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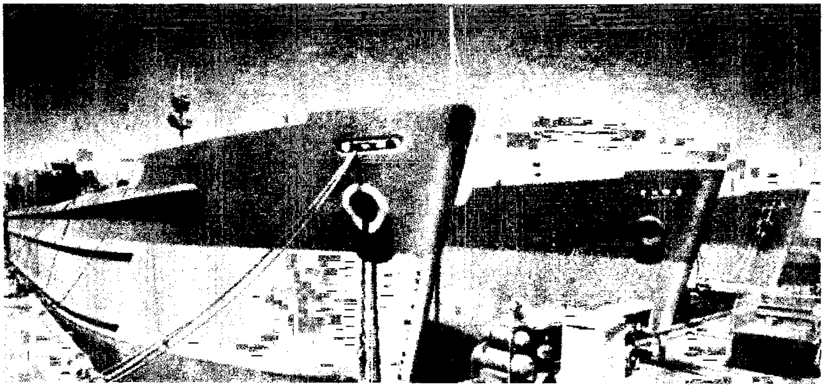
Now Reinforced Concrete Ships



Barrett and Hilp Are Building A Fleet of Twenty-six

First three reinforced concrete ships launched at the Belair Shipyard in South San Francisco. Others are being built six at a time.

Their Construction Will Save Great Quantities of Steel

Fig. 3—World War II concrete ship construction at San Francisco shipyard, 1943

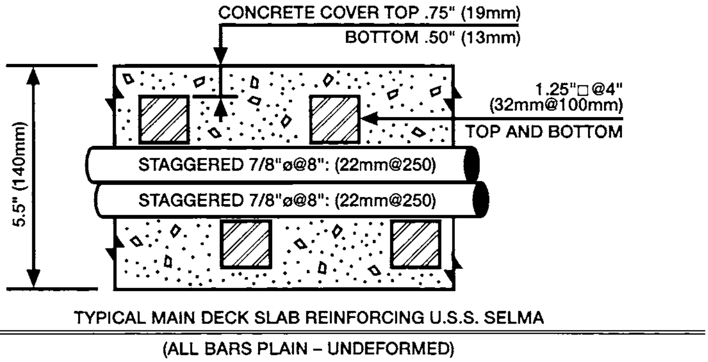


Fig. 4—Typical main deck reinforcing arrangement used in construction of World War I ships

SP 163-7

Long-Term Durability of Concrete Breakwaters in Cold Marine Environment

by T. Horiguchi, N. Saeki, and H. Kudoh

Synopsis: The deterioration of concrete structures for breakwaters in cold marine environment, situated in the northernmost part of Japan, was examined by means of physical inspections as well as chemical analysis. A total of 76 points is selected from 16 breakwaters for measuring deterioration. The 16 breakwaters consist of 10 fishing ports where four of them are situated in the north islands, two are situated along the Sea of Japan, and four are along the Sea of Okhotsk. At the time of examination, the ages of concrete ranged from 6 to 35 years. Physical inspection entailed measuring the vertical profile using a special frame. In addition, nondestructive tests were conducted to estimate the compressive strength of the concrete. Cylindrical cores (diameter 150 mm) were drilled from each breakwater for measuring the compressive strength, chloride contents and degree of carbonation. Chloride contents were measured at several depths, from the submerged surface to 80 cm inside of concrete. X-ray diffraction analysis as well as atomic absorption spectrometry, were conducted for microscopic analysis.

In some instances, more than 1.0 m depth of wear was found at the tidal zone between high and low tide level. The shapes of wear showed the typical hourglass shape. A high value of correlation coefficient was fond between the wear depth and in situ compressive strength estimated by a nondestructive test method. No significant correlation was found between the wear depth and the age of construction. It is found that the maximum chloride content was not always at the skin of concrete breakwaters, but it frequently was deep inside of the structures. From the tests results of the X-ray diffractometry and the atomic absorption spectrometry, aragonite, gypsum, ettringite and calcite were observed. This indicates the possibility of decomposing action of sea water on the constituents of hydrated portland cements. Finally, reliability analysis was used to predict the remaining service time based on the field data collected. Three factors were selected by the statistical significancy, these are the strength of concrete from nondestructive test results, the chloride penetration content and the depth between high and low tide levels.

Keywords: Chlorides; compressive strength; concrete cores; concrete durability; marine atmospheres; microstructure; seawater; underwater structures; wear; x-ray diffraction

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INTRODUCTION

In the northernmost part of Japan, concrete offshore structures are deteriorated not only by sea water attack, but also by freezing and thawing action and by impact and abrasive action of floating ice(1,2,3). As a result, concrete surfaces are often spalled or wore away in a very short time. The skin of concrete works as a protective coating against the chemical and physical attack. It is clear that the shorter the durability of concrete surface at early age is, the lower is the long-time durability of concrete.

The region called, Soya includes 39 fishing ports with 346 km along the coasts of the Sea of Japan and Okhotsk. The temperature in winter is below -20°C with northwest winds. The floating ice, which is often observed along the cost of the Sea of Okhotsk, impacts the breakwaters and appears to be the main cause of distress.

EXPERIMENTAL PROCEDURE

A total of 76 points was selected from 16 breakwaters for measuring the deteriorations. As for evaluating the geometrical deterioration, an original measuring device for longitudinal wear depth was developed(4). The device consists of an aluminium ladder with two vertical fixed bars and 30 horizontal aluminium bars that are 1.5 m in length and fixed every 5 cm. The device can measure the maximum depth of wear along a vertical height of 1.5 m of the breakwaters. Consequently, the device can then measure the geometrical feature of deterioration and longitudinal wear.

Cylindrical cores (diameter 150 mm) were drilled from the points of each breakwater for measuring the compressive strength, chloride contents, carbonation and microscopic analysis. Chloride contents were measured at several depths, from the submerged surface to 80 cm inside of concrete. A nondestructive test was also conducted with test hammer method at each point of vertical surface of breakwaters. X-ray diffraction analysis and atomic absorption spectrometry were conducted for the evaluation of microscopic analysis.

EXPERIMENTAL RESULTS

Geometrical Measurement of Deterioration

Fig.1 shows the typical test result for geometric measurement using the original measuring device. From the figure, it is clearly seen that the wear started below the superstructures (below the H.H.W. Line), and that the rate of wear increases in proportion to the longitudinal depth. The maximum wear was found in the mean-tide level between the high and low tide level. The profile between high and low tide was found to be of an hourglass shape.

Fig.2 shows the relationships between the depth of wear and the service life. In this paper, the age of the concrete structures ranged from 5 years to 35 years old. Although some of the old structures showed excellent durability, some of the relatively new structures showed poor durability. This implies that the age of structures is not the only factor that affects the life of marine structures. In other words, there exist more important factors that influence the durability of concrete breakwaters than the age of structure. This finding indicates the importance of studying the various factors which affect the durability of marine concrete structures.

Relationship between Wear Depth and Compressive Strength

Fig.3 shows the relationship between the wear depth and the compressive strength. The compressive strength, σ_c was estimated by the nondestructive test method (rebound number of test hammer method). The maximum wear depth, Dmax is then described as follows:

$$Dmax = 45.6 \exp(-0.12\ \sigma_c) \qquad (1)$$

It is clear that the rate of deterioration decreases with increasing compressive strength. This implies that the compressive strength is the one of the most important factors affecting the durability of marine concrete. As shown in the figure, the maximum wear depth was observed to be 100 cm. The estimated compressive strength varies from 1 to 30 MPa.

Chloride Penetration

Fig.4 shows the chloride contents as a function of the depth below the concrete surface of breakwaters from different fishing ports. As shown in the figure, the chloride content varies from 4 to 11 kg/m^3 (total of cl^- ions per 1 m^3 concrete); this is relatively high. The chloride values are not always decreasing with increased distance from surface. Their maximum chloride contents were observed to be at 50 to 60 cm from the surface of the concrete. This indicates that the chloride ions penetrate deeply into the concrete.

The relationship between the maximum wear depth and the chloride content is shown in Fig.5. From the figure, it is clearly shown that the maximum depth of wear tends to coincide with a high the chloride content.

Microstructural Evaluation

Fig.6 shows the test results of X-ray diffractometry. The sample was collected at a 26 years old fishing port. The maximum depth of wear was 29 cm at the sampling point. The estimated compressive strength was 6.8 MPa and the chloride content (total of cl^- ions per 1 m^3 concrete) was 10.30 kg/m^3 which was relatively high. The port was situated in a small island exposed to very severe conditions.

From the X-ray diffractogram of the Fig.6, aragonite, gypsum ettringite and calcite were observed. From these findings, it would appears that sea water has a significant role in the decomposition of portland cement concrete(5,6).

Magnesium content was analyzed by the atomic absorption spectrometry. The test results are shown in Fig.7. The maximum magnesium content occurred between 40 to 50 cm deep from the surface of concrete. Although the brucite ($Mg(OH)_2$) was not detected by the X-ray diffractometry analysis, the penetration of magnesium was confirmed by the atomic absorption spectrometry.

SERVICE LIFE PREDICTION

A reliability analysis was conducted for the prediction of the remaining service time using with the field data. The field data were carefully selected from the nondestructive test results, degree of the chloride penetration and the depth between high and low tide levels. "LIFEREG" program was applied for the reliability analysis estimating the life time due to the critical wear depth. The detail of calculation is shown in Appendix.

The fault time of LIFEREG was set to be the remaining service year T_0 due to the critical wear depth. The service life model for estimating the remaining service life is defined as follows.

$$T = \mu + \sigma \cdot t \qquad (2)$$

where

$$T = \log T_0, \quad \mu = \beta_0 + \Sigma\beta \cdot x, \quad t = \log t_0. \qquad (3)$$

The logarithmic service life t as the probability density function, could be described by using Weibull's function f(t);

$$f(t) = r \cdot \alpha \cdot t^{r-1} \cdot \exp(-\alpha \cdot t^{r}) \quad (4)$$

where

$$r = 1/\sigma, \qquad \alpha = \exp(-\mu/\sigma) \quad (5)$$

When the factors, x could be selected by the statistical analysis of significancy, such as the multivariate analysis, Eq.(3) and the logarithmic likelihood, L, with n sets of data for k factors are described as;

$$L = \sum_{i=1}^{n} \log \left\{ f(t_i) / \sigma \right\} \quad (6)$$

and

$$\mu_i = \beta_0 + \sum_{j=1}^{k} x_{ij} \cdot \beta_j , \quad i = 1 \sim k \quad (7)$$

β and σ could be solved in the condition when the logarithmic likelihood takes its maximum value. Table 1 shows the test result of a typical breakwater. β_1, β_2 and β_3 were the strength of concrete, degree of the chloride penetration and the depth between high and low tide levels, respectively. Fig.8 shows the reliability curve of the typical breakwater using the result of Table 1. As shown in the figure, the reliability at the 20 year life time corresponds to 0.8, approximately. This indicates about 20% of the breakwater will be deteriorated. The deterioration was defined, in this study, as the maximum depth of wear being 50 cm. The result of calculation has shown the good accordance with the experimental result.

The reliability analysis were conducted for several types of breakwaters using with the field data that were selected from the three factors. When the critical wear depth was assumed to be 50 cm, this yielded a reliability function R for each breakwater was shown in Fig.9

CONCLUSIONS

The deterioration of concrete breakwaters was measured and related to compressive strength (core specimen) and chloride ingress so as to evaluate the mechanism of deterioration in marine concrete. Finally, X-ray diffractometry was conducted for the evaluation of the micro chemical aspects of the mechanism of deterioration. From the test results, the following conclusions could be drawn:

1. An effective method of measuring the vertical profile of breakwater was

developed. The profile between high and low tide was found to be of an hourglass shape.

2. The age of structures was not a strong factor affecting the durability of marine structures.

3. The compressive strength of concrete was found to be a good parameter to correlate with the durability of concrete breakwaters.

4. It is found that the maximum chloride content was not always at the contact area between the sea water and breakwaters, but frequently showed a maximum deep inside of concrete.

5. From the test results of X-ray diffractometry, aragonite, gypsum ettringite and calcite were observed. This indicates that sea water acts as a decomposing agent on the constituents of hydrated portland cements.

6. It is found that the factors of compressive strength and degree of the chloride penetration can be used to predict the service time of breakwater using reliability analysis.

REFERENCES

1. Horiguchi, T., Saeki, N. and Endo, H.(1994) Deterioration of Marine Concrete Structures in Cold Region, Proc. of '94 Cold Region Technology Conference, pp.337-340.

2. Sarkar, S.L. and Malhotra, V.M. (1995) Microstructure Durability of Concretes Exposed to Arctic Conditions, Concrete Under Severe Conditions, E & FN Spon, Vol.1, pp.829-838.

3. Leivo, M.T. (1988) Testing Concrete for Arctic Offshore Conditions, 2nd International Conference on Performance of Concrete in Marine Environment - Supplementary papers, pp.159-171.

4. Horiguchi, T., Saeki, N. and Kamata, A.(1996) Deterioration of Concrete Breakwaters in Cold Climate, Proc. of 7th International Conference on the Durability of Building Materials and Components (in printing).

5. Mehta, P.K. (1980) Durability of Concrete in Marine Environment - A Review -, ACI, SP-65, ed. V.M.Malhotra, pp.1-20.

6. Conjeaud, M.L. (1980) Mechanism of Sea Water Attack on Cement Mortar, ACI, SP-65, ed. V.M.Malhotra, pp.39-61.

APPENDIX

Reliability analysis for service life prediction

Reliability function, R(t) is defined as the probability with the life time, t which doesn't exceed the ultimate service life, T, and is described as

$$R(t) = P(T>t) \qquad \cdots (1)$$

With using the probability density function, f(x), the Reliability function R (t) can be expressed

$$R(t) = \int_t^\infty f(x)dx \qquad \cdots (2)$$

$$F(t) = \int_0^t f(x)dx \qquad \cdots (3)$$

where F(t)=1-R(t).

Meanwhile, the failure rate for the period, (t, t+Δt) could be described as

$$P(t<T\leq t+\Delta t \mid T>t) \qquad \cdots (4)$$

Thus the generalised failure rate λ(t) is then calculated with Eq(4) for Δt→ 0 and described as

$$\lambda(t) = \lim_{\Delta t - 0} \frac{P(t<T\leq t+\Delta t \mid T>t)}{\Delta t} \qquad \cdots (5)$$

where

$$P(t<T\leq t+\Delta t \mid T>t) = \frac{P[(t<T\leq t+\Delta t) \cap T>t]}{P(T>t)}$$

$$= \frac{P[(t<T\leq t+\Delta t) \cap T>t]}{P(T>t)} \qquad \cdots (6)$$

Eq(6) can be described with using probability density function f(x);

$$P(t<T\leq t+\Delta t \mid T>t) = \frac{\int_t^{t+\Delta t} f(x)dx}{\int_t^\infty f(x)dx} \qquad \cdots (7)$$

From Eq(7), Eq(5) is described as

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{\dfrac{1}{\Delta t}\displaystyle\int_t^{t+\Delta t} f(x)\,dx}{\displaystyle\int_t^{\infty} f(x)\,dx} = \frac{f(t)}{\displaystyle\int_t^{\infty} f(x)\,dx} \qquad \cdots (8)$$

and

$$\lambda(t) = \frac{-\{\displaystyle\int_t^{\infty} f(x)\,dx\}}{\displaystyle\int_t^{\infty} f(x)\,dx} \qquad \cdots (9)$$

Then Eq(9) becomes

$$\int_t^{\infty} f(x)\,dx = e^{-\int_0^t \lambda(x)\,dx} \qquad \cdots (10)$$

Thus the reliability function, R(t) can be calculated by the failure rate function from Eq(2) and Eq(10);

$$R(t) = \int_t^{\infty} f(x)\,dx = e^{-\int_0^t \lambda(x)\,dx} \qquad \cdots (11)$$

In the same manner, the probability density function can be calculated as follows;

$$f(t) = -\lambda(t)\, e^{-\int_0^t \lambda(x)\,dx} \qquad \cdots (12)$$

Among the probability density funtions such as exponential distribution, logarithmic normal distribution or gamma distribution, Weibull distribution is applied widely in this field. The probability density function of Weibull distribution is

$$f(t) = \gamma\, \alpha\, t^{\gamma -1} \exp(-\alpha\, t^{\gamma -1}) \qquad \cdots (13)$$

Where $\gamma = 1/\sigma$ and $\alpha = \exp(-\mu/\sigma)$.

TABLE 1—TEST RESULT OF RELIABILITY ANALYSIS

	Estimate	STD err	Chi-square	Pr>Chi
β_0	0.9007	0.219	16.86	0.0001
β_1	0.0930	0.047	3.89	0.0484
β_2	1.8277	0.134	185.85	0.0001
β_3	-0.0172	0.002	67.84	0.0001
σ	0.067	0.021		

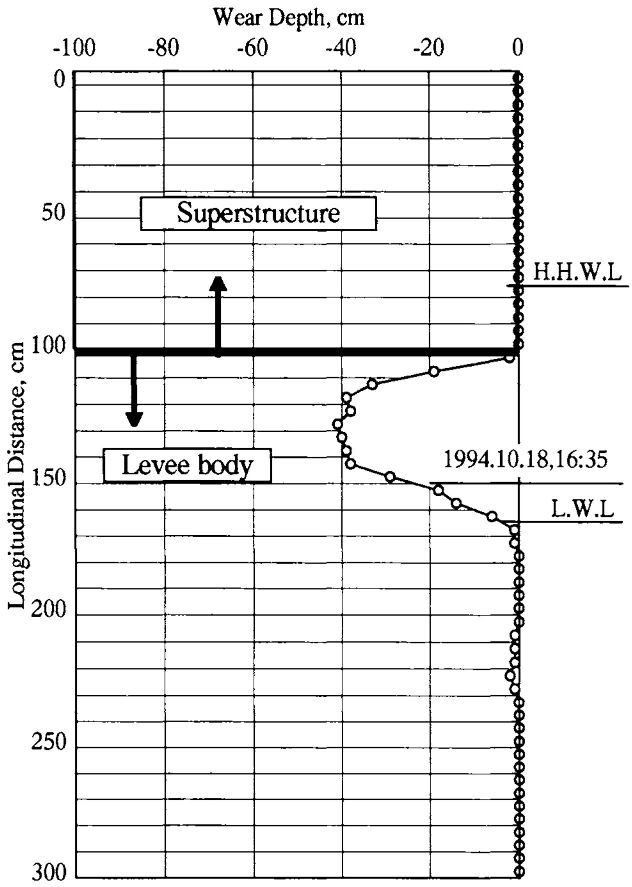

Fig. 1—Deterioration of typical breakwater