

## INFLUENCE OF SILICEOUS AND CALCAREOUS FLY-ASHES ON PROPERTIES OF CEMENT MORTARS

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### ABSTRACT

Care of the environment in accordance with the principles of sustainable development introduces the possibility and need for waste recycling. Construction and building industries have the greatest potential for reuse of waste. The article presents the results of investigations of cement mortars – tests of compressive and tensile strength after 28 and 56 days of curing – for normative mortars and mortars containing fly ashes – calcareous and siliceous ash – in their composition. To make the samples, the Portland cement CEM I 32,5 R, 42,5R and natural aggregate with graining of 0–2 mm were used. Concrete with siliceous and calcareous admixtures was made in six lots where the ash was added in the quantity of 2%, 5%, 10% of the cement mass or the 2%, 5%, 10% of cement was replaced by ashes. After the tests, it was stated that the siliceous fly-ash admixture increases the compressive and bending strength in comparison to the mortars with the calcareous ash admixtures.

**Keywords:** cement mortar, fly-ashes, strength of materials

### INTRODUCTION

Care of the environment in accordance with the principles of sustainable development and the perspective of depletion of mineral fuels influences the policy of European Union aiming at the promotion of a new approach to the problem of use of renewable energy sources and dynamic development trends in the states – members of the European Union. The introduction of innovative solutions within a framework of the strategy “Europe 2020” encompasses also energy sector. Apart from conventional fuels, successful attempts of biomass combustion are observed [Deja 2012, Golec 2007, Rutkowska 2014]. The combustion of by-products arising as a result of coal combustion have been disposed for many years on the earth surface or underground in mines. However, this form of fly-ash recycling results in degradation of surface and underground water due to the penetration of components from the wastes in the area of their disposal [Rosik-Dulewska and

Karwaczyńska 2008]. Hence, investigations are necessary to encompass i.a. the evaluation of possibilities of application of fly-ashes in the recycling of materials used in the building industry.

The idea of application of fly-ash in the production of concrete and cement mortars is not new. Even the ancient Romans discovered that the concrete properties can be improved by additions of volcanic ashes. Fly-ashes were applied in the USA in the 1930's [ACI 1996, Comões 2002, Joshi 1997, Malhotra and Wesche 1991]. In Poland and Europe, the siliceous fly-ashes have wide application in the cement and concrete technology [Giergiczny 2013]. Present among the ingredients of concrete, cement and cement mortar, the fly-ashes cause that the quantity of the applied cement clinker is lower and, in turn, it increases savings in mineral fuels and natural materials as well as reduction of the emitted carbon dioxide and environment pollution [Deja 2012]. It is an important problem because in the production of cement a lot of energy is used and there is ca.

1.6 billion of tones of CO<sub>2</sub> emitted per year [Elahi 2010]. Wide application of the fly-ash in the building industry is mainly due to: its high fineness, close to this of the cement, its chemical constitution and phase composition, close to those of clay materials, as well as its reactivity, particularly the pozzolanic activity [Giergiczny 2013].

The paper presents the results of investigations which were aimed to analyze how the siliceous and calcareous fly-ashes added to cement mortars influence the technical properties of the mortar.

## METHODOLOGY OF INVESTIGATIONS

The research and design procedures are based on the directives contained in the currently binding Polish building standards. The tests were performed in the Laboratory of Building Constructions of Warsaw University of Life Sciences.

The cement mortar samples being tested were calculated according to the standard PN-B-14501:1990 "Ordinary building mortars". To perform the tests, it was assumed a mortar composition according to the standard. To prepare the samples, ordinary aggregate with the graining 0–2 mm (sand) and Portland cement 32.5 without admixtures were used.

To investigate the bending strength, the samples of the size 40 x 40 x 160 mm were used. The investigations were performed according to the directives contained in the standard PN-EN 1015–11:2001. The investigations of the compressive strength were performed according to the standard PN-EN 1015–11:2001 on the halves of the beam samples remaining from the performed bending strength tests. The samples were subjected to the tests in a testing machine with special pads, after 28 and 56 days of the concrete curing period.

## FLY-ASHES FOR CONCRETES

Grains of fly-ash have a diameter from 1 to 150 μm – it is close to the cement grain diameter falling into the range 7–12 μm [Joshi 1997]. They usually have a spheroid shape, but they can also be prismatic and irregular. They are characterized by high fineness and contain ca. 80% of glass. The Blaine specific surface is equal 250–550 m<sup>2</sup>/kg [Alonso 1991]. According to Malhotra and Ramezani pour [Malhotra], the graining and the surface of the fly-ash is not connected to its source of origin. The grains bigger than 125 μm have high porosity. It is due to the higher share of coal. According Alonso and Wesche [Alonso 1991], the pozzolanic activity of the fly-ashes depends on the silica content.

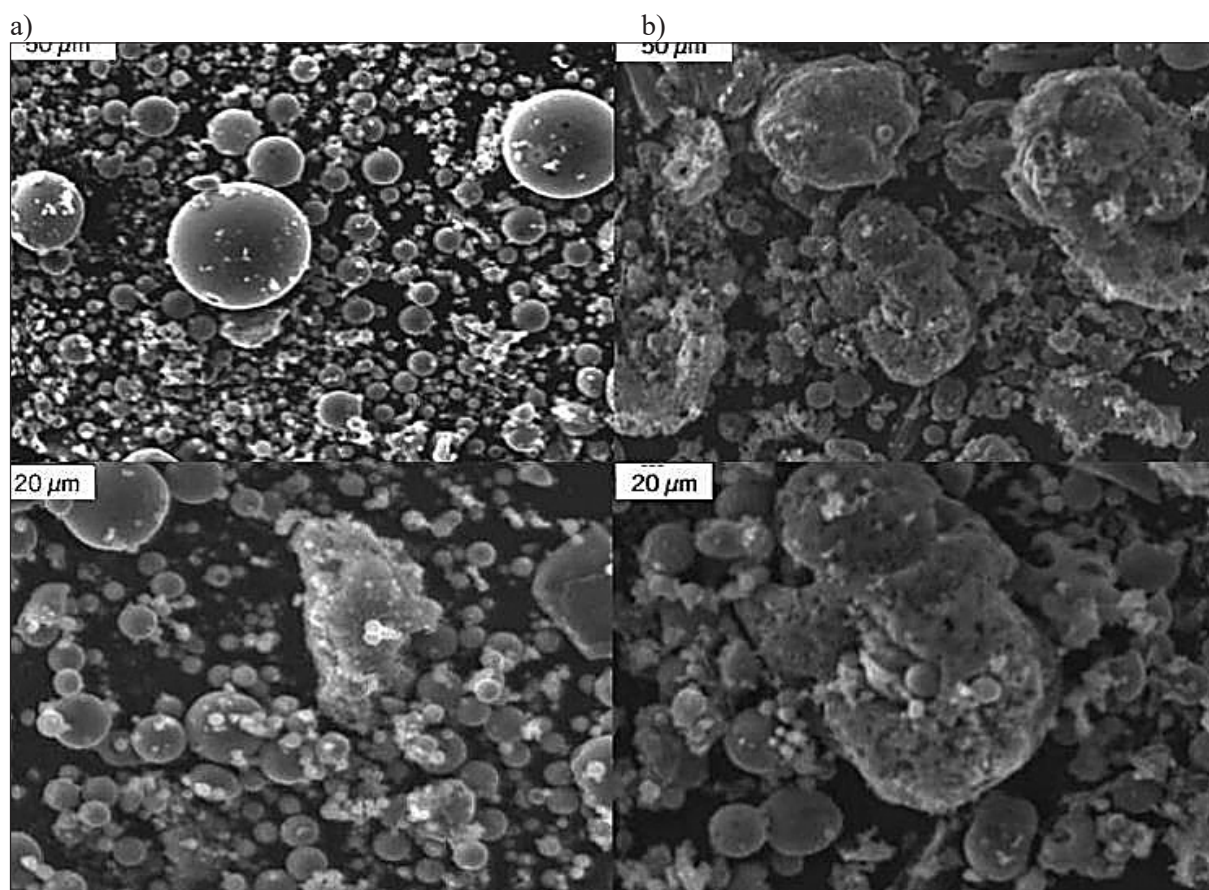
Taking the chemical properties into consideration, the siliceous fly-ashes contain mostly the reactive silica (SiO<sub>2</sub>) and aluminum oxide (Al<sub>2</sub>O<sub>3</sub>); they have pozzolanic properties – they react with calcium hydroxide in the presence of water, giving hydrated calcium aluminates and silicates. They also contain iron oxide (Fe<sub>2</sub>O<sub>3</sub>) and other compounds. The calcareous fly-ashes, however, have hydraulic and/or pozzolanic properties and contain mainly the reactive calcium oxide (CaO), reactive silica (SiO<sub>2</sub>) and aluminium oxide (Al<sub>2</sub>O<sub>3</sub>) [ACI 1996, Malhotra and Giergiczny 2013].

The fly-ash, applied in the investigations, is a very fine ash with hydraulic and/or pozzolanic properties. Table 1 shows the composition of fly-ashes used in the investigations.

Figure 1 shows fly-ashes with various level of ignition loss: a) ash with ca. 2.2% of ignition loss, b) ash with ca. 17.9% of ignition loss.

**Table 1.** Chemical composition of fly-ash [research report 2014]

Contents	Calcareous fly-ash [% of mass]	Siliceous fly-ash [% of mass]
Ignition loss	2.1	4.05
SiO <sub>2</sub>	42.8	50.5
Al <sub>2</sub> O <sub>3</sub>	20.5	21.8
CaO	22.5	4.1
MgO	0.9	2.5
SO <sub>3</sub>	4.3	0.7
Na <sub>2</sub> O	0.1	1.21
K <sub>2</sub> O	0.2	3.02
CaO free	4.1	-



**Figure 1.** Grains of fly-ashes with various level of ignition loss [Giergiczny 2007]:  
 a) ash with ca. 2.2% of ignition loss, b) ash with ca. 17.9% of ignition loss

## LABORATORY TESTS

To make the cement mortar, the 1<sup>st</sup> type Portland cement without admixtures (CEM I 32,5 R) was used (Cement Plant „Ożarów”, Poland). The fly-ashes used for the samples came from two thermal-electric power stations: Siekierki (Warsaw – siliceous fly-ash – Lafarge) and Bełchatów (calcareous fly-ash); they complied with the requirements given in the standard PN-EN 450-1+A1:2009 on the requirements for the fly-ashes applied in the concrete production.

The tests consisted in the comparison of features of cement mortars produced in the traditional way as well as the mortars containing the combustion by-products. To do this, three types of mortar samples were prepared:

- 1) without any admixtures,
- 2) with addition of the siliceous fly-ash,
- 3) with addition of the calcareous fly-ash.

Apart of this, for each type of the mortars 6 series were made – in the three of them the normative composition was doped by fly-ashes con-

stituting 2, 5 and 10% of cement mass, in the remaining three of them 2, 5 and 10% of the cement mass was removed and substituted by fly-ashes.

All of the mortars were prepared in the Laboratory of Building Constructions of the Faculty of Civil and Environmental Engineering of WULS. During the tests the compression and bending strength after 28 and 56 days of curing were investigated. To prepare the cement mortar samples, the normative sand CEN – Kwarcmix with grain size 0–2 mm as well as the Portland cement CEM I 42,5 without admixtures, with density 3.1 kg/m<sup>3</sup> and early strength R were used. The composition of normative mortar was prepared according to the standard PN-EN 196-1:2006 for each of the three beam samples, according to the following proportions: 1 part of cement, 3 parts of normative sand, 0.5 part of water (water/cement ratio W/C = 0.5). Due to this, the normative mortar to make three beam samples (1 mould) contains of:

- 450 ± 2 g of cement,
- 1350 ± 5 g of normative sand, according to the standard PN-EN 196-1:2006,
- 225 ± 1 cm<sup>3</sup> of water.

**Table 2.** Composition of a cement mortar modified with calcareous and siliceous fly-ashes

Sample marking	Quantity of compounds [g]				water/cement ratio
	cement	aggregate	water	calcareous / siliceous fly-ash	
Normative mortar	450	1350	225	0	0.500
+2%	450	1350	225	9	0.500
+5%	450	1350	225	22.5	0.500
+10%	450	1350	225	45	0.500
-2%	441	1350	225	9	0.510
-5%	427.5	1350	225	22.5	0.526
-10%	405	1350	225	45	0.556

Table 2 presents the composition of individual samples.

## TEST RESULTS – COMPRESSIVE AND BENDING STRENGTH

To determine the bending strength of the beam samples made of the cement mortar, the testing machine with a breaking set (Figure 2) has been used. The sample being tested was placed on the two lower supports (rollers), whereas the upper support was imposed by a load evoking the sample break. The pressure was increased evenly by  $50 \pm 10$  N/s, till the moment in which the sample is broken [PN-EN 1015–11:2001].

The compressive strength ( $f$ , MPa) is calculated from the formula

$$f = 1,5 \frac{F \cdot l}{b \cdot d^2} \text{ [MPa]} \quad (1)$$

where:  $f$  – compressive strength  
 $F$  – maximum loading force [N]  
 $l$  – distance between the lower supports [mm]  
 $b$  – sample width [mm]  
 $d$  – sample height [mm].

The compressive strength tests have been carried out on the halves of the beam samples, broken in the bending strength test (Figure 3). The test has been performed in the testing machine with a special pad. The surfaces of the samples were evenly imposed by the load increasing with velocity  $2400 \pm 200$  N/s, till the sample failure. The compressive strength is calculated according to the formula [PN-EN 1015–11:2001]

$$f_c = \frac{F}{A} \text{ [MPa]} \quad (2)$$

where:  $f_c$  – compressive strength  
 $F$  – maximum load [N]  
 $A$  – area of the compressed surface [mm<sup>2</sup>].

Tables 3–6 present the results of the compressive and bending strength tests for the cement mortar samples. The tests were performed after 28 and 56 days of mortar curing.

The results obtained from the tests show (Figures 3–6) that the compressive strength of the cement mortars exceeds the value predicted in the standards. The mortars without admixtures were the reference samples. For the siliceous ash series the average compressive strength of the reference samples after 28 days of curing was equal 44.22 MPa, for the calcareous ash series – 38.44 MPa; after 56 days of curing, it was equal 55.52 MPa and 44.90 MPa, respectively. Along with the increase of the siliceous ash content, the mortar's strength increased. For the mortars doped with the siliceous fly-ash constituting 2% of content, the average strength was equal 47.14 MPa, however, for the mortar sample with the 5% of ash content it was equal 48.44 MPa. The samples with the 10% of siliceous ash content reached lower compressive strength – equal to 45.57 MPa. If the cement was replaced by the fly-ash, the compressive strength decreases along with the increase of the ash amount. After 56 days of curing, next measurements were performed and they showed that the compressive strength increased. The mortars doped with the siliceous fly-ash constituting 2% of content showed the strength increase from 47.14 to 59.90 MPa. For the mortar samples doped with the 5% of ash content the strength increased to 60.47 MPa whereas for those doped with the 10% of ash content – to 64.59 MPa and it was the

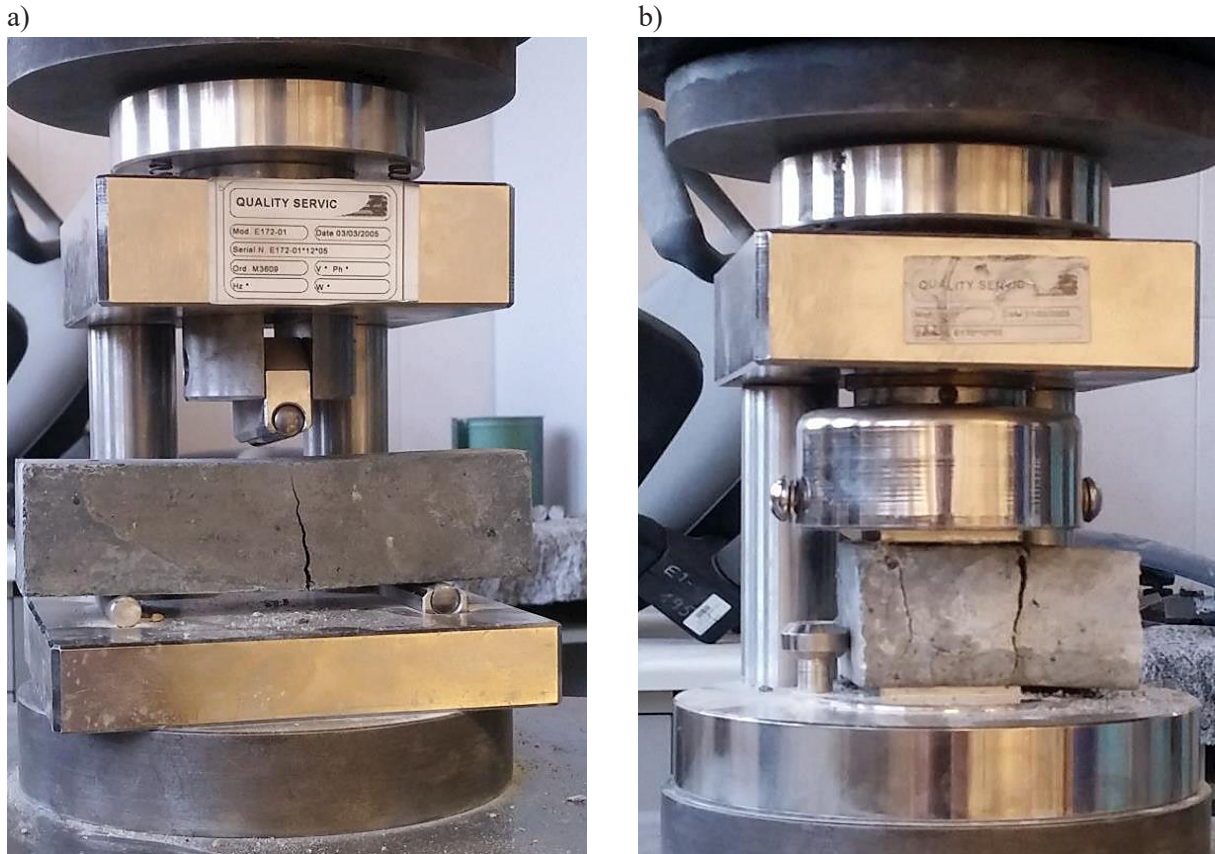


Fig. 2. Samples placed in the testing machine: a) bending strength test, b) compressive strength test

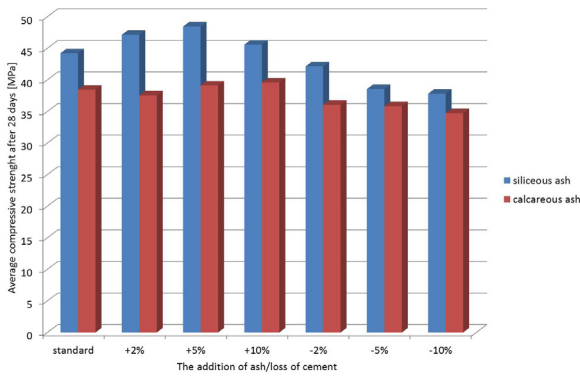


Figure 3. The average compressive strength after 28 days

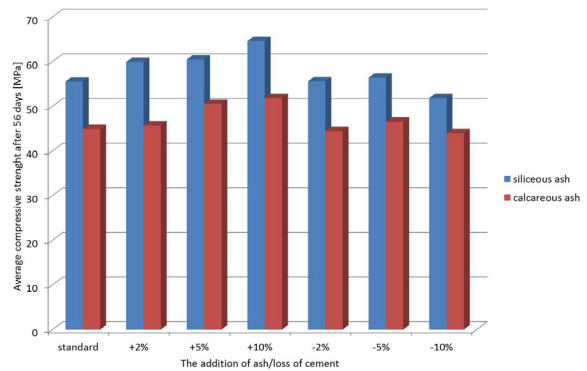


Figure 4. The average compressive strength after 56 days

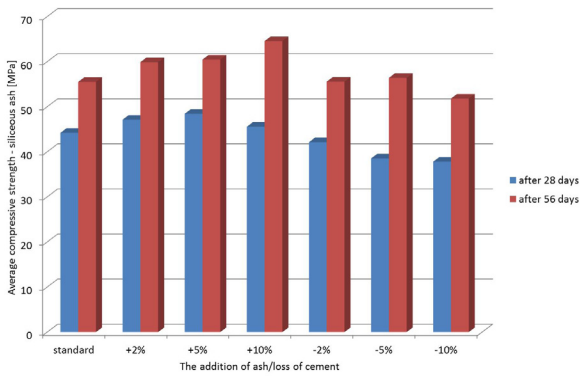


Figure 5. The average strength of concrete with siliceous ash after 28 and 56 days

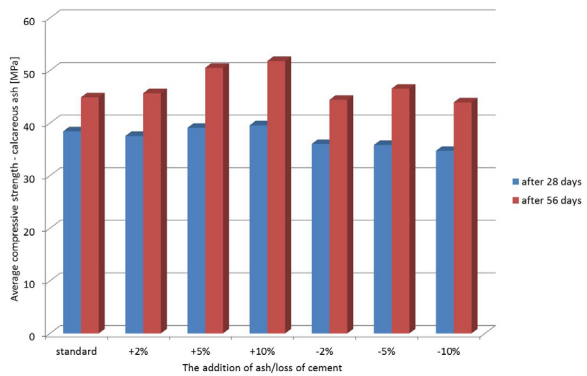


Figure 6. The average strength of concrete with calcareous ash after 28 and 56 days

**Table 3.** Results of the compressive and bending strength tests after 28 days of curing of the mortar with siliceous fly-ashes

Sample marking	Mass [kg]	Sample sizes			Bending strength [MPa]	Average bending strength [MPa]	Compressive strength [MPa]		Average compressive strength [MPa]
		height [mm]	width [mm]	length [mm]					
Norma-tive mortar	0.589	40.81	40.29	159.93	7.60	7.95	43.75	44.38	44.22
	0.577	41.56	40.15	159.58	8.44		44.69	43.75	
	0.586	40.90	40.09	159.44	7.83		44.38	44.38	
+2%	0.590	41.79	40.09	159.98	8.57	8.56	46.88	48.13	47.14
	0.595	41.55	40.41	159.76	8.60		47.81	46.88	
	0.597	41.86	40.17	159.61	8.52		46.25	46.88	
+5%	0.593	41.44	40.58	159.78	8.83	9.01	48.13	48.75	48.44
	0.588	40.76	39.92	160.09	9.27		48.75	48.13	
	0.589	40.90	40.21	159.91	8.92		48.44	48.44	
+10%	0.612	41.72	40.51	160.07	8.72	8.71	45.31	46.25	45.57
	0.605	42.07	40.16	160.19	8.44		44.69	45.31	
	0.601	41.71	39.87	160.04	8.97		46.25	45.63	
-2%	0.591	42.03	40.11	159.81	7.41	7.88	42.50	42.19	42.14
	0.587	41.32	40.25	159.89	8.19		41.88	42.19	
	0.588	41.50	40.08	159.89	8.04		42.19	41.88	
-5%	0.590	41.61	40.02	159.94	8.23	8.39	38.75	38.44	38.54
	0.593	40.85	40.50	160.07	8.32		38.4	38.75	
	0.584	40.34	40.03	160.33	8.64		38.13	38.75	
-10%	0.599	41.32	40.55	159.86	8.02	8.25	37.50	37.81	37.81
	0.582	40.70	39.89	159.80	8.17		37.50	38.13	
	0.588	41.59	40.46	159.91	8.57		38.13	37.81	

**Table 4.** Results of the compressive and bending strength tests after 56 days of curing of the mortar with siliceous fly-ashes

Sample marking	Mass [kg]	Sample sizes			Bending strength [MPa]	Average bending strength [MPa]	Compressive strength [MPa]		Average compressive strength [MPa]
		height [mm]	width [mm]	length [mm]					
Norma-tive mortar	0.581	40.88	41.07	160.42	7.87	8.64	55.63	55.31	55.52
	0.576	40.91	39.99	159.83	9.41		56.25	55.31	
	0.580	40.36	41.57	160.10	8.64		55.00	55.63	
+2%	0.586	41.25	39.95	159.73	8.83	8.79	58.13	60.31	59.90
	0.596	40.60	41.51	159.65	8.77		59.69	61.88	
	0.591	41.50	40.68	160.04	8.78		59.06	60.31	
+5%	0.600	40.76	40.49	160.49	9.37	8.22	60.00	58.75	60.47
	0.591	41.01	40.20	160.00	9.98		61.25	60.63	
	0.598	42.75	40.54	161.04	8.30		60.94	61.25	
+10%	0.597	40.95	40.08	159.86	9.82	9.50	64.69	66.25	64.58
	0.596	42.99	40.19	160.32	8.68		63.44	65.00	
	0.607	40.65	40.00	160.07	9.99		63.13	65.00	
-2%	0.591	40.63	40.70	159.55	8.71	8.69	54.38	55.00	55.57
	0.608	40.33	43.00	160.02	8.69		55.94	56.25	
	0.598	41.85	40.45	159.89	8.68		56.25	55.63	
-5%	0.599	40.83	40.14	160.49	9.41	9.35	55.00	56.25	56.41
	0.591	41.45	40.08	160.97	9.37		56.88	57.50	
	0.600	41.04	40.30	160.87	9.28		56.88	55.94	
-10%	0.586	41.38	39.96	159.85	8.77	8.87	51.25	51.25	51.82
	0.591	40.85	40.70	159.73	9.06		52.19	51.25	
	0.595	41.03	40.55	159.60	8.79		51.22	53.75	

**Table 5.** Results of the compressive and bending strength tests after 28 days of curing of the mortar with calcareous fly-ashes

Sample marking	Mass [kg]	Sample sizes			Bending strength [MPa]	Average bending strength [MPa]	Compressive strength [MPa]		Average compressive strength [MPa]
		height [mm]	width [mm]	length [mm]					
Norma-tive mortar	0.590	39.60	41.13	160.06	8.37	8.15	38.75	38.44	38.44
	0.591	39.68	41.41	159.87	8.05		38.13	39.06	
	0.591	39.78	41.27	160.17	8.04		38.13	38.13	
+2%	0.585	40.14	41.16	160.07	7.69	7.79	37.50	36.88	37.55
	0.584	39.89	41.24	159.96	7.66		38.13	36.25	
	0.592	40.22	41.64	159.96	8.02		40.31	36.25	
+5%	0.569	40.26	40.34	159.85	8.26	8.23	39.06	39.06	39.11
	0.574	39.78	40.98	159.96	8.33		40.31	39.06	
	0.577	40.07	40.33	159.53	8.11		38.13	39.06	
+10%	0.573	39.92	40.3	159.76	7.82	7.84	39.38	39.69	39.58
	0.578	40.10	41.25	159.66	7.91		39.06	40.00	
	0.572	40.03	40.87	159.33	7.79		39.38	40.00	
-2%	0.581	39.93	40.33	159.49	7.21	7.23	35.94	36.25	36.04
	0.577	39.84	40.42	159.64	7.25		36.25	35.94	
	0.579	39.95	40.89	159.87	7.36		36.25	35.66	
-5%	0.567	40.00	40.81	159.98	6.66	6.81	36.56	35.66	35.83
	0.570	40.34	40.49	160.21	6.83		36.25	35.66	
	0.570	40.50	40.24	159.75	6.93		35.94	35.00	
-10%	0.568	40.18	40.12	159.56	7.18	7.46	35.63	35.94	34.79
	0.569	39.90	40.57	159.67	7.90		35.00	34.38	
	0.563	40.16	40.66	159.86	7.32		32.81	35.00	

**Table 6.** Results of the compressive and bending strength tests after 56 days of curing of the mortar with calcareous fly-ashes

Sample marking	Mass [kg]	Sample sizes			Bending strength [MPa]	Average bending strength [MPa]	Compressive strength [MPa]		Average compressive strength [MPa]
		height [mm]	width [mm]	length [mm]					
Norma-tive mortar	0.583	40.27	41.30	159.84	8.96	8.82	42.50	47.81	44.90
	0.587	40.29	41.49	160.12	8.91		45.00	45.63	
	0.580	39.96	41.54	160.31	8.59		44.69	43.75	
+2%	0.574	40.31	41.54	160.02	8.65	8.79	46.88	46.25	45.68
	0.576	40.05	40.85	160.04	8.70		45.94	45.00	
	0.574	40.41	40.79	160.09	9.02		45.63	40.38	
+5%	0.582	40.40	40.84	160.42	8.55	8.87	51.56	50.69	50.52
	0.580	40.05	41.21	160.03	9.08		50.63	50.00	
	0.584	40.37	41.05	159.89	8.97		50.00	50.31	
+10%	0.577	39.91	40.92	159.97	8.52	8.82	51.25	50.94	51.82
	0.571	40.22	40.86	160.13	8.62		51.88	52.19	
	0.586	40.53	41.10	159.97	9.33		52.19	52.50	
-2%	0.574	40.32	40.86	159.93	8.96	8.12	42.81	43.13	44.43
	0.570	40.26	40.50	160.12	8.00		44.69	45.63	
	0.570	40.24	40.54	159.85	8.00		45.00	45.31	
-5%	0.570	39.95	40.31	159.98	8.39	8.44	46.88	47.50	46.56
	0.572	40.44	40.48	160.10	8.61		46.25	46.25	
	0.574	40.15	40.35	160.15	8.30		46.88	45.63	
-10%	0.578	39.97	41.10	160.17	8.68	9.06	43.75	44.69	43.96
	0.585	40.30	41.02	160.80	9.46		44.06	43.75	
	0.575	40.25	40.93	160.53	9.05		44.06	43.44	

highest value of the compressive strength reached by the samples. If the cement was replaced by the fly-ash, the samples with 2% and 5% ash content reached higher compressive strength than the samples without the ashes.

For the mortars doped with the calcareous ashes, the compressive strength both after 28 and 56 days of curing was lower than for the mortars doped with the siliceous ashes. The tests performed after 28 days of curing showed that the mortars doped with 2% content of the calcareous ash reached the strength lower by 9.59 MPa – it was equal 37.55 MPa. After 56 days the strength was lower by 14.22 MPa than the strength for the mortar samples with the siliceous ash – it was equal 45.68 MPa. For the samples doped with 5% of the ashes, the compressive strength was equal 39.11 MPa after 28 days of curing and 45.68 MPa after 56 days. For the samples doped with 10% of the calcareous ashes, the average value was equal 39.58 MPa after 28 days of curing and 51.81 MPa after 56 days. They were higher values of compressive strength. If the cement was replaced by the calcareous fly-ash, the compressive strength both after 28 and 56 days of curing was lower than the strength for the samples without admixtures.

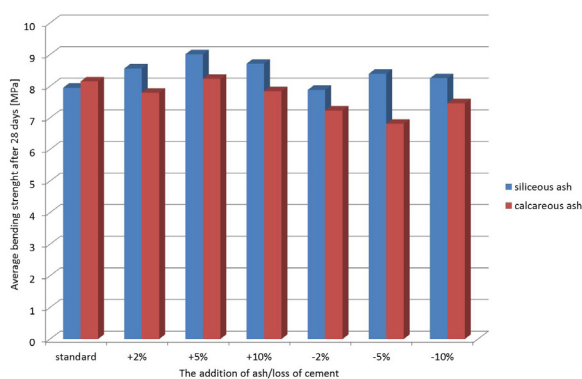


Figure 7. The average bending strength after 28 days

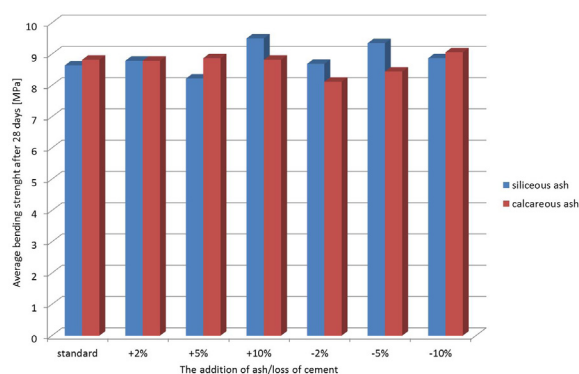


Figure 8. The average bending strength after 56 days

Figures 7 and 8 present the results of bending strength tests for the cement mortar samples. The tests were performed after 28 and 56 days of curing. The highest value of the bending strength after 56 days – equal to 9.35 MPa – was reached by the samples where the 5% of cement was replaced by the siliceous ash. The lowest value – equal 8.22 MPa – reached the mortar doped with the 5% ash content. The values of the bending strength reached by all of the samples after 28 days, fell in the range 7.88–9.01 MPa and after 28 days – in the range 8.22–9.35 MPa. The values of the bending strength for the mortars doped with the calcareous ash after 28 days of curing fell in the range 6.81–8.23 MPa and after 56 days all of the values increased and fell in the range 8.12–9.06 MPa. The highest value of the bending strength, equal to 9.06 MPa, was observed for the samples where the 10% of cement was replaced by the calcareous ash.

## ANALYSIS OF THE RESULTS OF THE PERFORMED TESTS

The tests of several cement mortars containing the admixture of siliceous and calcareous ash in quantity of 2, 5 and 10% of cement mass (the ash as an additional ingredient and as a cement substitute) were performed.

The influence of ashes was evaluated on the basis of the results of the tests performed for the cement mortars (tests of compressive and bending strength after 28 and 56 days of curing). The ash admixture had smaller or greater influence on each of the tested features. The compressive strength tests of the cement mortars showed that the increasing ash content positively affects the compressive strength – the higher ash content the higher compressive strength. If the cement was replaced by the ash, the compressive strength decreased along with the increase of the ash quantity. In the compressive strength tests performed after 28 and 56 days, the strength increase was observed along with the concrete curing time. The strength of the mortars with the siliceous ash admixture was higher than of the mortars with the calcareous ash admixture.

The bending strength for the mortars with the siliceous ash admixture was higher than this of the samples with the calcareous ash admixture. Moreover, the tests showed that along with the increase of the ash content till 5% (the ash



added and replaced) the value of the strength increases, whereas if the content is equal 10%, the strength decreases.

## CONCLUSIONS

The application of fly-ashes in production of cement mortar has significant ecological and economic advantages: it causes reduction in emission of carbon dioxide, optimization of cement consumption, savings of raw materials and consumption of combustion by-products. Basing on the performed investigations, the following conclusions have been put forward:

1. The admixture of siliceous and calcareous fly-ash affects the mechanical properties of cement mortars.
2. The compressive strength increase for the mortars with the siliceous fly-ash admixture in comparison with the mortars with the calcareous fly-ash was observed.
3. It was established that along with the concrete curing time the compressive strength of the mortars with the siliceous and calcareous ash increases. However, it does not exceed the values for the unmodified mortar and the mortar with the cement replaced by fly-ashes.
4. Basing on the bending strength tests, it was established that the highest value of this strength was reached by the mortar with the 10% admixture of siliceous ash.
5. It was observed that from among the fly-ash admixtures being applied the siliceous ash admixture improves the bending strength of the mortars made of the cement doped in such way.

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