WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2025.154105

ARCHIVES OF CIVIL ENGINEERING

Vol. LXXI ISSUE 2 2025

pp. 19 –35

Research paper

The use of bottom and a mixture of bottom and fly ash from wood-sunflower biomass combustion in concrete production

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Abstract: As part of the research, concrete mixes containing the addition of bottom ash as well as bottom and fly ash mixtures from the combustion of biomass only were made. The ashes were obtained from the combustion of 80% of wood and 20% of sunflower in a fluidized bed boiler. In the study, the elemental composition of ashes was determined by testing with an XRF X-ray spectrometer. Ashes in the amount of 10, 20 and 30% of the cement mass were used as a substitute for sand for testing concrete samples. During the preparation of concrete mixes, tests of consistency and air content in the mixes were carried out. Concrete samples were tested in terms of e.g. compressive strength, water absorption or frost resistance. The compressive strength of the samples with the addition of bottom ash was lower than the strength of the control samples. The use of a mixture of ashes allowed to improve this property and each of the samples obtained a higher compressive strength than samples without the addition of ash. The addition of ashes significantly improves the frost resistance of concrete, i.e. reduces the decrease in the compressive strength of concrete after frost resistance tests. The absorbability of the samples, regardless of the amount and type of added ash, changed slightly in relation to the control samples.

Keywords: bottom ash, concrete, fly ash, waste materials

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1. Introduction

The development of industry results in a systematic increase in the amount of generated waste, which, in accordance with the idea of sustainable development, should be effectively managed. Some wastes characterized by repetitive chemical composition and properties, such as fly ash or slag from the combustion of hard or brown coal, are used in construction [1], mainly as ballast material for mine reclamation (approx. 45%). This material can also be used to produce composite materials with a cement matrix, i.e. cement mortars [2–5] and concretes [6–9]. On a laboratory scale, other waste materials were also used for the production of cement-based composites, such as construction ceramics [10–14], sanitary and household ceramics [15–17], glass cullet [18–20], hemp hurds [21], polymeric materials [22–25], as well as ash from the incineration of municipal waste and sewage sludge [26–28]. Wastes from the metallurgical industry [29, 30] and concrete obtained from demolition works [31–35] were also used as an aggregate substitute. There have also been reports on the use of fly ash from the coal combustion process in laboratory tests together with other waste materials, such as flotation waste, blast furnace slag, sand from oyster shells or marble dust [36–38].

In recent years, scientists have been interested in the waste generated in power plants and combined heat and power plants during the combustion of biomass itself, which is increasingly used as a substitute for fossil fuels. The waste ash generated in the process of biomass combustion alone has no practical use at present and is deposited in landfills. The management of this waste is difficult due to the very diverse chemical composition and properties determined by the type of biomass burned [39]. Currently, there are no regulations allowing for the admission of this type of ash as a component of cements or as an additive to concrete mixes. However, taking into account the systematically growing amount of this type of waste and the need to protect the environment, it is worth considering the possibility of using this type of ash for the production of building materials. In laboratory tests, the ash from the biomass combustion process was used to produce mortars and concretes [40–53]. Most works concern the use of ash from burning rice husks or corn cobs [40–43] and wood [44–48], although there are works using other types of biomass (e.g. sugar cane [49] or wood with an admixture of coconut shells [49–52]). Our recent research [53] showed that for the production of concrete based on CEM I or CEM II / A-V 42.5R cement, waste fluidized fly ash from burning wood and sunflower biomass in the amount of up to 30% can be used (used as a substitute for sand) without lowering its quality (compressive strength and resistance to low temperatures) in relation to control concretes (without ash). In this paper, we present the results of research on the use of bottom ash and a mixture of bottom ash and fly ash from the combustion process of wood-sunflower biomass in a fluidized bed furnace. The use of ash from biomass in concrete mixes requires each time to determine the limit values of its use. This form of using biomass ash is consistent with the idea of sustainable construction and is particularly important due to the systematic increase in the share of biomass combustion in relation to fossil fuels, and thus the increase in the amount of this so far unmanaged waste.

2. Materials and Methods

2.1. Materials

The study used bottom ash and a mixture of bottom and fly ash from the biomass combustion process consisting of 80% waste wood and 20% sunflower in a boiler with a circulating fluidized bed in a power plant operating in the Świętokrzyskie Voivodeship. The composition of the ash was determined in accordance with the PN EN 450-1:2012 standard using an XRF X-ray spectrometer (Thermo Fisher Scientific, Waltham, USA) and is presented in Table 1. Roasting losses of fly ash were 0.9%, and of bottom ash 0.28%. According to the PN-EN 451-2:2017-06 standard, the fineness of the samples as a residue on the 0.045 mm sieve of fly ash is 7.9%, and the specific density is 2.35 g/cm^3, in the case of bottom ash, the fineness is 98.95% and the density is 2.61 g/cm^3. The fly ash consisted mainly of silicon oxide (50.2%), alumina (12,3%), calcium oxide (11.8%) and contained almost 8% of potassium oxide. Other compounds account for less than 4%, of which most oxides and elements occur only in trace amounts. On the other hand, the bottom ash consisted of 87% of silicon oxide, 3.4% of calcium oxide, 4% of potassium oxide and 2% of alumina. The other ingredients were present in trace amounts. The microstructure of the fly ash used for testing (LEO Electron Microscopy apparatus) shown in Figure 1 revealed that fly ash grains have a heterogeneous structure and sharp edges, characteristic of crushed aggregate. The structure of bottom ash is more homogeneous than that of fly ash, the grains have spherical shapes, a smooth surface and resemble grains of sand.

Table 1. Percentage of oxides and elements in fly and bottom ash

Fly ash			
Oxide / Element	**Content, %**	**Oxide / Element**	**Content, %**
SiO_2	50.20	Na_2O	0.44
CaO	11.82	MnO	0.28
K_2O	7.99	TiO_2	0.30
Al_2O_3	12.29	SO_3	4.91
MgO	3.34	Cl	1.63
Fe_xO_y	3.50	Other	3.30
Bottom ash			
Oxide / Element	**Content, %**	**Oxide / Element**	**Content, %**
SiO_2	86.94	Na_2O	0.21
CaO	3.42	MnO	0.11
K_2O	3.80	TiO_2	0.13
Al_2O_3	2.21	SO_3	0.58
MgO	0.83	Cl	0.06
Fe_xO_y	0.74	Other	0.97

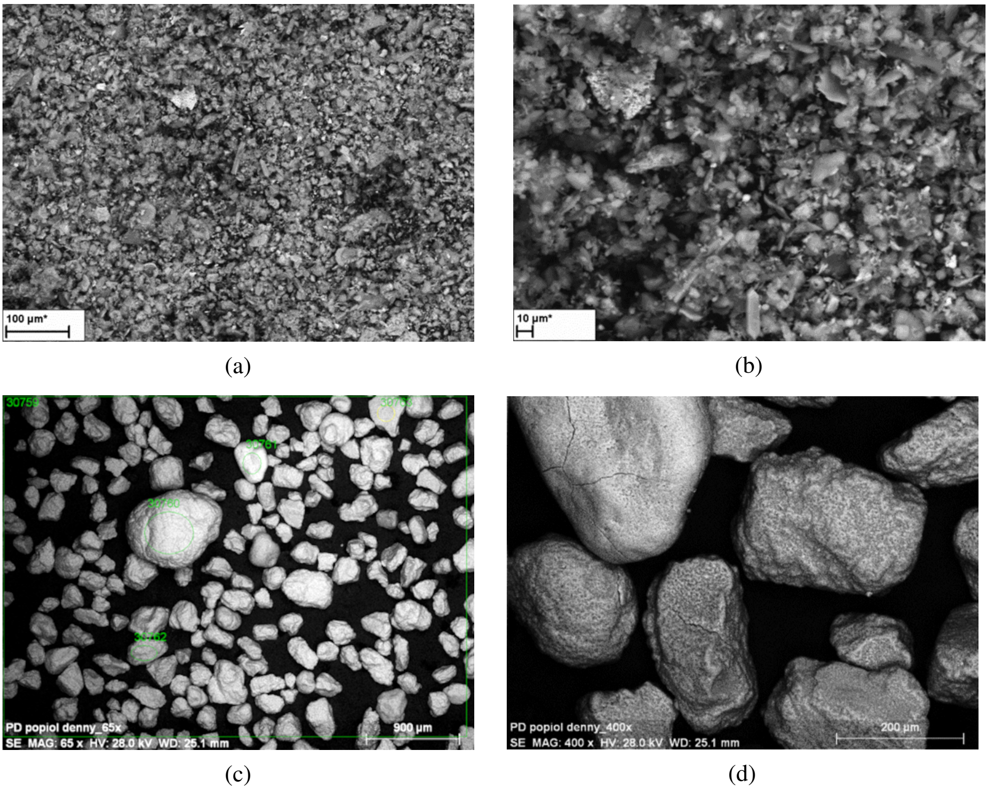


Fig. 1. Microstructure in magnification: (a), (b) fly ash (c), (d) bottom ash

The tested ashes were also subjected to TGA-DTA thermal analysis (Fig. 2 and Fig. 3). The test was carried out in a Jupiter STA 449 F5 device (Netzsch, Selb, Germany) in the range from 30 to 1000°C with a temperature increase rate of 10°C/min in air atmosphere, with a gas flow rate of 100 cm^3/min. The fly ash sample lost about 0.3% of its mass up to the temperature of about 100°C, which results from the evaporation of water from the sample. In the case of bottom ash, it was about 1% by weight. The next peak, which can be observed in the case of fly ash, occurred at a temperature of about 350°C and could be caused by transformations of iron compounds. At the temperature of 580–600°C, a peak is visible, which may be responsible for the conversion of α-quartz to β-quartz, as well as the reaction between unreacted particles and the activator trapped in the pores, and probably decomposition of aluminum hydroxide ($Al(OH)_3$). At the temperature of 700°C, endothermic or exothermic reactions occurred, which corresponded to the decomposition of $CaCO_3$, $Ti(OH)_4$ and $Mg(OH)_2$. The exothermic effect at about 900°C may be related to the crystallization of the amorphous phases of the ash. At the temperature up to 900°C, there was also a 6.51% weight loss of the sample due to the removal of volatiles. Above the temperature of 900°C, the coal residues were burned, which resulted in the loss of more than 1% of the mass of the fly ash sample. The total weight loss was 8.7%. The DTG analysis also showed that in the case of the tested ash, mass loss during heating was uniform. The highest amplitude deviating from the entire graph line was for the temperature range of 650–800°C. Differential scanning calorimetry (DSC) also made it possible to check the course of thermal effects in the sample. In the case of fly ash, the amount of heat obtained from the sample decreased almost uniformly.

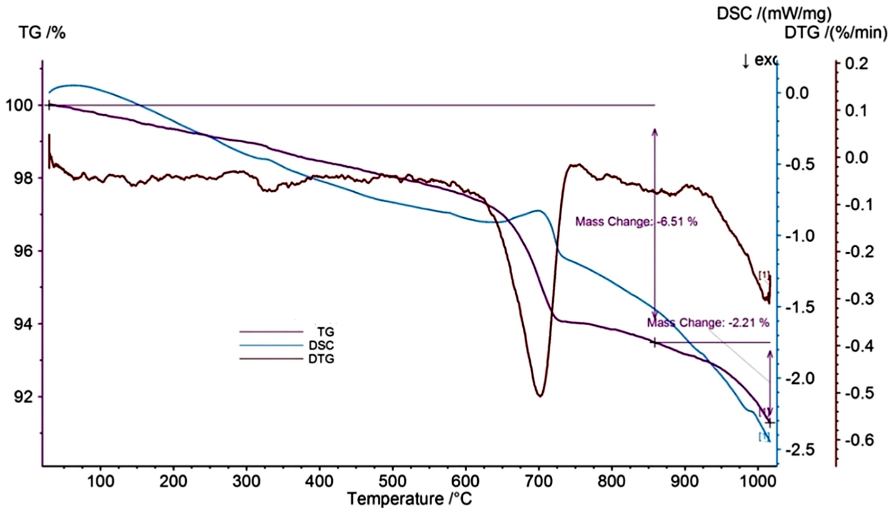


Fig. 2. TGA-DTA thermogram for fly ash

In the case of bottom ash, it can be seen that the sample lost about 2% of its mass up to the temperature of approx. 100–150°C, i.e. as a result of evaporation of water from the sample. At a temperature above 200°C, another peak can be seen where, during the endothermic reaction, water molecules were removed from the channels and pores of calcium silicate hydrate (CSH), CSH with Al (CASH) and channels and pores of sodium aluminosilicate hydrate (NASH). Then, at a temperature of about 350°C, transformations of iron compounds probably occurred in the bottom ash sample. At a temperature of about 600°C, the graphs show changes resulting from the conversion of α-quartz to β-quartz and the reaction between unreacted particles and the activator trapped in the pores, and probably decomposition of aluminum hydroxide ($Al(OH)_3$). However, at the temperature of 700°C, as in the case of fly ash, endothermic or exothermic reactions occurred due to the decomposition of $CaCO_3$, $Ti(OH)_4$ and $Mg(OH)_2$. At the temperature above 900°C, the coal residues were combusted, which caused the fly ash sample to lose about 1% of its mass. The total mass loss of the sample in the temperature range 0–1000°C was about 18%.

Portland cement CEM I 42.5 R by CEMEX with high early strength was used for the tests. The coarse aggregate (2–16 mm) was gravel, while the fine aggregate (0–2 mm) was quartz sand. Table 2 shows the composition of the control concrete (CC), concretes with the addition of bottom ash (BA) and with a 50/50 mix of bottom ash and fly ash (BFA) per 1 m^3 of concrete. Markings 10, 20, 30 informed about the amount of added ash or ashes corresponding to 10, 20, 30% of the mass of cement (used as a substitute for part of the sand calculated in a volumetric manner).

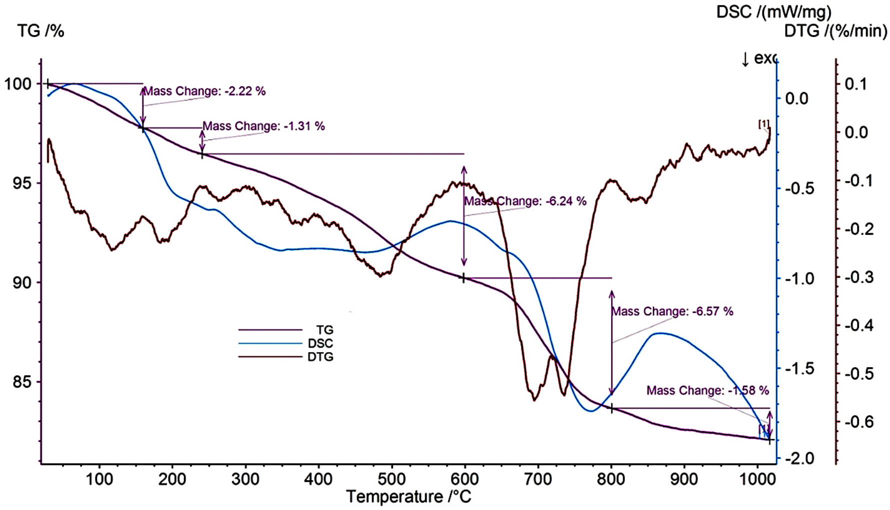


Fig. 3. TGA-DTA thermogram for bottom ash

Table 2. Composition of control concrete (CC), concretes series with the addition of bottom ash (BA) and bottom and fly ash mixture (BFA)

Concrete	**CC**	**BA-10**	**BA-20**	**BA-30**	**BFA-10**	**BFA-20**	**BFA-30**
Ingredient	**Quantity**						
Cement CEM I, kg	364.20	364.20	364.20	364.20	364.20	364.20	364.20
Water, dm^3	191.40	191.40	191.40	191.40	191.40	191.40	191.40
Aggregate – sand, kg	648.20	611.20	574.20	537.20	609.30	570.33	531.40
Aggregate G1 2–8 mm, kg	662.00	662.00	662.0	662.00	662.00	662.00	662.00
Aggregate G2 8–16 mm, kg	541.70	541.70	541.70	541.70	541.70	541.70	541.70
Aggregate $\sum$, kg	1851.90	1814.90	1777.90	1741.90	1813.00	1774.10	1735.20
Plasticizer, dm^3	1.82	1.82	1.82	1.82	1.,82	1.2	1.82
Bottom ash, kg	–	36.42	72.80	109.20	18.20	36.40	54.60
Fly ash, kg	–	–	–	–	18.20	36.40	54.60

2.2. Methods

Samples of concrete mixes made in accordance with the PN EN-12350-1:2011 standard were used for the tests. During the tests, the air content in the concrete mix was measured using the pressure gauge method in accordance with the PN-EN-12350-7 standard. To determine the compressive strength of concrete, samples in the form of a cube with a side of 150 mm were used in accordance with the PN-EN-12390-3 standard. For each series, 12 samples were tested with a force increase of 1.0 MPa/s (ToniTechnik 2030, Berlin, Germany). The load was increased to the highest load. The results are presented in MPa as the average of all tests.

In accordance with the PN-B-06250:1988 standard, the concrete absorption was tested. Cubic samples with a side of 150 mm after 28 days of curing were used. After obtaining a constant weight of the samples, they were placed in a laboratory dryer and dried at 105°C until constant weight, i.e. the moment when subsequent weighings showed differences of less than 0.2% of the weight of the samples. Water absorption in percent represents the ratio of the mass of water penetrating the material to its dry mass.

On the basis of the PN-B-06250:1988 standard, using the Toropol K-010 chamber (Toropol, Warsaw, Poland), the frost resistance of concrete was also tested on 12 samples with a side of 100 mm for each series, which were subjected to 150 cycles of freezing and thawing. Samples saturated with water were weighed and subjected to frost resistance tests. Six samples were left in water at a temperature of 18 ±2°C, while the remaining six were weighed with an accuracy of 0.2%, and then frozen in air at a temperature of (–18 ±2°C) for 4 hours, and then thawed for 4 hours in water (at +18 ±2°C). After 150 cycles of freezing and thawing, the samples were weighed again and subjected to a compressive strength test.

Penetration of concrete with water under pressure was tested on the basis of the PN-EN-12390-8 standard with a RatioTec WU60M apparatus (RatioTec, Essen, Germany). Three cubic samples with sides of 150 mm were used for the tests. Water pressure of 500 kPa was applied to the samples for 72 hours. The samples were then removed from the device and split in half. After the surface was slightly dry, the maximum depth of water penetration was measured with an accuracy of 1 mm.

3. Results

3.1. Properties of concrete mixes

During the preparation of concrete mixes, consistency and air content tests were carried out in the mixes (Table 3). The slump of the cone for the concrete mix of the control concrete CC was 145 mm, which qualifies it to the S3 consistency class. The air content was 3.4%. Concrete mixes BA-10, BA-20 and BA-30 containing bottom ash were slightly denser than the CC mix and based on the size of the cone slump (132, 124 and 120 mm) they were also classified as S3 consistency (according to the cone drop method, range 100–150 mm). In the case of the BFA concrete mix containing a mixture of bottom ash and fly ash, the cone slump decreased with the increase in the amount of additive, which resulted in classifying the mixes as S2 and S1 (S1 10–40 mm; S2 50–90 mm). In terms of air content in the concrete mix, there is also a relationship between the type of ash used and its amount in the mix. In the case of using the addition of bottom ash (BA) with the increase of its share in the mixture, it had a higher air content each time. However, compared to the control mixture, the mixture containing ashes (BFA) resulted in a decrease in air content.

Table 3. Consistency class and air content of CC, BA-10, BA-20 and BA-30 concrete mixtures

Series	**Consistency**		**Air content, %**
Ingredient	**mm**	**class**	
CC	145	S3	3.4
BA-10	132	S3	3.5
BA-20	124	S3	4.0
BA-30	120	S3	4.2
FBA-10	85	S2	3.2
FBA-20	55	S2	3.0
FBA-30	35	S1	2.6

3.2. Influence of ash addition on concrete compressive strength

Cubic concrete samples (6 samples for each series) were tested for compressive strength after 7, 28 and 56 days. The control concrete (CC) ripened in conditions consistent with the standard and after 7 days obtained a compressive strength of 43.4 MPa. Concrete containing the addition of bottom ash had lower strength than the control sample. An increase in the amount of additive resulted in a greater decrease resulting in a 7% strength loss for the 30% BA sample (Fig. 4). All concretes of the BFA series obtained higher strength than the control samples. The highest compressive strength was obtained by samples of the FBA-30 series containing 30% of the ash mixture, which was more than 15% higher than for the control series. It can be noticed that the bottom ash itself causes a decrease in strength, however, the addition of fly ash causes an increase in strength, which may indicate its binding properties.

For concrete samples, their compressive strength was also tested after 28 days of curing. In this case, similar relationships can be observed as in the case of 7-day endurance. The CC concrete obtained an average compressive strength of 49.7 MPa (Fig. 5. The strength of the concretes with bottom ash content was slightly lower than that of the control concrete. The lowest strength was obtained for BA-30 samples, but it was a decrease in relation to CC by about 10%. All BFA series concretes obtained higher compressive strength compared to the control samples (CC). For the addition of BFA in the amount of 10, 20 and 30%, the strength increase was respectively 1, 2 and 5%. The obtained test results allowed to classify the CC concrete to the C35/45 compressive strength class. Due to slight differences, all BFA series concretes can be classified to the same strength class, while BA concretes to the C30/37 strength class.

Tests of the compressive strength of concretes after 56 days of their maturation were also carried out (Fig. 6). Concretes containing bottom ash obtained lower strength than CC concrete. The decrease was related to the increase in the amount of additive and for the BA-30 series the concrete had 7% lower compressive strength than the control concrete of the CC series. In the case of concretes of the BFA series, they were characterized by an increase in compressive strength with the increase in the amount of additive, and for BFA-30 it was higher by 10% compared to the control concrete.

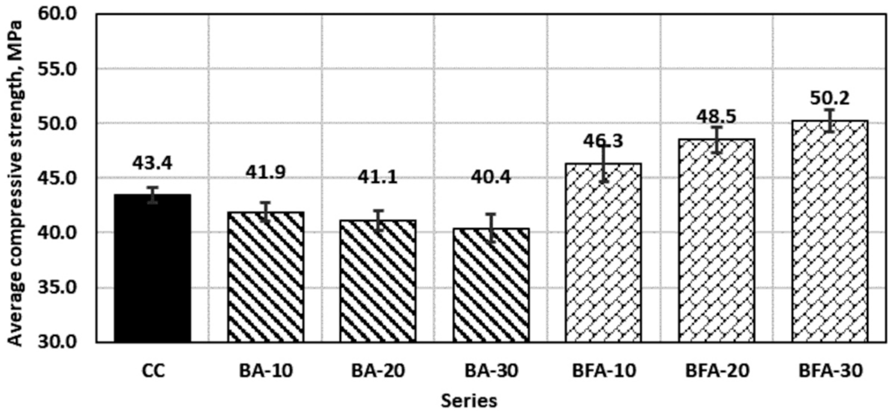


Fig. 4. Average compressive strength after 7 days

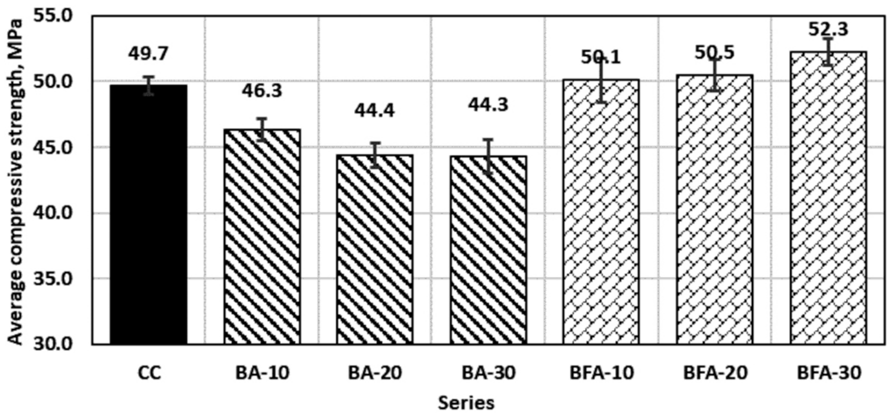


Fig. 5. Average compressive strength after 28 days

3.3. Influence of ash addition on concrete absorbability

Another tested property of concretes was their absorbability, determined on cubic samples (6 samples for each series) with a side of 150 mm. It was determined in accordance with the PN-B-06250 standard. Cubic samples with a side of 150 mm were prepared for testing. The CC control concrete samples had a water absorption of 4.6% (Fig. 7). Concrete samples modified by adding bottom ash, i.e. the BA series, obtained consistently lower compressive strength ranging from 4.53 to 4.59. The addition of two ashes mixed with each other in the proportion of 50/50 (bottom ash/fly ash), i.e. the BFA series, obtained a higher absorbability ranging from 5.77 to 6.11%, which increased with the increase in the amount of ashes. This level of concrete absorption allows it to be used for both internal and external elements.

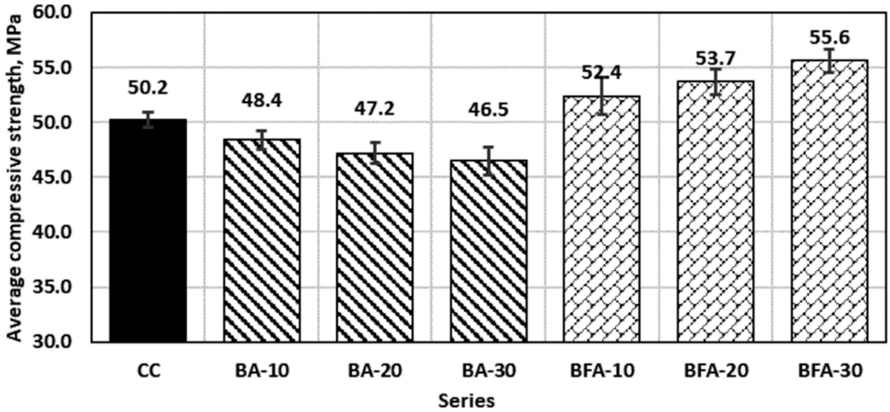


Fig. 6. Average compressive strength after 56 days

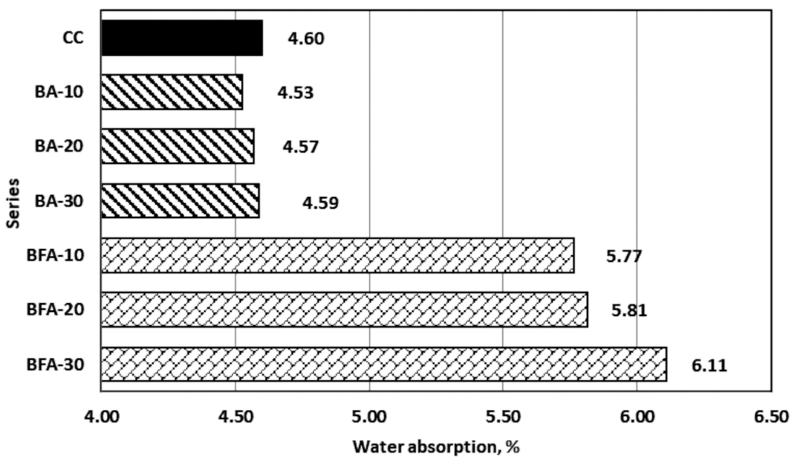


Fig. 7. Water absorption of control concretes and concretes with the fly ash addition

3.4. The influence of ash addition on the frost resistance of concrete

For the samples (12 samples for each series) made, frost resistance tests were also carried out in accordance with the PN-B-06250:1988 standard. In the control concrete, the decrease in compressive strength after freeze-thaw cycles was less than 19% (Fig. 8). The BA series concretes containing the addition of bottom ash showed a significantly lower decrease in compressive strength after frost resistance tests. In the case of these series, the increase in the amount of additive resulted in a further decrease in strength loss and for the BA-30 series it was only 5.6%, which is over 13 percentage points less than the control concrete. The mixture of fly ash and bottom ash caused a reduction in the decrease in strength at smaller amounts, however, with the increasing amount of the additive, the results were closer to those of the CC control concrete. From the analysis of the results, it can be concluded that using the addition of bottom ash, the concrete is more resistant to freezing than the control concrete, while the ash mixture also has no negative effect on this parameter. It can also be noticed that the standard deviation in the case of the BA concrete series is smaller than in the BFA concrete series. Figure 9 shows that the addition of bottom ash results in a smaller loss of sample weight after the frost resistance test than in the case of the standard mortar. In the case of a mixture of bottom ash and fly ash, this loss was greater, but the maximum 0.24% for samples BFA-30.

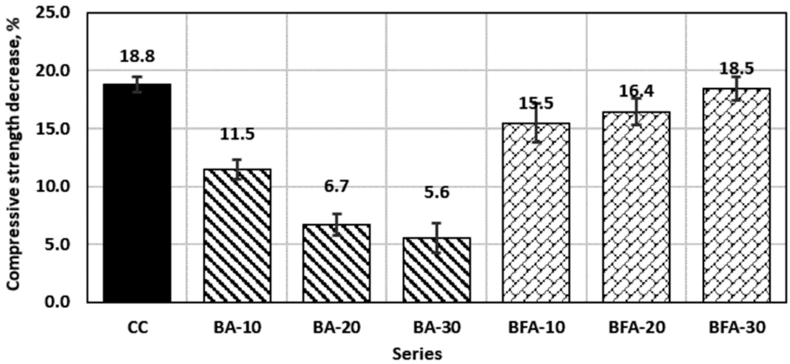


Fig. 8. Water absorption of control concretes and concretes with the fly ash addition

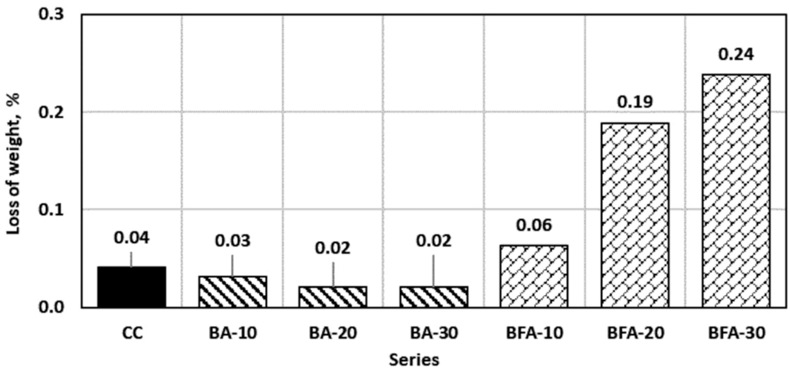


Fig. 9. Water absorption of control concretes and concretes with the fly ash addition

3.5. Water penetration of concretes containing ash from biomass combustion

The concretes were also subjected to a pressurized water penetration test (6 samples for each series). In this regard, the concrete of the control series CC obtained an average depth of water penetration of 42 mm (Fig. 10). The BA and BFA series concretes gained a greater depth of water penetration, which additionally increases with the increase in the amount of added ash. The BA series concretes had the smallest water penetration depth of 44 mm for the sample with 10% ash addition, and the highest for 30% ash addition of 58 mm. Concretes with a mixture of two ashes had the same tendency and water penetrated the samples at 45, 52 and 58 mm for 10, 20 and 30% addition of waste ashes, respectively.

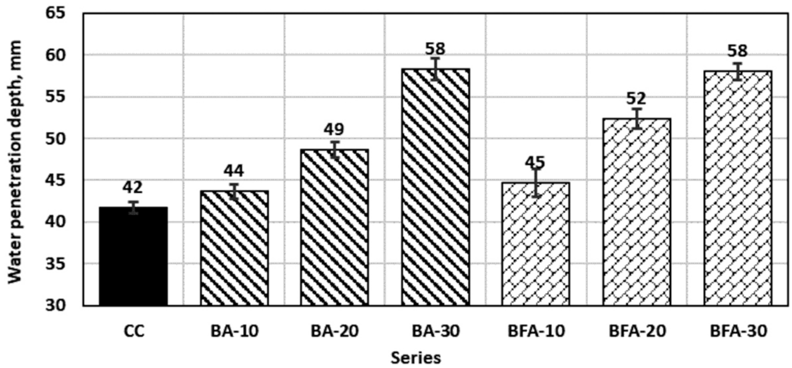
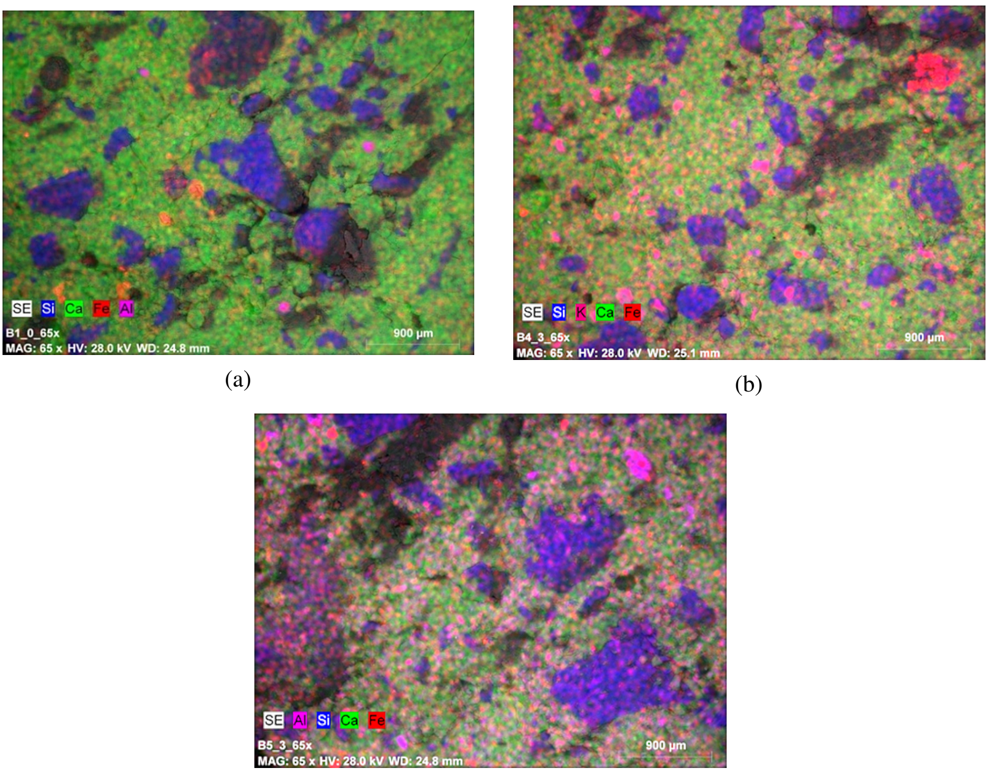


Fig. 10. Water absorption of control concretes and concretes with the fly ash addition

3.6. Microstructure of concrete composites

Microstructure tests were also performed on broken surfaces of concrete samples. Figure 11 presents microscopic photos of concretes enlarged 65 times. Additionally, energy dispersive X-ray analysis was performed. EDS analysis of the concrete surface performed in the area visible in the image showed the presence of calcium (24.65%; green), significant amounts of silicon (13.45%, blue), aluminum (2.31%; pink) and iron (2.72%; red). Sodium (1.56%) and potassium (0.39%) are present in smaller amounts. On the other hand, the remaining ingredients (Mg, C, S, P) are present in small amounts (below 0.7%). The microstructure of BA-30 concrete containing the addition of bottom ash from biomass combustion revealed grains of natural aggregate and smaller grains of bottom ash. In ash-modified concrete, there are continuous contact zones between the cement matrix and the aggregate grains. The EDS analysis of the concrete surface of the BA-30 series, performed in the area visible in the photo (Figure 11b), showed, in addition to the presence of calcium (26.30%), a significant content of silicon (14.57%) and iron (3.47%). The amount of sodium and potassium was small and amounted to 0.60 and 0.71%, respectively. It can be observed that in the BA-30 concrete, a large number of fine grains of bottom ash leads to the formation of a less tight aggregate pile and may be a factor affecting the compressive strength results and the decrease in strength after frost resistance tests. The results of destructive tests confirm that samples with ash obtain higher compressive strength.

The structure of BFA-30 concrete is very similar to control concrete. Aggregate grains and very fine grains are visible in the pictures, which may be the dust fraction of fine aggregate or fly ash. The photos show the existing silicon-based aggregate, cement matrix of hydrated calcium silicates and calcium aluminates. The BFA-30 concrete was characterized by a slightly higher content of calcium and silicon in comparison to the CC control concrete, and the total chemical composition does not differ from the previously presented compositions of other series of concretes. The obtained results are not a very precise method, because it does not analyze the entire surface of the sample, but only a few measurement points on the surface, additionally, the structure of the concrete is not uniform throughout the entire volume of the sample. However, it can be said that non-destructive testing methods using modern material structure testing techniques are a way to effectively draw conclusions regarding the impact of the structure on the strength of concrete.



(a) (b) (c)

Fig. 11. Maps of distribution of dominant elements in the studied area (a) CC; (b) BA-30; (c) BFA-30

4. Summary

The use of bottom ash and a mixture of bottom and fly ash from the wood-sunflower biomass combustion process in a circulating boiler with a fluidized bed for the production of building materials is a desirable solution in terms of sustainable construction. The analysis of the obtained data shows that ashes of this type in the amount of 10, 20 and 30% can be used as a substitute for sand for the production of concrete, without a significant reduction in the quality of the produced materials in terms of compressive strength and frost resistance compared to the control concrete. Concrete composites containing 10, 20 and 30% ashes from biomass combustion have a similar microstructure to the control concrete made without the addition of waste ash. The addition of bottom ash results in a slight compaction of the concrete mix and a decrease in the air content in it, and the use of a mixture of two ashes causes a greater compaction of the concrete mix and a decrease in the air content in the concrete mix. The compressive strength of concretes modified with the addition of bottom ash was slightly lower than the strength of control samples after 7, 28 and 56 days of curing (up to 11%). On the other hand, concretes modified with a mixture of ashes (bottom and fly ash) showed a higher compressive strength than the control samples (up to 15%). The use of bottom ash in the range of 10–30% causes a slight decrease in the water absorption of the tested concretes, and the use of a mixture of ashes causes a slight increase in this physical property. After the frost resistance tests, the waste-modified concretes did not show any chips, cracks or cavities.

The use of waste ashes has a positive effect on the natural environment by limiting the demand for natural resources. The use of ash in the amount of 30% of the cement weight as a substitute for sand, depending on the type of aggregate mix, allows reducing the consumption of sand by 115–120 kg/m^3, i.e. by about 15–20%. In addition, the use of such waste seems to be important as an alternative to the decreasing amount of coal ashes, due to the reduction of energy production from fossil fuels.

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Zastosowanie popiołów dennych oraz mieszanki dennych i lotnych ze spalania biomasy drzewno-słonecznikowej do produkcji betonu

Słowa kluczowe: beton, materiały odpadowe, popiół denny, popiół lotny.

Streszczenie:

W ramach badań wykonano mieszanki betonowe zawierające dodatek popiołu dennego oraz mieszanki popiołu dennego i lotnego pochodzących ze spalania wyłącznie biomasy. Popioły powstały ze spalania w kotle fluidalnym 80% drewna oraz 20% słonecznika. W badanich określono skład pierwiastkowy popiołów poprzez badania spektrometrem rentgenowskim XRF. Do badan próbek betonów użyto popiołów w ilości 10, 20 i 30% masy cementu jako zamiennik piasku. Podczas sporządzania mieszanek betonowych wykonano badania konsystencji oraz zawartości powietrza w mieszankach. Próbki betonów badano pod względem m.in. wytrzymałości na ściskanie, nasiąkliwości czy mrozoodporności. Wytrzymałość na ściskanie próbek z dodatkiem popiołu dennego była mniejsza od wytrzymałości próbek kontrolnych zarówno po 7, 28 i 56 dniach dojrzewania. Zastosowanie mieszanki popiołów pozwoliło na poprawienie tej właściwości i każda z próbek uzyskał a wyższą wytrzymałość na ściskanie niż próbki bez dodatku popiołu. Z analizy uzyskanych wyników wywnioskować można, że stosowanie takich dodatków w zależności od ich rodzaju oraz ilości dodatku popiołu powoduje, że modyfikowane odpadem betony charakteryzują się zbliżoną lub wyższą wytrzymałością niż beton kontrolny. Dodatek popiołów zdecydowanie poprawia mrozoodporność betonów czyli powoduje zmniejszenie spadku wytrzymałości na ściskanie betonów po badaniach mrozoodporności. Nasiąkliwość próbek niezleżnie od ilości oraz rodzaju dodanego popiołu zmieniała się nieznacznie względem próbek kontrolnych.

Received: 2024-01-18, Revised: 2024-04-16