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Increasing the Corrosion Resistance and Durability of Geopolymer Concrete Structures of Agricultural Buildings Operating in Specific Conditions of Aggressive Environments of Livestock Buildings

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Abstract: The problem of increasing the service life of buildings and structures for agricultural purposes operated in aggressive environments is relevant. The aim and scientific novelty of the work were to determine the relationship between the structure and properties of geopolymer concretes in aggressive environments. The properties of various concrete compositions under the influence of a solution of lactic, acetic, and oxalic acids were studied. With an exposure time of 90 days in an aggressive environment, samples of concrete based on a geopolymer binder had up to 6% less loss of strength and up to 10% less weight loss than concrete based on a cement binder. The effectiveness of the developed composition and technological solutions was confirmed, and it was quantitatively expressed in increased compressive strength and tensile strength in bending by 81.0% and 73.5%, respectively. It has been established that raising the heat treatment temperature to 80 °C leads to increased compressive strength for all compositions of geopolymer binders. The most favorable heat treatment conditions are created at 80 °C. The relations of the strength characteristics of geopolymer binders are revealed, which allow a detailed quantitative and qualitative assessment of the influence of the studied factors on the change in the system "composition—hardening conditions—properties" and can be used in the development of production compositions of binders and composites based on them, as well as their regulation—physical, mechanical, and operational characteristics.

Keywords: fine-grained concrete; geopolymer binder; corrosion resistance; durability; geopolymer concrete structures; compressive strength; flexural tensile strength

1. Introduction

1.1. The Relevance of Research

Enhancing the service life of buildings and structures for agricultural purposes is relevant nowadays. Therefore, the research to improve the durability and efficiency of agricultural facilities should be aimed at the rational use of building materials, products, and structures, as well as the development of new, more resistant, and durable materials, including based on recycled materials, which is dictated by both economic and environmental requirements.

In recent years, much attention has been paid to the problems of corrosion resistance of binders under the influence of media of organic origin. However, the nature of the aggressive impact of the organic environment is determined by processes that rarely occur when concrete structures interact with well-studied mineral aggressive environments.

The range of organic substances that aggressively affect concrete is vast and includes substances that enter direct chemical interaction with non-hydrated minerals and new formations of cement stone.

Increasing the durability of agricultural buildings and structures based on the use of materials from recycled materials requires solving significant scientific and applied problems related to substantiating the choice of materials, developing new technological methods and methods of application, and evaluating the effectiveness of their use in various operating conditions. Furthermore, with lower permeability and sorption, the material has more excellent resistance and, consequently, durability in aggressive media of various origins [1–15]. The paper considers the possibility of regulating concrete quality characteristics by determining the optimal ratio of the components of a modified binder based on fly ash, which makes it possible to increase the corrosion resistance and durability of building structures of agricultural buildings when working in specific conditions of aggressive environments of livestock buildings.

1.2. Literature Review

In Ref. [16], the authors studied the effect of the content of granulated blast-furnace slag (GGBFS) and fly ash (FA) on the durability of high-strength early-age concrete. So, according to the results of experimental studies, the best chloride diffusion resistance properties for 50% GGBFS and 30% FA in HPC were established with a coefficient of 0.37, showing the minimum value, and the effective porosity values decrease as follows: 9.89% for HPC, 7.30% for 30% FA in HPC, and 7.33% for 50% GGBFS in HPC. Furthermore, the assessment of the effect of class F fly ash on the durability of concrete, as carried out in [17], confirms the positive effect of this additive on the durability of concrete. Thus, concrete with the addition of fly ash showed lower water absorption and permeability for chlorides and a significant drop in sorption capacity and permeability for chlorides during the hardening period of 28–180 days [16–18].

So, in Refs. [19,20], the authors studied the mechanical properties and durability of various types of fiber-reinforced concrete. In Ref. [19], the authors studied the mechanism of penetration of chloride ions into a concrete reinforced with basalt fiber during compression after exposure to elevated temperatures. The results showed that the chloride ion content in concrete increases linearly with increasing temperature.

The studies carried out in [21–23] were also aimed at evaluating the durability of various types of binders and concrete. For example, in Ref. [21], the resistance of concrete to carbonization was studied in detail. To assess and predict the durability of the studied concrete, a numerical model was developed that relates the carbonization rate to the drying rate. As a result of the experiments carried out, it was found that the low content of clinker reduces the resistance to carbonization since there is not enough portlandite in the surface layers.

Works [24,25] aim to develop concrete with improved durability characteristics. In Ref. [24], the authors carried out experimental and information modeling to optimize the mechanical properties of an alkali-activated solution made with different concentrations of fly ash, granulated blast-furnace slag, and nano-silica from waste glass.

The effect of temperature on the behavior and properties of self-compacting concrete (SCC) has been studied in [26]. A comparison with a vibrated concrete mixture is given, and a mechanism of increasing the strength of concrete in the temperature range of 150–300 °C is described.

Geopolymer concrete based on fly ash was studied in detail in [27,28]. The analysis was carried out from the point of view of design of geopolymer concrete mixes by identifying significant factors affecting the properties of finished product, from the point of view of a detailed study of both short-term properties and durability indicators of geopolymer concrete, and finally from the point of view of application in the construction industry in the context of the behavior of geopolymer concrete during the operation of large-sized reinforced concrete elements. All the results obtained were also evaluated in comparison with economic and environmental efficiency [27].

In Ref. [29], specific examples of the practical application of geopolymer concrete in construction are given, both in terms of the material and in terms of the structural element. Furthermore, already implemented projects have proven the viability of geopolymer concrete as an alternative to the traditional one based on Portland cement [29].

The search for sustainable alternative concrete mixes to obtain "green concrete" to reduce environmental impact and consider economic efficiency is reflected in studies [30,31]. The effectiveness of alkali-activated concretes (AAC) with natural and recycled coarse aggregates and bacterial concretes (BC) was evaluated by the degree of environmental impact, cost, and global warming potential [30]. Of no small importance is the correct selection of the composition of concrete based on an alkali-activated binder in the form of fly ash and slag as a replacement for cement. Recommendations are given on the rational ratio of the components of concrete cured under environmental conditions, both in terms of strength and economic efficiency [31].

1.3. Assessment of the Degree of Aggressiveness of the Liquid Environment of Livestock Buildings

The chemical composition of the liquid medium obtained during the life of animals depends on the type and number of animals in the room, the method of feeding, watering, keeping animals, and the manure removal system. The liquid medium formed during the life of animals consists of 95.7% water and 4.3% solids: urea 2%, uric acid 0.05%, sodium ion 0.35%, potassium ion 0.15%, magnesium ion 0.04%, calcium ion 0.06%, chloride ion 0.27%, and sulfate ion 0.78% [32]. According to GOST 31384 "Protection of concrete and reinforced concrete structures against corrosion: general technical requirements" [33], aqueous solutions of acids, including uric acid, with a concentration of more than 0.05 g/L, have a highly aggressive effect on concrete.

The types of bacteria that cause these biochemical processes (decay and fermentation of organic substances; nitrification of ammonium compounds; denitrification of nitric and nitrous acids; sulfate reduction; hydrogen sulfide oxidation; chemical formation of carbonic acid) are listed in Figure 1.

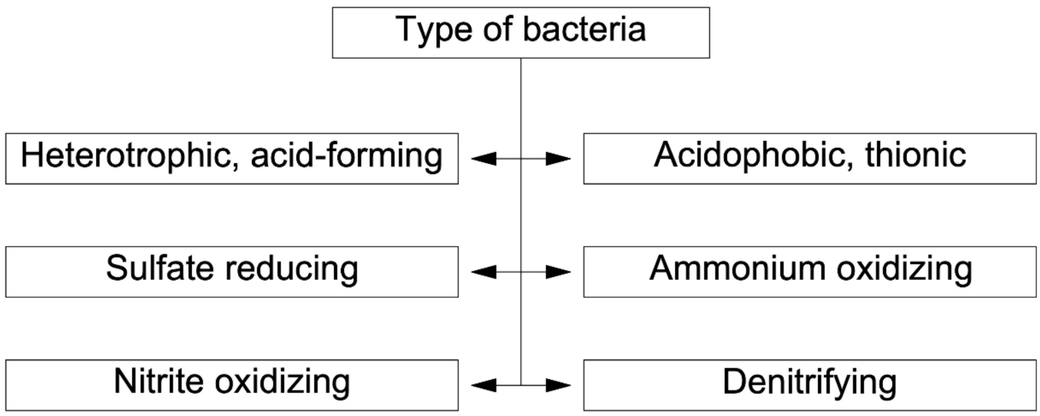


Figure 1. Types of bacteria that cause the above biochemical processes to occur.

The processes leading to the degradation of building composites, including cementless concrete, are united by a common property for heterogeneous reactions; they include several stages in their totality. The first of these is the stage of transferring an aggressively active medium to the surface on which the reaction occurs; at the second stage, the chemical interaction of the medium and the structure of the composite occurs; the third stage consists in the removal of reaction products from the reaction surface. The rate of the slowest stage determines the total rate of the degradation process. When the slow step is a chemical reaction, the concentration of the reactant near the surface is the same as the concentration in bulk, and the observed reaction rate depends on external parameters in the same way as the actual reaction rate on the surface. Such a limiting region of a heterogeneous process is called kinetic. If the slow stage of the process is the supply of reagents to the surface or the removal of reaction products, then the rate of the degradation process is determined by the rate of diffusion, and this limiting region of the heterogeneous process is called diffusion. Finally, if the rates of individual stages of the degradation process are comparable, the process proceeds in the transition region, and the observed reaction rate is determined both by the diffusion conditions and by the actual kinetics of the reaction on the active surface [32].

Thus, it is clear that the development of inevitable destructive processes in the cement stone of concrete and reinforced concrete parts of buildings and structures occurs under the influence of a combination of factors, both of natural origin and those associated with the features of the production process cycle. At the same time, concrete of increased resistance, as a rule, has good resistance to aggressive environments, regardless of the type and origin of the aggressive environment. Therefore, it seems expedient to increase the inherent resistance of concrete structures, using the variability and adaptability of its structure to environmental conditions, ensuring the durability of structures at several levels [34–37].

1.4. Purpose, Objectives, Scientific Novelty, and Practical Significance of the Study

The study aims to search for theoretical and applied solutions in terms of developing the composition and justification of the recipe-technological choice of such a composition of geopolymer concrete for agricultural buildings and structures operating in aggressive environments, with increased corrosion resistance and durability.

The objectives of the study follow:

- Interpretation of existing theoretical concepts and applied experience in terms of the development, application, and operation of geopolymer concrete for agricultural purposes;
- Identification of scientific and practical deficits in research of this kind;
- Development of a program of experimental research and writing a plan for fundamental theoretical studies of structure formation and correlation of properties of geopolymer concrete;
- Processing the results, formulating conclusions, building the obtained dependencies, deriving mathematical models in the form of formulas, graphs, and diagrams to obtain new knowledge about the properties and structure of durable concrete on a geopolymer basis for the agricultural complex.

The scientific novelty of the work is as follows:

- New interpretations of theoretical knowledge will be obtained, and theoretical and applied ideas about the composition, structure, properties, and operation of geopolymer concrete structures for agricultural purposes will be developed;
- Dependencies between the structure and properties of such concrete were determined and established, and an assessment was made using physical and chemical processes in the formation of the quality and operation of these concrete and structures made of them in aggressive environments.

The practical significance of the study lies in the following:

- Obtaining new recommendations for the operation of geopolymer concrete structures with increased reliability, durability, and corrosion resistance in the agricultural complex;
- Obtaining new compositions and recipe-technological recommendations for engineers, technologists, and researchers involved in the development of knowledge and ideas about geopolymer concrete;
- Application of the acquired knowledge and ideas in the real agriculture sector to ensure sustainable development following the goals set by the global framework and UN requirements.

2. Materials and Methods

2.1. Materials

Portland cement grade CEM I 42.5N produced by OAO Novoroscement (Novorossiysk, Russia) was used as a cement binder (CB). The physical and mechanical characteristics and chemical composition of cement are given in Tables 1 and 2.

Table 1. Physical and mechanical characteristics of cement.

Indicator	Units	Indicator Value
Residue on a 45 μm sieve	%	3.5
Blaine specific surface area	cm^2/g	3635
The standard density of cement paste	%	27.7
Beginning of setting	min	138
End of setting	min	187
Compressive strength, 28 days	MPa	52.2
Bending strength, 28 days	Mpa	8.5
Uniformity of volume change	mm	0

Table 2. Chemical composition of cement.

Element	Value, %
SiO_2	20.8
Al_2O_3	4.6
CaO	63.9
Fe_2O_3	3
MgO	3.6
TiO_2	0.2
P_2O_5	0.1
SO_3	2.8
Na_2O	0.1
K_2O	0.5
Na_2O	0.4
insoluble residue	0
Cl	0.01

Fly ash from the Novocherkassk State District Power Plant was used as the main component of the geopolymer binder.

The chemical composition and physical and mechanical characteristics of fly ash are shown in Table 3, and its particle size distribution is shown in Figure 2.

Table 3. Chemical composition and physical and mechanical characteristics of fly ash from Novocherkasskaya GRES.

Elements	Value
SiO_2, %	55.9
TiO_2, %	1.05
Al_2O_3, %	35.9
Fe_2O_3, %	1.67
CaO, %	0.85
MgO, %	1.35
MnO, %	0.36
K_2O, %	0.51
Na_2O, %	0.90
SO_3, %	1.28
P_2O_5, %	0.15
Loss on ignition, %	0.08
Bulk density, kg/m^3	480
True density, kg/m^3	2600
Activity index, %	after 28 days—80; after 90 days—89
Dispersity index, %	residue on sieve 45 μm—24

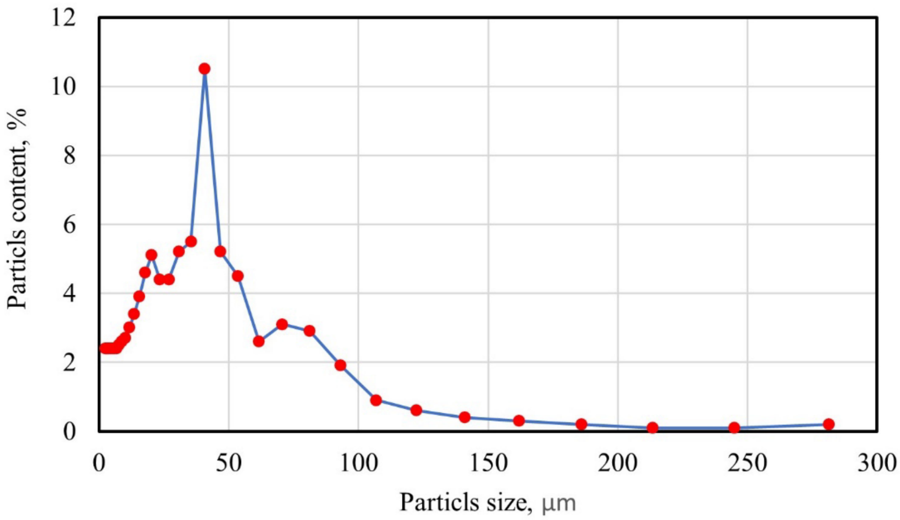


Figure 2. Particle size distribution of fly ash by size.

According to the data presented in Figure 2, it can be seen that the main size distribution range of the studied fly ash particles is within 2–200 microns. The main peak falls at 45 µm, and the predominant part of the grains (more than 75%) is located in the range from 6 to 35 µm.

X-ray phase analysis of fly ash particles is shown in Figure 3.

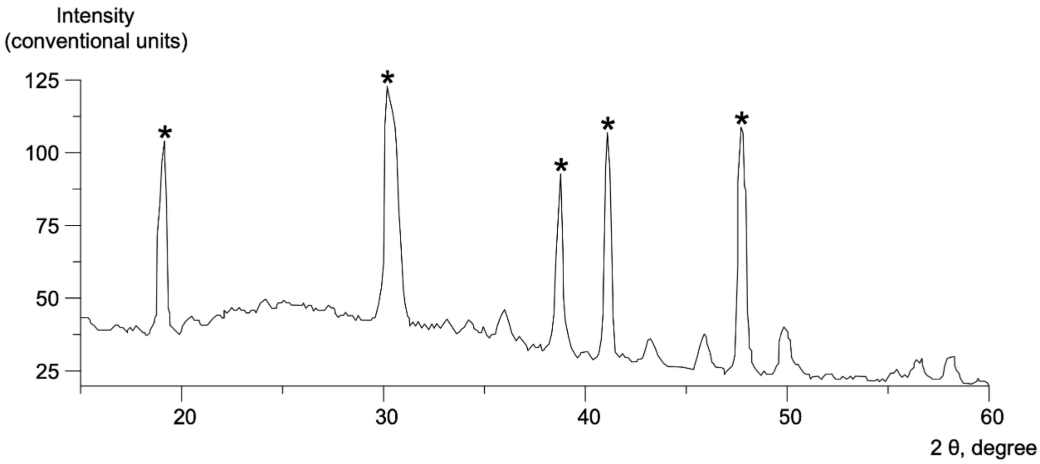


Figure 3. Diffraction pattern of fly ash microsphere samples (*—mullite phase).

According to XRD data, microspheres are represented by a mixture of $Al_6Si_2O_{13}$ mullite phases and an amorphous X-ray phase, which is referred to as a glass phase, while the mullite phase is the main one.

Sodium hydroxide (NaOH) produced by PJSC "Khimprom" (Novocheboksarsk, Russia), potassium hydroxide (KOH) produced by Soda-Chlorate (Berezniki, Russia), and water glass (Na_2SiO_3) produced by JSC Kubanzheldormash (Armavir, Russia) were used as alkaline activators. Characteristics of the alkaline activators used in work are presented in Table 4,Table 5 and Table 6.

Table 4. Characteristics of NaOH.

Title	Value
Mass fraction of sodium hydroxide, %, not less than	98.5
Mass fraction of sodium carbonate, %, no more	0.8
Mass fraction of sodium chloride, %, no more	0.05
Density, kg/m^3	2020

Table 5. Characteristics of KOH.

Title	Value
Mass fraction of KOH, %, not less than	90.52
Mass fraction of K_2CO_3, %, no more	0.39
Density, kg/m^3	2044

Table 6. Characteristics of sodium liquid glass.

Title	Value
Mass fraction of silicon dioxide, %	36.7
Mass fraction of sodium oxide, %	13.3
silicate module	23.3
Density, kg/m^3	1500

Quartz sand was used as a fine aggregate, the physical characteristics of which are presented in Table 7.

Table 7. Physical characteristics of dense fine aggregate.

Grain Composition							Pass Through a Sieve with Mesh No. 0.16, wt%	Size Modulus	Content of Dust and Clay Particles, %	True Density, kg/m^3	Bulk Density, kg/m^3
Sizes of Sieve Openings, mm											
Residues on Sieves		Private and Total Residues on Sieves, %									
10	**5**	**2.5**	**1.25**	**0.63**	**0.315**	**0.16**					
0	0	0.17	1.39	8.86	45.80	41.03	2.49	1.66	1.1	2650	1438
		0.17	1.56	10.42	56.21	97.25	99.74				

2.2. Methods

To carry out the granulometric analysis of fly ash particles, a Microsizer 201C laser particle analyzer (OOO VA Insult, St. Petersburg, Russia) was used. It is a fully automated instrument designed to quickly and accurately measure the particle size distribution in the range of 0.2–600 μm.

X-ray studies (XRD) were carried out on an X-ray diffractometer HZG-4C (Freiberger Prazisionmechanik, Berlin, Germany) on monochromatized CoK_{α} radiation in a continuous range of angles of $2\theta = 15-60°$.

Three beam samples (40 mm × 40 mm × 160 mm) were made for each experimental composition.

The production of geopolymer samples was carried out following the requirements of GOST 30744 "Cements. Methods of testing with using polyfraction standard sand" [38].

Tensile bending tests were performed using the same load model as described in GOST 30744 (Figure 4).

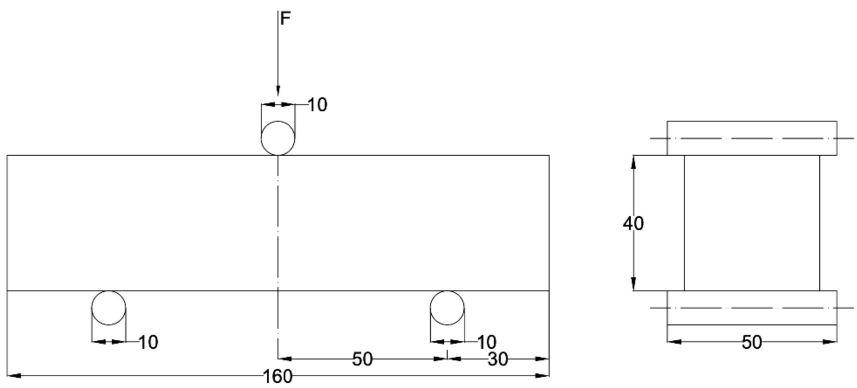


Figure 4. Scheme of the bending test of concrete beam specimens.

The sample was placed on the base plate of an IP-1000 hydraulic press (OOO NPK TEKHMASH, Neftekamsk, Russia) in a bending test device (OOO Kontros, Solnechnogorsk, Russia) and loaded at an average rate of load increase (50 ± 10) N/s. The error of the device when measuring the load was not more than ±1% in the upper 4/5 of the measurement range. The gripper for fixing the sample was equipped with cylindrical elements made of stainless steel with a hardness of 56–61 HRC. A photo of the bending test is shown in Figure 5.

Figure 5. Destruction of a sample-beam of concrete for tensile strength in bending.

The bending strength R_{btb}, MPa, of a single sample-beam was calculated by Formula (1):

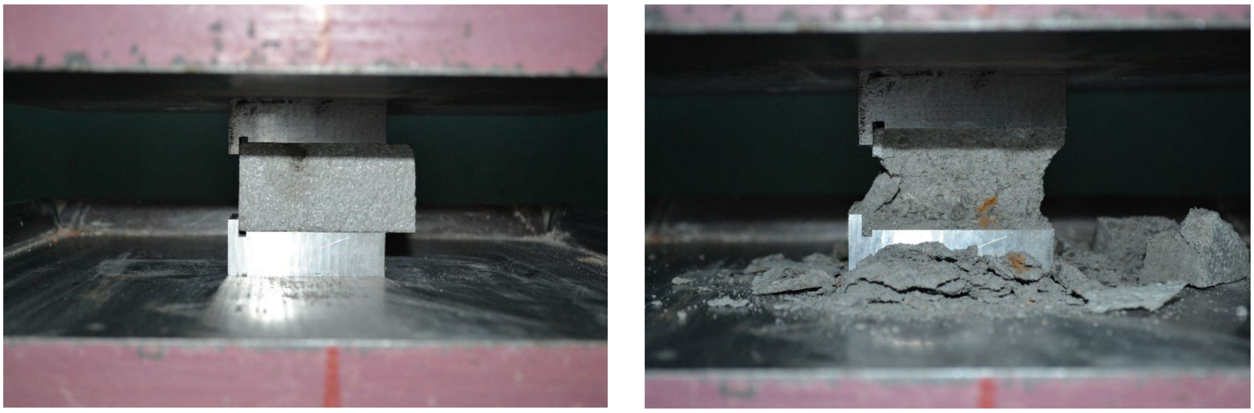
$$R_{btb} = \frac{1.5Fl}{b^3}, \quad (1)$$

where F is the breaking load, N; b is the size of the side of the square section of the sample-beam, mm; and l is the distance between the axes of the supports, mm.

For bending strength, the arithmetic mean of the test results of three samples was taken. The calculation result was rounded up to 0.1 MPa.

The compression test was carried out by loading the specimens in the pure compression mode. The load measurement error did not exceed ±1% in the upper 4/5 of the measurement range. The IP-1000 press is equipped with a movable ball bearing to compensate for the spatial non-parallelism of the reference faces of the sample and was equipped with pressure plates for transferring the load of the PLB (Kontros LLC, Solnechnogorsk, Russia) to the halves of the beam specimens and a device for centered installation of pressure plates, the displacement of which relative to the axis of the loading system did not exceed ±0.5 mm. Pressure plates are made of stainless steel with hardness not less than 60 HRC, thickness not less than 10 mm, width of (40 ± 0.1) mm, and length of (40 ± 0.1) mm.

Photos of the compression test are shown in Figure 6.



(**a**) (**b**)

Figure 6. Testing samples-half beams for compressive strength: (**a**) before testing; (**b**) after testing.

The compressive strength R_b, MPa, of a separate half of the sample-beam, tested for bending, was calculated by the formula:

$$R_b = \frac{F}{S}, \quad (2)$$

where F is the breaking load, N; and S is the area of the working surface of the pressure plate, mm^2.

The arithmetic mean of the test results for six halves of beam specimens was taken for compressive strength. The calculation result was rounded up to 0.1 MPa.

The chemical resistance of concrete was evaluated by comparing the actual coefficient of chemical resistance $K_{\text{ch.r}}$, which was determined on a series of samples (3 samples of beams 40 × 40 × 160 mm) kept in the environment for 90 days.

The coefficient of chemical resistance $K_{\text{ch.r}}$ was determined by the change in the compressive strength of the samples after each test period according to the formula:

$$K_{ch.r} = \frac{R_t}{R_0}, \quad (3)$$

R_t is the compressive strength of a series of specimens after holding in the medium for 90 days; R_0 is the compressive strength of a series of samples not immersed in the medium.

The heat treatment of the samples was carried out in a heat treatment chamber KUP-1A (JSC Smolenskoe SKTB SPU, Smolensk, Russia).

The study also used the following:

- Technological equipment—laboratory mortar mixer BL-10 (ZZBO LLC, Russia, Zlatoust); laboratory vibration platform SMZh-539-220A (OOO IMASH, Armavir, Russia) [39–43];
- Measuring instruments—metal measuring ruler 500 mm; laboratory scales [44,45].

3. Results

3.1. Designing the Composition and Properties of Geopolymer Binders Based on Fly Ash

Geopolymer binder (GB) is an inorganic polymer synthesized as a result of the reaction between a solution of an alkali or alkaline earth metal and an aluminosilicate component in the temperature range of 25–120 °C. The low-temperature process leads to a rapid setting of the material, which exhibits sufficiently high hardness and strength, indicating that geopolymers have similar properties to cement.

When choosing raw materials for the production of geopolymer binders, it is necessary to take into account such features as the origin of the aluminosilicate component: starting material, methods, and temperature of combustion, methods for removing ash from filters, etc., and chemical properties of the alkaline component in terms of its activating ability.

These factors have a significant impact on the kinetics and nature of structure formation, as well as geopolymerization products, and, ultimately, on the main performance characteristics of the finished binder.

According to literature sources [1–14,28,30,31,46], Na_2SiO_3, NaOH, and KOH are used as the most common alkaline components to obtain geopolymers. The choice of alkaline activators data is explained by the highest reactivity of the aluminosilicate component with respect to the glass phase and athermicity during their production.

So, to evaluate the effectiveness of the alkaline component, two control compositions of GB were made. In the first case, a solution based on sodium silicate and sodium hydroxide in a ratio of 1:1 was used as an activator of the hardening process. The concentration of the sodium hydroxide solution was 8 mol/L. In the second case, a solution based on sodium silicate and potassium hydroxide in a ratio of 1:1 was used as an activator of the hardening process. The concentration of the potassium hydroxide solution, as in the first case, was 8 mol/L.

In order to select the most effective alkaline component of the GB systems under study, beam samples were molded (three beams in a series, two series in total for each case).

Freshly molded products were placed in an environment with a temperature of 20 ± 5 °C; relative humidity of 45–50%, and kept for 24 h, after which the samples were subjected to heat treatment (HT) according to the following regime:

- Rise in temperature—4 h;
- Isothermal exposure—16 h;
- Temperature drop—4 h.

The isothermal holding temperature was 65 °C. In this case, the pre-exposure time before HT was chosen as a universal value sufficient for aluminosilicate components of varying degrees of activity and to ensure equality of experimental conditions.

The test results of these compositions are presented in Table 8.

Table 8. Strength characteristics of control compositions of geopolymer binders.

Composition Marking	Series No.	Compressive Strength of a Series of Samples, MPa	Average Compressive Strength, MPa	Tensile Strength in Bending, MPa	Average Tensile Strength in Bending, MPa
1N	1	29.2	28.5	3.2	3.4
	2	27.8		3.6	
2K	1	4.4	4.8	0.7	0.6
	2	5.2		0.5	

Analyzing the results of the test, it should be noted that the binder samples using the Na_2SiO_3:KOH combination as an alkaline activator have very low strength properties. Based on this, KOH is an ineffective activator for the studied fly ash. From a chemical point of view, it can be assumed that this phenomenon is probably associated with a large atomic radius of potassium, which leads to loosening of the structure of aluminosilicates and prevents the binding and structuring of the system.

The most reactive alkaline activator is the Na_2SiO_3:NaOH combination; this activator provides the highest compressive strength of geopolymer concrete.

The greatest reactivity of NaOH is explained by the fact that sodium ions have a large radius of the electron shell (an indicator of the degree of electrochemical activity). Therefore, when interacting with water, the substance wholly and quickly dislocates in water, easily giving up Na + ions. In this regard, aqueous solutions of NaOH have a consistently strong alkaline reaction for a long time, providing conditions for the dissolution of the aluminosilicate component and the further occurrence of structure-forming processes.

At the second stage of the experiment, an assessment was made of the effect of the NaOH concentration and the HT regime on the strength characteristics of concrete based on GB. The plan of the second stage of experimental studies is presented in Table 9.

Table 9. Experimental plan for evaluating the effectiveness of the effect of NaOH concentration and the HT regime on the strength characteristics of concrete based on GB.

Composition Marking	Type of Alkaline Activator	Hydroxide Concentration, mol/L	Heat Treatment Temperature, °C
1N			65
2N		8	75
3N			85
4N			65
5N		10	75
6N			85
7N			65
8N	Na_2SiO_3:NaOH÷(1:1)	12	75
9N			85
10N			65
11N		14	75
12N			85
13N			65
14N		16	75
15N			85

As output parameters, similarly as in the first stage of experimental studies, the compressive strength and tensile strength in bending of specimen beams based on fly ash were evaluated. Again, the strength indicators of experimental samples were determined at 28 days. The results of the obtained data are presented in Table 10 and in Figures 7 and 8.

From Table 10 and Figures 7 and 8, it can be seen that the maximum values of ultimate compressive strength and tensile strength in bending were recorded for specimens of composition type 11N and are respectively equal to 51.5 MPa and 6.2 MPa, which correspond to a processing temperature of 75 °C and NaOH concentration equal to 14 mol.

Thus, the heat treatment temperature, equal to 75 °C, is the most optimal for the obtained GB based on fly ash.

Analyzing the effect of sodium hydroxide concentration on the strength characteristics of GB, it can be seen that in the range of sodium hydroxide concentration from 8 to 14 mol/L, an intensive increase in the strength characteristics of GB samples is observed. However, as the concentration of NaOH increases to 16 mol/L, the values of strength characteristics begin to decrease. Thus, the concentration of sodium hydroxide solution, equal to 14 mol/L, is the most effective for the obtained GB based on fly ash.

Table 10. Results of determining the compressive strength and tensile strength in bending of concrete based on GB.

Composition Marking	Compressive Strength, MPa	Tensile Strength in Bending, MPa
1N	28.5	3.4
2N	37.8	4.5
3N	36.5	4.0
4N	37.5	4.5
5N	41.8	5.5
6N	40.8	4.9
7N	40.7	4.9
8N	44.4	5.3
9N	43.5	5.2
10N	45.7	5.5
11N	51.5	6.2
12N	48.9	5.9
13N	46.9	5.5
14N	48.7	5.7
15N	47.8	5.7

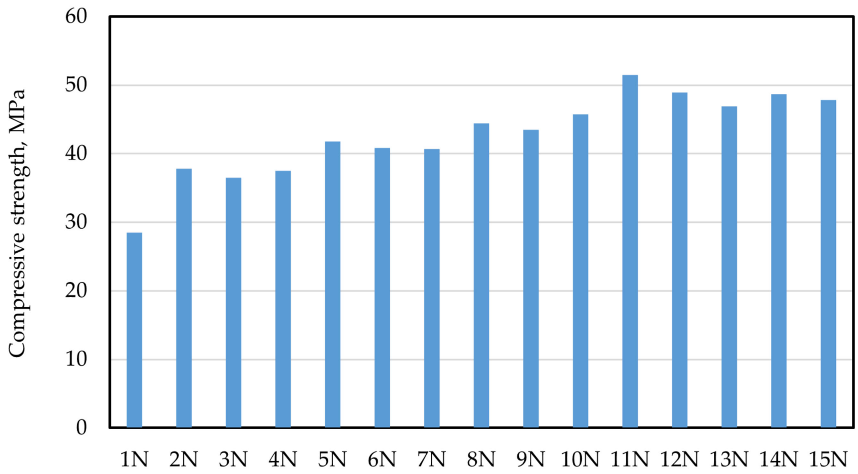


Figure 7. Dependence of the compressive strength of GB samples on the concentration of NaOH and the mode of HT.

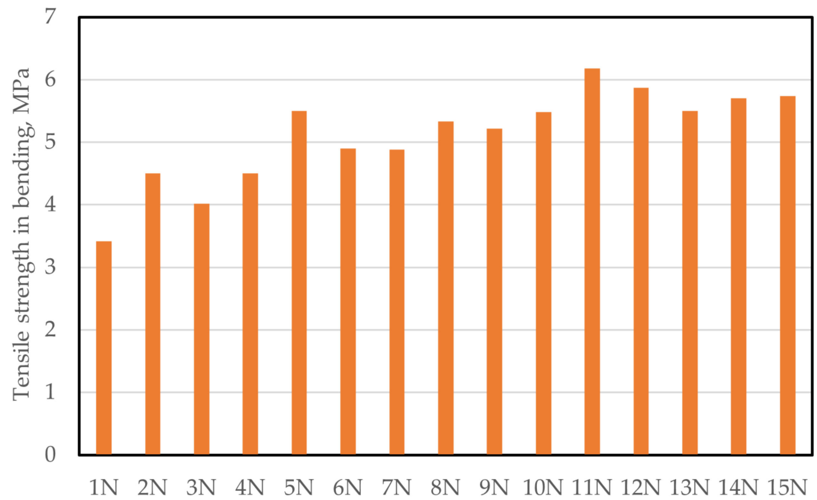


Figure 8. Dependence of the tensile strength in bending of GB samples on the concentration of NaOH and the mode of HT.

3.2. Development of the Composition of Fine-Grained Concrete (FGC) Based on Fly Ash and Evaluation of its Corrosion Resistance

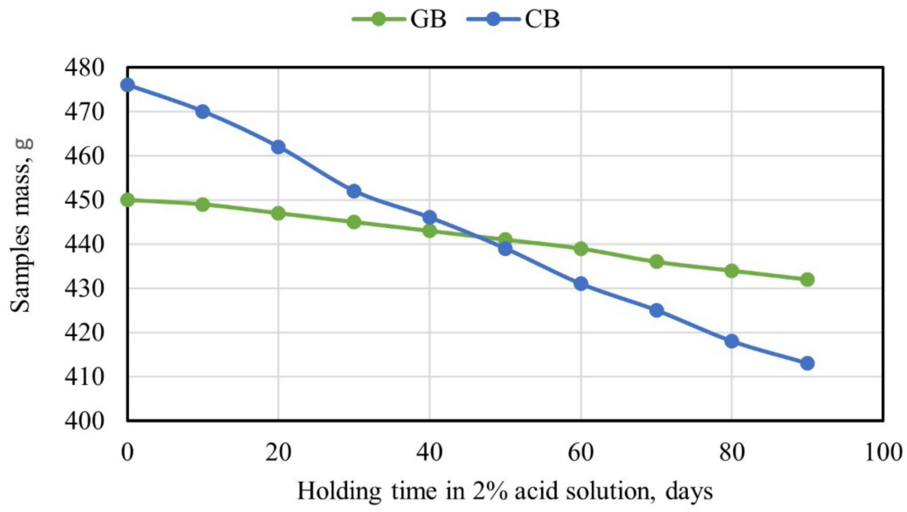
Within the framework of this work, studies were carried out to study the corrosion resistance of FGC based on the optimal compositions of GB.

A 2% mixture of a solution of lactic, acetic, and oxalic acids was chosen as an aggressive medium for the experiment. This choice of a mixture of acids is justified by the organogenic nature of corrosion resulting from the vital activity of microorganisms on the surface of concrete structures, which in the process of metabolism release organic acids that form complex compounds with the components of silicates and aluminosilicates, as well as easily soluble calcium salts.

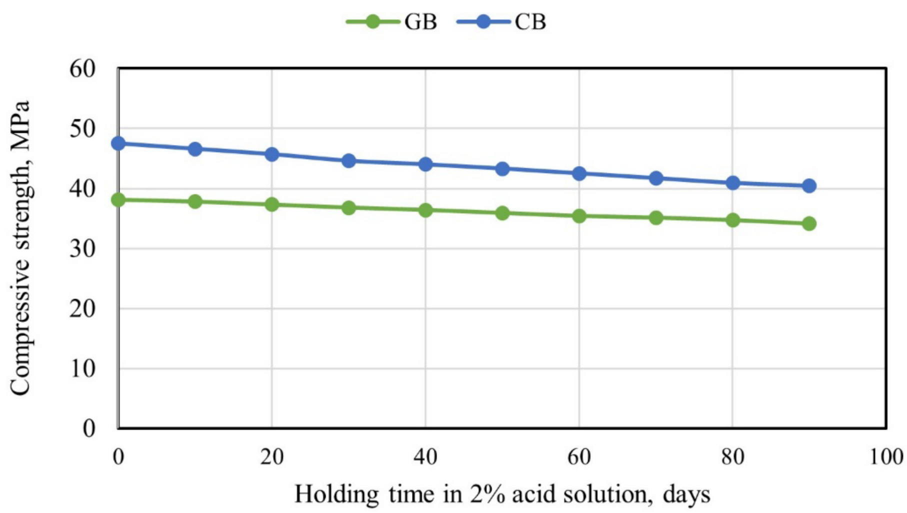
For the test, samples–beams of mortar mixtures were molded based on the optimal compositions of GB as well as a cement–sand mortar in the ratio of binder/sand—1/3.

The experimental samples were kept in the above-mentioned aggressive environment for 90 days with a control measurement of the weight loss and strength of the samples every 30 days.

As the main indicators of the corrosion resistance of the developed FGC compositions, the following were chosen: the change in the compressive strength and the change in the mass of experimental samples over time (Figure 9 and Table 11).



(**a**)



(**b**)

Figure 9. Kinetics of changes in the parameters of experimental FGC compositions over time under conditions of exposure to a 2% mixture of a solution of lactic, acetic, and oxalic acids (CB—samples on a cement binder; GB—samples on a geopolymer binder): (**a**) masses; (**b**) compressive strength.

Table 11. Main indicators of corrosion resistance of the developed FGC compositions in 2% acid solution.

Indicator	Type of Binder	Exposure Time in an Aggressive Environment, Days								
		10	20	30	40	50	60	70	80	90
Loss of compressive strength, %	On a geopolymer binder	0.8	2.1	3.4	4.5	5.8	7.1	7.9	8.9	10.5
	On a cement binder	1.9	3.8	6.1	7.4	8.8	10.5	12.2	13.9	15.7
Mass loss, %	On a geopolymer binder	0.2	0.7	1.1	1.6	2.0	2.4	3.1	3.6	4.0
	On a cement binder	1.3	2.9	5.0	6.3	7.8	9.5	10.7	12.2	13.2

Under conditions of aggressive action, for all FGC compositions, there is a tendency of a decrease in compressive strength within 10–16% (Table 11). The nature of the change in the strength of experimental samples is ambiguous and tends both to increase with an increase in the time of aggressive action of the medium and decline. The loss of compressive strength under conditions of exposure to a 2% acid solution at the age of 90 days for fine-grained geopolymer concrete based on fly ash is less than 5% in comparison with the loss of strength of samples made from the cement–sand mortar.

As for the weight loss of the FGC samples under the aggressive action of a 2% acid solution, the same trend is observed here as in the analysis of the loss of strength characteristics. For FGC samples on HPV, the weight loss did not exceed 4%, and the weight loss for FGC samples on CV was about 14% (Table 11).

Thus, the value of the coefficient of chemical resistance for FGC on HPV was 0.9, and the value of the coefficient of chemical resistance for FGC on CV was 0.86.

It should be noted that the developed FGC compositions based on HPV in terms of controlled indicators of compressive strength loss and weight loss, in comparison with samples of cement–sand mortar, demonstrate higher corrosion resistance.

4. Discussion

In order to evaluate the scientific novelty and practical significance of the study, it is necessary to perform a comparative analysis between the study and the results obtained earlier by other authors.

It is conditionally possible to divide the studies conducted by other authors by grouping them into several groups of factors. For example, some authors [12,15,18–20,23–25,34,36] were engaged in research aimed at improving the corrosion resistance of cement-based concrete, which are the most traditional type of concrete in current construction but are not environmentally friendly and cheap, leaving a high carbon footprint and not in line with the modern ESG agenda. Other authors [7–11,22,27,29,31,35] were engaged in developing compositions of geopolymer concrete aimed at improving the mechanical properties of such concrete: their strength and improvement of deformation properties.

However, mechanical properties alone are not enough for a number of industries. So, for agricultural construction, it is also necessary to maintain such a recipe, technology, and concrete composition, which increase the durability and corrosion resistance due to the specifics of such structures. Thus, we have conducted a study in which the physical and mathematical apparatus is phenomenologically specified and technological tools are used, which are based on existing knowledge and ideas about the operation of geopolymer concrete in aggressive environments. Based on the data obtained earlier by other authors [1–14,26–31], in terms of heavy concrete on a standard cement binder and geopolymer concrete with improved mechanical characteristics, we set a methodology, defining a range of certain assumptions and frameworks to improve and increase durability and corrosion resistance.

To do this, we have developed a unique methodology that differs from earlier studies, including the study of the impact of various aggressive substances on concrete made according to the developed compositions. Algorithmically, our study can be presented in the form of a diagram that simultaneously reflects the prescription aspect, which is expressed in the development of a new composition and its dosage, and the technological aspect, reflecting the order of components applied and the concrete manufacturing process. The research aspect is expressed in a deep study of not only the characteristics of concrete but also analysis of its composition from the point of view of the processes of physics and chemistry that occur during the formation of this concrete and when it works in an aggressive environment. Finally, there is also an applied aspect based on practical research and modeling of the operating conditions of concrete through the use of aggressive substances to obtain new knowledge about the work of this concrete in real conditions. At elevated temperatures, the reaction is faster. Under natural conditions, the reaction rate will be less, and the kinetics of concrete strength gain will also slow down.

Thus, after analyzing the qualitative picture of the study, we also reflect on the quantitative characteristics of this experiment. Thus, the increase in compressive strength of the studied concrete was 81%, the tensile strength in bending increased by 72% in the composition 11N compared to the initial composition 1N, which was taken as a control and in relation to which results were obtained that are scientifically and practically significant and recommended for implementation.

As shown above, this effect is explained by the fact that sodium ions have a large electron shell radius (an indicator of the degree of electrochemical activity); therefore, when interacting with water, the substance quickly and completely dissociates in water, easily giving up Na + ions. In this regard, aqueous solutions of NaOH have a consistently strong alkaline reaction for a long time, providing conditions for the dissolution of the aluminosilicate component and the further occurrence of structure-forming processes.

Prospects for further research are seen in obtaining new knowledge and developing theoretical ideas about the work of the composition developed by us in other aggressive substances, as well as under cyclic influences, for example, during freezing–thawing, moistening–drying, and dynamic mechanical influences during the work of our concrete used in specific designs and areas.

5. Conclusions

The study, aimed at improving the corrosion resistance and durability of geopolymer concrete structures of agricultural buildings, reflects qualitatively and quantifies the ability and effectiveness of geopolymer concrete when working in specific conditions of aggressive environments of livestock buildings:

(1) Its suitability and applicability for the indicated conditions have been proved, and its operation under the influence of such an aggressive environment as a mixture of a solution of lactic, acetic, and oxalic acids has been verified. With a duration of exposure to an aggressive environment of 90 days, concrete samples based on HPV had up to 5% less loss of strength and up to 10% less weight loss compared to concrete based on CV.

(2) It has been determined that the most reactive alkaline activator for the studied fly ash in the production of concrete based on HPV is the combination of Na_2SiO_3:NaOH (1:1).

(3) The effectiveness of the developed composition and formulation and technological solutions was confirmed, which is quantitatively expressed in the increase in characteristics in terms of "compressive strength" and "tensile strength in bending" by 81% and 72%, respectively.

(4) The most effective concentration of NaOH was determined—14 mol/L.

(5) It has been established that an increase in the HT temperature to 75 °C leads to an increase in the compressive strength for all compositions of concrete based on HPV. The most favorable heat treatment conditions are created at a temperature of 75 °C.

(6) The relations of changes in the strength characteristics of geopolymer binders are revealed, which allow a detailed quantitative and qualitative assessment of the influence of the studied factors on the change in the system "composition—hardening conditions—properties" and can be used in the development of production compositions of binders and composites based on them, as well as their regulation, physical, mechanical, and operational characteristics.

(7) The possibility of increasing the durability of structures of agricultural buildings and structures through cost-effective building materials made based on production waste and local raw materials has been substantiated and experimentally confirmed.

(8) The vector of further development of research in the direction of progress in the theory of geopolymer concrete and reduction of the carbon footprint in the production of cementless building composites of a new type has been determined; the current research and practical agenda for similar research in areas related to sustainable development following the UN goals have been determined as well.

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