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Freeze-Thaw Resistance of Concretes with BFSA

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Abstract**—**Air-cooled Blast Furnace Slag Aggregate (BFSA) is usually referred to as a material providing for unique properties of concrete. On the other hand, negative influences are also presented in many aspects. The freeze-thaw resistance of concrete is dependent on many factors, including regional specifics and when a concrete mix is specified it is still difficult to tell its exact freeze-thaw resistance due to the different components affecting it. An important consideration in working with BFSA is the granularity and whether slag is sorted or not. The experimental part of the article represents a comparative testing of concrete using both the sorted and unsorted BFSA through the freeze-thaw resistance as an indicator of durability. Unsorted BFSA is able to be successfully used for concretes as they are specified for exposure class XF4 with providing that the type of cement is precisely selected.

Keywords**—**Blast furnace slag aggregate, concrete, freeze-thaw resistance.

I. INTRODUCTION

TO meet the global demand of concrete in the future, it is becoming a more challenging task to find suitable alternatives to natural aggregates for preparing concrete. The demand for aggregates is increasing rapidly and so is the demand for concrete. Thus it is becoming more important to find suitable alternatives for aggregates in the future [1].

Various types of alternative aggregates are tested and discussed worldwide, including recycled aggregates and industrial by-products. As for slag, types coming from various industrial technologies can be found in research reports: blast furnace slag, steel slag, electric arc-furnace slag, as well as copper slag [2]-[5].

Blast furnace slag is a by-product and using it as aggregate in concrete might prove an economical and environmentally friendly solution in local region. Blast furnace slag is a non-metallic material consisting of silicates and alumina-silicates of calcium and magnesium together with other compounds of sulphur, iron, manganese, and other trace elements. It is produced from a molten state simultaneously with pig iron in a blast furnace. The solidified product is further classified according to the process by which it was brought from the molten state.

Air-cooled blast furnace slag is produced through relatively slow solidification of molten blast furnace slag under atmospheric conditions, resulting in crystalline mineral formation.

Air-cooled blast furnace slag aggregate (BFSA) is presented as a material providing for unique properties of concrete, and there are numerous articles dealing with testing and evaluation of this material [1], [6], [7]. On the other hand, also negative influences are presented in many aspects, as it can be seen in the literature review compiled by the authors in their article [8].

Based on the own practical experience, several reasons why producers of concrete are hesitant to use BFSA on a larger scale can be summarized here. These are mainly the following:

- Distrust of concrete producers to technical parameters of BFSA and sustained achievement in relation to the standard. This is also supported by often conflicting data from lots of research reports. Several key chemical properties are discussed, particularly the presence of chlorides, calcium oxide, total sulphur (as S), sulphur trioxide (as SO_3), total iron (as FeO). The physical property of the greatest concern is the high level of porosity compared to that present in naturally derived aggregates, which contributes to high absorption capacities. It is accompanied by technological problems during mixing.
- Risk of failure in the supply continuity of specified fractions at different times of the year
- Concern about the impact on corrosion of steel reinforcement (possible reduction of the pH of the concrete due to the acidity of the slag)
- Impaired aesthetics of concrete when coarser fractions are applied

An important consideration in working with BFSA is the granularity. The air-cooled blast furnace slag is normally processed in a crushing and screening plant to manufacture products of particular maximum sizes and gradings. Crushed air-cooled slag is angular, roughly cubical, and has textures ranging from rough, vesicular surfaces to smooth glassy surfaces with conchoidal fractures. Processed air-cooled slag exhibits good abrasion resistance, good soundness characteristics and high bearing strength [9].

Grading as a treatment technological process plays significant role for successful application into concrete. Research works are often aimed on the testing individual grain sizes, e.g. [8]. Authors here give results of testing the slag aggregate in concrete with a resolution of coarse and fine portion. They describe in detail the degree of increase/decrease in strengths for both kinds of aggregates. However, the process of grading is energy and technologically intensive and leads to increased costs. Therefore producers of slag aggregate call for finding the limits of utilization of unsorted aggregate.

Proving that the use of BFSA in concrete will improve physical-mechanical parameters of concrete, as well as its durability properties of concrete can help the designer choose a suitable material for construction.

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Water is the main cause of degradation of building materials as it enters porous materials and can rise to considerable heights through capillary reaction. It can also transport potentially damaging substances such as NaCl. When water, which has entered concrete through capillary reaction, freezes it expands and causes hydraulic pressure. The effects of repeated cycles of freezing and thawing have significant effects on concrete. They cause cracking and scaling, and ultimately failure. The rate of freeze-thaw damage is increased by de-icing agents or salty water.

The experimental part of the article represents a comparative testing of concrete using both the sorted and unsorted BFSA through the freeze-thaw resistance as an indicator of durability. The freeze-thaw test measures the resistance of concrete surface being in contact with de-icing agents to repeated freeze/thaw cycles. Testing was performed for confirmation of this indicator for specific, regional available components of concrete. Concretes were expected for utilization in road structures, so their composition were designed with the respect of limiting factors for the most severe freeze-thaw exposure class XF4 (according to EN 206-1 [10]).

II. MATERIALS AND METHODS

Four concrete mixtures were prepared with variations in the using of sorted/unsorted BFSA and type of cement. Reference mixture (RM) was prepared with natural aggregate only. BFSA was used as a partial or full substitution of natural aggregate (mixtures M1 – M3, see Tab. I). Difference between M2 and M3 is only in a type of cement. Materials were used as follows:

- Natural aggregates: 0/4, 4/8, 8/16, Eastern Slovakia
- BFSA sorted: 0/4, 4/8,
- BFSA unsorted: mono-fraction 0/16
  Both U.S.Steel Košice, Slovakia
- Cement: CEM II/A-S 42.5 N (Eastern Slovakia),
  CEM I 42.5 N (Western Slovakia)
- Admixtures: Plasticizer MC Techniflow 82
  Air-entrainment Centrament AIR 202

TABLE I
COMPOSITION OF TESTED MIXTURES

Components of concrete (kg.m^{-3})		RM	M1	M2	M3
Natural aggregate	0/4	847			
	4/8	225			
	8/16	650	650		
BFSA	0/4		847		
	4/8		225		
	0/16			1722	1722
CEM II/A-S 4.5 N		425	425	425	
CEM I 42.5 N					425
Water		172	172	172	172

Concretes exposed to class XF4 are characterized as follows:

- Exposed to high water saturation, with de-icing agent or sea water, e.g. road and bridge decks exposed to de-icing agents.
- Surfaces exposed to direct spray containing de-icing agents and freezing.
- Splash zones of marine structures exposed to freezing.

Limiting factors for exposure class XF4 as stated in NA (national annex) of [7] are:

- Max. w = 0.45
- Min amount of cement: 340 kg.m^{-3}
- Air content for D$_{max}$ 16: 4.5 – 5.5%
- Min strength class: C 30/37
- Scaling: the degree of surface damage should be max. 3 after 150 cycles, or max. 2 after 100 cycles.

The amounts of water and admixtures in tested mixtures were adjusted for keeping these limits and also the same consistency S4. Actual water/cement ratio was 0.4, and the air content was varied between 5.0 and 5.2%).

Four samples (cubes 150x150x150 mm) for each mixture have been prepared for testing the freeze-thaw resistance: two of them were taken for compressive strength test before freezing and two after. The mean value of each two samples is used for evaluation the freeze-thaw resistance.

Freeze-thaw resistance was evaluated in terms of the following:

- change in the compressive strength after freezing
- amount of scaling measured after specified number of cycles and calculated using formula (1)

The freeze-thaw test was performed under national standard [11]; however, the test procedure is very similar to the CDF test [12]. This procedure allows us to measure the amount of scaling per unit surface area due to a number of well-defined freezing and thawing cycles in the presence of de-icing salt - as a rule sodium chloride solution, and leads to an estimate of the freeze-thaw and de-icing salt resistance of the concrete tested. Basic steps were as follows:

The test liquid of 3% NaCl solution is at a depth of 5mm on the top surface of a cube of dimensions 150 mm x 150 mm x 150 mm. The curing process is stated as being 1 day in the mould, 27 days in water at 20°C followed by 5 days in standard laboratory storage at 20°C. Test procedure continues with measurement of water absorptivity of specimens. The freeze-thaw cycles are started after next 2 days, overall in 35th day after making the samples. The daily freeze-thaw cycle has a temperature range of +20°C to -15°C in accordance with a specified time-temperature curve. Scaling measurements are taken after 25, 50, 77, 100, 125 and 150 cycles and the cumulative value after 150 cycles is the figure used to determine the scaling resistance.

Scaling classification by [11] is given in Table II.

TABLE II
DEGREE OF SURFACE DAMAGE

Degree of surface damage	ρ_a(g/m^2)
1 – no damaged	up to 50
2 – slightly damaged	up to 500
3 - damaged	up to 1000
4 – heavily damaged	up to 3000
5 - disintegrated	above 3000

Parameter ρ_a is calculated by (1):

$$\rho_a = \frac{\Sigma m}{A}\ (g/m^2) \tag{1}$$

where: ρ_a is scaling (g/m^2); m is the mass of scaled material (g); A is the surface area of sample (m^2)

III. RESULTS AND DISCUSSION

Results of compressive strength before and after freeze-thaw cycles, as well as cumulative scaling after individual cycles are given in Tables III and IV.

The comparison of scaling process of all tested mixtures is shown in Fig. 1. In Fig. 2, some photos showing real state of sample´s surface after 50, 100 and 150 cycles of freezing and thawing are given for better understanding.

TABLE III
COMPRESSIVE STRENGTH OF MIXTURES BEFORE AND AFTER THE FREEZE-THAW TEST

Compressive strength (MPa)	RM	M1	M2	M3
Before the test	58	54	35	38
After the test	56	50	34	37
Meet the requirements of C 30/37	✓	✓	-	✓

TABLE IV
CUMULATIVE SCALING ρ_A (g.m^{-2}) AFTER INDIVIDUAL FREEZE-THAW CYCLES

Number of cycles	RM	M1	M2	M3
25	0	79,56	355,33	179,78
50	15,33	130,22	483,11	225,56
75	25,56	210,44	688,22	264,22
100	36,89	304,67	845,22	295,78
125	62,89	407,33	1012,44	366,44
150	***129,78***	***500***	***1141,78***	***412,22***
Degree of surface damage	***2***	***2/3***	***4***	***2***
Meet the requirements	✓	✓	-	✓

The compressive strengths are lower after freeze-thaw test, but only slightly. As for meeting criteria for strength class C 30/37, only the M2 mixture is unsatisfactory.

As it is apparent in Table IV, the reference mix RM shows the best result of scaling after 150 cycles. As for mixtures with BFSA, they show significantly worse results even after first 25 cycles. Samples M1 and M3 meet the criteria for XF4 exposure class, whereas M2 is not. This mixture exceeds the limit value after only 125 cycles. Sample M1, where coarse fraction of natural aggregate (8/16) was only substituted by BFSA, shows significantly better result than M2 having full dosage of unsorted monofraction (0/16) BFSA. On the other hand, M3 with the same dosage of BFSA, but different (CEM I) type of cement, shows the best scaling among the samples with BFSA.

Comparing samples M2 and M3 having unsorted BSFA only, M3 with CEM I type of cement shows better results. It is quite surprising, since the blended cements with ground granulated blast furnace slag (CEM II/A-S or B-S) generally provide for better durability of concrete. For example, [13] states that the use of GGBS as 50% cement replacement showed the benefit in using it to increase the freeze-thaw resistance of the concrete. The scaling values were much lower than the mixes which had the same water cement ratios and constituents apart from the GGBS. It should be mentioned here also that standard practice is oriented on blended cements for concretes to be exposed into aggressive environment. However, CEM I with natural aggregate only (RM) worked very well in this experiment.

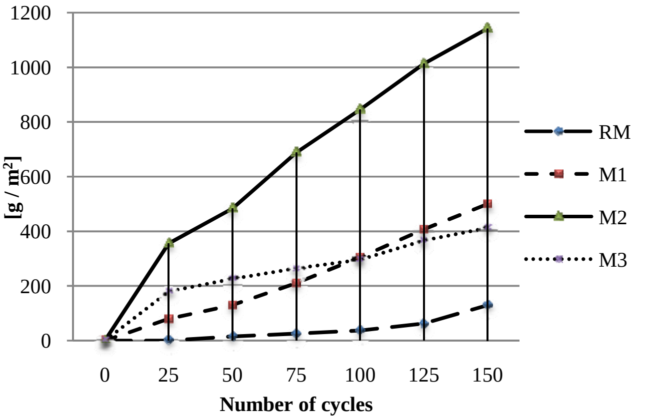


Fig. 1 Scaling process of tested mixtures

IV. CONCLUSION

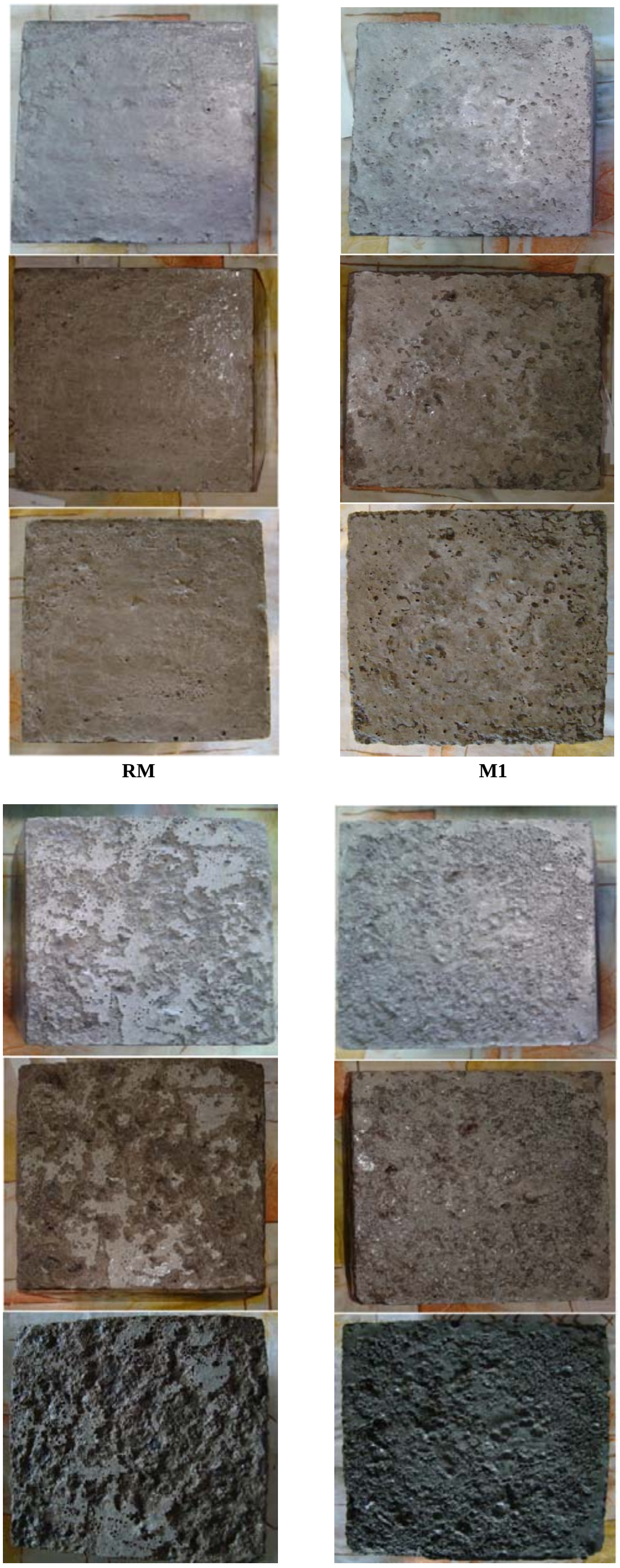
The freeze-thaw resistance of concrete is dependent on many factors and when a concrete mix is specified it is still difficult to tell its exact freeze-thaw resistance due to the different components affecting it and the variable relationships that they have when interacting with one another. This report is focused on the using of sorted and unsorted BFSA.

It is possible to successfully use unsorted BFSA for concretes when specified for exposure class XF4 (Vertical concrete surfaces of road structures exposed to freezing and airborne de-icing agents, road and bridge deck exposed to de-icing agents, concrete surfaces exposed to direct spray containing de-icing agents and freezing and splash zones of marine structures exposed to freezing), but the type of cement seems to be limiting this ability and must be precisely verified.

Except for XF4, the evaluation of scaling is required only for XF2 exposure class. The degree of surface damage in this case should be 2 after 50 cycles of freezing-thawing. In this light, resulting specifications of tested concretes with BFSA are as follows:

- M1: C 40/50, XF4
- M2: C 25/30, XF1
- M3: C 30/37, XF4

All tested mixtures may be successfully used in concrete structures with respecting appropriate exposure class. Due to the use of alternative aggregate in concrete, energy and cost of transportation of natural resources and excavation is decreased significantly. This in turn directly reduces the impact of waste material on the environment.



RM **M1**

M2 **M3**

Fig. 2 Degree of surface damage of samples after 50, 100 and 150 cycles (top to bottom)

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