Longevity of Concrete Maritime Structures in Harsh Service Environment

V V Malyuk

1Sakhalin State University (SakhSU), Sakhalinskaya St. 108a-22, Yuzhno-Sakhalinsk, 693000, Russia

E-mail: mvv.77@mail.ru

Abstract. This paper is devoted to the problems of longevity of concrete maritime structures in climatic conditions of Russian Far Eastern seas. The subject actuality is stipulated with the plans of building of hydroengineering and transport structures in harsh climatic conditions under the program of modernization and expansion of the seaports capability in the Far East and development of the Northern Sea Route. It analyses the experience of hydroengineering structures building in conditions of Sakhalin Island seacoast during the period from 1920 to 2019 years. Character types of maritime hydroengineering structures by longevity considering service environment in corrosive mediums with the XF4 index are allotted and described. It mainly focuses to estimating of longevity by the results of predictive freezing-tests. Concrete’s qualitative reliabilities, deciding longevity of structures in hard service environment are analyzed. The data on actual frost-resistance of base (reference) composition concrete, which quality indexes have to ensure longevity at least 50 years in harsh climatic conditions, are cited. It is noted, that during the exploitation period increasing of qualitative indices of concrete is possible due to hardening and stabilization of concrete’s structure. It has been ascertained, that within the exploitation period concrete’s qualitative indices may increase due to its structure hardening and stabilization. It suggests the line of further investigations for methods preparation to predict structures service lifetime in hard service environment on the basis of the frost-resistance index of concrete and accumulation of experimental data on structures behavior in aggressive and harsh conditions.

1. Introduction

The results of numerous researches of Russian scientists allowed to substantiate the qualitative indices of concrete, permitting to provide longevity of constructions of maritime hydroengineering structures for no less, than 50 years in severe hydrometeorological service environment [1, 2, 9, 13, 20, 21]. However, despite of many performed researches on durable concrete making for maritime structures, the problem of concrete and reinforced concrete durability in severe climatic service environment stays actual nowadays.

The subject actuality is stipulated with the plans of building of hydroengineering and transport structures in harsh climatic conditions under the program of modernization and expansion of the seaports’ capability in the Far East and development of the Northern Sea Route. Working out of the diagnostic system and prognostic methods to determinate concrete’s durability with reference to different service environments, by the decision of the II International Conference on concrete and reinforced concrete “Concrete and Reinforced Concrete – Prospection” (Moscow, 12th-16th of May
2014 year) relate to the main lines of theoretical and practical activity in field of concrete and reinforced concrete.

2. Relevance

The problem of concrete durability in aggressive environments predetermines need to bring up a question about constructions calculation by new limiting state – the longevity [10]. It means, that present calculation methods, designing, organizational and technological measures on concrete durability providing are obviously insufficient. Recently the new researches in the field of durability models making to predict service lifetime of constructions and buildings have appeared [11]. Important role in this problem decision is assigned to creating of practical model of a construction behavior in time in the basis of monitoring during its exploitation process with regard to all its real characteristics. Therefore, further gathering of experimental data about constructions behavior in aggressive and severe conditions, that allow to adequately estimate concrete degradation in structures, is a problem of current importance.

Numerous researches demonstrate frost-resistance of concrete to be main property of concrete for longevity of cement concretes, intended for exploitation in severe climatic environment of Far Eastern seas. From the end of 19th century to the present frost-resistance test is a main method to predict concrete durability in severe climatic conditions, where influence of sign-alternating temperatures in conditions of concrete water saturation is a prevalent factor. Despite of large number of researches, made on problems of concrete longevity in severe climatic conditions, up to present time there are no science-based methods, ascertaining relation between qualitative indices of concrete and its longevity. The standard methodology of concrete maritime hydroengineering structures primary protection designing has a prescriptive character [19]. To work out the mathematical model of longevity prediction it needs clear idea about factors, affecting kinetics of degradation process. Tendency to corrosive researches mathematization without experimental works development, to specialists’ opinion [16], brings to distortion of ideas about mechanism of corrosive processes. Lately the specialists in concrete paid their attention to development and studying of high technology concrete properties, that are remarkable with high density and low permeability. It is believed [21], that concrete for maritime and hydroengineering structures in extremal environment must have high qualitative indices: compressive strength no less than 70 MPa, grade on water resistance no less than W12, grade on frost-resistance no less than F400, abradability no more than 0,3-0,4 g/cm², water absorption at the level of 1,0-2,5 mass.%. However, in such concretes practical applying, due to significant complication of technology, it is needed more complete equipment and experienced staff. That is why the probability of operational errors with aftermaths, bringing to significant decrease of longevity, rises up.

3. Materials and methods

Difficulty and complexity of the problem, by the specialists’ opinion, need to be complex resolved, concrete properties development must be fulfilled with taking into account its properties in dynamics and with a view to gist of the processes, going in a construction under effect of the environment. Experience in maritime structures building in conditions of seacoast of Sakhalin Island shows [17], that traditional principles of the technology of concrete with high frost-resistance [15], on which the standards on concrete and reinforced concrete constructions protection from corrosion are based [3, 18], have potential abilities for improvement. The latter predetermines the importance of concrete fracture types studying in service environment and comparison with fracture in case of prognostic tests.

This work purpose is estimation of concrete state in constructions of maritime hydroengineering structures with a view to time stages of exploitation period and comparison with the results of actual concrete frost-resistance in these structures. The results in observation of maritime hydroengineering structures, exploited on the seacoast of Sakhalin Island, and the results of laboratory concrete frost-resistant tests, fulfilled on the laboratory base of the test center of “Transstroy-Test Ltd.”, are presented in the article.

The analysis of qualitative indices of concrete have been fulfilled by standard methodologies [4, 8], estimation of structures’ operating state has been made in accordance with rules of inspection of
hydroengineering structures [7]. The seacoast of Sakhalin Island is surrounded with waters of the Sea of Okhotsk. Hydrometeorological conditions of the Sea of Okhotsk by the classification [19] belong to hard, environment aggressiveness effect on concrete by the classification [3, 18] conforms to XF4 index, climatic region with calculation of winter temperature of outer air is less than minus 20°C.

According to the inspections of maritime structures on the seacoast of Sakhalin Island [13] it is possible to mark out three characteristic types of structures by their longevity:

A1 – structures with low longevity (1-2 years), which have concrete frost-resistance indices within F_{250}-F_{1100} in accordance with [4];

A2 – structures with long-life (more than 80 years), having not high actual frost-resistance indexes – no more than F_{2150};

A3 – structures with long-life (more than 50 years), having high actual frost-resistance indices – more than F_{2200}.

Considering longevity as temporal period of building object (construction) operating characteristics keeping till capital repair [5] it is appropriate to mark out three characteristic steps. On the figure 1 the scheme with separation of service lifetime into stages is represented. It is necessary to note, that all concrete’s qualitative indices, defining longevity period, are laid at the technological stage. In the scheme of the figure 1 this period corresponds to the segment 0 – T_0. Concrete’s qualitative indices, received in the technological stage, define constructions longevity or duration of the period without repair. On the scheme (figure 1) the stages of service lifetime of all three structures types are represented: A1, A2, A3. All marked structures are exploited in conditions typical for the coast of the Sea of Okhotsk: during winter period part of a construction in the zone of variable level is affected by cyclic freezing, when the tide is going out, and thawing, when the tide is rising, but another part of surface is frosted over and stay so within 3-4 winter months (figures 2,3).

![Figure 1](image1.png)

**Figure 1.** The scheme of temporal elements of concrete longevity during service lifetime of an object.

The structures of the A1 type have characteristic layered degradation of concrete’s surface layer for 10-20 mm depth per year (figure 2). It is ascertained, that the reason of degradation of surface layer of concrete after short-term service lifetime is violation of the specified normative requirements to the concrete work technologies [13].

3
The structures of the A2 type is exploited within 80-90 years, keeping operational reliability up to present time (figure 3). Nature of observed degradation of concrete in separate constructions give grounds to believe, that it relates to unstable quality of concrete work. Despite of long-term service lifetime of the structures and low qualitative indices of concrete on frost-resistance, operational reliability for constructive elements is provided in a zone of variable level nowadays. Considering the service lifetime of structures of the A2 type, it is appropriate to mark out the T1 – T2 stage for the constructions, which have damaging of surface layer for 100-200 mm depth. In the assumption of that service lifetime of a structure makes no less than 80 years, damaging of surface layer of concrete in a zone of variable level has been going with the intensity 0.1 – 0.2 mm per year. Hence, in this case after 10 – 20 years decrease of protective layer for 10 – 20 mm is happened, that may be a reason for corrosion of armature in reinforced concrete constructions. As the structure is made of massive constructions [13], given level of concrete degradation do not effect operational reliability of the structure from massive constructions.

Figure 2. Common view of concrete's condition of the A2 type structure in the zone of variable level: (a) – concrete's condition after 1 exploitation year; (b) – concrete's condition after 1 exploitation year; (c) service environment of concrete in winter.

Figure 3. Common view or the A1 the structure after 80 exploitation years: (a) – common view of concrete’s condition in the zone of variable level; (b) – service environment of concrete in winter.
However, the construction from reinforced concrete, obviously, after the T1 – T2 period will require to renovate of protective layer of concrete. Marked damages don’t have general character and refer to dissimilarity of concrete qualitative indices, defining longevity in a zone of variable level.

Figure 4. Common view or the A3 the structure after 45 exploitation years.

The structures of the A3 type is characterized with high durability. In this structure there are more than 70% of shaped constructions (tetrapods) have no any signs of surface layer degradation after 45 years of exploitation (figure 4). It is ascertained, that observable types of concrete disintegration relate to unstableness of technological process when constructions making [17]. It is necessary to note, that constructions for the structures of the A3 type are made by the technology of high frost-resistance [15], which principles are laid in the actual normative documents on protection of concrete and reinforced concrete from corrosion [3].

The process of concrete frost-resistance testing by analogy with the scheme of temporal stages of longevity of constructions within service lifetime (figure 1) may be divided into separate characteristic elements (figure 5), by which it may be judged about concrete durability to external actions.

Figure 5. The scheme of temporal elements of concrete durability when frost-resistance test.
However, the scheme of temporal elements of standard frost-resistance test (figure 5) has a distinctive feature in contrast with the scheme of service lifetime of constructions in a structure (figure 1) by a number of indices. First, the technological process of standard concrete specimens making is strongly controlled and regulated, and further hardening is going in optimal conditions [4]. In real conditions the parameters of technological process of constructions making and hardening conditions because of objective and subjective reasons may significantly differ from normative (optimal). Due to this in real conditions the questions rise on accordance estimation and possibility of constructions longevity prediction by the results of laboratory tests. Second, in real conditions within service lifetime hardening or structure stabilization may occur in a result of autogenous healing, that may positively affect the concrete qualitative indices, characterized constructions longevity. On the figure 1 this temporal stage for the structures of the A2 type is represented with the T2–T3 segment. Standard frost-resistance tests don’t assume a modelling of this stage. Modern methods of frost-resistance estimation due to test by more low freezing temperatures (speeded method) make the results of laboratory prognostic tests less comparable with real service conditions in aggressive environment of the XF4 index in the Sea of Okhotsk and the Sea of Japan. It is necessary to note, that by the reason of difficulty of standard frost-resistance tests, just normative frost-resistance is evaluated in technological environment. On the scheme of figure 5 frost-resistance is presented with the 0-T1 segment. In this connection there are practically no any data on actual frost-resistance, which is evaluated with the period of achievement of limit values of frost-resistance indices normative (critical) level. On the scheme on of figure 5 actual frost-resistance is evaluated with the 0-T1, 0-T2, 0-T3 temporal segments. The data on actual frost-resistance will allow to set duration of characteristic periods of forming of quality indices and structure parameters of concrete of different compositions to estimate the potential concrete’s abilities. As an example, on the diagrams of figure 6 the results of comparative frost-resistance tests of concretes, varying with quality indices, are given. In accordance with requirements [3, 18] for providing no less than 50 years of service lifetime (longevity) for concrete and reinforced concrete constructions normative demands are made of concrete’s qualitative indices depending on aggressiveness of service environment. For climatic conditions of the Sea of Okhotsk coast the normative quality indices of concrete are given in the table 1. Concrete’s composition with normative quality indices in the researches is taken as base or reference composition. In the table 2 and in the diagrams of figure 6 it gives concrete’s compositions and results of frost-resistance tests of base composition and compositions, which have low air content in concrete mix with regard to normative requirements.

| Concrete’s index                      | Index value         |
|--------------------------------------|---------------------|
| Water-cement ratio(W/C)              | no more than 0.45   |
| Cement consumption, kg/m³           | no less than 340    |
| Mix air entrainment, %              | no less than 4      |
| Strength class B                    | no less than 35     |
| Frost-resistance mark, cycles       | F2:300              |
| Water resistance mark, MPa          | W6                  |

Air content in concrete mix has been regulated as at the expense of applying of different types of modifiers additives, and due to their quantity dosing. As a structure forming additives polyfunctioning modifier of concrete PFM-NLK (TU 2493-010-04786546-2001) and neutralized air-entraining resin SNV (TU 13-00281074-75-98) were used.
Table 2. Compositions and concrete’s quality indices.

| № concrete’s composition | Additive type and content (% of cement mass) | Concrete mix indices | Durability $R_0$ and age $T$ before tests beginning |
|--------------------------|---------------------------------------------|----------------------|-----------------------------------------------|
|                          |                                             | slump, cm            | air content, % | $R_0$, MPa | $T$, day |
| 1                        | PFM = 0,50                                  | 8                    | 1.7          | 67.1       | 103      |
| 2                        | PFM + SNV = 0,45 + 0.01                    | 6                    | 2.4          | 61.6       | 61       |
| 3                        | PFM + SNV = 0,45 + 0.02                    | 14                   | 4.2          | 40.9       | 28       |
| 4                        | PFM + SNV = 0,60 + 0.02                    | 11                   | 3.7          | 48.9       | 28       |

Figure 6. The results of concrete frost-resistance tests by second base method.

Concretes were made with the following material using: portland cement PC500-D0-N [9], quartz sand (fineness modulus MK=2.5-2.8), amphibolite crushed stone 5-20 mm. All compositions had equal content of cement – 500 kg/m$^3$ and water-cement ratio (W/C) was 0.35. Frost-resistance were defined with second base method [4]. Frost-resistance was evaluated with the $K_F$ frost-resistance factor, which was assigned from the expression:

$$K_F = \frac{R_F}{R_0}$$

(1)

$R_F$, an ultimate compression strength after the test, MPa; $R_0$, an ultimate compression strength before the test begins, MPa.
4. Results of experimental studies
From the diagrams of figure 6 it is seen, that at equal values of normative frost-resistance, at \( F_0 = 300 \), for instance, the value of actual frost-resistance may significantly differ. Concrete’s base composition (composition 3) has actual frost-resistance several times more in comparison with concrete, that has lower quality index on air content. This difference is proposed to estimate with the \( K_f \) frost-resistance safety factor, which is worth to define from the expression:

\[
K_f = \frac{F_N}{F_0}
\]

\( F_N \), the frost-resistance in cycles; \( F_0 \), the normative frost-resistance in cycles.

The results of tests show (figure 6), that actual frost-resistance may significantly decrease by composition misfit to just by one of six rated quality indices (table 2). It is possible, that the \( K_f \) factor may characterize potential abilities of concrete’s structure for stabilization and hardening within service lifetime of an object. Experience in maritime structures building in the Far Eastern region of Russia gives grounds to believe, that proposed approach to estimation of potential abilities of concrete’s structure within service lifetime will allow to objectively approach to choosing of materials for concrete. Especially it concerns estimation of possibility of local materials applying for concrete: sand, crushed stone – which by qualitative indices do not correspond to normative.

5. Conclusions
Multiple researches of many years give grounds to suppose, that concrete’s frost-resistance is a main property of concrete for cement concretes longevity, which are designed to be exploited in severe climatic conditions of Russian Far Eastern seas. Despite of difficulty of standard methodology of frost-resistance estimation by tests cycles, there is no any alternative safe method of longevity prediction in aggressive and severe service environment in present time.

Working out of mathematical models of materials degradation properties when variable freeze-thaw without experimental works brings to distortion of ideas about mechanism of corrosive processes and unreasonable overdemanding to qualitative indices and materials of concrete. Experience in maritime structures building in conditions of seacoast of Sakhalin Island shows, that technology of concrete with high frost-resistance, based on traditional principles \([3, 15]\), has potential abilities for improvement.

The research of actual concrete’s stability to freeze-thaw cycles to normative level of frost-resistance indices allows to objectively estimate potential abilities of concrete’s structure to stabilization and hardening. This concrete’s property is proposed to estimate with the \( K_f \) frost-resistance safety factor. It is appropriate to continue the researches of dependence of concrete’s longevity in constructions on the \( K_f \) value for development of prognostic methods of constructions service lifetime estimation normative level of frost-resistance indices.

Presented results of the researches give ground to believe, that existent approaches to stable concretes production for exploitation in aggressive environments with the XF4 index provide service lifetime without repair no less than 50 years. Observable cases of constructions performance criterions decrease within structures’ normative service lifetimes relate to violation of prescriptive requirements to concrete work technology, technological stage (preoperational stage) is the weaker link in the system of required longevity providing. Due to this, one of main tasks in the constructions’ longevity problem is providing of normative level of qualitative indices of concrete work technological process.

6. References
[1] Alekseev S N, Ivanov F M, Modry S and Shissle P 1990 Durability of Reinforced Concrete in Corrosive Environments (Moscow: Stroyizdat) p 320
[2] Gladkov V S 1974 The technology of constructions making from durable concrete In the science works book of All-Union Scientific Research Institute of transport construction 78 (Moscow) 153 pp 41–48
[3] GOST 31384-2017 Protection of concrete and reinforced concrete structures against corrosion General technical requirements – Incorporated since 01.03.2018
[4] GOST 10060-2012 Concretes Methods for determination of frost-resistance – Incorporated since 01.01.2014
[5] GOST 27751-2014 Reliability of building structures and foundations Basic provisions – Incorporated since 01.07.2015
[6] GOST 27.002-2015 Dependability in mechanics Terms and definitions – Incorporated since 01.03.2017
[7] GOST R 54523-2011 Port hydraulic structures Rules of inspection and monitoring of the technical condition – Incorporated since 01.03.2012
[8] GOST 10181-2014 Portland cement and portland blastfurnace slag cement Specifications – Incorporated since 01.07.2015
[9] GOST 10178-85 Portland cement and portland blastfurnace slag cement Specifications – Incorporated since 01.01.1987
[10] Kuncevich O V 1983 Concretes high frost-resistance for Far North structures (Stroyizdat Leningrad department) p 132
[11] Karpenko N I, Karpenko S N, Yarmakovksy V N and Yerofeev V T 2015 The Modern Methods for Ensuring of the Reinforced Concrete Structures Durability (Moscow) pp 93-102
[12] Leonovich S N, Ltitinovskys D A, Chernyakevich O Yu and Stepanova A V 2016 Strength, Crack-Resistance and Durability of Structural Concrete at Temperature and Corrosion Impacts monograph in 2 parts vol 2 (Minsk: publishing house BNTU) p 393
[13] Malyuk V V 2018 Prediction of constructions longevity of maritime hydroengineering structures from concrete by experience in building and exploitation in severe climatic conditions Problems and perspectives in development of building, heat, gas and energy supply: Materials of the VIII National conference with international participation Edited by Abdrazakov F K (Saratov: publishing house “Nauka”) p 354
[14] Moskvin V M, Ivanov F M, Alekseev S N and Guzeev E A 1980 Corrosion of Concrete and Reinforced Concrete, Methods of Protection (Moscow: Stroyizdat) p 536
[15] VSN 34-91 Rules of Production and Acceptance of Works on Construction of New, Reconstruction and Expansion of the Operating Hydraulic Engineering Sea and River Transport Constructions Incorporated since 1991
[16] Rosental N K 2007 Problems of corrosive damaging of concrete Concrete and reinforced concrete pp 29-30
[17] Sviridov V N and Malyuk V D 2014 Assessment of the Durability of Concrete in Structures of Maritime Facilities Based on the Experience of Construction in the Far East Scientific works of III All-Russia (II Int.) Conf. on Concrete and Reinforced Concrete “Concrete and Reinforced Concrete – a Look into the Future” (Moscow 12-16 May 2014) vol 3 (Moscow: MCEI-MSCU) pp 388-398
[18] SP 28.13330.2012 Anti-Corrosion Protection of Building Structures – Incorporated since 08.05.2017
[19] SNiP 3.07.02-87 Hydrotechnical Maritime and River Transport Facilities – Incorporated since 01.07.1987
[20] Stepanova V F and Falikman V P 2014 Modern Problems of Ensuring the Durability of Reinforced Concrete Structures Scientific works of III All-Russia (II International) Conference on Concrete and Reinforced Concrete “Concrete and Reinforced Concrete - a Look into the Future” (Moscow 12-16 May 2014) vol 3 (Moscow: MCEI-MSCU) pp 430-444
[21] Slavcheva G S and Chernyshov E M 2015 The action of the structure of modified high performance concretes on dilatometric effects when freezing (FEFU: SCHOOL OF ENGINEERING BULLETIN) 1/22
[22] Sheikin A E and Dobschits L M 1989 High Frost-Resistant Cement Concrete (Leningrad) p 128
[23] Shestopereov S V 1966 Concrete Durability of Transport Facilities (Moscow: publishing house Transport) p 500