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Research on the Frost Resistance of Concretes Modified with Fly Ash

Jacek Halbiniak, Bogdan Langier

Department of Technology of Building Processes and Materials
Czestochowa University of Technology, Faculty of Civil Engineering
Akademicka 3, 42-200 Częstochowa, halbiniak@wp.pl;langier@op.pl

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Summary. The paper presents the influence of adding fly ashes and air-entraining admixture on the frost resistance of concrete tested by the direct method and on the characteristics of air pores. The frost resistance test was done for 150 freeze-thaw cycles. The porosity structure of concrete composites was tested by means of a device for automatic image analysis that uses the computer program Lucia Concrete. The analysis involved control concrete and concrete with the addition of fly ash – half the maximum permissible quantity – that was air-entrained with various doses of air-entraining admixture.
Key words: concrete, fly ashes, air pores characteristics, frost resistance.

INTRODUCION

Concrete durability is a set of designed properties that the material retains for the longest possible usage period of the engineering construction. The basic factor that determines the usefulness of concrete for a construction is its compressive strength. However, there are other factors that influence concrete durability in a construction besides its strength, like for example proper selection of ingredients and their appropriate quality, proper moulding, curing and processing, the influence of corrosive environments, as well as cement slurry microstructure and the structure of the aggregate-cement slurry transitory layer [5, 7. 9, 11, 12, 15, 16].

Concrete is a composite whose features can be shaped by additives: micro-fillers and admixtures. They make it possible to obtain concretes with special properties, but to obtain high frost resistance of concretes with a large quantity of additives a proper air-entrainment is necessary [10, 19].

The norm PN-EN 206-1 introduces concrete exposure classes from XF1 to XF4 dependent on the influence of frost on concrete. The XF1 class includes concretes (vertical elements) that are moderately saturated with water, without anti-icing agents. Vertical concrete elements exposed to weather conditions and anti-icing agents should be made with the XF2 class concrete. Horizontal concrete elements , highly saturated with water without anti-icing agents, exposed to frost should be made with the XF3 class concrete. Concrete surfaces of roads and bridges, exposed to high saturation with water and anti-icing with chemical agents should be made with the XF4 class concrete. The XF2, XF3 and XF4 concretes require air-entrainment of the concrete mix. Concretes that belong to the above-mentioned exposure classes should meet the following requirements, presented in Table 1.

The content of air in road surface concretes presented in the Polish catalogue [8] depends on the maximal diameter of aggregate grains. The values are shown in Table 2.

According to German requirements, the minimal content of air in road surface concretes should be: 4% for concretes without plasticizers and 5% for concretes with plasticizers, according to [20].

According to French requirements, the minimal amount of air in surface concretes should be 3%, and the -maximal – 6%, according to [1].

Air-entraining admixtures are used to form microscopic air bubbles with a diameter of approximately 50µm. The air bubbles are distributed in the cement slurry and they break the continuity of capillaries, which leads to higher resistance of concrete to freeze-thaw cycles. When water in saturated concrete turns from a liquid state to a solid state, its volume increases and the ice squeezes into empty air bubbles. Air-entraining makes concrete more frost resistant and the concrete mixture becomes more workable.

Air-entraining admixtures change the structure of the cement slurry from micro-capillary to micro-porous (Fig. 1). The admixture has a foaming effect and forms enclosed air bubbles with the diameter of approximately 20-50µm, which are evenly distributed. As the concrete hardens, the surface of the air bubbles undergoes mineralization and becomes the phase of the hardened concrete. They break the capillary network and reduce the rise of water [2,6].

Table 1. Concrete mix composition requirements according to PN-EN 206-1

Hazard type	Exposure class	Minimal quantity of cement [kg/m³]	Maximal W/C ratio	Minimal strength class of concrete
Aggression caused by freezing and thawing	XF1	300	0.55	C30/37
	XF2	300	0.55	C25/30
	XF3	320	0.50	C30/37
	XF4	340	0.45	C30/37

Table 2. Required content of air in the concrete mix, according to [8]

Maximal diameter of aggregate grains [mm]	Content of air in the concrete mix [%]			
	Without a plasticizing admixture		With a plasticizing admixture	
	Average	Minimal	Average	Minimal
Up to 8	5.5	5.0	6.5	6.0
Up to 16	4.5	4.0	5.5	5.0
Up to 31.5	4.0	3.5	5.0	4.5

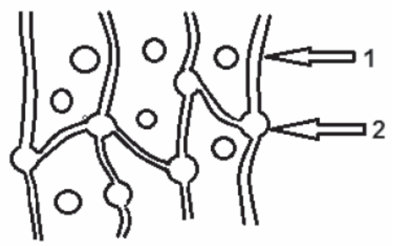

Fig. 1. The distribution of air bubbles in concrete: 1 – capillaries, 2 – micro-pores

Adding air-entraining admixtures to the concrete mix can also have unwanted effects. It leads to higher porosity of concrete and lower strength [3,4].

Jamroży [6] claims that the compression strength of concrete can be raised after air-entraining if the cement content is below 250kg/m³. If the [cement content is over 250kg/m³, concrete strength is lowered by about 4% for every additional 1% of air. According to Rusin [17], for concretes with the W/C ratio of 0.45÷0.72, the average drop of strength can be even 5% for 1% of additional air in the mix after air-entraining.

Air-entraining the concrete mix does not guarantee full frost-thaw resistance of the concrete. What is important in air-entraining the concrete mix is the distribution of air pores in hardened concrete and the distance between them. A large distance between the spots where ice is formed and the nearest void leads to higher hydraulic pressure. Small distances between pores are the effect of excessive air-entraining of the concrete mix, which leads to a large drop of compression strength. What determines the proper air-entraining of the concrete mix is the spacing factor L of pores in concrete. The factor determines the average largest distance from a random spot in the cement slurry (in the concrete) to the nearest air pore.

The norms PN-EN 206-1 and PN-EN 480-11 do not determine the porosity structure of hardened concrete. It is universally assumed that in order to obtain frost resistant concrete, the proper spacing factor should be $L \leq 0.20$mm and the content of micropores with the diameter smaller than 300 µm (class 18): $A_{300}>1,5\%$. Concretes with $L \leq 0,18$ mm and $A_{300}>1,8\%$ are considered to guarantee a very high level of frost resistance. However, some authors claim that the evaluation of frost resistance of fly ash concretes based on the values L and A_{300} are of little use because of air pores in the grains of ash [13, 14, 17, 18].

Concrete durability is also determined by proper moulding, maintenance and processing of the concrete composite [7, 9].

THE RESEARCH ON CONCRETES

The research program aimed at determining the influence of fly ashes and an air-entraining admixture on the quantity and quality parameters of concrete and the characteristics of the concrete mix. The base concrete (marked as "0-0") was made from: natural aggregate with grain size up to 16mm and the sand point – 33%; cement CEM I 42,5R and plasticizing admixture based on policarboxylates.

Table 3. Composition of the tested series of concretes

Ingredient [kg/m³]	Series of tested concretes							
	0-0	0-2	0-5	0-8	1-0	1-2	1-5	1-8
Cement	386	386	386	386	362.1	362.1	362.1	362.1
Water	193	193	193	193	193	193	193	193
Aggregate	1845	1845	1845	1845	1823	1823	1823	1823
Plasticizer	6.95	6.95	6.95	6.95	6.95	6.95	6.95	6.95
Fly ash	-	-	-	-	63.7	63.7	63.7	63.7
Air-entraining admixture	-	0.772	1.93	3.088	-	0.772	1.93	3.088

The modifications of the base version consisted in adding an air-entraining admixture in the amount of 0.2% (0-2 series), 0.5% (0-5 series) and 0.8% (0-8 series) in relation to the mass of cement.

Next, the base series was modified by adding half the maximum permissible quantity of fly ash (1-0 series). Then, an air-entraining admixture was added to fly ash concrete in the amounts corresponding to the control series.

This resulted in concrete series marked as 1-2, 1-5 , 1-8. Table 3 presents the composition of all 8 tested series of concrete mixes and concretes.

All concretes were tested for: air content in the concrete mix, consistency by the concrete slump method, compressive strength after 28 days of curing, saturation, depth of water penetration, and resistance to 150 freeze-thaw cycles. The porosity structure of selected concrete series was tested by determining: the total amount of air in hardened concrete A, the spacing factor F, the micro-pores content A_{300}, and the distribution of air pores. The tests were done with cubical samples with an edge of 150mm, that were demoulded 24 hours after they had been made, and then they were kept for 27 days in water at the temperature of 20°C.

THE RESULTS OF TESTS FOR CONSISTENCY AND AIR CONTENT

The tested concrete mixes were mixed in a paddle concrete mixer for 70 seconds and then the following was determined: consistency by the concrete slump method in accordance with PN-EN 12350-2, and air content by the pressure method according to PN-EN 12350-7.

The results are presented in Table 4.

The result of the slump test for the control series concrete mix 0-0 was 50mm (S2 consistency class) and air content test showed the amount of 2.35%. As the amount of the air-entraining admixture was raised, the liquidity of concrete mixes also grew together the air content. Concrete mixes without fly ash and with maximal quantity of the air-entraining admixture (0.8% of the cement mass) had the air content of 4.3%. At the same time this concrete mix has the highest level of liquidity and its consistency class was marked as S3.

The presence of fly ash (series 1) influenced consistency, the liquidity was considerably higher. The measured amount of air in fly ash mixes was also higher with the same amount of the air-entraining admixture.

Adding fly ash to concrete instead of cement raised the air content by 6.4%. With the addition of the air-entraining admixture in the amount of 0.2 and 0.5% the observed increase of the tested characteristics was by about 17% in fly ash mixes. The greatest difference in air content was noticed for the air-entraining admixture in the amount of 0.8%. The air content in the fly ash mix was higher by 55.8%.

THE RESULTS OF TESTS FOR COMPRESSIVE STRENGTH AND THE PENETRATION DEPTH OF PRESSURIZED WATER

The compressive strength test was done after 28 days of curing the samples in laboratory conditions. The saturation test was done on the basis of the PN-88/B-06250 norm. The results are presented in Table 5.

The series 0-0 control concrete had the average compressive strength f_{cm}=54.1 MPa. The test results classified the control series to the C40/50 strength class. Using fly ash as a cement substitute resulted in the drop of compressive strength by 4.4%. This changed the concrete strength class to C35/45.

The modification of the tested concretes by using an air-entraining admixture lowered the average values of compressive strength. The greatest drop was noted in the series where the amount of added air-entraining admixture was 0.8% of the cement mass (0-8 and 1-8 series). This resulted in classifying both the series to a still lower strength class C30/37.

Figure 2 presents the comparison of average compressive strength of concretes with and without fly ash.

The average compressive strength of the concrete containing half the maximal permissible amount of fly ash was lower in every tested sample. The largest strength drop caused by the use of fly ash was noticed in the series without an air-entraining admixture (4.7%) and with the largest amount of the air-entraining admixture (5.6%).

Figure 3 presents compressive strength drop together with the increasing amount of the air-entraining admixture.

Table 4. Concrete mix test results

Characteristics of concrete mixes	Series of tested concretes							
	0-0	*0-2*	*0-5*	*0-8*	*1-0*	*1-2*	*1-5*	*1-8*
Slump test [mm]	50	80	90	100	150	175	185	200
Consistency class	S2	S2	S2	S3	S3	S4	S4	S4
Air content	2.35	2.8	3.5	4.3	2.5	3.3	4.1	6.7

Table 5. Average values of compressive strength, and the penetration depth of pressurized water, of concreted modified with fly ash and air entraining admixture.

Characteristics of concretes	Series of tested concretes							
	0-0	*0-2*	*0-5*	*0-8*	*1-0*	*1-2*	*1-5*	*1-8*
Compressive strength f_{cm} [MPa]	54.1	50.1	49.0	48.2	51.7	49.4	47.6	45.5
Strength class	C40/50	C35/45	C35/45	C30/37	C35/45	C35/45	C30/37	C30/37
Depth of water penetration [mm]	70	75	82	98	90	90	75	80

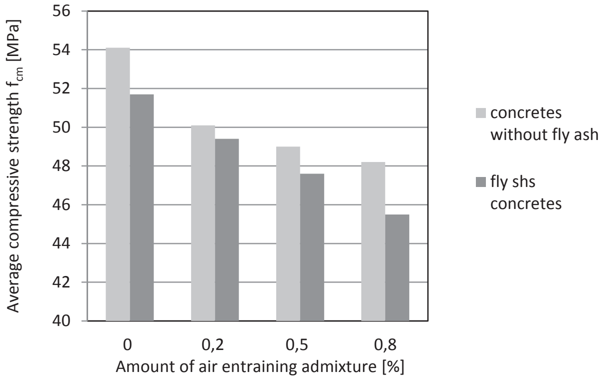

Fig. 2. The influence of an air-entraining admixture on compressive strength

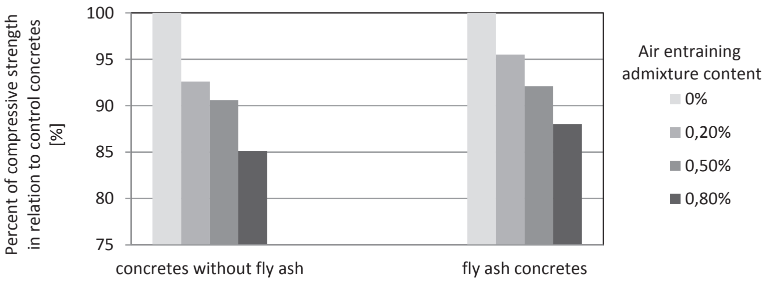

Fig. 3. The influence of the amount of the air-entraining admixture on the compressive strength percentage of concretes with and without fly ash

Adding an air-entraining admixture resulted in lower strength of the tested concretes. The amount of the air-entraining admixture equal to 0.2% of the cement mass resulted in lowering the average compressive strength to 50.1MPa (Table 5). The increase in the amount of the air-entraining admixture causes lowering the compressive strength, which dropped to 48.2 with the maximal amount of the admixture. A similar result was observed in fly ash concrete. The compressive strength dropped from 51.7MPa in the series without the admixture to 45.5MPa in the series with the maximal amount of the air-entraining admixture.

The water penetration test was done in accordance with the PN-EN 12390-8 norm. The results are presented in figure 4.

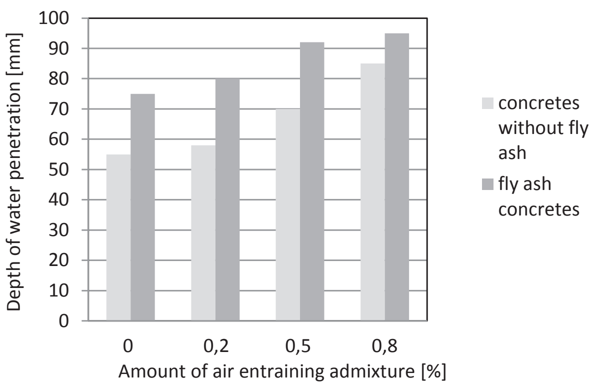

Fig. 4. The influence of the amount of the air-entraining admixture on the penetration depth by pressurized water in concretes with and without fly ash

The use of fly ash as a cement substitute caused an increase in the depth of water penetration in concretes both with and without the air-entraining admixture. Similarly, the amount of the air-entraining admixture increased together with the depth of water penetration.

THE RESULTS OF THE FROST RESISTANCE TEST (150 CYCLES)

The norm PN-EN206-1 does not mention any method for determining the frost-thaw resistance of concretes. However, the concretes that belong to the XF2 and XF4 exposure classes must contain an air-entraining admixture. At present, all concretes exposed to frost-thaw cycles are tested for frost resistance according to the PN-88/B-06250 norm.

The tested series of concrete underwent 150 freeze-thaw cycles. The results are presented in Table 6.

None of the tested series had any mass loss after 150 cycles. The compressive strength drop for the control concrete 0-0 was 32.0%. According to the PN-88/B-06250 norm, maximal strength drop cannot exceed 20%. The concrete series without fly ash: the control one 0-0 and the one with minimal amount of the air-entraining admixture 0-2 didn't have frost resistance after 150 freeze-thaw cycles. Fly ash concretes (1-0) and the ones with minimal amount of the air-entraining admixture (1-2) didn't have frost resistance after 150 freeze-thaw cycles either.

The remaining series of tested concretes with the amount of the air-entraining admixture of 0.5% and 0.8% had the frost resistance F150.

THE RESULTS OF TESTS CONCERNING THE CHARACTERISTICS OF AIR PORES IN HARDENED CONCRETE

The air pores characteristics tests were done in accordance with the research procedure described in the PN-EN480-11 norm. The test was done with the use of an automatic system for analysing the image of air pores in concrete (Fig. 5), and the computer program Lucia Concrete. For all tested concrete series, the following parameters determining concrete structure were obtained: the total amount of air in concrete A, the spacing factor F, the micro-pore content A_{300} (class 18), the distribution of chords in particular size classes of pores.

The obtained results are presented in Table 7.

All the series had the spacing factor $L < 0.20$mm, which is recommended to obtain frost resistance of concrete.

Figure 6 presents the cumulated air content in particular pore classes for concretes without fly ash, dependent on the amount of the air-entraining admixture.

Figure 7 presents cumulated air content in particular pore classed for fly ash concretes, dependent on the amount of the air-entraining admixture.

Fly ash concretes had considerably higher cumulated air content than concretes without fly ash. The obtained

Table 6. Compressive strength drop and mass loss after 150 freeze-thaw cycles

Characteristics of concretes	Series of tested concretes							
	0-0	*0-2*	*0-5*	*0-8*	*1-0*	*1-2*	*1-5*	*1-8*
Compressive strength drop after 150 freeze-thaw cycles [%]	32.0	25.1	12.4	6.6	26.9	23.4	8.1	8.0
Mass loss [%]	0	0	0	0	0	0	0	0
Frost resistance F150	NO	NO	YES	YES	NO	NO	YES	YES

Table 7. The results of tests concerning the characteristics of air pores

Characteristics of air pores	Series of tested concretes							
	0-0	*0-2*	*0-5*	*0-8*	*1-0*	*1-2*	*1-5*	*1-8*
Total air content in concrete A [%]	3.3	5.6	8.9	7.9	8.5	10.0	17.6	20.8
Spacing factor L [mm]	0.179	0.194	0.135	0.159	0.134	0.114	0.106	0.091
Micro-pore content A_{300} [%]	2.1	2.1	4.2	3.8	4.6	6.0	9.1	11.2

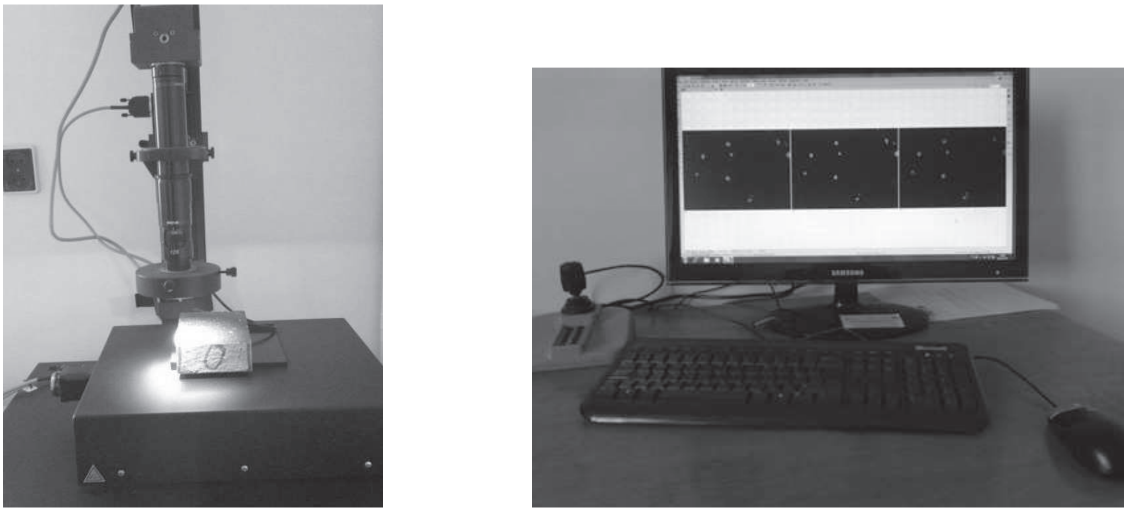

Fig. 5. A workstation for testing the pore structure in hardened concrete

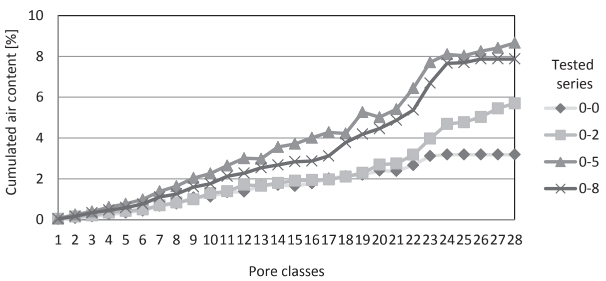

Fig. 6. The influence of an air-entraining admixture on cumulated air content in concretes without fly ash, dependent on the pore class

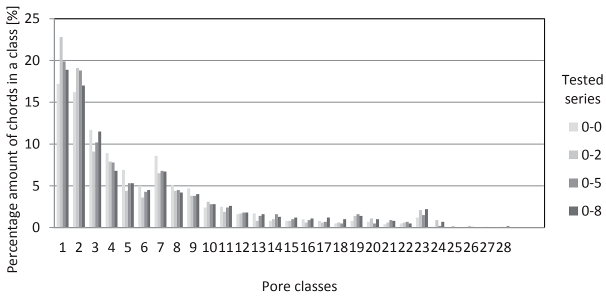

Fig. 8. A histogram of air pores distribution in concretes without fly ash

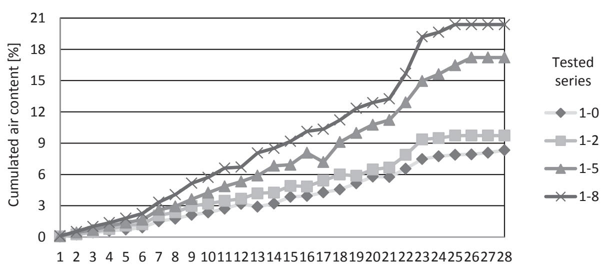

Fig. 7. The influence of an air-entraining admixture on cumulated air content in fly ash concretes, dependent on the pore class

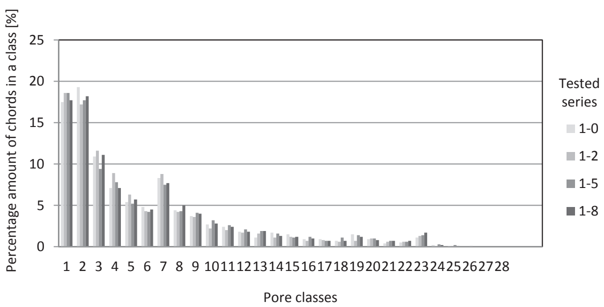

Fig. 9. A histogram of air pores distribution in fly ash concretes

values of the total pore content in hardened concrete (A) are quite clearly higher than the air content obtained in the pressure method tests of concrete mixes. Particularly large differences were noticed in fly ash concretes. This confirms the opinions expressed in [13, 14, 17, 18] that fly ash can increase the A parameter.

Figures 8 and 9 present histograms of the percentage distribution of air pores in all size classes.

The content of micro-pores A_{300} obtained in the test ranged from 2.1% in the series 0-0 and 0-2 to 11.2% in the series 1-8 (Table 7). All the tested series had the factor A_{300}, required for concrete frost resistance, with the value above the minimal 1.8%.

It is commonly assumed that in order to obtain frost resistant concrete, the proper spacing factor should be $L \leq 0.20$mm and the content of micro-pores with the diameter smaller than 300 µm (class 18): $A_{300}>1,5\%$. Concretes with $L\leq0,18$ mm and $A_{300}>1,8\%$ are considered to guarantee a very high level of frost resistance.

In a direct frost resistance test, despite having obtained proper parameters in the porosity structure test, in the series 0-0, 0-2, 1-0, 1-2 there were no concretes that could be included in the F150 frost resistance class.

CONCLUSIONS

The paper presents the results of research on the characteristics of air pores, compressive strength, the depth of penetration by pressurized water, and frost resistance after 150 cycles in concretes modified by fly ash and an air entraining admixture.

The research that was carried out has led to the following conclusions:

– fly ash raises the effectiveness of air-entraining the concrete mix and it helps to increase air content,
– an air-entraining admixture improves frost resistance of concrete, increases the liquidity of the concrete mix and improves its workability,
– air-entraining admixtures result in a considerable drop of compressive strength, up to 20% in comparison with concrete without the admixture. It can lead to lowering the strength class of concrete by even 2 degrees,
– additional air in the concrete mix can also lead to increasing the depth of water penetration, which is rarely mentioned by the admixture manufacturers. Therefore, the composition of concrete must be corrected at the designing stage,
– the characteristics of air pores distribution is an effective tool to estimate the frost resistance of concrete composites.

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BADANIA TRWAŁOŚCI MROZOWEJ BETONÓW MODYFIKOWANYCH DODATKIEM POPIOŁU LOTNEGO

Streszczenie. W pracy przedstawiono wpływ dodatku popiołów lotnych i domieszki napowietrzającej na mrozoodporność betonu badaną metodą bezpośrednią oraz charakterystykę porów powietrznych. Badanie mrozoodporności przeprowadzono dla 150 cykli zamrożeń i rozmrożeń. Dla betonów wykonano badanie struktury porowatości kompozytów betonowych, które przeprowadzono przy użyciu urządzenia do automatycznej analizy obrazu z wykorzystaniem programu komputerowego Lucia Concrete. Analizie poddano beton kontrolny oraz beton z dodatkiem popiołu lotnego w ilości połowy maksymalnej dopuszczalnej normowo ilości, napowietrzane różnymi dawkami domieszki napowietrzającej.
Słowa kluczowe: beton, popioły lotne, charakterystyka porów powietrznych, mrozoodporność.