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INFLUENCE OF ENVIRONMENTAL PARAMETERS ON THE PROCESSES OF OCCURRENCE AND DEVELOPMENT OF DEFECTS IN BRIDGE STRUCTURES

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Abstract

Environment influence in the form of precipitation, temperature variations, seasonal freeze-thaw cycles and human activity lead to the appearance of damages (defects) on the surface of reinforced concrete structures of buildings. As studies show, untimely performance of works on maintenance of objects and subsequent elimination of defects during operation increases the probability of premature destruction of the structure many times.

The article analyzes and classifies the main defects and damages of elements and structures of transport infrastructure structures depending on the place of formation on the structures, the nature of distribution, the impact on the main technical and economic indicators and parameters. The reasons of their appearance and subsequent influence on durability, traffic safety and load-carrying capacity of the structure are revealed. Based on the results of the inspection of the technical condition of the building structures of individual bridge structures, laboratory tests were performed to determine the physical condition of concrete by taking samples from the elements at the locations of identified damages and defects. The content of calcium ions, chlorides, pH, as well as the degree of carbonization were determined in the concrete samples under investigation, and the results were compared within the bridge structures under consideration and with the data of normative and technical literature. To obtain an objective picture, laboratory tests of water samples from the bridges crossing obstacles (rivers) were carried out. The influence of the geographical location of the structures on the condition of materials of building structures, the degree of their damage and operating conditions was assessed. The existing approaches to predicting the durability of transport infrastructure structures were analyzed separately – the reliability of the results obtained taking into account the technical condition of structures (damage and defects of materials), the quality of work performed during the construction of the structure and others.

Keywords: structural damage and defects, bridge structures, chloride content, calcium ions, water extracts, durability prediction.

ВЛИЯНИЕ ПАРАМЕТРОВ ОКРУЖАЮЩЕЙ СРЕДЫ НА ПРОЦЕССЫ ВОЗНИКНОВЕНИЯ И РАЗВИТИЯ ДЕФЕКТОВ МОСТОВЫХ СООРУЖЕНИЙ

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Реферат

Влияние окружающей среды в виде атмосферных осадков, перепадов температуры, сезонных циклов замораживания-оттаивания и деятельности человека приводят к появлению повреждений (дефектов) на поверхности железобетонных конструкций сооружений. Как показывают исследования, несвоевременное выполнение работ по содержанию объектов и последующее устранение дефектов при эксплуатации в разы увеличивает вероятность преждевременного разрушения сооружения.

В статье выполнен анализ и классификация основных дефектов и повреждений элементов и конструкций сооружений транспортной инфраструктуры в зависимости от места образования на конструкциях, характера распространения, влияния на основные технико-экономические показатели и параметры. Выявлены причины их появления и последующее влияние на долговечность, безопасность движения и грузоподъёмность сооружения. По результатам обследования технического состояния строительных конструкций отдельных мостовых сооружений выполнялись лабораторные исследования по определению физического состояния бетона путем отбора проб образцов из элементов в местах выявленных повреждений и дефектов. В пробах исследуемых образцов бетона определялось содержание ионов кальция, хлоридов, pH, а также выборочно оценивалась степень карбонизации и выполнялся сопоставительный анализ результатов в пределах рассматриваемых мостовых сооружениях и с данными нормативно-технической литературы. Для получения объективной картины осуществлялись лабораторные исследования проб воды пересекаемых препятствий (рек) мостами. Оценивалось влияние географического расположения сооружений на состояние материалов строительных конструкций, степень их повреждений и условия эксплуатации. Отдельно проанализированы существующие подходы прогнозирования долговечности сооружений транспортной инфраструктуры – достоверность получаемых результатов с учетом технического состояния конструкций (повреждений и дефектов материалов), качество выполняемых работ при возведении сооружения и другие.

Ключевые слова: повреждения и дефекты конструкций, мостовые сооружения, содержание хлоридов, ионы кальция, водные вытяжки, прогнозирование долговечности.

Introduction

External effects associated with temperature fluctuations with simultaneous frequent precipitation contribute to the acceleration of corrosion processes of building materials of engineering structures, formation of defects and damages in the concrete of structures. At the same time, the increase of carbon dioxide content in humid air leads to the acceleration of carbonization processes in the pore space of concrete of bridge and hydraulic structures, overpasses [1].

Influence of environmental parameters on the processes of occurrence and development of defects in bridge structures

According to [2], depending on the degree of influence, defects are divided into maintenance defects, which are the result of violation of the terms of routine maintenance of the structure; safety defects, which prevent the free and safe movement of vehicles and pedestrians on the structure and under it (if necessary) and load capacity defects, leading to a decrease in the load-carrying capacity of spans and supports.

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Durability defects [3, 4], which do not directly affect the operational performance of the structure, but if not eliminated in time, may lead to a decrease in load capacity and deterioration of safety performance in the future, can also be singled out as a separate category. The most common defects identified by the results of bridge structures inspection for each category are shown in Table 1 and Figure 1.

Table 1 – Defects of bridge structures

Defects of bridge structures		
influencing the durability of the structure	influencing traffic safety	influencing the load capacity of the structure
– destruction of the bridge deck waterproofing structure; – soaking, caking, efflorescence on concrete; – thawing (frost degradation) of concrete, including bare reinforcement (Figure 1a); – insufficient protective layer of concrete, corrosion of structural reinforcement; – corrosion cracks (corrosion of working reinforcement) (Figure 1b); – water filtration along the joint, leaching, suede, efflorescence, stalactites; – failure of concrete of span girder joints; – spalling of concrete without bareness with bareness of reinforcement; – destruction of expansion joints, their unsealing; – defrosting of beam ends, corrosion of anchor washers; – corrosion and destruction of support parts; – destruction of drainage pipes, their insufficient length; – cone subsidence under the nozzles of the end supports and transition plates (Figure 1d); – erosion of cones and embankment slopes	– cracks in the pavement of the bridge deck and approaches; – patching of the pavement and approaches (Figure 1c); – contamination of the bridge deck and sidewalks; – elements of barrier fencing or their fastening on the bridge and approaches do not meet regulatory requirements (no reflective inserts, corrosion of metal elements); – railings are wobbly; – cone subsidence under the end piers and transition plates; – erosion of cones and embankment slopes; – organized conjugation of sidewalks with approaches is destroyed; – through destruction of sidewalks; – sidewalks are not covered; – drainage pipes have no grids; – stairs on the approaches are destroyed or missing	– corrosion of working reinforcement; – thawing (frost degradation) of concrete, including bare reinforcement; – increased thickness of the roadbed; – corrosion of anchor washers; – destruction of supporting parts

a)

a) thawing (frost destruction) of concrete with bare and corroded reinforcement; b) corrosion cracks (corrosion of principal reinforcement); c) patching in the bridge deck covering; d) cone subsidence under the end piers nozzles
Figure 1 – Defects of bridge structures

When diagnosing and inspecting the technical condition of bridge structures, defects are identified on the basis of visual inspection, and its assignment to one or another category largely depends on the qualifications, experience and subjective opinion of the specialist conducting the inspection. At the same time, a number of defects and damages can be established visually – the presence of corrosion or force cracks, concrete thawing, non-compliance of some structural elements with the normative requirements [5]. Other defects cannot be detected without the use of modern highly specialized devices or laboratory tests, such as hidden corrosion of reinforcement, carbonization and chloride saturation of concrete, but can lead to rapid deterioration of the technical condition of structures [6, 7].

In the process of long-term operation of bridge structures their elements are exposed to the action of water ions chemically active in relation to cement stone, such as chlorides, nitrates, sulfates, which contribute to the destruction of concrete and reinforcement. One of the main factors determining the deterioration of technical building structures is the rate of diffusion and the rate of chemical reactions with hydration products of cement minerals.

The quality of natural water in water bodies where engineering structures are operated depends largely on the content of dissolved salts of mineral origin. The main salt content is due to calcium and magnesium compounds, which characterize water hardness. The content of chlorine anions, sulfate anions, carbonates and hydrocarbonates, iron cations and other ions determine the mineralization of natural water bodies. For each of the salt ions the normative value of MPC is established (Table 2).

Table 2 – Main indicators of maximum permissible concentrations of components that create water mineralization

Cations and anions of salts	MPC (maximum permissible concentration)
Calcium Ca^{2+}	200 mg/l
Magnesium Mg^{2+}	100 mg/l
Sulfate SO^{2-}	500 mg/l
Chloride Cl^{-}	350 mg/l
Total iron Fe^{2+}, Fe^{3+}	0,3 mg/l

The main indicator of water quality of a natural water body includes the hydrogen indicator – pH. The normative pH value for water bodies ranges from 6.5 to 8.5. Deviation of pH value in natural water from the established norm causes air pollution by acidic impurities, which fall into the water body with atmospheric precipitation. Change of pH can cause insufficiently treated and untreated wastewater from industrial enterprises, creating an aggressive environment in relation to hydraulic and bridge structures.

For this purpose, the study determined some water quality indicators in samples from water bodies.

To assess the impact of water bodies on bridge structures in the places of their operation, samples were taken from the Usa, Karpilovka and Poplavka rivers [8]. Water hardness, chloride content, and hydrogen index were determined in the samples. The results of the studies are summarized in Table 3.

Table 3 – Water quality indicators in samples of natural water bodies

Name of the river	pH	Hardness mgeq/l Ca^{2+}/ Mg^{2+}	Chlorides mg/l	Sulfates mg/l
Usa	8,06	5,5	45,67	57,2
Karpilovka	7,42	4,4	101, 18	48,8
Poplavka	7,86	4,3	49,70	58,7

It is known that when water hardness decreases, i. e. the content of ions Ca^{2+}, Mg^{2+} and the value of hydrogen index pH increases, the probability of free CO_2 in water increases, which accelerates the processes of corrosion of reinforcement and carbonization of concrete of bridge and hydraulic structures.

Analyzing the results of water samples in the rivers, it can be concluded that the studied indicators do not exceed the established standards of water quality in natural water bodies. It has been established that the natural content of sulfates in surface and ground waters is caused by weathering of rocks and biochemical processes occurring in aquifers. The maximum content of sulfate ions in water from centralized water supply sources should not exceed 500 mg/l, but, as a rule, in river water the concentration of sulfates is 100–150 mg/l. Increased concentration of sulfates may indicate pollution of a water body by industrial wastewater.

Chlorides are a constituent of most natural waters. However, in river water the concentration of chlorides is low – usually it does not exceed 10–30 mg/l, so the increased amount of chloride ions (Table 3) indicates pollution of the water body by wastewater. According to water quality standards for natural water bodies, chloride concentration should not exceed 350 mg/l. At certain ratios of sulfate and chloride, water becomes aggressive towards different types of concrete [9].

The rate of penetration of active components into the depth of concrete depends on both the nature of the medium and the structure of concrete [10]. It is necessary to take into account the hygroscopic property of nitrate, sulfate and chloride salts, which attract water and moisture from the atmosphere, i. e. as the salt content in the material increases, the water content also increases.

The practice of operation of concrete and reinforced concrete structures shows that waters containing aggressive carbon dioxide in the amount of more than 300 mg/l are highly aggressive. The process of carbonization of building materials proceeds in several stages. The first stage is the penetration of carbon dioxide by diffusion into the surface capillaries of the building material. In this case, the formation of carbonic acid takes place inside the capillary system of the material. This is followed by a neutralization reaction of carbonic acid by the alkaline components of cement mortars, bricks, natural and artificial stone.

$$H_2O + CO_2 \rightarrow H_2CO_3 \qquad (1)$$

$$Ca(OH)_2+CO_2+H_2O \rightarrow CaCO_3+2H_2O \qquad (2)$$

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca(HCO_3)_2 \qquad (3)$$

Thus, the mechanism of carbon dioxide corrosion of concrete cement stone is determined by two interrelated processes: formation of calcium carbonate (2) and its dissolution by reaction (3):

Reaction (3) is reversible and depends on the humidity and temperature of the environment, the porosity of the material, and the concentration of carbon dioxide in the atmospheric air. The dissolution and recrystallization processes of calcium carbonate depend on the same factors, as an increase in temperature promotes crystallization and the presence of moisture leads to the migration of hydrocarbonate to other areas of the material.

Corrosion of cement stone, in an environment containing corrosive carbon dioxide, proceeds with the decomposition of all Portland cement clinker minerals and their hydrate compounds in concrete.

The reversible reaction must be distinguished from the carbon dioxide bound in $Ca(HCO3)_2$ hydrogen carbonate. The appearance of a "super-equilibrium" amount of carbonic acid in solution causes the dissolution of more and more portions of $CaCO_3$. This excess acid is called corrosive acid. Carbonic acid corrosion acts on concrete the weaker, the more in the aqueous solution of calcium and magnesium hydrocarbonates.

Thus, the process of carbonic acid corrosion of concrete can be investigated by the change in the concentration of Ca^{2+}, $CO3^{2-}$, $HCO3^{-}$, pH in aqueous extracts from different layers of concrete specimens.

Carbon dioxide can be present in solution as three forms [9, 11]:

1) free carbon dioxide, which is formed by the interaction of CO_2 and H_2O;

2) carbon dioxide in the form of $HCO3^{-}$;

3) carbon dioxide in the form of $CO3^{2-}$.

All three forms can change from one to another depending on the pH of the medium.

The content of calcium and magnesium ions in the samples (Table 3) showed that the water in the rivers belongs to the category of water of medium hardness.

Concrete samples are taken from the main load-bearing structures to predict changes in the condition of the bridge structure in operation. The content of chlorides, calcium ions and pH in bridge elements (Table 4) was assessed and the influence of river water quality on their value was analyzed.

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The chemical process of carbonization, as a result of calcium carbonate formation in the porous structure of concrete, leads to a decrease in the pH value and to an increase a chlorine ion content [12]. As a result of the decrease in protective properties, salts accumulate in the material, causing deterioration and the formation of cracks. This leads to further penetration of aggressive medium, moisture and gases into the concrete, which in turn causes corrosion of reinforcement and propagation of structural defects. Therefore, the study of the properties of the material from which bridge structures are made is an important task in the development of sectors of the national economy. The chemical process of carbonization, as a result of calcium carbonate formation in the porous structure of concrete, leads to a decrease in the pH value. As a result of the decrease in protective properties, salts accumulate in the material, causing deterioration and the formation of cracks. This leads to further penetration of aggressive medium, moisture and gases into the concrete, which in turn causes corrosion of reinforcement and propagation of structural defects. Therefore, the study of the properties of the material from which bridge structures are made is an important task in the development of sectors of the national economy.

Table 4 – Results of determination of chemical parameters in aqueous extracts of concrete samples

Elements of bridge structures	Chemical parameters			
	pH	content Ca^{2+}(mg/l)	content Cl^{-} mg eq / 100g	content Cl^{-} in %
Ptich River Bridge				
Support 5	9,08	55	2,14	0,075
Head beam 4	9,26	16	2,34	0,082
Beam B1	9,13	37	5,99	0,209
Beam B3	9,43	56	3,99	0,138
Usa River Bridge				
Support 2	10,54	32	1,54	0,054
Head beam 2	9,74	24	0,48	0,017
Beam B2	9,63	14	0,75	0,026
Karpilovka River Bridge				
Support 2	8,94	13	0,25	0,009
Plate 3	8,95	11	1,45	0,051
Poplavka River Bridge				
Head beam 3	10,56	30	1.16	0,02
Head beam 4	8,49	30	1,68	0,059
Head beam 5	9,11	40	1,68	0,059
Strut 3	9	34	1,67	0,059
Beam 1	9,79	26	0,76	0,03

The chemical process of carbonization, as a result of calcium carbonate formation in the porous structure of concrete, leads to a decrease in the pH value. As a result of the decrease in protective properties, salts accumulate in the material, causing deterioration and the formation of cracks. This leads to further penetration of aggressive medium, moisture and gases into the concrete, which in turn causes corrosion of reinforcement and propagation of structural defects. Therefore, the study of the properties of the material from which bridge structures are made is an important task in the development of sectors of the national economy.

As it is known, the moisture content of the building material always depends on the air humidity. Since calcium carbonate is a hygroscopic salt, its formation in the pores of the material increases the moisture level even at temperatures below the dew point. Moreover, the thinner the pores, the more intensive is condensation on the pore surface, disturbing the equilibrium humidity of the building material (2). The equilibrium shifts towards soluble calcium hydrocarbonate.

The soluble calcium salt is subsequently washed out of the material by groundwater, seepage or rainwater, or penetrates deep into the material. This causes damage to the structure of the material.

Samples of bridge elements located in the vertical plane, such as piers and supports, have a higher calcium ion content, which corresponds to a higher pH value.

At the same time, the content of chloride ions in extracts of these elements is predominantly lower than in samples of elements located in the horizontal plane, i. e. in slabs, superstructures and girders.

When analyzing the research results, it is necessary to take into account the service life of bridge structures**.** The bridge over the Ptich River has been in operation for more than 40 years. The higher content of calcium ions in the vertical structures of this bridge indicates the transition of calcium into soluble compounds, which are washed out of the concrete by seeping water or precipitation. The high chloride content in the extreme girder of the bridge (more than 0,2 %) may indicate the long-term use of salt during winter operation of the structure.

In this work, along with the study on chloride and calcium content, the degree of carbonization of concrete of engineering structures of road infrastructure such as overpasses, bridges and reclamation structures and structures was determined.

The concentration of carbon dioxide in atmospheric air noticeably affects the carbonization process, the rate of which increases with increasing carbon dioxide content and increasing temperature. It should be noted that the diffusion of carbon dioxide in moist air is about 10000 times faster than in water moistening the protective layer of concrete.

In concrete that has been operated in an aggressive atmosphere containing acid gases, three main layers are usually distinguished [9]:

- external, neutralized by a gas forming a stronger acid than carbonic acid;
- middle, carbonized;
- internal, not exposed to acid gases.

After carbonization of the protective layer of concrete to its entire depth, corrosion of steel reinforcement is intensified, which is the main cause of failure of reinforced concrete structures.

In the work we determined the degree of carbonization for a bridge structure over the Usa River. The degree of carbonization of concrete is characterized by carbon dioxide chemically bound to the cement stone, which is determined as a percentage of the mass of cement in accordance with STB 1481-2011. The results of the research are given in Table 5.

Table 5 – Degree of carbonization of samples of elements of the bridge over the Usa River

Element name	Degree of carbonization (%)
Support 2	7,62
Head beam 2	8,36
Beam 2	5,87

However, the issue of criteria for assessing the state of concrete and its protective properties in relation to steel reinforcement is currently problematic [13]. According to the research of V. I. Babushkin [14] concrete loses its protective properties in relation to reinforcement at pH < 11.8, but this does not mean that the degree of carbonization at such an indicator will be maximum. The decrease in the values of the hydrogen index may be a consequence of internal physicochemical processes of salt recrystallization.

Decrease in pH value in concrete extracts is not a criterion for evaluating the carbon dioxide content in the pore structure of concrete. It is obvious that the content of carbon dioxide and other acidic gases in the surface layers of concrete will be higher and the pH value will be lower, but what is the depth of penetration of carbon dioxide into the depth of concrete in this case remains unknown.

Consequently, during the comprehensive inspection of objects of various infrastructure there is a need to determine the content of carbon dioxide in samples of materials at different depths from the surface of the sample.

An important stage in determining the technical condition of the structure is the prediction of the bridge durability [15] (Table 6). According to [16], it is recommended to perform the prediction based on the data from the results of previous surveys extrapolating the reduction of the load-carrying capacity class according to the elliptical dependence. Under unfavorable operating conditions (systematic freezing, exposure to chemically active de-icing agents) it is necessary to take into account the reduction of strength and deformative properties of concrete as a result of degradation processes in accordance with Appendix B [16]. Corrosion of reinforcement also affects the reduction of span load carrying capacity; therefore, the method developed in the Russian Federation [17] provides not only for prediction of concrete carbonization but also for corrosion of reinforcement.

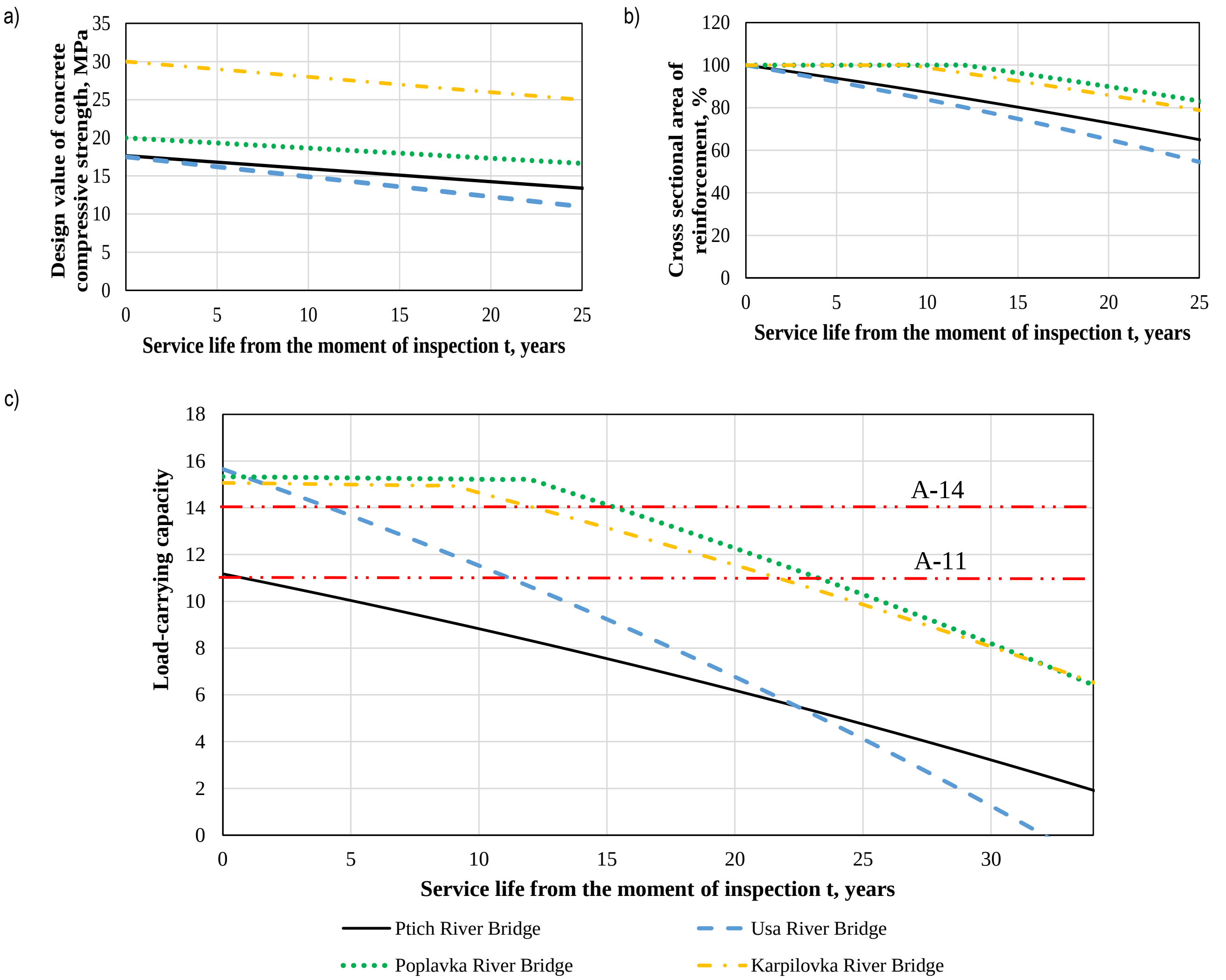
The methods given in normative documents [16, 17] do not always allow us to reliably obtain data on the predicted service life of structures, since the rate of development of concrete carbonization and reinforcement corrosion depends largely on the initial quality of materials, as well as on the operating conditions of the structure, which can be very different even within the same structure: end and middle beams of the span, structures located at the expansion joint, etc. [18]. It is obvious that in order to perform reasonable calculations of the predicted durability of bridge elements, it is necessary to have accurate and detailed information on the processes of concrete carbonization and reinforcement corrosion occurring in the structure at the inspection stage [19, 20].

In order to fully assess the technical condition and predict the residual life of structures, the specialist performing the inspection should have data on the condition of the structure, the degree of concrete carbonization, and the corrosion processes occurring in the reinforcement during the entire period of operation, which is not always possible.

Table 6 – Normative (forecast) indicators of durability of structures

Bridge name	Year of construction / last major repair (reconstruction)	Design service life of structures, years		Remaining service life of structures [16], years	
		Spans	Supports	Spans	Supports
Ptich River Bridge	1972	75	100	24	49
Usa River Bridge	1972 / –			24	49
Karpilovka River Bridge	1987 / 2012			63	63 / 88
Poplavka River Bridge	2012 / –			63	88

On the basis of actual data on the technical condition of structures (physical deterioration) and laboratory studies of their materials, the calculation of predicting the durability of the structure was performed by determining the load capacity of the structures of spans and supports (Figure 2).



a) degradation of design value of concrete compressive strength; b) decreasing of cross sectional area of reinforcement;
c) decreasing load-carrying capacity

Figure 2 – Prediction of the bridge durability

Prediction of the decrease in the design compressive strength of concrete during the operation period was made using coefficients that take into account the operating conditions of the structure, which were established during the inspection of the structure. The time variation of the working reinforcement corrosion degree was taken into account by decreasing the effective diameter of the reinforcing bar during t_i years of the bridge structure operation, taking into account the data obtained as a result of the survey. The actual degree of concrete carbonization and, consequently, the residual concrete protective layer determined in the present study were taken into account. The function of reinforcement cross-sectional reduction (reinforcement wear) in accordance with [17], can be described using the reliability theory failure function and transformed into the dependence of the effective cross-sectional area of the working reinforcement of the slab on the service life of the span. The results of numerical modeling are presented in Table 7.

Table 7 – Results of numerical modeling of durability of structures

Bridge name	Bridge load capacity category	Number of years until the expiration of the reliability requirements for the calculated load capacity
Ptich River Bridge	A-11	0,8
Usa River Bridge	A-11	11,2
Karpilovka River Bridge	A-14	12,2
Poplavka River Bridge	A-14	15,4

Conclusions

1. Diagnostics of defects in bridge structures can be carried out based on the results of visual inspection and appropriate measurements. The most promising methods are the methods of chemical analysis, which allow to obtain information about the condition of the structure and identify hidden defects.

2 The main indicators controlled by chemical analysis of concrete condition are chloride content, degree of carbonization and pH, which depend on the initial quality of materials, as well as the operating conditions of the structure, which can vary greatly even within the same structure.

3. The question of criteria for assessing on the basis of chemical analysis the condition of concrete, its protective properties in relation to steel reinforcement remains unresolved, because, as the experience of the performed surveys shows, a decrease in the pH of concrete does not always lead to an increase in the degree of carbonization and, consequently, more rapid development of defects.

4. Prediction of the bridge durability based on the data on its load carrying capacity, determined by the results of previous surveys, allows taking into account the development of degradation processes in concrete and corrosion of reinforcement. To perform appropriate calculations it is necessary to have information on the degree of concrete carbonization, corrosion processes in reinforcement during the whole operation period. Analysis of the obtained durability indicators (Figure 2, Table 7) of the bridge structures considered in the article indicates the necessity of systematic monitoring of their technical condition and performance of repair and rehabilitation works for some of them. In this connection it is urgent to create a database of bridge structures containing data not only on their structural design and main defects, but also on changes in chloride content, degree of carbonization and pH during different periods of operation.

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