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CONCRETE STRUCTURES IN COLD REGIONS

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SYNOPSIS

This paper summarizes the results of the past systematic investigations on the freeze-thaw durability of concrete structures, gives some examples of old structures in Hokkaido Island, the coldest region of Japan, and describes the results of some experimental research. From the experimental research, the surface scaling of concrete subjected to the action of sea water, and the bond strength between stone and mortar under some curing conditions are explained. Furthermore, strength properties and pore structures of concrete near the surface layer when dried and when exposed to sea water, become clear by using small mortar cylinder specimens of 1−5 cm in diameter. Lastly, the freeze-thaw durability of concrete of various air contents exposed to sea water, is shown by rapid freezing and thawing test.

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1. FOREWORD

Concrete structures have been called semipermanent structures or maintenance-free structures until the present, but contrary to our expectation some structures have been repaired or rebuilt on account of deterioration. Because the relationship between different types of environment and durability is not made sufficiently clear by reason of a short period of experience concerning concrete structures and an insufficient accumulation of research data. The durability of concrete is influenced by external factors such as wind, rain, snow, sunshine, temperature change, humidity change, water permeation, chemical action, abrasion and cavitation, and by internal factors such as materials, mix proportion and construction procedures. Accordingly, it is not easy to elucidate durability because these factors are overlapped and effected mutually. It has been recognized from past experience that concrete structures made under adequate design and construction are durable, but if there are some defects in the process, deterioration of concrete progresses at an early stage.

Freeze-thaw action and abrasion due to pack-ice and studded tires are listed as external factors peculiar to concrete structures in cold regions. On account of the repetition of these actions in winter, the tissues of concrete loosen as time goes on, then the near-surface area of hardened concrete flakes and deteriorates into small fragments or particles. Consequently, deterioration of concrete progresses inside a concrete member.

Fig. 1 shows the regions with mean air temperature below 0 °C and −10 °C in January. It is therefore possible for deterioration owing to freezing and thawing to occur throughout Japan as well as in Hokkaido, and many reports on deterioration in Japan have been published [1,2 etc.]. Table 1 shows the air temperatures in the main cities related to this paper.

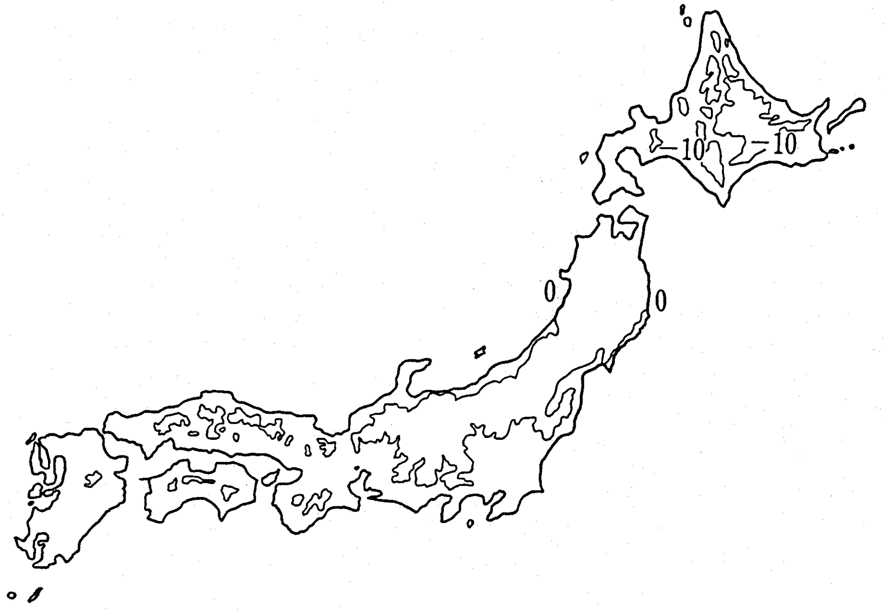


Fig. 1 Monthly mean air temperature, Jan.

Table 1 Air temperature, °C

City	Yearly mean	Jan.		Aug.		Record	
		Mean	Mean of daily min.	Mean	Mean of daily max.	Min.	Max.
Abashiri	5.9	−6.6	−10.3	18.6	22.3	−29.2	36.0
Obihiro	6.1	−8.5	−15.2	19.6	24.7	−34.9	37.8
Sapporo	8.0	−4.9	− 8.9	21.3	25.9	−23.9	35.8
Otaru	8.2	−3.8	− 6.7	21.2	25.1	−18.0	34.7
Hakodate	8.3	−3.6	− 7.6	21.2	25.1	−17.9	32.6
Tokyo	15.3	4.7	0.5	26.7	30.8	− 9.2	38.4

2. SYSTEMATIC INVESTIGATION OF FREEZE-THAW DURABILITY

Deterioration due to freezing and thawing is caused by essential defects in the concrete itself, faults in construction work, and the inadequacy of the design of the structure, but the former two are the causes of deterioration in a narrow sense. Systematic investigation of freeze-thaw durability in Hokkaido Island was performed four times in the past and gave much useful information.

2.1 Investigation in 1954–1956

The Hokkaido Society of Civil Engineering investigated 97 damaged structures by questionnaire [3]. All these structures had been made of non-air-entrained concrete, and consisted of water power facilities, harbor and river structures, bridges, pavements, retaining walls and ash pits etc. The main results of this investigation were as follows: (1) damaged structures had mostly been in contact with water, (2) the period from 16 to 35 years after construction accounted for 61 percent of the whole, (3) the porportion of 1:3:6 accounted for 85 percent of the whole and W/C was estimated to be 0.7–0.9, (4) the cause of damage was mostly the freeze-thaw cycle, but corrosion of reinforcement due to salt wind was also notable. Preventive measures were indicated, namely (1) concrete surfaces should not be in contact with water as far as possible: for instance, better drainage on the upper surface of the members and covering with more durable materials than concrete should be considered, (2) materials of good quality and concrete with richer proportions should be used, and construction procedures be carefully carried out. At the same time, the results of a study about the freeze-thaw durability of air-entrained concrete were accompanied by this report [4]. The author has reported some of the results of this survey in the past [5]. Photo. 1 shows the severe damage at the abutment

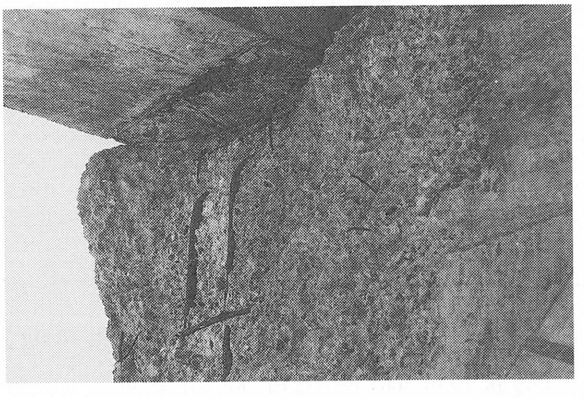


Photo. 1

of a certain inland RC bridge 24 years after construction, due to a high degree of saturation of the concrete by melting snow on the pedestal or the bridge surface.

2.2 Investigation in 1972

Severe damage was not observed around 1972, owing to the spread of air-entrained concrete, the perfection of standards for the design and specification of construction with the rapid increase in the construction of concrete structures as shown in Fig. 2, and the short lapse of time. However, damage due to freezing and thawing such as light surface scaling was noticeable. This damage occurred on the

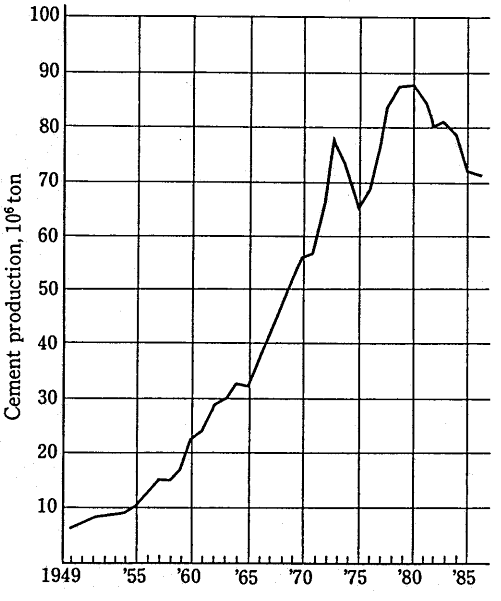


Fig. 2 Cement production in Japan

top or side of concrete members especially in coastal and harbor structures a few years after construction. The Hokkaido Development Bureau endeavored to clear up the cause by the accelerated test of surface scaling and many other tests [6]. Also, this organization made a systematic field survey of some 300 civil engineering structures which had concrete mix proportion data etc. in 1972. Their ages were 1–9 years. The results of this survey indicated that the number of structures damaged due to freeze-thaw action in sea water was about twice as many as in fresh water [7] and 59 % of 454 structures including later survey suffered some damage, and freeze-thaw damage was severer in blended cement concrete than portland cement concrete [8]. It was concluded that since such a situation was undesirable, though the mix proportion in these structures was determined by the regulation of W/C needed at the point of the freeze-thaw durability, and though the degree of damage had not affected the safety of the structures, there were some details to be improved in the standard of mix design or the method of construction [8].

2.3 Investigation in 1979

Considering the above results, the Hokkaido Society of Civil Engineering made an investigation into the actual conditions concerning mainly the surface scaling on the 194 coastal and harbor structures in one winter after construction in 1979. The results of this survey were as follows [9,10]: The percentage of occurrence of scaling was 69 % of the inspected structures. Blended cement was used in

92 % of the structures. Air entrainment was used in all concrete and W/C was 45–62.5 %, W/C of 52.5–55 % being the most frequent among them. The scaling of concrete with more than a standard-cured compressive strength of about 280 kgf/cm^2 at 28 days was reduced considerably. Surface scaling almost did not occur if the member was over 16 m away from the sea. Scaling was severe when the number of freezing and thawing cycles for one winter based on −2 °C in air temperature exeeded 60 cycles. Photo. 2 shows the surface scaling after two years on the vertical surface of a wall which faced the Okhotsk Sea and was constructed in 1986. Fig. 3 shows the percentage of the blended cement to the total quantity of cement sold in Japan.

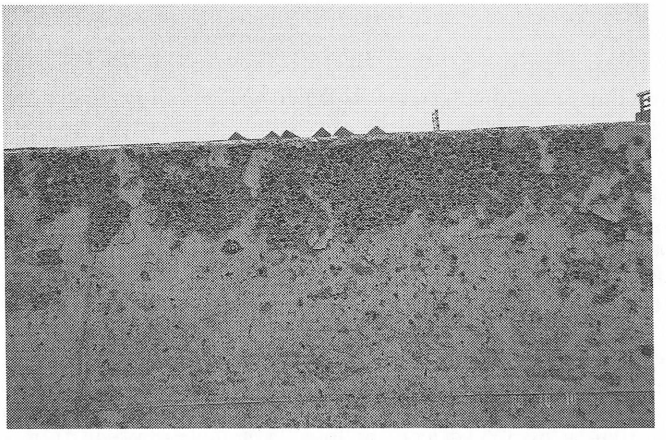


Photo. 2

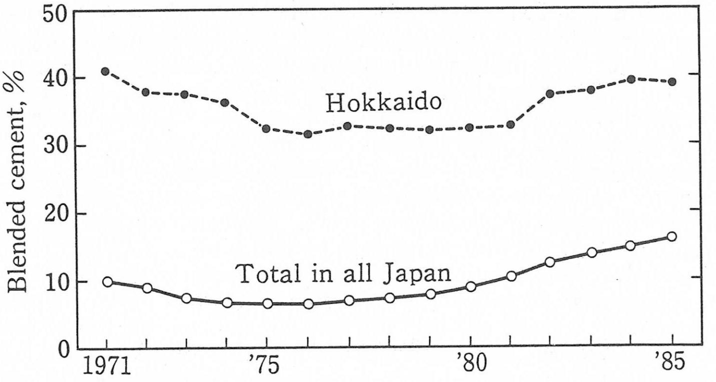


Fig. 3 Ratio of blended cement to the total quantity sold in Japan

2.4 Investigation of Pavements in 1980

This investigation was performed by the Hokkaido Society of Civil Engineering. It became clear that although the greater part of the concrete pavement constructed between 1955–1965 had a thickness of only 20 cm, had no mesh, and the countermeasures against frost-heaving of road bed were not enough, it had resisted severe natural weather conditions such as the freeze-thaw cycle, abrasion due to tire chains or studded tires, and the increase of traffic or load, and although cracks had occurred and partial patching had been performed the pavement has seen a lot of service [11]. Namely, the percentage of the pavement in service for more than 25 years was 33 %, more than 20 years 58 %, and 15 years or over 83 %. In other words, good quality of pavement, even a thin slab, with countermeasures against frost-heaving of the road bed, should be durable. Besides, unit cement content was mostly 300–340 kg/m^3. Moreover, it is a matter of course that the above-mentioned percentage would increase naturally with the lapse of time.

3. ACTUAL EXAMPLES OF OLD STRUCTURES

3.1 Otaru Harbor [12]

The north breakwater of Otaru Harbor is a representative old structure in service in Hokkaido Island. It was the first construction facing the open sea in Japan, and several investigations from 1894 and large scale test work in 1895 were performed by Hiroi. In accordance with these test results, the design for harbor construction was established. The first section of the work, the breakwater 1288 m in length, was started in 1897 and was completed in 1907. The breakwater, 91 years old in 1988 and still in service now, consists almost entirely of precast concrete blocks of 5.3–9.3 m^3 and in-situ concrete on these blocks. The mix proportion of these blocks was originally 1:2:4, but as volcanic ash was used from 1902, the proportion became 1:0.8:3.2:6.4. Several strict investigations extending over short and long terms on the selection of cement and the effect of volcanic ash and sea water were performed, because at that time it was directly after the scandal of the cracking concrete blocks in Yokohama Harbor [12–14]. In 1933 four 25 cm cube test specimens were saw-cut from a block 34 years old, and the compressive strengths of 402.1, 457.0, 412.1, 360.5 kgf/cm^2 and the mean value of 407.9 kgf/cm^2 were obtained. From in-situ concrete on the block, two 20 cm cube strengths of 332.5, 462.5 kgf/cm^2 and the mean of 397.5 kgf/cm^2 were obtained [15]. These values were higher than the mean strength of 305 kgf/cm^2 of four 25 cm cubes saw-cut from a block 37 years old in Yokohama Harbor [16]. This was probably due to the reason that the concrete in Otaru Harbor had a richer mix, more careful compaction and better cement quality than that at Yokohama Harbor [15]. Fujii said, looking back upon making the specimens and test results, ".....observed particularly each polished surface of the specimen.....no large void, and considering the smoothness of the whole surface the specimens were similar in appearance to natural stone. Therefore, no one can make better concrete than this, because of the perfection of the bond between coarse aggregate and mortar and the higher density than that at Yokohama. It seems that the major reasons were the better compaction and lower water cement ratio than that at Yokohama". He also said ".....I was struck with admiration for that necessary condition for sea water resistant concrete was almost perfectly achieved, namely higher density and more minute void. Furthermore, I think the quality of these concrete blocks will remain unchanged forever" [15]. The importance of careful compaction is also understood from the following specifications for manufacturing concrete blocks. ".....when the height of a layer of concrete placed reaches 18 cm, the concrete shall be tamped by means of using four large rammers, each worked by two laborers, who raise them 60 to 120 cm high. If water exudes from the surface about 15 minutes, all the corners shall be tamped by small rammers. When the compaction of one layer finishes, the concrete surface is raked and then the next layer of concrete can be placed......" [12] (author's comment: the mass of the large rammer is nearly 17 kg, and small nearly 5.6 kg). Because of a shortage of home-manufactured cement in the early stage of construction, overseas imports filled the gap, but domestic products only were used from 1900 and finally the greater parts of the first section of the work was executed by using the domestic products. The present state of Otaru Harbor has been independently reported on [17], and the condition of the original in-situ concrete on the blocks before the raising of the breakwater have also been reported on [18].

3.2 Abashiri Harbor

Abashiri Harbor which faces on to the Sea of Okhotsk is an important harbor which has undergone the extension work recently. The first work on this harbor started in 1919 and finished in 1930. The construction work on this harbor is considered of unparalleled difficulty in world harbor construction history, together with Rumoi Harbor, facing on to the Sea of Japan in Hokkaido [19]. Moreover, Hirao, the engineer in charge, said "Taking a look at the shape of the breakwater when finished makes us imagine how difficult the construction work must have been" [20]. As the maximum movement of the RC caissons due to the rough sea during construction reached 5.7 m, the main breakwater was strengthened by setting a sub-breakwater inside the harbor behind the main breakwater. The section when finished is shown in Fig. 4. Subsequently, the breakwater was levee raised. The concrete covering the caissons and the upper part of the caissons of the sub-breakwater, were subjected to abrasion owing to waves and the fluctuation of the water level for 60 years, as there had been no in-situ upper concrete from the first, and also the concrete was subjected to abrasion owing to floating ice entering the harbor, and the freeze-thaw cycle [Photo. 3]. The mix proportions of the in-situ upper concrete of the original breakwater and the caisson of both breakwaters were 1:2.5:5, 1:2:4 respectively.

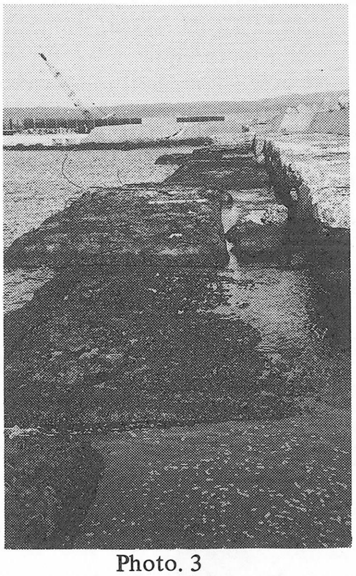
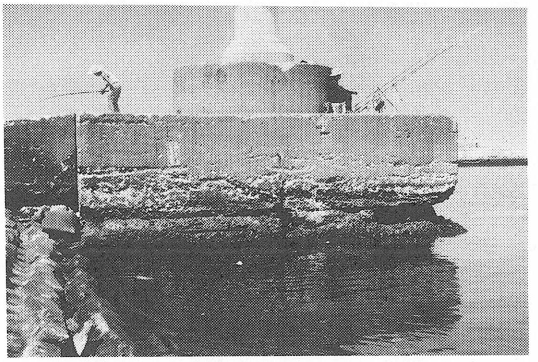


Photo. 3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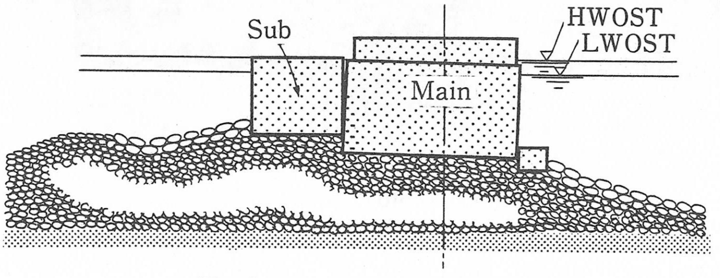

Fig. 4 Section of breakwater

Photo. 4 shows the present state at the head of the jetty of Abashiri River which flows into the harbor. This RC caisson was manufactured and set up in 1928 and 60 years had just run their course in 1988. The mix proportions of this caisson and the cover concrete were 1:2:4, 1:2.5:5 respectively and in-situ concrete was a mix of 1:2.5:5 containing rubbles. It appears the tidal zone of the caisson and the in-situ concrete was severely damaged owing to the complex action of abrasion and freezing. However, the underwater portion below about LWOST and the upper part of the in-situ concrete are scarcely damaged after 60 years. Therefore, great improvement in durability is practicable even on the coast of the Sea of Okhotsk provided that the concrete of the tidal part is strengthened and air-entrained concrete is applied.

According to the replies submitted to a questionnaire on the life of structures in cold regions and tablelands in Japan 1981, the estimation of 50 years was 41 % of 206 replies, and 100 years or more was 14 % in the matter of the breakwaters [21]. It seems that the respondents underestimated the durability of breakwaters considering the above-mentioned good results of Otaru Harbor and Abashiri Harbor.

3.3 Tokachi-oh-hashi Bridge and Others

In addition to the above, examples such as the Tokachi-oh-hashi Bridge performing its function without freeze-thaw damages for over 50 years in a severe environment in a cold region, are not few in number. There is also the instance of the Sasanagare buttress type RC dam to supply water for the city of Hakodate which was constructed in 1923, and is still in service now, although it was repaired and strengthened in 1983–1984. However, there are not a few small-scale structures and easily exchangeable manufactured items which have been abandoned or remade on account of freeze-thaw damage. Photo. 5 shows the condition of frost damage on armor blocks 20 years old on the coast of the Sea of Okhotsk, and melting snow. The difference of deterioration among the blocks is noticeable in that the blocks not being particularly damaged are in the majority. It is to be supposed that this difference was caused by variation of quality even though the external conditions such as waves, sea spray, and the melting of snow, differ. Therefore, it seems that the above-mentioned phenomena indicate the importance of maintaining the uniformity of concrete.

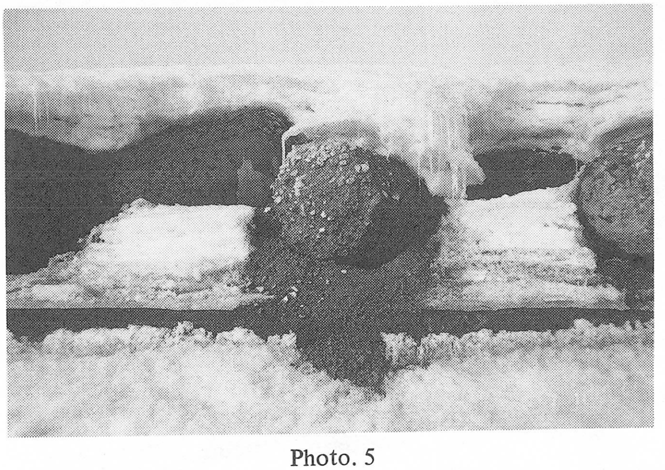

Photo. 5

4. EXPERIMENTS OF SURFACE SCALING

It is generally known that the qualities of the upper portion and the lower portion of concrete members differ owing to bleeding after placing concrete in the members. Also after the removal of the mold or after the specified wet curing, evaporation from the concrete surface, whether from the top, the bottom, or the sides, occurs and reaches gradually inside. It takes many days for the evaporation of the water inside [25 etc.], and still longer for those members exposed to rain. However, the area within a few centimeters of the exposed surface loses water easily, provided it is kept dry. Consequently, hydration doesn't progress sufficiently or there is the possibility of all sorts of cracks. If the quality of exposed surface of the concrete is worse than that inside, or defects arise, surface scaling occurs owing to freeze-thaw cycles in cold regions. Therefore, special caution is required for the quality of concrete for exposed surface, and the author has described this matter formerly as hot weather concreting in cold regions [26]. This near-surface area of the concrete is also important in the role of the protection of reinforcement, and many papers have reported on this as described in 5 below.

Maekawa and Imai obtained the graphs in Fig. 5 [7] from the accelerated scaling tests of two cycles of freezing and thawing a day at −10–+10 °C, which started at the age of 28 days, through covering the specimen surface with approximately 5 mm of fresh or sea water. The specimens were made of air-entrained concrete with a W/C of 0.60 in July and August, and after the specified wet curing they were placed outdoors (excluding rainfall) in the city of Sapporo. The result was that the extent of scaling in sea water was 2–4 times severer than in fresh water. The results also showed that scaling occurs more easily in blended cement concrete than in ordinary portland cement, and similar results were also obtained from the exposure test of large test blocks on the coast of the Sea of Okhotsk [27]. The author and Ayuta measured the scaled area on one side after 30 cycles of one direction freezing and thawing, at the rate of one cycle a day, at −6–+12 °C from the age of 28 days. The specimen concrete has three values of W/C and four curing conditions; these are shown in Fig. 6 [28]. Drying was carried out at 33 °C 25 % RH, wetting at 20 °C 90 % RH, and standard curing at 20 °C in water. From these tests, it seemed that the remarkably harmful effects due to drying were based on the coarsening of the pores, described below, in addition to the defects of the interface between aggregate and paste. Also, it was found that drying after the initial adequate curing was effective. This has already been pointed out in the freeze-thaw durability [29–31 etc.], and there is also a paper stating that the effectiveness differs owing to the degree of drying [32]. The author and Ayuta experimented with the effects of fresh water and sea water on surface scaling. Namely,

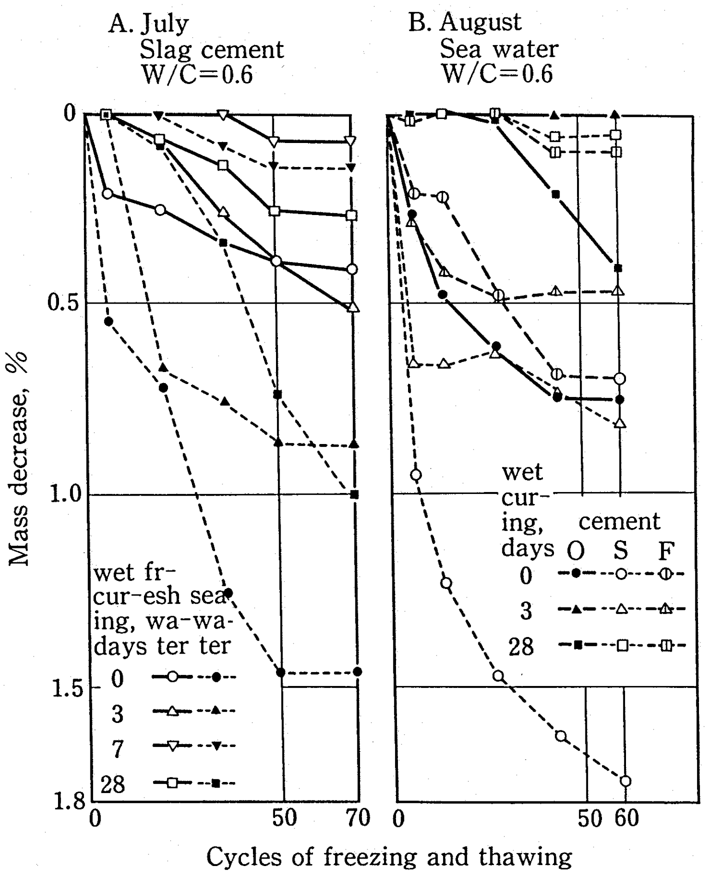

Fig. 5 Result of accelerated scaling test (O: ordinary portland cement S: slag cement B type F: fly ash cement B type)

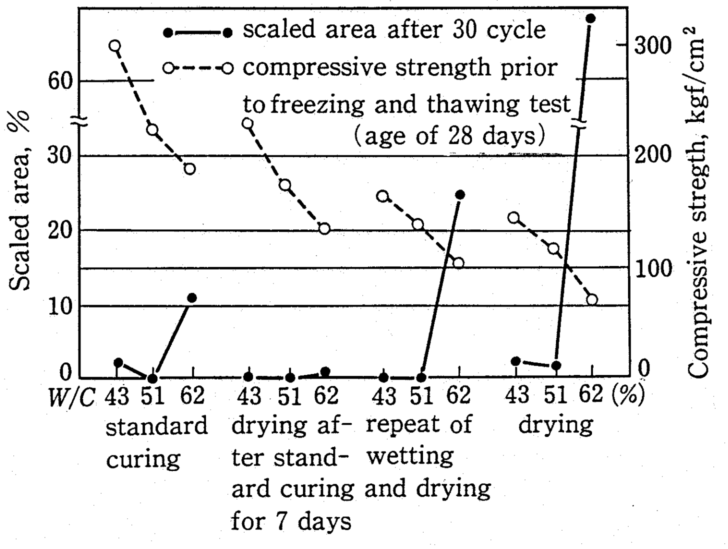

Fig. 6 Relation between curing condition and surface scaling

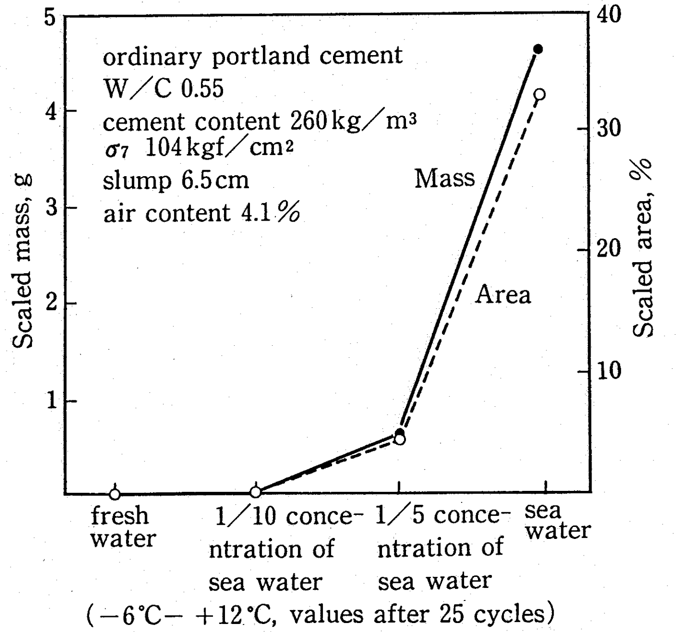

Fig. 7 Comparison of scaling in sea water and in fresh water

the scaled mass and area were measured after one direction freezing and thawing at the rate of one cycle a day, using specimens placed for 7 days outdoors at a mean temperature of 13 °C after demolding at the age of 2 days. Fig. 7 shows that sea water accelerates the surface scaling at the end of 25 freezing and thawing cycles [28]. The test method for scaling resistance on concrete surfaces exposed to de-icing chemicals is standardized as ASTM C 672, but further research has been continued [33].

The studies on the bond strength between cement paste and aggregate, the mechanism of combination in the interface, and so on, have been performed for some years [34–39 etc.]. Iwasaki and Tomiyama reported that as the bond layer is formed early after placing, the bond strength does not easily recover when the bond layer dries at early age, even if wet curing is applied after that. They also stated that as the interface is not a direct combination and it combines through a thin layer consisting of crystalline hydrate, the bond strength is influenced by the strength of the aggregate, the hardened paste and the bond layer itself, the combined force between the aggregate and the bond layer, and between the bond layer and the hardened paste. They also reported the thickness of the bond layer [36, 37]. The author and others performed tests on the bond strength by flexure (Fig. 8) between stone and mortar with W/C of 0.55, in five curing conditions, and as shown in Fig. 9 [40]. Mortar was covered by a wet cloth after molding, and kept at 20 °C 95 % RH. After 20–24 hrs the specimens were remolded and the specified temperature and humidity conditions were fixed. In the case of ① 20 °C water curing, the bond strength increases with age. In the case of ② curing at 20 °C after sealing by lap film, the strength increase with age but is lower than ① . In the case of ③, repeated temperature change from 50 °C for 8 hrs to 20 °C for 16 hrs during sealed curing, the strength is lower than ② (about 80 % of ② after 7 days). Namely, in the cases of ① to ③, the bond strength increases with age more or less. However, in the cases of ④, in which specimens are dried at 30 °C 25 % RH after the removal of the lap film following 20 °C sealed curing for specified periods, the bond strength drops with the increase of the drying periods, while in the case of ⑤, specimens are dried in the same conditions but following repeated temperature changes from 50 °C for 8 hrs to 20 °C for 16 hrs while sealed in lap film, the bond strength drops with the increase of the drying periods. Thus, drying has greater influence on the bond strength than repeated temperature change of 30 degree. Therefore, it appears that drying lowers the bond strength between aggregate and paste, then surface scaling occurs on account of the freeze-thaw cycle in winter.

An exposure test using 21 large specimens each approximately 1 m^3 employing various cements, mix proportions and curing conditions is in progress on the coast of the Sea of Okhotsk [41]; surface scaling is increasing even after eight winters, though the extent of scaling differs with the various conditions [42].

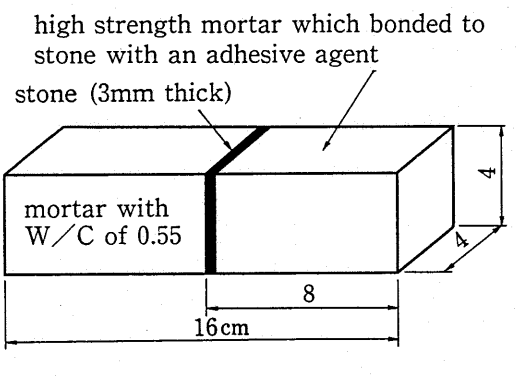

Fig. 8 Specimen

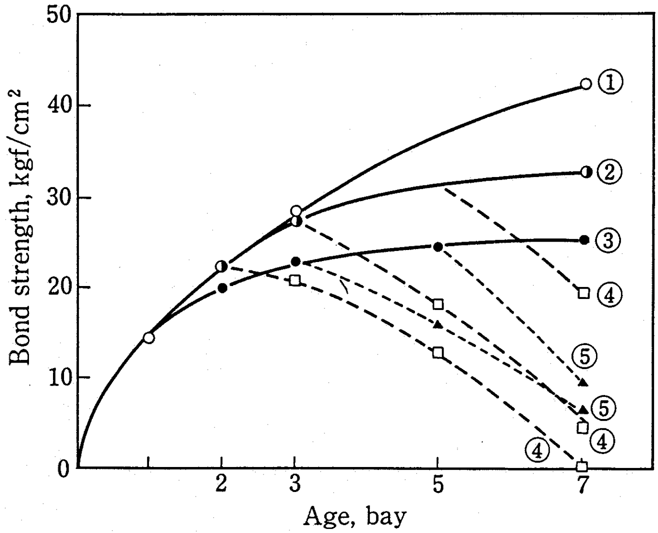

Fig. 9 Bond strength

5. STRENGTH AND PORE STRUCTURES OF EXPOSED SURFACE DUE TO DRYING

As freezing of concrete generally progresses from the surface inwards, the portion near the exposed surface has more opportunities to freeze, a greater number of freeze-thaw cycles, and is subjected to lower freezing temperature, all of which influence the freeze-thaw resistance of concrete [43]. Scaling of such exposed surface areas results mainly from drying, as stated before, and it is considered that drying has an unfavorable influence upon the strength properties of mortar matrix itself, as well as the bond strength of the interface between coarse aggregate and mortar.

In order to clarify the degree of hydration from the surface inwards under drying conditions, the author and Ayuta measured the combined water at each depth by slicing a mortar specimen of ϕ5x25 cm, dried only from one end, and obtained the results in Fig. 10 [44]. Mortar specimens with W/C of 0.55, Toyoura standard sand cement ratio of 2.0, were cured at 20 °C in a 95 % RH room until the age of 2 days, cut down to 2 cm thickness at one end and dried from this end at 20 °C 50 % RH. Furthermore, the specimens water-cured at 20 °C were added, and these were tested at the ages of 28 days and 91 days. Each sliced sample was 5 mm thick and eight specimens were prepared in the same experimental conditions. According to Fig. 10, the degree of hydration of the exposed surface hardly differs from the inside when water-cured, but in the case of 50 % RH, the combined water is considerably greater near the exposed surface, and subsequently decreases sharply towards the inside. The minimum occurred at a depth of 5 mm at 28 days, and at a depth of 10 mm at 91 days, then increased gradually with depth. Hydration in 50 % RH is retarded as compared with water-curing, except within a depth of 10 mm from exposed surface, and the extent of retarding is less at greater depth. It appears that more combined water in the area near the exposed surface is accounted for by carbonation as describe before.

As stated above, the author and Ayuta evaluated the properties of concrete near the exposed surface when dried by means of combined water, and much research on the quality of concrete cover has been carried out by all sorts of techniques from the standpoint of the protection of reinforcement. For instance, there is much research involving techniques such as evaluating the strength from the diameter of the hollow by means of a Ball-Impact-Tester using a steel ball of 10 mm in diameter applied to each plane of a terrace cut in 5 mm deep steps from the surface [45]; testing the distribution of pore diameter, X-ray diffraction, chemical analysis, density, void, absorption properties, air permeability, by means of a test specimen sliced from a few milimeters to one centimeter in thickness from the surface toward the inside of the specimen [46–50]. Evaluating the surface strength by means of the pop-out method or nail pull-out method are also performed [51]. However, the method of testing by compressive breaking strength has not been performed. Accordingly, the author and

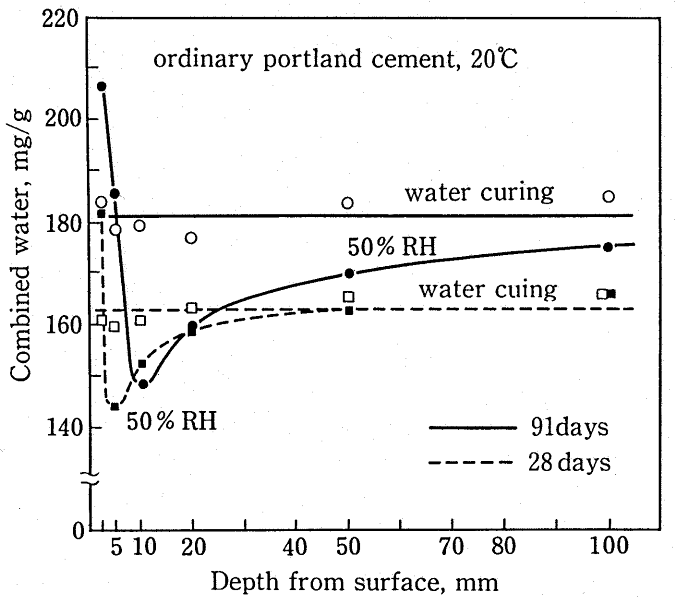

Fig. 10 Combined water and depth from surface

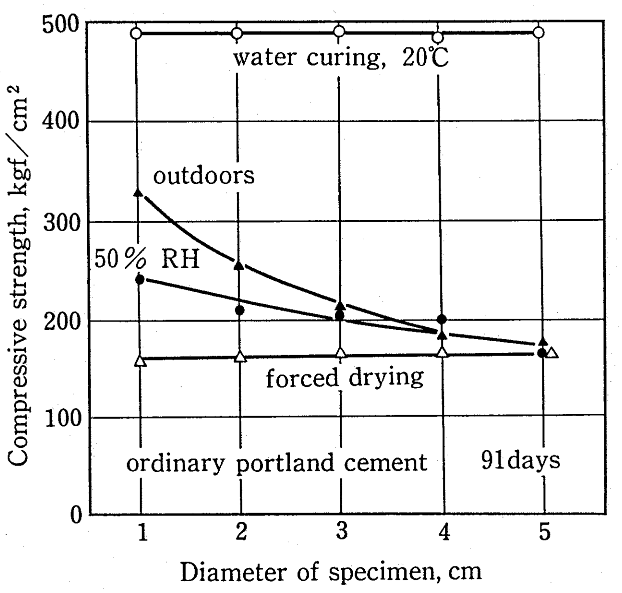

Fig. 11 Compressive strength of small specimens

Ayuta tested breaking strength by means of small mortar specimens (height diameter ratio of 2.0, ϕ1–5 cm) [44]. The W/C of the mortar was 0.55 and the Toyoura standard sand cement ratio was 2.0 by weight. The reason why small mortar specimens were used was that the influence due to drying and the properties of mortar near the surface are indicated more clearly as the diameter is smaller. It was clear that the small specimen below ϕ5 cm corresponds to the portion within a depth of 10 mm from the exposed surface based on the relation between the combined water of small specimens and

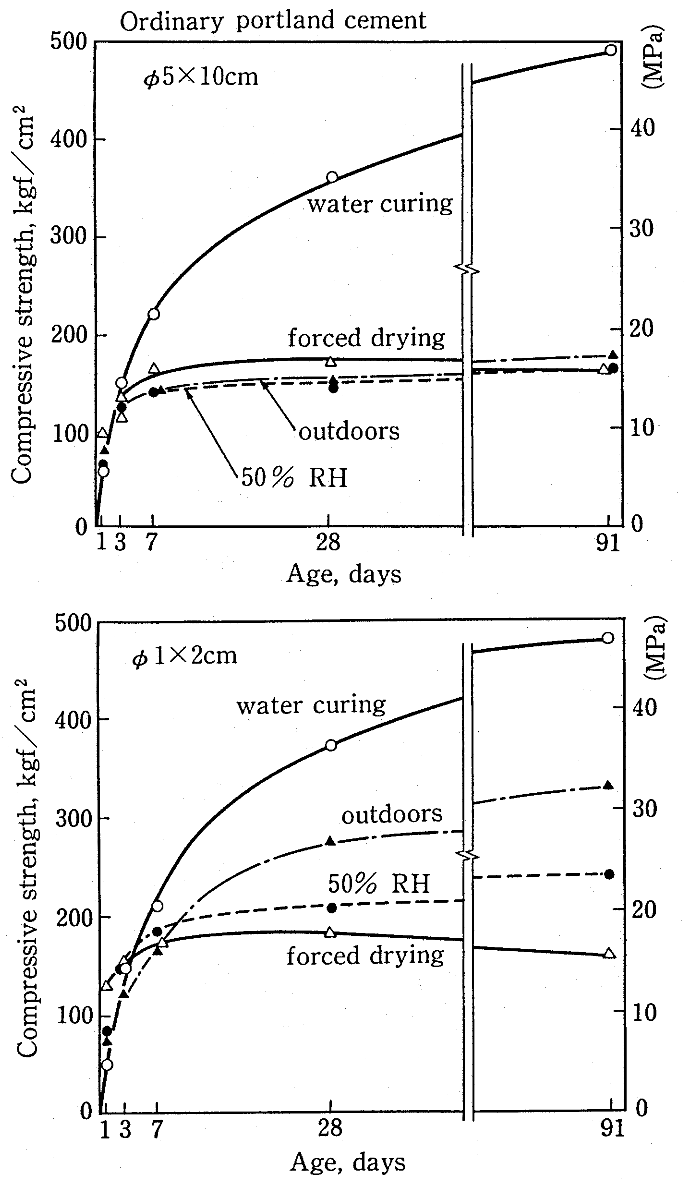

Fig. 12 Development of compressive strength

the distribution of combined water of specimens dried on one side previously mentioned. Moreover, as the compressive strengths of ϕ1–5 cm mortar specimens indicate different values owing to their difference in size, strength values were corrected in accordance with the compensation curve for seven strength levels based on the size of the specimens. Thus, the compressive strength of the small specimen is shown in Fig. 11, and the relationship between age and strength on the ϕ5 cm, ϕ1 cm is shown in Fig. 12. Fig. 12 demonstrates that any strength in the case of the outdoor exposure (mean air temperature 15 °C, 82 % RH, wind velocity 1.5 m/s, covered by a roof), 50 % RH 20 °C and forced drying at 25 % RH 30 °C is fairly lower than in the case of water curing. Moreover, a small specimen has higher strength than a large specimen in the case of outdoor exposure, and 50 % RH as shown in Fig. 11. It appears that this fact is due to the effect of the above-stated carbonation. In the case of forced drying, the strength is almost the same value through each size specimen. In Fig. 12 although in water curing the strength increases with age regardless of the size of specimen, in the above-mentioned three drying conditions the strength development is retarded considerably. Furthermore, in outdoor exposure the strength of ϕ1 cm specimens increase slightly with age. As mentioned above, the strength development of a portion near the exposed surface is retarded owing to drying, and in the outdoor exposure or 50 % drying, the strength of a portion very near the surface is higher, but for portions a little deeper, the strength development is retarded after 7 days. Fig. 13 shows test results on the carbonation mentioned above. In the 50 % RH air which contains carbon dioxide, the smaller the specimen the higher the strength, but in the 50 % RH air which contains little carbon dioxide, the smaller the specimen the lower the strength. In the combined water test too, the same results as mentioned above have been obtained. Therefore, the phenomena that the combined water of the portion near the surface is more than the inner portion when dried at 50 % RH from one side of the specimen as stated before [Fig. 10], and that the strength of the small specimen is higher than that of the large specimen in the case of drying at 50 % RH or outdoors, are due not to the progress of hydration, but to carbonation.

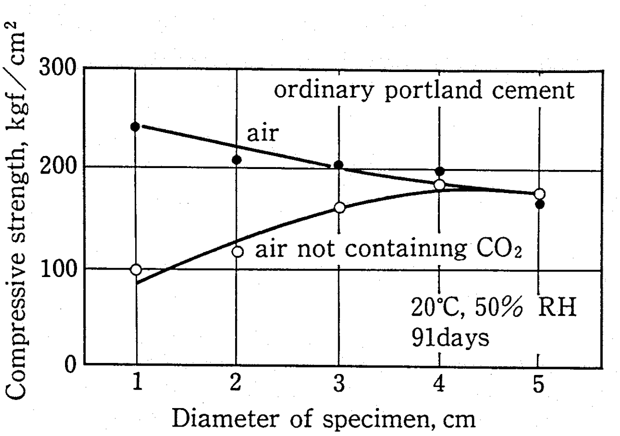

Fig. 13 Effect of carbonation on compressive strength

Fig. 14 shows the pore size distribution of the mortar, with W/C of 0.55, Toyoura standard sand ordinary portland cement ratio of 2.0, cured in water at 20 °C and at 50 % RH 20 °C [52]. The pore radii of mortar cured at 50 % RH is larger than that in water, and total pore volume also is much greater (V_P, pore radii 37–562000 Å). Therefore, it appears that the portion near the exposed surface has larger radii and much greater pore volume in the case of drying than the inner portion (nearly corresponding to water curing in Fig. 14), and the drying of the near surface area has such harmful influences as strength reduction and the raising of the freezing point of capillary water. Chino et al. also indicate that the pore radius is larger and the pore volume near the surface is more than the inner portion in air curing [46].

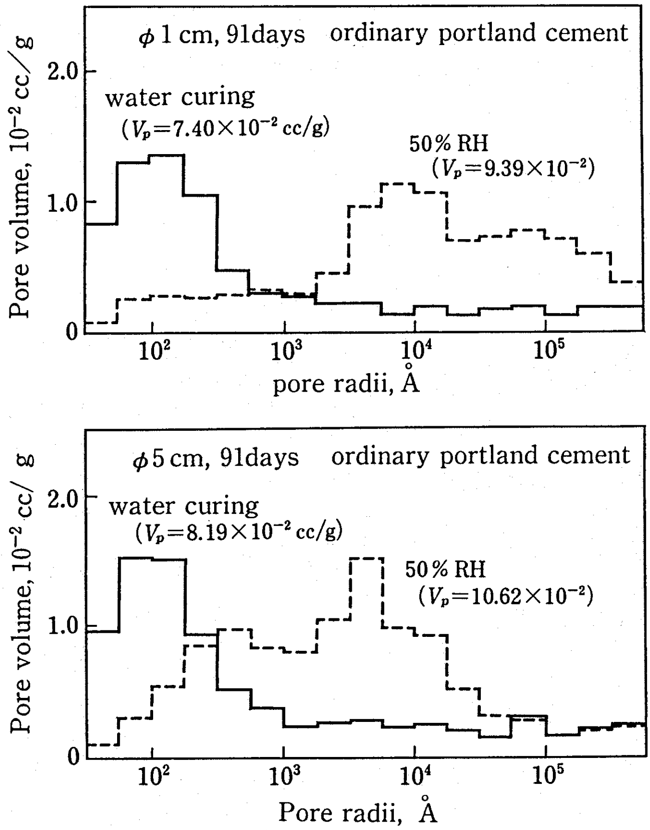

Fig. 14 Pore volume

6. STRENGTH PROPERTIES, PORE STRUCTURE AND FREEZE-THAW DURABILITY OF THE SURFACE OF CONCRETE MEMBERS EXPOSED TO SEA WATER

It has been definitely shown that chemical composition and pore structure differ between the exposed surface and inside of concrete members subjected to the action of sea water [47, 53, 54, etc.]. The strength of the surface area, however, has not become clear, because it has been unable to measure it directly. The author and Ayuta determined the strength of a surface subjected to fresh water and sea water by means of small mortar specimens which has W/C of 0.55. Fig. 15 shows the results at the age of 91 days [55]. Consequently the small specimen when immersed in sea water indicated a lower strength than in fresh water, particularly in the case of φ1 cm only fifty percent and more. Namely, strength development of the near surface area exposed to sea water is retarded considerably, in comparison with the inside. Also, there is little difference between ordinary portland cement and fly ash cement. Fig. 16 shows the relation between the size of specimens and the median values of pore radii when immersed in fresh or sea water for 91 days [55]. According to Fig. 16, in the case of sea water immersion, median value of pore radii become larger as the specimen decreases in size; namely this means coarsening of the pore structure near the surface. As a result of simultaneous mass measurement of specimens immersed in fresh or sea water from 7 days to 91 days, mass increasing rate in fresh water is constant regardless of the dimensions of specimen, but the mass increasing ratio in sea water is higher as the dimensions of the specimens become smaller. Thus, this fact indicates that sea water easily permeates. It is supposed that this fact is one reason why scaling by the freeze-thaw cycle occurs more easily in the case of sea water as compared with fresh water, because freezable water in the area near the exposed surface increases considerably due to the above-mentioned coarsening of pore structure also. In order to clarify the reason for the coarsening of the pore structure, identification of the reaction products of the specimens immersed in fresh water and sea water was performed by means of X-ray diffraction. Fig. 17 shows some of the results obtained. In the case of the smaller specimens immersed in sea water, the peak of $Ca(OH)_2$ is lower, and $Mg(OH)_2$ is also detected slightly. Consequently, it is confirmed that the coarsening of the pore structure of hardened cement paste depends on the evaluation of $Ca(OH)_2$ with the permeation of sea water.

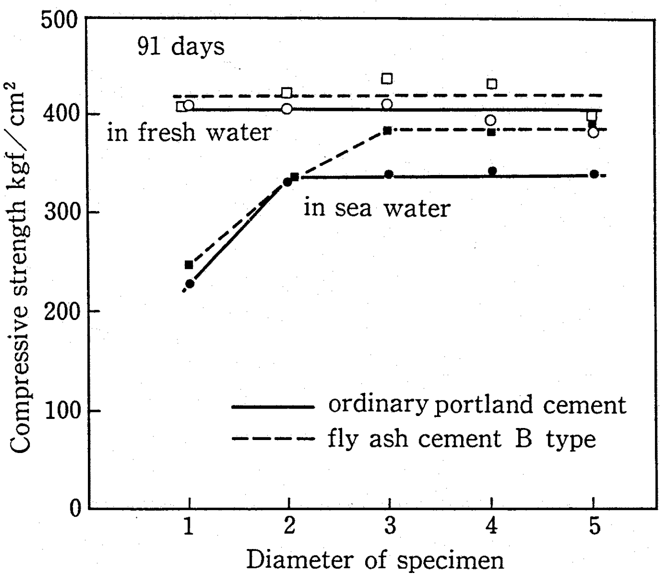

Fig. 15 Size of specimen and compressive strength

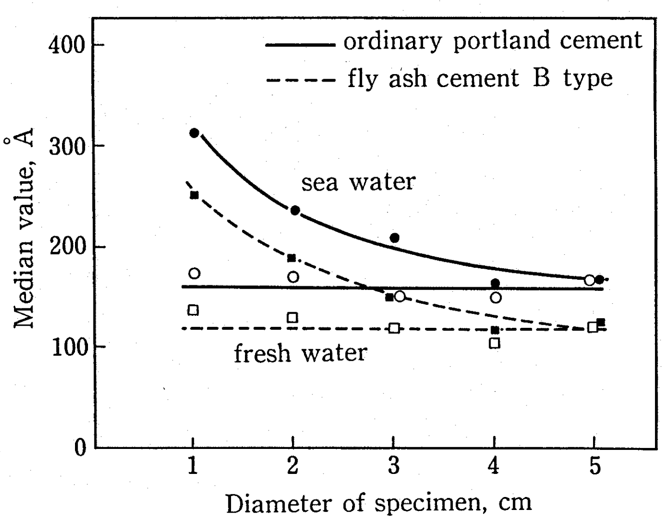

Fig. 16 Size of specimen and median value of pore radii

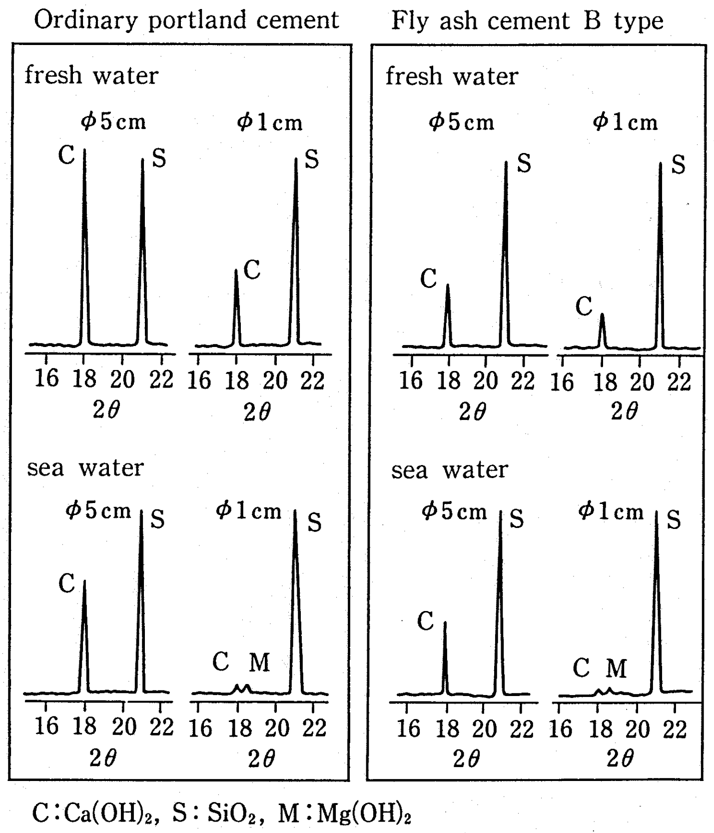

Fig. 17 X-ray diffraction diagram

The author discusses the freeze-thaw durability of concrete subjected to sea water action. Attention has been paid to freeze-thaw durability for some years, and slow freezing and thawing tests have been widely performed, including many tests at the time of the construction of the Hoover dam completed in 1936 [56]. It was common that the results of freezing and thawing test were evaluated by the decrease of compressive strength, dynamic modulus of elasticity, mass or the number of freeze-thaw cycles till deterioration [57]. Thereafter, ASTM Designation C 290, 291, 292, 310 were successively issued, though they were tentative, and the study on freeze-thaw durability progressed. Examples of freezing and thawing tests also increased rapidly in Japan, too. Considering the freeze-thaw durability in sea water, Lyse reported that air content of concrete in the case of fresh water and sea water in order to gain the best durability, needs to be 3–6 %, 10–12 % respectively [31], but doubtful points on air content or maximum size of aggregate were submitted [58]. The author and Ayuta carried out rapid freezing and thawing tests in fresh water and in sea water in accordance with Procedure A of ASTM C 666. However, freezing and thawing tests were started when the specimens were 28 days old and finished at 300 cycles, and the relation between environmental conditions, especially drying conditions until the start of freeze-thaw cycles, and freeze-thaw durability, was found along with the effect of air content on freeze-thaw durability. As shown in Fig. 18 [59], the specimens exposed in an airy shed in summer after water curing for 5 days (5W) did not deteriorate in either fresh or sea water as compared with the other conditions. Both the dynamic modulus of elasticity and mass of concrete exposed outdoors after remolding at the age of one day (D) lowered, and the change in length was also larger than 5W. Consequently, concrete dried after wet curing for 5 days has a tendency to increase its freeze-thaw durability, though the strength is lower than in those which continued to be water-cured (W). It seems that this is due to the decrease of freezable water, because the free water in concrete lost owing to drying after initial wet curing is not sufficiently reabsorbed.

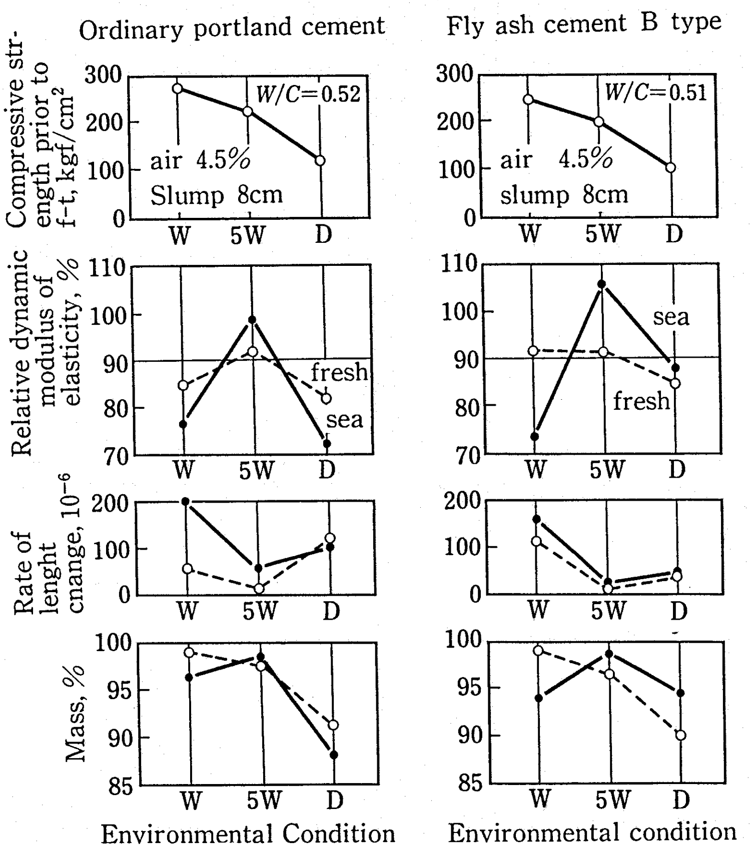

Fig. 18 Results of freezing and thawing test

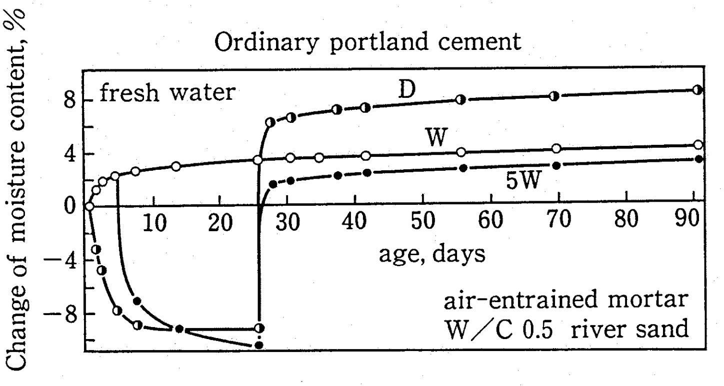

Fig. 19 Change of moisture content

In order to confirm this, the moisture content of the mortar after the removal of the coarse aggregate in the above-mentioned concrete was tested. From the test results [Fig. 19], 5W-mortar immersed in water has less moisture than W-mortar or D-mortar immersed in water, thus confirming the above-mentioned guess. Therefore, with the exception of the purpose of getting a higher degree of hydration, drying after initial wet curing is effective in order to improve the freeze-thaw durability. However, there is also some research that claims this differs due to the degree of drying [32].
In order to study the freeze-thaw durability of concrete of various air contents subjected to sea water and fresh water, the author and Ayuta carried out freezing and thawing tests on concrete with the same W/C and slump, air content of 1.8–19.2 % (cement content decreases considerably with the increase of air content) which indicated that higher air content lowers freeze-thaw durability [59]. Thereafter, freezing and thawing tests of concrete standard-cured till 28 days with a cement content of 260 kg/m^3 slump 8 cm, and air content of 4–8 %, in fresh and sea water from the age of 28 days according Procedure A of ASTM C 666, were carried out. Test results after 300 cycles are shown in Fig. 20 and Photo. 6. The above air content indicates the value in fresh concrete. Air void systems in hardened concrete were determined by means of ASTM C 457 and image analysis using a personal computer [Table 2]. It has been definitely shown by this experiment that provided both cement content and slump are constant, the freeze-thaw durability of concrete in fresh and sea water is improved without considerable change of compressive strength even if air content increases within 4–8 %. Also, concrete exposed to freezing and thawing in sea water has lower durability than in fresh water, and shows more surface scaling in particular.

The freeze-thaw durability of concrete in sea water was mentioned above. On the other hand, there are also investigations into the microstructural change of hardened cement paste due to freezing and thawing in sea water, and the effect of the reduction of deterioration by drying, based on the change of the microstructural features due to newly formed compounds [61, 62]. Accordingly, it is necessary to perform a many-sided study of the cement matrix itself and mortar or concrete containing aggregate.

7. AFTERWORD

This paper described the results of the systematic survey, mainly concerning freeze-thaw durability, of actual concrete structures in service in Hokkaido, the northernmost island of Japan, and the reason why concrete structures in Otaru Harbor constructed about 90 years ago are durable and still in service. Furthermore, the present state of surface scaling which has appeared on coastal or harbor structure recently, and the results of studies on preventive measures were explained. Freeze-thaw durability has become better owing to the spread of air-entraining concrete in recent years, but the problem of surface scaling has not been solved. Therefore, elucidation of its mechanism, and the formation of standard specifications, such as sorts of cement, W/C, air content, and curing, are urgently required, not only from the standpoint of aesthetics, but also to improve the reliability of concrete structure. Because the environmental conditions on different parts of concrete structures vary, and the quality of the concrete is not uniform, it is unavoidable that the degree of deterioration is uneven. Consequently, it is necessary to make the concrete suitable for the environmental conditions in each part of the structure. The structures have to be well ballanced on the whole, in order that only a partial defect does not determine the durability of the entire structure. Considering that non-air-entrained concrete subjected to the action of sea water in Hokkaido under severe weather conditions has been in service for the past 90 years, and the structure on the coast of the Sea of Okhotsk has been in service for 60 years to date, though it is partially damaged, it appears that there is a fair chance for making a structure maintenance-free for 100 years or more by means of the application of air-entrainment and the strengthening of certain necessary parts.

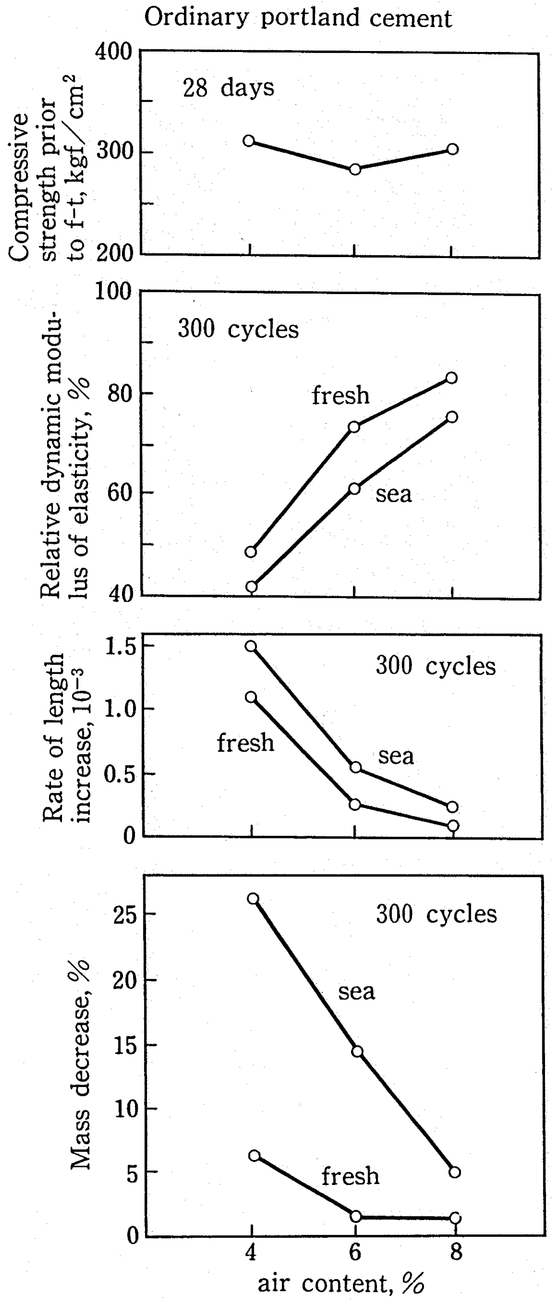

Fig. 20 Results of freezing and thawing test

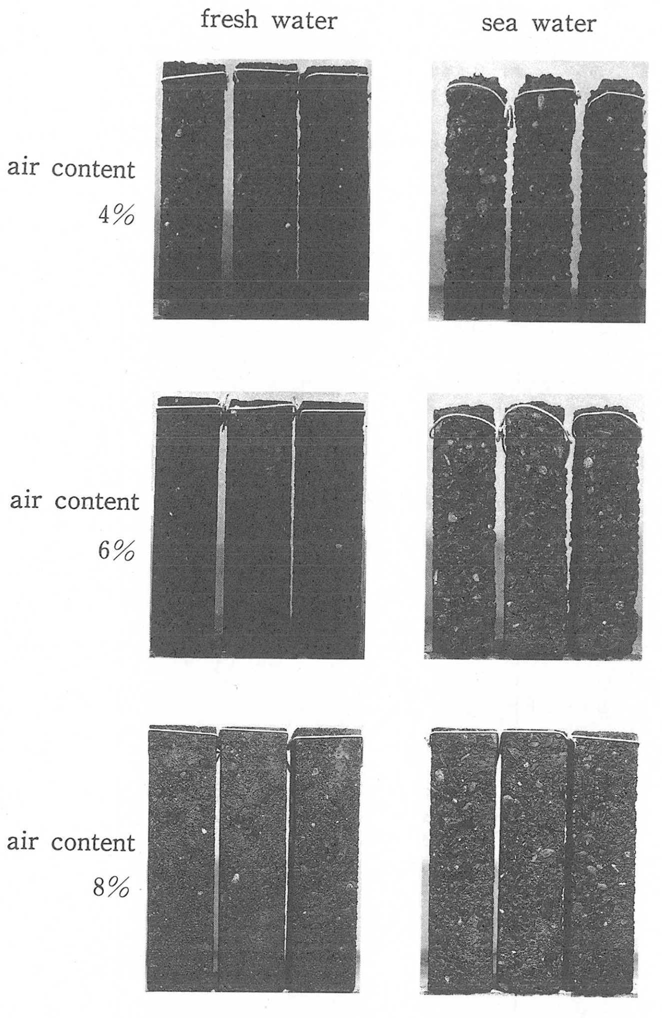

Photo. 6

Table 2　Pore structure of hardened concrete

Air content in fresh concrete	4 %			6 %			8 %		
	A	*a*	*L*	*A*	*a*	*L*	*A*	*a*	*L*
Image analysis	2.9	228	253	5.2	209	199	8.3	235	106
ASTM method	3.1	281	199	6.2	216	164	7.6	237	116

A : air content, %

a : specific surface, cm^2/cm^3

L : spacing factor, μm

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