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AIR-ENTRAINMENT PROBLEM IN SELF-COMPACTING CONCRETE

Janusz Szwabowski[1], **Beata Łaźniewska-Piekarczyk**[2]
Dept of Building Processes, Faculty of Civil Engineering Silesian University of Technology, Akademicka 5, 44-100 Gliwice, Poland
E-mail: [1]*Janusz.Szwabowski@polsl.pl,* [2]*Beata.Lazniewska@polsl.pl*

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Abstract. According to the actual state of knowledge and in accordance with the PN-EN 2006-1 norm, it is recommended to use air-entrainment as a basic way of assuring frost-resistance of concrete. In case of self-compacting concrete (SCC), achieving adequate air-entrainment is a problematic issue because of one of the side-effects of the functioning of a new generation of superplasticizers, i.e. excessive air-entrainment (considerably higher than 2%) in a self-compacting concrete mix. Thus, in this situation, the dosage of an air-entraining admixture has to be reduced. It was discovered that the cause of an air-entrainment effect of superplasticizers is a decrease of the surface tension value of the liquid phase in paste. In the paper, the problem of air-entrainment is discussed, formed as a result of the functioning of a superplasticizer on the characteristics both of concrete and a mixture, depending on the content. To verify the influence a superplasticizer and an air-entraining admixture have on concrete porosity structure parameters, concrete samples were tested during 300 cycles of freezing and testing the porosity structure according to PN-EN 480-11. The tests of the structure show that air pores, depending on the level of mix flowability, can be regular and similar in shape and size to pores formed as a result of air-entrainment admixture action. According to the actual state of knowledge on concrete technology, concrete is frost-resistant if the value of porosity structure parameter stays within precisely set limits. The results of concrete testing have shown that the parameters of porosity structure do not stay within the precisely set limits, but self-compacting concrete gets frost-resistance F300 according to PN-88/B-06250. Issues connected with this fact are the subject of this paper.

Keywords: frost resistance**,** concrete porosity structure, air-entrainment, superplasticizer, air-entraining admixture, self-compacting concrete (SCC).

1. Introduction

Although the mechanisms responsible for deterioration of concrete by frost are not perfectly clear, one of the ways to prevent internal cracking and disruption due to freezing and thawing cycles is known: it is simply ensuring that hardened concrete has an adequate system of entrained air voids. In accordance with the PN-EN 206-1, using air-entrainment as a basic way of assuring frost-resistance of concrete is recommended. According to the authors Fagerlund (1997) and Brandt and Kasperkiewicz (2003) and according to PN-EN 480-11, concrete will be frost-resistant if the values of porosity structure parameters are as follows (Fig. 1): $\bar{L}$ = 0.20 ÷ 0.22 mm, A = 4 ÷ 7%, A_{300} > 1,5÷ 1,8%, α > 15 ÷ 20 mm^{-1} (Fig. 1).

Generally $\bar{L}$ is used to determine frost-resistance of concrete. For physical interpretation, $\bar{L}$ stands for the average of the greatest distance from any point inside cement paste to the nearest air bubbles (Fig. 2), in order to decrease the value of pressure σ (Fig. 3).

According to Khayat (2000), Khayat and Assaad (2002), Szwabowski (1999), Kobayashi *et al.* (1981) in case of self-compacting concrete, air entrainment of a concrete mix, as well as obtaining adequate values of porosity structure parameters are problematic issues due

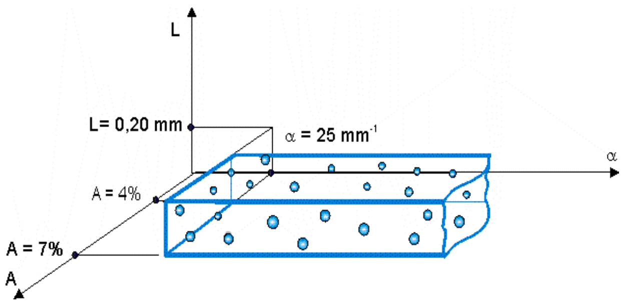

Fig. 1. Suggested values of porosity structure parameters of frost resistant concrete according to Brandt and Kasperkiewicz (2003)

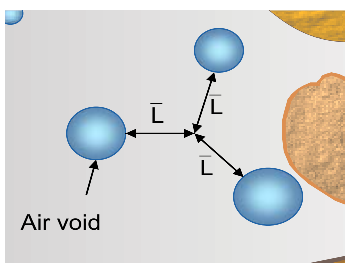

Fig. 2. Physical interpretation of $\bar{L}$ according to Rusin (2002)

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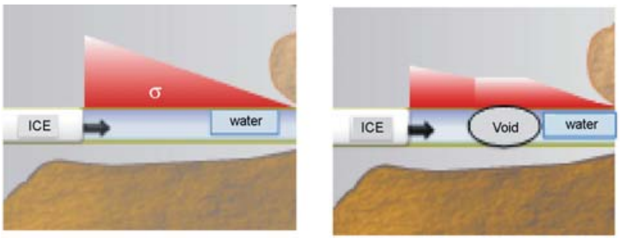

Fig. 3. The influence of air void n the reduction of σ pressure according to Rusin (2002)

to self-compaction of a concrete mix. As a result of considerable flowability of a self-compacting concrete mix, air bubbles present in air-entrained concrete mix can be unstable, which is caused by floating of large air bubbles, fading of air bubbles that are less than 0,10 mm in diameter, or coalescence of air bubbles.

Moreover, on the basis of different tests concerning self-compacting concrete mixtures, the authors discovered excessive air content in their volume which was a result of the functioning of a superplasticizer, in spite of fulfilling the self-compactibility criteria (i. e. self-venting). Moreover, the molecules of a superplasticizer should modify the surface of solid particles in such a way, that its hydrophilic character is maintained. Air bubbles can adhere only to hydrophobic surfaces.

The influence of an air-entraining admixture and a superplasticizer on the formation and behaviour of air bubbles in a self-compacting concrete mix are analysed in this paper. Some methods are suggested, which aim is to obtain the expected level of air-entrainment, depending on the characteristics of a mixture.

Moreover, to verify the influence a superplasticizer and an air-entraining admixture have on concrete porosity structure parameters, concrete samples were tested during 300 cycles of freezing and testing of porosity structure according to PN-EN 480-11.

2. The reasons of the influence of a superplasticizer on air-entrainment in a concrete mix

Superplasticizers belong to a widely understood group of surface-active substances. Most of superplasticizer molecules are elongated, asymmetric, have red and blue poles, and because of this a constant dipolar moment. One part of the molecule is usually a positively charged hydrophobic hydrocarbon group, another part is a negatively charged hydrophilic group. The anion placed at the end is directed towards the liquid phase causing a repellent effect (Fig. 4). This effect is connected with hydrophilic effect of a superplasticizer.

According to (Kucharska 2000; Kurdowski 2003; Młodecki and Stebnicka 1996; Mosquet 2003), depending on the chemical base of superplasticizers, they can produce the following effects in a concrete mix (Fig. 4):

- Creating a "grease" layer on cement and grains of micro-filler, decreasing internal friction of a concrete mix (SMF – sulfone melamine-formaldehygenic resin),
- Surrounding grains of cement with negative charge, causing their mutual repulsion (SNF – sulfone naphtelene-formadelhygenic resins), the type of a superplasticizer dictates the value of the dispersion force of molecules, which measure is zeta surface potential – with the increase of this potential, the dispersion force of molecules increases,
- Decreasing of water surface tension in relation to cement and micro-fillers (MLS – modified lime or sodium lingisulfones; other products are: copolymers of formic acid with naphtylic – sulfone acid, copolymers of methacrylate acid with sodium salt or polyethylene glycol),
- Sterole – they create long chains of polymers, physically precluding the grains in cement from approaching each other (new-second-generation of fluxing admixtures; substances from the polycarboxylants group (pc), copolymers of acryl acid with acrylate (CAE) and not acryl resins (CLAP). Such work results in a situation where admixtures of new generation function "preventively" – instead of smashing already formed grains of cement agglomerates, they do not allow their formation.

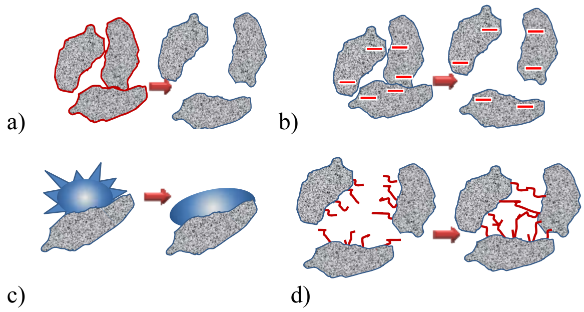

Fig. 4. Types of superplasticizer action: a – creating "grease" layer, b – surrounding grains of cement with negative charge, c – decreasing of surface water tension, d – long chains of polymer, physically precluding the grains of cement from approaching each other (Mosquet 2003)

According to Kucharska (2000), the presence of listed functional groups (oxygen in the form of etheric group (-0-), hydroxyl group (-OH) and carboxyl group) produce water surface tension decrease, causing flocculation of associated molecules and increase in moisture of not only grains of cement but also the whole mineral framework (Fig. 5).

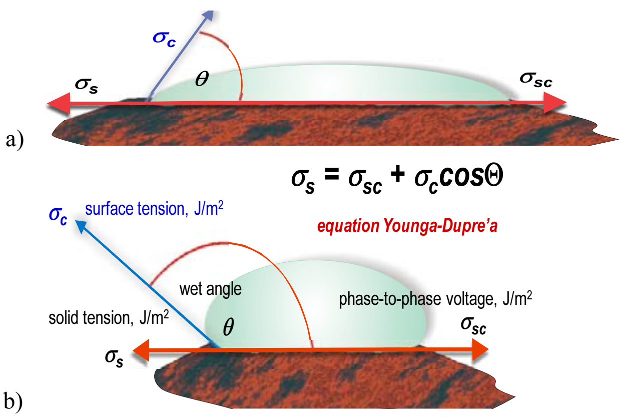

Fig. 5. The state of balance at the phases margins: solid body-liquid-air; a – lower moisture, b – higher moisture

In the group of superplasticizers there are some organic compounds that only show desperation effect without decreasing the surface tension. These are: hydrocarboxylen acid salts, sulphonic melamine-formaldehygenic resins, formaldehygenic picodensats salts of beta-naphtalensulphonic acid (Młodecki and Stebnicka 1996).

According to Kurdowski (2000), air bubbles formed by hydrophilic surface active compounds should not adhere to cement and grains of an aggregate, being uniformly dispersed in a concrete mix (Fig. 6). Moreover, according to Młodecki and Stebnicka (1996), these bubbles are slightly bigger than those formed as a result of the functioning of an air-entraining admixture, but their stability is lower (Litvan 1983). Air bubbles formed as a result of the functioning of air-entraining admixtures reach the size of 20÷250 μm. Moreover, they adhere to the surface of particles of cement (Fig. 6b) (Kurdowski 2003). During the process of hardening of concrete, the pores formed are not filled with products of hydration, because C-S-H gel can form only in water. From the point of view of the frost-resistance of concrete it would be best if bubbles were of 0.05÷0.10 mm diameter and were located in the volume of paste spread at a distance of 0.15÷0.20 mm from each other. However, the problem of the critical value of the distance between pores in frost-resistant concrete, depending on the type of concrete, is an issue which is still being considered (Kurdowski 2003).

a) b)

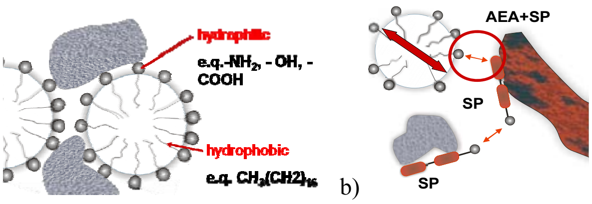

Fig. 6. Adsorption of flux molecules framework in grains of cement and a negative effect of the anion final group (a); a diagram of arrangement of cement – water and an aggregate – cement – water arrangement, with the use of air-entraining means (surface active anion substance) (b) (Kurdowski 2003)

According to Sakai *et al.* (2006), the type of a superplasticizer is crucial on account of the size and proportions of air pores participation, obtained as a result of its functioning, although the time of hardening of concrete does make a difference to further changes of these proportions (Fig. 7). With the use of polycarboxylen superplasticizers, air pores are characterized by diameters smaller than in case of pores formed as a result of the functioning of lingosulphonic or naphthalene superplasticizers.

However, the results of other researches (Mosquet 2003) presented in Table 1, prove that new generations of superplasticizers show an air-entraining effect, which has also been proved by the results of research conducted by the authors. The research results showed that excessive air-entrainment of a mixture is caused mostly by the decrease of surface tension of liquid phase in paste (Fig. 8) by PCP superplasticizer.

Table 1. The influence of the type of a superplasticizer on concrete mix air-entrainment (Mosquet 2003)

SP	LS	SNF	SMF	New Generation SP	
				PCP	AAP
Air volume	++	+	0	++	++

Were:
LS – Lignosulfonate Lignosulfian, SNF – Sulfonated Naphtalene Formaldehyde Condensate, SMF – Sulfonated Melanine Formaldehyde Condensate, PCP – PolyCarboxylate Polyoxyethylene, AAP – Amino Phosphonate Polyoxyethylene

a) b)

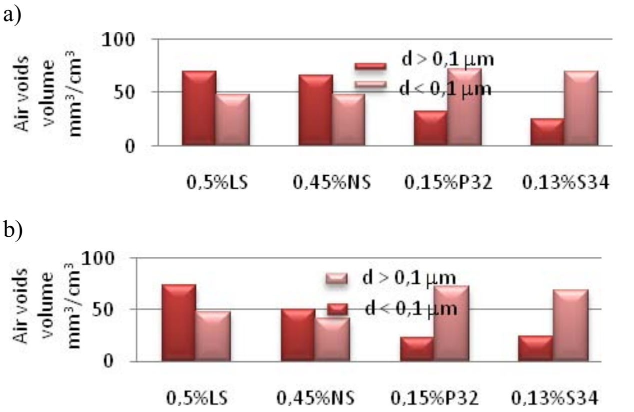

Fig. 7. The influence of a naphthalene superplasticizer (β-NS), a refined lignin sulfonate (LS) and a polycarboxylate (P34, S34) on the structure of concrete porosity (a) 28 days of curing, (b) 91days of curing (Sakai *et al.* 2006)

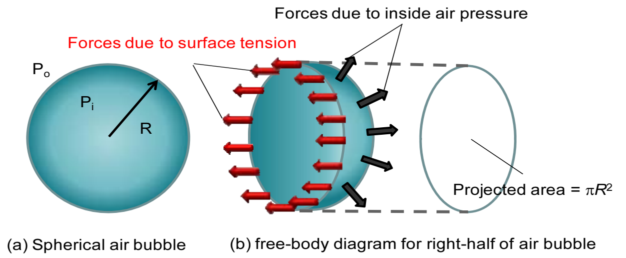

Fig. 8. The forces pointing to the left are due to the surface tension (a). The forces pointing perpendicular to the hemispherical surface are due the air pressure inside the bubble (Łaźniewska-Piekarczyk 2008b)

3. Composition of tested SCC

To verify the pertinent influence of the composition of a concrete mix on concrete porosity structure parameters, 4 factors were chosen for this research: the type of a mineral binder (m.b.), the water to binder ratio (w/b), the dosage of an air-entraining admixture (% AEA) and the volume of inter grains porosity of an aggregate $\varphi_{kz,}$ which determines the distance between aggregate grains in a mix and flowing air-bubbles (Fig. 9). In order to verify the pertinent influence of the above-mentioned factors on self-compacting effect of a concrete mix, and frost-resistance of SCC, a set of 25 concrete mixes (Table 2) was established for planning an experimental method. The size of aggregate grains was between 0 to 8 mm. The volume of sand (49%) was constant.

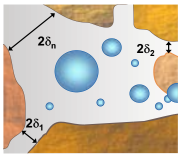

Fig. 9. The illustration of the scope of expansion between aggregate grains in mix

Table 2. Composition of self-compacting concrete (Łaźniewska-Piekarczyk 2007)

m.b. / AEA (%)	CEM II 32.5R B-S	CEM II 32.5 R B-V	CEM II 32.5 R B-M	CEM III 32.5 N	CEM I 32.5 R - 10% silica fume
0	S11		S6	S16	
	φ_{kz} = 1.5 w/b = 0.29	φ_{kz} = 1.2 w/b = 0.32	φ_{kz} = 1.4 w/b= 0.35	φ_{kz} = 1.1 w/b = 0.38	φ_{kz} = 1.3 w/b = 0.41
0,005		S2	S7	S17	S22
	φ_{kz} = 1.1 w/b = 0.32	φ_{kz} = 1.3 w/b = 0.35	φ_{kz} = 1.5 w/b = 0.38	φ_{kz} = 1.2 w/b = 0.41	φ_{kz} = 1.4 w/b = 0.29
0,010	S13	S3	S8	S18	
	φ_{kz} = 1.2 w/b = 0.35	φ_{kz} = 1.4 w/b = 0.38	φ_{kz} = 1.1 w/b = 0.41	φ_{kz} = 1.3 w/b = 0.29	φ_{kz} = 1.5 w/b = 0.32
0,015	S14	S4	S9		
	φ_{kz} = 1.3 w/b = 0.38	φ_{kz} = 1.5 w/b = 0.41	φ_{kz} = 1.2 w/b = 0.29	φ_{kz} = 1.4 w/b = 0.32	φ_{kz} = 1.1 w/b = 0.35
0,020	S15	S5		S20	
	φ_{kz} = 1.4 w/b= 0.41	φ_{kz} = 1.1 w/b = 0.29	φ_{kz} = 1.3 w/b = 0.32	φ_{kz} = 1.5 w/b = 0.35	φ_{kz} = 1.2 w/b = 0.38

In the first stage of investigation the air content in concrete (Table 2) was defined according to the procedure described in PN-EN 12350-7, the density of mixture was evaluated according to PN-EN 12350-6, whereas the flow diameter and its time were evaluated according to ASTM C 143. The listed tests of self-compacting concrete mixtures were carried out in temperature 20 °C, which is particularly essential as temperature influences both rheological characteristics of concrete and its air content (Szwabowski 1999).

On the basis of different tests concerning non air-entraining self-compacting concrete mixtures, the authors discovered that excessive air content was a result of the functioning of a superplasticizer, in spite of fulfilling the self-compactibility criteria (European Project Group 2005). The authors believe that the excessive air-entrainment of a mixture is caused – similarly to an air-entraining admixture – by the decrease of the surface tension of liquid phase in paste by a PCP superplasticizer. Thus, in the next stage of the research, the value of surface tension of liquid phase of cement paste was evaluated with the use of a stalagmometer method (Atkins 2003). Moreover, to verify the pertinent influence of the composition of cement paste on surface tension value, 4 factors were chosen for the research: the type of a mineral binder (m. b.), the water to binder proportion, the dosage of an air-entraining admixture (% AEA) and the dosage of a superplasticizer (% SP).

In the basic stage of the research, self-compacting concrete (Table 2) underwent frost-resistance tests, according to PN-88/B-06250. After 28 days, concrete samples 150×150×150 mm were subjected to freezing and thawing in water for 3 hours in temp. ±20 °C (4 cycles per day).

In the following stage of the research, concrete samples were put to test of porosity structure parameters (Fig. 10) according to PN-EN 480-11. Unfortunately, because of limited investment, only 8 concrete samples were put to test of porosity structure parameters according to PN-EN 480-11 (compare with Table 2 – dark shed).

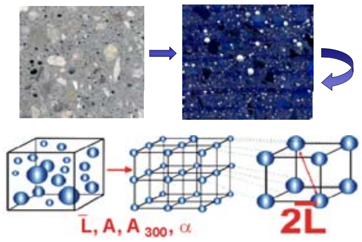

Fig. 10. The porosity structure parameters tested according to PN-EN 480-11

4. Research results of air-entrainment of a self-compacting concrete mix

The research results of the characteristics of self-compacting mixes (Table 2) are shown in Fig. 11–15. The mixtures were characterized by excessive air-entrainment (> 2%), which was the result of the functioning of a superplasticizer (Fig. 4) despite fulfilling the self-compatibility criteria (Figs 13, 14). The air content increased with the rise of w/b ratio (Fig. 12). The reason for such effect was the influence of the superplasticizer on the decrease of the surface tension of the paste liquid phase, as other tests proved (Łaźniewska-Piekarczyk 2008b). With the increase of liquid phase participation in the mix, the air-entrainment effect is greater, similarly to air-entraining admixture.

On the basis of different tests concerning non air-entraining self-compacting concrete mixes (Table 2), the authors discovered that an excessive air content in their volume (Fig. 11) was a result of functioning a superplasticizer, in spite of fulfilling the self-compactibility criteria (i.e. self-venting) (Figs 13, 14). On the other hand, the air-entrainment influences the flow diameter of SCC (Szwabowski and Łaźniewska-Piekarczyk 2007).

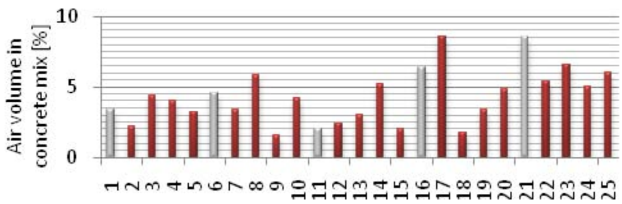

Fig. 11. The Ac air volume in air-entrained (dark column) and in non air-entrained (bright column) self-compacting concrete mixes

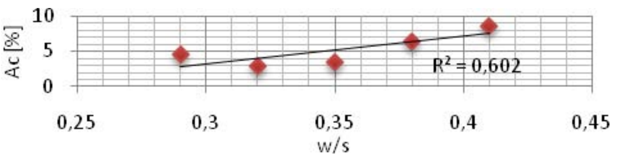

Fig. 12. The influence of w/s on the air volume Ac in non air-entrained self-compacting concrete mixes

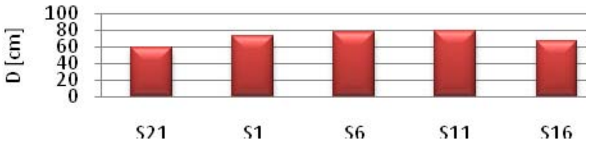

Fig. 13. The slump flow diameter D of non air-entrained self-compacting concrete mixes

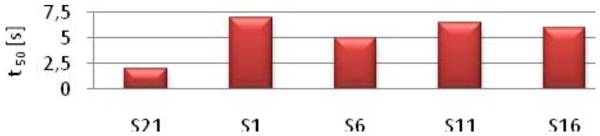

Fig. 14. The time of t_{50} flow of non air-entrained self-compacting concrete mixes

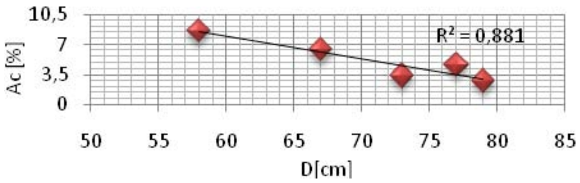

Fig. 15. The influence of slump flow diameter of non air-entrained self-compacting concrete mixes on air volume Ac

As it was shown in Fig. 15, diameters fulfilling accepted self-compactibility criteria (European Project Group 2005) in air-entraining superplasticizers turned out to be inadequate for effective SCC self-venting, which caused, among others, an excessive value of the flowing margin. Because of this, in the next stage of the research, its value was gradually decreased in a way which enabled air bubbles to escape freely from the concrete mix, increasing the dosage of the superplasticizer. Increased amount of the used superplasticizer in the mixes resulted in their slight segregation. The rest of self-compacting concrete mixes were stable, and the S11 mix was characterized by the lowest air content (Figs 13, 15). The results of the tests show that adequate fluidity of a self-compacting concrete mix is a necessary condition to achieve low air content in its volume. However, the change of concrete mix consistency only corrects intervention and it does not eliminate the reasons for forming of excessive air-entrainment.

5. The research results of the influence of surface tension of liquid phase in cement paste on SCC air-entrainment

The results of the tests presented in Fig. 17 prove that a superplasticizer air-entrains the concrete mix by reducing the surface tension of the liquid phase in paste. When a superplasticizer and an air-entraining admixture occur simultaneously in a self-compacting concrete mix, it should be noted that the decrease effect of the surface tension of the liquid phase in paste can be much higher (Fig. 16). However, because of greater liquidity of the mix, part of air-entrainment can undergo destabilization. As a result, air-entrainment of the mixture with the use of a superplasticizer and an air-entraining admixture is lower than when it occurs in its content (Fig. 17). It

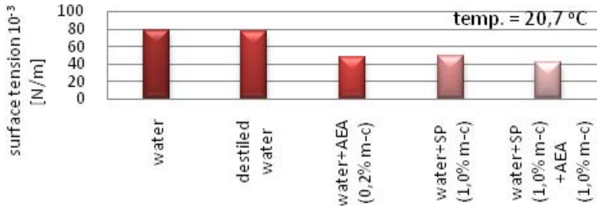

Fig. 16. The influence of a superplasticizer (SP) and an air-entraining admixture (AEA) on surface tension (Łaźniewska-Piekarczyk 2008a)

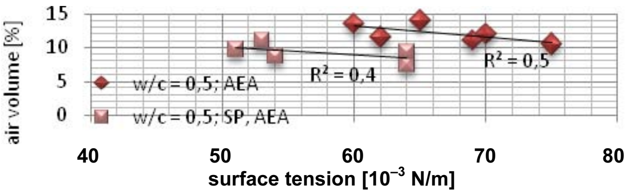

Fig. 17. The relationship between the surface tension of liquid phase and air-entrainment of a concrete mix (Łaźniewska-Piekarczyk 2008a)

should be mentioned that different conditions of a surface active substance form different porosity structures. Pure air-entraining admixtures (not blended with other admixtures) result in the formation of smaller pores with lower distance rate than in case of admixtures functioning in the presence of superplasticizers.

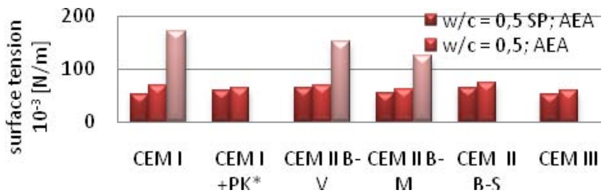

Fig. 18. The influence of SP (1% m.B.) on the air-entrainment of a concrete mix incorporating AEA (0.2% m.B.), (Łaźniewska-Piekarczyk 2008a)

Moreover, the level of the decrease of the surface tension by a superplasticizer depends on binder type (Fig. 18). Air-entrainment of a concrete mix is higher when the mix consists of (PK) silica powder or CEM III. It should be mentioned that in case of paste with listed supplements, faster adverse change of fluidity occurs, which influences the time limit in which the admixture automatically expels air bubbles.

6. The factors influencing frost-resistance and quality of the porosity structure of SCC

The results of the tests of the porosity structure of non air-entrained types of concrete S21 and S1 (Table 2) were shown in Table 3 and in Fig. 19÷21. The value parameters of porosity structure were compatible with accepted criteria, made in order to provide protection of concrete against periodic freezing and thawing, although the set up problem of recommended value of parameters to a bigger group of various types of concrete is still taken into consideration. In case of S1 concretes, the air porosity spacing factor was appropriate, but the concrete was not frost-resistant. The reason of this was the presence of irregular, incorrectly located air voids (Fig. 19). In connection with given remarks, the evaluation of potential S1 frost-resistance, carried out according to the procedure used for air-entrained types of concrete, is negative. Of course, in the tested types of concrete, the pores spacing factor was relatively low (0.22 mm) and the α ratio value was satisfactory, however the values of these parameters result from, as it was mentioned earlier, the presence of air in pores, which is the effect of insufficient contact between a matrix and an aggregate, and they do not resemble the regular spherical configuration of pores, introduced as a protection of the structure of concrete against the effects of freezing and thawing processes (Figs 22, 28). Whereas, in case of the S21 sample, the requirements concerning frost-resistance of concrete were fulfilled (Table 3), and its air-entrainment structure did not raise any reservations – one could only critically refer to excessive air content. This concrete was frost-resistant (Fig. 28). The exemplary picture of concrete microstructure from S21 sample was shown in Fig. 19.

Summing up, the SCC porosity structure formed as a result of the functioning of superplasticizers, showing air-entraining activity, can be characterized by adequate parameters values, under the condition that the flowability of the mix is not too high.

The results of the research conducted according to PN-EN 480-11 showed that the values of porosity structure parameters of S19 concrete were adequate (compare with Figs 23–27 and Table 4). The exemplary view of the adequate concrete porosity structure is shown on Fig. 19. Unfortunately, in case of S23, S24 and S25 the quality of porosity structure was inadequate. It was noticed that the value of porosity spacing factor was too high and the values of parameters α, A_{300} were too low, which may prove that porosity structure contained pores which were too large. It was noticed that the content of pores with diameter smaller than 300 µm was inadequate (particularly in case of samples S24 and S25), whereas in case of samples S1 and S10 pores which were not formed as a consequence of intentional air-entraining were noticed (Fig. 19), though they were formed as a result of high fluidity of a concrete mix, which is necessary for self-compacting.

Table 3. The values of non-entrained concrete porosity structure parameters (Table 2)

Symbol	$\bar{L}$, [mm]	α, [mm^{-1}]	A, [%]	$A_{300,}$ [%]	Δf_{cm}, [%]
S1	0,22	25,47	4,86	1,74	**21**
S21	0,13	36,14	7,19	2,1	14

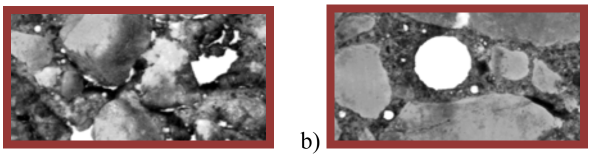

Fig. 19. The comparison of inadequate (a) and adequate (b) porosity structure of SCC. The microstructure: S1 (a); S21 and S19 (b)

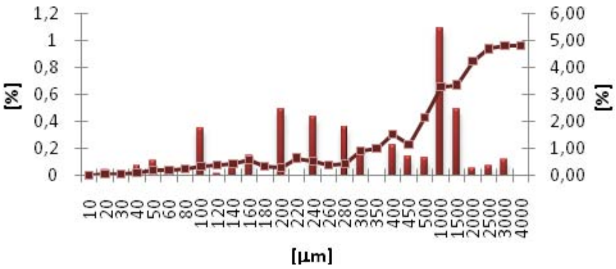

Fig. 20. The porosity characteristics of S21

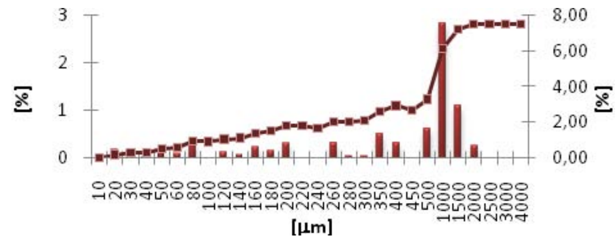

Fig. 21. The porosity characteristics of S1

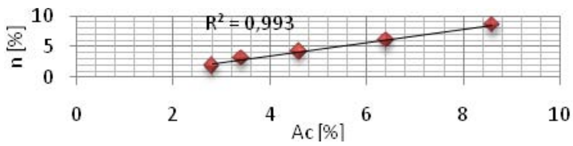

Fig. 22. The influence of air-volume on the absorbability of non entrained self-compacting concrete (Tab. 2)

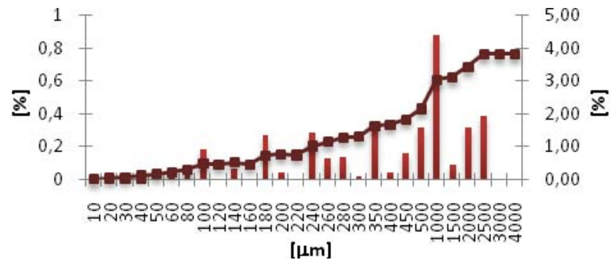

Fig. 23. Porosity structure of S19 (Szwabowski and Łaźniewska-Piekarczyk 2007)

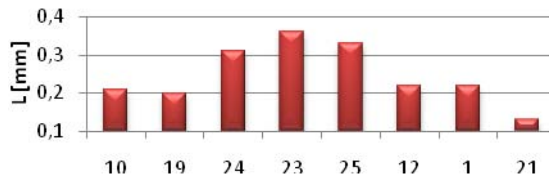

Fig. 24. $\bar{L}$ porosity structure parameter of SCC (Szwabowski and Łaźniewska-Piekarczyk 2007)

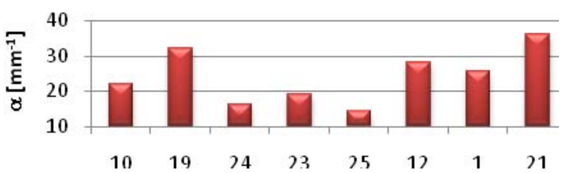

Fig. 25. α porosity structure parameter of SCC (Szwabowski and Łaźniewska-Piekarczyk 2007)

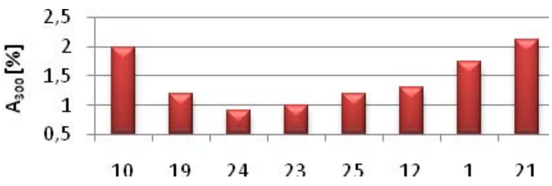

Fig. 26. A_{300} porosity structure of SCC (Szwabowski and Łaźniewska-Piekarczyk 2007)

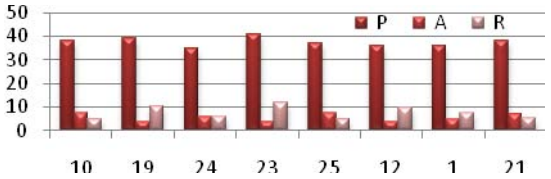

Fig. 27. Comparison of the porosity structure of SCC test results: P (cement paste content), A (total air volume), R (cement paste/air ratio), (Szwabowski and Łaźniewska-Piekarczyk 2007)

Because after 150 cycles of freezing and thawing concrete samples were not damaged, the testing of the frost resistance was continued. A laboratory research was discontinued when the amount of alternate cycles of freezing and thawing of concrete reached 300. It was noticed that only 2 types of SCC (S1, S12) were not frost resistant (because the decrease in compressive strength amounted to more than 20% after 300 cycles according to PN-88/B-06250).

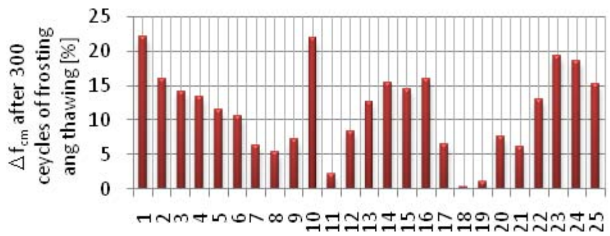

Fig. 28. The frost resistance test results of SCC (Szwabowski and Łaźniewska-Piekarczyk 2007)

Table 4. The results of SCC research according to PN-EN 480-11 and PN-88/B-06250 (Szwabowski and Łaźniewska-Piekarczyk 2007)

No	Series	$\bar{L}$ [mm]	α [mm^{-1}]	A [%]	A_{300} [%]	Δf_{cm} [%]
1	1	0.22	25.47	4.86	1.74	**21**
2	12	0.22	27.98	**3.69**	**1.30**	**23**
3	10	0.21	21.93	7.54	1.97	0
4	19	0.20	32.02	3.72	1.18	0
5	21	0.13	36.14	7.19	2.10	14
6	23	**0.36**	19.04	**3.49**	**0.99**	**0**
7	24	**0.31**	16.07	5.82	**0.91**	**16**
8	25	**0.33**	14.24	7.30	**1.18**	**0**
Suggested 0		**0.2–0.22**	**> 5–20**	**4–7**	**> 1.5–1.8**	**< 20**

Among eight concrete samples there were two which were not frost-resistant and six which were frost-resistant, but had different decrease in compressive strength, which amounted to more than 20% after 300 freezing and defrosting cycles (compare with Fig. 28).

In further part of the analysis of the research results it was perceived, that concrete which was characterized by inadequate porosity structure parameters gets frost resistance degree amounting to F300 according to PN-88/B-06250 (Table 4).

In order to explain partial discrepancy in research results according to PN-88/B-06250 and PN-EN 480-11, a problem was approached by detailed analysis of similar researches which are available in professional literature.

7. Theoretical and practical values of porosity structure parameters in frost-resistance of concrete

The reason of inconsistencies between the research results obtained according to PN-88/B-06250 and PN-EN 480-11 is submitting conditions regarding the porosity structure parameters in too generally understood concrete (Szwabowski and Łaźniewska-Piekarczyk 2007). One kind of concrete incorporates particular porosity structure with different size of capillary pores. Then the size of capillary pores influences the freezing temperature of water. Therefore, the size of capillary pores influences the pressure value (Fig. 29).

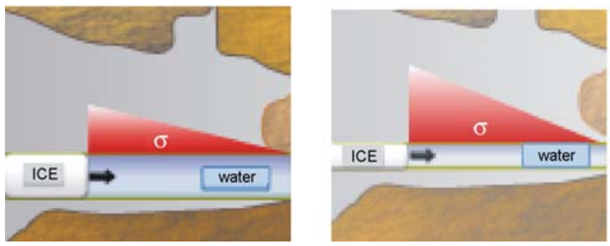

Fig. 29. The influence of capillary pore diameter on the σ pressure value according to Rusin (2002)

Fagerlund (1997) considers that the critical value of $\bar{L}$, which was calculated in order to protect concrete from the results of freezing and thawing, in reality depends on cement-water ratio (compare with Table 5 and 7). Moreover, the suggested value of $\bar{L}$ must be adjusted to the velocity of water freezing in the capillaries of concrete (Fig. 30). The established $\bar{L}$ = 0.20 mm was determined as a result of tests during which the velocity of the temperature decrease was 8° C/h. In practice, the temperature decrease velocity did not exceed 2°C/h (Rusin 2002). Pigeon *et al.* (1996) investigated the relationship between $\bar{L}$ and freezing rate.

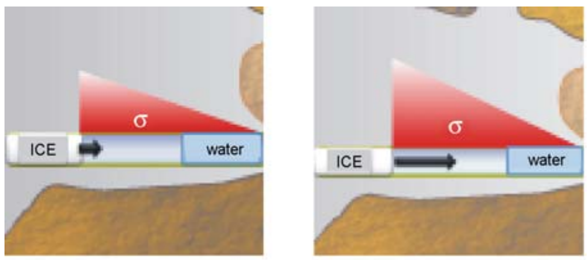

Fig. 30. The influence of velocity of water freezing (arrow) in the capillaries of concrete on the σ pressure according to Rusin (2002)

Table 5. Suggested $\bar{L}$ criteria according to the type of concrete (Petersson 2003)

Type of concrete:	Critical value of $\bar{L}$ [mm]
normal (w/c = 0.5)	0.50
with silica fume	0.25
high performance	0.60

In order to verify the influence of the w/c ratio on the critical value $\bar{L}$, the author of publication (Grodzicka 2005) presents the results of laboratory research of freezing and thawing cement paste water-logged in critical degree as well as the results of porosity parameters research. The results of this research enabled the estimation of the theoretical and practical value of porosity structure parameter $\bar{L}$ (Table 6). Moreover, it was noticed, that common concrete with w/c of the order of 0.40 ÷ 0.45 and $\bar{L}$ of the order of 0.40 mm can withstand a test of 300 cycles of freezing and thawing. Whereas, high performance concrete where w/s < 0.36 and $\bar{L}$ < 0.25 mm ensures, as it was shown in (Grodzicka 2005), adequate frost-resistance. The residual criteria, in respect of critical value $\bar{L}$ in dependence on w/c of high performance concrete, are presented in Table 7. On the basis of the research results (Grodzicka 2005), it was concluded, that in case of high performance concrete with silica fume and w/c = 0.30, practical value $\bar{L}$ amounts to 0.40 ÷ 0.50 mm, and by w/c = 0.25, without silica fume $\bar{L}$ = 0.75 mm. Further research (Grodzicka 2005) lead to a conclusion that concrete with compression strength about 100 MPa, w/c = 0,33, with silica fume 7,5% m.C., by $\bar{L}$ of the order of 0,80 do 0,85 mm, withstands a test of 112 cycles of freezing and thawing in the presence of salt. Whereas concrete with w/c = 0.35, with silica fume 6%, without air entrainment admixture, possessed a remarkable scaling resistance, and $\bar{L}$ reached as much as 0.90 mm.

Table 6. Theoretical and practical value of $\bar{L}$ (Grodzicka 2005)

FREEZING:	CRITICAL VALUE OF $\bar{L}$ [MM]	
	theoretical $\bar{L}$	practical $\bar{L}$
in water	0.22 ÷ 0.25	0.35 ÷ 0.40
in water with deicing salts	0.16 ÷ 0.20	0.22 ÷ 0.25

However, in case of concrete frost-resistance on scaling, the problem of the suggested value of $\bar{L}$ is still an open issue (Beaupré *et al.* 1999; Petersson 2003). Rickne and Nyqvist determined the critical value of $\bar{L}$ = 0.20 mm for the concrete containing various amounts and types of an air-entraining admixture. As the research results show, the values of $\bar{L}$ = 0.25 mm to $\bar{L}$ = 0.30 mm also guarantee good frost-resistance of the surface of concrete when defrosting agents are present. Although, on the basis of observations of concrete constructions exposed to periodic freezing and thawing, the value of $\bar{L}$ = 0,40 mm or even higher was estimated, ensuring the frost-resistance.

Table 7. Suggested $\bar{L}$ criteria according to w/c high performance concrete (Grodzicka 2005)

W/C	PROPOSED $\bar{L}$	CRITICAL $\bar{L}$	FROST-RESISTANT DEGREE
>0.40	230 μm	260 μm (deicing salts)	300 cycles ASTM C666 50 cycles ASTM C672
0.40–0.35	350 μm	400 μm (deicing salts)	300 cycles ASTM C666 50 cycles ASTM C672
0.35–0.30	450 μm	500 μm	500 cycles ASTM C666
<0.30	No data, the above criteria are suggested		

An alternative method of evaluating the quality of air-entrainment of concrete, as mentioned by the author of publication, is the method proposed by Phiello. According to Phielleo's conception, the „*flow length*" index determines protected volume of cement paste by one air pore (Fig. 31). The index is based on the maximum distance between any point in the cement paste and the nearest air void wall.

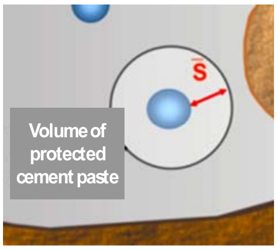

Fig. 31. Physical interpretation of the Phielleo's flow length according to)

The research results proved that various types of concrete with different values of air void spacing factors deteriorated in the same way after 300 cycles of freezing and thawing. When we use Phielleo's index ("flow length") instead of the $\bar{L}$ value, we receive a lower dispersion of the results. Moreover, Attigobe compared the research results of frost-resistance according to ASTM C 666, estimated for those types of concrete with the values of $\bar{L}$ and $\bar{S}$. Research data has shown that only 40% of concrete which was frost resistant (DF > 60%) incorporated $\bar{L}$ ≤ 0.20 mm but $\bar{S}$ ≤ 0.20 mm, was obtained by 90% of concrete. It is considered that the average value of $\bar{S}$ permits a more reliable determination of frost resistance of concrete, but it still requires investigation.

8. Final discussion

The results of frost resistance research of air entrained self-compacting concrete according to PN-88/B-06250 and PN-EN 480-11 were shown in this paper. On the basis of the analysis shown, it may be noticed, that concrete which is not characterized by adequate values of porosity structure can have a frost-resistance, amounting to F300. Therefore, it can be said that prevalent values of concrete porosity structure are too severe. Moreover, the requirements related to porosity structure parameters are determined for all kinds of concrete. However, different types of concrete (a type of concrete according to PN-EN 206 is understood as concrete containing: one type of cement, aggregate, type II additions and admixtures) are characterized by different porosity structure. Therefore, do the requirements related to porosity structure parameters concern the whole series of concrete? Moreover, frost resistance of concrete is estimated on the basis of laboratory research results. Therefore what is the procedure to determine critical value $\bar{L}$ to adequate degree of frost resistance of a particular type of concrete?

Prospective frost-resistance of concrete depends on exposure conditions. Frost-resistance degree is determined according to freezing-thawing test method. Therefore, which method should we choose to estimate the appropriate $\bar{L}$ value of frost-resistant concrete?

The adequate concrete air-entrainment, understood as creation of pores in concrete in a special net of proper sizes and permissible spacing is a problematic issue, because of at least 2 reasons. Firstly, the resulting indicator of pores is not inversely proportional to the used amount of an air-entraining mixture, as cited research results show in this paper. It is hard to foresee the effect of special spacing of pores in concrete using the defined amount and a kind of an air-entraining mixture. Secondly, as the results show, for various types of concrete the permissible value of pore spacing is different. The values of porosity structure parameters of one type of concrete do not have to be correct for other types of concrete. Different values of these parameters may be considered to be permissible for particular types of concrete. Furthermore, the theoretical and practical value determined for one particular type of concrete is fundamentally different.

On the basis of conducted researches, practical values of searched parameters can be assessed. During these tests, the composition of mixture, including the type and dosage of an air-entraining mixture and probable technological treatments that the concrete mix is subjected to (for example pumping), should be taken into account. The temperature of a mixture is also important because, as it is presented in this paper, it had a strong influence on air-entrainment of concrete. It is also fundamental to distinguishing the requirements regarding porosity structure parameters for the predicted type of concrete exposure, with the assistance or not of deicing salts during the cyclic frosting and thawing. The question is whether such intermediate evaluation of frost-resistance, demanding the use of highly advanced research technique, in situation in which the porosity structure parameters turned to be dependable on many factors, can be not only reliable but also useful in concrete technology?

Moreover, because of relatively large and still rising amount of the types of concrete, it looks as if it is a really laborious and complicated task to determine universal values of porosity structure parameters. Moreover, the research conducted to determine specific values of these parameters concerning a particular type of concrete would require considerable financial outlays because of relatively high cost of this type of research. Because the access to such research is limited, the researches of immediate frost-resistance should be conducted first. What is more, as it was mentioned in the paper, there are cases when concrete is frost-resistant according to immediate researches, while the structure does not fulfil the desired requirements used mainly in common concrete. The opposite proceedings, that are making the research of the concrete structure first, according to PN-EN 480-11, would not guarantee the degree of frost-resistance of concrete, mostly because of the fact that the critical values of the porosity of concrete structure do not correlate to given degree of its frost-resistance. So, taking into account the above data, the first step, as the author reckons, is to use the immediate methods of frost-resistance testing. The question is, which of the methods of frost-resistance testing are the best? As it is known, the choice of the optimum method of frost-resistance testing depends to a great extend on climate conditions in a given geographical area. Therefore, depending on the predicted conditions of concrete exposure (that is, predicted average amount of frosting cycles, the range of temperatures, the speed of temperature changes, the presence or not of deicing salts, etc.), the used method of frost-resistance testing should be chosen.

To summarize, the issue of theoretical and practical values of the parameters of porosity structure of concrete was not entirely explained in this paper, taking into account the limited volume, and it requires further tests in this area. Moreover, in order to correctly determine the value of the parameters, first we should correctly correlate the intermediate research results and also intermediate frost-resistance continuously creating new types of concrete.

9. Conclusions

1. Some of the new generations of superplasticizers cause excessive air-entrainment of self-compacting concrete, although the mixture fulfils commonly accepted self-compactibility criteria.

2. The reasons for air-entraining effects of superplasticizers include the decreasing of the tension value of the liquid phase in paste. The measurement of surface tension value of paste can be one of the methods of verifying air-entraining effect of a superplasticizer.

3. Formed air-entrainment of a mixture, depending on its content, can reduce its ability to flow.

4. Flowability of SCC fundamentally influences the characteristics of SCC porosity structure. Research results of porosity structure show that air pores which are the effect of the functioning of a superplasticizer, depending on flowability of a mix, can have irregular shape or can also be regular, and because of their shape and size look similar to pores formed as a result of acting of an air-entraining admixture. Pores listed in the first sequence increase absorbing abilities of concrete, which can lead to frost-resistance of concrete.

5. In order to prevent excessive occurrence of air-entrainment, not only superplasticizers compatible with cement should be used, but also ones that do not cause air-entraining effect; or anti-foaming admixtures should be used, counteracting air bubbles forming.

6. Based on the actual state of knowledge, and in accordance with the PN-EN 2006-1, it is recommended to use air entrainment as a basic way of assuring frost-

resistance of concrete. Concrete should be frost-resistant if the value of porosity structure parameter stays within the precisely set limits. To verify if the self-compaction process has an effect of air-void stability, concrete samples were subjected to 300 cycles of freezing and thawing, testing the porosity structure according to PN-EN 480-11. Results of concrete testing have shown that the parameters of porosity structure are not included in precisely set limits but self-compacting concrete is F300 frost-resistant according to PN-88/B-06250.

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ORO ĮSIURBIMO Į SAVAIME TANKĖJANTĮ BETONĄ PROBLEMA

J. Szwabowski, B. Łaźniewska-Piekarczyk

S a n t r a u k a

Laikoma, kad betono atsparumą šalčio poveikiui galima užtikrinti naudojant orą įsiurbiančius priedus. Savaime susitankinančio betono orą įsiurbiančių priedų taikymas ypač painus, nes šiuo atveju galima naudoti tik naujos kartos plastiklius, kurie pasižymi didesniu oro įsiurbimu – >2 %. Norint įvertinti superplastiklių ir orą įsiurbiančių priedų įtaką betono porėtosios struktūros parametrams, buvo ištirta betono bandinių po 300 šaldymo ciklų struktūra pagal PN-EN 480-11 normų reikalavimus. Tyrimų rezultatai parodė, kad nors porėtosios struktūros parametrai nevisiškai atitinka reikalavimus, savaime sutankėjantis betonas pagal PN-88/B-06250 reikalavimus yra F300 klasės. Būtent šis klausimas išsamiai nagrinėjamas straipsnyje.

Reikšminiai žodžiai: atsparumas šalčiui, betono porėtoji struktūra, orą įsiurbiantys priedai, superplastikliai, savaime sutankėjantis betonas.

Janusz SZWABOWSKI. Professor of building materials and construction, head of Department of Building Processes at the Silesian University of Technology in Gliwice, Poland. Member of the Committee on Civil Engineering and Hydroengineering of the Polish Academy of Sciences. His research interests include concrete technology, particularly reology of cement-based mixes and self-compacting concrete.

Beata ŁAŹNIEWSKA-PIEKARCZYK. Reader of engineering in the Department of Civil Engineering at the Silesian University of Technology in Gliwice, Poland. Her research interests include the technology of self-compacting concretes, high and very high-performance self-compacting concretes (HPSCC and VHPSCC). The formation of workability, resistance and durability of self-compacting concretes containing various chemical admixtures (fluxing and stabilizing – VMA – viscosity modifying admixture), air-entraining and anti-foaming admixtures and also mineral additives. The problems concerning the characteristic of porosity structures of the concretes containing various chemical and mineral additives used in technology of concretes and their influence on the mechanic parameters and resistance of the concrete.