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Review Paper

Advance concrete and technologies for construction in Arctic Zone

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Abstract: Today, in the Arctic and sub-Arctic regions, measures are being taken to build social infrastructure, airfields and facilities serving them, as well as autonomous residential complexes. In Russia, the development of new regulatory documents for construction in the Arctic Circle was initiated, the basis for which will be the ongoing scientific research. The paper analyzes the parameters that affect the service life of structural concrete in the Arctic, and provides examples of corrosion-resistant concrete and durable structures creating for unfavorable natural operating conditions in the harsh climatic conditions of the North. It is shown that in order to ensure the efficiency of construction in the Arctic, it is necessary to update regulatory documents for the full life cycle in terms of design, material requirements, construction technology, and, finally, inspection and repair.

Keywords: Arctic zone, development trends, concrete and technologies, durability, technical regulation.

1. Introduction

The Arctic zone of the Russian Federation has an area of about 9 million km^2 and is home to 2.5 million people, which is less than 2% of the country's population and about 40% of the population of the entire Arctic of the globe. In Evenkia and Taymyr, the population rate is only 1-2 people per 30 km^2.

The most powerful industrial complex has been created in the Arctic zone of the Russian Federation, and the scale of economic activity significantly exceeds the indicators of other polar countries: 15 % of the country's GDP is created in the Arctic, and about a quarter of Russia's exports are provided. The share of added value of extractive industries and enterprises is unprecedentedly high here. It amounts to 60% (for example, in Greenland, Norway, Sweden, Finland, Iceland - no more than 15%; in Alaska and Arctic Canada - about 30%). Two thirds of the total wealth of the Arctic is created in Russia.

Today, activities are underway in the Arctic and subarctic regions to build social infrastructure, airfields and facilities serving them, as well as autonomous residential complexes. According to the Ministry of Defense of the Russian Federation, in the Arctic, in recent years, new 425 facilities have been put into operation, more than 770 buildings and structures of military infrastructure with a total area of more than 1,400 thousand m^2 have been constructed, including 590 facilities with a total area of more than 720 thousand m^2 using innovative technologies. In accordance with the adopted Strategy for the development of the Arctic zone of the Russian Federation and ensuring national security in the Arctic zone it is planned to build additionally 6 military camps, 13 airfields, a ground aviation range, 10 technical positions for radar stations and aviation guidance points [1].

No other country in the world has carried out such large-scale construction. It should be added that the development of oil and gas fields on the continental

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shelf of the Arctic seas is the most important national economic problem that determines the development of the fuel and energy complex of the entire country.

Thus, construction in the Arctic is highly diversified and includes both civil and industrial construction facilities and infrastructure development, erection of special structures, main pipelines, etc. It is clear that this requires the development and application of efficient concretes of a given functionality and performance, as concrete and reinforced concrete still remain among the main construction materials.

2. Peculiarities of construction in the Arctic zone

The Arctic zone is characterized by extreme natural conditions, namely, low temperatures throughout the year, long polar night and long polar day, frequent magnetic storms, strong winds and blizzards, dense fogs, monotonous Arctic deserts and tundras, permafrost, and high dynamics of climate change in recent decades, significantly outpacing the global average. Natural extremes are intensified by the negative impact of socio-economic factors - transport inaccessibility, high production costs and cost of living, underdeveloped economy and tendencies to its monopolization, isolation and dispersed settlement.

The share of transportation costs in the final cost of production in the Arctic zone reaches 60% (the national average is 10%). The population's livelihood and economic activity depend crucially on the supply of fuel, food, and industrial goods along the Northern Sea Route during the limited period of polar navigation. Extreme natural conditions oblige to create local reserve and insurance systems everywhere in the Arctic cities and towns, as well as to ensure minimum material intensity of any production, including construction.

Construction in the Arctic is complicated by the great remoteness from the places of production of most building materials and structures. Often, construction is carried out on islands, and all construction materials are imported from the mainland. Three types of transportation of general cargo and inert materials are used for delivery of construction materials: road, rail and water. At the same time, delivery is possible only during the summer navigation period - only 4-5 months a year.

The third, modern wave of development of the Russian Arctic has shown that construction above the Arctic Circle requires special rules. Today, builders are forced to use documents that do not meet either technical innovations or the changed climate of the Far North, which continues to warm little by little. That is why the Ministry of Construction of the Russian Federation initiated the development of new rules for construction above the Arctic Circle, the basis for which will be the ongoing scientific research.

Conventionally, we can distinguish several main factors affecting the service life of concrete and reinforced concrete structures in the Arctic conditions. They are: environmental parameters (maximum values of pressure (load) created by the impact of ice on the structure; maximum parameters of hydrodynamic damping (vibration from ice load); seismic zoning, etc.), physical and technical characteristics of concrete (strength; its volumetric mass; concrete structure; resistance to freezing and thawing; thermal characteristics of concrete, including thermal conductivity, heat capacity and coefficient of linear expansion; stability of concrete in the Arctic, etc.); level of reinforcement; use of fibers (including polymer fibers); state of reinforcement, which is related to corrosion caused by chemical or electrochemical effects of the external environment (Russian normative documents distinguish several degrees of reinforcement corrosion), etc.), and finally, secondary protection of structures, where permissible, and in-service maintenance (use of polymers to impregnate concrete to increase strength and reduce permeability; coatings to reduce ice adhesion; protection against freeze-thaw degradation in water-filled cracks; selection of repair materials, etc.).

3. Approaches to creating durable concrete for the Arctic

Based on experience in the Arctic zone of the Nordic countries [2, 3], the standard concrete for offshore platforms, for example, is concrete of compressive strength class B70, which corresponds to an empirical abrasion rate of 0.05 mm/km at a total normal ice pressure of 1 MPa. The actual abrasion rate for this case is 0.025 mm/km. The theoretical abrasion depth would result in a loss of 350 mm in 20 years without any protection measures. Concretes with low water-binding ratio of 0.35 - 0.45 made using high performance polycarboxylate superplasticizers and air-entraining (or gas-forming) admixtures are typical in road construction.

The Russian experience of technical surveys, laboratory and field tests of concrete and structures shows that there is a real possibility of creating durable structures for the most unfavorable natural conditions of operation in the North harsh climate conditions [4].

Our studies show, for example, that the joint application of effective superplasticizers with active mineral additives of microsilica contributes to reducing the rate of sulfate ions absorption by cement-sand mortar on sulfate-resistant Portland cement by 5 times and on medium-aluminate Portland cement by 2 times; increasing the resistance coefficient of concrete on high-aluminate Portland cement by 2 times; reduction of expansion strain by 1.5-3 times, and allows to obtain concrete of high grades of water resistance W16 and higher, which has a positive effect on the corrosion resistance of concrete.

Studies [5] have shown that simultaneous application of such multifunctional chemical admixtures allows to obtain concretes with very low permeability, to prevent accumulation of dangerous amounts of chlorides in the zone of reinforcement location. Table 1 presents some test results, from which it can be seen that due to the right combination of the protective layer thickness with low diffusion coefficient/low permeability of concrete, reinforced concrete structures designed for marine environment are fully protected from chloride corrosion.

Table 1 Chloride diffusion in concrete containing microsilica and superplasticizer

W/C	Diffusion coefficient, m^2/sec		
	13 days	44 days	354 days
0.254	$5.52 \cdot 10^{-12}$	$3.68 \cdot 10^{-12}$	$0.596 \cdot 10^{-13}$
0.292	$10.67 \cdot 10^{-12}$	$4.01 \cdot 10^{-12}$	$0.815 \cdot 10^{-13}$
0.332	$10.30 \cdot 10^{-12}$	$4.67 \cdot 10^{-12}$	$0.744 \cdot 10^{-13}$

Generally speaking, active mineral admixtures (supplementary cementitious materials - SCM) have been intensively used in recent years in modern concrete technology, providing a reduction in the cost of concrete, increasing durability, reducing shrinkage deformations and fulfilling the requirements of the concept of sustainable development, first of all, in terms of reducing the level of “greenhouse gas” emissions and energy intensity [6]. It is important to emphasize that the optimization of the particle size distribution in concrete allows reducing a cement content without loss of its strength. In this regard, the water-binding ratio plays a more important role than the W/C ratio

This predetermines the need to supplement a number of domestic standards with the introduction of an important guiding principle - the concept of k-factor, described in detail in EN 206:2013+A2:2021 for fly ash, microsilica and finely ground granulated blast furnace slag.

The k-factor concept is based on a comparison of the durability and performance parameters (or strength as a proxy criterion where appropriate and acceptable) of a cement-based reference concrete with a test concrete in which part of the cement has been replaced by an SCM. It allows the specifics of the Type II additive to be taken into account by replacing the term “water-cement ratio” with the ratio of water / (cement + k × SCM). The amount of binder (cement + k × SCM) should not be less than the required minimum cement content for the relevant exposure classes.

Modern practice of critical structures construction shows that with cement consumption at the level of 230 kg/m^3 with the use of SCM it is possible to obtain concrete B60 W10 with low exotherm based on self-compacting mixtures. The average value of the effective diffusion coefficient of carbon dioxide in concrete is 0.0189×10^{-4} cm^2/s, which corresponds to concrete of especially low permeability according to GOST 31383 (effective CO^2 diffusion coefficient D` < $0.04 \cdot 10^{-4}$ cm^2/s). The reinforcement in such concrete, as shown by our studies, is in a stable passive state.

In the North special and hydraulic engineering construction, concrete of reinforced concrete structures should have higher requirements for frost resistance (up to frost resistance grade F_2500 - F_2600 in salts) depending on the operating conditions, which predetermines the need to use special chemical admixtures - so called concrete multifunctional modifiers - PFM. Application of PFM increases the total air content in concrete mixture up to 4-6 %, while the volume of conditionally closed pores in concrete (A - value, V_c) is 3-4 %, the spacing factor (L- value) does not exceed 0.25 mm. When using aggregates and cements that do not fully meet the requirements of the standards, justification studies according to GOST 26633-2015 are required. In this case, concrete frost resistance tests should be carried out when reaching its critical values.

It should be emphasized that for concrete, including high-strength and ultra high-strength concrete, designed for Arctic operating conditions, it is necessary to additionally develop a method for determining frost resistance for temperatures of minus 55 - minus 65 ˚C with subsequent amendments to GOST 10060-2012.

The developed compositions of very high-strength ordinary concretes and fine-grained fast-hardening concretes with compressive strength at the age of 1 day not less than 50 MPa and at the age of 28 days not less than 80 MPa, and in most cases - at the level of 100-120 MPa, allow to carry out the design of structures with a significant reduction in their material intensity using the traditional calculation apparatus, as for conventional concretes [7]. The revealed increased indices of frost resistance and water resistance of especially high-strength fast-hardening concretes (frost resistance exceeds the mark $F_1$600, and water resistance - the mark W20) allow to recommend them for structures subjected in the process of operation not only to intensive mechanical loads, but also to aggressive chemical and climatic attacks.

Studies [8] have revealed the possibility to obtain high-strength concrete based on expanded clay aggregates with a strength of 40 MPa and a dry density of 1.4 kg/dm^3. At the same time, the criteria for classifying lightweight concrete as high-strength in terms of compressive strength (N/mm^2) and concrete density in the dry state (kg/dm^3) have been determined, which should be used in updating the relevant regulatory documents.

Concreting at low temperatures should be performed taking into account the specified requirements of codes SP 70.13330. It is recommended to use periodic profile reinforcement bars with yield strength not less than 500 MPa. In the production of concrete should be used cements, the composition of which should provide the requirements for concrete with regard to the operating environment and take into account the technology of concrete works in the construction site.

Structural concrete may be calculated according to the requirements of SP 63.13330.2018, taking into account the specified design values of strength and deformation characteristics of concrete and reinforcement, as well as the linear temperature deformation coefficient.

When calculating structures for emergency impacts, the design values of strength and deformation characteristics of concrete and reinforcement should be selected for the calculation of structures under the second group of limit states (serviceability limit state (SLS) associated with safe operational requirements).

Concreting of structures in arctic conditions should be carried out only according to specially developed process charts.

The conditions and the terms after which concrete freezing is allowed for transport and massive hydraulic facilities shall be specified in the project of works taking into account the requirements for the design and erection of these structures.

Mix design for Arctic construction is carried out by any methods proven in practice and accepted.

At the same time, it is recommended to take into account that concrete subjected to electric heat treatment under strict conditions, insufficient protection from moisture loss, lack of additives, etc., by 28-day age after heating can have a strength deficiency of up to 10%. If necessary to obtain the design strength of concrete in the prescribed time, it’s allowed to increase the strength class of concrete against designed or use other methods of curing. In this case, the water-cement ratio (W/C) of the concrete mixture should be assigned no more than 0.45, and for concrete with increased requirements for frost resistance (F_1>500) - no more than 0.35.

The peculiarities of concrete mix preparation in harsh arctic conditions should be reflected in a special technological regulation, which will take into account the requirements for water and aggregate temperature, duration of mixing, taking into account of transportation time, and other necessary conditions for maintaining fresh concrete original workability, homogeneity, and temperature at the concreting place.

High-strength lightweight concrete is of particular importance in the conditions of construction in the Arctic. Reducing material intensity and reducing the weight of building structures without failure their load-bearing capacity and other operational properties is one of the main factors in improving construction efficiency, including energy efficiency, which is extremely important in Arctic conditions. In addition, in offshore construction, due to shallow water along the towing routes from fabrication to installation, prefabricated structures for transportation should ideally have a certain buoyancy.

In order to ensure the required strength of concrete in extremely short time (no more than 3 days) with minimal material costs at the place of manufacture, it is recommended to use intensive technology of production of concrete mixtures and concretes based on ready-mixed modified dry mixtures with increased energy potential [9].

When justifying the mandatory use of effective accelerating and antifreeze admixtures with a predicted reduction in the passivation capacity of concrete in relation to conventional steel reinforcement, the use of special corrosion-resistant reinforcement or non-metallic composite reinforcement will be required.

4. Standardization and technical regulation

In order to ensure the efficiency of construction in the Arctic, it is necessary to update the regulatory documents on the full life-cycle. The role of the regulatory framework, as a rule, is to simplify and improve the reliability of design, approval, construction and operation of buildings and structures. One of the successful practices is the formation of the normative base in the process and on the basis of the experience of pilot projects realization, as distinguished, for example, by the work of a number of technical committees of the American Concrete Institute (ACI). The experience of developing Norwegian standards is also indicative, which, as a rule, regulate the level of safety of structures, maximum probabilities of occurrence of events, but the methods of realization and justification of the required probabilities are not rigidly fixed and allow a certain flexibility in the choice of the construction scheme.

Old design rules in the Arctic have often failed due to the instability of permafrost soils and the climate. For example, temperature fluctuations, which can reach 70 °C or more, had a negative impact on the durability of buildings. In addition, permafrost is subject to thermal fluctuations depending on the time of year, which requires designers to take these factors into account with maximum precision.

In 2020-2024, five new codes of practice were developed concerning requirements for engineering surveys, design and construction rules, inspection of technical and operation condition of buildings on permafrost soils. It should be assumed that this is only the beginning of a lot of work.

With regard to concrete and reinforced concrete, in the near future the current provisions in the Codes of Regulations SP 25.13330.2020 "Soil bases and foundations on permafrost soils", SP 28.13330.2017 "Protection of building structures against corrosion", SP 63.13330.2018 "Concrete and reinforced concrete structures. Basic provisions", SP 70.13330.2012 (2017) 'Bearing and enclosing structures', SP 72.13330.2016 'Protection of buildings, facilities and structures against corrosion', SP 349.1325800.2017 "Concrete and reinforced concrete structures. Rules for repair and reinforcement", as well as a number of fundamental standards: GOST 7473-2010 "Concrete mixtures. Technical requirements", GOST 24211-2008 "Admixtures for concrete and mortars. General technical requirements", GOST 25192-2012 "Concretes. Classification and general technical requirements", GOST 25820-2014 "Lightweight concretes. Technical requirements", GOST 26633-2015 "Ordinary and fine-grained concretes. Technical requirements", GOST 27006-2019"Concretes. Rules for mix design", GOST 27751-2014 "Reliability of building structures and foundations. Basic provisions" and a number of other supporting standards. It is necessary to harmonize Russian and international standards. For example, [10] shows how approaches to the requirements and recommendations in different countries may differ for determining the durability under freezing and thawing of concrete and methods of testing frost resistance, including those applicable to harsh Arctic conditions.

5. Recommended requirements and standardized parameters

A significant part of these tasks has already been solved in recent years. Thus, the design rules for soil bases and foundations of buildings and structures, including underground ones, erected on the territory of perennially frozen ground spreading have been changed, and a number of standards have been amended and supplemented.

The durability parameters of reinforced concrete structures according to SP 28.13330.2017 and GOST 31384-2017 have a special place. The recommended requirements and standardized concrete parameters for Arctic zone are given in Table 2, and they should be specified in the course of next laboratory and field tests.

Table 2 - Recommended requirements and standardized parameters of concretefor arctic conditions

№№	Concrete requirements	Suggested values
1.	Concrete compressive strength class, not less than	
	for civil engineering	B 30 – B 45
	for offshore platforms	B 70
2.	Early strength, % R_{28} , not less than	40
3.	Waterproofness, grade, not less than	
	for civil engineering	W12
	for hydraulic engineering	W14 - W16
4.	Permeability for CO_2, not more, cm^2/sec	0.04×10^{-4}
5.	Relative shrinkage limit, m/m	$30\cdot10^{-5}$
6.	Limit value of creep coefficient	2.0
7.	Frost resistance, grade, not less	
	for civil engineering	F_1300
	for hydraulic engineering	F_2500 - F_2600
8.	Sulfate resistance, annual deformations, %, in solutions of concentration 34000 mg SO_4^{2-}/l, not more than	0.050
9.	Chloride diffusion coefficient, m^2/sec, max.	$0.7\cdot10^{-13}$
10.	Stability against ice abrasion, mm/km	0.025

Thus, to ensure the structural concrete durability in the above conditions it is necessary to use concrete of a defined performance [11], characterized by high frost resistance; high resistance to sea water and frost; effective protection of steel reinforcement in chloride aggressive environment; high stability against abrasion by ice; high early strength, and low shrinkage and creep, i.e. properties, the combination of which provides high reliability of structures.

6. Conclusions

Polar areas with extreme environmental impacts on the construction of buildings and structures have an extremely low population density that has an impact on their development. The technologies and requirements that were used for construction in this region are outdated, and the infrastructure and buildings created have exceeded their useful life. Due to the approval of the state program “Social and Economic Development of the Arctic Zone of the Russian Federation” the region is in urgent need of new materials and technical solutions.

Given the population growth and the need for housing in the Arctic zone, it is crucial to develop not only modern but also sustainable solutions for construction. For concrete and reinforced concrete for Arctic conditions, new provisions in the Code of Practice and in a number of supporting standards analyzed in this article should be clarified or re-developed.

In addition to strength, durability,and serviceability requirements, other factors should include cost, environmental conditions, placement method and associated requirements, availability of suitable materials of construction, properties of the supporting soils, and site topography. Economy may also dictate some aspects of design and construction, including the choice of type of structure for a given site.

Taking into account the accumulated experience and the results of experimental work in the future it is advisable to generalize in a separate document - the Code of Rules for the organization of construction in Arctic conditions.

CRediT authorship contribution statement:

Faikman V.R: Conceptualization (lead); writing – original draft (lead); review and editing (equal).

Stepanova V.F.: Methodology (lead); writing – review and editing (equal).

Declaration of competing interest:

In accordance with journal policy and our ethical obligation as researchers, we are reporting that we haven't any potential competing interest.

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