Effect of fly ash on frost resistance of SCC

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 Abstract. The standard determination of frost resistance requires a long period of the test duration, especially for self-compacting concrete characterized by high performance properties. Self-compacting concrete has low water-cement ratio and, as a result, high density, strength and frost resistance, low water permeability and reduced capillary porosity. In this paper is considered a rapid evaluation of frost resistance using the method of dilatometric analysis of the structure. It is based on the dependence of frost resistance of the concrete samples on the characteristics of pore space during only one cycle of freezing and thawing. The dilatometric method is associated with the measurement of deformations of a dry and water-saturated concrete sample caused by the change in temperature, humidity, structure, and also the phase composition of the material. The study of behavior of the concrete under freezing to identify the nature of the occurrence of degradation was conducted. The three-stage water saturation of the concrete samples to determine the content of the different groups of porosity was used. The pore volume of each of the three groups was determined by weighting after each stage of saturation and expressed as a fraction of the volume of concrete. The measurement results of different groups of porosity is: P_1=5.3%; P_2 = 3.8%; P_3=2.0%; P_t = 11.1%. Frost resistance of concrete is function of porosity (P_2) and according to this parameter it can be estimated of 300 cycles.

1.   Introduction

Self-compacting concrete has low water-cement ratio and, as a result, high density, strength and frost resistance, low water permeability and reduced capillary porosity. Rapid methods for determination of frost resistance provided by the national standard also require a long period of the test duration. This paper considers a rapid evaluation of frost resistance using the dilatometric analysis of the structure. It is based on the dependence of frost resistance of the concrete samples from the characteristics of pore space during only one cycle of freezing and thawing. The water saturated concrete samples while freezing are characterized by the presence of anomalous expansion deformations. It takes place at the temperature from -5 to -10 °C which is related to ice occurrence and the increase of its volume in pore space of concrete.

The dilatometric method is associated with the measurement of deformations of dried and water-saturated concrete sample caused by a change in temperature, humidity, structure, and also the phase composition of the material.

The microstructure of concrete is mainly characterized by the structure of the cement paste, the size and nature of its pore space. The study of the pore structure of concrete was implemented in a three-

stage water saturation of concrete samples that allows to separate the pores of the concrete into three groups. Fillers are constant components of self-compacting concretes. In the present investigation a mixture with very high amount of fly-ash type F was used, it's dosage was of 215 kg per 1 m³. Fly ash has big specific gravity, which makes the mortar more stable [1, 2, 3]. The form of the ash particles is round, which causes the effect of the bearing and decreases the structural viscosity of the mortar [4, 5, 6].

The ability of use of such big amount of fly ash is provided by the high content of SiO_2 amorphous. Many publications and investigations prove the fact that adding fly ash type F into concrete mixture makes the structure denser and increases compressive strength in early and late periods of curing (7-day and 90, 180-day compressive strength) [7, 8, 9, 10].

SiO_2 reacts with soluble $Ca(OH)_2$ producing insoluble C-S-H-gel. This chemical reaction makes the concrete more corrosion resistive [11, 12]. Concretes with fly ash type F bare more resistive to the filtration of water through its volume and to ettringite delayed formation [13, 14].

The use of fly ash as a filler in concretes provides technical and economical, ecological benefits [15].

2.   Materials and methods

Self-compacting concrete with workability parameters determined by slump-flow test (550 – 650 mm, SF1) in this study was prepared. The cube samples 100x100x100 mm were cased in accordance with Russian standard 10180-2012 without any compaction to determine strength and frost resistance and prisms samples 70,7x70,7x220 mm to evaluate frost resistance by rapid method. The weights of constituent materials for producing one cubic meter of SCC mixture were calculated using the absolute volume method are presented in table 1.

Table 1. Quantities of the constituent materials for 1 m³ of the SCC mixture.

Material	Unit mass (kg/m³)
CEM I 42.5 N	360
Fly ash	215
Quartz sand	750
Crushed granite	810
Water	180
BASF MasterGlenium 115	5.4

Ordinary Portland Cement CEM I 42.5 N with standard consistence 27%, specific surface area 350 m²/kg and true specific gravity 3.05 g/cm³ was used according to the Russian Standard 31108-2016. The chemical composition of cement is reported in Table 2.

Table 2. Chemical composition of CEM I 42.5 N.

Component	Percentage	Component	Percentage
SiO_2	18.6	TiO_2	0.3
Al_2O_3	4.5	P_2O_5	0.1
CaO	63.6	SO_3	3.1
Fe_2O_3	3.1	Na_2O	0.2
MgO	3.2	K_2O	0.6

Fly ash with specific surface area equal to 420 m²/kg and true specific gravity equal to 2630 kg/m³ was used as a filler in this study.

Crushed granite as coarse aggregate with maximum size 20 mm according to Russian standard 8267-93, true specific gravity 2600 kg/m³ and water absorption 0.2% according to Russian standard 8269.0-97 was used.

Quartz sand as fine aggregate with specific gravity 2.63 kg/m^3, fineness modulus 2.6 and 70% of 0.63 mm fraction content and true specific gravity 2630 kg/m^3 was used.

Superplasticizer based on polycarboxylate ethers BASF MasterGlenium 115 in dosage of 1.2% by mass was chosen to adjust workability while the concrete mixture contained 180 kg/m^3 of water. The proportion of sand (r) in mixture of applied aggregates was equal to 0.48.

The compressive strength and total porosity (P_t) of the concrete at the age of 28 days were of 63.7 MPa and 11.1% respectively. The researched SCC demonstrated 300 cycles of freezing and thawing.

The three-stage water saturation of the concrete samples to determine the content of the different groups of pores was used. The pores are divided into three groups. At the age of 28 days the concrete samples were dried to constant weight, and then exposed into three-stage saturation with water. The first stage of saturation (porosity (P_1)) includes the exposure of the samples to constant weight in 100% relative humidity and temperature 20±2 °C. In this case the saturation is caused by the ability of the microcapillaries to absorb and condensate the moisture from the air, which occurs due to their radius less than 10^{-5} cm.

The second stage (porosity (P_2)) involves saturation of the samples to constant weight in water. The samples are filled with water mainly by the absorption. Water fills all the interconnected pores and cracks.

The third stage involves the saturation of the samples with water in vacuum. Such conditions of saturation contribute to fill by water conditionally closed pores, not filled by regular saturation of the pores. It identifies P_3 as the third group of the pores.

The pore volume of each of the three groups was determined by weighting after each stage of saturation which expressed as a fraction of the volume of concrete. The measurement results of different groups of porosity is: P_1=5.3%; P_2 = 3.8%; P_3=2.0%; P_t = 11.1%.

3.   Results

The porosity (P_2) characterizes the volume of capillary pores. Frost and water resistance of concrete depends on pores, which size is more than $1 \cdot 10^{-5}$ cm.

Frost resistance of concrete is the function of porosity (P_2) and according to this parameter it can be estimated of 300 cycles.

The value of dilatometric method is the study of the sample with size 70x70x220 mm. The prism has to be covered around before the test with frost resistant rubber and installed into lever arm of device (Fig.1). After that the dilatometer inserts to the climate chamber.

Temperature control was carried out in the climate chamber and in the middle of the sample. Effect of the temperature and humidity deformations were measured every 5 °C in the range of 20 up to -60°C. The dependence of relative deformation (ε) from temperature (°C) of the sample is presented on diagram.
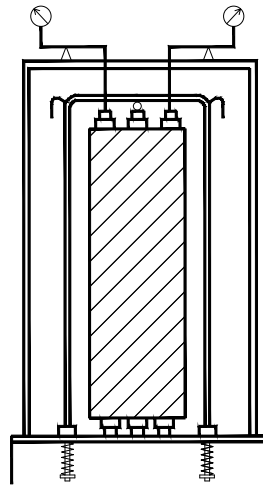
Figure 1. Schematic representation of the lever dilatometer.

The of linear thermal expansion coefficient and the effect of temperature and humidity on deformations in a dried and water saturated concrete are presented by Figure 2.
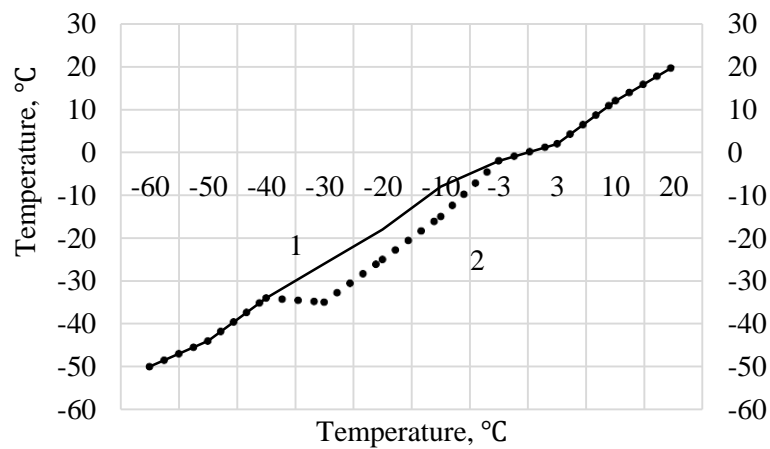

Figure 2. The linear thermal expansion coefficient and the temperature and humidity deformations of the concrete: 1 - in the dried state; 2 - in a water saturated state.

In Figure 2, the curves show an anomalous expansion of the samples at low temperatures in a water saturated condition. The deformations characterized by the reduced elongation, which can be determined from the equation:

$$e_r = e_s - e_d \tag{1}$$

e_s, e_d - relative deformations of the sample in saturated and dried states respectively.

The frost resistance of the tested concrete can be determined by the using the nomogram presented on Figure 3. It was estimated that value e_r is equal to $9.6 \cdot 10^{-5}$ cm. The frost resistance of the tested concrete was 300 cycles.
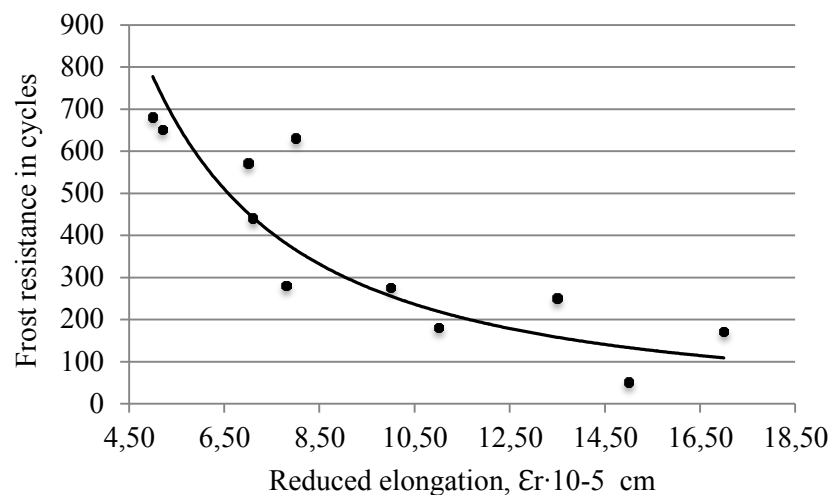

Figure 3. Dependence of frost resistance of the concrete on reduced elongation (e_r).

The water-saturated concrete samples while freezing are characterized by the presence of anomalous expansion deformations. It takes place at the temperature from -5 to -10 °C which is related with ice occurrence and the increase of its volume in pore space of concrete.

The work of deformation (W_d) is proportional to the change of volume ($\mathrm{D}V$) caused by the phase transition of water located in the pore space of concrete:

$$W_d = W_V \square \mathrm{D}V \tag{2}$$

W_V - coefficient of proportionality, equal to the work of deformation per unit volume of the material, i.e. specific work of deformation.

Specific work of deformation can be expressed on the basis of deformation of the material during freezing.

The dilatometric curve (Fig. 2) characterizes the development of material deformations during freezing and heating. The forces of the internal pressure of freezing water cause the elongation of the water saturated material.

The volume deformations of the material $e_0 = 3E$, while the volume change is:

$$\mathrm{D}V = e_0 \square V. \tag{3}$$

When the value of the actual internal pressure is replaced by fictitious forces P acting in three mutually perpendicular directions and causing the same deformation of the selected cube element with an edge equal to a, could be obtained the absolute elongation:

$$l = e_0 \times a \tag{4}$$

and:

$$P = e_0 \times k \times a^2$$

(5)

k - bulk modulus of the frozen material expressed in terms of the elastic modulus E and Poisson's ratio (m):

$$k = \frac{E}{3(1 - 2m)}$$

(6)

Potential energy accumulated in frozen water saturated self-compacting concrete at a certain temperature is expressed by the shaded area (Fig. 4):

$$A = \int_0^1 P(x)\,dx,$$

dx - increment of the coordinate on the direction of the force.

The work of the deformation forces can be approximately represented by a triangular diagram with slow cooling and a gradual the transition of water into ice (Fig. 4):

$$A = \frac{1}{2}Pl$$

(7)

Specific work of deformation with a rapid transition of water to ice in the capillary pores (Fig. 4, 5) is:
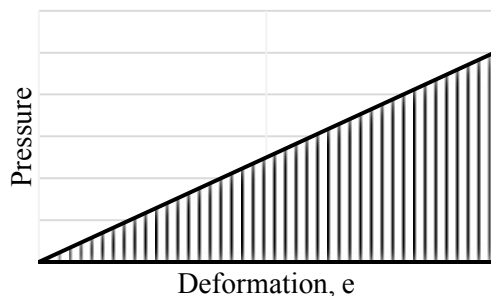
$$A_V = \frac{1}{2}e_r^2 \times k$$

(8)

Figure 4. The work of deformation during freezing of concrete with gradual freezing.
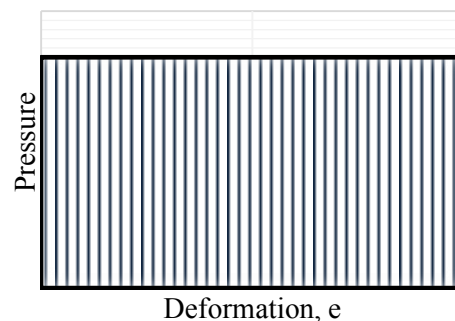
Figure 5. The work of deformation during freezing of concrete with the rapid transition of water into ice in capillary pores.

4.Conclusion

Thus, the dilatometric method is the study of behavior of concrete under freezing to identify the nature of the occurrence of degradation and it leads to the conclusion that a physical measure of frost resistance of self-compacting concrete is work causing a certain degree of destruction, estimated by the magnitude of the "given elongation". The "given elongation" depends, mainly, on the volume of capillary pores [16].

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