Jan. 2010, Volume 4, No.1 (Serial No.26)
Journal of Civil Engineering and Architecture, ISSN 1934-7359, USA

Analysis of the Influence of Type, Amount and Way of Introduction of Anti-foaming Admixture (AFA) on the Properties of Self-compacting Concrete (SCC) Mix

Beata Łaźniewska-Piekarczyk

Department of Building Processes, Faculty of Civil Engineering, Silesian University of Technology, Akademicka 5, Gliwice 44-100, Poland

Abstract: The properties of the self-compacting concrete mix depend on an automatic introduction of air bubbles caught during the process of mixing. What is interesting, the criterion for self-compactibility is not taken into consideration in commonly used self-compacting tests. On the basis of different tests concerning self-compacting concrete mixes, it has been found out that too high air content in their volume was the result of superplasticizer, in spite of meeting the self-compactibility criteria (i.e., self-venting). For the decrease of too high air volume in SCC, the use of anti-foaming admixture (AFA) is proposed. As a result, the effect of AFA mix flow diameter is increased and the flow time is decreased. Moreover, the workability loss is lower. In case of mix incorporating AFA, their high flowability does not cause segregation of the mix, what is possible in case of SCC incorporating only superplasticizer. However, the time of the introduction of AFA and its type is essential to get higher flowability degree, but it is not important to achieve low air volume in SCC.

Key words: Superplasticizer, anti-foaming admixture, methodology decreasing the air-volume, self-compacting concrete, rheological properties.

1. Introduction

The characteristic of self-compacting concrete mix is an effective elimination of air bubbles caught during the process of mixing. The condition of the self-compacting of mix depends on the size of the rheological parameters: yield stress and plastic viscosity of cement paste [1-2]. Because the availability of the direct measurement of rheological properties is limited, technological tests are used in building practice, assessing the self-compactibility of the concrete mix (SCC), such as: flow test (Tables 1 and 2). The value of SCC flow diameter depends on the mix yield stress τ_{0m}, whereas SCC time flow depends on its plastic viscosity η_{pl}. The diameter and time flow of SCC should correspond with the classes presented in Tables 1 and 2.

In the European guidelines for self-compacting concrete [3], detailed outlines in respect of SCC classes and other technical tests of the self-compacting concrete mix depending on its purpose are given. The following are typical slump-flow classes for a range of applications [3]:

SF1 (550 – 650 mm) is appropriate for:

- unreinforced or slightly reinforced concrete structures that are cast from the top with free displacement from the delivery point (e.g., housing slabs);
- casting by a pump injection system (e.g., tunnel linings);
- sections that are small enough to prevent long horizontal flow (e.g., piles and some deep foundations).

Beata Łaźniewska-Piekarczyk, PhD, research fields: technology of self-compacting concretes, high and very high-performance self-compacting concretes, the formation of workability, resistance and durability of self-compacting concretes containing various chemical admixtures, air-entraining and anti-foaming admixtures, mineral additives and so on. E-mail: Beata.Lazniewska@polsl.pl.

Table 1 Slump-Flow classes [3].

Class	[mm]
SF1	from 550 to 650
SF2	from 660 to 750
SF3	from 760 to 850

Table 2 Viscosity classes [3].

Class	[s]	
	T_{500}	V-funnel
VS1/VF1	≤ 2	≤ 8
VS2/VF2	>2	from 9 to 25

SF2 (660 – 750 mm) is suitable for many normal applications (e.g., walls, columns).

SF3 (760 – 850 mm) is typically produced with a small maximum size of aggregates (less than 16 mm) and is used for vertical applications in very congested structures, structures with complex shapes, or for filling under formwork. SF3 will often give better surface finish than SF2 for normal vertical applications but segregation resistance is more difficult to control.

Target values higher than 850 mm may be specified in some special cases but great care should be taken regarding segregation and the maximum size of aggregate should normally be lower than 12 mm [3].

Viscosity (low or high) should be specified only in special cases such as those given below. It can be useful during mix development and it may be helpful to measure and record the T_{500} time while doing the slump-flow test as a way of confirming uniformity of the SCC from batch to batch. VS1/VF1 has good filling ability even with congested reinforcement. It is capable of self-levelling and generally has the best surface finish. However, it is more likely to suffer from bleeding and segregation. VS2/VF2 has no upper class limit but with increasing flow time it is more likely to exhibit thixotropic effects, which may be helpful in limiting the formwork pressure or improving segregation resistance. Negative effects may be experienced regarding [3].

On the basis of the results of various tests it was stated that in numerous cases a problem of excessive air-entrainment of concrete mix appears [4-5]. Tests of the porosity characteristics of the concrete proved that the excessive air-entrainment of the mix influences the air-entrainment of concrete (during the process of concrete hardening, formed pores are not filled with the hydration products, because C-S-H gel may form only in water), [4]. Also, the tests results [6] (presented in Tables 3, 4 and 7), prove that new generations of superplasticizers (SP) show air-entrainment effect. It should be emphasized that according to standard requirements concerning chemical additives of the concrete, superplasticizers should not cause air formation in the mix higher than 2%.

The reason for the PCP air-entrained superplasticizer effect is its influence on the decrease of the surface tension of the liquid phase in the paste, as it was proved by other tests [8]. The air content developed with the superplasticizer effect increases with the increase of w/s ratio (Figs. 1 and 2). With the increase of the liquid phase part in mix, the air-entrainment effect is higher, similarly as in case of the air-entraining admixture.

On the basis of tests results shown in Ref. [9], we can conclude the influence of etheric and poly-carboxyl superplasticizer the SCC porosity structure. The test results of A ÷ D fresh mix properties are presented in Table 4, whereas in table 5 test results of the porosity characteristics of the hardened concrete are shown.

Tests results presented in Table 5 prove that superplasticizers on the basis of poly-carboxyl ether cause considerable SCC air-entrainment. The air-entrainment of concrete is higher in case of higher w/c value and amounts to even 8.30%. It should be emphasized that mix achieved relatively high flow, which is 660 mm (which corresponds with class *SF2*, Table 1). Despite this fact, no suitable self-compactibility took place (self-venting). The air-entrainment of fresh mix was probably higher than 8.3%, because the air content marked in hardened

Table 3 The influence of the superplasticizer on the mix air-entrainment [6].

SP type	Ligno-sulfian, LS	Sulfonated naphtalene formaldehyde condensate, SNF	Sulfonated melanine formaldehyde condensate, SMF	New generation superplasticizers	
				Poly carboxylate polyoxyethylene, PCP	Amino phosphonate polyoxyethylene, AAP
Air-content	++	+	0	++	++

Table 4 Test results of the rheological properties of concrete mix with the use of Abrams cone [9].

Symbol	Binder type	SP based on:	w/b	T_{500}, [s]	Slump-Flow, [mm]
A	CEM I 42,5, fly ash	Polycarboxylic ether (PCE)	0.34	5.0	680
B			0.45	4.6	660
C		Polycarboxylate (PCP)	0.34	4.9	690
D			0.45	4.1	710

Table 5 The set of test results of air pores structure in concretes [9].

Porosity structure parameter	Series			
	A	*B*	*C*	*D*
Air-content, A [%]	6.7	8.30	2.90	4.45
Content of micropores below 0.3 mm, A_{300} [%]	1.50	2.96	0.70	1.74
Spacing factor, L [mm]	0.26	0.11	0.33	0.13
Specific surface, α [mm^{-1}]	17	36	21	45

concrete is approximately by 1%÷2% lower than that found in the mix. The reason for the excessive air-entrainment of the fresh mix is probably the influence of the mechanism of working and structure of superplasticizer on the formation and behavior of air bubbles in its volume. In the case of poly-carboxyl superplasticizer the air content was lower and amounted to 4.45% with w/c = 0.45. Test results concerning the effects of poly-carboxyl superplasticizer comply with other test results published in Ref. [4]. The conclusions from the analysis of the test results presented in Table 5 also confirm test results of mercurial porosimeter. And in this case, the superplasticizer on the basis of poly-carboxyl ether causes higher SCC air-entrainment. An excessive air content appeared although the fresh mix achieved even 710 mm flow. A well-founded question is formed concerning the effectiveness of commonly used tests aiming to qualify the mix as self-compacting [10-11], in case when a superplasticizer shows the air-entraining effect.

2. Negative Effects of the Excessive Air-entrainment in Case of Self-compacting Mix and Concrete

The air-entrainment of the fresh mix may decrease its flow depending on the degree of the initial fluidity, as the result of internal compression of the air bubbles and lower density of the fresh mix. The air-entrainment may also initially increase the flow when the fresh mix characterizes with originally low fluidity [12-13]. However, other amounts of the air-entrained admixture cause the decrease of the diameter of flow of fresh mix.

The sizes of pores formed during the effect of superplasticizer in hardened concrete characterize with too big sizes (Figs. 1 and 2). They are the reason of the decrease of concrete mechanical parameters and are not beneficial from its frost resistance and absorptivity point of view [4]. In order to protect concrete against

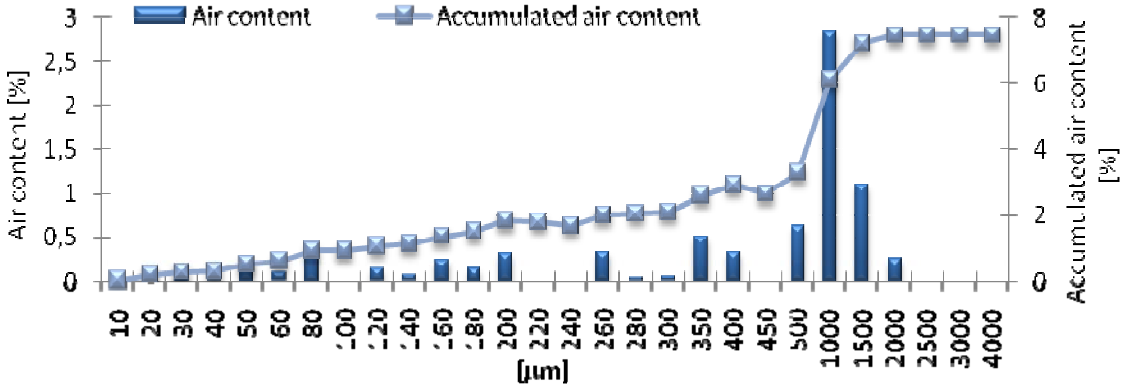

Fig. 1 The porosity characteristics of non air-entrained SCC (CEM I 32.5 R + 10% silica fume; w/b=0.41) [4].

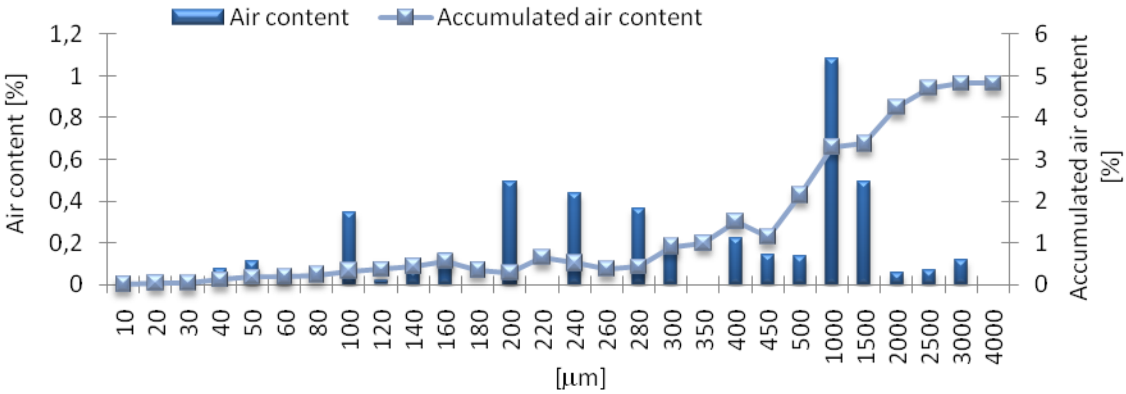

Fig. 2 The porosity characteristics of non air-entrained SCC (CEM II 32.5 R B-S; w/b=0.29) [4].

the effects of cyclic freezing and thawing it is beneficial when the bubbles are characterized with diameters of 0.05 ÷ 0.10 mm and are in the paste volume in the range of 0.15 ÷ 0.20 mm from each other [14]. Although the problem of the critical value of the pores range in frost resistant concrete, depending on its type, is still a considered issue [2].

Analyzing the results of other tests shown in Ref. [4], it is proved that 4% of the air-entrainment (being the result of a superplasticizer) cause the resistance decreases down to 24% when SCC concrete with ratio *w*/*c* = 0.4 with zero air volume is considered.

Considering these above mentioned tests results it may stated that certain super-plasticizers of new generation cause excessive air-entrainment which remains in the self-compacting volume of the fresh mix and concrete, causing deterioration of their properties, although the mix meets commonly accepted criteria of technical tests (Tables 1 and 2). Desired suitable fluidity of the fresh mix, essential for its efficient self-compacting, is not included in any commonly used technical tests. Commonly accepted criteria for such tests are insufficient in this scope and do not guarantee effective self-compacting. It can be obtained by increasing the fluidity of the fresh mix with the superplasticizer, however it may cause its segregation. Due to this fact, in order to prevent the presence of the excessive air-entrainment, the superplasticizers should not only be compatible with cement, but also do not create air-entraining effect in the paste. In order to counteract the excessive air-entrainment anti-foaming admixtures (AFA) may be used against the formation of air bubbles. Such admixtures are not commonly used in building practice. Hence, the mechanism of their functioning is not well-known, as well as their effectiveness in decreasing the air content in fresh mix

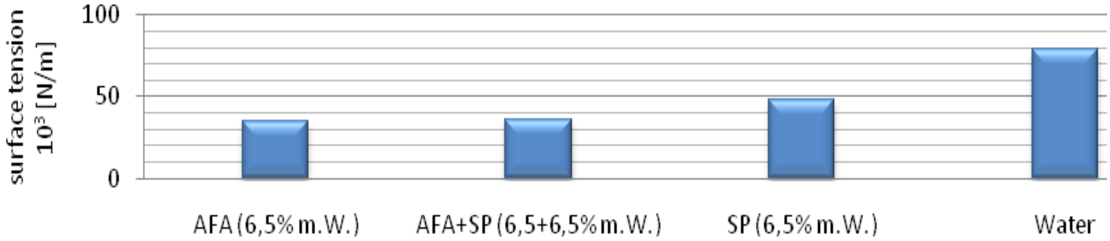

Fig. 3 **Influence of type admixture on surface tension of water; SP based on polycarboxylate (PCP); and AFA based on polyalcohol.**

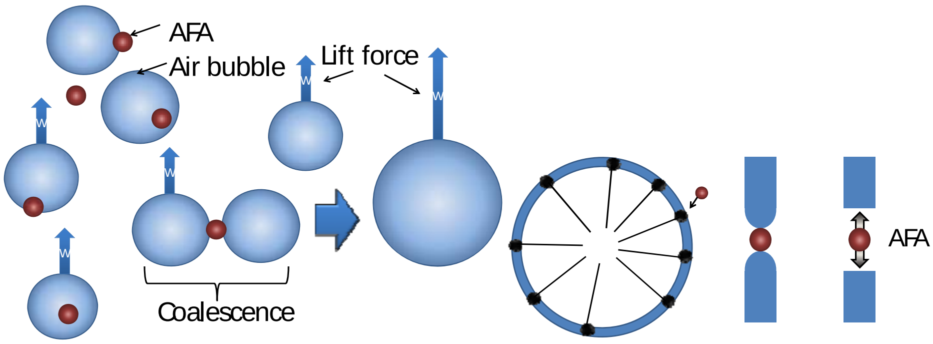

Fig. 4 **Stages of the mechanism of action of an anti-foaming admixture.**

and its influence on fresh mix properties and on properties of hardened concrete. So, it is advisable to carry on proper tests aiming at verification of the influence of anti-foaming admixtures on air-entrainment, rheological properties and stability of self-compacting concrete mix, also depending on the time of their introduction.

3. Anti-foaming Admixtures

Components and their proportions used in the anti-foaming admixtures, as in superplasticizer, are known only to their producer. They may be: mineral oils, silicone oils, organic modified silicones, hydrophobic constant molecules (silica, waxes, higher fatty acids soaps, alcohols and fatty acids), emulsifiers, polyalcohol, alcohol derivatives of organic compounds. They may be mixes of above active components acting in a synergetic way. Unfortunately, high price and not widely tested influence on properties of the fresh mix and concrete do not favour wider use of the anti-foaming admixtures.

To analyze the influence of properties of those admixtures on properties of the fresh mix and concrete, first their mechanism of functioning should be known. Research results (Fig. 3) show that the effectiveness in decreasing air content in cement paste of the anti-foaming admixtures does not consists in increasing the value of surface tension of its liquid phase. Surface tension of water solution of anti-foaming admixture, superplasticizer and anti-foaming admixture characterize with even smaller value than the surface tension of the water solution of air-entraining superplasticizer (Fig. 3).

The mechanism of functioning of anti-foaming admixture may be explained in the following way. The active components are distributed around gas bubbles, displacing surfactant molecules. In result, the thickness of the lamella wall built from surfactant causes its destabilization and results in the fracture or coalescence of the bubble (Fig. 4).

To identify the wider unknown influence of the anti-foaming admixtures on air-entrainment of the self-

Table 6 The mix composition of self-compacting mixes.

Series	Cement type	Cement	w/b	W/b W= water + liquid chase of admixture	Sand	Gravelly aggregates			SP*	AFA**
					[kg/m³]					
					0-2	2-4	2-8	8-16		
		[kg/m³]			[mm]				[% m.C.]	
M1	CEM II B-S	541	0.40	0.41	890	200	228	256	0.77	0.00
M1-f				0.42						2.02
*M1-f-t****				0.42						2.02

* based on polycarboxylate (PCP), ** based on polyalcohol, *** AFA added after 20 min.

Table 7 Mix composition of mortars; cement CEM II B-S: 541 [kg/m³], w/b = 0.40; sand: 890 [kg/m³].

Series	w^1/b	SP [%m.C]	AFA [%m.C]	AFA based on:
*Z2**	0.40	0.77	0.00	-
Z		0.00		
Z2-a		0.77	2.21	Froth breaker on the PDMS basis/ silicone oil/ hydrophobic silica
Z2-a1			4.42	
Z2-b			2.21	Froth breaker on the basis of mineral oil or amidol wax
Z2-c				Froth breaker on the basis of alcohol derivative of saturated fatty alcohol, mineral oil and PE wax
Z2-d				Fiakyl derivative of saturated fatty alcohol/mineral oil/PE and amidol wax
Z2-d1			4.42	
Z2-d2			1.11	
Z2-e			2.21	Alkoxyl derivative of fatty alcohol, 100%
Z2-f				Polyalcohol
*Z1-d***				Oxiakyl derivative of saturated fatty alcohol/mineral oil/PE and amidol wax
*Z3****	0.41	0.56	0.00	-
*Z3-d****			2.21	Oxiakyl derivative of saturated fatty alcohol/ mineral oil/PE and amidol wax

* SP based on polycarboxylic ether (PCE), ** SP based on polycarboxylate (PCP), *** SP based on polycarboxylic ether (PCE) (another type than *), [1]water + admixtures liquid part.

compacting mix and its properties, suitable tests were carried out.

4. Methodology of the Research

The mix proportions of the tested self-compacting concretes is showed in Table 6. The process of mixing started with dry components (about 0.5 min). Then water was added where superplasticizer was earlier distributed at the end of the process of mixing, the anti-foaming admixture was added (in case of one series such admixture was introduced after 20 minutes, Table 7), and all ingredients were mixed for another 6 minutes in case of ordinary concrete and 12 minutes in case of high-performance concrete. After 15 minutes, the fresh mix was subjected to another short mixing and then rheological measurements were carried out and the air content in the fresh mix was checked. After filling up the container, the fresh mix was kept for 10 minutes.

The air content was defined after proceedings described after EN 12350-7, mix density after EN 12350-6, whereas the flow and its time after ASTMC 143.

The effectiveness of anti-foaming admixture depending on its type and the most air-entrained superplasticizer (identified on the basis of earlier tests of fresh mix, Tables 6 and 7), was checked by the tests of flow and air-entrainment of mortar after EN 1015-3: 2000/A2: 2007 and EN 1015-7: 2000 respectively. The volume of mortars corresponded to that used in the fresh mix (Table 6).

The process of mixing of the mortars started with dry ingredients, and then superplasticizer was added and next anti-foaming admixture of particular type (Table 7). The mixing of components of mortars was carried out after the proceedings accepted for standard mortar after EN 197-1/2002. Mortar *Z*, because of containing *SP*, was subjected to densification through shaking. The mortar was put in three layers in the container being the part of the apparatus that tests the air content in its volume. Each layer was shaken before laying another one. After 20 minutes, in case of all tested mortars, the air-entrainment measurements and mortar flow were carried out, because after such time the effectiveness of superplasticizer is the highest. To assess AFA influence on the workability loss of the mortar in relation to time, the assessment of paste flow was checked after 20 and 60 minutes, counting from the time of mixing the remaining components.

5. Research Results and Discussion

Research results presented in Table 8 show the effectiveness of anti-foaming admixture in decreasing the air content in the fresh mix. The air content in case of tested mixes may be decreased even by about 3% and more in case of mixes of low w/b. Additional advantage that was achieved due to the use of anti-foaming admixtures, was high increase of fresh mix flow, and what was essential, in considerably shorter time (Table 8). Moreover, in case of the fresh mix containing AFA, the loss of initial consistency was considerably slower. Despite shorter time and low viscosity of the mix the segregation did not occur. On the contrary, the fresh mix containing anti-foaming admixture was more stable than the mix with similar diameter of flow, but containing higher amount of superplasticizer. The advantage achieved as a result of the usage of anti-foaming admixture due to its fluxing effect was the decrease of the volume of the necessary superplasticizer. In result, similar consistency was obtained but, what should be emphasized, of non air-entrained excessively self-compacting mix.

In Table 8 test results on technology of preparation of the fresh mix containing anti-foaming admixture are shown. In one case, the admixture was immediately introduced after the superplasticizer, in another one, 20 minutes after starting the process of mixing and introduction of superplasticizer to the mix volume. The test results prove that the time of introduction the anti-foaming admixture is not essential for the effectiveness of this admixture in decreasing the air-entrainment of the mix. This conclusion is very important because the anti-foaming admixtures may be used in order to:

- prevent the occurrence of the excessive air-entrainment of the mix (introducing anti-foaming admixture with air-entrained superplasticizer),
- decrease already existing air content (caused by air-entrained superplasticizer) in fresh mix.

Other tests proved that it was not possible to air-entrain the fresh mix for the second time, if the anti-foaming admixture was introduced. So, anti-foaming admixtures should not be used in a case of mixes that were air-entrained on purpose.

The test results presented in Table 8 show that the time of introduction of anti-foaming admixture influences significantly the diameter and flow time of the fresh mix. In order to achieve the highest fluxing of

Table 8 Test results on the properties of mixes.

Series	Air-volume *Ac*, [%]	Flow diameter after 20 min, [mm]	Flow time *T* after 20 min, [s]
M1	4.0	63	3
M1-f	2.8	70	1
M1-f-t	2.8	65	1

Table 9 Test results on the properties of mortars.

Series	Air-volume *Ac*, [%]	Flow diameter after 20 min, [mm]	Flow time *T* after 20 min, [s]	Flow diameter after 60 min, [mm]	Flow time *T* after 60 min, [s]
*Z3****	3.0	29.5	5	24.5	7
*Z3-a****	2.2	31.0	4	27.0	6

*** SP based on polycarboxylic ether (PCE) (another type than *).

Table 10 Test results on the properties of mortars.

Series	Air-volume *Ac*, [%]	Flow diameter, after 20 min, [mm]	Flow time *T* after 20 min, [s]
*Z2**	12.0	26.0	2
Z	4.0	11.0	4
Z2-a	3.0	29.9	6
Z2-a1	3.0	27.0	6
Z2-b	5.2	36.3	5
Z2-c	3.8	39.1	4
Z2-d	3.4	37.0	6
Z2-d1	3.4	34.0	6
Z2-d2	4.0	32.0	6
Z2-e	5.4	30.6	6
Z2-f	2.8	36.0	5
*Z1***	3.0	31.0	6

* SP based on polycarboxylic ether (PCE), ** SP based on polycarboxylate (PCP).

mix, the anti-foaming admixture should be introduced as fast as possible.

In Tables 9 and 10 the test results on mortars are presented. It was noticed, that different type of superplasticizers causes radically different volume of air in mortars (Tables 9 and 10). In case of mortars subjected to concentration (*Z*), 4% of air volume was observed. The mortar, in which air-entraining superplasticizer was used, was characterized with even about 12% air volume. Both mortars were considered as a reference in the assessment of AFA effectiveness. Tests results of *Z2-a*÷*Z2-f* mortars prove that due to the reduction of the air-entrainment in mortar and its rheological properties, the most effective ones were characterized with AFA on the basis of polyalcohol. Comparing test results of *Z2-d* and *Z2* mortars it can be concluded that the superplasticizer type is essential because of the AFA effectiveness.

Test results of *Z2-d*, *Z2-d1* and *Z2-d2* mortars prove that the effectiveness of AFA depends on its volume, and when certain point of saturation is exceeded, no further reduction of the air-entrainment is possible, but only the improvement of the fluidity of the mortar. The reduction of the air-entrainment with the use of AFA may be higher than in case of the use of mechanic concentration of mortar (*Z*). The mortar, despite considerable fluidity and containing AFA, does not undergo segregation, as it is in case of the mortar with no AFA of similar fluidity level. Moreover, test results of *Z3* and *Z3-a* mortars prove that mortars with AFA maintain initial consistency longer in comparison to mortars with only superplasticizer (Table 10). Other tests prove that conclusions on AFA based the tests on mortars may be successfully accepted in fresh mixes.

6. Conclusions

In the scope of carried out tests on anti-foaming admixtures, the following conclusions may be proposed:

(1) Anti-foaming admixtures may be used in order to prevent excessive air-entrainment of the mix (introducing anti-foaming admixture with air-entrained superplasticizer), or in order to decrease already existing air volume, caused by air-entrained superplasticizer in the fresh mix.

(2) As to the results of use of AFA, the increase of the flow of mixture achieved in shorter time (the bigger the smaller *w/s* is) follows, and without its segregation. Moreover, in the case of fresh mix with AFA, the loss of its initial consistency is slower, as it was proved in the latest tests. So, due to the use of anti-foaming admixtures, it is possible to decrease the need of a superplasticizer in order to achieve suitable flow of the mix.

(3) The essential for mentioned above rheological properties modifications developed by the effect of anti-foaming admixtures, is the moment of its introduction to the fresh mix. The best effectiveness is obtained by the introduction of that admixture immediately after superplasticizer. However, the moment of introduction of this admixture is not essential to achieve the low air volume in the fresh mix.

(4) Test results of mortars show that because of the reduction of the air-entrainment in mortars and their rheological properties, AFA on the basis of polyalcohol is characterized by the highest effectiveness. The effectiveness of AFA depends on the used amount of superplasticizer, and after exceeding some point of saturation, there is no further reduction, only improvement of the fluidity of the mortar. It should be emphasized, that the mortar, despite considerable fluidity and containing AFA, does not undergo segregation, as it is in the case of mortars with no AFA of similar degree of fluidity (caused by higher amount of superplasticizer). Moreover, test results prove that mortars with AFA maintain initial consistency for longer time in comparison to mortar with only superplasticizer.

Because certain producers already use anti-foaming admixtures, the problem of compatibility of AFA depending on the SP type and other admixtures types in their content, and also introduced to fresh mix on purpose, will be the subject of future tests, where the influence of AFA and other chemical admixtures on the properties of hardened self-compacting concrete will be analyzed.

References

[1] J. Szwabowski, Rheology of Cement Based Mixes (in Polish), Wydawnictwo Politech-niki Śląskiej, Gliwice, 1999, p. 239.

[2] J. Szwabowski and B. Łaźniewska-Piekarczyk, The suggested values of parameters of porosity structure of self-compacting concrete (SCC), Cement-Wapno-Beton 3 (2008) 155-165.

[3] European Project Group, The European Guidelines for Self-compacting Concrete: Specification, Production and Use, available online at: http://www. efnarc. org/ pdf/SCCGuidelinesMay2005.pdf, 2005.

[4] J. Szwabowski and B. Łaźniewska-Piekarczyk, Air-entrainment problem in self-compacting concrete, Journal of Civil Engineering and Management 15 (2009) 137–147.

[5] J. Szwabowski and B. Łaźniewska, Influence of the properties of self-compacting concrete on the effect of air

entrainment, in: The 9th International Conference of Modern Building Materials, Structures and Techniques, Vilnius, Lithuania, Selected papers, May 16-18 2007, pp. 182-189.

[6] M. Mosquet, The new generation admixtures (in Polish), Budownictwo Technologie Architektura (special Ed.) 2003, pp. 21-23.

[7] V. S. Ramachandran, Concrete Admixtures Handbook: Properties, Science and Technology, 2nd Ed., Noyes Publications, Park Ridge, New Jersey, USA, 1995, p. 1154.

[8] B. Łaźniewska-Piekarczyk, The surface tension of cement paste and its affects to formation air bubbles, 6th International Conference AMCM'2008 Analytical Models and Concepts in Concrete and Masonry Structures, Łódź 2008, pp. 229 -230. (abstract with paper in CD).

[9] T. Gorzelańczyk, The assessment of the failure of self-compacting concretes by acoustic techniques (in Polish), Ph.D. dissertation, Wrocław, 2007, p.134.

[10] J. Szwabowski and B. Łaźniewska-Piekarczyk, The increase of air content in SCC mixes under the influence of carboxylate superplasticizer, Cement-Wapno-Beton 4 (2008) 205-215.

[11] E. Sakai, T. Kasuga, T. Sugiyama, K. Asaga and M. Daimon, Influence of superplasticizers on the hydration of cement and the pore structure of hardened cement, Cement and Concrete Research 36 (2006) 2049–2053.

[12] B. Łaźniewska-Piekarczyk, The influence of air-entrainment on rheological properties of SCC (in Polish), X Sympozjum Naukowo-techniczne Reologia W Technologii Betonu, Gliwice, 2008, pp. 113-124.

[13] A. M. Neville, Properties of Concrete (in Polish), Polski Cement, Kraków, 2000, p. 874.

[14] G. Fagerlund, Durability of Concrete Structures (in Polish), Arkady, Warsaw, 1999, p.93.