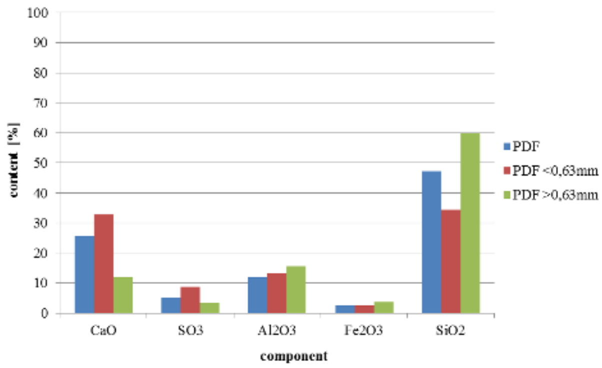

Figure 2. Content of the main ingredients in the PDF bottom ash by particle size.

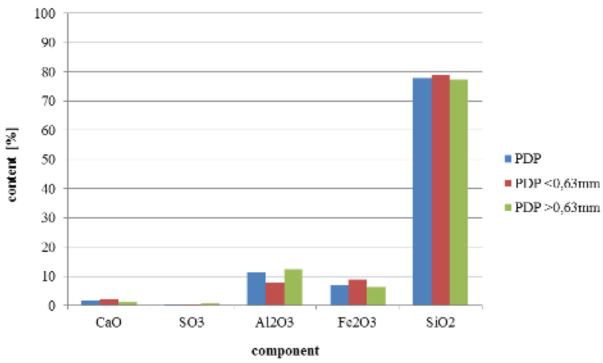

Figure 3. Content of the main ingredients in the PDP bottom ash by particle size.

The PDF ash fractionation caused the diversification of content of individual ingredients within a given fraction. The fraction below 0.63 mm contains considerably more CaO and SO_3 than the fraction with the particle size above 0.63 mm. In turn, the fraction above 0.63 mm contains greater quantities of Al_2O_3 and SiO_2. This situation – i.e. the low content of SO_3 (3,3%), the high content of silicon dioxide and oxides of iron and aluminium – can be very beneficial for the application of the PDF fraction >0.63 mm as an ingredient of concrete and also for meeting the requirements of building standards or obtaining appropriate technical approvals.

Loss on ignition of the PDF bottom ash was 4.4%. It was lower (3.6%) for a finer fraction and 5.3% for the fraction >0.63 mm. All these values meet the requirements of PN-EN 450-1: 2012: Fly ash for concrete [9], in which the maximum loss on ignition of ashes are set at 9%.

The main ingredients of the PDP ash was silica (77.7%), alumina (11.3%) and iron oxide (6.9%). Ash fractionation on a 0.63 mm sieve did not have a significant impact on the content of SiO_2 in the obtained fractions, but there were differences particularly for the content of Al_2O_3 (the fraction below 0.63 mm contained 7.8% and the fraction above 0.63 mm contained 12.3%). Quite clear differences can be seen in the organic matter content. The loss on ignition for the fraction below 0.63 mm was 2.7%, while for the fraction above 0.63 mm, it was as high as 11.5%. Such high loss on ignition may disqualify this fraction for the application as an additive in construction concretes because of the requirements set out for materials used in the manufacture of construction concretes.

3 Test plan

The aim of the tests was to determine the impact of the type and content of the two bottom ashes in cement-ash binder and aggregate particle size distribution on the properties of hardened concretes and concrete mixes. The bottom ashes resulted from coal combustion in the fluidised bed boiler (PDF) and pulverised coal boiler (PDP). Two waste fractions were used with a particle size above and below 0.63 mm. The addition of individual ash fractions was treated as a substitute for some of the cement in the binder or a substitute for the aggregate in the concrete mix.

For the preparation of various concrete mixes, CEM I 42.5R cement was used, whose characteristics are summarised in table 1. The cement was adequately protected from external influences throughout the period of its use.

Table 1. CEM I 42.5R cement properties

Properties	Value
Apparent density [Mg/m^3]	1.82
Setting start time [min]	570
Setting end time [min]	645
Compressive strength [MPa] - after 2 days - after 28 days	 14.99 46.60

Natural river aggregates in the form of sand and gravel were used to produce the concretes. The aggregates that were used to produce the aggregate mix for the tested concretes were sand with a nominal particle size of 0/2 mm and gravel with a nominal particle size of 4/16 mm. The entire aggregate composition used to make the analysed concretes was formulated based on own research on previously produced concrete mixes and the properties of separated fractions of PDF and PDP ashes (PDF>0,63, PDF<0,63, PDP>0,63, PDP<0,63) and non-separated ashes. As a result of the performed analyses and laboratory tests, it was decided to formulate the aggregate mix for concretes using the aggregate mixing mass ratios presented in table 2.

The composition of the B1 reference concrete was determined on the basis of the adopted amount of cement *c* and ratio *w/c*, which was established at 0.4. In addition, the amount of admixtures was determined experimentally in order to obtain a mix with certain rheological properties.

In the case of other mixes (B2–B8), an assumption was adopted regarding the constant *w/c* ratio, as for the reference mix. Therefore, in order to obtain adequate workability of the mixes with the addition of individual fractions of bottom ashes, it was necessary to use admixtures. It should be noted that the superplasticiser was dosed into the individual mixes in amounts that enabled to work them by laying them in moulds and thickening them in an appropriate manner. The composition of the reference mix was shown in table 3.

Table 2. The mass ratio of the aggregates used in the concrete.

Mix	Aggregate	Mass ratio
B1- reference mix	0/2 mm sand 4/16 mm gravel	32% 68%
B2 – 15% PDF>0.63 mass of sand and gravel	0/2 mm sand 4/16 mm gravel PDF>0.63	21% 64% 15%
B3 – 30% PDF>0.63 mass of sand and gravel	0/2 mm sand 4/16 mm gravel PDF>0.63	10% 60% 30%
B4 – 15% PDF<0.63 mass of cement	0/2 mm sand 4/16 mm gravel PDF<0.63	32% 68% 15% m of cement
B5 – 15% PDF (non-separated) mass of sand and gravel	0/2 mm sand 4/16 mm gravel PDF (non-separated)	27% 58% 15%
B6 – 15% PDP>0.63 mass of sand and gravel	0/2 mm sand 4/16 mm gravel PDP>0.63	21% 64% 15%
B7 – 30% PDP>0.63 mass of sand and gravel	0/2 mm sand 4/16 mm gravel PDP>0.63	10% 60% 30%
B8 – 15% PDP<0.63 mass of cement	0/2 mm sand 4/16 mm gravel PDP<0.63	32% 68% 15% m of cement

Table 3. Composition of the reference concrete mix.

Ingredients	kg/m^3	dm^3/m^3
CEM I 42.5R Cement	350	-
Water	-	140
Gravel	1387.5	-
Sand	653.1	-
Plasticiser	-	2.7
Superplasticiser	-	-

4 Testing the properties of concrete mixes

For each of the developed mixes, tests of consistency were performed using the concrete slump method, as per PN-EN 12350-2:2001 Testing fresh concrete. Part 2: Slump tests [10]. The properties of the concrete mixes were assessed each time by making a batch of concrete from which specimens were formed. The obtained results of the consistency tests are graphically presented in figure 4.

Based on the results of the tests of the impact of the applied bottom ashes on the rheological properties of fresh concrete mixes, it can be said that the impact is significant.

In the case of B1, B4 and B8 concrete mixes, mix consistency was obtained that corresponded to S4 class. For other mixtures, S1 class was obtained. It should be noted that in the case of concrete mixtures B2, B3, B5, B6 and B7 in order to obtain their workability it was necessary to use a superplasticiser. The used superplasticiser amounts in individual concrete mixes are shown in figure 5.

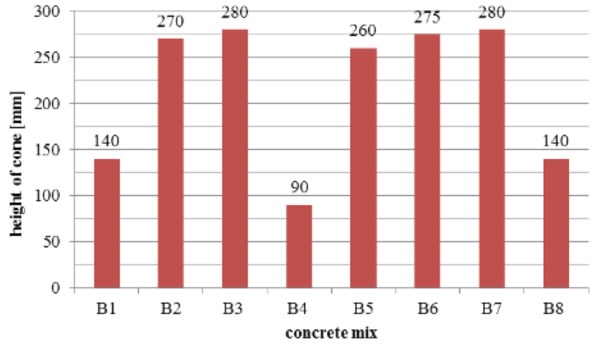

Figure 4. The height of the test cones for individual concrete mixtures.

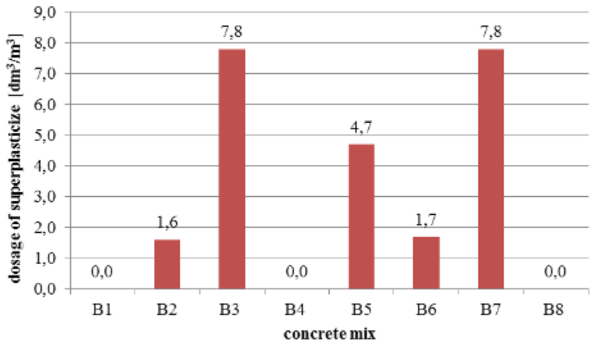

Figure 5. Usage of superplasticiser in individual concrete mixes.

It can be concluded that the use of separated bottom ashes with fractions >0.63 mm as a partial substitute for aggregate (B2, B3, B6 and B7) significantly reduces the wetness of the mixes. In order to obtain their adequate workability, it is necessary to use specialised admixtures.

Application of non-separated PDF fluidised bed bottom ashes (B5) as a substitute for part of the aggregate also resulted in a significant reduction of their workability.

In the case of the application of separated bottom ashes with fraction <0.63 mm as a partial substitute of cement (B4 and B8), one obtains a greater mix wetness, which is comparable to the reference mix (B1).

5 Hardened concrete tests

All the specimens from the analysed concretes were made as part of one-time mixing. 100 mm block specimens were formed in metal moulds. They were compacted on a vibrating table in accordance with PN-EN 12390-2:2001 Testing hardened concrete. Part 2: Making and curing specimens for strength tests [11]. Each time, specimen preparation times from one batch was approx. 30 minutes from the end of mixing. Specimens remained covered with a plastic film until demoulding, i.e. for a period of 28 hours. After demoulding, samples were placed over water in a closed container that maintained a constant temperature, where they remained until the tests were carried out after 3, 7 and 28 days of curing.

The testing of the hardened concretes included determining the following properties:
- the development of uniaxial compressive strength f_c after 3, 7 and 28 days in accordance with PN-EN 12390-3:2002 Testing hardened concrete. Part 3: Compressive strength of the test specimens [12];
- the development of splitting tensile strength f_t after 3, 7 and 28 days in accordance with PN-EN 12390-6:2001 Testing hardened concrete. Part 6: Tensile splitting strength of test specimens [13];
- brittleness characteristics (f_c/f_t relation);
- apparent density after 3, 7 and 28 days in accordance with PN-EN 12390-7:2001 Testing hardened concrete. Part 7: The density of concrete [14];
- water absorption after 28 days in accordance with PN-B-06250:1988 normal concrete [15].

5.1 Compressive strength

Figure 6 shows the results of the compressive strength tests after 28 days of curing of individual concretes and the obtained average strength values are summarised in table 4.

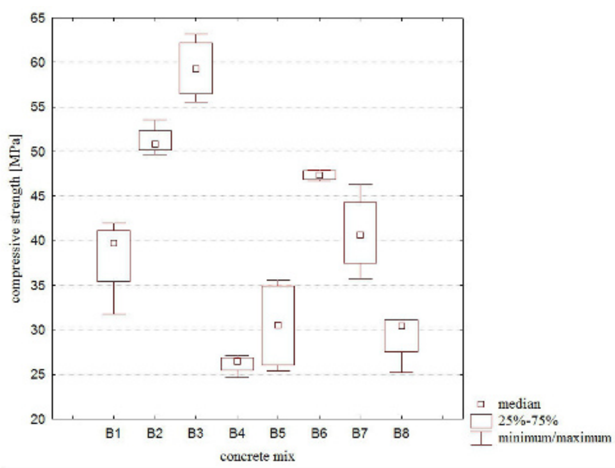

Figure 6. Results of the concrete compressive strength tests.

Based on the obtained results, it can be stated that the use of bottom ashes with the fraction >0.63 mm as aggregate substitutes causes an increases in the compressive strength. It should be noted, though, that in the case of PDF ashes >0.63 mm this increase is proportional to the amount of ash used. On the other hand, in the case of the PDP ashes >0.63 mm, a greater increase in the compressive strength was recorded for the 15% participation than in the case of the 30% participation.

Table 4. Results of the concrete compressive strength tests.

Concrete	Compressive strength f_c [MPa]		
	after 3 days	after 7 days	after 28 days
B1	24.74	27.65	38.30
B2	37.41	38.80	51.25
B3	42.64	54.74	59.33
B4	10.25	16.93	26.20
B5	26.08	28.42	30.51
B6	24.57	33.21	47.33
B7	33.75	37.12	40.86
B8	17.14	26.67	29.31

The highest increase in the compressive strength after 28 days of curing compared to the reference concrete were obtained for concrete B3 (an increase by 54.91%). In concrete B2, this increase was 33.81%. In the case of concretes, where the PDP ash >0.63 mm was used instead of the aggregate, the following increases in the compressive strength were recorded - 23.58% for concrete B6 and 6.68% for concrete B7. Other concretes, i.e. B4, B5 and B8, registered decreases in the compressive strength of up to 31.59%.

The graphs in figure 7 show the increase in the compressive strength of individual concretes. In all the concretes, the strength development after 28 days is quite similar and its intensity is greater than or comparable to that exhibited by the reference concrete.

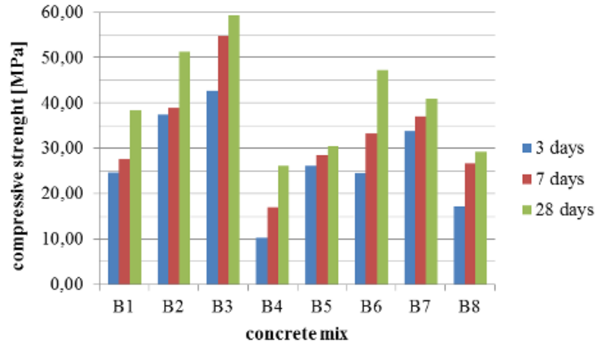

Figure 7. The compressive strength gain of each concrete.

5.2 Tensile Strength

Figure 8 shows the results of the tensile strength tests after 28 days of curing of individual concretes and the obtained average strength values are summarised in table 5.

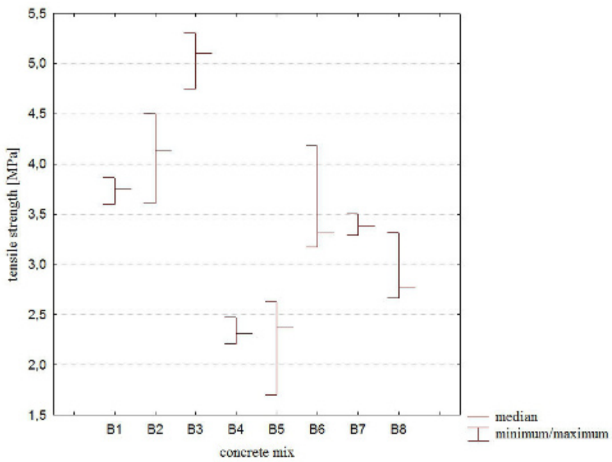

Figure 8. Concrete tensile test results.

Based on the results, it can be stated that the use of bottom ashes with the fraction >0.63 mm as aggregate substitutes causes an increases in the tensile strength.

The highest increase in the tensile strength after 28 days of curing compared to the reference concrete were obtained for concrete B3 (an increase by 35.03%). In the case of concrete B2, this increase was 9.36%. Other concretes recorded decreases in the tensile strength of up to 40.37%, as was the case for concrete B5.

Table 5. Concrete tensile test results.

Concrete	Tensile strength f_t [MPa]		
	after 3 days	after 7 days	after 28 days
B1	2.16	3.19	3.74
B2	3.20	3.69	4.09
B3	4.77	5.02	5.05
B4	1.00	2.11	2.33
B5	2.05	2.20	2.23
B6	2.47	2.83	3.55
B7	2.67	2.75	3.39
B8	2.05	2.75	2.92

The graphs in figure 9 show the increase in the tensile strength of individual concretes. In all the concretes, the strength development after 28 days is quite similar and its intensity is greater than or comparable to that exhibited by the reference concrete.

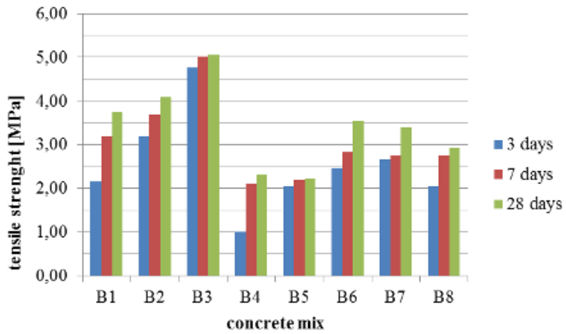

Figure 9. Tensile strength gain of each concrete.

The ratio of the tensile splitting strength f_t to compressive strength f_c that characterised all the test concretes 28 days old or less is in the range from approx. 0.07 to approx. 0.12. The average value of f_t/f_c characterising all the analysed concretes was 0.092. This value tends to decrease slightly with the duration of concrete curing and the increase in the compressive strength. The test results do not indicate that the type and content of bottom ashes have a significant impact on the relationship between the two types of strength in the scope being analysed.

5.3 Apparent density

Figure 10 shows the results of the apparent density tests after 28 days of curing of individual concretes and the obtained average values are summarised in table 6.

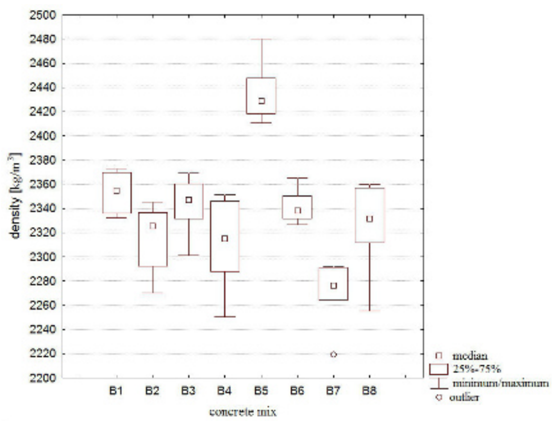

Figure 10. The concrete apparent density test results.

DOI: 10.1051/e3sconf/20161000099

Based on the obtained results, it can be seen that the apparent density of each concrete depends slightly on the duration of curing. The greatest density was obtained by concretes B5, where 15% non-separated PDF ash was used instead of sand and gravel. For these concretes, average apparent density was 2434.5 kg/m^3. Compared to other concretes, the higher density of concretes B5 results mainly from the difference in the density of the PDF ash itself and the sand and the used gravel. The slightly lower density of concretes B7 (2271.80 kg/m^3) compared to other cements can be explained in a similar way. It results from a lower density of the PDP fractions >0.63 mm compared to that of sand and gravel. The average density values for the remaining concretes ranged from 2312.50 to 2344.00 kg/m^3, with the density of the reference concrete being 2351.60 kg/m^3.

Table 6. Test results for the apparent density of concretes.

Concrete	Density [kg/m^3]		
	after 3 days	after 7 days	after 28 days
B1	2342.1	2345.6	2351.6
B2	2284.1	2307.6	2318.1
B3	2303.9	2302.3	2344.0
B4	2288.0	2302.5	2312.5
B5	2418.1	2431.5	2434.5
B6	2302.1	2276.1	2341.5
B7	2273.3	2261.6	2271.8
B8	2331.6	2332.6	2325.9

5.4 Absorption

Water absorption by weight of all the analysed concretes was in the range from 5.0% to approx. 7.7%. The increase in the absorption compared to the reference concrete was exhibited by concretes B4 and B8, i.e. those where 15% of cement was replaced by bottom ashes <0.63 mm. For other concretes, there were no significant differences in the absorption compared to the reference concrete. Only in the case of B3 concrete, a decrease in the absorption to 4.97% was recorded, which confirms the general principle that the absorption of concretes with the addition of fluidised bed ashes is almost always slightly lower than that of the comparative concretes made of cement only.

The obtained results of water absorption of each concrete is shown in figure 11.

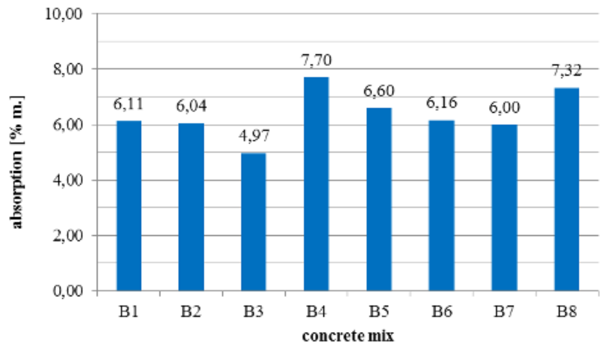

Figure 11. Average values of absorption of the concrete being analysed.

6 Conclusions

Preparation of the concrete mixes with a partial substitution of cement and aggregate with bottom ashes requires special attention, in particular if the aggregate is replaced in large quantities by ash >0.63 mm. This substitution substantially affects the workability of the mixes and therefore it is very important to carefully select the type and amount of plasticiser, superplasticiser and/or the air entraining admixture. A little smaller problem occurs when substituting some cement with ashes <0.63 mm. It should be emphasised that the reduced workability of the mixes can significantly reduce their potential industrial usability and cause negligible economic benefits due to the need to apply substantial amounts of plasticizer and superplasticiser.

If you attempt to use concrete mixes with a partial substitution of cement and aggregate with bottom ashes, it seems necessary to carry out experimental tests to determine the durability of this type of concrete. It is now one of the basic criteria for the selection of materials for the production of building structures.

The PDF ash fractionation caused the diversification of content of individual ingredients within a given fraction. The fraction below 0.63 mm contained considerably more CaO and SO_3 than the fraction with the particle size above 0.63 mm. In turn, the fraction above 0.63 mm contained greater quantities of Al_2O_3 and SiO_2. This situation – i.e. the low content of SO_3 (3,3%), the high content of silicon dioxide and oxides of iron and aluminium – can be very beneficial for the application of the PDF fraction >0.63 mm as an ingredient of concrete.

Loss on ignition of the PDF bottom ash was 4.4%. This result meets the requirements of PN-EN 450-1: 2012: Fly ash for concrete [16], in which the maximum loss on ignition of ashes is set at 9%

It should be stressed that the tests have shown a positive impact of bottom ashes with the fraction >0.63 mm on the strength parameters of the concretes. The highest increase in the compressive strength after 28 days of curing compared to the reference concrete were obtained for concrete B3 (an increase by 54.91%). In the case of B2 concrete, this increase was 33.81%. In the case of concretes, where the PDP ash >0.63 mm was used instead of the aggregate, the following increases in the compressive strength were recorded - 23.58% for concrete B6 and 6.68% for concrete B7. For the tensile strength, the increases were not as high.

The compressive strength and tensile strength development is quite similar and its intensity is greater than or comparable to that exhibited by the reference concrete.

The tests showed no significant effect of the used bottom ashes on absorption, which ranges from approx. 5.0% to approx. 7.7% for all the analysed concretes .

Analysing the results, it can be stated that it will be difficult to meet the criteria set out for construction concretes due to the chemical and phase composition of the analysed bottom ashes if they were to be used. Currently, the good use of this material may be the production of concrete members, whose durability and service life is limited. Such members include e.g.:

- concrete road slabs,
- concrete fence members,
- working platforms to ensure safe working with, e.g pile drivers and cranes,
- concrete facing for mining supports.

In the case of the attempts to use bottom ashes in the production of concrete members, it seems necessary to perform additional testing whose scope should include:

- assessment of the impact of bottom ashes on the durability of standard mortars and concretes in a chloride environment,
- assessment of the impact of bottom ashes on the durability of standard mortars and concretes in a sulphate environment,
- assessment of the resistance of concrete with bottom ash to the permeation of chlorides,
- assessment of the resistance of concrete with bottom ash to the aggression of frost and de-icing agents,
- assessment of the impact on bottom ash on the carbonation of concrete,
- assessment of the impact of bottom ash on the corrosion of steel reinforcement in concrete.

It should be emphasised that these tests are lengthy. However, they can determine the possibility and limitations of using different fractions of bottom ash as an ingredient substituting a part of Portland cement or aggregates in concrete.

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