Inspection was carried out by the consultant responsible for the design and also by inspectors employed by the owner. Testing for air content of the fresh concrete was not done. Concrete cylinders were made for compressive strength testing at 28 days. Some test results were lower than the desired strength of 20.7 MPa (3000 p.s.i.) and the highest strength was 23.4 MPa (3400 p.s.i.).

Following construction, the inside of each tank was coated with a layer of a propriatory cementitous water proofing membrane.

History of Use

Following construction, the tanks were used for rearing fish. Each tank was filled to within 300 mm (12 inches) of the top with spring fed water. The water flowed from a standpipe at one end and out of a drain at the other end of each tank. The flow of water was rapid so that only a thin coating of ice formed on the surface during the winter. The temperature of the spring fed water was constant during the winter at about 4.5^{o} C.

Table salt (NaCl) was used about twice a year for treatment of the tanks. After each treatment, the tanks were flushed with fresh water before fish were put back. No other chemicals were used.

Environment

The climate in this part of Canada is extremely severe. The mean daily temperature in December is -10^{o} C. In January and February, the mean daily temperature is -15^{o} C and the mean daily minimum temperature is about -20^{o} C (1). Minimum temperatures are often less than -30^{o} C and may go to below -40^{o} C. The tanks were protected from the radiant heat of the sun by the roof over the top. Thus there was no warming by the sun.

Failure

During the first winter, the exterior concrete wall of tank 6 failed. The wall cracked and delaminated in a local area so that water leaked at such a rate that it became unusable (Figure 2). As a result of this failure and associated damage to some other tanks (Figure 3), the whole facility was closed.

INVESTIGATION

In July 1981, the authors were asked to conduct an investigation into the cause of failure of the fish tanks. A site visit was made and concrete cores and bulk samples collected.

Site Visit

Of the ten tanks, only the exterior wall of tank 6 had failed (Figure 2). The concrete had failed locally in an area of 0.4 m^2 (4 ft^2), just above the floor of the tank. There was delamination and cracking, parallel with the surface, at a depth of between 40-80 mm (1 $^1/_2$- 3 inches). The reinforcing steel, which was uncorroded, was exposed. The top of the common wall between tanks 6 and 7 also showed severe deterioration, but had not failed (Figure 3). Concrete to a depth of 100 mm (4 inches) had delaminated and lost all strength. A 4 mm wide crack on an otherwise undamaged upper surface of part of this wall was partly filled with a white, crystalline powder, which on subsequent testing was found to be Trona (sodium carbonate), Figure 4.

Samples were taken of deteriorated concrete from the wall of tank 6 and the top of the wall between tanks 6 and 7. 100 mm (4 inch) concrete cores were taken from apparently sound areas of the wall of tank 6 and also from the wall between tanks 6 and 7. Cores were also taken from other tank walls and floors and the surrounding walkway which did not show deterioration.

The cementitous waterproofing coating applied to the inside of the tanks had largely failed. There were many areas where the membrane (2-10 mm thick) had flaked and spalled away from the concrete.

Petrographic Examination

All cores and fragments were subjected to petrographic examination following the ASTM procedure (3), using a stereo-microscope. A petrographic microscope was used for confirming the identity of secondary minerals.

The coarse aggregate, maximum size 20 mm ($^3/_4$ inch), made up 35-45% by volume of the concrete. The aggregate was a well graded, partly crushed natural gravel of Precambrian igneous and metamorphic rock. The rock types in decreasing order of abundance were: diabase, granite, granodiorite, gneiss, metavolcanics and metasediments. Traces of sulphides were found dispersed throughout all the rock types. The particles were sound and unaffected by freezing and thawing.

The fine aggregate made up 25-35% by volume of the concrete. It was a well graded, natural sand from the same source as the coarse aggregate. The fraction 5.0-0.5 mm was mainly composed of the same rock types as found in the coarse aggregate. The fraction smaller than 0.5 mm was composed of quartz, feldspar and ferromagnesian minerals. The amount of mica was estimated to be less than 1% by volume.

The source of the coarse and fine aggregate had a long history of use in concrete. No problems had been encountered that could be attributed to the nature of the aggregate.

The cement paste made up about 20-30% by volume of the concrete. The paste was soft and chalky and had an even white colour. The paste was so soft that there was some difficulty in preserving and retaining the paste when grinding the concrete with abrasives on a rotary lap. None of the samples showed good quality paste which is characterized by a glossy, vitreous lustre on a freshly broken surface. The concrete was uncarbonated except on surfaces previously exposed to the air.

The secondary minerals, ettringite and portlandite were found in most samples. The samples of undeteriorated concrete had minor amounts of these minerals. The deteriorated concrete had relatively large amounts of these minerals in air voids, lining fracture surfaces, and in sample No. 20, at aggregate-paste interfaces.

The concrete was unfractured except in samples 4, 7, 20, 21 and 22, which had numerous fracture surfaces through the paste and around the coarse aggregate particles. When the concrete was broken in compression or with a hammer, the fracture in all samples was usually through the paste and rarely through the coarse aggregate particles. There was generally a poor aggregate-paste bond.

A visual estimate was made of the air void system in these samples not tested for their air void properties. Sample 9 had an adequate air void system. All other samples were poorly air-entrained (less than 3% air by volume).

Concrete Quality

According to the governing CSA standard (4) the exposure of this concrete was class B. The concrete should have had a maximum water-cement ratio of 0.5 and the air content of the fresh concrete should have been between 4 and 7 percent. Table 1 shows that the mean air content of the hardened concrete was 2.6%. Only three samples had air contents greater than 4% and in these samples, the air void spacing factors exceeded the ACI 201 recommendation of 0.20 mm (5). The mean air content of the failed concrete (samples 4, 7, 20, 21 and 22) was 1.6%. The soft, chalky texture and white colour of the paste, the low compressive strength and the poor aggregate-paste bond indicated that the probable water-cement ratio was considerably in excess of 0.5.

It is not surprising that the concrete failed in view of its poor quality, lack of adequate air entrainment and the severe environment. What is remarkable is the nature of the failure.

MECHANISM OF FAILURE

The condition of exposure was unusual. There was a continual supply of warm (4.5° C) water on one side of the concrete wall of tank 6 and continually cold (-15° C) temperatures on the other side for a period of at least two months. Because the tanks were covered with a roof, there was no warming of the concrete walls by the sun.

The surface temperature on the outside of the concrete would, of course, have varied with the ambient temperature which in the months of January and February is between about -10° C to -40° C. For practical purposes, the surface temperature can be assumed to have been close to the mean air temperature, for these months, of about -15° C. Water would have moved through the concrete toward the cold side of the wall. Frozen water on the cold side of such a system has a low vapour pressure compared to unfrozen water on the warm side of the wall. Water will have moved in the adsorbed water film on the cement gel surfaces toward the low temperature side as a response to the lower vapour pressure. This is the same process as occurs during the upward movement of water in partly frozen soil to produce frost lensing.

Litvan (6) showed that on cooling saturated cement paste, freezing of water commenced at about -8° C. The majority of the water had finished freezing at about -12° C. This only applies to non-salt (sodium chloride) contaminated cement paste solutions as presumably found at Dorion. The reason for the reduction in the freezing point of water in the cement paste is due to the reduced vapour pressure of water in the pores and capillaries of the hydrated cement paste. As predicted by Lord Kelvin's equation, water in narrow capillaries will not freeze until the vapour pressure of the ice is equal to that of the water in the capillary. The narrower the capillary, the lower the vapour pressure above the meniscus and the lower the temperature at which it will freeze.

Freezing of water vapour would have taken place in the body of the concrete in that zone with a temperature of -8° to -12° C. Freezing of the water would block pores, making the concrete impermeable to water vapour transmission toward the outside surface. Water would have continued to move from the warm water reservoir toward the freezing site where ice must have formed.

The amount of ice formed, would have depended on the amount of water transmitted which would have been governed by the permeability of the concrete. In a well hydrated cement of low water-cement ratio, the permeability is rather low. Verbeck (7) considered that a cement paste with a water-cement ratio of 0.8 was a thousand times more permeable than a paste with a water-cement ratio of 0.4. The condition of the cement paste in the concrete indicated a high water-cement ratio. The concrete must have been sufficiently permeable to transmit enough water to allow formation of a macroscopic ice lens in the interior of the concrete wall. The process of formation of the ice lens would have fractured and ultimately destroyed the concrete.

Figure 5 shows this system diagramatically. The zone of ice formation, assuming this temperature gradient, should have been at a depth of 45-85 mm behind the outside surface. This corresponds approximately with the position of fractures found within the concrete walls (Figure 2, 6 and 7).

It is significant that those areas which failed (represented by samples 4, 7, 20, 21 and 22) had the poorest quality concrete. The water absorption was above average and the air content was below average compared with the average of all the samples (Table 1). After failure occurred, the tanks were drained and the severe conditions ceased to exist. The concrete of poorest quality failed first, the slightly better quality concrete may have failed given sufficient time.

Samples 2, 5 and 8 represented cores taken from the lower part of the common wall between tanks 6 and 7. There was water at 4.5^{o} C on both sides of this wall, thus there was no adverse environment and failure did not occur despite the poor quality of the concrete.Samples 20 and 21 represented concrete from the top of the common wall between tanks and 6 and 7 (Figure 3). The same process of ice formation must have been going on there as in the exterior wall of tank 6 (Figure 2), although the zone of freezing must have been more complex due to the geometry of the element.

Tank 6 was the only tank with a major exterior wall exposed to freezing temperatures. The other tanks only protruded above the ground surface for a distance of 300 mm (12 inches), or the same height as the level of water in the tanks. These other tanks were all protected, to some extent, by the insulation given by the surrounding fill. The original breeding facility, which is still in use, is also protected by being buried in the ground. The concrete for these tanks was mixed by hand, without an air-entraining agent. After over 30 years of use, no damage was apparent.

SIMILAR OCCURRENCES

Hughes and Anderson (8) reported damage to farm silos in the northern United States that was similar to that found in the fish tanks at Dorion. They postulated a high humidity inside the concrete silos with moisture movement toward the outside which was exposed to freezing temperatures.

Collins (9) reported laminations in concrete pavement which he attributed to the formation of ice lenses parallel to the cold surface. He noted that the laminations were similar to those observed in soils during frost heaving. He suggested that the mechanism of frost damage he observed might be similar to that occurring in soil with growth of ice crystals perpendicular to the outside surface. The forces of this growth exceeded the tensile strength of the concrete and caused delamination. Collins developed a one surface freezing test to support his hypothesis. A concrete cylinder had its lower end in a container of heated water, the upper end of the cylinder was exposed to cold air. The remainder of the cylinder was insulated to prevent freezing except on the upper surface. He showed that water moved into the concrete during freezing and that a horizontal delamination could be produced in poor quality concrete identical to that produced in soil under the same conditions and similar to those observed in concrete in the field.

Kamada et al (10) while studying the freeze-thaw deterioration of cellular concrete used a modification of Collins (9) one surface freezing test. They found a relationship between water absorption and time to cracking in their test. In some cases, cellular concrete and porous stone failed within 4 days.

Slater (11) reported that of the 53 concrete water supply tanks in Ontario, 62% would require or required replacement or major repairs within 10 years of construction. Slater found that the most serious defect was delamination of the exterior concrete walls. He attributed this damage to leakage of water into the walls and subsequent freezing. He noted that low head tanks (10-15 m) performed better than high head tanks (40 m). Also deterioration was frequently worse at the bottom of the tanks where hydraulic pressures were greatest. Two concrete standpipes had failed suddenly and been replaced with steel tanks. An unpublished report on these Ontario water tanks (12) noted that fracturing of the walls of these standpipes occurred "... with explosive force accompanied by noise, which caused the structure to vibrate".

All the Ontario water tanks that showed general exterior deterioration had an ineffective internal water proofing coating. Slater (11) recommended that tank walls should either be water proofed to prevent water movement into the concrete or insulated so as to prevent freezing of the concrete. In some severe cases, he recommended the adoption of both measures.

PREVENTIVE MEASURES

There are three possible ways of preventing damage to concrete exposed to this environment:

1. Use concrete of sufficiently low permeability so that insufficient water passes through the concrete to the site of freezing to form macroscopic ice lenses. All concrete is permeable to some extent. Thus if the period of exposure to

freezing temperatures were long enough, it might be expected that even well air-entrained concrete of low permeability might fail. In most environments there is, of course, a period during the summer when thawing of the concrete takes place.

2. Prevent movement of water into the concrete by using an effective water proofing membrane. The inside walls of the tanks at Dorion were coated with a cementitous water-proofing membrane which failed.

3. Insulate the concrete so that no freezing takes place within the concrete wall. This is the solution adopted in Finland and parts of Sweden to prevent frost damage to concrete and freezing of water inside concrete water retaining structures. In one system, exterior insulation of rock wool panels is applied to the finished tank. This in turn is covered with a sprayed concrete surface (13) or exterior wood or metal cladding. In another system, 50 mm of polyurethane foam insulation is applied inside the reservoir together with a PVC water-proofing membrane (14). In central and southern Sweden, where the climate is not so severe, protective measures are not usually taken. The quality of the concrete is, however, strictly controlled. Air entrained concrete with a compressive strength of more than 30 MPa (4000 p.s.i.) is specified with moist curing for two weeks. There are over 300 elevated concrete water tanks in Sweden. Serious damage due to frost action is unknown.

DISCUSSION

The literature shows that the deterioration observed in the fish tank at Dorion is not unique. There are, no doubt, unreported cases where this mechanism has caused deterioration. The exposed faces of concrete dams, retaining walls supporting water saturated material, or concrete pavements on water saturated base in cold climates without exposure to significant radiant heat from the sun are possible environments.

How does the proposed mechanism agree with existing theories? The nature of the deterioration in the fish tank and the work of Collins (9) suggests water movement toward sites of freezing. In 1953, Powers and Helmuth (15) predicted and observed that unfrozen water would travel toward sites of freezing by diffusion in the unfrozen water film on the gel surfaces and in small unfrozen capillaries. Usually in freezing concrete there is a finite amount of water. It is a closed system with respect to water. The forces generated by freezing of this water are normally taken care of by unfilled air voids which accommodate excess water or ice volume. In the special case where there is a continual supply of unfrozen water and if the period of freezing is long enough, it may be expected that the air voids will eventually fill with ice. The fish tank concrete was poorly air entrained, of high water cement ratio and consequently failed rather quickly. However, well air-entrained concrete of low water-cement ratio may also fail under these conditions if the period of freezing is long enough. In most environments there is a period of warm weather during the summer, so good quality concrete never fails because of this mechanism. However, improperly insulated concrete exposed to continual cyrogenic temperatures might be expected to fail under these conditions.

Powers in 1945 (16) acknowledged that concrete might fail by "... ice segregation if the condition is maintained long enough, and if the concrete next to the lens is kept virtually saturated while the lens grows". He questioned "whether such a condition is ever found in the field, or at least whether it is found frequently enough to be considered the usual mode of concrete destruction by frost action". The observations by Collins (9) and of water tanks in Ontario (11, 12) demonstrates that such a condition is found in the field and can be extremely destructive. The circumstances necessary to cause failures of this type are as follows: a supply of water above 0°C on one side of a concrete element and continually cold temperatures on the other. Time to failure will be a function of permeability, temperature and rate of cooling. At present, North American codes and specifications for concrete water structures do not adequately recognize the severity of this environment (11). In future, it is essential to recognize the importance of this process of ice lens formation in the design of durable concrete water retaining structures in cold climates.

The one surface freezing test developed by Collins (9) and used by Kamada et al (10) is an excellent model of the conditions in concrete water tank walls in cold climates and should be preferred to conventional freeze-thaw tests. Current freeze-thaw tests suffer from problems of excessive complexity, poor precision and/or unrealistically rapid freezing and thawing. In the one surface freezing test the environmental conditions remain static. The test does not require sophisticated control equipment and should be cheaper and have better precision than current methods. Correlation of the results of this test with concrete pavements susceptible to D-line cracking would be most interesting.

CONCLUSIONS

1. The concrete in the fish tanks was of poor quality, being poorly air-entrained and having a high water-cement ratio.

2. The failure occurred by the probable formation of an ice lens in the concrete wall. The conditions for this type of failure are a source of water on one side of a concrete

element and continually cold temperatures on the other side. Time to failure will be a function of concrete permeability, temperature and rate of cooling.

3. A significant number of concrete water retaining structures in Ontario have failed or deteriorated because of this mechanism.

4. A one surface freezing test is an excellent model of this unusual environment and should be preferred to conventional freeze-thaw tests for assessing durability of concrete exposed to these conditions.

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