

СТРОИТЕЛЬНЫЕ МАТЕРИАЛЫ И ИЗДЕЛИЯ/CONSTRUCTION MATERIALS AND PRODUCTS

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DEVELOPMENT OF A COMPUTATIONAL AND ANALYTICAL METHODOLOGY FOR EVALUATING THE EFFECTIVENESS OF SELF-HEALING CONCRETE AND CRYSTALLINE WATERPROOFING IN FOUNDATION STRUCTURES

Research article

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Abstract

The study aims to develop an analytical assessment methodology for the application of self-healing concrete and crystalline waterproofing in foundation structures exposed to groundwater and cyclic wetting. The relevance of the research is determined by the increasing requirements for the durability of underground building elements, the growing risk of flooding, and the need to improve the watertightness of reinforced concrete foundations without a proportional increase in maintenance costs. The paper systematizes the main mechanisms of concrete self-healing, including autogenous healing, crystalline admixtures, microencapsulated systems, and biomineralization. A decision-making model is proposed that considers watertightness, microcrack closure capacity, strength retention, freeze-thaw resistance, constructability, and life-cycle cost. A calculation example is presented for a foundation slab under high groundwater conditions. The results demonstrate that the combined use of concrete with crystalline admixtures, waterproofing of construction joints, drainage, and monitoring increases the integral effectiveness index compared with a conventional solution. The scientific novelty lies in integrating materials science and construction technology into a single calculation model for preliminary selection of concrete composition and waterproofing strategy for foundation structures. The practical significance stems from the fact that the suggested methodology can be used by design and construction organisations when substantiating waterproofing solutions for the underground parts of buildings.

Keywords: self-healing concrete, crystalline waterproofing, foundation structures, watertightness, microcracks, durability, groundwater, waterproofing protection.

РАЗРАБОТКА РАСЧЕТНО-АНАЛИТИЧЕСКОЙ МЕТОДИКИ ОЦЕНКИ ЭФФЕКТИВНОСТИ ПРИМЕНЕНИЯ САМОЗАЛЕЧИВАЮЩЕГОСЯ БЕТОНА И КРИСТАЛЛИЧЕСКОЙ ГИДРОИЗОЛЯЦИИ В ФУНДАМЕНТНЫХ КОНСТРУКЦИЯХ

Научная статья

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Аннотация

Цель исследования заключается в разработке расчетно-аналитической методики оценки эффективности применения самозалечивающегося бетона и кристаллической гидроизоляции в фундаментных конструкциях, эксплуатируемых в условиях воздействия грунтовых вод и циклического увлажнения. Актуальность работы обусловлена ростом требований к долговечности подземных частей зданий, увеличением рисков подтопления и необходимостью повышения водонепроницаемости железобетонных фундаментов без непрерывного роста эксплуатационных затрат. В статье систематизированы основные механизмы самозалечивания бетона, включая автогенное заживление, применение кристаллических добавок, микрокапсулированных и биоминерализующих систем. Предложена модель выбора защитного решения, учитывающая водонепроницаемость, способность к закрытию микротрещин, сохранение прочности, морозостойкость, технологичность и затраты жизненного цикла. Выполнен расчетный пример для фундаментной плиты здания с высоким уровнем грунтовых вод. Показано, что комплексное применение бетона с кристаллической добавкой, конструктивной защиты рабочих швов, дренажа и мониторинга позволяет повысить интегральный индекс эффективности гидроизоляционной защиты по сравнению с базовым решением. Научная новизна исследования состоит в объединении материаловедческого и конструктивно-технологического подходов в единую расчетную модель, предназначенную для предварительного выбора состава бетона и системы гидроизоляции фундаментных конструкций. Практическая значимость заключается в возможности использования предложенной методики проектными и строительными организациями при обосновании гидроизоляционных решений для подземных частей зданий.

Ключевые слова: самозалечивающийся бетон, кристаллическая гидроизоляция, фундаментные конструкции, водонепроницаемость, микротрещины, долговечность, грунтовые воды, гидроизоляционная защита.

Introduction

Foundation structures are among the most critical elements of a building: they transfer loads from the superstructure to the soil base and are continuously exposed to groundwater, capillary moisture and aggressive underground environments. The durability of such structures therefore depends not only on the bearing capacity of concrete and reinforcement, but also on the reliability of waterproofing protection throughout the service life of the building [15], [17], [18], [19], [24].

Traditional foundation waterproofing systems include external membranes, rolled and coating materials, injection compounds, drainage systems, waterstops and protective screeds. These solutions are widely used in practice, but their effectiveness can decrease because of construction defects, mechanical damage, aging, local discontinuities and insufficient protection of joints. For underground structures, even local waterproofing failure may lead to leakage, reinforcement corrosion, deterioration of indoor conditions and increased repair costs [14], [15], [16], [18], [19].

In recent years, international construction research has actively developed materials capable of partially restoring the watertightness of cement stone after microcracking. Such solutions include autogenous self-healing concrete, cementitious capillary crystalline waterproofing admixtures, encapsulated agents and biomineralization technologies. Their common idea is to reduce permeability by forming insoluble products within pores, capillaries and cracks under the influence of moisture [1], [2], [8], [23].

For foundation structures, concrete self-healing is particularly important. Microcracks with widths of tenths of a millimeter may not immediately reduce the bearing capacity of a foundation slab; however, they can become preferential filtration paths. Under cyclic groundwater exposure, such cracks increase the risk of leaks, reinforcement corrosion and local degradation of concrete. Consequently, the waterproofing protection of foundation structures should be considered as a complex system combining material properties, external barriers, joint protection and drainage [4], [5], [9], [13].

Despite the growing number of studies on self-healing concrete and crystalline admixtures, practical foundation design still lacks applied methods for comparing waterproofing alternatives that simultaneously account for watertightness, crack closure capacity, strength, frost resistance, constructability and life-cycle costs. This gap is particularly important for structures operating under variable groundwater conditions [3], [6], [7], [11].

The object of the study is reinforced concrete foundation structures of buildings operating under groundwater exposure. The subject of the study is the technological and calculation parameters affecting the efficiency of self-healing concrete and crystalline waterproofing in foundation slabs and underground structures.

The purpose of the study is to develop an analytical model for assessing the efficiency of self-healing concrete and crystalline waterproofing in foundation structures. The research tasks include: systematizing self-healing mechanisms; forming criteria for evaluating waterproofing protection; developing an integral efficiency index; performing a computational comparison of alternative solutions; assessing microcrack closure dynamics and life-cycle costs; and formulating practical recommendations for foundation design and construction control.

Analysis of modern applications of self-healing cementitious materials

Self-healing concrete is the ability of a cementitious material to partially restore continuity and reduce crack permeability without direct external repair. In general terms, self-healing mechanisms can be divided into autogenous and engineered mechanisms. Autogenous healing is associated with continued hydration, carbonation and deposition of products in the crack. Engineered healing is achieved by adding crystalline admixtures, capsules, bacteria, mineral additives or other components capable of activating sealing processes when moisture enters the crack [1], [2], [8], [23].

Crystalline waterproofing occupies an intermediate position between traditional waterproofing and self-healing concrete technology. Unlike an external membrane, which acts as an independent barrier on the surface of the structure, crystalline compounds operate inside the cement stone. In the presence of water, active components react with hydration products and form insoluble crystalline products that reduce capillary permeability and may contribute to the sealing of microcracks [4], [5], [6], [7], [13].

Modern studies show that crystalline admixtures can reduce concrete permeability and, in some cases, increase the ability to close microcracks. Reviews of crystalline admixtures note their positive influence on water resistance and durability, although the final effect depends on the concrete mix, admixture dosage, curing conditions, crack width and moisture availability [3], [4], [5], [6], [7].

Biomineralization systems are based on the ability of certain microorganisms to initiate calcium carbonate precipitation in cracks. Such solutions are promising for sustainable construction, but their practical application in foundation structures is limited by requirements for the environment, survivability of biological agents, cost and technological complexity [8], [12]. For this reason, the present article focuses primarily on crystalline and mineral self-healing mechanisms that are easier to integrate into conventional monolithic concrete technology.

Domestic studies also emphasize the relationship between self-healing, penetrating admixtures and improved watertightness, reduced reinforcement corrosion risk and increased maintainability of underground structures. Russian-language sources consider both material aspects of self-healing concrete and applied waterproofing solutions for foundations and underground structures [9], [10], [11], [13], [14].

For foundation structures, the most practical interest is represented by systems that can be integrated into standard concreting procedures and do not require complex maintenance. Therefore, the proposed methodology considers a combined solution: concrete with a crystalline waterproofing admixture, external membrane protection, waterstops in construction joints, drainage and quality control procedures [15], [16], [18], [19].

Table 1 - Comparison of concrete self-healing and waterproofing mechanisms

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Approach	Mechanism of action	Advantages	Limitations
Autogenous healing	Continued hydration, carbonation and deposition of products in the crack	Low cost, natural mechanism	Limited crack width, dependence on moisture
Crystalline admixtures	Formation of insoluble crystalline products in capillaries and cracks	Constructability, applicability in monolithic concrete	Correct dosage and mix control are required
Microcapsules	Capsule rupture during crack opening and release of a healing agent	High local activity	Cost, possible influence on concrete structure
Biomineralization	$CaCO_3$ precipitation as a result of microbiological processes	Promising for sustainable construction	Limited practical applicability and environmental requirements
Integrated system	Combination of admixtures, external protection, waterstops, drainage and monitoring	Higher reliability due to multiple barriers	Higher initial cost

Note: compiled by the authors on the basis of [1], [2], [3], [4], [5], and also [6], [7], [8], [23]

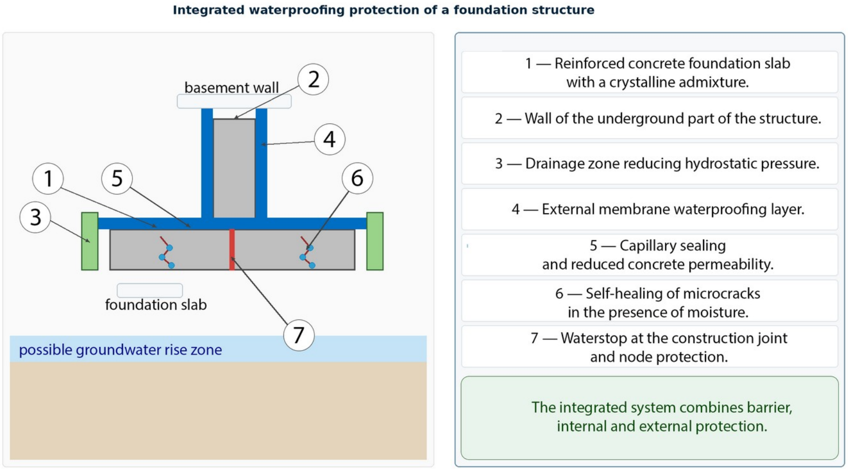

Figure 1 - Functional scheme of integrated waterproofing protection of a foundation structure
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Materials and methods

3.1. Regulatory and computational basis

The research methodology combines regulatory, materials-science and analytical approaches. The regulatory component is associated with requirements for the protection of underground structures against groundwater and with standard test methods for concrete watertightness, strength and frost resistance [18], [19], [20], [21], [22]. The materials-science component concerns the mechanisms of crystalline waterproofing and self-healing in cementitious materials [1], [2], [3], [4], and also [5], [6], [7], [8]. The analytical component is used to compare alternative waterproofing solutions through an integral efficiency index.

The computational part is intended for preliminary comparison of waterproofing alternatives for a foundation slab. Efficiency in this paper is understood as the ability of a solution to provide the required watertightness, reduce filtration risk through microcracks, preserve strength characteristics and remain economically justified over the life cycle of the underground structure [17], [21], [22], [23], [24].

3.2. Characteristics of the computational object

The case-study object is a monolithic reinforced concrete foundation slab of the underground part of a public building with one basement level. The structure operates under periodic groundwater exposure. Water pressure is assumed to be moderate; however, seasonal groundwater fluctuations create conditions under which microcracks and construction joints become potential leakage paths [15], [16], [18], [19].

Four alternative protection variants are considered:

A0 — basic concrete with external membrane waterproofing;

A1 — concrete with a crystalline waterproofing admixture and local joint protection;

A2 — self-healing concrete combined with a crystalline admixture;

A3 — an integrated system including self-healing concrete, crystalline waterproofing, an external membrane, waterstops, drainage and quality control of joints [3], [4], [5], [6], [7], and also [13], [14].

Table 2 - Initial characteristics of the computational object

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Parameter	Accepted value
Structure type	monolithic reinforced concrete foundation slab
Design slab thickness	800 mm
Operating conditions	periodic groundwater exposure, cyclic wetting
Main risk	filtration through microcracks and construction joints
Basic requirement	increased watertightness and maintainability
Purpose of calculation	comparison of waterproofing alternatives at the solution selection stage

3.3. Criteria for evaluating efficiency

A system of six criteria is formed to evaluate alternative solutions. The criteria are selected to account for both the technical properties of concrete and the constructability of the solution on site. They also reflect the fact that waterproofing protection of foundations cannot be assessed only by the initial price of material; repair complexity and indirect losses caused by leaks are also significant [14], [15].

The criteria have different dimensions and physical nature; therefore, before aggregation they are converted to a normalized scale from 0 to 1. A value of 1 corresponds to the best state of a criterion, while a value of 0 corresponds to an unsatisfactory or limiting state. For benefit criteria, direct normalization is used; for cost criteria, inverse normalization is applied [11], [17], [24].

Table 3 - Criteria for evaluating the efficiency of waterproofing protection of foundation structures

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Designation	Criterion	Indicators	Weight	Justification
C1	Watertightness	W class, water penetration depth, relative permeability	0.27	key indicator of protection against groundwater
C2	Microcrack self-healing	crack closure ratio, maximum self-healable crack width	0.22	determines the ability to restore tightness
C3	Strength retention	relative compressive strength, no reduction in concrete class	0.15	prevents deterioration of bearing capacity
C4	Frost and water resistance	resistance to water saturation and freeze-thaw cycles	0.13	important for variable moisture and negative temperatures
C5	Constructability	dosage complexity, compatibility with concreting and quality control	0.10	affects reliability of site implementation
C6	Life-cycle economy	initial cost, repair, indirect losses from leaks	0.13	accounts for operating costs, not only material price

Note: compiled by the authors on the basis of [1], [2], [3], [4], [5] and also [6], [7], [17], [20], [21]

3.4. Novelty of the proposed methodology

The scientific novelty of the study lies not in the general statement of the known effect of crystalline admixtures, but in forming a calculation procedure that includes this effect in the selection of a waterproofing system for foundations. The proposed method links the material ability of concrete to self-heal with structural and technological protection measures such as membranes, waterstops, drainage and life-cycle cost assessment [13], [14], [15], [16].

The methodology can be used for preliminary comparison of solutions before detailed design and laboratory testing. At the same time, it does not replace regulatory requirements for concrete and waterproofing, but serves as an auxiliary analytical tool for design justification and construction control [18], [19], [20], [21], [22].

Table 4 - Novelty of the article and difference between the proposed methodology and traditional approaches

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Position	Content	Scientific and practical significance
Traditional approach	Selection of external waterproofing by water type and structure	The protective layer is evaluated, but concrete self-restoration is not considered
Materials-science approach	Testing concrete with admixtures for permeability and strength	Provides material properties, but does not link them with foundation technology
Proposed approach	Joint assessment of concrete, crystalline admixture, joints, drainage and life-cycle cost	Allows alternatives to be compared using an integral index and weak criteria to be identified
Novelty element	Introduction of a self-healing criterion into the model for selecting foundation waterproofing	Accounts for restoration of watertightness after microcracking
Practical result	Tabular calculation and graphical interpretation of alternatives	Creates a basis for design justification of the selected solution

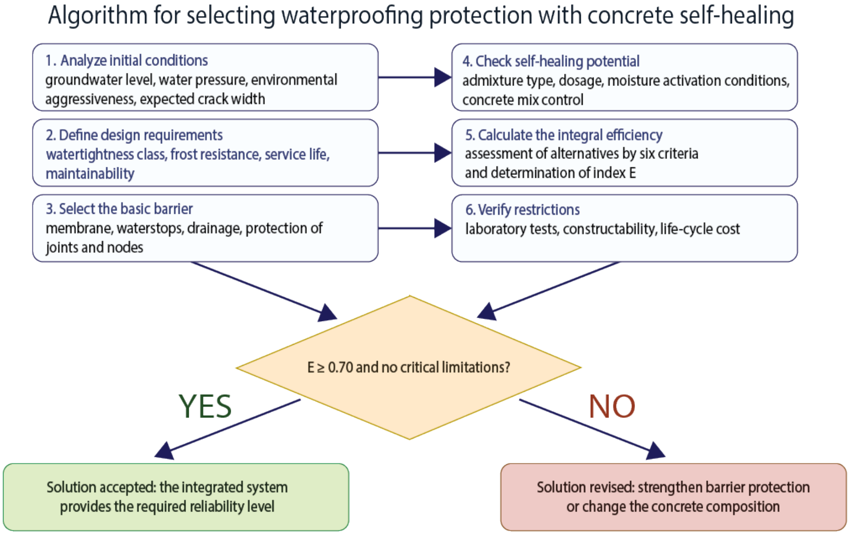

Figure 2 - Algorithm for selecting waterproofing protection considering concrete self-healing

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3.5. Calculation model

The integral efficiency index of waterproofing protection is denoted by E. It is calculated as a weighted sum of normalized criterion values. The index is intended for preliminary comparison of design alternatives and should be used together with regulatory checks and laboratory verification [17], [20], [21], [22], [24].

$$E = \Sigma\left(w_i \cdot q_i\right), \quad \Sigma w_i = 1, \quad 0 \le q_i \le 1$$

where:
E is the integral efficiency index;
w_i is the weight of the i-th criterion;
q_i is the normalized value of the i-th criterion.
For benefit indicators the formula: $q_i = (x_i - x_i \min) / (x_i \max - x_i \min)$) is used;
for cost indicators the formula: $q_i = (x_i \max - x_i) / (x_i \max - x_i \min)$ is used.
The normalization of heterogeneous indicators makes it possible to compare technical, technological and economic parameters within a single assessment model [11], [17], [24].
The following interpretation scale is proposed for index E:
below 0.55 — low efficiency;
0.55–0.70 — acceptable efficiency with limitations;
0.70–0.85 — high efficiency;
above 0.85 — increased efficiency for critical underground structures.

Computational testing of the methodology

4.1. Initial indicators of alternative solutions

At the first stage, primary indicators are assigned for each protection alternative and then converted to a normalized scale. The values in the computational example are project-analytical: they do not replace laboratory testing of a specific concrete mix, but demonstrate the procedure for comparing technical solutions. Laboratory confirmation should be performed using standard methods for watertightness, frost resistance and concrete quality control [20], [21], [22].

The basic variant A0 involves traditional concrete with external membrane waterproofing. Variant A1 adds a crystalline waterproofing admixture. Variant A2 includes self-healing concrete combined with a crystalline admixture. Variant A3 represents an integrated system supplemented by membrane protection, drainage and enhanced joint control. The choice of crystalline admixture and self-healing alternatives reflects published data on the influence of capillary crystalline materials on permeability reduction and microcrack closure [3], [4], [5], and also [6], [7], [13].

Table 5 - Primary indicators of waterproofing protection alternatives

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Variant	Watertightness class	Calculated healable crack width, mm	Water penetration depth, mm	Relative strength	Initial cost index	Life-cycle cost index
A0	W6	0.05	70	1.00	1.00	1.85
A1	W10	0.20	38	1.05	1.10	1.61
A2	W12	0.30	28	1.07	1.18	1.58
A3	W12+	0.35	22	1.09	1.25	1.51

Table 6 - Normalized criterion values and integral efficiency index

DOI: https://doi.org/10.60797/IRJ.2026.170.122.8

Variant	Watertightness	Self-healing	Strength	Frost resistance	Constructability	Life-cycle economy	E
A0	0.38	0.20	0.74	0.66	0.82	0.62	0.506
A1	0.70	0.62	0.79	0.76	0.74	0.72	0.710
A2	0.82	0.82	0.81	0.82	0.60	0.76	0.789
A3	0.90	0.88	0.84	0.86	0.68	0.84	0.852

Table 7 - Decomposition of the efficiency index for the integrated A3 system

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Criterion	Weight	Normalized value	Contribution to E
Watertightness	0.27	0.90	0.243
Self-healing	0.22	0.88	0.194
Strength	0.15	0.84	0.126
Frost resistance	0.13	0.86	0.112
Constructability	0.10	0.68	0.068

Criterion	Weight	Normalized value	Contribution to E
Life-cycle economy	0.13	0.84	0.109
Total	1.00	–	0.852

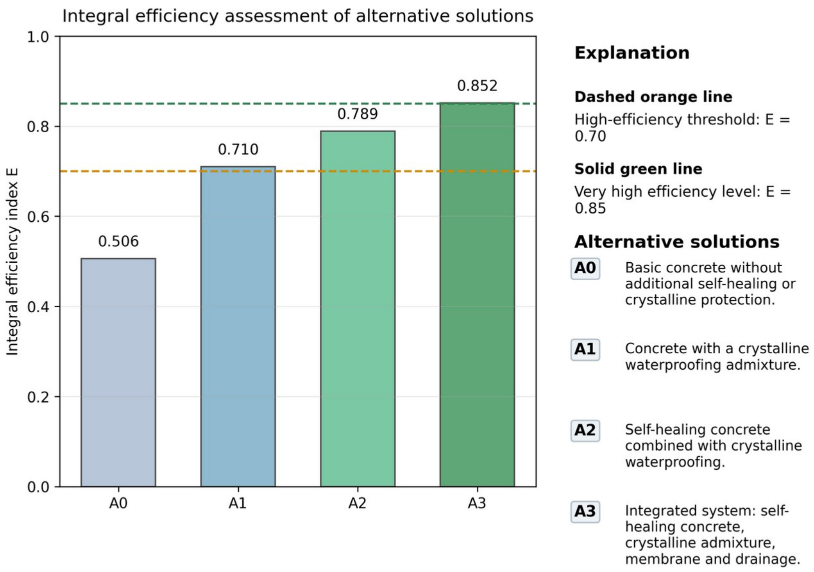

Figure 3 - Integral efficiency assessment of alternative solutions
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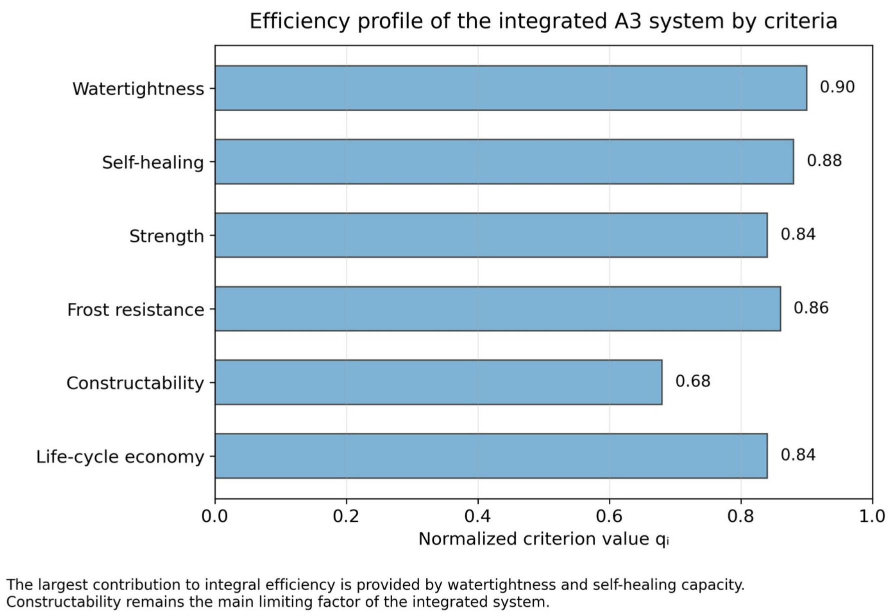

Figure 4 - Efficiency profile of the integrated A3 system by criteria
DOI: https://doi.org/10.60797/IRJ.2026.170.122.11

4.2. Initial indicators of alternative solutions

The calculation shows that the basic variant A0 obtains E = 0.506, which corresponds to acceptable efficiency with limitations. The main limitation of the basic solution is low self-healing capacity. Even if an external membrane is installed, local defects or microcracks may remain critical filtration paths [14], [16], [18], [19].

Variant A1 demonstrates an increase in efficiency due to the use of a crystalline admixture. The normalized value for the self-healing criterion increases from 0.20 to 0.62, reflecting the ability of cement stone to partially seal capillaries and microcracks. However, the result remains dependent on proper dosing, mixing and curing [3], [5], [6], [13].

Variant A2 provides a higher index due to the combination of self-healing concrete and a crystalline admixture. Its weak point is constructability: the use of special components requires stricter control of concrete production, delivery, placement and curing [3], [6], [17], [21].

The highest efficiency index is obtained by variant A3, the integrated system. Its advantage consists not only in material properties but also in the combination of several barriers: concrete watertightness, self-healing, external membrane protection, waterstops and drainage. This solution is most justified for structures where leakage after commissioning is difficult and expensive to eliminate [14], [15], [18], [19].

4.3. Calculation of microcrack closure dynamics

For foundation slabs, not only the final watertightness value is important, but also the dynamics of tightness recovery after microcracking. In the computational example, a microcrack with an initial width of 0.30 mm is accepted. The degree of closure is estimated as a percentage of the reduction in the effective open crack width over time under water saturation. Similar approaches to evaluating crack closure and permeability recovery are discussed in studies of autogenous, crystalline and engineered self-healing mechanisms [1], [3], [7], [23].

The crack closure dynamics are shown in Figure 5 (add. mat.). The values are computational and analytical; they are intended to illustrate the proposed assessment procedure. In a real project, the values must be verified by laboratory testing of the selected concrete mix and waterproofing admixture under conditions that reproduce the expected exposure of the foundation structure [20], [21], [22].

Table 8 - Calculated microcrack closure degree over time

DOI: https://doi.org/10.60797/IRJ.2026.170.122.12

Time, days, %	Basic concrete, %	Concrete with crystalline admixture, %	Self-healing system, %
0	0	0	0
7	8	22	30
14	15	42	56
28	24	61	78
56	31	72	88

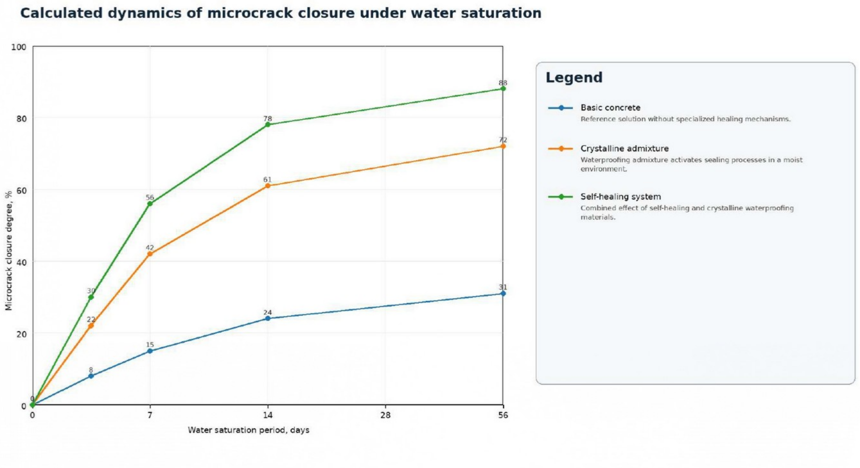

Figure 5 - Calculated dynamics of microcrack closure under water saturation

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4.4. Life-cycle economic assessment

The use of self-healing materials is often accompanied by an increase in initial costs. However, for underground structures, economic efficiency should be assessed not only by material price but also by the expected cost of repair, disruption of operation, injection works, restoration of finishes and indirect losses caused by leakage. Previous studies emphasize that durability-oriented concrete technologies should be evaluated not only by initial material cost, but also by their influence on service life, repair frequency and permeability-related damage [1], [2], [4], [17], [24].

The calculated cost structure in Figure 6 (add. mat.) and Table 9 shows that variant A3 has the highest initial cost index, but reduces expected repair costs and indirect losses. This is especially important for underground parking areas, technical rooms, archives, storage facilities and other underground spaces where water leakage can lead to significant operating losses [15], [16], [18], [19].

Table 9 - Calculated life-cycle cost assessment

DOI: https://doi.org/10.60797/IRJ.2026.170.122.14

Variant	Initial costs	Repair	Indirect losses	Total	Self-healing availability
A0	1.00	0.60	0.25	1.85	no
A1	1.10	0.35	0.16	1.61	partial
A2	1.18	0.28	0.12	1.58	yes
A3	1.25	0.18	0.08	1.51	yes

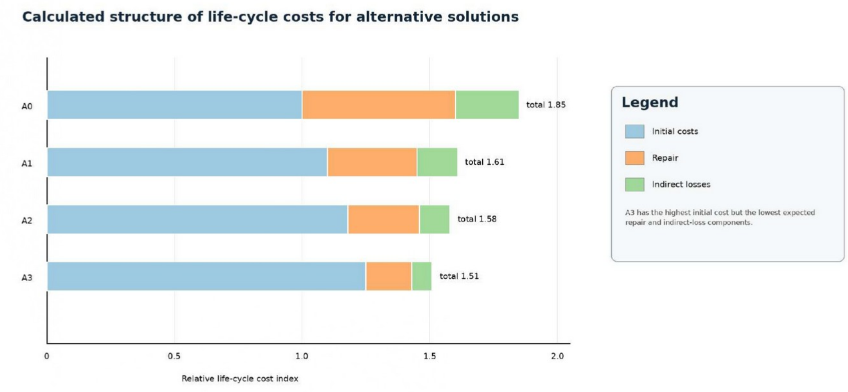

Figure 6 - Calculated structure of life-cycle costs for alternative solutions
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Discussion

The results obtained make it possible to formulate several provisions for the design and construction of foundation structures. First, crystalline waterproofing should not be considered a complete substitute for external waterproofing in all cases. Its most effective application is as part of a combined system that includes concrete with increased watertightness, external protection, joint sealing and drainage [3], [4], [6], [7], and also [13], [14], [15], [16].

Second, self-healing is effective primarily for microcracks of limited width. Large, through and moving cracks, deformation joints, local voids, concreting defects or serious violations of construction technology cannot be regarded as self-removable. In such cases, additional solutions are required: waterstops, injection hoses, repair mortars or design modification [1], [5], [7], [23].

Third, the effect of crystalline admixtures depends on the quality of the concrete mix. A high water–cement ratio, poor curing, non-uniform distribution of the admixture, contaminated aggregates or insufficient compaction reduce the expected effect. Therefore, the use of self-healing concrete should be accompanied by a detailed quality control program [3], [4], [6], [17], [21].

Fourth, the economic feasibility of self-healing concrete is most pronounced in facilities where leak repair after commissioning is difficult or expensive. These include basements, underground parking lots, technical rooms, tunnels, underground passages and structures with restricted access for repair [14], [18], [19].

Fifth, the proposed methodology may be integrated into BIM environments and digital construction control systems. In a building information model, elements of the foundation slab and basement walls can be associated with waterproofing parameters, crack-width limits, quality control requirements and life-cycle cost indicators [11], [24].

Table 10 is included in the discussion section to define the practical limits of applying the integrated A3 system. It shows the conditions under which the calculated efficiency index should not be used mechanically and must be supplemented by laboratory verification, technological control and life-cycle assessment [20], [21], [22].

Table 10 - Applicability limits of the integrated A3 system and ways to account for restrictions

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Application limitation	Why it matters for the calculation method	How to account for it in design and control
No laboratory verification of a specific concrete mix	Calculated E values provide comparative assessment but do not replace specimen testing	Test watertightness, frost resistance and crack closure ability
Dependence of crystallization on moisture and curing conditions	Poor curing reduces the effect of capillary and crack sealing	Record curing regime, moisture care, admixture dosage and compaction quality
Limited width of effectively healable cracks	Large, through and moving cracks should not be considered self-removable	Introduce a crack-width threshold and provide waterstops, injection or repair compounds
Higher requirements for technological discipline	Non-uniform admixture distribution and concreting errors reduce the result	Include control operations in method statements, technological maps and construction control programs
Economic uncertainty when only initial costs are assessed	An integrated system may be more expensive initially but cheaper over the life cycle	Compare alternatives by life-cycle costs: installation, repair, downtime and indirect losses

Practical recommendations

As a result of the study, an analytical methodology for assessing the efficiency of self-healing concrete and crystalline waterproofing in foundation structures has been developed on the basis of published studies on self-healing cementitious materials, crystalline waterproofing and durability of concrete structures [2], [3], [4], [6], [7], and also [8], [17], [23], [24]. The methodology links material properties with structural and technological conditions and makes it possible to compare alternative waterproofing solutions at the preliminary design stage.

The scientific novelty of the work lies in forming an integral model that links materials-science properties of self-healing concrete with structural and technological conditions of foundation operation. In contrast to traditional approaches focused mainly on external waterproofing, the proposed methodology considers the concrete itself as an active element of waterproofing protection [1], [5], [13], [16].

The computational testing showed that the use of a crystalline admixture increases waterproofing efficiency compared with the basic alternative; however, the maximum result is achieved when the material mechanism of self-healing is combined with external membrane protection, waterstops, drainage and construction quality control. The integrated system A3 obtained the highest efficiency index, E = 0.852 [3], [5], [15].

The practical significance of the study lies in the possibility of using the proposed model by design organizations, technical clients and construction companies at the preliminary selection stage of waterproofing protection for foundation structures. The methodology enables alternatives to be compared, weak criteria to be identified and the need for additional laboratory testing and technological control to be justified [18], [22].

Further research should be aimed at laboratory verification of calculated indicators, assessment of long-term performance of crystalline admixtures in real foundation structures, refinement of normalization ranges and integration of the methodology into BIM-based construction control systems [3], [11], [20], [22].

Table 11 - Recommendations for selecting a protective solution for foundation structures

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Operating condition	Recommended solution	Comment
High groundwater level	High-watertightness concrete + crystalline admixture + external waterproofing + drainage	the system should include at least two independent barriers
Risk of temperature and shrinkage cracks	Self-healing concrete + crack-width control	crack resistance calculation is mandatory
Large number of construction joints	Crystalline admixture + waterstops + injection hoses	special attention should be paid to concreting joints
Aggressive groundwater	Crystalline admixture + anti-	requirements for corrosion

Operating condition	Recommended solution	Comment
	corrosion protection + concrete mix selection	protection must be considered
High repair cost after commissioning	Integrated system A3	life-cycle cost assessment is necessary

Conclusion

As a result of the study, an analytical methodology for assessing the efficiency of self-healing concrete and crystalline waterproofing in foundation structures has been developed. The methodology links material properties with structural and technological conditions and makes it possible to compare alternative waterproofing solutions at the preliminary design stage.

The scientific novelty of the work lies in forming an integral model that links materials-science properties of self-healing concrete with structural and technological conditions of foundation operation. In contrast to traditional approaches focused mainly on external waterproofing, the proposed methodology considers the concrete itself as an active element of waterproofing protection.

The computational testing showed that the use of a crystalline admixture increases waterproofing efficiency compared with the basic alternative; however, the maximum result is achieved when the material mechanism of self-healing is combined with external membrane protection, waterstops, drainage and construction quality control. The integrated system A3 obtained the highest efficiency index, E = 0.852.

The practical significance of the study lies in the possibility of using the proposed model by design organizations, technical clients and construction companies at the preliminary selection stage of waterproofing protection for foundation structures. The methodology enables alternatives to be compared, weak criteria to be identified and the need for additional laboratory testing and technological control to be justified.

Further research should be aimed at laboratory verification of calculated indicators, assessment of long-term performance of crystalline admixtures in real foundation structures, refinement of normalization ranges and integration of the methodology into BIM-based construction control systems.

Конфликт интересов

Не указан.

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Conflict of Interest

None declared.

Review

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Список литературы / References

1. Wen X. Advancements in self-healing concrete: material design, mechanisms and applications / X. Wen [et al.] // Alexandria Engineering Journal. — 2025. — Vol. 131. — P. 104–124.

2. Pooja K. Self-healing concrete: a path towards advancement of sustainable construction materials / K. Pooja [et al.] // Discover Applied Sciences. — 2025. — — Vol. 7, № 1. — P. 703.

3. Wang H. Influence of different mixing methods for cementitious capillary crystalline waterproofing materials on concrete self-healing performance / H. Wang [et al.] // Materials. — 2025. — Vol. 18, № 1. — P. 159.

4. Ammar M.A. The effects of crystalline admixtures on concrete permeability and durability: a comprehensive review / M.A. Ammar [et al.] // Buildings. — 2024. — Vol. 14, № 9. — P. 3000.

5. Zhong J. Influences of cementitious capillary crystalline waterproofing materials on self-healing behavior of cracked concrete / J. Zhong [et al.] // Journal of Building Engineering. — 2024. — Vol. 98. — P. 114265.

6. Li F. Effect of nanocomposite cementitious capillary crystalline waterproofing materials on self-healing performance of cement-based materials / F. Li [et al.] // Case Studies in Construction Materials. — 2024. — Vol. 20. — P. e02874.

7. Fu G. Effect of cementitious capillary crystalline waterproofing materials on self-healing behavior of concrete / G. Fu [et al.] // Materials. — 2025. — Vol. 18, № 20. — P. 4659.

8. Elgendy I.M. Bacteria-powered self-healing concrete: mechanisms and applications / I.M. Elgendy [et al.] // Journal of Industrial Microbiology and Biotechnology. — 2024. — Vol. 52, № 1. — P. kuae051.

9. Zhukova G.G. Research on the use of self-healing concrete / G.G. Zhukova, A.I. Saifulina // Construction and Geotechnics. — 2020. — Vol. 11, № 4. — P. 58–68. — DOI: 10.15593/2224-9826/2020.4.05.

10. Kodzoev M.-B.Kh. Self-healing concrete / M.-B.Kh. Kodzoev, S.L. Isachenko // Bulletin of Science and Practice. — 2018. — Vol. 4, № 4. — P. 287–290.

11. Nizina T.A. Current state of scientific research in the field of self-healing concretes / T.A. Nizina, A.O. Kovshov // Smart Composites in Construction. — 2024. — Vol. 5, № 4. — P. 35–54. — DOI: 10.29296/27130231-2024-5-4-4.

12. Chernykh T.N. Biomineral additives for self-healing of concrete / T.N. Chernykh, K.A. Gorbachevskykh, M.V. Kriushin [et al.] // Vestnik MGSU. — 2024. — Vol. 19, № 4. — P. 569–579. — DOI: 10.22227/1997-0935.2024.4.569-579.

13. Abzalilova A.V. Use of a penetrating additive to increase concrete watertightness / A.V. Abzalilova, V.V. Strokova // Bulletin of BSTU named after V.G. Shukhov. — 2020. — № 5. — P. 18–24. — DOI: 10.34031/2071-7318-2020-5-5-18-24.

14. Мельниченко М.С. Современные методы гидроизоляции подземных сооружений / М.С. Мельниченко, В.А. Ильичев // Universum: технические науки. — 2022. — № 7-2(100). — С. 5–7. — DOI: 10.32743/UniTech.2022.100.7.14038.

15. Абелев М.Ю. Гидроизоляция фундаментов и подземных частей сооружений / М.Ю. Абелев, И.В. Аверин, Д.Ю. Чунюк. — Москва : Изд-во АСВ, 2023. — 104 с.

16. Туголуков А.М. Рекомендации по проектированию гидроизоляции подземных частей зданий и сооружений / А.М. Туголуков, Ю.А. Фролов. — Москва : ЦНИИПромзданий, 2009. — 118 с.

17. Баженов Ю.М. Технология бетона : учебник / Ю.М. Баженов. — 5-е изд. — Москва : Изд-во АСВ, 2011. — 524 с.

18. СП 250.1325800.2016. Здания и сооружения. Защита от подземных вод (название исправлено) : свод правил : утвержден Приказом Министерства строительства и жилищно-коммунального хозяйства Российской Федерации от 8 июля 2016 г. № 484/пр : введен в действие с 1 сентября 2016 г. / разработан АО «НИЦ «Строительство» — НИИОСП им. Н. М. Герсеванова. — Москва : Минстрой России, 2016. — 70 с.

19. СП 28.13330.2017. Защита строительных конструкций от коррозии : актуализированная редакция СНиП 2.03.11-85 : свод правил : утвержден Приказом Министерства строительства и жилищно-коммунального хозяйства Российской Федерации от 27 февраля 2017 г. № 127/пр : введен в действие с 28 августа 2017 г. / разработан АО «НИЦ «Строительство» — НИИЖБ им. А. А. Гвоздева. — Москва : Минстрой России, 2017. — 86 с.

20. ГОСТ 12730.5-2018. Бетоны. Методы определения водонепроницаемости : межгосударственный стандарт : введен в действие Приказом Федерального агентства по техническому регулированию и метрологии от 4 декабря 2018 г. № 1056-ст : введен впервые : дата введения 1 сентября 2019 г. — Москва : Стандартинформ, 2019. — 15 с.

21. ГОСТ 26633-2015. Бетоны тяжелые и мелкозернистые. Технические условия : межгосударственный стандарт : введен в действие Приказом Федерального агентства по техническому регулированию и метрологии от 17 марта 2016 г. № 165-ст : взамен ГОСТ 26633-2012 : дата введения 1 сентября 2016 г. — Москва : Стандартинформ, 2016. — 20 с.

22. ГОСТ 10060-2012. Бетоны. Методы определения морозостойкости : межгосударственный стандарт : введен в действие Приказом Федерального агентства по техническому регулированию и метрологии от 27 декабря 2012 г. № 1989-ст : взамен ГОСТ 10060.0-95 — ГОСТ 10060.4-95 : дата введения 1 января 2014 г. — Москва : Стандартинформ, 2013. — 25 с.

23. Van Tittelboom K. Self-healing in cementitious materials — a review / K. Van Tittelboom, N. De Belie // Materials. — 2013. — Vol. 6, № 6. — P. 2182–2217. — DOI: 10.3390/ma6062182.

24. Neville A. M. Properties of Concrete / A. M. Neville. — 5th ed. — Harlow : Pearson Education Limited, 2011. — 846 p.

Список литературы на английском языке / References in English

1. Wen X. Advancements in self-healing concrete: material design, mechanisms and applications / X. Wen [et al.] // Alexandria Engineering Journal. — 2025. — Vol. 131. — P. 104–124.

2. Pooja K. Self-healing concrete: a path towards advancement of sustainable construction materials / K. Pooja [et al.] // Discover Applied Sciences. — 2025. — — Vol. 7, № 1. — P. 703.

3. Wang H. Influence of different mixing methods for cementitious capillary crystalline waterproofing materials on concrete self-healing performance / H. Wang [et al.] // Materials. — 2025. — Vol. 18, № 1. — P. 159.

4. Ammar M.A. The effects of crystalline admixtures on concrete permeability and durability: a comprehensive review / M.A. Ammar [et al.] // Buildings. — 2024. — Vol. 14, № 9. — P. 3000.

5. Zhong J. Influences of cementitious capillary crystalline waterproofing materials on self-healing behavior of cracked concrete / J. Zhong [et al.] // Journal of Building Engineering. — 2024. — Vol. 98. — P. 114265.

6. Li F. Effect of nanocomposite cementitious capillary crystalline waterproofing materials on self-healing performance of cement-based materials / F. Li [et al.] // Case Studies in Construction Materials. — 2024. — Vol. 20. — P. e02874.

7. Fu G. Effect of cementitious capillary crystalline waterproofing materials on self-healing behavior of concrete / G. Fu [et al.] // Materials. — 2025. — Vol. 18, № 20. — P. 4659.

8. Elgendy I.M. Bacteria-powered self-healing concrete: mechanisms and applications / I.M. Elgendy [et al.] // Journal of Industrial Microbiology and Biotechnology. — 2024. — Vol. 52, № 1. — P. kuae051.

9. Zhukova G.G. Research on the use of self-healing concrete / G.G. Zhukova, A.I. Saifulina // Construction and Geotechnics. — 2020. — Vol. 11, № 4. — P. 58–68. — DOI: 10.15593/2224-9826/2020.4.05.

10. Kodzoev M.-B.Kh. Self-healing concrete / M.-B.Kh. Kodzoev, S.L. Isachenko // Bulletin of Science and Practice. — 2018. — Vol. 4, № 4. — P. 287–290.

11. Nizina T.A. Current state of scientific research in the field of self-healing concretes / T.A. Nizina, A.O. Kovshov // Smart Composites in Construction. — 2024. — Vol. 5, № 4. — P. 35–54. — DOI: 10.29296/27130231-2024-5-4-4.

12. Chernykh T.N. Biomineral additives for self-healing of concrete / T.N. Chernykh, K.A. Gorbachevskykh, M.V. Kriushin [et al.] // Vestnik MGSU. — 2024. — Vol. 19, № 4. — P. 569–579. — DOI: 10.22227/1997-0935.2024.4.569-579.

13. Abzalilova A.V. Use of a penetrating additive to increase concrete watertightness / A.V. Abzalilova, V.V. Strokova // Bulletin of BSTU named after V.G. Shukhov. — 2020. — № 5. — P. 18–24. — DOI: 10.34031/2071-7318-2020-5-5-18-24.

14. Melnichenko M.S. Sovremennyye metody gidroizolyatsii podzemnykh sooruzheniy [Modern methods of waterproofing underground structures] / M.S. Melnichenko, V.A. Ilyichev // Universum: tekhnicheskiye nauki [Universum: Technical Sciences]. — 2022. — № 7-2(100). — P. 5–7. — DOI: 10.32743/UniTech.2022.100.7.14038. [in Russian]

15. Abelev M.Yu. Gidroizolyatsiya fundamentov i podzemnykh chastey sooruzheniy [Waterproofing of foundations and underground parts of structures] / M.Yu. Abelev, I.V. Averin, D.Yu. Chunyuk. — Moscow : ASV Publishing House, 2023. — 104 p. [in Russian]

16. Tugolukov A.M. Rekomendatsii po proyektirovaniyu gidroizolyatsii podzemnykh chastey zdaniy i sooruzheniy [Recommendations for the design of waterproofing of underground parts of buildings and structures] / A.M. Tugolukov, Yu.A. Frolov. — Moscow : TsNIIPromzdaniy, 2009. — 118 p. [in Russian]

17. Bazhenov Yu.M. Tekhnologiya betona [Concrete technology] : textbook / Yu.M. Bazhenov. — 5th ed. — Moscow : ASV Publishing House, 2011. — 524 p. [in Russian]

18. SP 250.1325800.2016. Zdaniya i sooruzheniya. Zashchita ot podzemnykh vod [Buildings and structures. Protection against groundwater] : set of rules : approved by Order of the Ministry of Construction and Housing and Communal Services of the Russian Federation of July 8, 2016 No. 484/pr ; put into effect on September 1, 2016 / developed by JSC "Research Center "Construction" – Gersevanov Research Institute of Bases and Underground Structures. — Moscow : Ministry of Construction of Russia, 2016. — 70 p. [in Russian]

19. SP 28.13330.2017. Zashchita stroitel'nykh konstruktsiy ot korrozii [Protection of building structures against corrosion] : updated version of SNiP 2.03.11-85 : set of rules : approved by Order of the Ministry of Construction and Housing and Communal Services of the Russian Federation of February 27, 2017 No. 127/pr ; put into effect on August 28, 2017 / developed by JSC "Research Center "Construction" – Gvozdev Research Institute of Reinforced Concrete. — Moscow : Ministry of Construction of Russia, 2017. — 86 p. [in Russian]

20. GOST 12730.5-2018. Betony. Metody opredeleniya vodonepronitsayemosti [Concretes. Methods for determining water permeability] : interstate standard ; put into effect by Order of the Federal Agency for Technical Regulation and Metrology of December 4, 2018 No. 1056-st ; introduced for the first time ; date of introduction September 1, 2019. — Moscow : Standartinform, 2019. — 15 p. [in Russian]

21. GOST 26633-2015. Betony tyazhelyye i melkozernistyye. Tekhnicheskiye usloviya [Heavy-weight and fine-grained concretes. Specifications] : interstate standard ; put into effect by Order of the Federal Agency for Technical Regulation and Metrology of March 17, 2016 No. 165-st ; replaces GOST 26633-2012 ; date of introduction September 1, 2016. — Moscow : Standartinform, 2016. — 20 p. [in Russian]

22. GOST 10060-2012. Betony. Metody opredeleniya morozostoykosti [Concretes. Methods for determining frost resistance] : interstate standard ; put into effect by Order of the Federal Agency for Technical Regulation and Metrology of December 27, 2012 No. 1989-st ; replaces GOST 10060.0-95 – GOST 10060.4-95 ; date of introduction January 1, 2014. — Moscow : Standartinform, 2013. — 25 p. [in Russian]

23. Van Tittelboom K. Self-healing in cementitious materials — a review / K. Van Tittelboom, N. De Belie // Materials. — 2013. — Vol. 6, № 6. — P. 2182–2217. — DOI: 10.3390/ma6062182.

24. Neville A. M. Properties of Concrete / A. M. Neville. — 5th ed. — Harlow : Pearson Education Limited, 2011. — 846 p.