INFLUENȚA SILICEI ULTRAFINE ŞI A REGIMULUI DE ÎNTĂRIRE ASUPRA UNOR PROPRIETĂȚI ALE BETONULUI
THE INFLUENCE OF SILICA FUME AND CURING REGIME ON SOME PROPERTIES OF CONCRETE

KSENIJA JANKOVIC[1*], ANDJELIJA ILIC[2], MARKO STOJANOVIC[1]
[1]*Institute for Testing Materials - IMS, Bulevar vojvode Misica 43, Belgrade, Serbia*
[2]*Faculty of Civil Engineering, Subotica, Kozaračka 2a, Serbia*

The investigation of posibilities of concrete structure modification by silica fume to improve concrete properties was presented in this report. Percentage of silica fume in regard to cement varied between 0% and 20%. Concrete was cured as follows: in water, steam – curing regime at +60°C and +90°C. The results of the compressive and tensile strength, freeze / thaw resistance with de-icing salts, and depth of penetration of water under pressure.

Keywords: *silica fume, steam – curing regime, concrete durability*

1. Introduction

The development of new building materials such as composite materials with cementations matrix enables the design and execution of increasingly complex and demanding structures [1]. Ordinary concrete has a number of disadvantages such as low tensile strength, cracking on drying shrinkage, insufficient ductility, relatively large capillary porosity, low chemical resistance, etc.

Most of the listed imperfections have a impact on the formation of the structure of ordinary concrete. One of the attempts to eliminate the defects of ordinary concrete, while improving its good properties, is investigating the possibilities of change or modification of the internal concrete structure using concrete with the addition of silica fume (hereafter SFC) [2].

2. Component materials and mix design

Concrete properties relevant to the durability, are the result of the components' properties, mix proportions and the methods of making, transporting and placing concrete, and concrete care. Each of the concrete components and their relationship in the mix, more or less, directly or indirectly affect the durability of hardened concrete. The choice of concrete quality in terms of durability must include the prediction of conditions throughout the life and service life of concrete construction because the environment that is not favourable for the concrete can be more important to evaluate the parameters of durability than concrete strength [3]. Experimental results of concrete prepared with cement type CEM III / A, as an example for obtaining the necessary date in order to establish the service life of constructions were presented in [4].

Experimental part of the work was done in the Laboratory for Concrete, Institute IMS in Belgrade, Serbia. The materials that have been used for making concrete with the addition of silica fume, are the ones that are available in our area and that are used for making commercial concrete. Preliminary testing has confirmed their compatibility. Potable water has been used for the preparation of mixtures.

In the experimental work, the pure Portland cement CEM I 42.5R Lafarge BFC, Serbia was used. This cement has no ingredients other than those which are included in Portland cement clinker, except the addition of gypsum, which is necessary to regulate the setting time. Initial and final setting times of the cement were 4 and 5 h respectively. Specific gravity is 3150 kg/m^3. Its Blane specific surface area was 4120 cm^2/g and chemical composition is given in Table 1.

As a mineral addition type II silica fume Sikafume HR was used. According to the manufacturer's data sheet density is 700 kg/m^3, and over 95% of the particles size is below 0.1µm. Its chemical composition is given in Table 1. Silica fume is obtained as a by-product in the production of ferro alloys. By the use of these ultra-fine particles of amorphous SiO_2, as well as using suitable superplasticizer, concrete with strengths that are 2 times higher than the strength of ordinary concrete can be obtained [5]. In addition, concretes with silica fume have improved workability and reduced water allocation, lower permeability to liquids and gases, better frost resistance and greater durability in aggressive environments [6, 7].

* Autor corespondent/Corresponding author,
E-mail: ksenija.jankovic@institutims.rs

Table 1

Chemical composition of cement and SF (%)

Oxide	Cement CEM I 42,R	SF Silica fume
SiO_2	20.59	81.40
Al_2O_3	6.10	4.47
Fe_2O_3	2.81	1.40
CaO	63.44	0.82
MgO	1.89	1.48
SO_3	2.69	1.35
Na_2O	0.29	NA
LOI	1.55	7.26
LSF	0.95	-
SR	3.38	-
AR	2.17	-
C_3S	49.11	-
C_2S	16.20	-
C_3A	11.41	-
C_4A	8.55	-
Cl^-	0.003	-

Applying concrete admixtures can significantly affect the properties of fresh and hardened concrete. Superplasticizer Sika ViscoCrete 4000 BP was used. This admixture allows reduction of the amount of water in concrete up to 30%, which significantly contributes to the reduction of capillary porosity.

Dry and clean, natural, river, separated aggregate from the Danube River in the fraction 0/4, 4/8; 8/16 mm has been used in concrete mixture. The absorption value of the sand used was 1.2%, and relative density was 2640 kg/m^3. The volumetric mass of water saturated and surface dry aggregate is in the given range of 2000 to 3000 kg/m^3, specifically 2644 kg/m^3 for fine aggregate, while the coarse aggregate ranges from 2630 do 2641 kg/m^3.

The percentage of aggregate fractions for all types of concrete, was the same (46%, 22%, 32%), grain size distribution is given in Figure 1.

Five types of concrete were made. Each type of concrete was made with a certain percentage of silica fume, which varied between 0%, 5%, 10%, 15% and 20%. The components were mixed on dry for 3 minutes so that fine particles of silica fume, can be evenly distributed throughout the concrete mixture, after which water was added, and also the chemical admixture (superplasticizer). Composition of concrete mixtures with the addition of silica fume and various curing regimes are shown in Table 2.

3. Results of investigation

3.1. Properties of fresh concrete

Rheological properties of fresh cement paste play an important role in determining the workability of concrete. The water requirement for flow, hydration behavior, and the properties of the hardened state largely depends upon the degree of dispersion of cement in water. Properties such as fineness, particle size distribution, and mixing intensity are important in the determining of the rheological properties of cement paste.

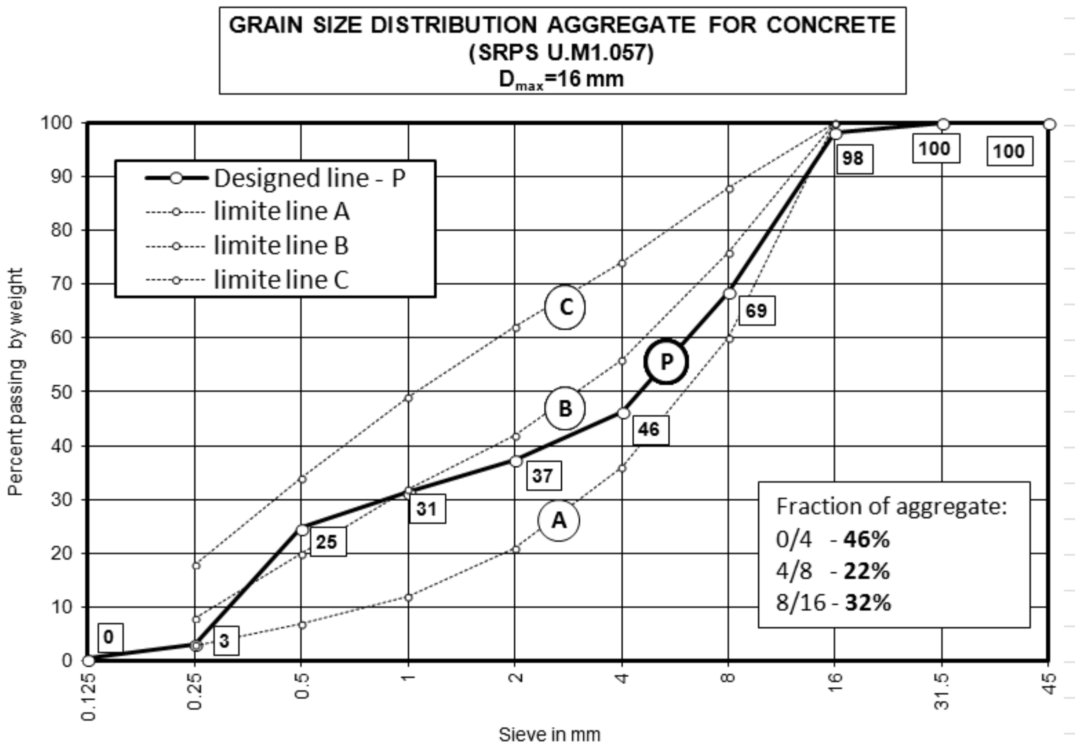

Fig. 1 - Grain size distribution aggregate for concrete.

Table 2

Composition of concrete mixtures with the addition of silica fume

Curing regime			SF-Silica fume		Viscocrete 4000 BP		Water	
in water	steam curing regime							
+20 ^{0}C	+60 ^{0}C	+90 ^{0}C						
Mix N^0			%	kg/m^3	%	kg/m^3	kg/m^3	w/b
SFC -1	SFC -6	SFC -11	0%	0	1%	3.50	168	0.480
SFC -2	SFC -7	SFC -12	5%	17.5	1%	3.68	168	0.457
SFC -3	SFC -8	SFC -13	10%	35.0	1%	3.85	168	0.436
SFC -4	SFC -9	SFC -14	15%	52.5	1%	4.03	168	0.417
SFC -5	SFC-10	SFC -15	20%	70.0	1%	4.20	168	0.400

Cement = 350 kg/m^3; Aggregates = 1838 kg/m^3

Fresh concrete containing silica fume is more cohesive and less prone to segregation than concrete without silica fume. Concrete containing silica fume shows substantial reduced bleeding. Additionally silica fume reduces bleeding by physically blocking the pores in fresh concrete. The use of silica fume does not significantly change the unit weight of concrete.

After making concrete in the mixer, the measuring of concrete consistency was performed. Consistency of all types of concrete satisfied class S4 (> 160 mm). For concrete with the addition of silica fume the temperature of fresh concrete mixtures after preparing ranged from +22 to +26 ^{0}C. The air content was in the range of 1.8 to 2.9%. Concrete density varied from 2360 to 2430 kg/m^3. Cubic specimens with 150 mm side were prepared from each fresh concrete. Complete compaction of fresh concrete was obtained by the means of vibrating [8].

The first group of 5 types of concrete was cured in water at +20 ^{0}C. The second and the third group were 6h in air, then exposed to steam-curing regime at temperatures of +60 and +90 ^{0}C and a relative humidity of about 95%. After cooling, the testing of concrete compressive strength was performed at the age of 18 hours. Figure 2 shows the curing regimes of concrete.

3.2. Compressive strength

The samples for testing were prepared in dimensions of 15x15x15cm cube shape.

For concrete which was cured at a temperature of + 60 ^{0}C, the obtained results clearly show that the concrete not containing silica fume has a minimum strength of 36.2 N/mm^2 while the compressive strength with the addition of silica ranging from 5 to 20% reached the strength of 43.4 to 47.5 N/mm^2.

With the increase of silica fume content for the specimens which were exposed to steam-curing regime at + 90 ^{0}C compressive strength increases. It can be explained by the acceleration of the chemical reactions of hydration with the increase in temperature. According to [5] the addition of silica fume accelerates all stages of hydration process of Portland cement in + 90 ^{0}C which results in early strength enhancement. The obtained values are much higher compared to the testing results of the specimens exposed to steam-curing regime at temperature of + 60 ^{0}C. Results of compressive strength of concrete with silica fume are shown in Table 3.

For each curing regime the results of compressive strength of concrete with the addition of silica fume in the function of the content of cement and silica fume were given in Figure 3.

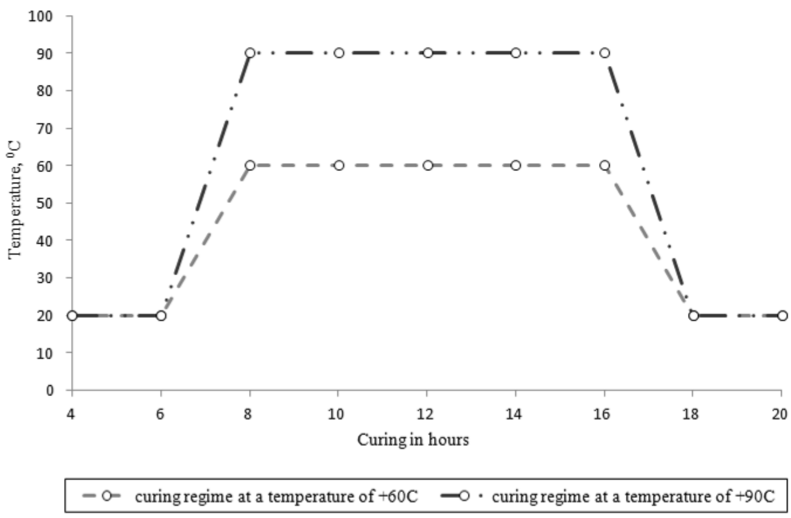

Fig. 2 - Steam – curing regime at temperatures of +60^{o}C and +90^{o}C.

Table 3

Compressive strength of concrete

Curing regime		Mix N°	SF	Compressive strength of concrete $f_{c,cube}^{18hours}$	Compressive strength of concrete $f_{c,cube}^{28days}$
			%	N/mm²	N/mm²
in water	20 °C	SFC -1	0	-	56.0
		SFC -2	5	-	68.6
		SFC -3	10	-	66.1
		SFC -4	15	-	67.1
		SFC -5	20	-	70.8
Steam-curing regime	+60 °C	SFC -6	0	36.2	-
		SFC -7	5	46.1	-
		SFC -8	10	43.4	-
		SFC -9	15	46.1	-
		SFC -10	20	47.5	-
	+90 °C	SFC -11	0	45.7	-
		SFC -12	5	54.8	-
		SFC -13	10	61.7	-
		SFC -14	15	64.9	-
		SFC -15	20	74.7	-

Aggregate=1838 kg/m³; Cement=350 kg/m³; Water=168 kg/m³

Table 4

Tensile splitting strength of concrete

Curing regime		Mix N°	SF	Compressive tensile strength of concrete $f_{ct}^{18hours}$	Compressive tensile strength of concrete f_{ct}^{28days}
			%	N/mm²	N/mm²
in water	20 °C	SFC -1	0	-	4.53
		SFC -2	5	-	4.67
		SFC -3	10	-	5.52
		SFC -4	15	-	4.86
		SFC -5	20	-	4.53
Steam-curing regime	+60 °C	SFC -6	0	4.53	-
		SFC -7	5	4.90	-
		SFC -8	10	4.53	-
		SFC -9	15	4.43	-
		SFC -10	20	3.68	-
	+90 °C	SFC -11	0	3.44	-
		SFC -12	5	3.68	-
		SFC -13	10	4.62	-
		SFC -14	15	4.86	-
		SFC -15	20	5.42	-

Aggregate=1838 kg/m³; Cement=350 kg/m³; Water=168 kg/m³

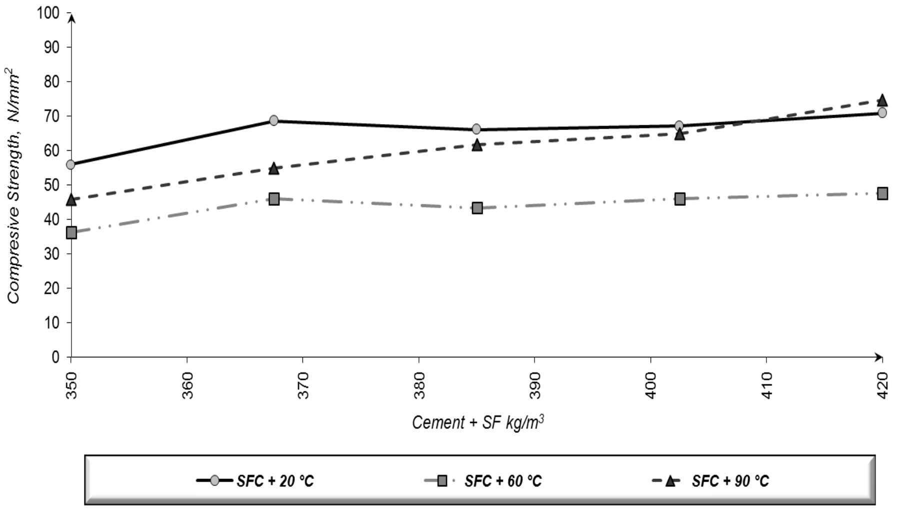

Fig. 3 - Concrete strength in the function of content of cement and silica fume.

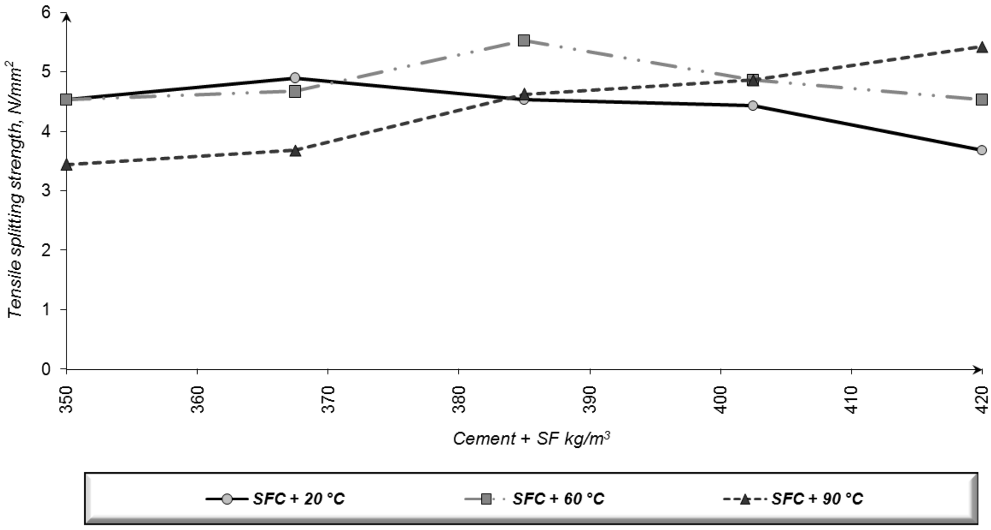

Fig. 4 - Concrete tensile strength in the function of content of cement and silica fume.

3.3. Tensile splitting strength

The first batch of concrete was cured in water at + 20^{0}C and tested at the age of 28 days. Concrete with 10% of silica fume achieved 5.52 N/mm^2, while concrete with the addition of 15% had tensile splitting strength of 4.86 N/mm^2. After preparing the second batch it was cured by steam-curing regime at temperature of +60^{0}C. Concrete with the 5% addition of silica had the highest value in testing the splitting tensile strength - 4.90 N//mm^2. A constant decline in tensile strength was achieved by adding silica fume containing 10 to 20%. It can be explained by the increase in micro-cracking due to autogenous shrinkage which affects the flexural strength [5]. After preparing the third batch it was cured by steam-curing regime at temperature of +90^{0}C. Contrary to the results of the tests obtained in the second group, where there was a constant decline in tensile strength with the increase in silica content, this concrete shows a constant rise in tensile strength with the increase in silica content, so that the highest test value of 5.42 N/mm^2 is achieved in concrete with the highest silica content - 20%. Results are shown in Table 4 and Figure 4.

Hooton [9] reported the splitting tensile strength of silica fume concretes up to the age of 182 days. He found that except at 28 days, the splitting tensile strength was not improved for silica fume concrete mixes. Also it was observed that with increasing replacement of cement by silica fume split tensile strength decreased.

3.4. Waterproof

This property of concrete was tested on samples of cubic shape, edges 15x15x15cm. Surfaces of concrete samples were exposed to the water pressure in the regime of: 48h - 100 kPa, 24h - 300 kPa and 24h - 700kPa, according to [10]. Water penetration is shown in the function of cement and silica fume in Figure 5.

Water penetration in concrete was reduced with the increase in silica fume, due to pore size refinement and matrix densification, reduction in $Ca(OH)_2$ content and cement paste-aggregat interfacial refinement [11]. A greater amount of hydration products was formed on high temperatures because they promote the hydration reaction rate of Portland cement. The total pore volume was decreased and the bulk density was increased since more hydration products filled up the open pores. In addition, since silica fume was thermally activated, the rate of the pozzolanic reaction of silica fume with the liberated $Ca(OH)_2$ was increased with the increase in the curing temperature, thus forming additional amounts of dense hydrates [5].

Maximum penetration of water was observed in concrete which was cured in water; and minimum penetration of water in concrete which was exposed to steam-curing regime at temperature of +90 ^{0}C. At concrete with the content of silica fume of 15% depth of water penetration was only 0.5 cm.

3.5. Freeze / thaw resistance with de-icing salts

Concrete resistance to frost and de-icing salts is determined by the degree of damage to the concrete surface of the sample after 25 cycles of freezing and thawing. The surface is covered with a 3% NaCl solution. The samples are exposed to temperature of -20 ^{0}C for 16 to 18 hours and then at temperature of 20^{0}C for 6 to 8 hours, according to [12]. Test results are shown in Table 5 and Figure 6.

According to [12] there are four degrees of degradation: «0», «1», «2» and «3». With the increase in silica fume content the degree of degradaton decreases. The best results, i.e. «0» degree of degradation, had concrete with 20% of silica fume for all curing regimes. If we compare the specimens with the same silica fume content, the degree of degradation decreases with the increase in curing temperature.

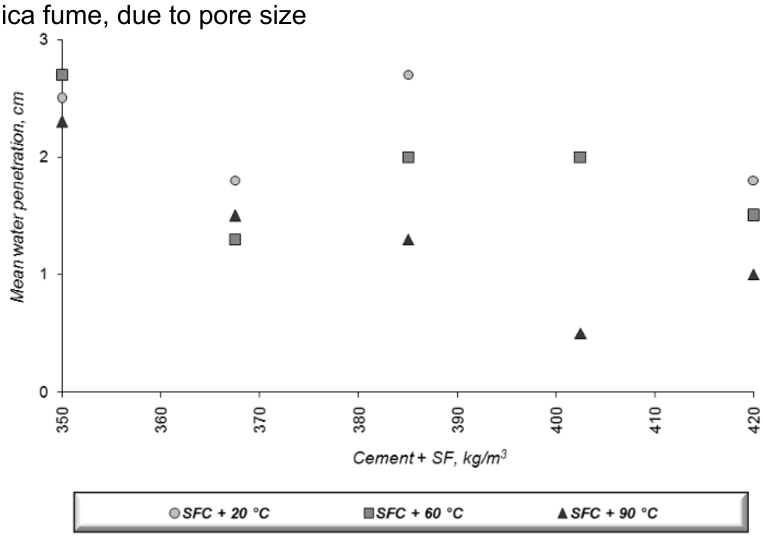

Fig. 5 - Mean water penetration of concrete.

Table 5

Mass loss of concrete after 25 freeze/thaw cycles

Curing regime		Mix N°	SF	Mass loss of concrete after 25 freeze/thaw cycles	Degree of degradation [11]
			%	N/mm^2	
in water	20 °C	SFC -1	0	1.2014	«3»
		SFC -2	5	1.0975	
		SFC -3	10	0.8357	
		SFC -4	15	0.6511	
		SFC -5	20	0.1894	«0»
steam curing regime	+60 °C	SFC -6	0	1.1786	«3»
		SFC -7	5	1.0731	
		SFC -8	10	0.8148	
		SFC -9	15	0.6960	
		SFC -10	20	0.1015	«0»
	+90 °C	SFC -11	0	1.1489	«3»
		SFC -12	5	0.6310	
		SFC -13	10	0.5267	
		SFC -14	15	0.4975	«2»
		SFC -15	20	0.0823	«0»

Aggregate=1838 kg/m^3; Cement=350 kg/m^3; Water=168 kg/m^3

3.6. Porosity

According to [11] concrete become dencer with the addition of silica fume. The benefits of using silica fume are that the concrete pore structure is improved under steam or standard curing conditions [13]. The results are shown in Figure 7.

There is no significant difference between concrete with silica fume cured at +60 ^{0}C and the one cured in water at +20 ^{0}C. When comparing specimens with the same content of silica fume, concrete cured at +90 ^{0}C had lower porosity. For that curing regime with increasing percent of silica fume concrete porosity decreased.

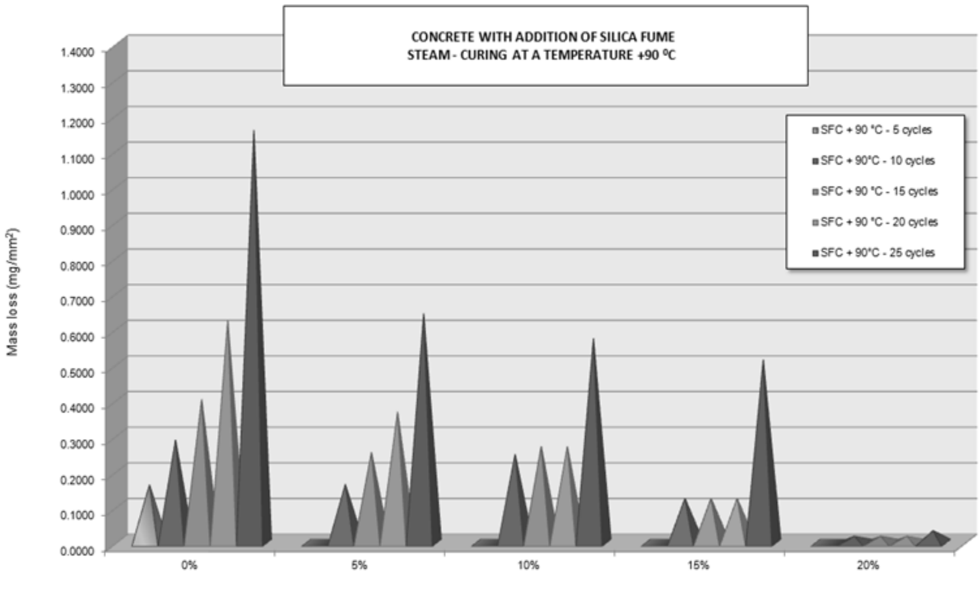

Fig. 6 - Mass loss of concrete after freeze / thaw cycles

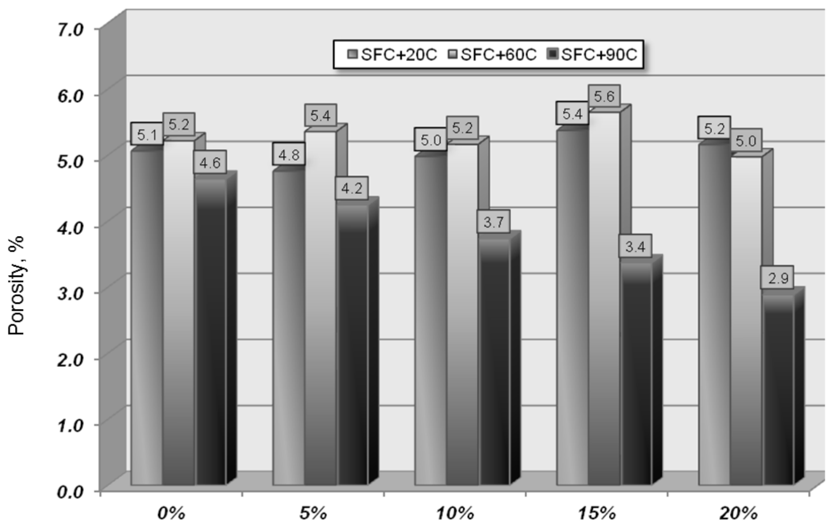

Fig. 7 - Porosity of concrete with silica fume.

4. Conclusion

The experimental work presented in this paper is primarily based on the influence of silica fume on improving properties of concrete such as compressive and tensile strength, freeze / thaw resistance with de-icing salts and depth of water penetration under pressure.

Compressive strength of concrete with the addition of silica fume increases with increasing the addition of silica fume for all types of curing. Concrete with the addition of silica fume which is cured in water at +20 ^{0}C and tested at the age of 28 days achieved the growth of 26% in relation to the concrete cured under the same conditions without the addition of silica fume. The addition of silica fume to Portland cements gives rise to physical (i.e. filler) and chemical (i.e. pozzolanic) effects on the hardened pastes microstructure. In this way, macro-properties utilized in concrete technology, such as higher strength, are improved [14, 15].

Maximum penetration of water was observed on concrete which was cured in water; and minimum penetration of water on concrete which was exposed to steam-curing regime at temperature of +90 ^{0}C. At concrete with the content of silica fume of 15% the depth of water penetration was only 0.5 cm. With the addition of silica fume, concrete pore structure is optimized and pore size distribution is more reasonable [16]. High temperatures promote the hydration reaction rate of Portland cement, resulting in a greater amount of hydration products formation which fill up the open pores, thus decreasing the total pore volume and increasing the bulk density [5]. With increasing the amounts of silica fume penetration of water in concrete was reduced [11].

According to [12] there are four degrees of degradation: «0», «1», «2» and «3». On the surface of concrete made with 20% silica fume and cured at temperature of +90 ^{0}C after 25 cycles of freezing and thawing with de-icing salts the degree of degradation was „0“ (mass loss 0.0823 mg/mm^2), with 15% silica fume the degree of degradation was „2“ and for other types of concrete „3“. Concrete cured at temperature of +60 ^{0}C with 5, 10 and 15% silica fume had the degree of degradation „3“, while concrete with 20% silica fume had mass loss 0.1015 mg/mm^2 and the degree of degradation „0“. Other types of concrete cured in water with 5, 10 and 15% silica fume had the degree of degradation „3“, while concrete with 20% silica fume had mass loss 0.1894 mg/mm^2 and the degree of degradation „0“. Concrete microstructure changes when silica fume is added. Concrete is more homogeneous and low permeable which results in increase durability compare to ordinary concrete. Durability mainly depends on the possibilities of penetration of hazardous ions into the porous material with water [11].

Based on the results of testing it can be concluded that the addition of silica fume increases the durability of concrete. Comparing concrete with and without silica fume it can be concluded that specimens made with 20% silica fume had 6 to 14 times less mass loss after 25 cycles of freezing and thawing with de-icing salts. Using additon of 10% silica fume reduction of mass loss were 30% for concrete cured in water and at temperature of +60 ^{0}C and 55 % for concrete cured at temperature of +90 ^{0}C related to concrete without silica fume. For concrete cured at temperature of +60 ^{0}C and exposed to water pressure with addition of 10% silica fume water penetration was reduced 30% while with addition of 20% silica fume water penetration was reduced 50%. For concrete cured at temperature of +90 ^{0}C and exposed to water pressure with addition of 10% silica fume water penetration was reduced 43% while with addition of 20% silica fume water penetration was reduced 56%.

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