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Investigation into the properties of concrete modified with biomass combustion fly ash

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HIGHLIGHTS

- Biomass combustion fly ash are among the most promising of concrete components.
- Fly ash waste may be used for concrete by replacing upto 15% of cement.
- Fly ash additives can be used for modification of cementations systems.

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ABSTRACT

Concrete is the most widely used construction material obtained after the setting of the mix composed of coarse and fine aggregates, cement and water. The main properties of concrete are determined by the quality and characteristics of aggregates, W/C ratio, and the uniformity of mix compaction. Compressive strength is one of the key characteristics of concrete. Materials used: Portland cement CEM I 42.5 R, 0/4 fraction sand, 4/16 fraction gravel, biomass combustion fly ash, superplasticizer, and water. Seven batches of specimens were made with different biomass fly ash content: 0%, 5%, 10%, 15%, 20%, 25%, and 30% (replacing cement in the mix, %). The following properties of modified concretes were tested: compressive strength, water absorption, density, ultrasonic pulse velocity, porosity (open and closed), and predicted resistance to freezing and thawing cycles. Concrete, where 15% of cement is replaced with biomass combustion fly ash, has higher density (2360 kg/m^3), compressive strength after 28 days (38.3 MPa), ultrasonic pulse velocity (4466 m/s), lower water absorption rate (3.72%) and higher closed porosity (2.54%). All these characteristics improve the freeze-thaw resistance of concrete. The tests revealed that concrete modified with 15% of biomass fly ash had better durability and freeze-thaw resistance characteristics and can be used in construction works. The obtained linear regression equations illustrate the relationships between the density, compressive strength after 28 days of curing, ultrasonic pulse velocity after 28 days of curing, and predicted freeze-thaw resistance of modified concrete.

1. Introduction

Different types of concrete are used in construction. Concrete has a wide range of applications as it is produced from locally available aggregates at relatively low cost. Aggregates make up to 80% of concrete volume. Concrete manufacturing is energy intensive industry. Energy is used in the production of raw materials, final products, and in transportation. Energy consumption must be minimised in all manufacturing stages and also by reducing the cement content in concrete. In spite of the great interest in waste recycling and recovery, ash is utilised at low levels. Germany and Japan utilise only 10% of ash and only 5% of ash is recycled in the USA. It is expected that recycling and recovery of ash will receive greater attention in the future [1].

Cement production from local mineral resources is energy intensive industry. The current global trend is to save non-renewable sources of energy and to obtain energy from renewable sources with lower environmental impact. However, the development of renewable energy industry and large-scale biomass incineration demand higher amounts of combustible raw materials. Biomass incineration plants burn logging waste, straw, and other biological waste and generate big amounts of incineration waste. Biomass incineration waste is mainly ash that is disposed in landfills.

Utilisation of biomass fly ash has become an acute problem. Tests with coal ash have proven that it can be used as a binder in

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concrete to improve certain characteristics of concrete. Replacing a certain amount of cement with ash also reduces the cost of concrete products. Utilisation of ash in concrete manufacturing enables to reduce the amount of Portland cement in concrete and also to lower CO2 emission. The abatement of CO2 emission in cement industry is a priority axis in the European Union and in the world too.

Biomass incineration for energy production enabled to decrease the cost of energy production. However, high amounts of ash is generated in this process. Biomass incineration ash causes serious environmental problems. At present, a major part of this waste (25,000–30,000 tonnes of wood ash per year) is disposed in landfills in Lithuania. Research results demonstrate that such waste can be effectively recycled in the industry of construction products [2–8].

Chemical composition of biomass fly ash is a very important factor for its utilisation in concrete industry. This composition depends on different factors, such as biomass growing area and conditions, soil and biomass type, incineration parameters, etc. The chemical composition can vary across a very wide range [9–12].

Extensive research into industrial by-products and ash from agricultural materials, such as wood ash or rice husk ash, is conducted looking for possibilities to utilize ash as cement replacement in concrete. The current boom in construction industry has escalated the demand for cement, which is the main constituent in concrete. Cement industry is also one of the primary sources of carbon emissions and a major consumer of natural resources, such as aggregates. It is also energy intensive industry. Therefore, utilisation of biomass incineration ash solves a twofold problem: the disposal of waste and substitution of cement in concrete products [13–16]. Researchers had conducted tests that showed promising results proving that wood ash can be used to replace a certain part of cement in concrete products [17–19]. Thus, using biomass incineration ash in modified concrete helps to transform ash from an environmental concern to a useful resource for the production of a highly effective alternative cementing material [20].

Biomass incineration ash can be also used for the production of multi-purpose ceramic products [21–23] by introducing up to 50% of ash into the moulding mixes. The mixed samples were fired at 950 °C without the addition of additives. The results showed that water absorption increased and apparent density and compressive strength decreased with higher ash content. The authors state that the optimal amount of ash to be utilised in ceramic products manufacturing shall not exceed 20%. Other authors state that from 5% to 10% of biomass ash additive decreases the density of ceramic products by 210 kg/m^3, thermal conductivity up to 0.13–0.16 $W/(m^2K)$ and increases water absorption by 7%. However, this ash must be additionally washed before recycling it for fired brick manufacturing, and the washing impedes the manufacturing process and increases the production costs [24].

Researchers tested the recycling of biomass ash in concrete manufacturing by replacing part of the cement with fly ash and found that the optimal replacement percentage is 10% by weight of cement. The highest compressive strength after 28 and 90 days of curing was observed in specimens containing 2.7% of fly ash by weight of the mix and from 0 to 21.7% of bottom ash by weight of the mix. Compared to the control specimens, the lowest result was observed in all batches containing 8.1% of fly ash where cement content was reduced to 18.8% [25].

Naik et al. investigated the effects of wood ash on freeze-thaw resistance of concrete [19]. Changes in relative dynamic modulus, pulse velocity and length were investigated. The replacement percentages 5%, 8% and 12% by weight of the binder were tested. There was no important effect on freeze-thaw cycles (300 cycles) and relative dynamic modulus of concrete mixes; thus it was concluded that incorporation of wood ash did not produce any significant difference in the relative dynamic modulus. The relative dynamic modulus of the control mix was 97.7%; it reduced to 95.7% in specimens containing 5% of wood ash, changed to 97.8% in specimens containing 8% of wood ash and to 95.7% in specimens containing 12% of wood ash by weight of the binder. Also, no significant effect was observed on ultrasonic pulse velocity with the incorporation of wood ash. In the control mix the pulse velocity was 5425 m/s, in specimens containing 5% of ash it was 5480 m/s, in specimens containing 8% of ash it was 5560 m/s and in specimens containing 12% of ash the pulse velocity was 5435 m/s.

Tests with concrete mixes containing river sand revealed that the mixes where calcium-rich wood ash was used as cement replacement had a higher water demand to obtain the suitable workability. Mixes with replacement percentages up to 16% by weight of cement were tested. The highest compressive strength values were recorded in specimens containing 8% of wood ash [26].

The paper by M. Limbachiya et al. presents the results of tests into the properties of concrete mixes made of sand, coarse aggregates and recycled concrete aggregate, where a certain proportion of cement was replaced with fly-ash. Researchers found that specimens with ash additive had better mechanical characteristics compared to the control specimens. The specimens were tested after 3, 7, 14, 28, 56, 91, and 365 days of curing. The authors claim that specimens containing ash additive had a lower W/C ratio than specimens without ash. A linear relationship between the compressive strength and the rate of carbonation was detected. Higher resistance to sulphate attack and thus better durability characteristics of concrete were also observed [27].

Porosity is a very important parameter for the durability of concrete. Freeze-thaw resistance of concrete mainly depends on capillary porosity and entrained air. These parameters are controllable in concrete manufacturing process.

There are four types of pores in the pore system of concrete: gel pores; capillary pores of 5–5000 μm in size; macropores resulting from entrained air and macropores resulting from insufficient compaction. Gel pores have a negative effect on concrete strength. Capillary pores and bigger pores reduce the strength of concrete [28].

It is generally known that low W/C ratio and appropriate curing conditions are the key factors for producing freeze–thaw resistant concrete products [29–32].

N. Asrara claims that amorphous silica dioxide provides corrosion protection and increases the strength of concrete by reducing porosity and participating in the building of CSH crystals through the reaction with calcium hydroxide. The reaction outcomes are the reduction of $Ca(OH)_2$ content and increase of C-S-H content, which improves the strength and durability of concrete [33].

2. Materials and research methods

CEM I 42.5 R type Portland cement complying with LST EN 197–1:2001 requirements was used in the tests. Characteristics and chemical composition of Portland cement are presented in Tables 1 and 2. Characteristics and chemical composition of biomass fly ash are presented in Tables 3 and 4. 0/4 fraction sand complying with

Table 1
Physical-mechanical properties of the cement.

Properties	Portland cement CEM I 42.5 R
Specific surface area, cm^2/g	3700
Particle density, kg/m^3	3200
Bulk density, kg/m^3	1200
Standard consistency paste, %	25.4
Initial setting time, min	140
Final setting time, min	190
Compressive strength after 7 days, MPa	28.9
Compressive strength after 28 days, MPa	54.6

Table 2
Chemical and mineral characteristics of the cement.

Chemical composition of cement, %									
SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	SO_3	Na_2O	H_2O	MgO	Other
20.76	6.12	3.37	63.50	1.00	0.8	0.3	–	–	4.45

Table 3
Chemical and mineral characteristics of biomass combustion fly ash.

Chemical composition of fly ash, %										
SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	SO_3	Na_2O	P_2O_5	MgO	MnO_2	Cl
68.53	6.51	2.15	9.96	7.16	1.04	0.98	2.09	1.14	0.33	0.11

Table 4
Characteristics of biomass combustion fly ash.

Characteristics	Value
Bulk density, kg/m^3	687
Particle density, kg/m^3	2039

Table 5
Physical properties of gravel and sand.

Aggregate	Particle density, kg/m^3	Bulk density, kg/m^3	Water absorption, %
Sand 0/4	2622	1640	0.40
Gravel 4/16	2597	1572	0.50

LST EN 12620:2003 requirements was used as the fine aggregate. 4/16 fraction gravel complying with LST EN 12620:2003 requirements was used as the coarse aggregate. Physical characteristics of gravel and sand are presented in Table 5.

Characteristics of water used to prepare concrete mix: clean, without any harmful deposits, which would prevent the normal setting of concrete, i.e. potable water complying with EN 1008:2003 requirements. Polycarboxylate resin-based plasticizer, pH value 4.5, solution density 1040 kg/m^3, was added to the mix. The recommended plasticizer content was 0.4–3.0%. Biomass incineration ash was used as cement replacement additive. 7 batches of concrete mixes (five specimens of each mix) were mechanically produced under laboratory conditions for the tests. The batches differed by ash content ranging from 0% to 30% by weight of cement (ash replaced a certain percentage of binding material). Table 6 illustrates compositions of the mix required to produce 1 m^3 of concrete. 100 × 100 × 100 mm size specimens were formed in metal casting moulds. Specimens were removed from the moulds after 24 h of curing and soaked for 28 days in 20 ± 2 °C waster. After 7 and 28 days of curing in water the compressive strength of the specimens was measured according to EN 12390-3:2009 (the compressive load was added at the rate of 5 kN/s), the density was measured according to EN 12390-7:2009, and ultrasonic pulse velocity was measured according to EN 12504-4:2004 (the frequency of oscillation was 40–100 kHz). The total water absorption of specimens was measured after soaking in water for 96 h. The specimens were soaked into potable (20 ± 5) °C water and kept there until the constant mass was achieved. Specimens in the bath must be placed at 15 mm distance and the layer of water above the specimens must be at least 20 mm. The constant mass was achieved when the difference in weight measured every 24 h was less than 0.1%. Prior to weighting specimens were dried with a damp cloth to remove excessive water.

Freeze-thaw resistance of concrete depends both on the open porosity (the amount of capillary pores), and on the closed porosity (air content in the mix), and quantitatively can be determined by the freeze-thaw durability factor K_F, which is derived from the equation [34]:

$$K_F = \frac{P_u}{0.09P_a} \tag{1}$$

where P_u is closed porosity of concrete; P_a is open porosity of concrete.

The total porosity of concrete is calculated from the following equation:

$$P_b = \left(1 - \frac{q_c}{q_s}\right) \tag{2}$$

where P_b is the total porosity of concrete, %; ρ_c is density of concrete, kg/m^3; ρ_s is specific density of concrete, kg/m^3.

The open (capillary) porosity of concrete is calculated from the following equation:

$$P_a = W_p \cdot \frac{q_c}{1000} \tag{3}$$

where P_a is the open porosity of concrete, %; W_p is the total water absorption of concrete, %;

The closed porosity of concrete is calculated from the following equation:

$$P_u = P_b - P_a \tag{4}$$

where P_u is the closed porosity of concrete, %; P_b is the total porosity of concrete, % P_a is the open porosity of concrete, %;

With the known value of freeze-thaw durability factor K_F, the resistance of hardened cement paste to freezing and thawing can be predicted from the function of freeze-thaw resistance and freeze-thaw durability factor [34].

The structure of hardened cement paste containing biomass incineration ash and cement was analysed by using the scanning electron microscope SEM JOEL JSM-7600F with resolution of 1.5 nm and magnification from 25 to 1,000,000 times. 10.0 kV voltage was used for the tests and the surface of tested specimens was covered with gold.

3. Analysis of test results

The following chemical components of biomass combustion fly ash were found by SEM imaging tests (Fig. 1): SiO_2, CaO, MgO, K_2O and other. A high content of silica dioxide makes biomass incineration ash an appropriate hydraulic admixture for use in concrete manufacturing. Fig. 1 illustrates that biomass combustion fly ash contains amorphous silica dioxide with spherical particles of some tens of micrometers in size. Particle size was impossible to measure by SEM imaging technique, therefore additional tests with

Table 6
Concrete mix 1 m^3 compositions.

Biomass combustion fly ash, %	Biomass incineration fly ash, kg	Cement, kg	Sand, kg	Gravel, kg	Water, kg	Plasticizer, kg	W/C	Consistence class
0	0	306.0	925	1006	159	1.836	0.52	S3
5.0	15.3	290.7	925	1006	159	1.836	0.52	S3
10.0	30.6	275.4	925	1006	159	1.836	0.52	S3
15.0	45.9	260.1	925	1006	159	1.836	0.52	S3
20.0	61.2	244.8	925	1006	159	1.836	0.52	S3
25.0	76.5	229.5	925	1006	159	1.836	0.52	S3
30.0	91.8	214.2	925	1006	159	1.836	0.52	S3

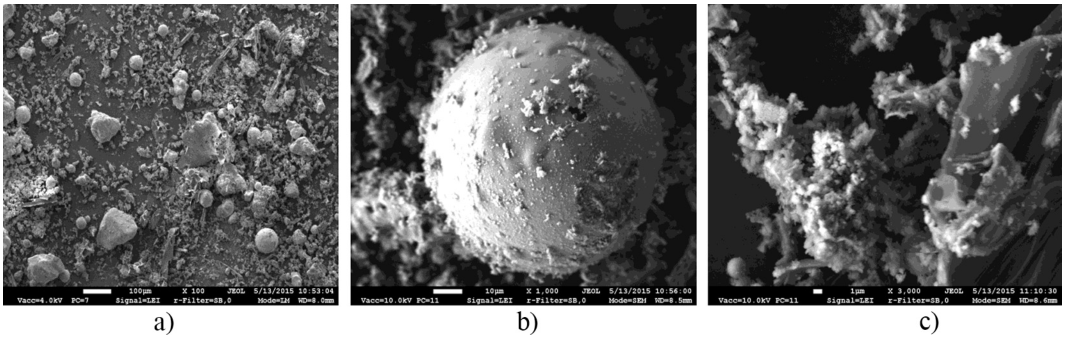

Fig. 1. SEM images of biomass combustion fly ash: a) magnification 100 times; b) magnification 1000 times; c) magnification 3000 times.

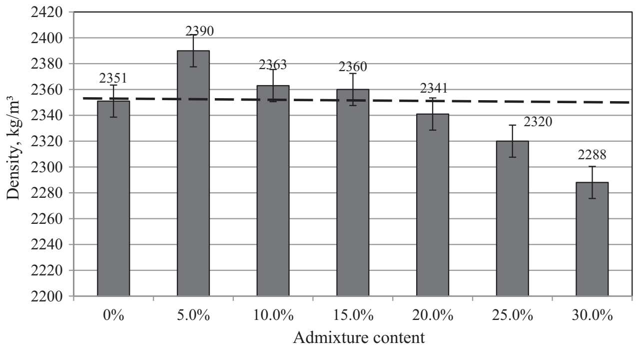

Fig. 2. Relationship between density and biomass combustion fly ash content in concrete.

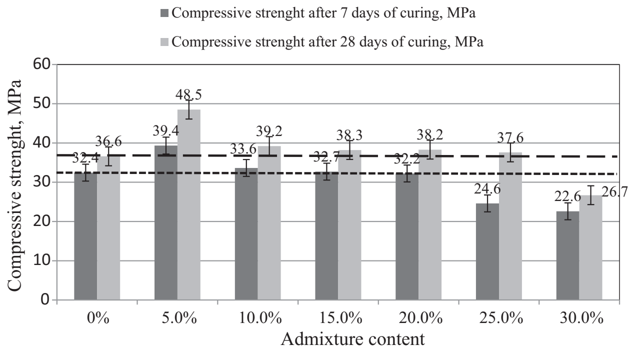

Fig. 3. Relationship between the compressive strength and biomass combustion fly ash content after 7 and 28 days of curing.

laser particle size analyser were done. The measured particle size was 69.33 μm.

Modified concrete density tests (Fig. 2) revealed that the highest density of 2390 kg/m^3 was obtained in the batch where 5% of fly ash was used and the lowest density of 2288 kg/m^3 was obtained in the batch where 30% of fly ash additive was used. Compared to the control specimens, density increases by increasing the additive content up to 15%. However, densities in experimental batches differ insignificantly. The highest difference is 39 kg/m^3, i.e. 1.63%.

Fig. 3 illustrates the relationship between the compressive strength after 7 and 28 days of curing and biomass combustion fly ash content in concrete mix. After 7 days of curing the compressive strength of the control mix containing 0% of ash was 32.4 MPa. The highest compressive strength value was recorded when 5% of the binding material was replaced with biomass combustion fly ash. The compressive strength increased by 7.0 MPa, i.e. by 17.8%. When biomass combustion fly ash was added at 10% by weight of cement, the compressive strength of hardened cement paste increased up to 33.6 MPa. This increase represents a 3.6% growth compared to the control specimen. When ash content was increased to 15%, the compressive strength increased to 32.7 MPa. When 20%, 25% and 30% of cement was replaced with biomass combustion fly ash, the compressive strength of hardened cement paste was lower than the strength of the control specimen.

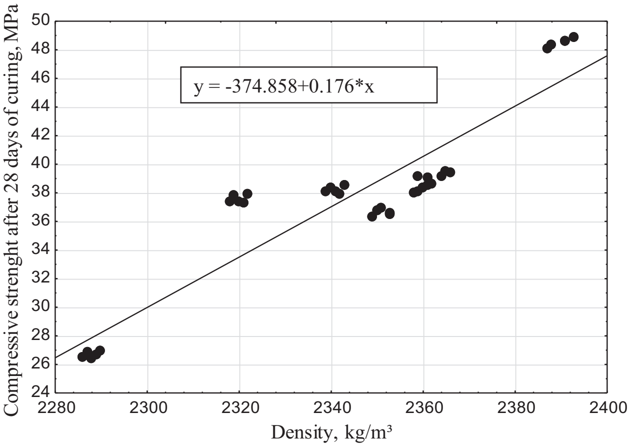

Fig. 4. The relationship between compressive strength and density after 28 days of curing.

After 28 days of curing, the compressive strength of the control specimen was 36.6 MPa. The highest compressive strength was achieved when 5% of biomass combustion fly ash was added to the mix. Compared to the control specimen the compressive strength increased by 11.9 MPa, i.e. by 11.9%. In specimens containing up to 10% of biomass combustion fly ash the compressive strength increased. The compressive strength testing results revealed that in specimens where up to 15% of cement was replaced with biomass combustion fly ash the compressive strength increased by 1.2% after 7 days of curing and 4.2% after 28 days of curing. The best effect in compressive strength increase is observed when 5% of cement in concrete mix is replaced with biomass combustion fly ash. In this case the compressive strength of hardened cement paste increased by 11.9 MPa after 28 days of curing. The increase in compressive strength of modified concrete is related to the active SiO_2 present in biomass combustion fly ash.

The analysis of test results with the software "*Statistica*" produced a linear regression equation, which describes the relationship between the density and compressive strength of concrete after 28 days of curing. This relationship is presented in Fig. 4. The coefficient of determination is 0.832; it means that 83% of the change in compressive strength is affected by density. The coefficient of correlation $r = 0.912$ indicates a high correlation between the compressive strength and density after 28 days of curing. The regression in this case is positive. It was found that the compressive strength of concrete increased with the increase of density.

Ultrasonic pulse velocity test results are relative to compressive strength test results because with lower ultrasonic pulse velocity the propagation of ultrasonic waves becomes longer. The growing number of microcracks in concrete increases the pulse propagation distance and reduces the velocity. That means that microcracks formed in hardened cement paste practically stop the propagation of ultrasonic pulse generated by ultrasonic wave diffractions around the microcrack. Fig. 5 illustrates the relationship between changes in ultrasonic pulse velocity and biomass combustion fly ash content. After 7 days of curing, the highest ultrasonic pulse velocity of 4570 m/s was recorded in specimens containing 5% of biomass combustion fly ash. The lowest value of 4173 m/s was observed in specimens, where 30% of cement was replaced with biomass combustion fly ash. After 7 days of curing a 2.3% increase in ultrasonic pulse velocity was observed in specimens modified with biomass combustion fly ash. After 28 days of curing the highest ultrasonic pulse velocity value of 4849 m/s was recorded in specimens containing 5% of biomass combustion fly ash. The lowest value of 4459 m/s was observed in specimens containing 30% of ash. After 28 days of curing a 3.5% increase in ultrasonic pulse velocity was observed in specimens modified with biomass combustion fly ash. The test results revealed that with the increase of biomass combustion fly ash content up to 15% the ultrasonic pulse velocity after 7 and 28 days of curing also increased. The best effect in ultrasonic pulse velocity increase is observed when 5% of cement in concrete mix is replaced with biomass combustion fly ash. In these specimens the ultrasonic pulse velocity after 7 and 28 days of curing increased by 106 m/s and 171 m/s respectively.

A linear regression equation, which describes the relationship between the density of concrete and ultrasonic pulse velocity after 28 days of curing, was obtained. This relationship is presented in Fig. 6. The coefficient of determination is 0.904; it means that 90% of the change in ultrasonic pulse velocity is affected by density. The coefficient of correlation $r = 0.950$ indicates a high correlation between the ultrasonic pulse velocity and density after 28 days of curing. A positive regression was obtained. It was found that ultrasonic pulse velocity increased with the increase of density.

Water absorption of concrete (Fig. 7) was tested after 96 h soaking. The highest water absorption of 3.29% was recorded in specimens containing 5% of biomass combustion fly ash. In specimens containing up to 10% of biomass combustion fly ash the water absorption increases up to 3.68%, and in specimens containing up to 15% of ash the water absorption increases up to 3.72%. When 20%, 25% and 30% of cement was replaced with biomass combustion fly ash, the water absorption continued to increase compared to the control specimen. Water absorption test results showed that in specimens where up to 15% of cement was replaced with biomass combustion fly ash, the water absorption of hardened cement paste reduced to 4.12% compared to control specimens. The best effect in water absorption decrease is observed when 5% of cement in concrete mix is replaced by biomass combustion fly ash. In this case water absorption of concrete reduced 0.59%. Researchers state that amorphous silica dioxide increases the strength of concrete by reducing porosity (water absorption) of concrete matrix [33].

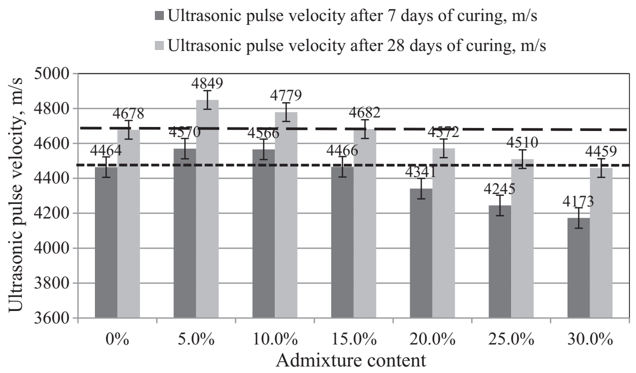

Fig. 5. Relationship between ultrasonic pulse velocity and biomass combustion fly ash content after 7 and 28 days of curing.

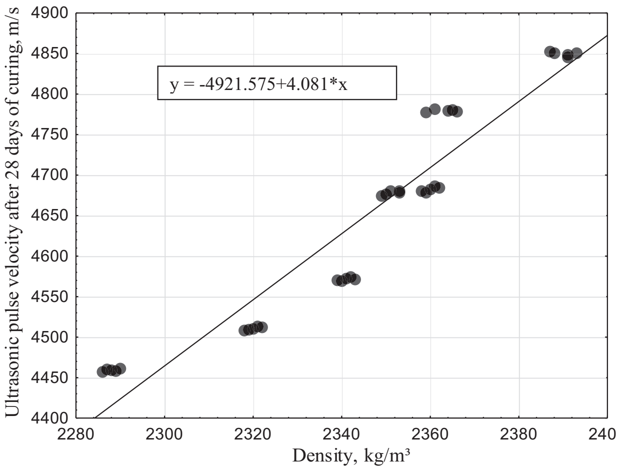

Fig. 6. Relationship between ultrasonic pulse velocity and density after 28 days of curing.

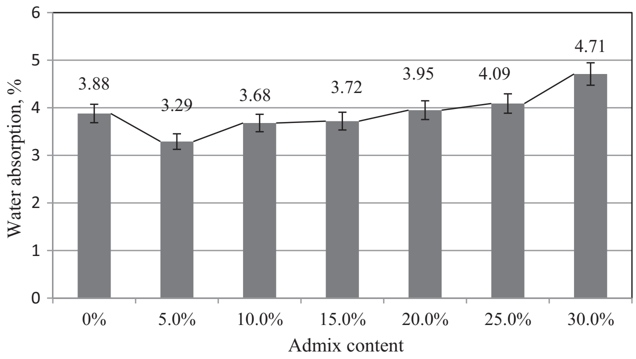

Fig. 7. Relationship between water absorption and biomass combustion fly ash content.

The analysis of test results with the software “Statistica” produced a linear regression equation, which describes the relationship between the density and water absorption of concrete. This relationship is illustrated in Fig. 8. The coefficient of determination is 0.960; it means that 96% of the change in water absorption is affected by density. The coefficient of correlation $r = 0.980$ indicates a high correlation between water absorption and density. The regression in this case is negative. Test results revealed that water absorption is inversely proportional to the density of concrete, i.e. the higher is the density of concrete, the less water it will absorb and vice versa.

Open and closed porosities of modified concrete specimens were tested. The obtained results are presented in Fig. 9. The lowest open porosity value of 6.4% was obtained in specimens containing 5% of biomass combustion fly ash. Specimens of this

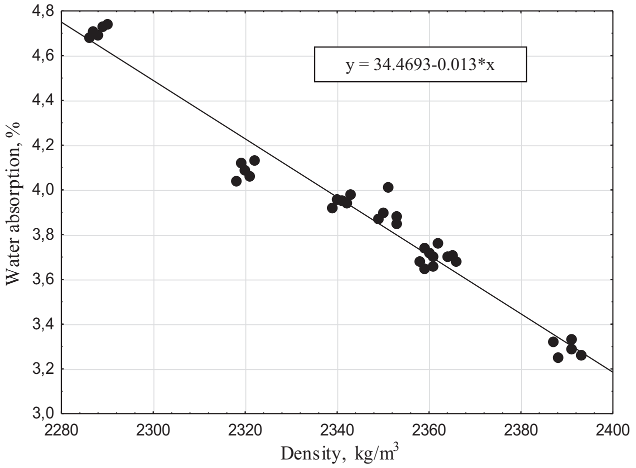

Fig. 8. Relationship between water absorption and density.

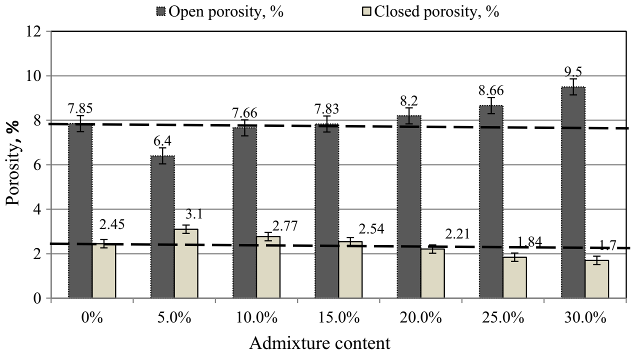

Fig. 9. Relationship between open and closed porosity and biomass combustion fly ash content.

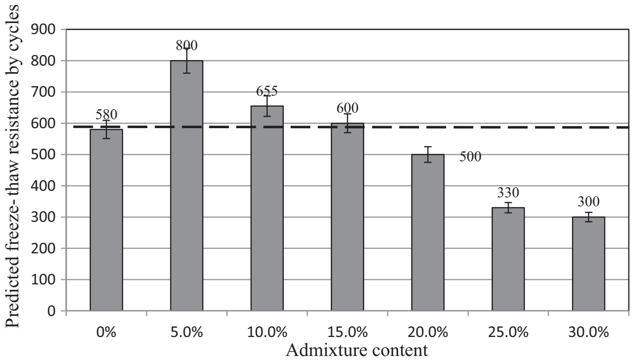

Fig. 10. Relationship between resistance to freezing and thawing cycles and biomass combustion fly ash content in concrete.

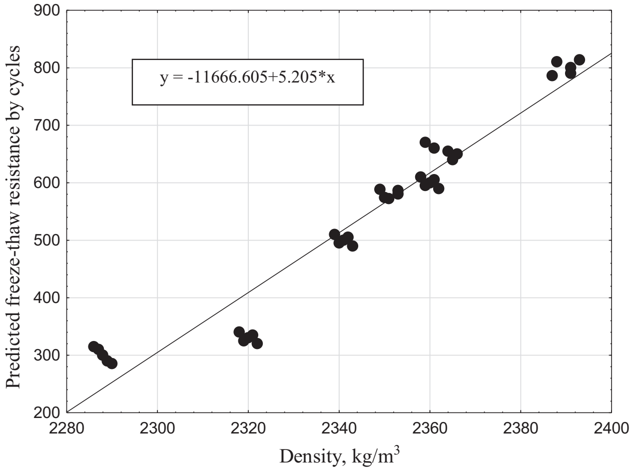

Fig. 11. Relationship between density and resistance to freezing and thawing cycles.

composition had the highest density and the lowest water absorption. They contained much less free water, which affects the development of open pores. The lowest value of open porosity compared to specimens not modified with fly ash was lower by 18.5%. The highest open porosity value of 9.5% was recorded in specimens where 30% of cement was replaced by biomass combustion fly ash. The highest value of open porosity compared to specimens not modified with fly ash was higher by 17.4%. The test results (Fig. 9) revealed that the highest closed porosity value of 3.1% was obtained in specimens containing 5% of biomass incineration ash. The lowest closed porosity value of 1.7% was recorded in specimens where 30% of cement was replaced with biomass combustion fly ash.

The predicted resistance of concrete to freezing and thawing cycles was determined by using the freeze-thaw durability factor. The relationship of predicted resistance to freezing and thawing cycles and biomass combustion fly ash content is presented in Fig. 10. Figs. 9 and 10 illustrate that concrete's porosity is in proportion to its durability, i.e. resistance to freezing and thawing. The closed pores play the key role because they increase the resistance of concrete to freezing and thawing cycles. During the freezing ice is formed in the open (capillary) pores. The volume of ice increases up to 9%, thus creating a high hydraulic pressure of unfrozen water and internal stress in the binder's matrix. More water enters the pores of conglomerate in repeated freezing and erode the conglomerate's structure until the total failure. The predicted freeze-thaw resistance by the number of freezing and thawing cycles ranged from 300 to 800 cycles depending on the content of biomass combustion fly ash in the specimens. Specimens containing 30% of fly ash had the lowest freeze-thaw resistance and collapsed after 300 cycles. The highest freeze-thaw resistance of 800 cycles was recorded in specimens containing 5% of biomass combustion fly ash.

The obtained linear regression equation illustrates the relationship between the density and predicted freeze-thaw resistance of concrete. This relationship is illustrated in Fig. 11. The coefficient of determination is 0.931; it means that 93% of the change in resistance to freezing and thawing cycles is affected by density. The coefficient of correlation $r = 0.965$ indicates a high correlation between resistance to freezing and thawing cycles and density. A positive regression was obtained. It was found that freeze-thaw resistance of concrete increased with the increase of density.

The tests described above prove that biomass combustion fly ash can be used to modify concrete mixes by replacing 15% of cement in the mix with fly ash. The tests revealed that biomass combustion fly ash increase the density, ultrasonic pulse velocity and compressive strength of concrete, reduce water absorption and increase the closed porosity of modified concrete; subsequently the very important characteristics of concrete structures, namely the resistance to freezing and thawing cycles, is improved.

4. Conclusions

1. The highest density of 2390 kg/m^3 was obtained in the batch where 5% of ash was used and the lowest density of 2288 kg/m^3 was obtained in the batch where 30% of fly ash

additive was used. Compared to control specimens, the density of concrete increases by increasing the additive content up to 15%. However, densities in experimental batches differ insignificantly. The highest difference is 39 kg/m^3, i.e. 1.63%.

2. The results of compressive strength tests with modified concrete mixes revealed that in specimens where up to 15% of cement was replaced with biomass combustion fly ash the compressive strength increased by 1.2% after 7 days of curing and by 4.2% after 28 days of curing. The best effect in compressive strength increase is observed when 5% of cement in concrete mix is replaced with biomass combustion fly ash. The compressive strength of concrete increased 17.8% after 7 days of curing and 11.9% after 28 days of curing.
3. Concrete, where 15% of cement is replaced by biomass incineration ash, has higher closed porosity and subsequently better freeze-thaw resistance and durability characteristics. Depending on the biomass combustion fly ash content in concrete mix, the lowest predicted freeze-thaw resistance of 300 cycles was recorded in specimens containing 30% of ash. The highest freeze-thaw resistance of 800 cycles was recorded in specimens containing 5% of biomass combustion fly ash.
4. The tests revealed that biomass combustion fly ash added to the concrete mix up to 15% by weight of cement increases the density, ultrasonic pulse velocity and compressive strength of concrete, reduces water absorption and increases the closed porosity of modified concrete; subsequently the resistance to freezing and thawing cycles is improved.
5. The obtained linear regression equations illustrate the relationships between the density, compressive strength after 28 days of curing, ultrasonic pulse velocity after 28 days of curing, and predicted freeze-thaw resistance of modified concrete.
6. The tests revealed that concrete modified with 15% of biomass combustion fly ash had better durability and freeze-thaw resistance characteristics and can be used in construction works.

Conflict of interest

None.

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