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Destructive and non-destructive assessment of the frost resistance of concrete with different aggregate

D Kocáb[1], **B Kucharczyková**[1], **P Daněk**[1], **T Vymazal**[1], **P Hanuš**[1] **and R Halamová**[1]

[1] Brno University of Technology, Faculty of Civil Engineering, Veveří 331/95, Brno, Czech Republic

Email: dalibor.kocab@vutbr.cz

Abstract. The paper focuses on determining the frost resistance of concrete using selected destructive and non-destructive test methods. The experiment was performed with four specially made concretes, which differed only in the origin of sand and coarse aggregate. The primary outcome of the experiment are the differences in frost resistance as measured by different methods. In addition, it briefly describes the influence that the choice of aggregate has on the frost resistance of concrete.

1. Introduction

In recent years, new trends have been introduced into the design of reinforced concrete structures. Current concepts of structures and especially materials from which the structures are constructed place emphasis on properties related to environmental impact, specifically, durability, reliability and sustainability [1]. Durability is broadly used as a general term meaning the resistance of concrete to harsh environment. The character, intensity and mechanism of each influence may, however, vary considerably, making the concept of concrete durability somewhat vague. Moreover, no available method can be used to determine the durability of concrete in general terms [2]. The degradation of concrete in a structure is influenced by various factors such as carbonation, mechanical wear, cracks formed by (for example) inappropriate curing, etc.

Frost resistance is thus another important factor that needs to be considered during the design of concrete structures. The effects of frost are one of the most frequently observed forms of damage to the surface layer of concrete as well as its internal structure. When concrete is dry during exposure to frost, the structure does not usually sustain significant damage. However, if the structure or its part is in contact with water (road panels, railway sleepers, water reservoirs, etc.), the concrete absorbs it into its pore structure. If the water freezes, there is a risk of cracking and other defects caused by the expansion of ice in the pore structure. Water located in the capillary pores of concrete begins to freeze at approximately -0.5°C. The volume of the ice thus produced is larger by approximately 9% compared to the original water. This generates high internal strain in the concrete and, as a result, causes damage to its internal structure, which irreversibly leads to the reduction of basic material properties [3].

Frost resistance of concrete is influenced by many factors, most of which are related to its composition. The most important factor is the distribution and size of air pores in the concrete structure [4]. Air-entraining agents are the most reliable means of increasing the resistance of concrete against frost, because they form a system of closed spherical air voids inside the concrete. These provide space for the ice to expand, thus reducing the risk of damage to the internal structure of the concrete [3].

Another important aspect of the frost resistance of concrete is the amount, quality, type and grain size of the aggregate used [5].

Although standards do not prescribe a method for determining the frost resistance of concrete in structures, this property can be evaluated in several ways in laboratories using test specimens. These testing procedures are, for example, those described in ASTM C 666-03 [6], GB / T 50082-2009 [7], BS 5075-2 [8], ČSN 73 1322 [9] or ČSN 73 1380 [10]. The principle is always to monitor the decrease in the value of a certain property of concrete after a freeze-thaw cycle (F-T cycle) in the presence of water. According to [6], the most appropriate means of determining the frost resistance of concrete is to observe the changes in its dynamic modulus of elasticity after F-T cycles, as this method can detect initial defects in the internal structure of concrete much earlier than during the observation of the decrease in other properties, particularly strength. In principle, this involves determining the percentage of the value of the modulus determined after a given number of F-T cycles and the original value of the modulus of elasticity determined before the cyclic freezing and thawing. The result is the value of the relative dynamic modulus of elasticity (RDM).

2. Experiment

The experiment aimed primarily to compare the suitability of each of the available methods for measuring the frost resistance of concrete. A secondary aim was to determine the influence of aggregate on the concrete's frost resistance.

2.1. Material and test specimens

Four types of concrete with designations D, E, F and G were produced for the purpose of the experiment. These concretes (their composition is shown in Table 1) differed mainly in the type and origin of aggregate (sand as well as coarse aggregate). The other components were always the same.

Table 1. Composition of the concrete used in the experiment.

	kg / 1 m^3 of fresh concrete			
Component	Concrete D	Concrete E	Concrete F	Concrete G
CEM II/B-S 32.5 R (Mokrá)	400	400	400	400
Water	185	185	185	185
Sand 0-4 mm (Bratčice)	760	-	760	-
Sand 0-4 mm (Tovačov)	-	745	-	745
Aggregate 4-8 mm (Luleč)	135	135	-	-
Aggregate 4-8 mm (Tovačov)	-	-	135	135
Aggregate 8-16 mm (Luleč)	460	460	-	-
Aggregate 8-16 mm (Tovačov)	-	-	450	450
Aggregate 11-22 mm (Luleč)	345	345	-	-
Aggregate 11-22 mm (Tovačov)	-	-	335	335
Plasticiser (Sika ViscoCrete-4035)	2.00	1.80	1.80	1.60
Air-entraining agent (Sika LPSA 94)	0.25	0.25	0.25	0.25

Two types of sand and two types of coarse aggregate were used. Both sands 0/4 mm consisted of naturally mined aggregate with one from the Bratčice site and the other from Tovačov. One type of the coarse aggregate (consisting of grading 4/8, 8/16 and 11/22) was a naturally crushed aggregate from Luleč quarry (petrographic name of the raw material: greywacke) and the second type of the coarse aggregate (of the same grain sizes) was a naturally mined aggregate from Tovačov (gravel). The composition of the concrete was designed to combine both sands with both coarse aggregates. In order to achieve similar consistency of each concrete, plasticiser was added with minor variations in amount. The slump test values ranged within (200 ± 20) mm for all the concretes, see Table 2.

Table 2. Properties of each concrete in the fresh (FC) and hardened (HC) state.

	Concrete			
Property	D	E	F	G
Slump test (FC) [mm]	200	220	180	220
Air content (FC) [%]	5.5	5.5	6.5	6.0
Density (FC) [kg/m^3]	2230	2250	2190	2220
Compressive strength after 28 days (cube, HC) [N/mm^2]	51.4	54.6	44.9	49.9
Density (HC) [kg/m^3]	2270	2270	2230	2270
Flexural strength before F-T cycles (prism, HC) [N/mm^2]	5.1	6.1	4.2	4.5
Tensile splitting strength before F-T cycles (fragment, HC) [N/mm^2]	4.60	5.25	4.05	4.20

Six test specimens were made from each concrete with the nominal dimensions of 100 × 100 × 400 mm. The test specimens aged for 24 hours in special plastic (Hakorit) moulds covered with a PE foil. They were then removed from the moulds and stored in an environment with the air temperature of 20 ± 2°C and humidity of at least 95%. At the age of 25 days, the specimens were submerged for three days in water with the temperature of 20 ± 2°C.

2.2. Testing methods

At the age of 28 days, the test prisms were removed from the water bath and subjected to measurements of the dynamic modulus of elasticity using the ultrasonic (US) pulse velocity test and the resonance method. The ultrasonic pulse transit time was the first to be measured. The measurements were always carried out along three longitudinal lines evenly spaced over the height of the test specimen using a Pundit PL-200 ultrasonic device. The transit times thus recorded were used to calculate first the propagation of the US wave through the concrete and then the dynamic modulus of elasticity E_{cu} according to ČSN 73 1371 [11]. Using a Handyscope HS4 oscilloscope (with an acoustic emission sensor and software, which works on the basis of a fast Fourier transform), the natural frequencies of longitudinal, flexural, and torsional vibrations were then determined. These values were then used to calculate the dynamic modulus of elasticity E_{crL} (from longitudinal vibrations) and E_{crf} (from flexural vibrations) in accordance with the standard ČSN 73 1372 [12]. More information on the pulse velocity test and the resonance method can be found for example in [13].

Based on the results of these measurements, the test specimens of each concrete type were divided into two groups of three, so that the average value of the dynamic modulus of elasticity was approximately the same for both groups. One group of specimens was used for reference. These specimens were first used for the determination of the flexural strength f_{cf} according to EN 12390-5 [14] and the tensile splitting strength f_{ct} measured on their fragments according to the standard EN 12390-6 [15]. The second group of test specimens was subjected to cyclic freezing in accordance with the standard [9]. One hundred and fifty freeze-thaw cycles were conducted with the test specimens and the value of the dynamic modulus of elasticity was determined after each 25th cycle. Based on the changes in its average value, the relative dynamic modulus of elasticity (RDM) was determined. It represents the ratio between the value of the modulus of elasticity after F-T cycles and the value of the modulus of elasticity before the test of frost resistance. RDM (U) stands for the relative modulus of elasticity determined using the US pulse velocity test, RDM (FL) was measured using the resonance method of the natural frequency of the longitudinal vibrations and RDM (FF) was calculated from the natural frequency of flexural vibrations. After 150 freeze-thaw cycles, the test specimens were subjected to the flexural strength test and the fragments to the tensile splitting strength test. The strength parameters thus determined were then used to calculate the ratio of their values before and after the freeze-thaw cycles (f_{ct} ratio and f_{cf} ratio).

3. Results and discussion

Figure 1 presents the RDM (U) results for all four types of concrete (D, E, F, and G) in relation to the number of F-T cycles performed. It is in fact a record of the decrease of the dynamic modulus of elasticity E_{cu} during freezing and thawing. Figures 2 and 3 show the relative dynamic moduli of all the concrete types determined using the resonance method, again in relation to the number of freeze-thaw cycles.

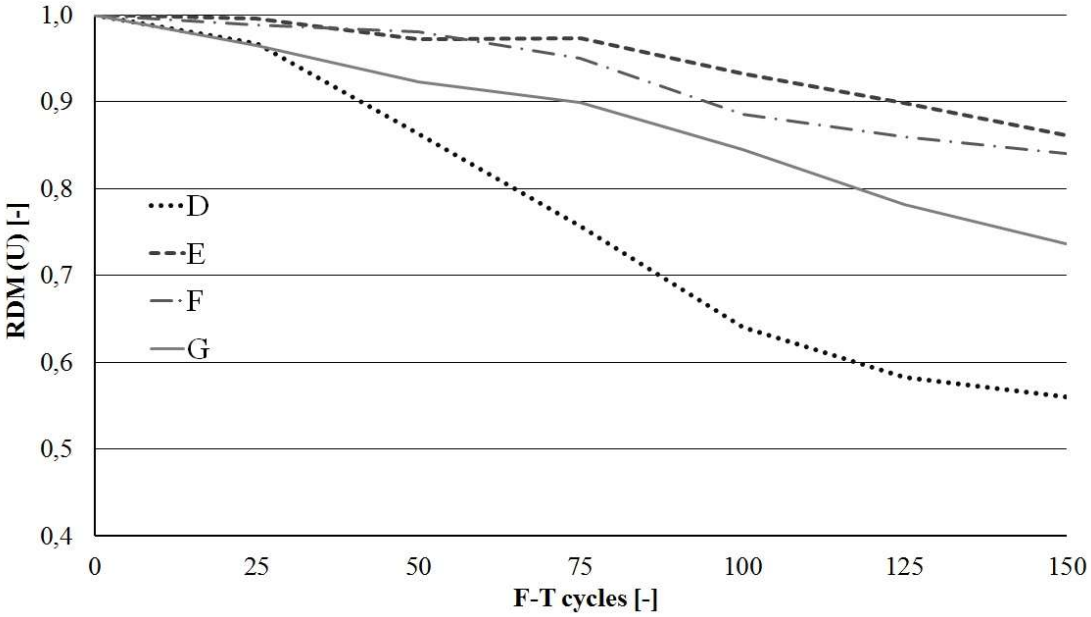

Figure 1. Progress of RDM (U) for concrete D, E, F and G in relation to the number of F-T cycles.

Table 3 lists the ratios of all the moduli of elasticity and of both strength parameters determined before and after 150 freeze-thaw cycles. The higher the value of this ratio, the higher the resistance of the concrete.

The measurement results show that the choice of aggregate has a major effect on the frost resistance of concrete. However, it is not clear which of the aggregates is the best in this respect. Concrete E (made with Tovačov sand and coarse aggregate from Luleč) reached the highest RDM values, while the highest strength was achieved by concrete F (with Bratčice sand and Tovačov coarse aggregate). The worst results, both in destructive and non-destructive tests, were determined for concrete D (with Bratčice sand and Luleč coarse aggregate).

What is more interesting and more important is the comparison of the different testing procedures used for the determination of frost resistance of the concrete. The harshest criterion is the decrease in flexural strength of concrete (the ratio between values before and after F-T cycles), which applies to all four concretes. On the other hand, the ultrasonic pulse velocity test seems to be the least sensitive method for assessing the degree of internal damage to concrete after F-T cycles. It can also be stated that all three observed RDM exhibit a similar trend, while measurement by the resonance method using the natural longitudinal and transverse vibration frequency is almost identical. Thus, when using the resonance method, it could be sufficient to assess frost resistance only on the basis of E_{crL} (the measurement of the natural frequency of longitudinal vibration is not dependent on the dimensional accuracy of the specimen's cross-section). Yet, it is still advisable to measure the natural frequencies of all types of vibration and calculate the dynamic Poisson's ratio with them. This can be useful e.g. for calculating the dynamic modulus of elasticity E_{cu} determined by the ultrasonic pulse velocity test.

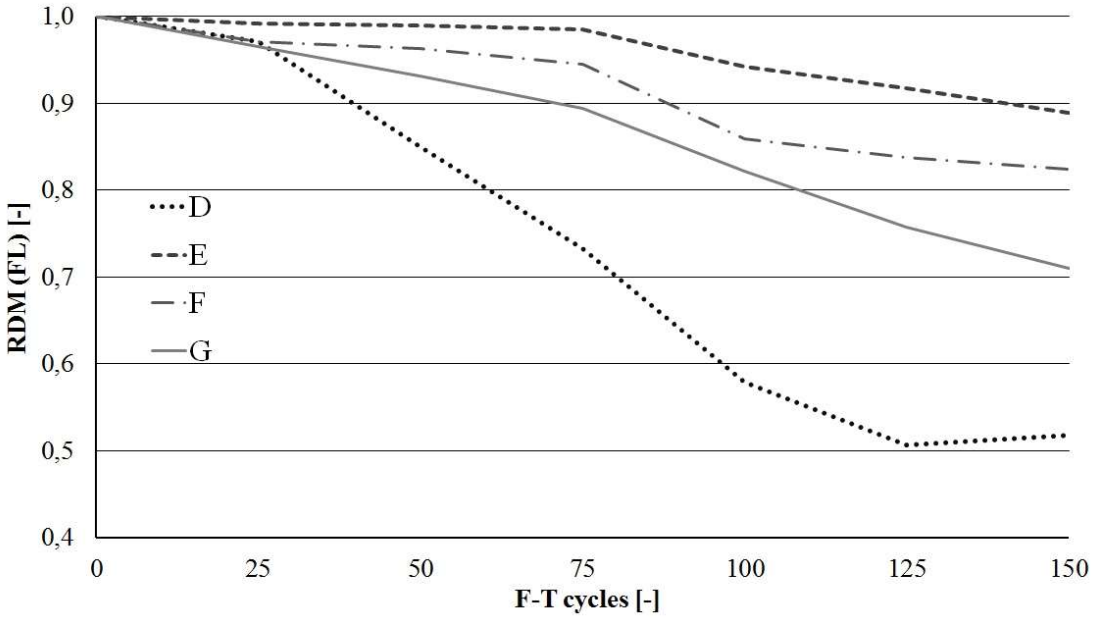

Figure 2. Progress of RDM (FL) for concrete D, E, F and G in relation to the number of F-T cycles.

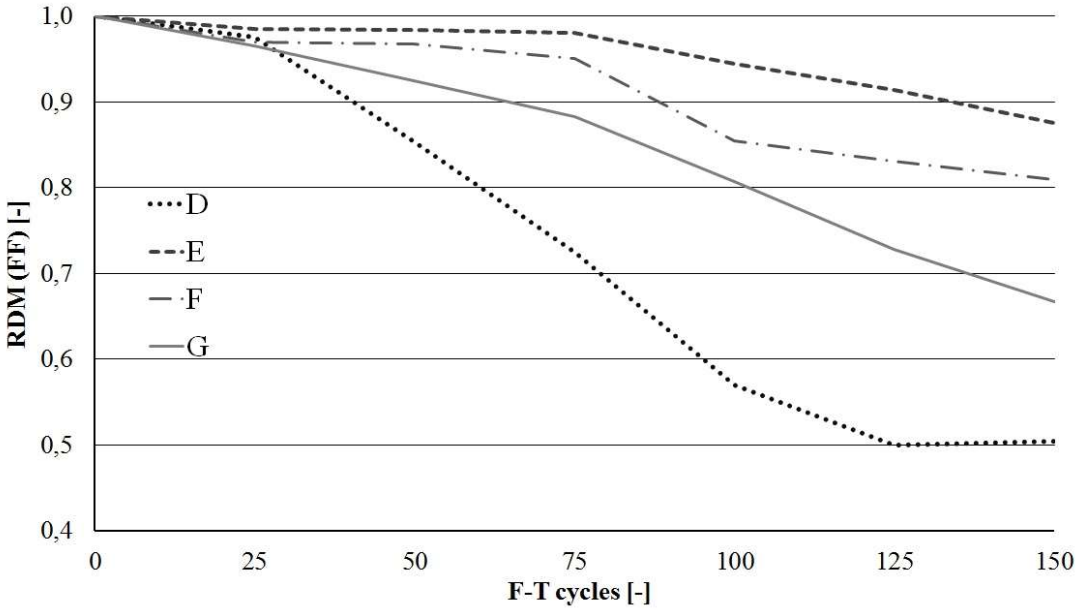

Figure 3. Progress of RDM (FF) for concrete D, E, F and G in relation to the number of F-T cycles.

Table 3. Results of RDM and ratios f_{ct} and f_{cf} after 150 F-T cycles (in percent).

	Concrete			
Parameter	D	E	F	G
RDM (U)	56.0	86.1	84.1	73.7
RDM (FL)	51.8	88.9	82.4	71.0
RDM (FF)	50.4	87.6	80.9	66.7
f_{ct} ratio	55.8	75.2	78.9	75.8
f_{cf} ratio	42.6	66.5	72.5	59.9

4. Conclusion

The experiment results show that RDM values measured non-destructively during frost resistance testing correspond more to a decrease in tensile splitting strength than to loss of flexural strength. A crucial advantage of non-destructive test methods in terms of assessing frost resistance is the possibility to observe the progress of internal damage sustained by the specimens throughout the duration of the test. Destructive tests may give information about this damage only when using a much higher number of specimens, and even so, the results will be affected by the fact that every testing session will be performed with a different (new) set of specimens. The loss of flexural strength compared to RDM or tensile splitting strength is more severe and in terms of assessing concrete for frost resistance also sets a much stricter standard for failure.

Acknowledgments

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