Laboratory Investigation of Conventional and Polymer-Modified Concretes and Their Use for Repairs

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ABSTRACT

Four-inch (10-cm) concrete cubes were cast by using conventional portland cement concretes with a water-to-cement ratio of 0.35, 0.44, and 0.54 and polymer-modified concretes made with latex and epoxy modifiers. Four-inch cubes were also cut from latex-modified shotcrete repairs in the field. All cubes were immersed for 21 days in 15 percent NaCl solution and then stored in a controlled-climate room in accordance with the test procedures described in NCHRP Report 244. During 21 days of soaking and 21 days of final air drying, weight gains and losses were determined at 3, 7, 14, and 21 days during each period. Following air drying, powder samples were removed by drilling at several intervals of depth from the center of each face to the center of the cube. Then half of each cube was crushed to powder and the acid-soluble chloride ion contents of all samples were measured by a potentiometric titration procedure. At a depth of 1 1/2 to 2 in. (37 to 50 mm), the latex-modified concretes had the least amount of chloride. Laboratory tests of the influence of high temperature and wind on hand-placed and on form-cast large vertical repairs using the modified concretes showed that under arid conditions, the hand-placed repairs always cracked. Accelerated-weathering tests on small repairs made with the polymer-modified concretes left the repairs intact. On the basis of these test results, the acrylic latex modified cast-in-place concrete was successfully used to repair columns, spandrels, and balcony slabs of a high-rise housing complex and modified shotcrete acrylic latex was used to repair underground garages. Both types of repairs were in excellent condition after 5 years' service.

Deterioration of reinforced-concrete structures that contain calcium chloride (the most commonly used admixture) or that are exposed to chloride ion during their service life by exposure to ocean water or deicing salts during the winter is common and is a serious problem in many parts of the world. On the basis of research undertaken especially during the last two decades, it is now well known that the delamination and spalling of reinforced-concrete structures is caused by the electrochemical corrosion of embedded reinforcing steel within chloride-contaminated concrete. If the supply of water or oxygen can be excluded, the corrosion process will not take place.

One form of corrosion protection for concrete against the ingress of water and oxygen (and chloride ion from external sources) is the surface application of sealers, coatings, and membranes; another form can be based on the use of various chemicals added to the fresh concrete. Such specialty concretes are commercially available, and they are being used to construct new structures as well as to repair older, deteriorated ones. Such concretes have low to extremely low permeability when compared with normal concrete. The lower permeability could be attributed primarily to a reduction in the water-to-cement (w/c) ratio (1). The presence of various chemicals in concrete allows the routine production of w/c ratios of 0.26 to 0.35, values significantly lower than 0.40 to 0.55, which are commonly used and specified for concrete structures. Especially during the last decade, the polymer-modified concretes have been commonly used for vertical and horizontal patches and also for repairs by shotcrete.

The laboratory experiments described here were designed

1. To determine the saltwater weight gain and subsequent weight loss by vapor transmission, and the chloride ion content and actual chloride ion distribution profiles in conventional portland cement and polymer-modified concrete,
2. To investigate the influence of high temperature and wind on hand-placed or form-cast large vertical repairs made from polymer-modified concretes, and
3. To investigate the influence of accelerated-weathering tests on small repairs made from polymer-modified concretes.

LABORATORY INVESTIGATION

Determination of the Saltwater Weight Gain and Subsequent Weight Loss

The testing method was based on techniques developed and used by Wiss, Janney, Elstner Associates, Inc. (WJE), in a research project for the National Cooperative Highway Research Program as reported in NCHRP Report 244 (2). Six concrete mixtures were prepared, and the following materials were used in this investigation:

Wiss, Janney, Elstner Associates, Inc., 330 Pfingsten Road, Northbrook, Ill. 60062.

TABLE 1 Properties of Fresh and Hardened Concretes

Type of Concrete	SSD Quantities[a] (lb/yd³)					Air Content (%)	Slump (in.)	w/c Ratio by Weight	28-Day Compressive Strength (psi)
	Cement	Sand	Gravel	Water	Admixtures[a]				
Conventional	522	1,226	1,857	281	–	5.4	7 1/2	0.54	4,330
Conventional	524	1,230	1,866	230	–	7.0	5	0.44	4,790
Conventional	561	1,317	1,998	196	–	6.0	2	0.35	6,640
With acrylic latex	666	1,234	1,830	192	184	2.2	10	0.29	4,200
With S-B latex	664	1,200	1,793	224	178	3.5	10	0.34	5,200
With epoxy modifier	661	1,255	1,891	171	132	4.3	9 1/4	0.26	4,850

Note: 1 psi = 6.89 kPa, 1 in. = 25 mm, SSD = saturated surface dry; S-B = styrene-butadiene.

[a]Including water contained in admixtures.

1. Cement: Type I portland cement;
2. Sand and gravel: natural river sand and river gravel [with maximum-size coarse aggregate = 3/4 in. (19.05 mm)] from the American Materials Corporation, Eau Claire, Wisconsin (both chloride-free materials);
3. Air-entraining agent: neutralized vinsol resin; and
4. Polymers: high-viscosity and low-modulus epoxy, acrylic, and styrene-butadiene latex.

The properties of the fresh and the hardened concretes are listed in Table 1.

Casting of nominal 4-in. (10-cm) concrete cubes is shown in Figure 1. After being stripped at the age of 1 day, the cubes were lightly sandblasted (Figure 2) and then, as shown in Figure 3, placed in sealed heavy-duty plastic bags for moist curing. At 21 days the cubes were removed from the plastic bags, weighed to the nearest 0.1 g, and then stored in a controlled-climate room at 73 ± 3°F (23 ± 2°C) and 50 ± 4 percent relative humidity for 14 days of air drying before being immersed in a 15 percent NaCl solution. Six cubes stored in a plastic container are shown in Figure 4. Following soaking, the cubes were stored again for 21 days in the controlled-climate room to determine vapor transmission characteristics. Cubes stored in the climate room are shown in Figure 5. During the 21 days of soaking and 21 days of final air drying the weight of each cube at 3, 6, 9, 12, 15, 18, and 21 days was determined to the nearest 0.1 g. After the final 21-day air-drying period, a 1/4-in. (6-mm) hole was drilled through the center of the face of all six sides of the cube to obtain powder samples for chloride determination at different depth intervals. These intervals were 0 to 1/2 in. (0 to 12 mm), 1/2 to 1 in. (12 to 25 mm), 1 to 1 1/2 in. (25 to 37 mm), and 1 1/2 to 2 in. (37 to 50 mm). The chloride ion content of the drilled powder from the composite sample from the six holes was determined by using an acid-digestion, potentiometric titration procedure. Then each cube, as shown in Figure 6, was mechanically

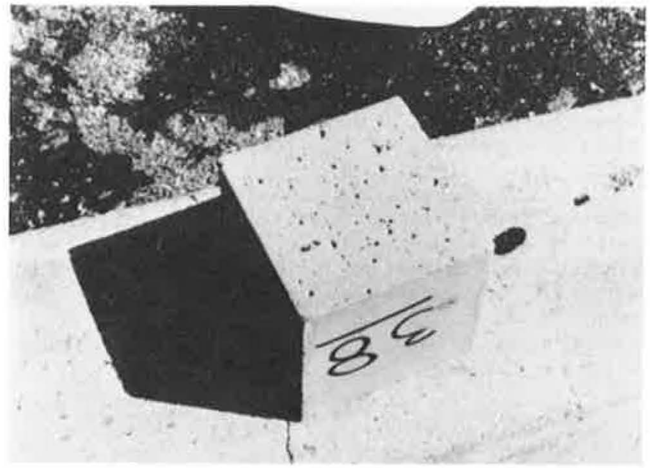

FIGURE 2 Concrete cube before (side surface) and after (top surface) light sandblasting.

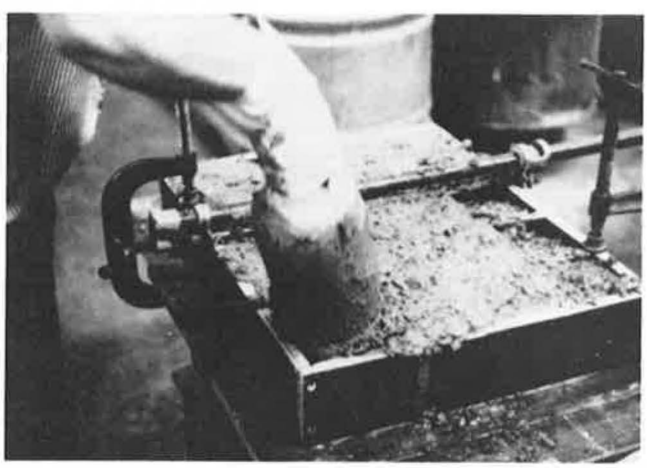

FIGURE 1 Casting the cubes.

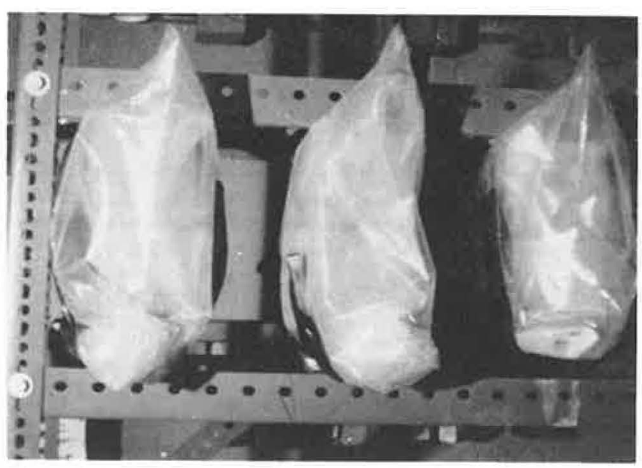

FIGURE 3 Cubes being cured in sealed heavy-duty plastic bags.

FIGURE 4 Six cubes in plastic container with 3 gal of 15 percent NaCl solution.

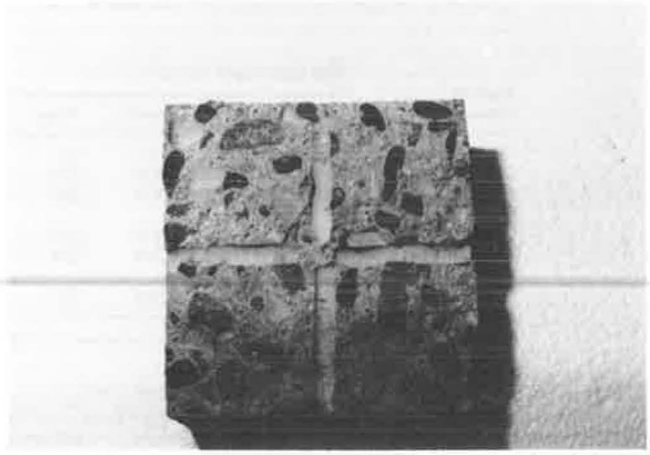

FIGURE 6 Cube drilled with holes to obtain samples for chloride ion determination at different depths.

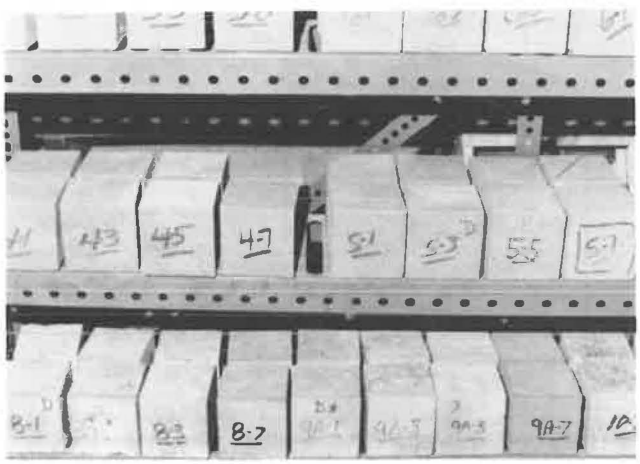

FIGURE 5 Cubes stored in a controlled-climate room at 73 ± 3°F (23 ± 2°C) and 50 percent relative humidity.

split in half. One-half was crushed and the acid-soluble chloride ion content was determined by using the method discussed earlier.

In addition the same type of testing was performed by using the 4-in. cubes that were cut during field inspection from latex- modified shotcrete.

All tests were performed on duplicate specimens and average values are listed. The test results of saltwater weight gain, weight loss by vapor transmission after the final air-drying period, and chloride ion content are listed in Table 2. The chloride ion content at different depths is given in Table 3.

The chloride ion profiles of the cubes, expressed as percentage of chloride ion at the depth interval from 0 to 1/2 in. (0 to 12 mm), are shown in Figure 7.

As shown in Table 2, the weight gain and chloride ion content in conventional concrete decreased with decrease of the w/c ratio. The three polymer-modified concretes exhibited low but widely different weight gains and chloride ion contents. The epoxy-modified concrete with the highest weight gain had the lowest w/c ratio, 0.26. The concrete containing acrylic latex (cast cubes or shotcrete) exhibited the lowest chloride ion content from all tested concretes. In terms of chloride ion content, no differences were found between the cast concrete and in-place shotcrete. All concretes were able to expel some of the absorbed water by normal vapor transmission. With the exception of acrylic-latex modified concrete (which lost 105 percent of the water), the concretes were able to expel about 65 percent of the absorbed water.

Plots of maximum weight gain and absorbed chloride ion content versus w/c ratio of half cubes are shown in Figure 8. These data show a good relationship among the cube weight gain, half-cube chloride content, and w/c ratio. Only the epoxy-modified concrete lacked this good relationship.

The data in Table 3 show that the depth interval 0 to 1/2 in. has extremely high levels of chloride, ranging from about 0.30 to 0.45 percent by weight of concrete. These values are thus about 10 to 15 times the corrosion threshold level (for acid-soluble

TABLE 2 Weight Gain and Weight Loss During Soaking and Final Air-Drying Period and Chloride Ion Content

Type of Concrete	w/c Ratio	Weight Gain after 21 Days of Soaking (%)	Weight Loss after 21 Days of Air Drying (%)	Chloride Ion Content (% by wt of concrete)
Conventional	0.54	2.50	0.82	0.259
Conventional	0.44	2.03	0.76	0.245
Conventional	0.35	1.23	0.43	0.159
With acrylic latex	0.29	0.65	−0.03	0.094
With S-B latex	0.34	1.04	0.35	0.146
With epoxy modifier	0.26	1.43	0.42	0.226
Shotcrete with latex acrylic	0.30	0.98	0.33	0.097

TABLE 3 Acid-Soluble Chloride Ion Content

Type of Concrete	w/c Ratio	Chloride Ion (% by wt of concrete) by Depth (in.)			
		0-1/2	1/2-1	1-1 1/2	1 1/2-2
Conventional	0.54	0.451	0.263	0.052	0.036
Conventional	0.44	0.267	0.121	0.020	0.017
Conventional	0.35	0.427	0.085	0.014	0.012
With acrylic latex	0.29	0.273	0.032	0.018	0.008
With S-B latex	0.34	0.296	0.028	0.012	0.007
With epoxy modifier	0.26	0.343	0.115	0.027	0.017

Note: Values are averages of two samples. 1 in. = 25 mm.

chloride ion content in normal-weight concrete) of about 0.03 percent. The conventional concrete with a w/c ratio of 0.54 contains chloride levels totally above the 0.03 level at all depth intervals. The conventional concretes with w/c ratios of 0.35 and 0.44 have values less than the 0.03 value at depth intervals of 1 to 1 1/2 in. and 1 1/2 to 2 in.

Concretes with acrylic and styrene-butadiene (S-B) latex show similar profiles at all depths even though their weight-gain behavior was different. The epoxy-modified concrete that had the lowest w/c ratio, 0.26, exhibited relatively poor performance when compared with the two latex-modified concretes.

The plot of chloride content within the depth intervals 0 to 1/2 in., 1/2 to 1 in., and 1 to 1 1/2 in. versus the w/c ratio in Figure 9 shows that interval 0 to 1/2 in. has extremely high chloride levels irrespective of the w/c ratio or concrete type. Thus, the chloride content in the first 1/2-in. interval does not appear to correlate well with the w/c ratio. The interval 1/2 to 1 in. shows an excellent relationship between chloride content and w/c ratio for seven of the eight concretes. Here again, the epoxy-modified concrete was inconsistent. In this interval, the chloride content was reduced by over 90 percent as the w/c ratio decreased from 0.54 down to about 0.29. A similar 90 percent decrease is not apparent in the interval 0 to 1/2 in.

The interval 1 to 1 1/2 in. shows a good relationship between chloride content and w/c ratio. In this interval, the chloride content was reduced by over 75 percent as the w/c ratio decreased from 0.54 to about 0.29 to 0.35.

It is noteworthy that five of the six concretes had less than the 0.03 percent chloride content level in the interval 1 to 1 1/2 in.

As anticipated, the poorest performance was by

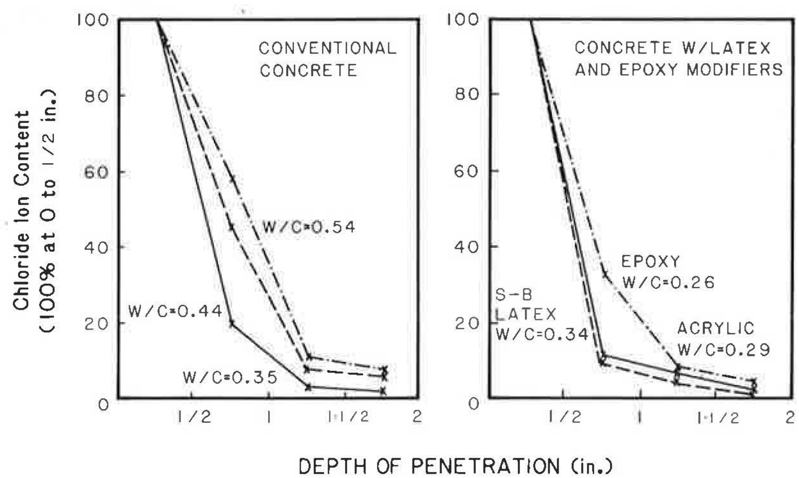

FIGURE 7 Chloride ion content at different depths.

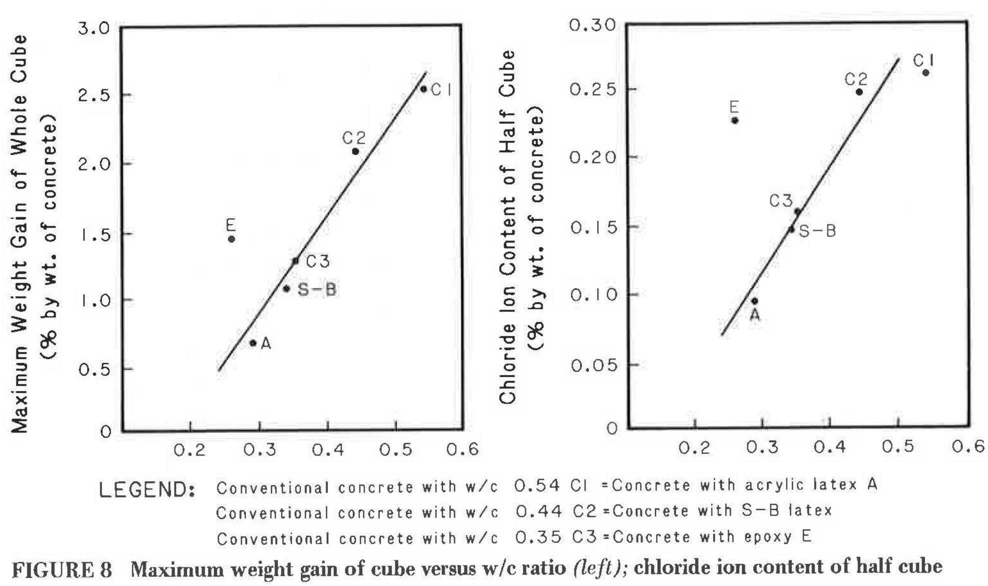

FIGURE 8 Maximum weight gain of cube versus w/c ratio *(left)*; **chloride ion content of half cube versus w/c ratio** *(right)*.

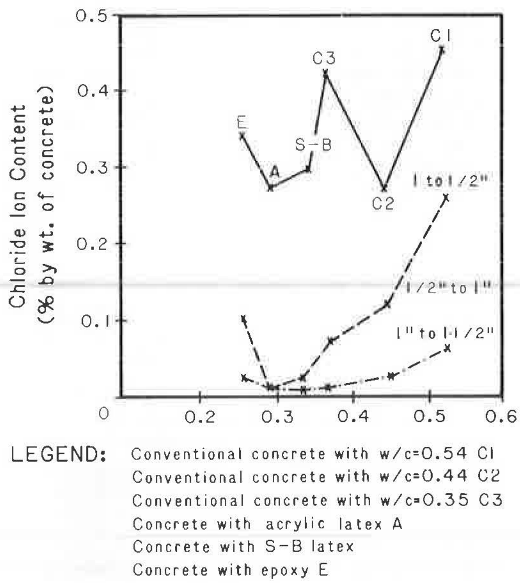

FIGURE 9 Chloride ion content within different depths versus w/c ratio.

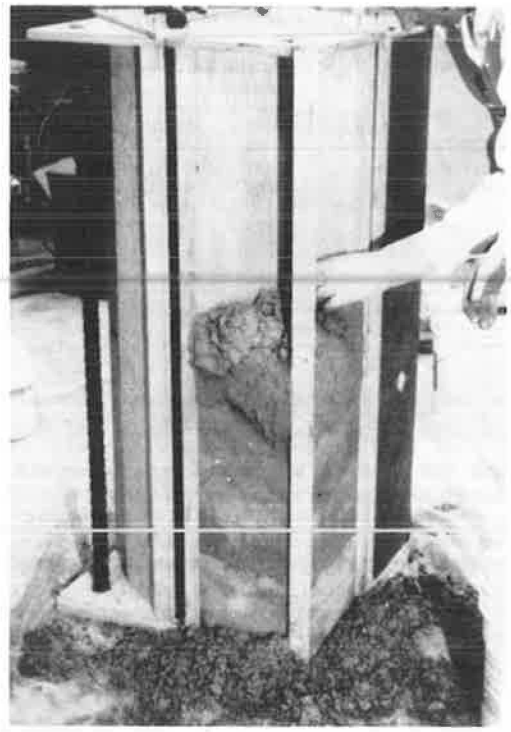

FIGURE 10 Concrete being hand placed into the large vertical wooden form.

the conventional concrete with a w/c ratio of 0.54. The best performance was by the two latex-modified concretes. Both concretes with w/c ratios of 0.29 to 0.34 show almost identical chloride ion profiles.

Figure 7 shows that the shape of the chloride ion distribution within these cubes is extremely steep within the first 1 in. In fact, from 90 to 96 percent of all the absorbed chloride is contained within the first 1 in. The shape of these distribution profiles is influenced by the w/c ratio and the concretes with the lowest w/c ratios possess the steepest gradients.

Influence of High Temperature and Wind on Hand-Placed or Form-Cast Large Vertical Repairs

The concretes with acrylic and S-B latexes and with epoxy modifier were hand placed (Figure 10) and cast into large vertical wooden forms in rooms having an air temperature of 70° and 105°F (21.1° and 40°C) with fans providing air circulation similar to that normally occurring on the side of the building during the summer. These tests with hand-placed polymer-modified concretes were totally unsuccessful because all tested specimens developed cracking problems due to cold joints and surface crazing and cracking (Figure 11). When the same polymer-modified concretes were used to make pea-gravel-sized concrete repairs in the laboratory under the same conditions with the exception that they were cast into forms, absolutely no cracking developed, even after 6 months of exposure to the aforementioned temperature conditions. The poor performance of the hand-placed repairs was similar to that observed on several actual repair projects.

Influence of Accelerated Weathering Tests on Small Repairs

As shown in Figure 12, the polymer-modified concretes were hand placed into vertically positioned lightweight and normal-weight concrete beam specimens in which repair holes had been prepared. Each beam contained three holes: two 2 in. deep and one 1 in. deep. As shown in Figure 13, dikes were added into one 2-in.-deep filled hole and the beams were then subjected to 16 weeks of accelerated-weathering tests that included wetting, freezing temperatures to 15°F (-10°C), thawing, ultraviolet light exposure, and elevated temperatures of 130°F (54.4°C). After these tests, the specimens were examined for cracking or spalling. The concretes containing latexes and a high-viscosity and low-modulus epoxy modifier did not show any surface changes.

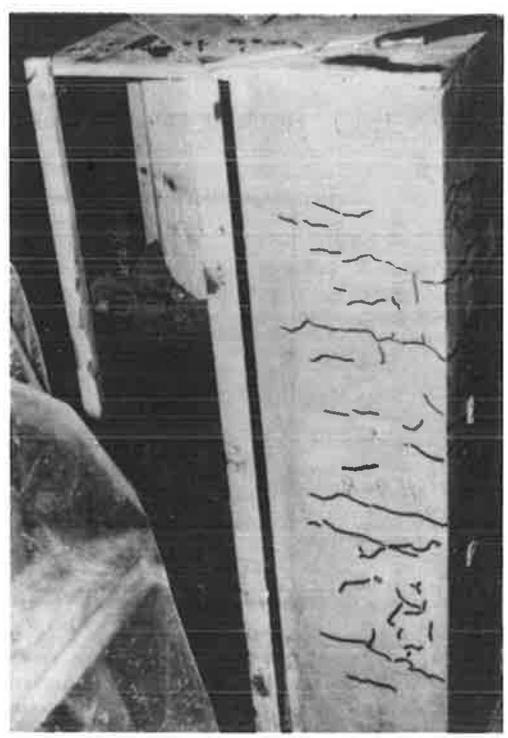

FIGURE 11 Cracking on concrete surface.

FIGURE 12 Concrete being hand placed into vertically positioned repair holes.

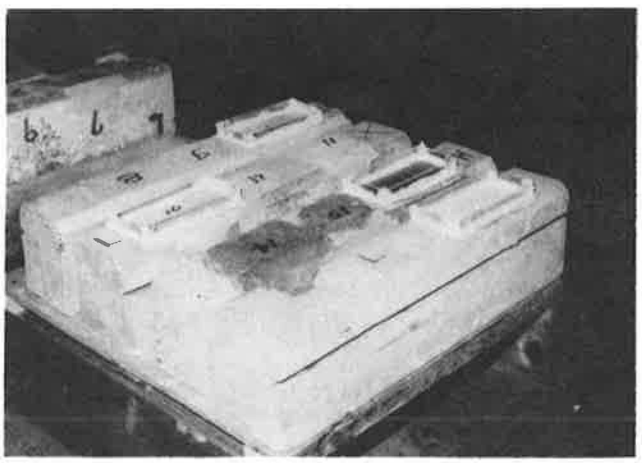

FIGURE 13 Repairs during the laboratory testing.

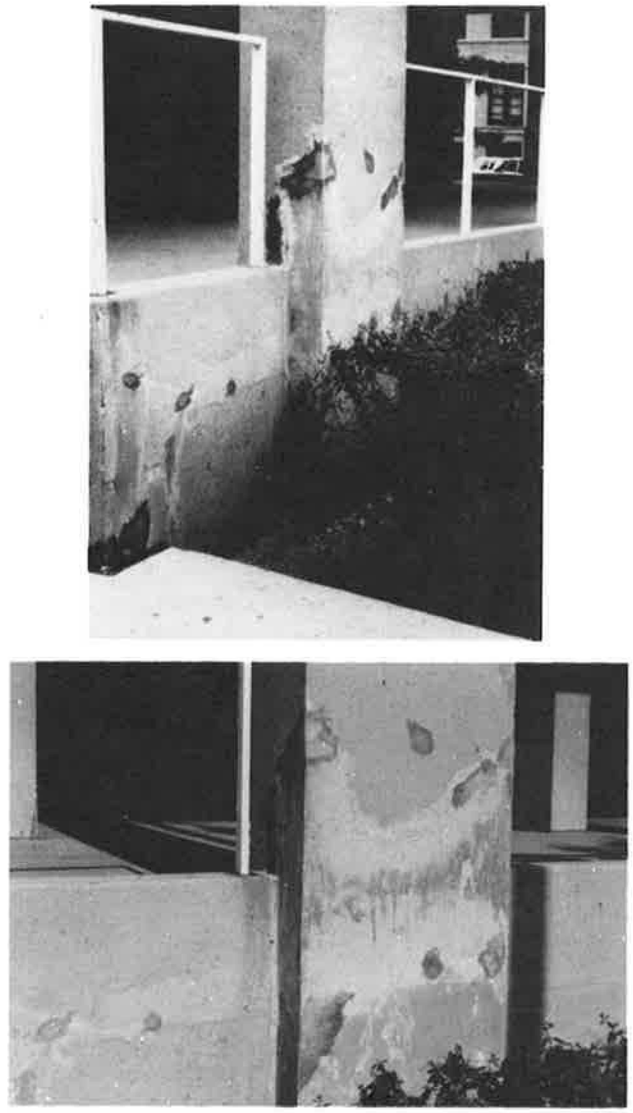

FIGURE 14 Repairs initially *(top)* and after 5 years in service *(bottom).*

USING THE POLYMER CONCRETE FOR REPAIRS

On the basis of laboratory experiments, the concrete containing acrylic latex was recommended and used to repair columns and spandrels of a high-rise apartment housing complex by casting in place (3,pp.157-174). The original concrete had been made using calcium chloride as an admixture and severe deterioration, especially of concrete columns, began after 18 years in service. The repairs after 5 years of service are shown in Figure 14.

The concrete containing the acrylic latex was also recommended and used to repair underground garages by shotcrete. The original concrete had also been made by using calcium chloride as an admixture, and it had been exposed to deicing salt during the winter seasons. Severe deterioration occurred after 15 years in service.

Both types of repairs were in excellent condition after 5 years in service.

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