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Influence of Biofuel Combustion Fly Ash on the Properties of Concrete

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Abstract **– Cement as the binding agent in the production of concrete can be replaced with active mineral admixtures. Biofuel combustion fly ash is one of such admixtures. Materials used for the study include Portland cement CEM I 42.5 R, sand of 0/4 fraction, gravel of 4/16 fraction, biofuel fly ash, superplasticizer, and water. Six compositions of concrete were designed by replacing 0 %, 5 %, 10 %, 15 % 20 %, and 25 % of cement with biofuel fly ash. The article analyses the effect of biofuel fly ash content on the properties of concrete. The tests revealed that the increase of biofuel fly ash content up to 20 % increases concrete density and compressive strength after 7 and 28 days of curing and decreases water absorption, with corrected water content by using plasticizing admixture. It has been found that concrete where 20 % of cement is replaced by biofuel ash has higher frost resistance.**

Keywords **– Biofuel fly ash, compressive strength, concrete, frost resistance, density, water absorption.**

I. Introduction

Concrete is one of the most used industrial materials. It is produced from local raw materials and therefore is a relatively cheap construction material. Rheological and mechanical properties of concrete enable to form products and monolithic structures of required forms and characteristics.

In the recent years, power plants producing energy from biofuel have gained popularity in Lithuania. The burning of biofuel produces big amounts of fly ash that is disposed in landfills. Recycling of biofuel combustion fly ash is an important issue in Lithuania. At present, biofuel combustion fly ash is not used in the manufacturing of construction materials in Lithuania. The tests with fly ash have proven that fly ash used as a binder improves certain properties of the hardened cement paste. It also reduces the costs of manufacturing concrete structures. Fly ash enables to reduce the amount of cement and also reduces CO_2 emission in cement manufacturing. At present, the reduction of carbon print in the cement industry is one of the priority issues in the European Union and in the world.

Concrete industry is energy intensive: energy is used for the production of materials and products, and for their transportation. Therefore, it is important to minimize energy costs in the entire production cycle and this can be done by reducing the amount of cement in concrete.

Concrete structure depends on the shape, size and distribution of particles and their interconnection [1]. Each component has a certain function in the mixture. Coarse aggregates make the framework of concrete, fine aggregates fill in voids between the coarse aggregates, cement and water produce hydration products that bind all aggregates into one system – a conglomerate [2], whereas the added admixtures and additives change the properties of concrete.

Researchers [3] determined that fly ash added up to 40 % by mass of cement together with chopped sandstone, marble chips or concrete waste into the mix of paving slabs had reduced the compressive strength, density and freeze-thaw resistance of concrete and increased water absorption of all specimens.

Researchers A. Gumuliauskas and G. Abromavičius claim that the strength of conglomerate structure is mainly determined by the strength of the binding media. The highest compressive strength of concrete is obtained with the optimal concentration of the coarse aggregate, which is approximately 0.35 [4], [5].

Researchers who tested concrete mixes, where part of the cement was replaced with fly ash, determined that after 28 and 90 days of curing the highest compressive strength was obtained in the specimens containing 2.7 % of fly ash and 0–21.7 % of bottom ash, whereas the lowest compressive strength was observed in the specimens with 8.1 % of fly ash in concrete mix where cement content was reduced to 18.8 % [6].

The authors who reviewed the use of wood combustion ash in concrete manufacturing determined that higher content of ash increases water absorption of concrete specimens and reduces the density of concrete mixes. The replacement of part of the cement with ash has a negative effect on the strength properties of concrete (compressive and flexural); however the strength properties of concrete containing 10 % ash are almost the same as the properties of the control mix. Researchers also found that a number of factors, such as chemical composition, humidity and grain size distribution of ash have an effect on the properties of concrete where part of the cement is replaced by ash. These properties depend on the type of wood, combustion temperature, type of incinerator. When part of Portland cement is replaced with ash, water demand of the mix must be increased in order to maintain the same rheological properties [7].

Tests results have shown that basic components of ash are silicon dioxide, calcium, and alumina and magnesium compounds [8].

According to paper [9] describing the tests with mixes containing quartz river sand, wood ash with high calcium content increases water demand of the mix. Tests were done with the mixes where up to 16 % of cement was replaced with ash. The compressive strength of the hardened cement paste with 8 % of ash was the same as the strength of control specimens.

According to J. Deltuva, the strength and durability of any type of concrete depend on the strength, coarseness, distribution and binding properties of the aggregates, as well as the uniformity of compression of the mix [10].

J. Deltuva [10] and A. Naujokaitis [11] highlight that water in concrete mixes exists in three forms: absorbed, physically and chemically bound and free. The content of water adhered onto the surface of aggregate grains is still disputable. According to the authors [10], water permeability of the aggregates and adsorbtion of water on the aggregates' surface depends on the mineral composition, density and specific surface of the aggregates. It is difficult to determine water demand of the aggregates, especially the fine aggregates; however, the amount of water must be sufficient to wet the surface of the dry mix.

The goal of the tests described in this paper was to determine the effect of biofuel combustion fly ash on the properties of concrete.

II. Materials and Methods

The concrete was made from Portland cement, fine aggregates, coarse aggregates and biofuel combustion fly ash.

Portland cement CEM I 42.5 R meeting EN 197-1:2001 [12] requirements was used in the tested mixes. Physical and mechanical properties of the cement are presented in Table I. Chemical composition of the cement is presented in Table II.

TABLE I

Physical-Mechanical Properties of the Cement

Parameter	Value
Compressive strength after 2 days, N/mm^2	28±2
Compressive strength after 28 days, N/mm^2	54±3
Initial setting time, min	160
Soundness, mm	1.0
Consistency for normal, %	25.1
Sieve residue (90 µm sieve), %	1.5
Specific surface, cm^2/g	3700

TABLE II

Chemical Composition of the Cement

SO_3, %	Na_2O equivalent	Ignition loss, %	Insoluble matter, %	Cl^-, %
2.8	≤ 0.8	1.4	0.4	0.003

4/16 fraction gravel complying with standard EN 12620:2002 [13] requirements was used as the coarse aggregate in the tested mix.

0/4 fraction sand complying with standard EN 12620:2002 [13] requirements was used as the fine aggregate. Characteristics of the aggregates were determined prior to concrete testing. Physical properties of the sand and gravel are presented in Table III. Very effective superplasticizer added at very small amounts was used to improve the properties of concrete. This superplasticizer accelerates the initial setting time and provides high early strength to concrete. The superplasticizer is based on polycarboxylate ether. The physical properties of biofuel combustion fly ash used in the tested mixes are presented in Table IV.

Water used to produce the concrete mix must be clean and without harmful admixtures that inhibit the normal setting of concrete, i.e. potable water complying with standard EN 1008:2003 requirements [14].

TABLE III

Physical Properties of Gravel and Sand

Aggregate	Characteristics	Value
Sand	Particle density, kg/m^3	2488
	Bulk density, kg/m^3	1643
Gravel	Particle density, kg/m^3	2739
	Bulk density, kg/m^3	1381

TABLE IV

Physical Properties of Biofuel Combustion Fly Ash

Material	Bulk density, kg/m^3	Particle density, kg/m^3
Biofuel combustion fly ash	1074	2365

Six batches of concrete were produced manually in laboratory conditions for the test. The batches differed by the content of biofuel combustion fly ash. The cement content was reduced in the mix from 0 % to 25 % by replacing it with biofuel combustion fly ash. Chemical composition of the fly ash is presented in Table V. Biofuel fly ash particle size was up to 0.125 mm. The W/C ratio was maintained by reducing the amount of water and adding the required amount of plasticizer so that concrete consistency (concrete mix slump) remains the same. Additional plasticizer changes the consistency of concrete mix to the consistency value of control mix without the supplement. Concrete compositions material amount for 1 m^3 of concrete mix are presented in Table VI.

Concrete mixes were produced in the laboratory. Specimens of 10x10x10 cm dimensions were formed. After 24 hours the specimens were taken out of the forms and soaked in 20 °C water for 28 days.

The density of the specimens was determined in accordance with EN 12390-7:2009 requirements [15].

Concreted cubes were tested after 7 and 28 days of curing in water. The compressive strength of concrete was determined according to EN 12390-3:2009 [16]. The loading rate used in the compression test was 5 kN/s.

Water absorption was measured after 4 days of soaking in water. The specimens were soaked in potable (20 ± 5) °C water and kept there until the constant mass was achieved. There must be at least 15 mm space between the specimens and at least 20 mm of water above the specimens. The constant mass was achieved when the difference between weighting results every 24 h was less than 0.1 %. Prior to weighting the specimens were cleaned with a moistened cloth to remove excessive water.

The frost resistance factor K_F was calculated basing on the assumption that the specimen is frost resistant when the volume of closed pores is higher than the volume increase of water in capillary pores when it turns into ice.

TABLE V

CHEMICAL COMPOSITION OF THE FLY ASH

SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	MgO	P_2O_5	SO_3	Na_2O	MnO_2	Cl
68.53	6.51	2.15	9.96	7.16	1.14	2.09	1.04	0.98	0.33	0.11

TABLE VI

CONCRETE COMPOSITION DEPENDING ON BIOFUEL FLY ASH CONTENT

Fly ash content, %	Cement, kg	Sand, kg	Gravel, kg	Fly ash, kg	Water, kg	Plasticizer, kg	W/C	Consistence class
0	408	740	1001	0	208	0	0.51	S3
5	388	740	1001	20	197	0	0.51	S3
10	367	740	1001	41	187	0.411	0.51	S3
15	347	740	1001	61	177	0.951	0.51	S3
20	326	740	1001	82	166	1.727	0.51	S3
25	306	740	1001	102	156	2.455	0.51	S3

The frost resistance factor K_F is calculated from the following equation:

$$K_F = \frac{P_u}{0.09\,P_a} \qquad (1)$$

where: P_u – closed porosity; P_a – open porosity.

From the frost resistance factor K_F, the frost resistance of concrete was forecasted testing the function of frost resistance and frost resistance factor K_F [17].

III. RESULTS

Concrete density was tested and the test results are presented in Fig. 1. The highest density (2431 kg/m^3) was observed in specimens with 20 % of biofuel combustion fly ash added as a mineral admixture. The density of control specimens without the mineral admixture was 2411 kg/m^3. The density tended to increase from 2411 to 2431 kg/m^3. When the fly ash content was increased up to 25 %, the density decreased to 2430 kg/m^3.

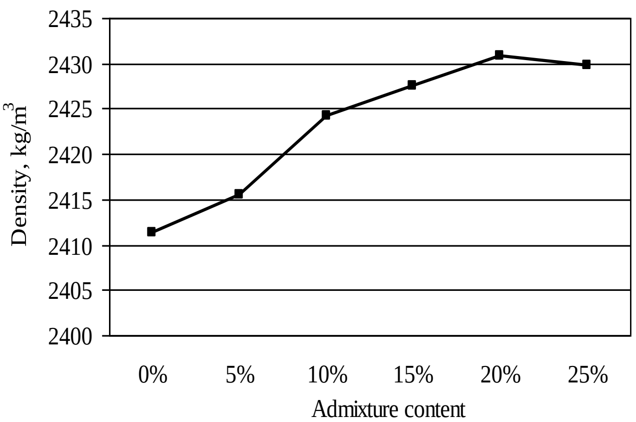

Fig. 1. Relationship between concrete density and fly ash content.

The relationship of compressive strength of specimens after 7 days of curing and biofuel fly ash content is presented in Fig. 2. The tests revealed that the strength properties of concrete directly depend on biofuel fly ash content. Specimens with 20 % of biofuel combustion fly ash demonstrated the highest strength; the average compressive strength of these specimens after 7 days of curing was 57 MPa. The lowest compressive strength of 32 MPa was observed in control specimens without biofuel fly ash admixture. With the increase of biofuel fly ash admixture up to 25 % by mass of cement the compressive strength dropped to 51 MPa.

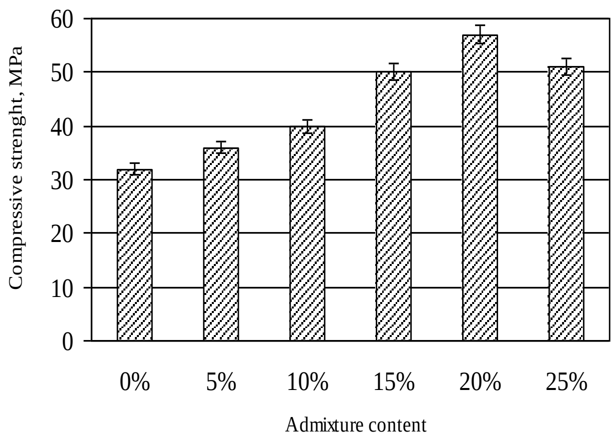

Fig. 2. Relationship between compressive strength and fly ash content after 7 days of curing.

The results of compressive strength tests after 28 days of curing are presented in Fig. 3. Specimens containing 20 % of biofuel fly ash demonstrated the best strength properties with compressive strength of 64 MPa. The lowest compressive strength of 45 MPa was observed in control specimens without biofuel fly ash admixture. The comparison of specimens with different content of biofuel combustion fly ash revealed that specimens with 20 % of mineral admixture reached 88.7 % of compressive strength during the first 7 days of curing, whereas specimens without biofuel fly ash reached 70.9 % of compressive strength after 28 days of curing. Apparently, biofuel combustion fly ash has a greater effect on the early strength of concrete.

The relationship of compressive strength after 6 months of curing and biofuel fly ash content is presented in Fig. 4. According to the test data, the strength of concrete is directly related to biofuel fly ash content. After 6 months of curing specimens containing 20 % of biofuel fly ash demonstrated the best strength properties with compressive strength of 68 MPa. The lowest compressive strength of 55 MPa was observed in control specimens without biofuel fly ash admixture. With the increase of biofuel fly ash admixture up to 25 % by mass of cement the compressive strength dropped to 62 MPa. The strength of concrete increases because fly ash is a pozzolanic admixture and reacts with calcium hydroxide produced during cement hydration. Additional quantity of calcium silicate hydrate is also contained in cement stone pores.

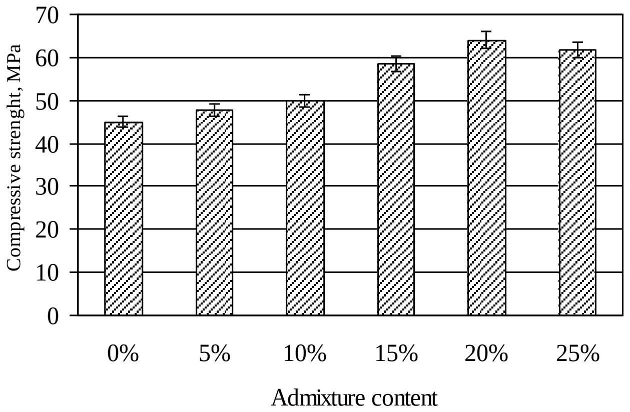

Fig. 3. Relationship between compressive strength and fly ash content after 28 days of curing.

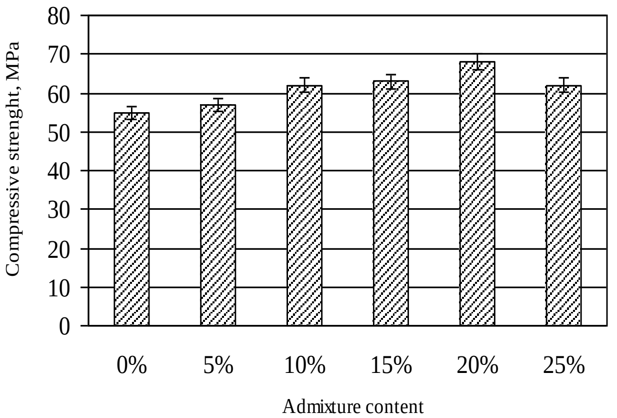

Fig. 4. Relationship between compressive strength and fly ash content after 6 months of curing.

The results of water absorption are presented in Fig. 5. Water absorption of concrete specimens tended to decrease until the fly ash content in the cement mix reached 20 %; with further increase of the fly ash content in the mix the water absorption of the specimens started to increase. The highest water absorption of 4.72 % was observed in the control specimens without biofuel fly ash and the lowest water absorption was observed in the specimens containing 20 % of biofuel fly ash. The diagrams illustrate a direct relationship between water absorption, density and compressive strength. Water absorption and open porosity of concrete specimens decrease with higher density and compressive strength.

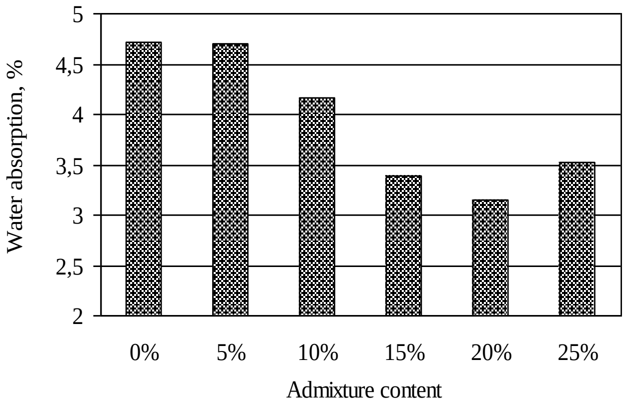

Fig. 5. Relationship between water absorption and fly ash content.

The diagrams illustrate that water absorption data correlate with density data. Water absorption decreases with higher density of the specimens and, on the contrary, lower density causes water absorption to decrease.

The compressive strength of concrete increases and water absorption decreases with higher biofuel fly ash content due to hydraulic properties of biofuel combustion fly ash.

Fig. 6 illustrates absorption kinetics of concrete specimens with different biofuel combustion fly ash content. The specimens were soaked in water for 7 days. After 7 days of soaking, the highest water absorption of 4.75 % was observed in the control specimen without biofuel fly ash, whereas the lowest water absorption of 3.20 % was recorded in the specimens containing 20 % of biofuel fly ash. The highest water absorption rate was observed in the specimens without biofuel fly ash because after one day of soaking their water absorption reached 95 % of the total absorption. The slowest water absorption rate was recorded in the specimens containing 20 % of biofuel combustion fly ash: after one day of soaking their water absorption reached 81 % of the total absorption.

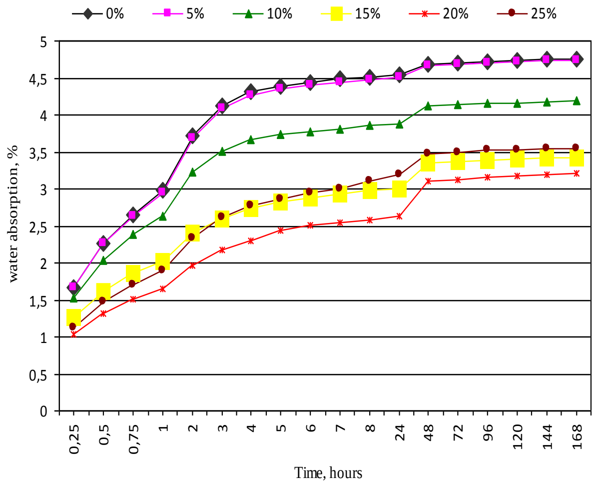

Fig. 6. Relationship between water absorption kinetics and fly ash content.

After the tests of porosity and water absorption in hardened concrete specimens, the frost resistance factor K_F was calculated. The calculation results are presented in Table VII. The data illustrate that frost resistance factor increases with the increase of biofuel fly ash content up to 20 %.

TABLE VII

FROST RESISTANCE FACTOR K_F VALUES

Ash content in concrete mix, %	K_F
0	2.28
5	2.83
10	2.82
15	4.73
20	8.18
25	6.16

The forecasted frost resistance of the specimens according to the number of freeze-thaw cycles ranged between 350 and 1030 cycles depending on biofuel combustion fly ash content. The lowest forecasted frost resistance in cycles was observed in the specimens without biofuel fly ash. The forecasted frost resistance in control specimens was approximately 350 cycles. The highest forecasted frost resistance up to 1030 cycles was calculated for the specimens containing 20 % of biofuel combustion fly ash. With the increase of biofuel fly ash content up to 25 % the forecasted frost resistance in cycles starts to decrease.

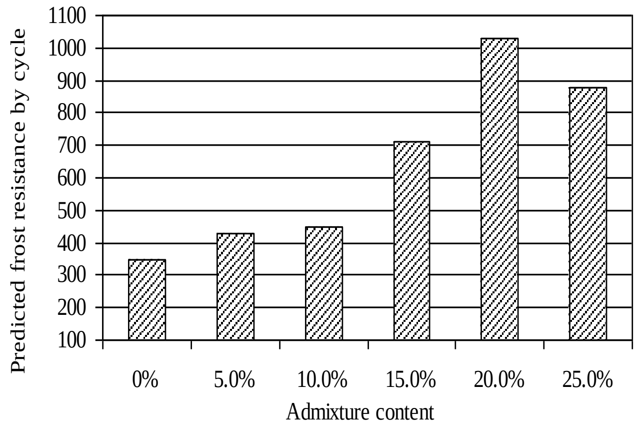

Fig. 7. Relationship between the forecasted freeze-thaw cycles and fly ash content.

IV. CONCLUSION

The test results revealed the trend of improving properties of the hardened cement paste when up to 20 % of cement in concrete mix is replaced by biofuel combustion fly ash.

The with the increase of biofuel fly ash content the density of the specimens increased and at 20 % of biofuel fly ash in the mix the density reached 2430 kg/m^3. Meanwhile, the density of control specimens without biofuel fly ash was 2411 kg/m^3.

The highest compressive strength of the hardened cement paste was observed in the specimens containing 20 % of biofuel fly ash; after 7 and 28 days of curing the compressive strengths of the specimens modified with ash were 57 and 64 MPa respectively. The lowest compressive strength was observed in the control specimens without the mineral admixture: after 7 days of curing their compressive strength was 32 MPa and after 28 days of curing it was 45 MPa.

Specimens containing 20 % of biofuel fly ash demonstrated the lowest water absorption of 3.15 % and the highest water absorption of 4.72 % was recorded in the control specimens not modified with biofuel fly ash.

The forecasted frost resistance in freeze-thaw cycles ranged between 350 and 1030 cycles depending on biofuel fly ash content in the specimens. The highest forecasted frost resistance of 1030 freeze-thaw cycles was in the specimens containing 20 % of biofuel fly ash and the lowest forecasted frost resistance of 350 cycles was in the control specimens without biofuel fly ash.

The properties of concrete specimens depend on biofuel combustion fly ash content. The tests revealed that the optimal biofuel fly ash content is 20 %. The specimens produced from concrete mix where 20 % of the cement is replaced by biofuel fly ash demonstrated higher compressive strength, density, forecasted frost resistance and lower water absorption.

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