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Freeze-thaw resistance of concrete with porous aggregate

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Abstract

This paper deals with the influence of periodic freezing on lightweight concrete characteristics. Sets of lightweight concrete prismatic specimens are cyclically frozen in range from +20°C to -20°C and non-destructively tested after every 25 cycles. Freeze-thaw resistance is determined from measurement of the frost-attacked and non-frost-attacked (referential) specimens. The referential specimens are air/water-cured. Non-destructive methods, especially ultrasonic impulse method and resonance method are used for determination of specimen's degradation. Experiments are finished with destructive test in order to determine the static modulus of elasticity.

Keywords: Lightweight concrete; freeze-thaw resistance; modulus of elasticity; non-destructive testing; porous aggregate

1. Introduction

In recent years, the research and development in the field of cementitious materials have been focused increasingly on its durability and service life. The freeze-thaw resistance is one of the many parameters which can define concrete durability. The durability parameters are especially related to the concrete air void system and to the bond between the aggregates and matrix.

Lightweight aggregate concretes (LWAC) are a special type of concrete characterized by a specific distribution and content of air voids in matrix as well as in the aggregate particles. The main disadvantage of these concretes is the high sensitivity to the curing conditions which can significantly influence the initiation and propagation of cracks. This fact leads to the changes of physico-mechanical, fracture and durability parameters.

One of the approaches to reduce the crack initiation especially in the early stage of concrete setting and hardening is the aggregate pre-conditioning (pre-wetting) before it is batched into the mixing device. Nevertheless, this solution brings a lot of problems, especially during the design of fresh as well as harden concrete.

It can be said that the choice of the method of the porous aggregate conditioning (pre-saturation) has an essential influence on the final strength and durability characteristics of the LWAC because the various sizes and amount of the pores are filled in with water during the pre-saturation process. One of the approaches of the examination of the factors including its risks, affecting the process of the LWAC behaviour, is the usage of the mathematical model based on fuzzy sets [1].

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Many research studies deal with the characteristics of the lightweight aggregate concrete [2-5].

This paper deals with a part of results of the experimental analysis focused on the freeze-thaw resistance of the lightweight concrete. The aim of the experimental part is to compare three types of the lightweight concrete from the determination of specimen's degradation point of view. In these concretes the aggregate with a different degree of saturation are used.

2. Composition of lightweight concrete

Three concrete mixtures LC1, LC2 and LC3 were made for the experimental part. They differed only in the degree of the porous aggregate saturation at the moment of batching to the mixing device.

The aggregate used in the *"LC1"* mixture was dried up to the steady-state in the oven plant and its saturation was 0 %. The *"LC2"* mixture contained the aggregate with the storage moisture of 13 % (the aggregate was not conditioned for the batching at all and it is possible to describe this saturation as natural) and the *"LC3"* mixture contained the aggregate which was immersed in water up to achievement of 29 % moisture (the aggregate was dried before the immersion).

The fresh concrete mixture was prepared from Liapor 4–8/600 lightweight expanded clay aggregate (year of delivery 2008), heavy–weight aggregate (DTK – Zaječí) of 0–4 mm fraction, CEM I – 42.5 R cement, fly ash (Třinec), plasticizer (Sika Viscocrete 1035), stabilizing agent (Sika Control – 5 SVB) and water. The water, lightweight aggregate of 4–8 mm fraction, plasticizer, and stabilizing agent were dosed by volume, the remaining components by weight.

The composition of the concrete mixtures was designed similarly to the composition of the self compacting concrete, i.e. the mixtures contained a high amount of the fine particles, low w/c ratio and high dosage of the plasticizer. The high fluidity and viscosity is one of the typical characteristics of the final mixture. The self compacting LWAC is a special kind of this type of concrete. The low bulk density of the porous aggregate essentially influence the fluidity and viscosity as well as the stability of the concrete mixture. There is a high risk of mixture segregation. Thus, it is very important to pay attention to the mixture compacting during the test specimens manufacturing.

The period and the method of compacting were designed with regard to the workability of the fresh concrete that was determined according to the European guidelines for SCC [6].

All manufactured test specimens were stored in the same curing conditions. Immediately after removing from the steel moulds they were stored in vessels with the temperature 20°C and RH ≥ 95% for 7 days. After that the specimens were removed from the vessels and air-stored in the laboratory until the testing time occurred.

The freeze-thaw test started after the test specimens achieved age of 28 days. The composition of the fresh concrete mixture is given in Table 1, the differences between mixtures are mentioned in Table 2.

Table 1. General mixture proportion of lightweight concrete

Components	Units	Quantities per 1 m^3
Liapor 4–8/600	m^3	0.36
DTK 0–4 mm Zaječí	kg/m^3	700
Cement 42.5 R	kg/m^3	440
Fly ash Třinec	kg/m^3	80
Sika Viscocrete 1035	kg/m^3	5
Sika Control – 5 SVB	l	1.6
Batching-water	l	180
Pre-wetting water	l	52

In the case of the lightweight concrete it is always very useful to verify the actual characteristics of the used porous aggregate before the start of the mixture proportion design. In Table 3 there are given the basic physico-mechanical characteristics of the Liapor aggregate. The curve of the overall Liapor-aggregate mass absorption determined within the first 48 hours is illustrated in Figure 1.

Table 2. Mixture details

	LC1	LC2	LC3
Aggregate saturation	0 %	13 %	29 %
Pre-wetting water	52 litre	37 litre	0 litre
Batching-water	180 litre	179 litre	184 litre
Workability: T500/Slump-flow	5.8/600	3.6/660	7.6/480
Class	VS2/SF1	VS2/SF2	VS2/-

Table 3. Physico-mechanical properties of Liapor aggregate

Liapor 4 – 8 /600	Units	Value
Loose bulk density	kg/m^3	615
Compacted bulk density	kg/m^3	637
Particle density (24 h)	kg/m^3	1026
Crushing resistance	N/mm^2	6.0

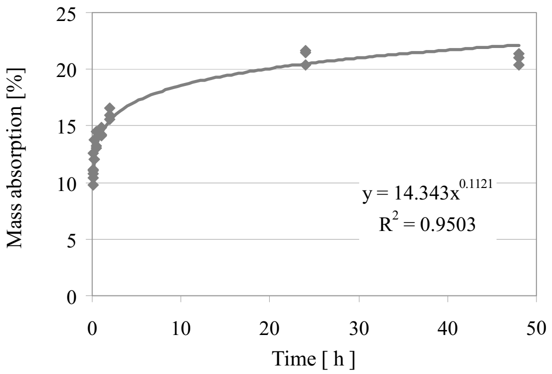

Fig. 1. Overall curve of mass absorption within the first 48 hours – aggregate Liapor

3. Freeze-thaw test

The freeze-thaw resistance is one of the many parameters which can define concrete durability. Currently two Czech standards are simultaneously applicable to determination of the concrete freeze-thaw resistance [7], [8]. The testing approaches differ especially in the cycles lengths, in the requirements of test specimens preparation and in the results interpretation. While the first one [7] prescribes the cycle of 4 freezing hours and 2 thawing hours, the second one [8] prescribes the cycle of 8 freezing hours and 4 thawing hours. Further, the first standard [7] requires saturated concrete specimens whereas the second one [8] doesn't prescribe strict rules for the specimens pre-conditioning. The results interpretations of the performed test are the last but not least differences between these two standards. While the first one [7] is focused especially on the determination of the frost resistance coefficient from the bending strength values, the second one [8] evaluate the frost resistance as a value of the relative dynamic modulus of elasticity and for the measurement prefer especially NDT methods. It is very hard to decide which standard is "better" and should be used for the evaluation of the concrete freeze-thaw resistance. For the experimental analysis the modified testing procedure was used.

Two sets of prismatic specimens were used for the experimental analysis. The specimens were not in the saturated state before the start of the tests. The first set was exposed to the cyclical freezing and thawing (4 hours freezing and 2 hours thawing), the second set was not frost-attacked (specimens were air and water cured only).

The first set of the test specimens was stored in the automatic freezing plant KD-20 which holds the temperature at -20 ± 2 °C during the freezing period and at 20 °C during the thawing period. For the second set special curing conditions were prescribed. All specimens were air-stored in the laboratory. Each week, after every 25 freeze-thaw cycles, the specimens were immersed in the water bath for 50 hours. These conditions conformed to the conditions in the freezing plant during the 25 freeze-thaw cycles. The curing conditions of the second set followed above prescribed instructions during the whole time of the freeze-thaw test.

Each set contained three different types of the lightweight concrete – “LC1” (mixture contained dried aggregate), “LC2” (mixture contained aggregate with the storage moisture of 13 %) and “LC3” (mixture contained 29 % saturated aggregate). The total number of testing specimens was 36 prismatic specimens with dimensions 100x100x400 mm, each set contained 18 specimens (6 specimens manufactured from each mixture). Both sets were non-destructively tested regularly in the defined intervals after each 25 freeze-thaw cycle. The final evaluation of the destructive and non-destructive tests was performed after the first set achieved 200 freeze-thaw cycles.

4. Experimental

4.1. Testing methods

Two non-destructive methods were used during the freeze-thaw test. The first one is the ultrasonic impulse method and the second one is the resonance method.

The ultrasonic impulse method is widely used for non-destructive determination of the concrete quality. The method is based on the measurement of the transmit time of the ultrasonic impulse in the tested material. The method is useful to provide information about uniformity of concrete, cavities, cracks and defects, the modulus of elasticity and compressive strength.

The resonance method is intended primarily for detecting significant changes in the dynamic modulus of elasticity of laboratory or field test specimens that are undergoing exposure to weathering or other types of potentially deteriorating influences. The test method may also be used to monitor the development of dynamic elastic modulus with increasing maturity of test specimens. This test method covers measurement of the fundamental transverse, longitudinal, and torsional resonant frequencies of concrete specimens (ASTM International [9]).

Fig. 2. Testing equipment for ultrasonic impulse method (left); testing equipment for resonance method (right)

After the freeze-thaw test was performed the specimens were tested destructively – the static modulus of elasticity was determined by the four-point bending test.

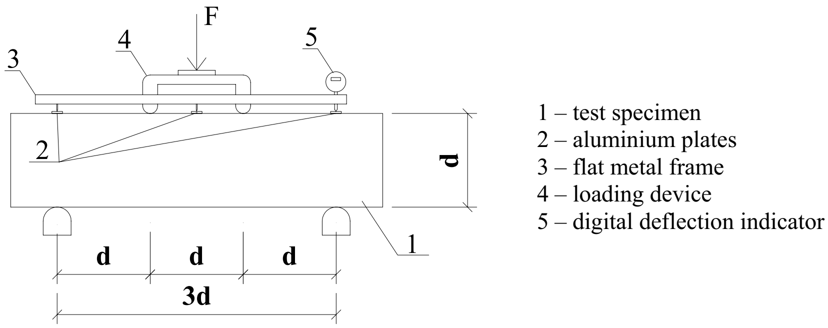

Fig. 3. Schema of four-point bending test

4.2. Dynamic modulus of elasticity

Internal damage, which can arise during freezing, leads to changes of concrete properties. The volume of the internal damage is related to the value of the dynamic elastic modulus and according to the Czech standard ČSN 73 1380 [8] it is possible to use two methods to determine the relative dynamic elastic modulus of prismatic specimens. The first method is an ultrasonic impulse method and the second one is a resonance method.

Both methods are non-destructive testing methods and for determination of the relative dynamic elastic modulus it is possible to use following equations:

$$RDM_{UPPT,n} = \left(\frac{t_{S,0}}{t_{S,n}} \right)^2 \times 100 \quad [\%] \tag{1}$$

where $RDM_{UPPT,n}$ is the relative dynamic modulus of elasticity evaluated from the ultrasonic impulse method;

$t_{S,0}$ is the transmit time of the ultrasonic impulse in [μs] at the starting measurement;

$t_{S,n}$ is the transmit time of the ultrasonic impulse in [μs] at measurement after n number of the freeze-thaw cycles.

$$RDM_{FF,n} = \left(\frac{f_n}{f_0} \right)^2 \times 100 \quad [\%] \tag{2}$$

where $RDM_{FF,n}$ is the relative dynamic modulus of elasticity evaluated from the resonance method;

f_n is the fundamental transverse resonant frequency in [Hz] at measurement after n number of the freeze-thaw cycles;

f_0 is the fundamental transverse resonant frequency in [Hz] at the starting measurement.

Both the equations lead to the value that is interpreted in percentage. It is also possible to express the results of the dynamic elastic modulus in specific units according to the Czech standards ČSN 73 1371 [10] for the ultrasonic impulse method and ČSN 73 1372 [11] for the resonance method.

4.3. Static modulus of elasticity

Methodology of the static modulus of elasticity determination is described in Czech standard ČSN 73 6174 [12] and it was determined according to this standard.

5. Experimental results

Results of the experimental analysis are given in following figures. There are shown mean values and the standard deviations of the relative modulus of elasticity during and after the freeze-thaw test.

The Figure 4, Figure 5 and Figure 6 show the mean values of the relative value of the dynamic elastic modulus for the mixture LC1, LC2 and LC3. The left part of each figure represents the values evaluated from the ultrasonic impulse method and the right parts of the figures show the results from the resonance method. Every couple of bars in the figures is a comparison of the non-frost-attacked and the frost-attacked specimens in the same time during the cyclical freezing.

Figure 4 presents results for the concrete LC1 (mixture contained dried aggregate).

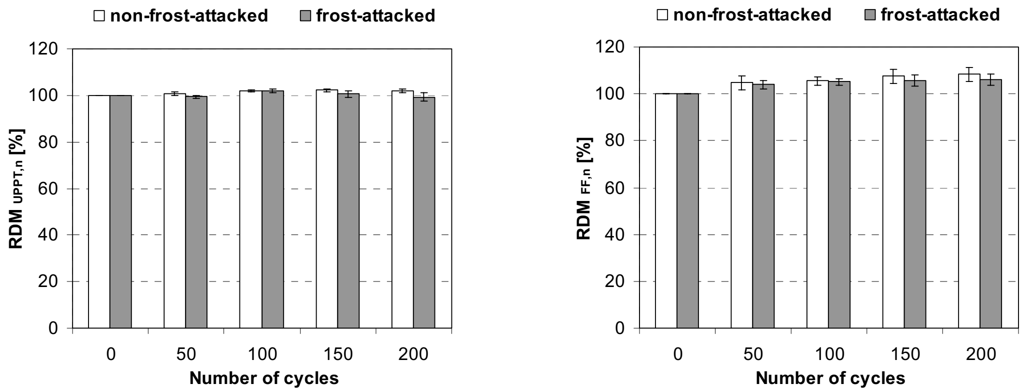

Fig. 4. Relative dynamic modulus of elasticity – concrete LC1

Figure 5 presents results for the concrete LC2 (mixture contained aggregate with the storage moisture of 13 %).

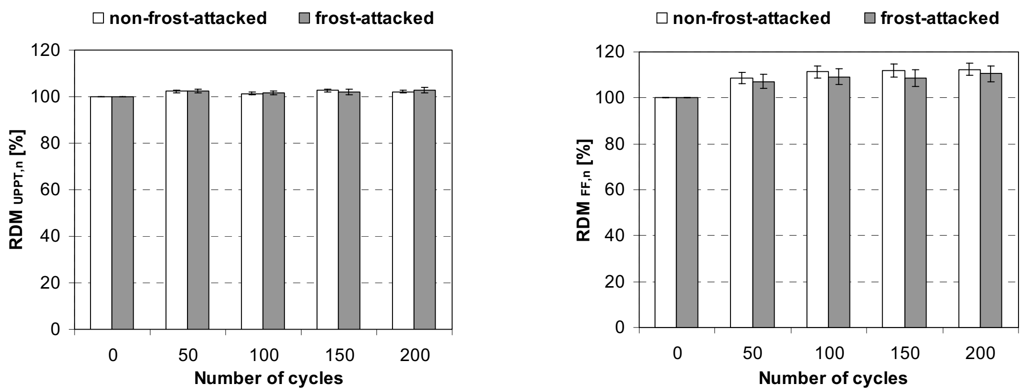

Fig. 5. Relative dynamic modulus of elasticity – concrete LC2

Figure 6 presents results for the concrete LC3 (mixture contained 29 % saturated aggregate).

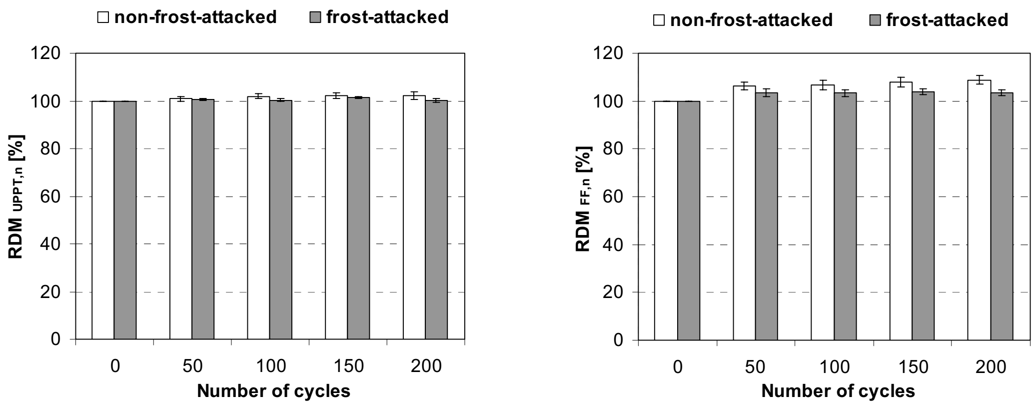

Fig. 6. Relative dynamic modulus of elasticity – concrete LC3

The following Figure 7 shows the mean values of the dynamic elastic modulus in specific units GPa of all three types of concrete after 200 freeze-thaw cycles. Figure 7 (left) presents the values evaluated from the ultrasonic impulse method and Figure 7 (right) from the resonance method. Every couple of bars in the figures is a comparison of the non-frost-attacked and the frost-attacked specimens after the cyclical freezing.

The Figure 8 shows the mean value of the static elastic modulus in specific units GPa of all three types of concrete after 200 freeze-thaw cycles.

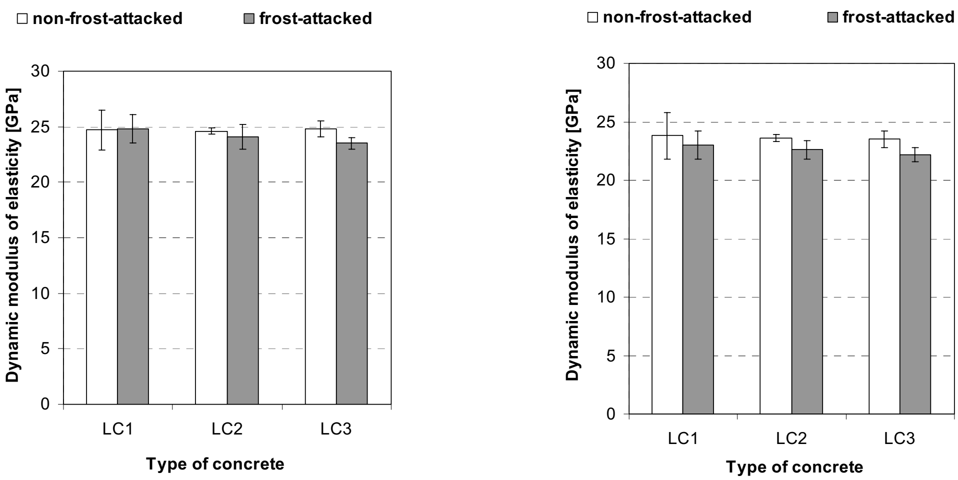

Fig. 7. Dynamic modulus of elasticity in GPa evaluated for three types of concrete: the ultrasonic impulse method (left); the resonance method (right)

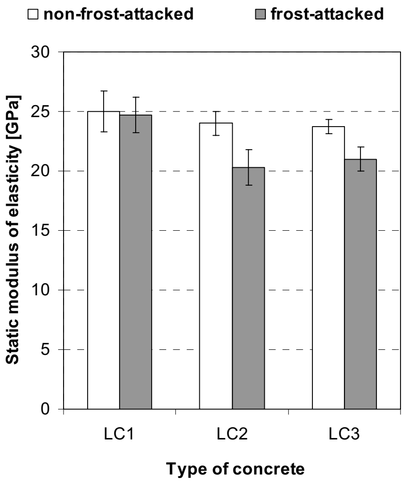

Fig. 8. Static modulus of elasticity in GPa evaluated from the four-point bending test.

6. Conclusions

First of all we have to remind, that the sets of test specimens contained 6 specimens from each mixture for the determination of the dynamic modulus of elasticity (only 3 test specimens from each mixture for static modulus of elasticity determination), it is not enough for the generalization of our conclusions.

The analysis of variance (ANOVA) was used for the evaluation of the freeze-thaw cycles influence on the obtained fracture and strengths parameters. Frozen and non-frozen sets of the test specimens were compared separately for the mixtures LC1, LC2 and LC3. The test was performed on the significance level of 95%. Pursuant to the analysis results following statements for the particular mixtures may be stated:

- Mixture LC1 (mixture contained dried aggregate): There *were not found any* statistically significant *differences* between frost and not frost attacked specimens *in the investigated parameters (value of the dynamic modulus of elasticity determined by the ultrasonic and resonance method, static modulus of elasticity determined by the four-point bending test).*
- Mixture LC2 (mixture contained aggregate with the storage moisture of 13 %): There *were not found* statistically significant *differences* between frost and not frost attacked specimens only *in the value of dynamic modulus of elasticity determined by the ultrasonic method.* On the contrary, it can be stated that the freeze-thaw cycles *negatively influenced* the value of *dynamic modulus of elasticity determined by the resonance method and static modulus of elasticity determined by the four-point bending test*.
- Mixture LC3 (mixture contained 29 % saturated aggregate): There *were not found* statistically significant *differences* between frost and not frost attacked specimens only *in the value of the static modulus of elasticity determined by the four-point bending test*. On the contrary, it can be stated that the freeze-thaw cycles *negatively influenced* both values of the *dynamic modulus of elasticity determined by the ultrasonic and resonance method.*

From the performed experiments it is possible to draw yet additional conclusions:

- In the accordance to the requirements of the Czech standard ČSN 73 1380 it can be stated that all three tested types of concrete are good-quality enough from the freeze-thaw resistance point of view. There were not observed any mechanical damages or opened cracks on the specimen’s surface.

- The ultrasonic impulse method appeared as not so sensitive for monitoring of the structural changes in concrete during the freeze-thaw test as the resonance method, nevertheless both method are useful for the evaluation of the dynamic modulus of elasticity. From this point of view measured results show that all three tested types of concrete are freeze-thaw-resistant.
- These non-destructive methods are insufficient for the description of the total rate of damage of the internal structure in case of the high freeze-thaw resistance concrete. For more detailed overview of material properties it is indispensable to apply more testing methods which are more sensitive to micro-cracks damages, for example determination of the static modulus of elasticity in bending, fracture parameters, compressive strength or splitting tensile strength on the prism fragments.
- Non-destructive measuring after each 25 freeze-thaw cycles is probably not effective for these types of concretes. Application of, for example, destructive methods during freeze-thaw cycling appears much more useful. However, this procedure is not so economical, because we need much more testing specimens.

At last it is necessary to emphasize that different specimens could have different defects on the surface as well as in the inner structure and it is necessary to verify it on the alternative specimens. Currently the testing and measuring on slabs with dimensions 300x300x80 mm are started.

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