Research Article

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Study of changes in concrete durability during the operation of buildings

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Abstract: The purpose of this study is to select the best methodologies for determining the condition of concrete structures. Semi-destructive concrete exposure methods were used to determine resistance parameters: the impact echo test to determine internal structure, the Figg test for air permeability, the initial surface adsorption test for water adsorption, titrimetric for chloride amounts, and a chemical and physical method to determine carbonation levels. In addition, two situations were simulated: a fire and a pipe burst and their impact on the condition of reinforced concrete structures. It was shown that the exposure to temperatures decreases the level of acidity, resulting in increased corrosion of steel. During a pipe burst, the amount of chlorides increases, which affects the reinforcement, oxidizing it. A search for possible correlation between concrete structure and carbonation, air permeability and water adsorption was also carried out. It was found that there is an almost linear dependence of these parameters on the presence of cracks, the deterioration of the structure leads to an increase in the transport properties of concrete, which becomes a danger to steel.

Keywords: air permeability, carbonation, chlorides, reinforced concrete structure, resistance, simulation, water adsorption

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1 Introduction

Concrete structures are among the most used building materials and are characterized by reliability, affordability, fire resistance and processability. In this regard, a huge number of new variations of these structures are being developed, and there is a need to find suitable methods of testing their durability [1–3]. The term “durability” refers to the ability to resist the effects of physical, chemical, mechanical, biological and other factors in the period between the commissioning of a building and the time when it ceases to function [4, 5].

Concrete itself is tensile and resists compression. The most widespread in practice are reinforced concrete structures (RCS), which are even more durable and strong. Sometimes in order to save money, the wrong ratio of materials in the preparation of concrete or low-quality cement grades are used, which affects the performance characteristics and leads to the destruction of buildings [6, 7]. In addition, the concrete structure deteriorates during the action of natural and other human-made factors: temperature fluctuations, high humidity, excessive loads, products of microorganisms, transport of charged particles, seismic action, etc. To analyze the structure, the formation of microcracks is studied, as they indicate the beginning of concrete deterioration, and disrupt even the reinforcement structure [1, 8–10].

Considering the environmental situation, bamboo reinforced concrete panels are created, which are characterized by relative durability [11]. Layered structures with added fiberglass can also be used to achieve this goal [12]. Buildings based on wood and concrete composite boards are also being created. It is indicated that they are significantly exposed to moisture [13].

Most often there is a combined effect of media on concrete, which penetrate into the interior of structures by means of transport mechanisms characteristic of concrete: adsorption, absorption, diffusion, capillary suction forces, filtration. The transport of cations and anions in the concrete structure directly depends on its electrical resistivity. The main role in the process of concrete destruction is played by the transport of chlorides and carbon dioxide molecules [4].

One of the most serious problems that significantly reduce RCS service life is carbonation – the interaction of carbon dioxide from the atmosphere with calcium hydroxide, during which calcium carbonate and water are formed [14]. This increases concrete acidity level. When the pH changes to the acidic side, metal corrosion and a decrease in structure durability occur [15].

There is a high rate of use of concrete as a material for construction of buildings all over the world. Thus, for residential buildings it is 43%, for commercial buildings – 72% [16]. The minimum service life of buildings based on concrete load-bearing walls is about 50 years, but there is still a need to periodically check RCS durability, especially older buildings, because they are more exposed to self-destruction [5]. An example is one recent disaster: the collapse of the 40-year-old Surfside Condo Tower (Miami, USA) in early 2021. Reports say that 27 people died in the collapse, and more than 100 were reported missing [17].

This paper considers the use of non-destructive techniques in situ to assess the strength of concrete walls in multi-store panel houses in Kaliningrad. Topicality of the work is stipulated by a considerable quantity of this type of constructions in Russia (about 50%, where almost 40% of the population of the country live since 70th of the last century) [18].

In the 2nd section of the article, the parameters, which can form the basis of forecasting RCS life span, as well as the methodology for their analysis, are considered. Section 3 defines the tasks and objectives of the work. In the 4th section, the characteristic of the methods used in the course of the experiments is given. Section 5 presents the results of this study. The following section presents a comparison of the results obtained with similar ones from other works. This work may be interesting and useful for those working in the field of strength assessment of concrete structures, builders and architects.

2 Literature review

There are a number of methods for testing concrete structures: destructive, semi-destructive, and non-destructive. In addition, analysis can take place on site (in situ methodology) or in the laboratory (ex situ methodology) [10, 19, 20].

The easiest way to check RCS integrity is visual inspection. In this case, the external structure is clearly visible, and in some cases even the internal structure. To improve the quality of the analysis, special equipment (microscopes, video defectoscopes, etc.) or the creation of 3D models can be used to study the roughness. Visual methods are best for the initial inspection and can only provide a rough indication of problems [10, 21].

The concrete compression test is the fastest method. It is an indirect test due to correlations between relative strength and other parameters. It is mainly used to compare the strength of a structure at different points. It is not used to give accurate readings, as erroneous conclusions can be drawn [19, 21].

Another relatively quick method is the determination of electrical resistivity. In this case, the changes in hydration, transport of ions and substances, which affect the electrical properties, are observed [22]. These transformations are caused by the aging of reinforced concrete due to the effects of atmospheric moisture, temperature, steel quality, etc. [4].

Ultrasonic waves have also found application in concrete testing. It is based on determining wave velocity by measuring the travel time to a certain point and establishing the strength with a correlation curve [19, 21]. Wide use of the method is limited by 1) the need to build curves for each experiment, based on concrete composition; 2) the high level of error in the presence of steel rod [23].

The shock echo method involves a short-term impact (pulse) of a steel ball. The shock wave propagates along the structure, noticing small cracks, delaminations or voids, bounces off the opposite wall and transmits the signal to the transducer [21, 24]. The method can be used to check concrete strength after fire or other damage. The presence of reinforcement does not affect the readings [24].

The probe penetration test measures compressibility at a specific point where a hardened steel rod is driven in. After the probe is inserted with high initial kinetic energy, the concrete is crushed along the way and the structure breaks down at the end. The depth of penetration is directly proportional to the strength [21, 23].

The LOK test begins while the concrete is still being poured: a steel rod is inserted into new, non-solidified mixture. After curing, it is removed, which leads to the removal of the conical part [23]. To a large extent, the diameter and depth of the tear-off depend on the density and fraction of the aggregate [21]. Since the use of this model must be planned in advance, it cannot be applied to existing structures. To remedy the situation, a variation of the method was developed. A ring is inserted into the drilled hole and expanded. The essence of this test is to remove the plug and determine the force required to pull it out. This is a reliable approach to measuring force in cases of unknown concrete composition but is limited in its use in the presence of reinforcement in the vicinity of the surface [19].

It is important to determine the rate and amount of penetration of gases, water, chlorides and sulfates, because they are factors that accelerate reinforcement corrosion [25].

To measure the diffusion activity of gaseous substances, the most commonly used method is Figg method, which consists in drilling a small hole and pumping out air from there with a vacuum pump to form a pressure of –0.055 MPa. The time is recorded during which the pressure rises to –0.05 MPa by air penetration through the concrete [19, 22, 25]. In method configuration, they calculate the rate of pressure increase, when changing from 0.0213 to 0.004 MPa [25].

The oxygen permeability index test was developed to study oxygen penetration. This method involves extracting a portion of the concrete, drying it out and analyzing it. It is most often used to check for cracks, voids, compaction condition, etc. [26].

In the initial surface adsorption test (ISAT), they use a container of water and connect it with a tube to a sample of concrete. The water level is monitored using a glass capillary and a scale [25, 27]. The Autoclam sorption capacity index involves plotting the water inflow through concrete (at a pressure of 0.002 MPa) as a function of time [25]. The Figg test is also used to measure the water permeability of concrete with a similar technique. A method based on the Figg method and ISAT has been developed using dried concrete samples, followed by drilling a hole and acting according to ISAT [19].

Some semi-destructive models for assessing concrete durability are based on calculating diffusion processes - that is, the solution of Fick's 2nd law [5]. The penetration of chlorides and sulfates is determined this way. It is important to determine the depth of penetration in RCS because they cause reinforcement corrosion [26]. To determine chloride ions' amount and distribution, potentiometric or titrimetric method is used [10]. It is also possible to use X-ray fluorescence, namely to compare the wavelength with standard samples. The method requires sophisticated equipment [19]. They determine the diffusion coefficient by dipping the samples in a salt solution and measure the amount of ions penetrated, comparing it with the external concentration. The unsteady state chloride migration coefficient is used to study the resistance to chloride penetration from a solution in an artificial electric field. Correction factors are used to compare the two methods [25]. The modification – the rapid chloride permeability test – is most often used. It measures the charge that passes through the concrete sample and establishes the ability to resist chloride penetration [27].

The depth and rate of carbonation are determined chemically using a phenolphthalein indicator on a cylindrical sample cut lengthwise. The penetration depth is determined by a qualitative reaction [21]. To determine the degree of carbonation in situ, pH meters can be used [10].

It follows that the analysis of the presence of cracks and the beginning of oxidation of steel can be used to check the durability of concrete structures.

3 Problem statement

Destruction of buildings based on RCS in the course of aging or the action of various factors of natural origin or subjective is a fairly common phenomenon, which carries not only significant economic losses, but also, in the worst cases, human losses. To prevent this, the durability of structures can be evaluated using non-destructive or semi-destructive methodologies.

The purpose of this study is to determine the durability of residential high-rise buildings using the techniques of impact echo, Figg test, initial surface adsorption test, potentiometric quantification of chloride ions and chemical reactions to detect carbonation in simulating two situations: a fire and a pipe burst.

To achieve this goal, the following tasks should be solved:

1. establish characteristics confirming the reliability of methods for determining durability;
2. conduct a series of experiments and compare the data obtained for different methods;
3. compare the results with existing ones and draw conclusions.

4 Methods and materials

4.1 Impact echo method

The experiment was conducted according to the methods [28–30]. Concrete blocks 0.15 m × 0.15 m × 0.11 m were extracted from the walls. The VU-CON instrument consists of an impactor (8 mm hardened steel sphere), a receiver-converter, and an analyzer of the collected data. The impactor was placed at a distance of 5 cm from the concrete, the receiver was located near the impactor. The impact contact time was at least 650 ms. To obtain the resonant frequency f, the fast Fourier transform was used, and then wave propagation velocity was calculated:

$$V_p = \frac{2Tf}{\beta} \tag{1}$$

where T – item thickness; f – resonant frequency; β – shape factor ($\beta = \frac{T}{W}$; T – thickness, W – width; $\beta = 1$). Thus, the velocity is:

$$V_p = 2Tf \tag{2}$$

To calculate the elasticity modulus E, the following relationship was used:

$$V_p = \sqrt{\frac{E(1-\upsilon)}{\rho(1+\upsilon)(1-2\upsilon)}} \tag{3}$$

where υ – Poisson's ratio, which is 0-0.2 (depending on temperature); ρ – concrete density [31].

4.2 Figg method for determining air permeability

As follows from [19, 32], for this experiment, it is necessary to drill a hole perpendicular to the wall with a depth of 4 cm and a diameter of 1 cm, then clean and insert a 0.3 cm thick polyester disk inside to a depth of 2 cm and fill with silicone rubber to provide greater elasticity. Porosiscope Plus^{TM} consists of a manual vacuum pump, timer, pressure gauge, plugs, tube. A medical syringe pumps the pressure down to -0.055 MPa, and then automatically displays the time for which the pressure increases by 0.005 MPa.

4.3 ISAT method for determining water permeability

In this case, a tank of water connected by a tube to the concrete through a plug with a known contact area was used. The tank was placed in such a way that the water level exceeded the contact point by 200 mm. The outflow of water is controlled by a scale. The value of surface absorption is calculated by the following formula:

$$G = \frac{V}{S \cdot t} \tag{4}$$

where V – volume of water absorbed; S – the contact area of the plug with the concrete; t – experiment duration [19].

4.4 Method for determining the concentration of chloride ions

In the case of potentiometric titration, chloride-selective electrodes and a hydrogen reference electrode are used. To determine the number of ions, the following formula is used:

$$E_{\frac{Ag}{AgCl}} = E^0_{\frac{Ag}{AgCl}} - 2.303\frac{RT}{nF} lg\left[a_{Cl^-}\right] \tag{5}$$

where $E_{\frac{Ag}{AgCl}}$ – potential of the selective electrode under these conditions; $E^0_{\frac{Ag}{AgCl}}$ – standard potential of the selective electrode; R – gas constant, which is 8.314 J/Mol*K; T – absolute temperature; n – the number of electrons involved in the reaction; F – Faraday's constant, which is 96485.3415 C/Mol; a_{Cl^-} – activity of chloride ions near the electrode [33].

For the analysis, concrete dust after drilling with a perforator was used. Thus, 7 samples were collected, with a distance of 1 cm from 9 different points, the distance between them was 10 cm. 5 g of dust were dissolved in 50 ml of distilled water, after 10 minutes of continuous stirring, 5 ml of the solution was filtered into a 25 ml conical flask and titrated with 0.009 n silver nitrate solution, using a 25 ml glass burette. A series of 3 experiments to improve the accuracy of the results was performed. The temperature of the solutions was 25°C [19, 34]. The concentration of chloride ions in the solution is calculated by the formula:

$$C_{Cl^-} = \frac{C_{Ag^+} \cdot V_{Ag^+}}{V_{Cl^-}} \tag{6}$$

where C_{Ag^+} – silver nitrate solution concentration; V_{Ag^+} – volume of silver nitrate solution used for titration; V_{Cl^-} – sample volume of chloride solution [34].

4.5 Method for determining carbonation degree

Concrete cylinders with a diameter of 10 cm, length 7 cm, external surface temperature – 27±3°C were used for the analysis. Cylinders were cleaned of dust, soaked with a standard solution of phenolphthalein, and carbonation depth was measured by the qualitative sign with a ruler [10, 35].

Simulation of operating conditions

4.6 Fire simulation

The approximate temperature of the fire is 800-900°C. Thus, it is assumed to act on the concrete wall with an XM42 flamethrower for 4 hours. Besides, strength measurements during heating were made using the impact echo method while heating the concrete at 100-degree intervals. Temperature measurements were made with a TM-902C digital thermometer.

4.7 Simulating a pipe burst

For this purpose, the action of water at a temperature of 20°C at a pressure of 0.3 MPa for 1 hour with a wetting area of 1 m^2 was used.

5 Results

The data obtained from the experiments are shown in Figure 1.

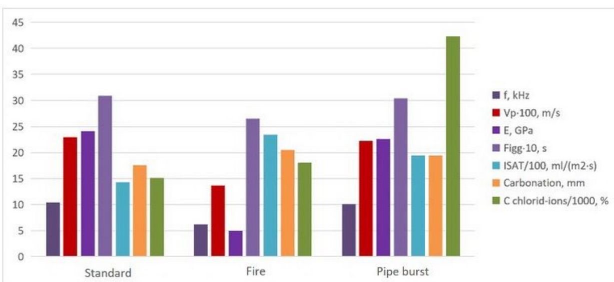

Figure 1: Summary histogram of the results of five experiments. (*Source: authors' elaboration*)

From Figure 1 one can see that the average frequency of oscillation waves and the speed of their propagation after the fire are 40% less than for the standard, and elasticity modulus differs almost 5 times. The rate of air penetration has not decreased significantly. As for water, it penetrates almost twice as fast after the fire than before it. The carbonation depth was increased by 3 mm. The level of chloride ions also increased by 0.03%. In the case of a pipe burst, there is a slight decrease in the impact echo method: more than 3% for f and V_p, almost 6.5% for E. The Figg values for air were almost unchanged, while the water permeability increased significantly. The carbonation level increased by about 1 mm. The concentration of chloride ions increased almost threefold.

It follows that concrete structure deteriorates significantly under the influence of high temperatures and slightly as a result of exposure to water. After a fire, the number of internal micro- and macro-cracks increases, resulting in a drop in the air and water tightness of the concrete, which increases carbonation and slightly increases chloride diffusion. During water action, crack formation is most likely due to leaching of components. As a result, the rate of air penetration is almost unchanged, and the water permeability increases by 15%. The carbonation level increases by 1 mm, which is due to the large amount of moisture for the reaction to take place. The high level of chlorides is due to their presence in the water and increased diffusion during high humidity.

Thus, the pH level in the concrete decreases after a fire, which negatively affects reinforcement resistance and leads to its acid corrosion. Similarly, in the case of a pipe burst, chloride-induced corrosion is observed.

Since water permeability, air permeability, and carbonation depth directly depend on the concrete structure, it was decided to build corresponding graphs to establish the level of dependence of these indicators on the damage of concrete.

As can be seen from Figure 2, there is a slight linear correlation for air permeability, and slightly less for carbonation, in the case of water adsorption – almost none.

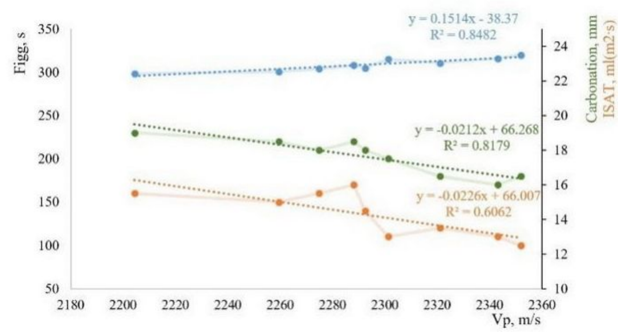

Figure 2: Plots of the dependence of the Figg index and carbonation degree on wave propagation velocity for concrete in the normal state. (*Source: authors' elaboration*)

Figure 3 shows that there is a stronger linear dependence for air permeability and adsorption than for the previous case and much less for carbonation.

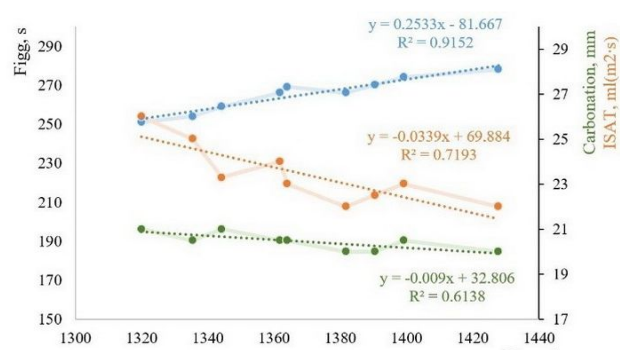

Figure 3: Plots of the dependence of the Figg index and carbonation degree on wave propagation velocity for concrete after fire simulation. (*Source: authors' elaboration*)

Figure 4 shows that there is a reduced dependence for air permeability, while the dependence for water adsorption is higher, compared to standard and fire simulation. The dependence of carbonation on concrete structure is insignificant and is between normal concrete and after fire.

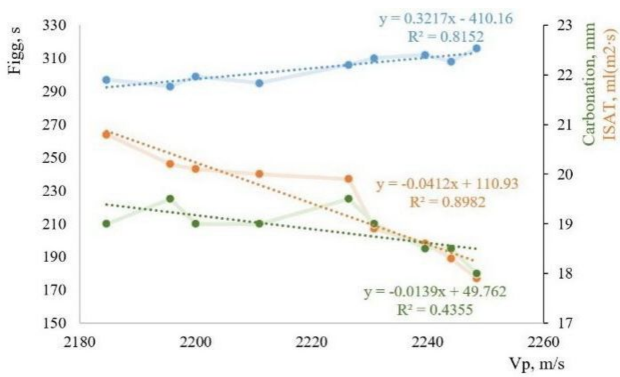

Figure 4: Plots of the dependence of the Figg index and carbonation degree on wave propagation velocity for concrete after pipe burst simulation. (*Source: authors' elaboration*)

Figure 5 shows that when heated, there is a rapid deterioration of concrete microstructure. There is a strict linear dependence (almost 99%) of wave frequency and propagation velocity on temperature. In the case of elasticity modulus, there is an almost 100% degree correlation with the current temperature.

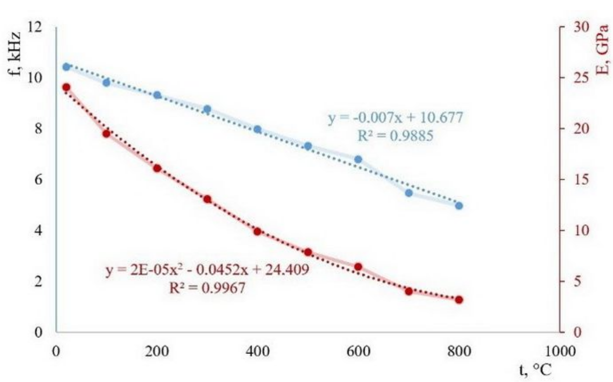

Figure 5: Plots of the dependence of the shock echo method resonant wave frequency and concrete elasticity index on the temperature in fire simulation. (*Source: authors' elaboration*)

6 Discussion

Concrete structure deterioration under the influence of high temperatures is reported by Krzemien K. and Hager I. The resonance frequency of the shock echo method is on average 16% higher than in the present study. This confirms that self-destruction of concrete structures occurs over time. The linear dependence of frequency on temperature obtained in the present study is higher. In addition, the present study showed a quadratic dependence of elasticity modulus on concrete temperature with the coefficient R^2 99.67%, while K. Krzemien and I. Hager indicate a linear dependence (96.59%). The obtained discrepancies can be caused by differences in concrete composition and age [29]. Wróblewska and Kowalski [24] also studied the problem. They found that at 600–700°C, concrete destruction is almost 60%, and at 800°C, it is more than 80%. In the case of the present experiment, the data are significantly different: at 600°C, there is preservation of 65% of the initial strength, at 700°C – 52%, and at 800°C – 47.5%. More rapid deterioration of strength properties can be explained by the higher heating rate in the Polish scientists (300 deg/h), while the present study authors heated the concrete at 200 deg/h. They used a slightly different approach: studying resistance by measuring the compressive strength. The disadvantage of using the present study's method is only establishing the internal concrete structure, but, at the same time, it is the main indicator of corrosive substances' migration [24]. Alwash [28] consider the dependence of resonant frequencies on the level of reinforcement and concrete structure corrosion. Similar to the present study results, they obtained a decrease in wave frequency depending on the level of corrosion. The decrease in resonance frequency is also associated with the formation of voids and cracks around the steel rod and rust accumulation in these places.

Frenzer *et al.* [36] showed little dependence of air permeability on strength characteristics for new concrete structures, and no dependence at all for old structures, while the present study found a small linear relationship between these parameters for the three conditions. Besides, similar data were obtained in this work that as concrete structure deteriorates, its permeability to other substances increases. In addition, they indicate that the increase in adsorption and air passage may be due to an increase in free internal space due to voids formation [36].

According to the literature, for good quality concrete, the ISAT (in ml/(m^2·s)) is less than 0.1, and for poor quality concrete it is greater than 0.2. Folagbade [37] showed that for most samples, the adsorption coefficient is between 0.15–0.20 ml/(m^2·s), which he attributes to the leaching of fly ash. In addition, he points out that for more durable concrete, the ISAT value is significantly lower than for less resistant concrete. This is consistent with the results obtained in the current study [37]. In [36] it is also stated that an increase in air permeability also indicates an increase in water adsorption. Similar data were obtained in the present study: the ISAT value decreases with the growth of the Figg test time.

Palacios-Munoz *et al.* [20] studied the accumulation of carbon dioxide in concrete. It was shown that with the age of the building, the CO_2 mass gain decreases, which can be explained by a decrease in the gas concentration difference in the air and the bordering concrete. At the same time, the total amount of carbonized compounds increases as CO_2 diffuses into the inner layers, resulting in structure life reduction. In the present study, the obtained results may indicate that during a fire, the amount of absorbed CO_2 increases significantly, as evidenced by the increase in the carbonized layer, compared with the norm [20]. In [6], the dependence of the carbonation depth on the oxygen permeability index (OPI) and structure age was studied. It was reported that carbonation level depends on the OPI value: the higher the OPI, the lower CO_2 penetration. It was also found that, under normal conditions, carbonation depth is in a logarithmic relationship with concrete age. The maximum observed depth is 45 mm for low OPI and almost 20 mm for high OPI. Thus, one can speak of a high OPI value for the concrete considered in the present study. These results are also confirmed in [26]. Since the diffusion rate of CO_2 in water is much lower than in air, there is a difference in carbonation depth in the simulation of fire and burst pipe, which corresponds to the values obtained by Tongaria *et al.* [35]. Carbonation is considered one of the main causes of reinforcement corrosion and RCS destruction [38].

The decrease in OPI is directly proportional to the increase in the chloride diffusion coefficient [6, 26]. As mentioned earlier, OPI is related to carbon dioxide diffusion by the same principle. It follows that the growth of carbonate concentration can be combined with the growth of chloride ions. However, in the case of the present study experiments, this dependence was not observed. Significant presence of chlorides relative to carbonation level during pipe burst simulation may be related to the presence of Cl^- in the water. Silvestro *et al.* [5] compared the dependence of chloride concentration on its penetration depth for experimental samples and the mathematical model according to Fick's second law. It has been shown that with increasing distance from the surface, there is a decrease in chlorides percentage for both cases [5]. In the present study, this dependence was not investigated, which may have influenced the final result in some way.

7 Conclusions

To assess building durability, the authors chose to check the condition of the reinforcing bar and concrete. This was done by checking the change in the internal concrete structure, the air permeability time, and the adsorption coefficient. Tests were conducted to determine carbonation level and the concentration of chloride ions as the main substances that interact with iron. There was a significant increase in corrosion parameters in simulated situations compared to the standard (%): 40.3, 79.34, 14.09, 64, 16.07, 19.87 (for fire) and 3.18, 6.26, 1.52, 35.92, 10.22, 180.13 (for pipe burst) of the resonance frequency and wave propagation rate, elastic modulus, Figg test time, adsorption factor, carbonation depth, and chloride amount, respectively. It was shown that as the resistance of concrete deteriorated, there was a decrease in the time of air permeability, an increase in the depth of carbon dioxide penetration, and an increase in the adsorption capacity.

In addition, an experiment was conducted to study the dependence of the impact echo test values on concrete temperature. It is shown that the change in waves' resonant frequency is linear with a correlation of 98.85%, and elasticity modulus – quadratic (R^2 = 99.67%).

Thus, the survey data can be used to determine the approximate level of reinforcement corrosion or to predict the appearance of possible rust. The results obtained can be used to check the condition of reinforced concrete structures of panel houses or other buildings.

This work can be improved by using other methods of determining concrete resistance and determining the presence of corrosion parameter dependence. The proposed methodology can be used to test the durability of layered concrete structures with different insert.

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Conflict of Interest: Authors declare that they have no conflict of interests.

Data Availability Statement: Data will be available on request.

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