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Performance of concrete wharves constructed between 1901 and 1928 at the Port of Montréal

K.H. Khayat*, A. Tagnit-Hamou, N. Petrov

Department of Civil Engineering, Université de Sherbrooke, 2500, boulevard de l'Universite, Sherbrooke, Québec, Canada J1K 2R1

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Abstract

An evaluation of concrete properties of five wharves in the Port of Montréal, constructed between 1901 and 1928, was undertaken to investigate the underlying causes of deterioration. The evaluated wharves consisted of either reinforced concrete caissons or massive concrete elements. The wharves were used in the past either as cargo loading docks or for the storage of various materials, some of which were detrimental to concrete.

The evaluation program included visual examination of distressed concrete located above water level and the determination of compressive strength, modulus of elasticity, rapid chloride ion permeability (RCP), water soluble chloride ion penetration profiles, as well as a detailed microstructural examination. This article discusses the various results pertaining to the quality of the concrete and Gunite repairs found in old marine structures such as these, where various modes of degradation were present including ice abrasion, cracking and spalling, alkali–silica reaction (ASR), sulfate attack, and frost damage. These various modes of deterioration affected the quality of concrete in all examined wharves as well as that of previous repair work, demonstrating the need for new repairs. However, despite exhibiting signs of severe damage, the concrete wharves had reasonable strength and elastic modulus values enabling rehabilitation to increase service life.
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Keywords: Alkali–silica reaction; Corrosion; Durability; Microstructure; Sulfate attack

1. Introduction

A detailed evaluation of the properties of concrete in five wharves, constructed between 1901 and 1928 in the Port of Montréal, Canada, was undertaken to determine the underlying causes of deterioration. The investigation also included the examination of the quality of a Gunite repair carried out in 1936. The wharves consisted of either thin shell reinforced concrete caissons or massive concrete walls and have been used as cargo loading docks and for the storage of various materials that can be detrimental to concrete durability, including coal, deicing salts, oil, and fertilizers.

Variations in water level in the St. Lawrence River in the vicinity of the project are limited to 3 m between late summer and early spring. The local river water is not salty. The sulfate content of the river water is approximately 25 mg/l of SO_4^{-2}. This is lower than the 150 mg/l of SO_4^{-2} value considered as negligible level of sulfate in water in contact with concrete, according to ACI 318-94. Approximately 100 days per year, the air temperature falls below 0 °C; however, the river water temperature remains at approximately 1 °C during the coldest period of the winter season. During harsh winter months, the water surface is frozen along the sides of the wharves, but not necessarily in the main navigation channel, which remains open. The wharves investigated in this study are situated along the main navigation channel where the water depth is approximately 9 and 10 m to mean water level.

This article summarizes the results of an investigation of the quality of the old wharves that had undergone various physical and chemical modes of deterioration, including ice abrasion, corrosion of reinforcing steel, cracking, gel exudation, and other signs of alkali–silica reaction (ASR), delamination of repair overlay, and extrusion of bituminous materials through construction joints and cracks. In situ compressive strength, modulus of elasticity, rapid chloride ion permeability (RCP), as well as profile of water-soluble chloride ion contamination, were determined. Detailed microstructural examination of the old non-air-entrained marine concrete was also carried out.

* Corresponding author. Tel.: +1-819-821-8062; fax: +1-819-821-6949.
E-mail address: Kamal.Khayat@USherbrooke.ca (K.H. Khayat).

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Selected concrete wharves were examined to cover a wide range of distress types, including corrosion, map cracking, spalling, and scaling. The investigated structures included three types of wharf designs typical of old construction; two of these structures were also repaired in 1936.

The first type of wharf design consists of a series of reinforced concrete caissons extending from the mud line to a short distance above the water line. The caissons are generally filled with granular materials. A nonreinforced mass concrete wall extends from the caisson to the top of the wharf. The reinforced wall of the caissons has a total thickness of 450 mm with two layers of reinforcing steel in each direction. The mass concrete section above the water line has varying thicknesses. Wharves 58 and 105 investigated in this study belong to this type of design and were constructed in 1928.

The second type of wharf design consists of a series of rectangular reinforced concrete caissons extending from the mud line to the top of the wharf. This caisson also has two layers of reinforcing steel in two directions and has a total thickness of 450 mm. Wharf 97 East investigated here is constructed with this type of design and was constructed in 1928. The third wharf design is a nonreinforced concrete mass wall supported by wood cribbing under water. The front side of the submerged cribbing is lined with concrete blocks. Wharves 45 and B4, constructed in 1901 and 1905, used this type of design.

2. Testing program

Six cores were taken from each of the five investigated wharves, 2.0–3.3 m above the water line. The length of the core samples varied from 450 to 600 mm. The cores were examined, photographed, and transported to the laboratory in moist plastic bags to avoid drying. Compressive strength and static modulus of elasticity were tested in accordance with ASTM C 39 and C 469, respectively. All samples were water saturated before testing. RCP was determined for each concrete in compliance with ASTM C 1202.

The levels of water-soluble chloride ion contamination were determined using transversely cut disks taken at various depths from the outer surfaces, in compliance with CAN/CSA A23.2-4B.

Table 1
Results of compressive strength and modulus of elasticity

Wharf	Proximity from exterior surface	E (GPa)	f_c' (MPa)	Estimated E (GPa)
105	Near outer surface	10	19.0	21
97 East	100–300 mm	21	21.1	25
58	300–475 mm	16	34.3	26
45	350–550 mm	22	14.6	20
B4	370–570 mm	33.1	11	26

Table 2
Results of RCP

Wharf	Proximity from exterior surface	Coulombs (C)	Comments
105	220–270 mm from surface	1600	
97 East		2100	
58	510–560 mm from surface	2300	lots of cracks at ~ 85 mm from surface
45	130–180 mm	520	~ 20 mm of length of 50-mm samples consists of new concrete
	near surface	340	
B4	500–550 mm	2400	cracks on one side of sample
	near surface	1700	

A detailed microstructural examination using a scanning electron microscope (SEM) along with energy dispersive X-ray analysis and X-ray diffraction (XRD) analysis were carried out to investigate various degradation modes and hydration products.

3. Results and discussion

The results of the mechanical properties are summarized in Table 1. A sharp deviation between the measured and estimated elastic modulus values indicates the presence of internal cracking, including cracking at the interface between the hydrated cement paste and aggregate, which is not easily reflected by the measurement of compressive strength.

The RCP results are given in Table 2 and the XRD analysis results are summarized in Table 3. The profiles of water-soluble chloride ion content are shown in Fig. 1.

The condition of concrete surfaces of all wharves examined with regard to the age of concrete was generally acceptable, except for a significant level of scaling damage near the water line and ice abrasion, as shown in Figs. 2 and 3. Extensive pattern map cracking was also observed in some areas, which is typical of frost damage and the presence of ASR. In some places at the water level, the horizontal construction joints are seriously damaged with spalled-off concrete reaching 350 mm. In this zone near the water level, the scaled surface usually has several exposed aggregate particles (Fig. 4). Since the wharves are constructed with non-air-entrained concrete, the presence of the

Table 3
Results of XRD analyses

Sample of wharf	Phases content		
	Ettringite	Gypsum	Portlandite
45	very high	very high	very low
B4	very high	very high	very low
105	medium	medium	medium
97 East	low	low	high
58	low	low	high

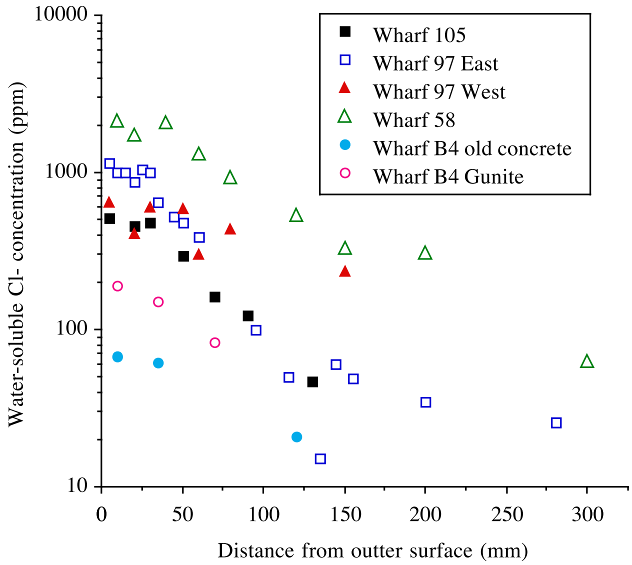

Fig. 1. Penetration of free chloride ions in various investigated concretes.

frost damage is not surprising. A relatively high permeability and low mechanical properties indicate that the hydrated cement paste is porous and has low resistance to abrasion. Damage due to freezing and thawing cycles and ice abrasion is common in all examined wharves, but it is more visible on surfaces where other types of damage have also occurred, such as ASR or corrosion of reinforcement. Once cracking or scaling begins due to frost action or abrasion, the internal structure of the concrete becomes more porous facilitating the penetration of water, oxygen, CO_2, and chloride ions. This can promote corrosion of the reinforcement and further cracking as well as coarse aggregate pop-out due to ASR gel formation.

3.1. Performance of wharves constructed in 1928

The investigation of three wharves constructed in 1928 showed that the concrete exhibits significant damage due to freezing and thawing. Such concrete is typical of old bridge and marine structures constructed in the era prior to the introduction of air-entraining admixtures [1].

Visual inspection revealed some signs of corrosion. Corrosion products were visible on the outer surface; however, the reinforcing steel was not exposed along the main caisson wall. Whenever large cavities were found near the water line between adjacent circular caisson walls, the reinforcing steel in these locations was exposed and severely corroded.

Two of the three wharves evaluated (Wharves 97 East and 58) are found to present a significant degree of damage due to ASR, which is characterized by map cracking and by the exudation of silica gel at construction

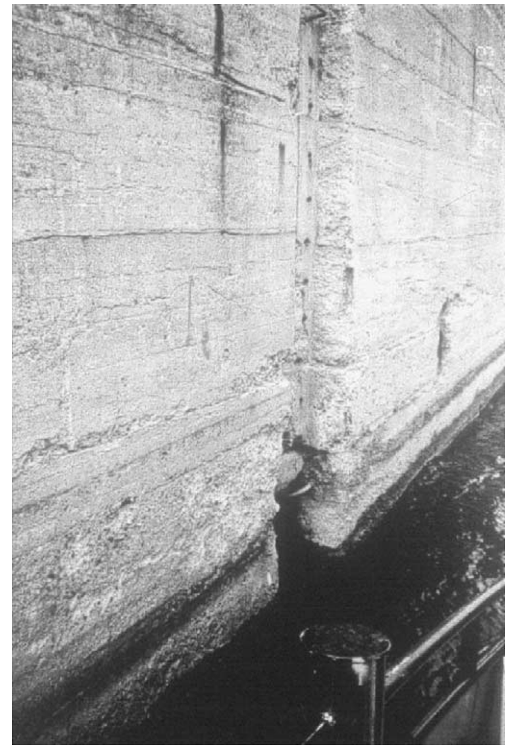

Fig. 3. Photograph of typical ice abrasion damage of Wharf 58.

Fig. 2. Photograph of typical scaling damage of Wharf 105.

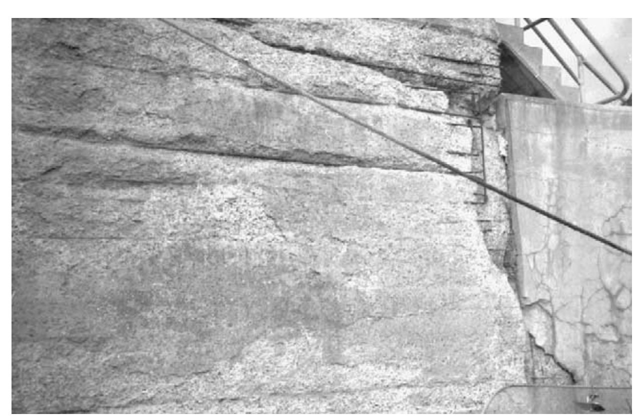

Fig. 4. Photograph of typical scaled surface damage and exposed aggregate particles of Wharf 97 East.

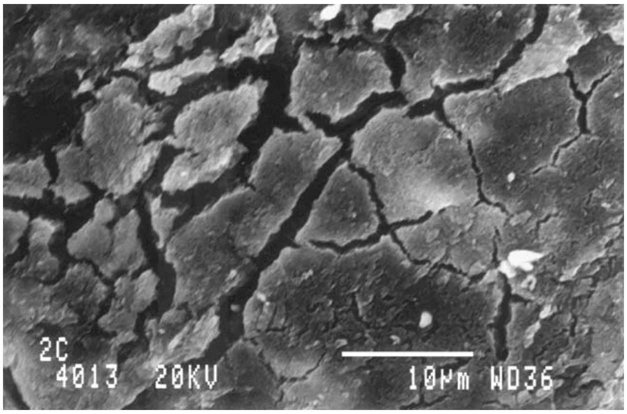

Fig. 5. Micrograph of concrete in Wharf 97 East showing ASR product.

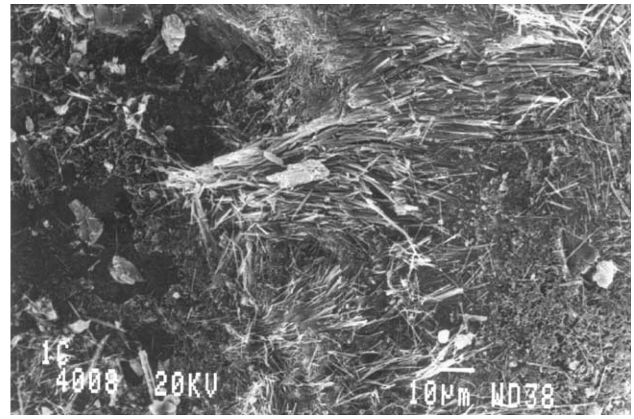

Fig. 7. Micrograph of concrete in Wharf 105 showing secondary ettringite.

joints. Such damage was confirmed by petrographical analysis of the aggregate and SEM examination of the concrete. This shows that the examined ASR is not related to the period of construction. However, the wharves where ASR is observed in advanced stages are often used for the storage of deicing salt and cement clinker. Therefore, the alkali contamination of concrete is probably due to outside sources. The presence of ASR gel and leaching at the construction joints was systematically observed at surfaces of ASR-affected wharves. As was the case in Wharf 105, petrographical analysis showed that coarse aggregate particles often contain veins filled with silica gel [2]. SEM observation revealed the presence of ASR reaction products in the paste (Figs. 5 and 6) that coexist with secondary ettringite (Figs. 7–9). The coarse aggregate was observed to have some cracks (Fig. 10).

Secondary ettringite and gypsum, which are characteristic of sulfate attack, are also present. However, Wharf 105 had a relatively greater concentration of secondary ettringite and gypsum than the other two wharves. The level of ettringite in these concretes was far less than that observed in Wharves 45 and B4, as discussed below.

The water-soluble chloride ion concentration in Wharves 58 and 97 East was more than two times greater (1000–2000 ppm) than those found in the other wharves. This may be due to the higher concentration of cracks and spalling of the cover of such concrete. The higher chloride ion permeability in Wharf 58 points to greater porosity of the concrete, which enables the absorption of higher quantities of expansive corrosion products without creating significant cracking. In this wharf, the reinforcing bars in the caisson were not uniformly spaced to effectively control cracking, and together with the high intrinsic porosity of such concrete, this has led to sporadic cracks over the outer reinforcing steel.

In general, it can be speculated that the corrosion damage to reinforcing steel is due to high permeability, insufficient concrete cover, considerable contamination by chloride ion, cracking of the concrete aggravated by spalling caused by cracking due to freeze–thaw cycles, and sometimes ASR damage. Such cracking can increase the ingress of water, chloride ions, oxygen, CO_2, and sulfates inside the concrete mass. It is important to note that the source of chloride ions is believed to be deicing salts from the upper surface of the wharves. In some cases, deicing salt is even stored on the wharves and is present in snow

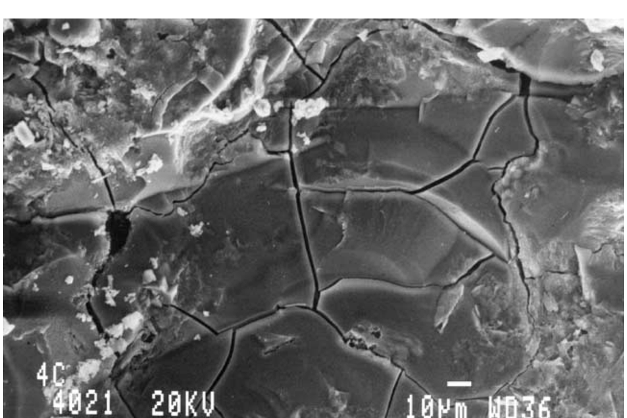

Fig. 6. Micrograph of concrete in Wharf 58 showing ASR product.

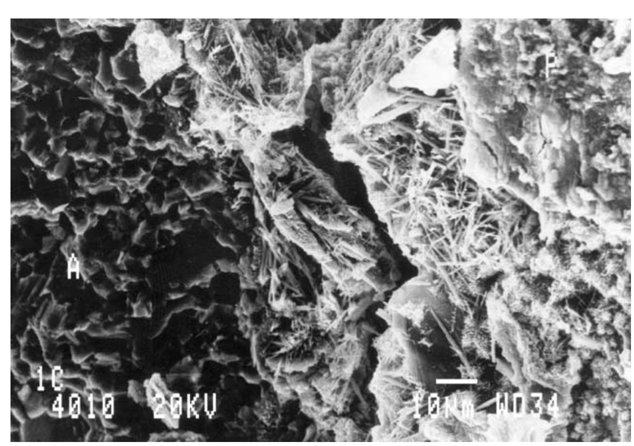

Fig. 8. Micrograph of concrete in Wharf 105 showing secondary ettringite in the paste–aggregate interface.

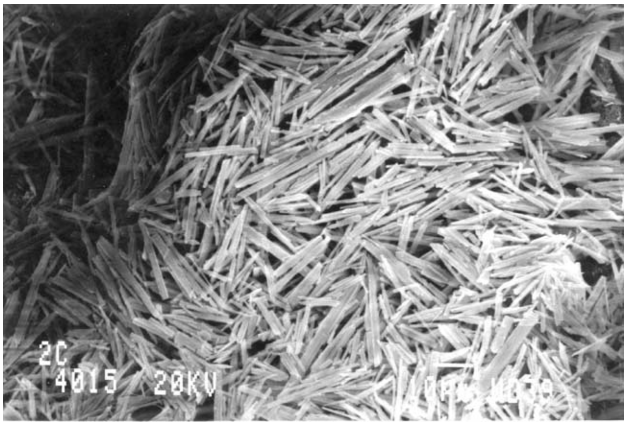

Fig. 9. Micrograph of concrete in Wharf 97 East showing secondary ettringite.

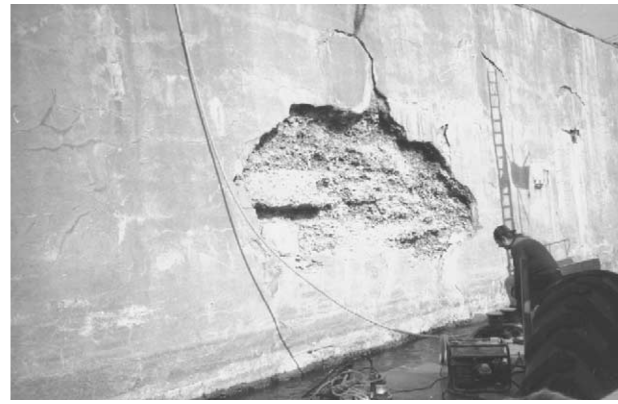

Fig. 11. Photograph of typical damage of Wharf 45 showing the bad anchoring of previous repair concrete.

removed from city streets that is dumped from the surface of the wharves into the river.

It is interesting to point out that these old wharves showed similar causes of deterioration as those at the Port of Saint John in Eastern Canada, also constructed between 1920 and 1930 [3].

3.2. Performance of wharves constructed in 1901 and 1905

Wharves 45 and B4, constructed in 1901 and 1905, consist of a nonreinforced concrete mass wall extending approximately 8 m from low water level to the top of the wharf and form a special case of examined wharves because they were surface repaired. The mass wall is supported by wood cribbing under water (Type 3 design).

In the case of Wharf 45, the base concrete making up the mass concrete caisson is made of coarse aggregate of 100 mm nominal size. The coarse aggregate is mainly composed of limestone with clay mineral content. The base concrete is covered with a repair concrete of approximately 150 mm in thickness. The repair concrete is not reinforced and contains 14-mm nominal-size coarse aggregate. The photograph of Wharf 45 in Fig. 11 illustrates the type of severe damage observed in the structure. In several places, large cavities were visible on the exterior concrete surface, which is mainly due to the fact that the repair shell was not properly anchored to the base concrete when shallow pin anchors were used. As the base concrete continued to undergo degradation following the 1936 repair, the damage weakened the bond between the base and repair concrete and eventually resulted in spalling of the repair concrete (Fig. 12). In such cavities, the concrete is noncohesive and can be removed easily with a geological hammer.

The in situ compressive strength and modulus of elasticity values of the base concrete were quite low, 14.6 MPa and 22 GPa, respectively. The repair concrete appears to be of good quality, and its rapid chloride ions permeability is very low (340 C). The water-soluble chloride ion content in the repair concrete was measured at 0.01% of the mass of cement [2], which is considered to be quite low.

The microscopical investigation revealed severe sulfate attack in the base concrete. In the internal part of the core,

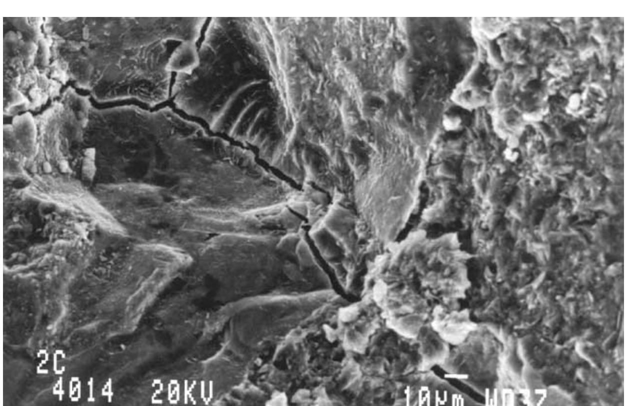

Fig. 10. Micrograph of concrete in Wharf 97 East showing cracks in aggregate.

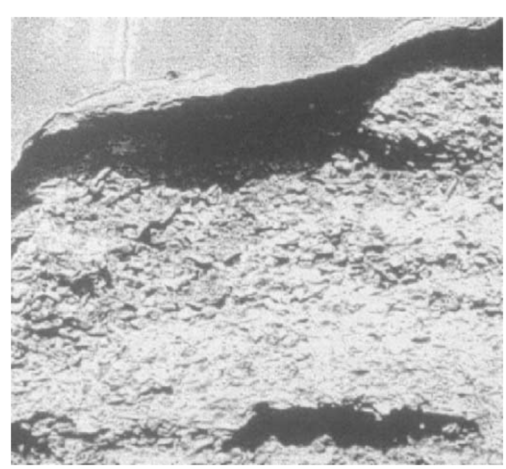

Fig. 12. Photograph of typical damage of Wharf 45 showing large cavities with noncohesive concrete.

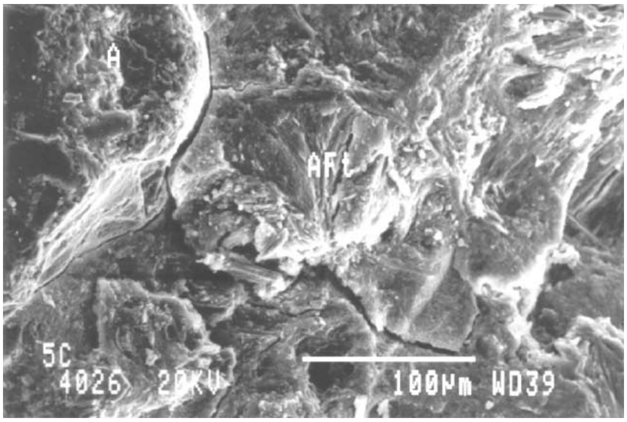

Fig. 13. Micrograph of concrete in Wharf 45 showing secondary ettringite.

located 450 mm from the surface, large concentrations of ettringite and gypsum were found in the paste (Fig. 13). The limestone aggregate is shown to be porous and contains several microcracks. Furthermore, the calcium silicate hydrate (C-S-H) was often observed to be porous (Fig. 14). Concrete samples examined near the outer surface of the wall showed greater concentrations of ettringite than gypsum. No $Ca(OH)_2$ crystals were found by SEM in the investigated concrete section. On the other hand, a small content of $Ca(OH)_2$ was detected by XRD analysis (Table 3). The XRD analysis of the repair concrete showed signs of sulfate diffusion and precipitation of secondary ettringite.

Wharf B4 was constructed in 1905 and received on outer repair shell of approximately 100 mm in thickness of Gunite mortar reinforced with a welded wire mesh grid and anchored using shallow pins. The surface of the repair concrete is divided through large cracks into several sheets that appear to be poorly bonded to the base concrete, as shown in Fig. 15. In certain places, large cavities were present in the concrete, which is mainly due to the fact that the outer concrete shell was not properly anchored to the base concrete. Therefore, the base concrete continued to undergo degradation after the repair, which weakened the bond between the base and repair sections, eventually resulting in spalling of sections of the repair concrete.

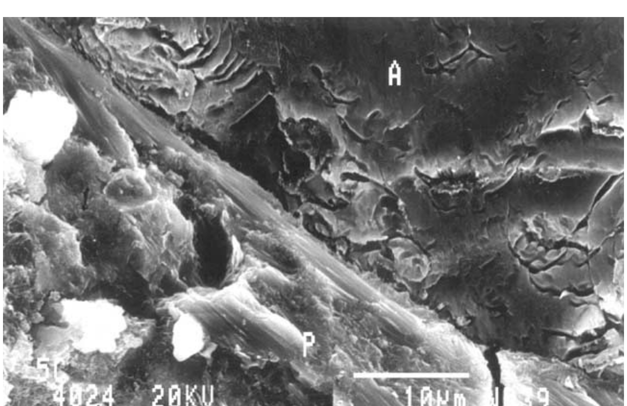

Fig. 14. Micrograph of concrete in Wharf 45 showing porous C-S-H.

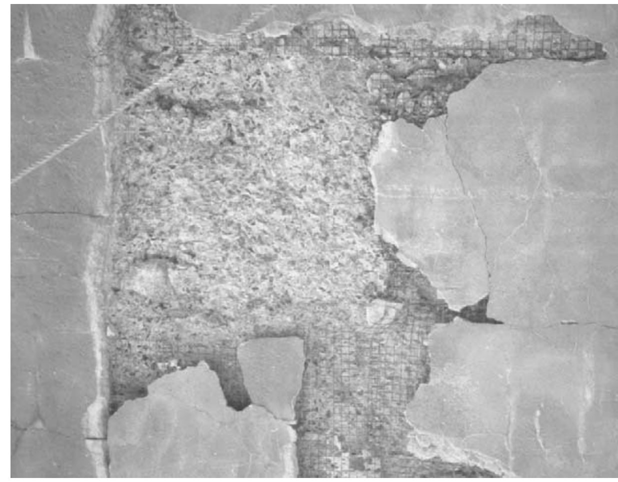

Fig. 15. Photograph of poorly bonded repair concrete and typical large cracks of damaged Wharf B4.

The base concrete making up the mass concrete caisson is made with nepheline syenite and corneal coarse aggregate with a nominal size of 100 mm. Such corneal is sometimes present alongside silica gel veins [2]. The mean in situ compressive strength and elastic modulus values of the base concrete were 33 MPa and 11 GPa, respectively. The estimated modulus of elasticity was 26 GPa, which is much higher than the measured value. The RCP of the Gunite section is relatively high, 1740 and 2370 C in the base concrete, at an approximate depth of 500 mm from the outer surface. The water-soluble chloride ion content in the old concrete ranged between 70 and 20 ppm (0.05% and 0.02%, by mass of cement) at the surface, up to a depth of 120 mm. In the Gunite repair mortar, these values were 190 and 80 ppm (0.14% and 0.06%, by mass of cement) at the surface and at 70 mm of depth, respectively.

The microstructural characteristics of the base concrete in B4 wharf are similar to those of Wharf 45. The base concrete

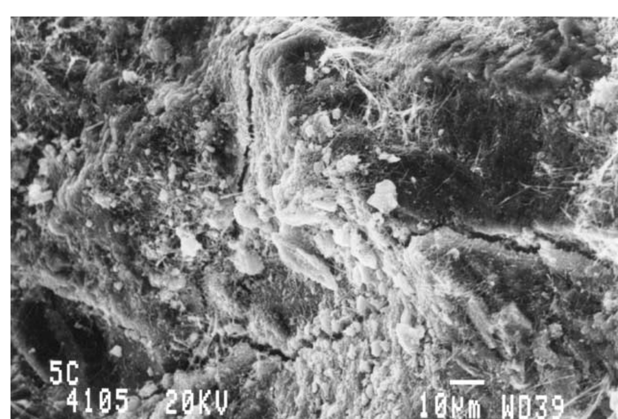

Fig. 16. Micrograph of concrete in Wharf B4 showing microcracking in the paste.

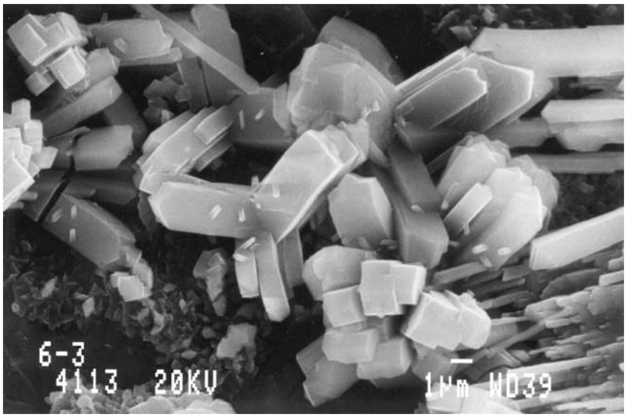

Fig. 17. Micrograph of concrete in Wharf B4 showing gypsum.

was found to be highly cracked. The amount of ettringite and gypsum was quite significant (Figs. 16 and 17), with silica gel from ASR found in several places. Secondary ettringite was also observed in the Gunite repair section. XRD analysis confirmed the SEM observations (Table 3).

The deterioration of the cement paste in Wharves 45 and B4 due to ettringite and gypsum formation reduced the strength and stiffness of the concrete [4]. The large amount of gypsum and ettringite is caused by reaction of sulfate ions with $Ca(OH)_2$, monosulfate and C-S-H [5]. These phases, especially $Ca(OH)_2$ and monosulfate, are dissolved to provide calcium and aluminum ions needed for the formation of secondary ettringite and/or gypsum. The limestone aggregate can also contribute some calcium ions. In addition to the expansive nature of the formation of secondary ettringite and gypsum, the dissolution of the $Ca(OH)_2$ and C-S-H can contribute to the decrease in mechanical properties. Mehta [6], in a critical review of sulfate attack on concrete, cited several cases of deterioration by this process and noted that some structures exhibited deterioration although the concrete mixture was of a high quality. Although the concrete of Wharves 45 and B4 show some deterioration due to freezing and thawing cycles and ASR, the main cause of damage is due to sulfate attack. The origin of the sulfate is not certain. As indicated above, the river water's concentration of sulfate content is negligible. It is believed that the main source of the sulfate is coal, as the old wharves were used for many years as a storage area for coal. The sulfate from the coal in a water solution can percolate through the freeze–thaw damaged concrete, thereby causing deterioration of the concrete. Price and Peterson [7] noted that frost damage can lead to an increase of microcracking that can accelerate the penetration of sulfate ions and sulfate attack.

4. Conclusions

The evaluation of the properties of the five concrete wharves constructed between 1901 and 1928 at the Port of Montréal revealed various modes of physical and chemical deteriorations necessitating the repair of the wharves.

The following conclusions can be drawn from this study:

1. The old concrete was non-air-entrained and presented surface scaling and cracking due to frost damage, and in some cases, damage from ice abrasion at the water level. Four main causes of degradation were found: ASR, sulfate attack, freeze and thaw, and corrosion of the reinforcing steel.
2. Reinforced concrete caissons reached advanced corrosion states with severe spalling and exposure of the outer layer of the reinforcement. Such caissons had the highest level of chloride ions concentration.
3. Repair concrete and mortar applied on the outer section of Wharves 45 and B4 in 1936 was not properly anchored to the base concrete and is often cracked with resulting large spalled-off sections forming cavities in the base concrete.
4. In general, the concrete wharves had reasonably adequate strength and elastic modulus values and can be upgraded through proven rehabilitation methods to increase their service lives.

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