Freezing Mechanisms of the Concrete in an Area of Variable Water Level of Port Facilities

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Abstract. The article deals with the problem of concrete durability in the area of variable water level of port facilities. Particular attention was paid to the exposure of both negative temperatures and sea water. The reasons for the destruction of concrete in the first winter season under prolonged freezing of structures with sea ice were analyzed. The authors come to the conclusion that alternating freezing and thawing is not always a major critical value of the severity of frost exposure on the concrete in an area of variable water level. Based on the study of the mechanism of the concrete freezing, they concluded that in the course of prolonged freezing, the classical approach to ensuring the durability of the concrete by increasing the frost resistance with the use of air-entraining agents does not solve one of the important practical problems – provision of the resistance of the concrete in the first winter period. The authors believe that the concrete technology requirements should factor in the mechanism of the concrete freezing in a structure. They proposed the technological methods that make it possible to reduce the sensitivity of the concrete to the prolonged frost exposure in massive structures.

1. Introduction

The priority scientific and practical aspect in the field of the concrete and the reinforced concrete is the development of predictive methods of the durability of the concrete under various operating conditions [1–3].

The modern concept of facilities construction designing in accordance with operational characteristics assumes a varied approach to determining the requirements for structures and materials for structures, which must guarantee the predicted service life while maintaining the economic rationality of the service life [3, 16].

In this regard, the accumulation of data on the prolonged operation of the concrete in aggressive environment reflecting the real kinetics of corrosion processes has a particular importance.

The planned construction of hydraulic and transport facilities for the implementation of a comprehensive plan for the reengineering and expansion of the main infrastructure of the Russian Baikal-Amur Railway and Trans-Siberian Railway, an increase in the capacity of national seaports in the Russian Far East, and the development of the Northern Sea Route predetermine the necessity to make well-grounded effective design and technological decisions. The duration of the winter period is an important feature in these areas that prearranges the need to increase those quality indicators of the concrete during construction there, which determine the durability of structures.
Despite the large volume of work on creating the resistant concrete for offshore hydraulic engineering structures, the issue of the long time performance of the concrete and the reinforced concrete in harsh operating conditions remains important at the present time [4-12, 19].

The article presents the results of the preliminary stage of field surveys of offshore structures on Sakhalin Island in order to establish a mechanism of the concrete freezing in the area of variable water level of port facilities.

2. Database and research methods

As a rule, the severity of external exposures in the area of variable water level of offshore structures is assessed by the freezing temperature and the number of freeze-thaw cycles. In this work, the term “an area of variable water level” corresponds to the definition given in the specification document [14] - the range from the lowest water level (ice for freezing port areas) to the highest water level and higher to the height of the water splash.

It is generally accepted that the process of the concrete freezing in the open air during the low tide and its thawing in water during the high tide is decisive for the durability of the concrete in the area of variable water level. This exposure is accepted as a determining factor in the development of methods for improving the concrete technology to increase durability in the area of variable water level. However, other processes can occur during frost exposure [4].

This article provides an analysis of the frost exposure on the concrete of port structures in the area of variable water levels on the southern coast of Sakhalin Island.

Severe hydro-meteorological conditions for the operation of port facilities on the southern coast of Sakhalin Island are most apparent in winter. Specific weather conditions caused by the influence of the cold Sea of Okhotsk and the warm Sea of Japan create, on the one hand, mild conditions for navigation - the port areas do not freeze, on the other hand, harsh operating conditions for the concrete: during three winter months, concrete structures of port facilities in the variable level area are subject to different freezing conditions. In accordance with the international and national classifications of aggressive environments [14, 16], these conditions come under the most severe class - XF4 (strong water saturation in sea water and the exposure of freezing).

The hydro-meteorological conditions of the southern Sakhalin are characterized with the following indicators [15]:

In winter, the sea is the roughest - an average frequency of waves is 35%-50%, the wave height reaches four to six meters.

The tides are complex, though there are two main types of them there: diurnal and mixed tides. The tidal wave enters from the South and Southeast of Pacific Ocean. In the southern part of the island, the tide height is 0.8-2.5 meters.

In winter, the water temperature on the sea surface is about -1.0°C. Salinity of water on the surface is 31‰ - 33‰.

There are almost no periods of gentle breezing and zero wind in January and February there; the usual wind speed is 10-11 meter/second.

The estimated winter temperature of the outside air ranges from -17°C to -19°C [14].

A visual assessment of the structures’ behavior in the area of variable water level based on the constant (daily) monitoring of the state of structures in the winter period made it possible to establish that since December, the structures of the port facilities are exposed to waves, which at negative air temperatures create conditions for the freezing of structures in the area of variable water level. (Fig.1)
It has been established that in winter the concrete of structures in the area of variable water level is exposed to various mechanisms of freezing: freezing and thawing in the intertidal zone and prolonged freezing due to icing of the splash wave zone. Consequently, in the area of variable water level, three sections can be distinguished, which differ in terms of freezing conditions (Fig.2). Dividing the area of variable water level into sections allows to highlight the critical indicators of external exposures at them.

**Figure 1.** General view of the berthing structure in winter (December): a) low tide; b) high tide.

**Figure 2.** Scheme of dividing the area of variable water level into sections taking into account the water saturation and the mechanism of the concrete freezing: a) at the initial and final winter periods; b) during the main winter period.
The severity of external exposures for each selected area can be assessed by the following indicators:
- number of freeze-thaw cycles ($N_{FT}$);
- thawing temperature ($t_T$);
- freezing temperature ($t_F$);
- freezing duration ($T_F$);
- thawing duration ($T_T$);

The significance of these severity indicators for each section will be different, therefore, generally, the severity of frost exposure can be estimated with the $P_F$ index, which can be represented as follows:

$$P_F = \sum (n_i t_F; n_2 t_T; n_3 T_F; n_4 T_T; n_5 N_{FT}),$$

where $n_1$... $n_5$ are the coefficients of significance, respectively, for the indicators of severity $t_F$; $t_T$; $T_F$; $T_T$; $N_{FT}$.

Based on theoretical aspects of mechanisms of the concrete destruction under the frost exposure [17], the main factor of the long time performance of the concrete is the ability to saturate the concrete pores with water, i.e., the degree of saturation of the concrete pores with water during the initial period of operation $S_{ACT}$ and additional water saturation $\Delta S_{ACT}$ during the operation.

In the intertidal zone, the mechanism of the concrete freezing is not always determined with the swing of tides. Cyclic freezing and thawing of the concrete at section A (Fig.2a) occurs at the beginning of winter until mid-December, when the temperature of water in the port area does not drop below 0ºC, and at the end of winter, the third decade of February/the first decade of March, when the air temperature and water temperature at the port area rises to above 0ºC. It should be noted that the freezing temperature of the concrete at low tide will be higher than the air temperature because of the microclimate in this zone due to the mirror of non-freezing water. During these winter periods, the air temperature is higher. The amplitude and duration of the intertidal cycle has a softening exposure.

| Tide marks | Winter month | period, month | Air temperature, ºC | Water temperature, ºC | Freezing mechanism |
|------------|--------------|---------------|---------------------|-----------------------|-------------------|
| BTV – 0.00 (high water level) | December | from -5ºC to 10ºC | from +1ºC to -2ºC | Prolonged freezing |
| Fig.3 | January | from -10ºC to 20ºC | from 0ºC to -2º0 ºC | The same |
| | February | from -5ºC to 10ºC | | The same |
| 0.00– HTB (low water level) | December, 1st decade | from -5ºC to 10ºC | from +2ºC to 2ºC | Freeze-thaw cycles |
| Fig.3 | December, 2nd decade | from -10ºC to 20ºC | from 0ºC to -1º0 ºC | Prolonged freezing |
| | January | from -10ºC to 20ºC | from 0ºC to -2º0 ºC | Prolonged freezing |
| | February, 2nd and 3rd decades | from -5ºC to 10ºC | from 0ºC to -1º0 ºC | Prolonged freezing |
| | February, 3rd decade | from -5ºC to 10ºC | from 0ºC to -1º0 ºC | Freeze-thaw cycles |
In winter months from mid-December to the end of February, when the air temperature has the highest absolute value and the water temperature drops below 0°C, the concrete does not have time to thaw during the high tide. At section A (Fig. 2b), due to periodic fluctuations in the water level in the port area, ice build-up occurs and persists until the end of February. Consequently, in winter, there are two periods in the intertidal zone, in which frost exposure on the concrete differs significantly:

a) a period in which freeze-thaw cycles dominate;

b) a period of prolonged freezing during the icing.

The table 1 shows the winter periods and dominating mechanisms of the concrete freezing in section A of the area of variable water level.

3. Discussion
The differentiation of winter months into periods and areas of variable water level into sections provides a basis for planning a targeted detailed examination of concrete, since this will determine the exposure of the concrete freezing mechanism on the durability of structures. Theoretical provisions on the mechanisms of the concrete destruction, when the water-saturated concrete is exposed to negative temperatures, pays special attention to the role of the concrete freezing mechanisms [17], since they determine the mechanism of saturation of the concrete pores with water. In our case, the basic provisions of the theory of frost destruction of the concrete state that in the area of variable water level during the operation of structures, additional water saturation of the concrete $\Delta S_{ACT}$ can occur as a result of the action of two different mechanisms. During the cyclic freezing and thawing, pores can be “pumped” with water [17]. Analysis of the work of structures at section A (Fig. 2) in the winter period shows that the critical parameters of the external exposure are the concrete freezing temperature ($t_F$) and freezing cycles ($N_{FT}$). Therefore, to determine the concrete technology and predict the durability of the concrete, it is necessary to know the influence of the parameters ($t_F$) and ($N_{FT}$) on the process of saturation of concrete pores with water, i.e., to investigate the dependence ($S_{ACT} + \Delta S_{ACT} = f(t_F, N_{FT})$).

For all other sections of the area of variable water level, starting from the mark 0.00 and above (see Fig. 2), the icing of structures is typical. The critical indicators of the concrete freezing under these conditions are the concrete freezing temperature ($t_F$) and its duration ($T_F$). Therefore, in this case, it is advisable to study the process of water saturation of the concrete pores based on the dependence ($S_{ACT} + \Delta S_{ACT} = f(t_F, T_F)$, since in this case the redistribution of free water is possible under the influence of a temperature gradient [13, 17, 18]. After the freezing of the surface layer due to thermal and moisture conductivity, moisture can migrate from the inner layers of concrete to the periphery. As a result of the redistribution of moisture at the frost line, an additional saturation of the concrete pores ($\Delta S_{ACT}$) can occur. Provided that the value of the indicator ($S_{ACT} + \Delta S_{ACT}$) becomes equal to or more than the critical degree of water saturation ($S_{CR}$), i.e., with ($S_{ACT} + \Delta S_{ACT}$) $\geq$ ($S_{CR}$), the concrete structural will be destroyed.

The peculiarity of the operation of structures under conditions of the prolonged icing fundamentally changes the mechanism of the concrete freezing and the mechanism of the water saturation of pores. The formation of the concrete structure under the prolonged freezing, based on the theory of structure formation and hypotheses of mechanisms of the concrete destruction under the frost exposure, will obviously be associated with the processes of heat and moisture exchange. Due to these processes, it is possible to redistribute the moisture and saturation of the concrete pores in certain layers of concrete to a critical degree. Standard frost resistance tests do not simulate the process of the prolonged freezing, since the samples represent a closed system, in which the processes of heat and moisture exchange, characteristic for massive structures, are practically excluded. There is a reason to believe that the destruction of the concrete in structures of port facilities after the first year of operation is due to these very processes [19]. Therefore, such technological methods should be developed that will reduce the sensitivity of the concrete to these operating conditions, i.e., the processes of moisture transfer in conditions of the prolonged freezing and icing should be limited. A classic technique in the concrete technology, which excludes the destruction of the concrete under various freezing mechanisms, is the concrete technology compliance to the current regulatory
documents. However, the main problems at the construction site arise, when the regulatory requirements for the hardening conditions should be complied, i.e., the conditions for the formation of critical maturity of the concrete structure [19] should be created. In this case, it is advisable to consider the use of agents that provide a sufficient content of reserve pores in the cement stone, while minimizing the volume of capillary pores. Based on the provisions of the structural theory of the concrete and the influence of agents of different classes on the formation of the structure of the cement stone in the concrete [11], it makes sense to study the exposure of complex agents of electrolytes and surfactants on the durability of the concrete in an area of variable water level, when the predominant factor of the frost exposure is its duration.

4. Conclusion

The Ie of operating port facilities shows that the durability of the concrete largely depends on the ability to saturate water in the first winter period. It proves that freeze-thaw cycles are not always the defining critical parameter of epy external exposure. At some sections of structures, the temperature (t_F) and duration (T_F) of the concrete freezing can be the defined as the critical indicators during the freezing.

The peculiarity of the operation of structures under the prolonged icing fundamentally changes the mechanism of the concrete freezing and the mechanism of the pores water saturation. The formation of the concrete structure under the prolonged freezing, based on the theory of structure formation and hypotheses of the mechanisms of the concrete destruction under the frost exposure are associated with the processes of heat and moisture exchange. Due to these processes, a redistribution of moisture and saturation of pores in certain concrete layers can occur to a critical degree. It stands to reason that the destruction of the concrete in the structures of port facilities after the first year of operation is due to these very processes. Therefore, technological methods should be developed to reduce the sensitivity of the concrete to these operating conditions, i.e. to minimize the process of moisture transfer under the prolonged freezing and icing. The provisions of the structural theory of the concrete and the influence of agents of different classes on the formation of the structure of cement stone in the concrete give grounds for conducting further studies of the exposure of complex agents of electrolytes and surfactants on durability of the concrete in the area of variable water level, when its duration is the predominant factor of the frost exposure. This approach to increasing the frost resistance of the concrete was considered in scientific works, but it found no practical application.

5. References

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