Degradation and Sudden Failure of Concrete of Maritime Hydraulic Structures in Severe Hydrometeorological Operating Conditions

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Abstract. The experience of construction of marine hydraulic structures in severe hydrometeorological operating conditions on the coast of the Far Eastern seas has been considered. The characteristic failures of concrete in a zone of variable level after first wintertime have been analyzed. The reasons of an evident sudden failure of concrete are detected. A scheme of concrete structure forming under the impact of frost and salt depending on the “structural maturity” of concrete is proposed. The lines of further researches on forecasting of longevity of concrete and reinforced concrete facilities for maritime hydraulic structures have been evolved.

1. Introduction

Despite the large number of researches, that have been carried out to create the resistant concrete for maritime structures, the question of durability of concrete and reinforced concrete in severe hydrometeorological operating conditions is now still remaining urgent. Researchers note [1,8,9,14,17,18] that today there is no any problem in production of durable concrete, even for rather aggressive environments. The problem is to build reliable and long-life structures.

This means that the existing calculation and designing methods and engineering and organizational arrangements for providing durability of concrete are obviously insufficient, as it is nearly impossible to take the influence of all critical factors into account by calculating.

Therefore, over recent years, new researches have appeared in creating durability models to forecast the service life of structures and facilities [7,11]. An important place in this problem solution is devoted to creation of a practical model of a structure behavior in time based on monitoring during the operation of a structure in a view of all its real characteristics. That is why, the further accumulation of the experimental data on behavior of the structures under aggressive and severe conditions allowing an adequate evaluation of wear-out of concrete in structures is a very urgent task. It should be noted that since 1970 to the present in the Far East the systematic field and laboratory researches of durability of concrete of marine hydraulic structures have being carried out. Within the period from 1970 to 1990 these researches were being carried out at the Sakhalin Scientific Research Laboratory of the All-Union Research Institute of Transport Construction, and then, after the laboratory reorganization, the relevant researches were being carried out at the “Transstroy-Test” company [12,13]. Present article describes the results of the researches on durability of concrete based on the experience of building of maritime structures in the Far East over the last 15 years where the employees of the Transstroy-Test Company have participated.

When building maritime berthing and protective structures, made of concrete and reinforced concrete, builders often face the problem of failure of new structures in a zone of variable level after the first winter season, i.e. in 3 – 4 months of exploitation.
Such failure cannot be defined as degradation [3] or wear-out failure [4] of concrete, as this means a gradual decrease of the level of material performance characteristic. In compliance with the general technical terminology [4] such type of failure is classified as an evident sudden failure—an abrupt transition of an object to an inoperative state, which can be detected visually when the object is being prepared for use or in the process of its exploitation.

Present article shows the analysis of typical cases of concrete failure when building the maritime hydraulic facilities in the Far East within the period from 2003 to 2010. For instance, when building the bank protection facility on the root section of the MOF’s berth at the LNG plant in Prigorodnoye settlement (Sakhalin Island) from shaped hexabit slabs (hereinafter slabs), failure of concrete has been observed in separate slabs, located in a zone of variable level, after the first winter season (figure 1).

Figure 1. (a) — general view of the bank protection structure on the root section of the MOF’s berth at the LNG plant in Prigorodnoye settlement (Sakhalin Island) in winter; (b) — failure behavior of hexabit slabs after first winter

A distinctive feature of the marine bank protection structures, used on Sakhalin Island, is that the layer of sea ice is growing on the surface of concrete slabs when air temperature is becoming negative (figure 1 (a)).

The slabs freeze in sea ice in a zone of variable level and stay ice-bound within 3 – 4 months. Such operating conditions surely differ from the usual tidal effect on concrete of vertical berth walls in a zone of variable level. This feature of the operating conditions of the slabs, frozen in the sea ice, was revealed in March of 2004 after ice melting. On separate slabs it was observed destruction of the surface layer of concrete to a depth of up to 4 cm (figure 1(b)). Slabs were manufactured in the factory using soft steaming. On the basis of analysis of technological conversion of items fabrication, the experts of the “Transstroy-Test” have established the following facts. Manufacturer’s quality control was carried out at all process stages, therefore, the probability of producing a concrete mix with quality indicators that did not meet the project requirements – В22,5, F300, W6 – was excluded. To fabricate a concrete mix, the CHB+C3 complex additive was used, it allowed providing the air content in the mix within 4 ... 6% and frost resistance of concrete not lower than F2300 grade. Therefore, all the established requirements, which have to provide a service life of constructions within 50 years, were met at the stage of preparation of a concrete mix. Analysis of the process of slabs fabrication has revealed the following. At the age of 3 – 4 days after the concrete has obtained a handling strength – 70 % of design strength B22,5 – the slabs have been shipped to the facility. According to the technical requirements for prefabricated products, this strength is sufficient for the slabs to be shipped to the consumer [5]. Due to organizational reasons of storage, the slabs manufactured in November-December 2003, were immediately placed in a variable-level zone – It was ascertained by the stamps on the slabs. However, in accordance with the requirements [15], steamed slabs may be placed in a zone of variable level after being cured for at least 15 days at positive temperatures. Based on this, it
was concluded that inobservance of the time, required to get the concrete cured, became the main cause of the failure of surface layer after the first winter season. Experts of the "Transstroy-Test" company have recommended the builders to move the slabs with surface damage to the underwater zone. This decision has been taken on the grounds that on the one hand, the structural feature of the bank protection structure, made from the shaped slabs, has allowed moving the separate slabs from the variable-level zone to the underwater zone without significant costs, on the other hand – the laboratory and experimental field tests, earlier conducted in the laboratory of the "Transstroy-Test" company, have shown that in the underwater zone, further failure of concrete is not occurred, since there are no major destructive factors, such as freezing and thawing cycles and icing.

Further surveys of the structure show that in the underwater zone the processes of concrete failure in damaged slabs are stopped, and they keep their operational performance within 15 years. The precured slabs, installed in a zone of variable level, retain their original appearance within the entire operation period equal to 15 years.

![Figure 2](image1.png)  
**Figure 2.** View of concrete failure in a zone of variable level after first winter: (a) – hexabit bank protection in Kozmino sea-port (Nakhodka, Primo Primorsky Krai, 2008); (b) – berth wall in Uglegorsk sea-port (Sakhalin Island, 2010)

The similar cases of concrete failure due to inadequate holding time for concrete curing have been observed when arranging the bank protection structure in the port of Kozmino (Primorsky Krai, Nakhodka) in 2008 (figure 2 (a)) and reconstructing of the berth wall in Uglegorsk seaport (Sakhalin Island) in 2010 (figure 2 (b)). These examples show that inobservance of the technology requirements, such as curing time, results in serious consequences. Due to the engineering feature of maritime bank protective structures, made from shaped slabs such as tetrapods or hexabits, these consequences can be corrected without significant costs, as it has been done at the LNG plant or in the port of Kozmino. However, the berth wall restoration in the port of Uglegorsk up to serviceable condition has required significant costs. Depending on the level of loss of operating ability the failure can be classified both for criticality and for its occurrence reasons. In considered cases, the failure relates to a production failure, because it has been occurred because of production defects. An evident sudden failure is caused by, on the one hand, due to the character of external influences – icing of structures by sea ice, and on the other hand, the conditions for concrete curing at positive temperatures after steaming are not provided. There is every reason to believe that the process of structural defects accumulation in concrete when icing with sea ice occurs more intensively, than when affecting of freezing and thawing cycles from ordinary tidal effects, in a zone of variable level on the vertical walls of marine berthing structures.

So, the severity of real operating conditions of maritime structures may differ from the normative severity, which is classified according to the design winter temperature of the ambient air [16]. The above examples serve as evidence that the severity of the conditions is one of the parameters that determines the rate of destruction of concrete. When assessing the real severity of external influences,
it is necessary to take into account such parameters of the freezing process as duration and temperature. The exploitation experience of maritime structures on the seacoast of Sakhalin suggests that in a zone of variable level in the winter period under the influence of only tidal effect without icing of the structure, the rate of failures accumulation in the concrete structure is much slower and does not result in sudden destruction of concrete. The icing process is not modelled in the standard frost resistance tests, therefore, in earlier laboratory researches it has not been revealed any influence of further curing on steamed frost resisting concretes. Given examples show the destruction rate of the steamed concrete to depend on curing duration at positive temperatures. On the assumption of the fact that duration and temperature affect the hydration rate and, accordingly, affect the development of concrete strength, A.M. Neville [10] has proposed that the holding period should be evaluated with the indicator of concrete “maturity”, which should be measured in degree-days or degree-hours. It was ascertained [18], that frost resistance has a more stable connection with the parameters of concrete structure than with concrete strength. In compliance with the general concepts of cement concretes [1,17,18], both destructive and constructive processes occur in its structure. Based on the obtained results, it can be supposed that in term of an equal degree of aggressiveness of external natural and climatic influences, the character of these processes development in concrete depends on the level of “structure maturity” by the beginning of exploitation. If the “structure maturity” of concrete is estimated with the criterion $K^F$, then, obviously, must be such value of $K^F$, when constructive processes would predominate over destructive processes during exploitation. Conditionally, it can be assumed that when $K^F \geq 1$, constructive processes predominate over destructive processes. In this case, it is possible to present a schematic development of processes in the concrete structure at the exploitation stage as a function of $K^F$ (figure 3).

Schematically the development of the processes of concrete’s structure formation at the exploitation stage, depending on $K^F$, is shown in figure 3.

![Figure 3. Schematic representation of the process of the concrete structure formation under frost and salt influences, depending on the value of the $K^F$ criterion](image)

$\Delta k$ – measure of structural strength of concrete; $\Delta d$ – measure of destructive processes.

Numerous studies of frost resistance of concrete and exploitation experience, cited in this article, suggest that the resistance of water-saturated concrete to the effects of freezing and thawing cycles depends on the value of the $K^F$ criterion, i.e. the durability of the structure under specific operating conditions can be determined by the value of the $K^F$ criterion.

As can be seen (figure 3) when $K^F \geq 1$, the structure of concrete with the predominance of constructive processes should be formed, i.e. $\Delta k > \Delta d$. Schematically, it is represented as curve 1 in...
the figure 3. The formation of the structure when $K^F < 1$ occurs with the predominance of destructive processes ($\Delta q < \Delta q$) – curves 2 and 3 in the figure 3. In this case, the rate of destructive processes will be determined by the value of $K^F$ towards the beginning of exploitation impact. The reviewed in this article examples of destruction of concrete in the structures correspond to the case when the value of $K^F$ has such a low value, when not degradation but sudden failure is occurred ($\Delta k = 0$) – curve 4 in the figure 3.

The experience of building of maritime hydraulic structures in the Far East evidences of the fact that the durability or expected service life of a facility depends on the level of the concrete structure maturity by the beginning of exploitation, which is formed at the stage of structures fabrication and holding. It should be noted, that higher requirements have to be determined to ensure the level of reinforced concrete’s structure maturity, than for concrete structures, because it is not allowed decreasing or losing of concrete’s protective functions regarding a reinforcement in the exploitation process within the estimated service life.

Based on the above examples, it is appropriate to design the models of concrete durability in terms of the criterion of “maturity” level of concrete structure before the exploitation to forecast the estimated service life of concrete and reinforced concrete structures.

Experience in the construction of maritime berthing and bank protective hydraulic structures in the areas with severe hydrometeorological conditions shows that in a zone of variable level when icing of structures by sea ice, the failure of concrete can occur within the first winter season. Actually it is not a degradation but a sudden failure occurred. Therefore, when the structure is frozen into the ice, concrete is subjected to more severe conditions than influence of freezing and thawing cycles due to ordinary tidal phenomena in a zone of variable level. An objective assessment of the causes of concrete destruction in structures with account for the operating conditions and technology of structures making allows improving the methodology of durability forecasting. It is ascertained that one of the factors, that cause a sudden concrete failure, is the inadequacy of holding (curing) period after the structures have been manufactured. The quality of concrete in the constructions, to which the requirements for durability are made, is proposed to be evaluated by the $K^F$ – a criterion of the "structure maturity" of concrete. Sudden failure of concrete should be considered as one of the special cases in which the value of the $K^F$ criterion is significantly lower than the normative value that is proposed to be taken as a unit.

2. Conclusion

Further researches is advisable to conduct in the direction of studying the parameters of the structure of concrete, with help of which it possible to calculate the $K^F$ criterion of the “structure maturity” of concrete. The $K^F$ criterion should be attributed to the characteristics of durability of concrete and use it as a quality indicator for evaluation of compliance at the stage of taking over the structures in exploitation and as a parameter for forecasting the structures durability.

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