THE ANALYSIS OF FROST RESISTANCE OF SELECTED MODIFIED CONCRETES

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Abstract
In this paper, experimental studies of frost resistance of two types of basalt concrete are presented. The two concrete mixes were unmodified and modified by superplasticizer and silica fume. The influence of two cement matrix modification on the frost resistance of concrete in three kinds of curing condition has been discussed: laboratory conditions, hydroisolated conditions and in water. Analysis of compressive strength and tensile strength at bending after 100 cycles of freezing and thawing was used. Frost resistance was tested at temperatures from +18°C to -20°C. The highest loss of frost resistance was observed in ordinary concrete saturated with water in 100%. The tests showed that apart from modification of concrete microstructure, concrete storage conditions are also important. The testing showed that concrete modified with superplasticizer and microsilica fume is characterized by greater frost resistance compared to normal concrete.

Streszczenie
W artykule przedstawiono odporność mrozową zwykłego betonu oraz modyfikowanego betonu superplastyfikatorem i mikrokrzemionką. Wpływ modyfikacji na mrozoodporność betonu przedstawiono dla betonów twardniejących w trzech różnych warunkach: laboratoryjnych, hydroizolowanych oraz nasączonych do stałej masy wodą. Analizę wytrzymałości na ściskanie i rozciąganie przy zginaniu przeprowadzono po 100 cyklach zamrażania i rozmrażania. Badanie mrozoodporności przeprowadzono w temperaturze od +18°C do -20°C. Największy spadek odporności mrozowej zaobserwowano dla betonu nasączonego w 100% wodą. W przeprowadzonych badaniach zaobserwowano, iż niezależnie od modyfikacji struktury betonu, równie ważny jest sposób pielęgnacji podczas jego twardnienia. W badaniach wykazano, iż modyfikowany beton charakteryzuje się większą mrozoodpornością w porównaniu z betonem zwykłym.

Keywords: **Frost resistance; Ordinary concrete; High Performance Concrete; Frost resistance test; curing conditions.**

1. STRUCTURAL CONDITIONS OF FROST RESISTANCE OF CONCRETE

1.1. Nature of structure

Concrete is a heterogeneous and capillary-porous material. Its three-dimensional structure is composed of aggregate surrounded by products of cement hydration. The hydrates found in concrete are mostly in colloidal state forming C-S-H phase and some crystal phases, whereas the hydrates are of different degree of consolidation. The empty spaces in the framework are filled with water (pore solution) not combined with other chemicals and air. A microstructural model of hardened cement paste is presented in Fig. 1.

The pores in cement materials differ in shape and size. Depending on the size of effective radius, the pores can be divided into three groups [3]:

- micropores ($r_{ef}<2x10^{-9}m$),
- mezopores ($2x10^{-9}<e_{ef}<50x10^{-9}m$) and
- macropores ($r_{ef}>50x10^{-9}m$).

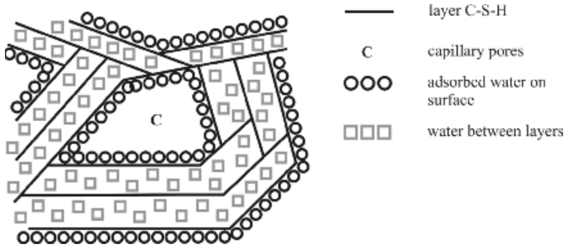

Figure 1.
The model of cement paste microstructure (phase C-S-H), according to T.C. Powers [1], [2]

The pores in hardened cement paste are created due to the ratio of ingredients (mainly w/c), method of mixing and consolidation as well as curing conditions.

In order to decrease the number of capillary pores in concrete one can reduce water-cement ratio, add chemical and mineral admixtures (e.g. plasticizers, superplasticizers, fly ashes, limestone powder, microsilica) that modify the microstructure of concrete. Superplasticizers improve workability of concrete mixture with lowered water-cement ratio. Mineral admixtures seal concrete structure and the aggregate-mortar contact zone.

1.2. Mechanism of frost-induced destruction

With respect to frost resistance, concrete structure defects include microcracks occurring in the first stage of hardening and capillary pores.

Capillary pores occur in areas which were occupied by water in fresh cement paste and which were not filled with hydration products. As it was already said, porosity of hardened cement paste depends on its water-cement ratio (w/c) and degree of cement hydration.

About 20% of water is needed for cement to hydrate in 100%. It is the equivalent of the water-cement ratio of 0.25. The volume of capillaries decreases with the progress of hydration. In mature hardened cement paste, capillary pores are partially filled with gel [2], [4].

Due to large specific area of concrete water freezing in pores is largely dependent on surface forces. These forces increase water pressure in narrow pores. The most significant fall of temperature occurs in very small pores, because the freezing point of water decreases with the increase of pressure. When water freezes in concrete pores, the excess of pressure occurs, caused by the increase in water volume by 9% and negative pressure caused by surface forces [3].

Macropores are filled with free water which freezes at -10°C. The water in mezopores freezes at the temperature from -12°C to -25°C, and in micropores at -40°C to -60°C [5]. Concrete as a porous material contains pores in its structure which may be filled with water. If macropores are saturated with water then increase in material volume occurs followed by water flow towards lower pressure areas or towards pores which are not filled with water. If there are air-pores nearby, then water can flow towards them. Otherwise the pressure generated in the pores can lead to excess in tensile stress of pore walls, which leads to concrete weakening [6]. Repeating stages of freezing and thawing cause bigger and bigger damages. This is especially dangerous for concrete thawing in water. It can absorb additional volumes of water. Expansion of ice caused by increase in water volume while freezing can be reduced by contraction caused by flow of dampness [3].

The mechanism of frost-induced destruction looks differently when concrete is exposed to

de-icing salts. De-icing salts when dissolved in water permeate to surface layers of concrete. Due to the influence of concentration gradient the salts permeate deep into concrete and osmotic pressure causes water migration towards upper concrete surface. Porous cement paste, which has contact with damp air and saturated salt solution, reaches higher level of water saturation. This decreases concrete resistance to freezing and thawing [6], [7]. Harmful effects of de-icing agents start with damages to surface layers and progresses until the construction is completely destroyed [2]. It should also be noted that the biggest damage of concrete occurs when it is exposed to low concentration of salt solutions, about 2-4% [7].

2. METHODS OF MEASURING FROST RESISTANCE

Methods of measuring frost resistance are divided into methods of testing internal and external resistance (so-called resistance to surface spalling) The methods of testing internal resistance include: ordinary method [6], ASTM C 666 A [6], [8], [9], ASTM C 666 B [6], [8], [9], ASTM C 671 [6], [9], ÖNORM B 3303 [10], RILEM: CIF [9], [10], RILEM: CDC [9], *"Würfelverfahren"* [10], Slab – test [10], Gost 10060 [9].

Methods of testing external frost resistance include: ASTM C 672 [9], SS 137244 (Borås method) [9], RILEM: CDF [9], [10], ÖNORM B 3303 [9], [10], *"Würfelverfahren"* [10], Slab – test [10], ordinary method [9].

Methods of testing external frost resistance are used for elements that have contact with de-icing agents. The testing methods differ in the size, shape and number of samples, methods of their test preparation, number and duration of freezing and thawing cycles and maximum freezing and thawing temperatures. Frost resistance is evaluated by mass loss, decrease in strength, frequency of vibrations, deformability. Selection method depends on the intended use of tested concrete, its place of exposure and climate in the construction site. The number of cycles or passages through 0°C and freezing and thawing periods play an important role in the process of water freezing in concrete pores. Presented methods cannot be compared due to a high number of variable factors present in the testing process. The method of care used in the period of concrete hardening as well as the preparation of concrete for testing greatly affect the final result. Setzer and Liebrecht [11] conducted subject-related research. They tested frost resistance of samples hardening in water and air in relative humidity of 100% and 91%. The samples that hardened in water displayed the highest decrease in frost resistance. Due to the fact that care applied in the process of concrete hardening has got a significant effect on its frost resistance, research on this subject was initiated.

3. OBJECTIVE AND SCOPE OF THE PAPER

In order to identify the influence of some technological processes on frost resistance, two types of concrete were tested. The ratio of water – binding agent of concrete mixtures – was assumed to be 0.32 and 0.52. Composition of the two concrete mixtures was established by iteration and consistency of V3 was adopted, which according to Ve-Be method is equivalent to 6÷10 s. All the concrete samples were made of Bridge Cement 42.5, sand (0÷2 mm) and basalt grit (4÷8 mm). Admixture of a superplasticizer and microsilica fume was used in the mixture of w/c=0.32. The characteristic of the tested compositions was presented in the table 1 [5].

4. EXPERIMENTAL METHODS

Samples of the dimensions 40×40×160 mm were used in the test, due to limited capacity of the temperature controlling equipment. Selection of small samples is justified by maximum size of coarse aggregate grains limited to 8 mm. For each series three prisms were manufactured. The samples for frost resistance testes were divided into three groups depending on curing method employed during the hardening process:

L – samples cured under laboratory conditions (temp. +18°C and w_z = 90%),

H – samples cured under hydroisolated conditions (the samples were protected against humidity exchange with the environment with the use of PVC foil, temp. +18°C),

N – samples cured under water (temp. +18°C).

After the 28-day period of hardening the test of compressive strength and tensile strength at bending was performed. Analysis selected feature of the material (in this case it was compressive strength and tensile strength at bending) after 100 cycles of freezing (4 hours) and thawing (4 hours) was used. It could be better of course, to make more freeze-thaw cycles. However we had a little time to realised this research program. Frost resistance was tested at temperatures from +18°C to -20°C.

Table 1.
Mix proportions

Lp.	Component name	Type of mix		
		OC	HPC	W – water,
1.	$W/(C+M_K)$	0.52	0.32	C – cement,
2.	C [kg/m^3]	340.0	388.0	M_K – silica fume,
3.	M_K [kg/m^3]	—	43.0	SP – superplasticizer
4.	Sp[kg/m^3]	—	10.781	Melment L10/40%
5.	P [kg/m^3]	989.0	988.0	$M_K/(M_K+C)$=10%,
6.	G [kg/m^3]	989.0	988.0	P – sand,
7.	W [kg/m^3]	177.0	132.0	G – basalt grit,

5. RESULTS OF FROST RESISTANCE TEST AND THEIR ANALYSIS

Sample results of compressive and tensile strength at bending tests for concrete samples cured under laboratory and hydroisolated conditions are presented in the fig. 2 and 3. Compressive strength of high performance concrete is more than twice higher compared to compressive strength of normal concrete. This effect is related to reduced water-binder ratio and admixture of microsilica fume which reacts with Portlandite $Ca(OH)_2$ and increases the amount of released calcium silicate hydrates C-S-H [5]. Tensile strength at bending of HPC concrete has also increased compared to normal concrete, however to a lesser extent.

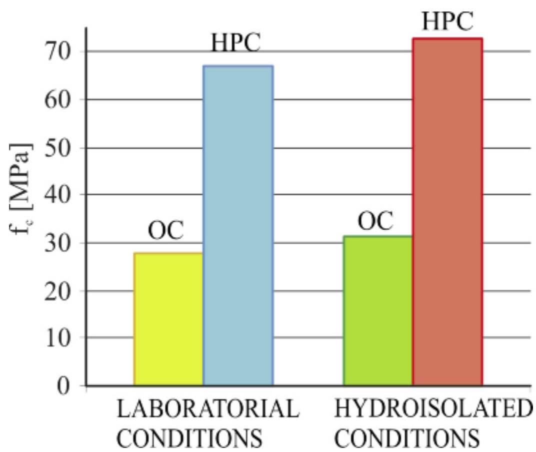

Figure 2.
Twenty eight days compressive strength (f_c) of concrete

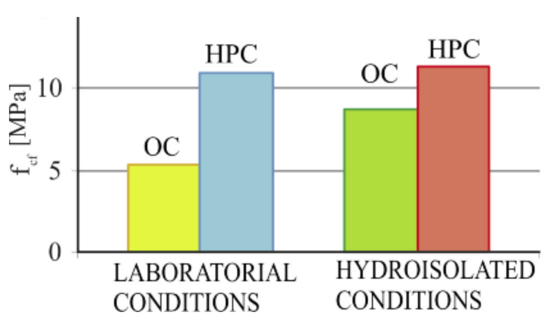

Figure 3.
Twenty eight days tensile strength at bending (f_{cf}) of concrete

In case of concrete cured under laboratory conditions, the strength increased twofold, and in case of concrete cured under hydroisolated conditions only by about 25%. It should be noticed that tensile

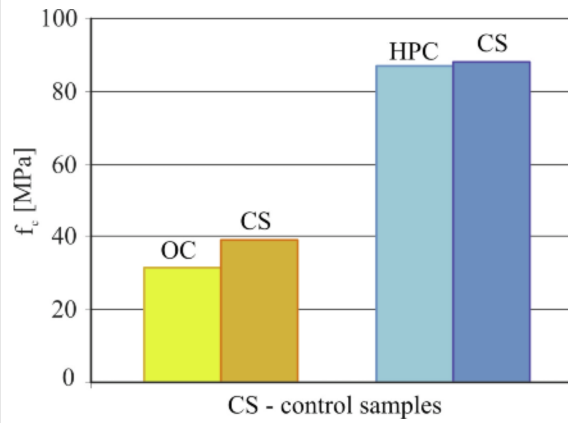

Figure 4.
Compressive strength (f_c) of concretes after 100 freeze-thaw cycles for laboratorial conditions

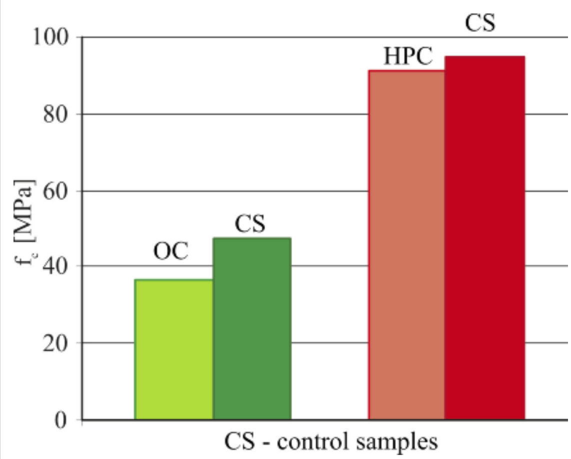

Figure 5.
Compressive strength (f_c) of concretes after 100 freeze-thaw cycles for hydroisolated conditions

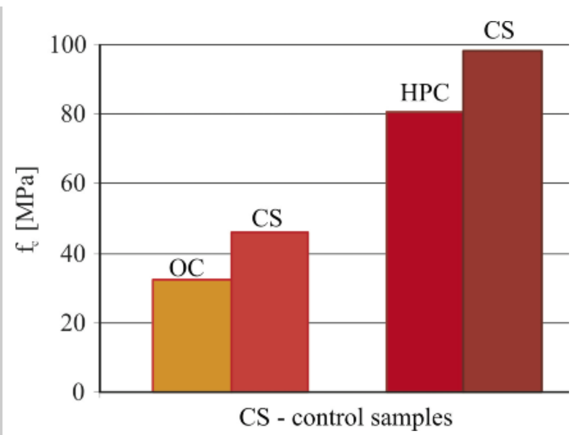

Figure 6.
Compressive strength (f_c) after 100 freeze-thaw cycles of concretes saturated with water to solid mass

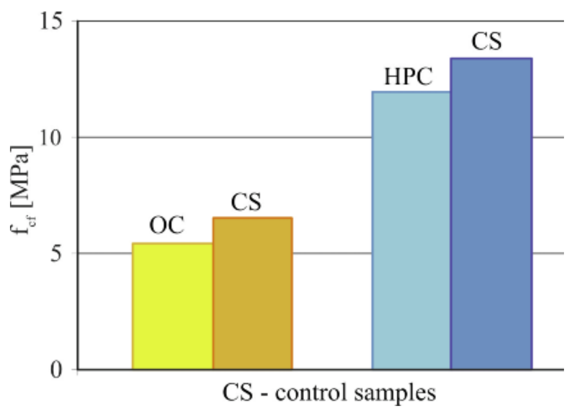

Figure 7.
Tensile strength at bending (f_{cf}) of concretes after 100 freeze-thaw cycles for laboratorial conditions

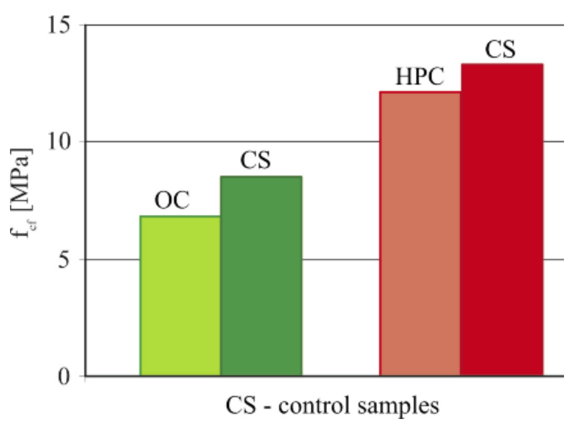

Figure 8.
Tensile strength at bending (f_{cf}) of concretes after 100 freeze-thaw cycles for hydroisolated conditions

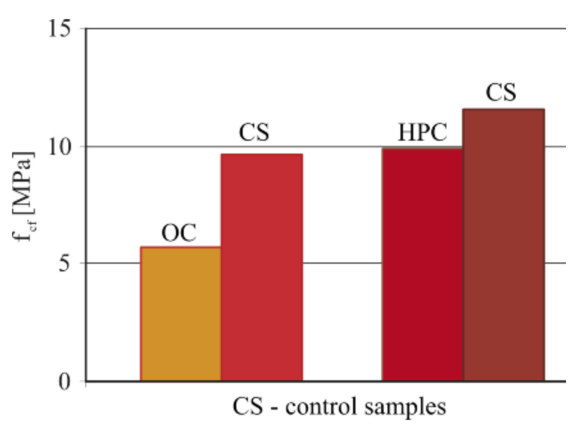

Figure 9.
Tensile strength at bending (f_{cf}) after 100 freeze-thaw cycles of concretes saturated with water to solid mass

strength at bending of normal concrete cured under hydroisolated conditions is higher compared to Ordinary Concrete (OC) cured under laboratory conditions. With respect to concrete hardening conditions, one can state that concrete cured under hydroisolated conditions have got a slightly higher strength compared to concrete cured under laboratory conditions.

Evaluation of frost resistance after 100 cycles of freezing and thawing was conducted with the tests of compressive and tensile strength at bending. The results of the tests are shown in the fig. 4-9. Loss of compressive and tensile strength at bending was observed in all cases after 100 cycles of freezing and thawing. Concrete saturated with water to solid mass displayed the biggest loss of compressive strength. The samples which were curing under water over 72h were used also saturated with water in 100% in a mass. In this research program there was no statistical estimation analysis because not sufficient number of samples were used.

For the purpose of more accurate analysis, an indicator of relative compressive strength reduction Δf_c and tensile strength at bending reduction Δf_{ct} were introduced, described with the formula:

$$\Delta f_{c(ct)} = \frac{f^s_{c(ct)} - f^i_{c(ct)}}{f^s_{c(ct)}} \times 100\% \qquad (1)$$

f^s_c, f^s_{ct} – compressive strength/tensile strength at bending of concrete sample by flex test – comparative sample,

f^i_c , f^i_{ct} – compressive strength/tensile strength at bending of concrete sample by flex test – sample after frost test,

The testing showed that concrete modified with superplasticizer and microsilica fume is characterized by greater frost resistance. Diagrams (fig. 10 and 11) compare frost resistance of ordinary concrete and high performance concrete. The greatest frost resistance was achieved in case of concrete cured under hydroisolated conditions, whereas the lowest frost resistance was achieved in case of concrete cured under water. The results may be caused by excessive amount of water in concrete, which caused greater damage during freezing. Also in case of Δf_{ct} indicator the greatest damage occurred in concrete saturated with water to solid mass. In case of concrete modified with microsilica fume and superplasticizer there has been a greater increase of Δf_c indicator than Δf_{ct} indicator.

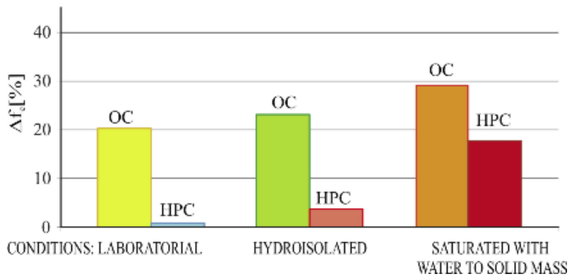

Figure 10.
Relative reduction of compressive strength (Δf_c) factors for concrete

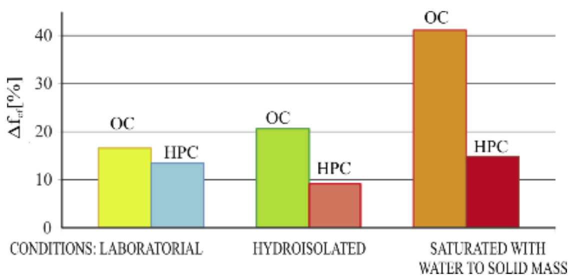

Figure 11.
Relative reduction of tensile strength at bending (Δf_{cf}) factors for concrete

6. SUMMARY

Two types of concrete were tested – non-modified with basalt crushed aggregate and modified with superplasticizer and microsilica fume. Water-ice transformations were applied to test samples cured under laboratory conditions, hydroisolated and cured under water with the temperature of +18°C. Decrease in water-binder ratio and use of liquefying and microsilica fume admixtures increased strength of concrete by 100%. By using admixtures, frost resistance of concrete has been improved, which shows that its microstructure has been sealed.

The tests showed that apart from modification of concrete microstructure, concrete storage conditions are also important. On the basis of the tests it has been observed that modified concrete is characterized by increased frost resistance compared to normal concrete.

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