The object of the study is the processes of structural degradation and changes in the physico-mechanical properties of cement paste, cement–sand mortars, and concretes under cyclic freezing–thawing under different exposure conditions.

The problem considered in the study is the insufficient compliance of traditional methods for assessing frost resistance with real freezing conditions. Most structures in the natural environment are subjected to one-sided or local cooling, rather than comprehensive.

The article analyzed building composite materials: cement stone, mortars and concretes, as the object of the study. These materials are most often subjected to prolonged climatic influences during their operation.

The obtained experimental results give grounds to conclude that the conditions of exposure to negative temperatures on products and structures play a significant role in their ability to resist frost damage.

A comparison of different freezing conditions showed that with local exposure, the zone with higher humidity is destroyed more intensively. This indicates that traditional methods for assessing frost resistance, which are based only on comprehensive freezing, do not fully reflect the real operating conditions of structures.

Quantitatively, it was shown that after five freeze–thaw cycles, the damage coefficient under local exposure was about 30% higher than under uniform (all-sided) freezing.

The obtained results showed the need to develop recommendations for assessing the frost resistance of building materials depending on the operating conditions of the objects for which they are intended. Taking into account the identified dependencies in the current regulatory documents will allow for a more differentiated assignment of requirements for frost resistance of materials, which will inevitably lead to a decrease in the material intensity of products while simultaneously increasing the level of safe functioning. This is the practical significance of the research carried out.

The proposed approach allows for a more objective assessment of the frost resistance of building materials, which will contribute to increasing the durability of structures and reducing the material intensity of products without losing the level of their reliability

Keywords: frost resistance of cement materials, durability of cement materials, material damage coefficient, climatic factors

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DETERMINATION OF THE RESISTANCE OF BUILDING COMPOSITES UNDER DIFFERENT TYPES OF FREEZING

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1. Introduction

The primary task in the field of construction has been and remains to ensure the reliability and design characteristics of structures, taking into account the fact that they have to work in a rather complex and changing environment. Structures must remain safe throughout their entire service life, so it is natural that the issue of preserving their properties under the influence of external factors is always in the spotlight. It is customary to distinguish two types of safety – internal and external [1, 2]. External is associated with the stability of the subsystem during interaction with the environment. If such stability is violated, this can pose a threat to neighboring structural elements. Internal characterizes the ability of the system itself to maintain integrity and operational properties, which, as researchers note, is determined by its homeostatic capabilities [3]. Comprehensive safety of a structure actually means that internal and external properties are in a certain equilibrium ratio, thanks to which the system is able to adapt to the action of constantly changing factors. It is known that the durability of concretes and mortars largely depends on how well they retain their properties and quality parameters during a given service life [4]. The conditions in which they operate are often far from favorable – these are cyclic wetting and drying, temperature drops, freezing, periodic contact with aggressive environments, as well as various types of loads [5–7].

The combined effect of these factors gradually destroys the structure of the material: residual deformations accumulate in it, microdamage appears, and protective and mechanical properties deteriorate [8, 9]. As a result, a decrease in normalized indicators can reach a critical level at which the structure no longer performs its functions.

The climatic conditions of the study area, in particular the southern regions, are known for a significant number of temperature transitions through 0°C during the cold part of the year. Such a transition is observed almost every year from autumn to spring. Average daily values often do not reflect the real situation: even when the average for the day is +2°C, at night the temperature drops to minus values, and during the day it rises to plus values. In winter, the difference can reach from +3...+5°C to –5...–10°C. In certain periods in temperate climates, a decrease in temperature to –20...–30°C can be observed [10].

The fact of the temperature passing through 0°C is fundamentally important, because it is at this moment that the moisture in the pores of the material freezes. As is known, ice has a larger volume than water, and this increase (up to 9%) leads to significant internal stresses that can damage the structure of cement stone, mortars and concretes [11, 12].

In existing standards, the frost resistance of materials is assessed mainly under conditions of volumetric freezing of samples. However, the analysis of operational situations shows a different picture: in real structures, cooling most often occurs locally – for example, on one side or in separate sections. This is how piles and bridge supports, external wall elements, channel linings and many other structures work. In such cases, zones with different temperatures exist simultaneously, which means that specific heat transfer processes occur inside the material, which can differ significantly from those that occur during bulk freezing. This logically allows to assume that the behavior of the material and its destruction will also be different.

Therefore, studies devoted to taking into account real operating conditions and the features of the destruction of cement materials under the influence of cyclic freezing and thawing are relevant. The results of such studies can shed light on the mechanisms of structural change, increase the reliability of durability assessments and ensure reliable operation of building structures in difficult climatic conditions.

2. Literature review and problem saement

The mechanisms of frost damage of building materials are based on certain hypotheses. It is known that the volume of ice is 9% greater than the volume of water [11] and because of this, stress is formed inside the material, which can be destructive for the structure. This formed the basis of the main hypotheses that explain the occurrence of stresses that arise in building materials, such as capillary-porous bodies, as a result of ice formation. This is the hypothesis of the direct action of crystallized ice on the pore walls. According to calculations by some scientists, the ice pressure when water freezes is about 12 MPa, while the tensile strength of concrete rarely exceeds 7 MPa, so concrete collapses where ice has formed. Destruction increases with each cycle of freezing and thawing [6]. However, these models do not take into account the complex structure of micropores and the different state of water in them, which reduces the accuracy of predictions.

In studies on the hypothesis of thermal incompatibility of concrete components, it is assumed that aggregates and cement stone have different coefficients of thermal expansion. At sub-zero temperatures, the thermal incompatibility of the components increases sharply, since the coefficient of thermal expansion of ice is 3–7 times greater than that of concrete [13]. However, the authors did not assess the extent to which these processes manifest themselves in water-saturated materials, where ice partially compensates for temperature deformations. Hydraulic pressure is the pressure of the liquid inside the material. In [14], hydraulic pressure is presented, but for granite and hard rocks. Due to the fact that the density of water differs during the water-ice phase transition, an increase in volume occurs by approximately 9%, i.e. an equivalent volume of water must be displaced. If there is no suitable space (water-free pores, surface) for the displaced water in the immediate vicinity of the ice formation site, an internal pressure arises, which is referred to as hydraulic pressure [15, 16].

The magnitude of the hydraulic pressure depends primarily on the length of the path that the displaced water takes to the nearest water-free expansion space. Frost damage occurs only when the hydraulic pressure exceeds the tensile strength of the concrete. The authors of [15, 16] explain this by the positive effect of pore formers and the fact that they provide additional expansion space. He calculated what the maximum path from the ice formation site to the edge of the expansion space (distance factor) can be for the hydraulic pressure not to exceed the tensile strength of the concrete. The hydraulic pressure also depends on the amount of freezing water and the cooling rate during freezing [17].

High hydraulic pressure occurs when concrete has an elongated capillary pore system and a high degree of water saturation, and the rate of ice formation is high. However, hydraulic pressure can also lead to damage in the case when the water content in the pores is less than 91%. The authors of [15, 16] explain this by the fact that the liquid first freezes in larger pores. When the process of freezing of the liquid begins in smaller pores, the displacement of water through the ice that has already formed in large pores is complicated. With complete blockage of the displaced water, the hydraulic pressure can theoretically reach 200 N/mm^2. Hydraulic pressure is one of the most important factors at the microscopic level that cause damage under the influence of frost [17].

However, such thermal stress plays an important role only in unsaturated moisture concrete. Currently, many tests of concrete for the effect of subzero temperatures are being carried out. Based on the tests, it was found that as the freezing rate of concrete increases, the destruction of concrete accelerates accordingly, but the ice pressure on the pore walls does not increase. This fact cannot be explained by the hypothesis mentioned above.

It has also been established that concrete destruction under the influence of sub-zero temperatures is possible even when filled with water by less than 90%, and this is not a rare fact.

In the study [18], a model of internal interface surfaces and technological cracks was proposed. The authors pointed out a change in the geometry of cracks during freeze-thaw cycles. They proposed a model of the structure of composite building materials, which includes technological cracks and internal interface surfaces. The fundamental difference between internal interface surfaces (IIS) and technological cracks (TC) is that TC lacks the distinctive feature of a crack – the mouth.

Due to the fact that TC and IIS are present both on the surface of the samples and in their volume, it is logical to assume that water will freeze in surface cracks first. The change in the temperature of the sample occurs from its surface, forming a freezing front. The phase transformations of water over time may not coincide with the speed of advance of the temperature front. This is due to the fact that with increasing alkalinity of the pore fluid as it deepens into the volume of the material, its freezing temperature decreases. In addition, for structures consisting of discrete blocks interacting through the VPR, the diffusion mass transfer coefficients can change by orders of magnitude. Therefore, in such cases, it is advisable to speak not about the front, as a fairly uniform line formed under the action of constant temperature gradients, but about the local (“stream”) mechanism of heat and mass transfer.

Analysis of work [18] showed that a change in the width of the crack opening and the redistribution of the types of bound water significantly affect the development of microdamage. In this case, new crack elements are formed on the banks of the initial crack in the zone of the "ice-water" interface, in the zones of change in the direction of the trajectory of the curvilinear crack, and an increase in the length of the initial crack occurs.

An increase in the width of the opening causes an increase in the volume of the crack section filled with bound water. The decrease in pressure in the volume of the crack section filled with bound water leads to a spontaneous redistribution of water bond forms. It can be assumed that due to the decrease in partial pressure, part of the polyadsorption water will pass into the free state. In this case, free water will accumulate in the crack section with the maximum opening width – at the ice boundary. In addition, taking into account that the material in which the crack is located is a water-filled capillary-porous system, it is possible to conclude that part of the capillary fluid is sucked into the crack volume. However, the authors did not provide a quantitative assessment of these processes, which complicates the use of the model for predicting durability. The liquid in the pores of cement stone contains dissolved substances that come from the cement stone matrix and from the used deicing salts [17]. When the diluted solution freezes to the eutectic point, only ice crystals are released. In parallel, the concentration of the residual solution increases. Since the freezing process depends on the size of the pores, this leads to different concentrations of the solution. While the unfrozen solution in the smaller pores has an initial concentration, the concentration of the solution in the larger pores increases due to the freezing that has begun. This difference in concentrations leads to a diffusion process that proceeds in the same direction as the diffusion caused by the vapor pressure difference (the liquid moves from the small pores to the large ones). Thus, the capillary effect, in particular when using deicing salts, can be enhanced by the resulting difference in the concentrations of the pore liquid. Osmotic pressure as the primary cause of damage can be excluded [12]. The main drawback of the osmotic pressure theory is the limit at which this pressure becomes significant and can affect the structure.

The thermodynamic model takes into account the effect of surface forces on frost damage. When creating the model, it was assumed that, together with the adsorbed water layer, the solution in the small pores of the gels also freezes on the surface of the particles at the appropriate temperature. As a result of the creation of a new interface, a thin layer of water and crystals, additional surface tension arises during freezing.

The pressures caused by this surface tension are higher, the smaller the hydraulic radius of the pores. This leads to pressure differences between ice-filled pores of different sizes, which can lead to significant stress in the microstructure of the cement stone.

If to proceed from the freezing point of the smallest pores, the maximum pressure drops can be up to 37 N/mm^2. The effect of these pressure drops depends largely on the cooling rate. At low cooling rates, compression occurs exclusively in smaller pores, while at high cooling rates, excessive pressure also occurs in larger pores.

The thermodynamic model is consistent with a number of effects that occur when frost acts on cement stone. Due to the specific nature of cement stone pores (most pores are helium and capillary pores), it should be assumed that the described processes of concrete damage under frost have a significant impact. However, this theory does not take into account the heterogeneity of real concrete and different rates of local cooling throughout the thickness of the structure. This limits the accuracy of predicting the behavior of products during operation.

Crystallization effects can create three types of pressures: hydrostatic crystallization pressure, linear crystal growth pressure, and hydration pressure.

Hydrostatic pressure occurs when the volume of the formed crystal together with the residual solution exceeds the volume of the initial supersaturated solution. During freezing and the action of de-icing salts, the ice pressure is decisive as a type of hydrostatic crystallization pressure.

Linear pressure is associated with the growth of crystals in a certain direction. If the pore space is limited, such crystals are able to exert mechanical pressure on the pore walls.

Hydration pressure occurs during the transition of a phase with a lower water content to a phase with a larger volume. However, this mechanism does not cause the destruction of the concrete structure during the growth of ice crystals or the possible formation of salt crystals [19].

Unequal coefficients of thermal expansion. At large temperature differences, due to differences in thermal expansion coefficients, a stress arises that is within the tensile strength of concrete. For example, at a temperature difference of 40°C, a tensile stress of > 6 N/mm^2 may arise.

However, experimental evidence of the action of this failure mechanism in concrete has not been obtained, therefore, there are different opinions regarding the influence of unequal coefficients of thermal expansion on material damage. The occurrence of concrete damage due to different coefficients of thermal expansion of components in concretes manufactured in accordance with standards can be excluded [12].

The layered freezing model was originally developed for freezing concrete in the presence of de-icing salt. When de-icing salts are used, a salt gradient effect occurs, which causes the freezing point to decrease more in the surface areas of the concrete than in the deeper areas. On the other hand, when freezing occurs, the lowest temperatures are observed first on the surface of the concrete, while the inner areas cool slowly. The interaction of salt concentration and temperature differences can lead to ice formation first on the surface of the concrete and in the inner area, while the intermediate layer remains unfrozen. If this intermediate layer also freezes during further cooling, this leads to delamination of the surface layer. Layered freezing of concrete can also occur when exposed to frost alone. In this case, the cause of this phenomenon, together with the already mentioned temperature difference, may be the fact that due to the heterogeneity of the concrete, caused by the process of its preparation, the properties of the concrete responsible for damage (water-cement ratio, porosity, strength, elastic modulus, coefficient of thermal expansion, etc.) change when moving from the inner zone to the surface [19].

This work is considered classic [14], in which a hypothesis for permafrost soils was proposed and analyzed – the effect of the "freezing front". This hypothesis describes the process that occurs during volumetric freezing, where a kind of "freezing front" is formed, which contributes to the displacement of free water into the deep layers of the material [14].

Historically, such a mechanism of water displacement was accepted as the main one when describing the processes occurring in a separate capillary. This is the basis for the hypothesis of a decrease in the frost resistance of building materials, and formulation and technological measures are being developed to create the so-called reserve porosity for the outflow of displaced water when it freezes in the capillary volume. However, the model was developed for soils and was not adapted to composite building materials.

Data from many researchers indicate that when a water-saturated sample freezes, its volume increases. If only part of the product (sample, structure) freezes, volumetric changes during freezing will occur only in the frost zone. This causes a discrepancy between the objective operating conditions of products and structures and between the current methods for assessing the frost resistance of the materials from which these products and structures are made. In order to study this discrepancy, the task was set to assess the influence of freezing conditions on the nature of the development of volumetric integral deformations in building products.

The above-described analysis of various theories of the freezing and thawing process has shown that there is no information on the distribution of deformations and stresses in building products and structures under local action of negative (minus) temperatures. Unilateral freezing should lead to a change in moisture migration, processes of redistribution of deformations not only in the material itself, but also at the product level, which should be reflected in the frost resistance of the material. This also poses the task of analyzing the processes occurring during unilateral and local freezing of products for the purposeful development of methods for ensuring the normative frost resistance of the material.

3. The aim and objectives of the study

The aim of the study is to determine the influence of the method of freezing samples on the frost resistance of cement, mortar and concrete materials. This will make it possible to increase the accuracy of assessing the durability of building products in real operating conditions, improve regulatory methods for determining frost resistance and substantiate technological solutions for increasing the resistance of materials to cyclic freezing-thawing.

To achieve this aim, the following objectives were defined:

– to determine the influence of freezing conditions on the change in the damage coefficient of composite building materials;

– to assess the influence of freezing conditions on the change in the physical characteristics of composite building materials;

– to determine the change in the strength and stability of composite building materials under different conditions of cyclic freezing-thawing.

4. Materials and methods

The object of the study is the processes of structural degradation and changes in the physical and mechanical properties of cement stone, cement-sand mortars and concrete under the action of cyclic freezing-thawing under different conditions of exposure.

The hypothesis of the study is that the method of freezing the samples (the nature of heat and mass transfer, the direction of the temperature gradient, the rate of formation of phase transition zones) significantly affects the development of volumetric deformations, crack formation and the rate of degradation of the physical and mechanical characteristics of the material. Accordingly, traditional methods of assessing frost resistance, built on volumetric freezing, may not reflect the real operating conditions of products.

The main assumptions on which the work was based are that the structure of cement stone and concrete is considered a capillary-porous system with the initial presence of technological cracks.

In the process of conducting the study, the following simplifications were adopted:

1. The structure of cement stone, cement-sand mortar and concrete was considered as a capillary-porous system, without detailed consideration of local heterogeneity of the microstructure, grain composition of aggregates and the orientation of individual pores and cracks.

2. The presence of technological microcracks and internal interface surfaces was considered initial and inevitable for all samples.

The studies were conducted on samples:

– $4 \times 4 \times 16$ cm in size – from cement stone (W/C = 0.28) and mortar (C/S = 1/2; W/C = 0.5);

– $10 \times 10 \times 10$ cm and $10 \times 10 \times 40$ cm in size – from concrete of class C30/35 (mixture composition: C = 315 kg/m^3, S = 660 kg/m^3, CS = 1200 kg/m^3, W = 140 l/m^3).

The composition and characteristics of the samples selected for the studies met the requirements of current regulatory documents. Samples of concrete of class C30/35 were manufactured in accordance with the requirements of DSTU B V.2.7-176:2008 "Concrete. Rules for selection of composition" [20] and DSTU B EN 206:2013 "Concrete. Technical conditions, operational characteristics, production and compliance" [21].

The compositions of cement-sand mortars met the requirements of DSTU B V.2.7-126:2011 "Construction mortars. General technical conditions" [22].

Cement stone was manufactured on the basis of Portland cement, which meets DSTU B EN 197-1:2015 "Cement. Part 1. Composition, technical conditions and compliance criteria" [23], in compliance with the regulatory water-cement ratios.

Studies of the physical and mechanical properties of cement stone, mortar and concrete were carried out in accordance with current standards and generally accepted methods in accordance with DSTU.

The compressive strength and tensile strength in bending of cement stone and mortar samples were determined in accordance with the requirements of DSTU B V.2.7-187:2009 [24]. and DSTU B V.2.7-126:2011 [22].

The compressive strength of concrete was determined in accordance with DSTU B EN 12390-3:2019 [25], and the tensile strength in bending was determined in accordance with DSTU B EN 12390-5:2019 [26]. The tensile strength in splitting was determined in accordance with DSTU B EN 12390-6:2019 [27].

The water absorption of the samples was determined by the change in the mass of the samples in the dry and water-saturated states in accordance with the requirements of DSTU B V.2.7-170:2008 [28].

The ultrasonic wave velocity propagation in the samples was determined by a non-destructive method in accordance with DSTU B EN 12504-4:2019 [29].

To detect technological cracks in cement stone and concrete, the method described in the article [30] was adopted.

The adopted method was based on the quantitative assessment of the change in the structure of cement stone, mortar and concrete by determining the change in the damage coefficient (Kp) under conditions of repeated freezing and thawing.

Photofixation of samples after n-number of freeze-thaw cycles allowed to trace the dynamics of the growth of cracks and other discontinuities. The AutoCAD program (USA) was used to combine and overlay photographs for their further analysis.

After every five freeze-thaw cycles, the changes in the following parameters were monitored: mass (Δm), water absorption (W), ultrasonic wave velocity (V), damage coefficient (K_p), tensile strength at bending ($f_{c.tk}$), tensile strength at splitting ($f_{c.tn}$), compressive strength ($f_{c.cube}$).

An original research methodology was developed to analyze one-sided freezing. The scheme of one-sided freezing of samples is shown in Fig. 1.

Conventional designations of temperature exposure modes:

O1 – samples tested under conditions of volumetric cyclic freezing-thawing, in which the temperature effect was carried out evenly from all sides of the sample;

O2 – samples tested under conditions of one-sided (local) freezing-thawing. In this case, different surfaces of one sample were in different temperature conditions.

For O2 type samples, the following were distinguished:

O2+ – the side of the sample isolated from the action of negative temperatures and the one that was constantly in the region of positive temperatures;

O2– – the side of the same sample that was directly subjected to cyclic freezing and thawing.

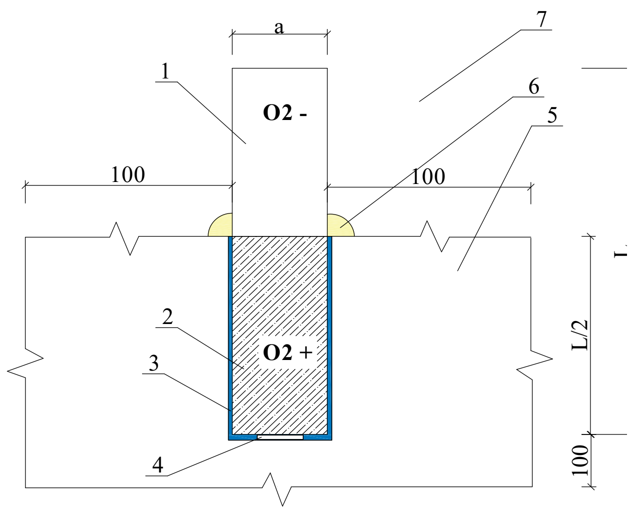

Fig. 1. Scheme of one-sided freezing of samples: 1 – part of the sample that was subjected to freezing-thawing; 2 – part of the sample that was maintained in the positive temperature range; 3 – fomisol; 4 – thermometer; 5 – foam; 6 – mineral wool; 7 – freezer

To analyze the development of volumetric changes in the samples depending on the freezing conditions, a graph-analytical method was used, which allows obtaining quantitative and qualitative dependencies. In addition, the graph-analytical method allows analyzing the mechanisms of crack development during freezing in their volume of free water. Statistical processing of experimental data was performed using methods of elementary mathematical statistics. For each indicator, the average values were determined based on the results of serial tests, and the nature of their change was analyzed depending on the number of freezing-thawing cycles and temperature conditions. Processing and comparative analysis of the results were carried out using the Microsoft Excel spreadsheet (USA), which made it possible to systematize experimental data, construct graphical dependencies and identify the main trends in changes in the physical and mechanical characteristics of materials.

The results of the experiments are given below.

5. Results of the study of the local effect of freezing-thawing on composite materials

5. 1. The effect of freezing conditions on the change in the damage coefficient of composite building materials

5. 1. 1. The effect of freezing conditions on the change in the damage coefficient of cement stone

It was found that after five cycles of freezing-thawing, the damage coefficient (K_p) in samples with local influence (O2–) was 31.5% higher, and in samples O2+ – by 28% compared to O1. This dependence in the development of damage was maintained up to 15 cycles. Analysis of the length of discontinuities relative to the area of their manifestation showed that the most intensive crack growth is observed during the first five cycles of freezing-thawing, while after 10 cycles the rate of damage growth decreases (Fig. 2).

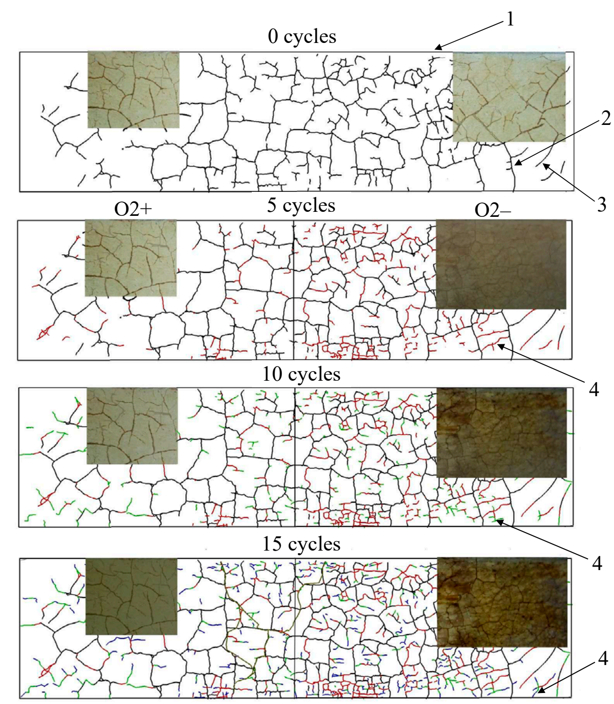

Fig. 2. The effect of the number of freezing and thawing cycles on the change in K_p during local exposure for cement stone samples: 1 – sample; 2 – cracks; 3 – interface surfaces; 4 – newly formed discontinuities

The change in damage after the first five cycles is the most intense, which indicates the beginning of irreversible structural changes in cement stone already at the initial stage of exposure. Further analysis confirmed that with an increase in the number of cycles, the destruction of the structure acquires a progressive character. In particular, after 20 cycles, the damage coefficient increased by 2.5 times both with volumetric and local freezing-thawing. The kinetics of damage development (Fig. 3) showed that the critical period for intensive crack growth is the 20th cycle, after which the sample begins to collapse.

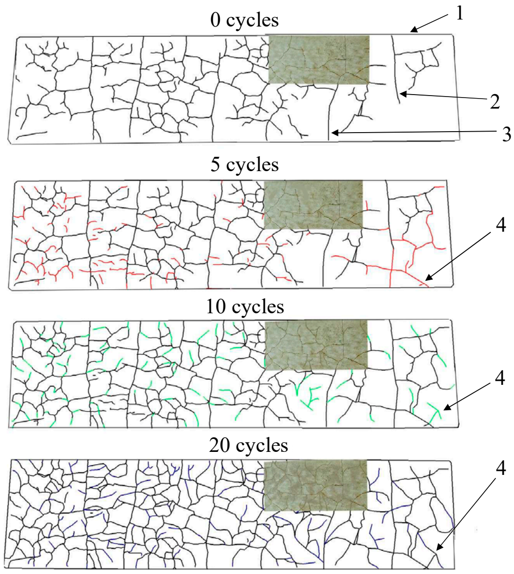

Fig. 3. The effect of the number of freezing and thawing cycles on the change in Kp during volumetric exposure: 1 — sample; 2 — cracks; 3 — interface; 4 — newly formed discontinuities

A comparative analysis revealed that the K_p values in samples after 20 freezing-thawing cycles under local exposure (O2+ and O2–) practically coincide, while the intensity of damage in the O2– zone was higher at intermediate stages. On average, the K_p of samples subjected to local exposure was 6% lower than that of samples after volumetric freezing-thawing.

5. 1. 2. The influence of freezing conditions on the change in the damage coefficient of cement-sand mortar

It was established that after five cycles the damage coefficient for the O2– zone increased by 31.5%, and for the O2+ zone – by 28% compared to the control sample O1. This pattern persisted up to 15 freeze-thaw cycles, which indicates a stable effect of the process on the formation of defects in the structure of cement stone.

Analysis of the length of discontinuities confirmed that the first five cycles are the most intensive in terms of damage development, while after 10 cycles the growth intensity decreased (about 30%). This allows to state that it is the initial stage that is the main one for the creation of microcracks, and they only develop further.

The change in the damage coefficient (K_p) during the experiment is nonlinear. The most intensive increase in K_p was observed again at the 5th cycle, which is explained by the beginning of irreversible changes in the structure of the cement stone. The second critical jump in damage occurred already at the 20th cycle, when the coefficient increased by 2.5 times compared to the initial value. It was at this stage that the active process of destruction of the samples began (Table 1).

It is interesting that the kinetics of damage change is similar both with volumetric (O1) and local impact (O2+ and O2–). However, the dynamics of defect development in the O2 – zone was more intense, which is explained by local (zonal) stress and defect concentration. While the K_p of samples with local impact was 6% lower than that of samples after volumetric freeze-thaw, which indicates a certain stabilizing role of the one-sided thermal gradient.

Table 1

The influence of the number of freeze-thaw cycles on the change in K_p

Number of cycles	K_p with volumetric exposure, cm/cm^2	K_p with local exposure to O2+, cm/cm^2	K_p with local exposure to O2–, cm/cm^2	K_p of control samples, cm/cm^2
0	100	100	100	100
5	178	118	112	174
10	246	145	265	218
15	280	161	338	240
20	413	256	370	261
25	508	402	415	261

5. 1. 3. The influence of freezing conditions on the change in the damage coefficient of concrete

The analysis showed that the change in the structure of cement stone and mortar depends on the type of freeze-thaw impact and occurs differently. Structural changes also occur with an increase in the number of freeze-thaw cycles.

Due to the fact that the concrete component includes cement and sand as ingredient materials, concrete samples were selected for the last stage of studying the type of freezing and thawing effect on cement-containing materials. The study of concrete as a separate material will allow to consider in detail the different effects of freezing and thawing on the characteristics of the material. This, in turn, sets the task: to investigate the effect of freezing and thawing conditions of concrete samples on the change in structure, physical and physico-mechanical indicators.

The data obtained made it possible to construct a graph of the effect of the number of freezing and thawing cycles on the change in the damage coefficient under different types of impact for prism samples. Analysis of the obtained results showed the effect of the number of freezing and thawing cycles on the change in the damage coefficient. The damage coefficient in samples with volumetric impact after 40 freeze-thaw cycles increased by 4 times (Table 2).

Table 2

Effect of the number of freeze-thaw cycles on the change in K_p of prism samples

Number of cycles	Volumetric effect K_p, cm/cm^2	Local effect O2+ K_p, cm/cm^2	Local effect O2– K_p, cm/cm^2	Control samples K_p, cm/cm^2
0	100	100	100	100
8	213	75	113	106
13	233	113	138	113
20	263	263	350	113
25	300	275	367	125
30	350	306	394	144
40	413	331	419	150

The method of calculating the damage coefficient (K_p) allowed to quantitatively assess the effect of cyclic freezing and thawing on the structure of concrete samples. With a comprehensive effect, K_p increases faster than with a local one: after 40 freeze-thaw cycles, the damage coefficient of prism samples and cube samples increased by 3–4 times. The most intense changes occurred at the initial stages – at 13 cycles, after which the growth of K_p slowed down.

Analysis of the damage coefficient showed that volumetric deformations of the material under the influence of temperature changes lead to a change in the structure and an increase in the damage coefficient.

5. 2. The influence of freezing conditions on the change in the physical characteristics of composite building materials

5. 2. 1. The influence of freezing conditions on the change in the physical characteristics of cement stone

The study of water absorption showed that after 20 cycles in samples with volumetric impact it increased by 24.6%, and with local impact – by 21%, while in control samples it decreased by 4%. This confirms the active changes in the structure, accompanied by the destruction of cement stone.

The study of the influence of freezing-thawing conditions on the speed of ultrasonic wave velocity transmission showed a significant decrease in this parameter. In particular, in samples O1 after 20 cycles the speed along the base L (160 mm) decreased by 37%, and transversely (40 mm) – by 22%. With local exposure to O2, the speed reduction was even more intense: by 42% along and by 9.5% (O2+) and 16.3% (O2–) transversely. This indicates the formation of defects that violate the integrity of the structure.

5. 2. 2. The influence of freezing conditions on the change in the physical characteristics of cement-sand mortar

The change in the water absorption index reflects the accumulation of structural damage. After 20 freeze-thaw cycles, the water absorption of samples with volumetric exposure increases by 24.6%, while in samples with local exposure - by 21%. Control samples that were not exposed to freeze-thaw – reduced water absorption by only 4%.

These results indicate that an increase in the number of discontinuities (microcracks and pores of the distribution surfaces) in the structure of cement stone, which contributes to more intensive moisture absorption. These results are confirmed by the damage coefficient.

The ultrasonic wave velocity in the samples showed a significant decrease with an increase in the number of cycles. For samples with volumetric impact (O1) after 20 cycles, the velocity along the base L (160 mm) decreased by 37%, and in the transverse direction (base 40 mm) by 22%.

With local impact (O2), a decrease was also observed – 42% along and by 9.5–16.3%, respectively (O2+ and O2–). This indicates a gradual accumulation of internal defects and a decrease in the integrity of the cement stone structure.

5. 2. 3. The influence of freezing conditions on the change in the physical characteristics of concrete

In prism samples O1, after 20 freeze-thaw cycles, water absorption increased by 34%.

With local exposure (O2) after 20 cycles of freezing and thawing, water absorption increased by 20%.

Further increase in the number of freeze-thaw cycles to 40 leads to a decrease in water absorption in concrete prism specimens with local freezing by 13% and with all-sided freezing by 1%.

With local exposure in base a in the O2+ part of the specimen after 20 freeze-thaw cycles, V decreased by 4%. In base a in the O2– part of the specimen after 20 freeze-thaw cycles, the ultrasonic wave velocity decreased by 11%.

Further increase in the number of cycles to 40 leads to a decrease in the ultrasonic wave velocity in O1 specimens in base L for prism specimens by 39%. In the same specimens, but with base a, the ultrasound velocity decreased by 22.2%.

In O2 samples with base L after 40 freeze-thaw cycles, V for prism samples decreased by 1%. The ultrasound transmission velocity in base a, for O2+ and O2– halves increased by 2% and 2.5%, respectively.

5. 3. Change in strength and durability of composite building materials under different conditions of cyclic freezing-thawing

5. 3. 1. Change in strength and durability of cement stone

The results of mechanical tests confirmed that cyclic freezing-thawing significantly reduces the strength of cement stone. The tensile strength at bending ($f_{c.tf}$) in samples after 20 cycles decreased by 54% under volumetric impact and by 44% under local impact. The compressive strength ($f_{c.cube}$) decreased by 43% under volumetric impact and by 27–40% in samples with local impact, depending on the study area.

The stability coefficient, defined as the ratio of the strength indicators after freeze-thaw cycles to the initial values, for samples with volumetric impact was 0.44 (for bending) and 0.56 (for compression), while for samples with local impact – 0.55–0.62 and 0.62–0.73, respectively. In control samples, this indicator was 0.97, which confirms insignificant changes in the absence of freeze-thaw impact.

5. 3. 2. Change in strength and stability of cement-sand mortar

Strength tests confirmed a significant decrease in the stability of cement stone after cyclic freeze-thaw.

The samples showed that:

– tensile strength in bending ($f_{c.tf}$) after 20 cycles decreased by 54% with volumetric impact and by 44% with local;

– compressive strength ($f_{c.cube}$) with volumetric impact decreased by 43%, with local – from 27% in the O2+ zone to 40% in the O2– zone.

The stability coefficient confirmed the destruction of the structure:

– for volumetric impact it was 0.44–0.56;

– for local – 0.55–0.73;

– in control samples it remained at the level of 0.97.

5. 3. 3. Change in strength and stability of concrete

Strength characteristics are one of the most important in KBM, since they are a direct reflection of structural changes occurring in the sample.

After 20 freeze-thaw cycles, the tensile bending strength ($f_{c.tf}$) in prism specimens that underwent local freezing decreased by 15%, in specimens that underwent volumetric freezing by 25%. The tensile splitting strength (fc.tn) in specimens with volumetric freezing-thawing exposure decreased by 51%, in specimens with local exposure by 32% for the half of the specimen that did not undergo freezing, and by 45% for the half of the specimen that underwent freezing. The compressive strength ($f_{c.cube}$) in the samples that underwent freezing on all sides decreased by 29%, in the samples that underwent freezing locally, in the half of the sample that underwent freezing – by 24%, in the half of the sample that did not undergo freezing – by 20%.

Prism samples under the volumetric type of freeze-thaw exposure after passing 40 cycles significantly changed their strength characteristics. Tensile strength at bending ($f_{c.tf}$) decreased by 49%, tensile strength at splitting ($f_{c.tn}$) decreased by 78%, compressive strength ($f_{c.cube}$) decreased by 26%.

Under local exposure after 40 freeze-thaw cycles, the bending strength of prism samples ($f_{c.tk}$) decreased by 20%.

The tensile strength at split ($f_{c.tn}$) in the parts of the samples that did not undergo freezing and thawing (O2+) at the 40th cycle decreased by 71%, in the parts that underwent freezing and thawing (O2–) – by 78%.

After 40 freeze-thaw cycles, the compressive strength ($f_{c.cube}$) in the parts of the samples that did not undergo freezing and thawing (O2+) decreased by 15%, in the parts that underwent freezing and thawing (O2–) – by 31.2%.

6. Discussion of the results of the resistance of building composites to different types of freezing

The analysis of damage coefficients made it possible to analyze the change in the structure from the outside of the sample. The surface structure of the material does not always coincide with the internal one, that is, it is not always possible to assess the change in the structure of the entire material based only on the change in the damage coefficient. The fact of the change in water absorption and mass in itself indicates the presence of a change in the structure. This characteristic is one of the main ones used in regulatory documents for the analysis of the resistance of the material to frost damage.

Analysis of the change in the speed of ultrasonic wave velocity propagation allows for additional observation and analysis of the change in the structure during freezing and thawing. The change in mass leads to a change in water absorption, the change in water absorption, in turn, should be reflected in the change in the speed of ultrasonic wave velocity propagation in the sample (V). The speed of ultrasound propagation indicates the state of integrity and density of the internal structure of the material.

The results obtained show that the conditions of cyclic freezing-thawing differently affect the change in the stability of cement stone, cement-sand mortar and concrete. The numerical data presented in Tables 1 and 2 make it possible to compare the nature of damage accumulation under volumetric and local temperature effects.

The analysis of cement stone showed that the most intense structural changes occur in the first five and the twentieth freeze-thaw cycle. It was found that local and volumetric effects affect the dynamics of damage differently, but in the end both lead to a significant decrease in strength, stability and ultrasound propagation speed, which indicates the destruction of the cement stone structure.

According to Table 1, for cement stone and cement-sand mortar, the increase in the damage coefficient occurs already at the initial stages of testing. After five freeze-thaw cycles, a sharp increase in K_p is recorded, which is associated with the formation of primary microcracks in the material structure. A further increase in the number of cycles is accompanied by the accumulation of damage, but their intensity decreases.

Analysis of the results presented in Table 2 shows that concrete reacts differently to the type of freezing. With volumetric exposure, damage accumulates throughout the volume of samples, which is manifested in a gradual and significant increase in the damage coefficient. After 40 cycles, the damage coefficient increases fourfold. Local freezing forms an uneven pattern of destruction: the zone that was directly exposed to cold is damaged faster, while the opposite part retains higher integrity indicators.

Analysis of changes in water absorption, ultrasound velocity and strength characteristics confirmed the differences between freezing modes. With volumetric exposure, the indicators decrease more intensively, which indicates a deeper destruction of the structure. Local exposure causes asymmetric changes: one part of the sample demonstrates a significant deterioration in properties, while the other loses strength more slowly.

The conducted studies have shown that the frost resistance of cement stone, mortars and concretes significantly depends on the type of freezing and the nature of the thermal and moisture effects. It was established that the first five cycles are the most critical for the formation of microcracks, while after the twentieth cycle, destruction accelerates sharply.

The obtained data show that the vulnerable period for cement-containing materials is precisely the first 5 cycles of freezing and thawing. During the first 5 cycles, new formations (cracks, internal surfaces of the interface) appear and develop in the material, which determine the nature of further changes (Fig. 2).

The conducted studies have shown a significant influence of freezing conditions on the change in the physical and mechanical properties of CMD. It can be assumed that during one-sided freezing, more favorable situations are created in the samples, capable of relaxing part of the dangerous deformations that arise when water freezes in the pore volume of the material.

The proposed approach makes it possible to assess the development of damage in dynamics, and not only by final indicators, as provided for by the current regulatory methods (DSTU). The results of one-sided freezing are nonlinear in nature, which is much closer to the behavior of the material in real structures, where temperature and humidity effects are local and uneven in nature.

Analysis of stability under different types of freezing and thawing effects made it possible to identify the criticality of the first five and twentieth freeze-thaw cycles. The study can also be used in the development of new regulatory approaches to testing the frost resistance of building materials, in particular in regions with unstable temperature and humidity regimes, such as the south of Ukraine.

Thus, the results of the study not only confirmed the known mechanisms of frost damage to concrete, but also expanded the understanding of the role of local and volumetric freezing in the formation of material damage.

The practical value of the work lies in the possibility of using the results obtained to assess the frost resistance of concrete and mortars operated under local or volumetric temperature exposure. The results can be used in analyzing the condition of structures which elements are subjected to uneven freezing.

The presented patterns allow to clarify the approaches to choosing the composition of concrete mixtures and predicting their durability taking into account real operating conditions. The obtained data can be used as a scientific justification for further improvement of the frost resistance testing methodology of building materials, especially for regions with unstable temperature and humidity conditions

The limitations of the study are that the tests were performed under stable temperature and humidity conditions, while in real operating conditions these parameters change cyclically and unevenly. In addition, the study was conducted on materials of a specific composition, so the obtained patterns may change for cement-containing systems with other types of binder or additives. The assessment of structural changes was carried out mainly by integral and indirect indicators, which does not allow to fully characterize the internal microdamage of the material.

The disadvantages of the study include a limited number of methods for analyzing the internal structure and the lack of consideration of variable climatic factors characteristic of natural operating conditions. This limits the possibility of directly transferring the obtained results to all types of structures without additional verification.

Further development of research should be directed towards studying the influence of variable temperature and humidity regimes, the use of additional methods for controlling internal damage, and the expansion of the range of studied material compositions.

7. Conclusions

1. It was found that the freezing method significantly affects the rate of accumulation of discontinuities. After 20 cycles, the damage coefficient of cement stone increased by 2.5 times with full-sided freezing, while with one-sided freezing - by 1.6 times. This difference is explained by the different depth of penetration of the freezing front and the uneven redistribution of stresses in the material.

2. The water absorption of cement material samples increased by 24% with full-sided freezing and by 21.2% with one-sided freezing after 20 cycles of freezing and thawing. The speed of ultrasonic wave velocity transmission in cement stone samples decreased by an average of 40.5%. This indicates the development of microcracks and discontinuities. Such changes are due to an increase in the volume of water during freezing, which causes a local change in the pore space.

3. Different types of freezing lead to a significant decrease in strength. After 20 cycles, the strength of cement stone during full-sided freezing decreased by 54% (bending) and 43% (compression), while during one-sided freezing – by 44% and 27%, respectively. The decrease in strength is associated with the development of microcracks and discontinuities, loss of density and destruction of structural bonds.

Conflict of interest

The authors declare that they have no conflict of interest regarding this study, including financial, personal, authorship or other, which could affect the study and its results presented in this article.

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Data availability

Data will be provided upon reasonable request.

Use of artificial intelligence

The working group declares the use of generative AI in the process of research and preparation of the manuscript. Tasks delegated to generative AI tools under full human supervision: grammar editing.

Generative AI tool used: ChatGPT – GPT-5.1.

The working group bears full responsibility for the final manuscript.

The generative AI tool is not credited as an author and is not responsible for the final results.

Authors' contributions

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