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Using polymers to minimize corrosion of steel in concrete

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Abstract

Efforts to restrict chloride transport can lead to changes in the corrosion rate of steel in cement-based materials, such as concrete. Two potential methods have been examined for several years. They include: the addition of polymer fibers to the concrete at the time of mixing; and the encapsulation of previously contaminated concrete using polymer resin or polymer composites. It has been reported that the first method could minimize initial chloride intrusion and that the latter method could prevent additional chloride intrusion if concrete is already salt-contaminated. The effectiveness of these methods in minimizing corrosion was evaluated based on changes in corrosion rates determined using polarization resistance measurements. The results, which have been observed over a period of several years, will be reported. Limitations of polarization resistance measurements to evaluate the effectiveness of these methods as means of minimizing corrosion will also be discussed.

Keywords: Concrete; Steel corrosion; Polymer; Polypropylene; Encapsulation

1. Introduction

It is generally believed that the alkaline nature of reinforced concrete is responsible for the initially protective environment that concrete provides for steel. This is usually reflected in passive or more noble corrosion potentials (or E_{corr} values) for steel in concrete. Once aggressive ions such as chlorides migrate into concrete, conditions can become favorable for steel corrosion. As critical amounts of aggressive species are achieved, the potentials become more active and thus a shift in E_{corr} values is often associated with the intrusion of aggressive ions [1–4]. The result is penetration of the protective barrier and/or the depassivation of a protective film on the surface of the steel. The result is often an increase in the corrosion rate. This is of particular interest in cases where concrete will be exposed to chloride environments, such as marine environments or bridge decks subjected to deicing salts.

While there are many variables such as water/cement ratio (w/c), method and length of consolidation and curing, and amount of cover, the controlling factor seems to be permeability. Two methods that can potentially decrease this permeability are the addition of polymer fibers [5–8] and the encapsulation or encasement of concrete in a polymer resin or polymer composite [9–18]. Moreover, electrochemical techniques such as polarization resistance and electrochemical impedance spectroscopy (EIS) applied to steel-reinforced concrete can be useful in assessing the effect of the intrusion of aggressive ions on the corrosion rate of the steel inside [19–21].

The objectives of the research described in this paper are to examine the use of polymer fibers and polymer or polymer composite encapsulation as means of minimizing the corrosion rate of steel in concrete. The project involved the examination of (1) lollipop specimens (cylindrical concrete specimens made with a centrally located bar of steel) cast with and without the addition of polymer fibers and (2) lollipop specimens from a previous project in which salt exposure had already occurred. In the previous project, specimens from concrete made using 26 mix designs were examined. This examination involved measurements of strength, chloride permeability, chloride penetration, and polarization resistance (which is inversely proportional to the corrosion rate) as a function of chloride exposure. It also involved measurement of the macrocell current between top and bottom bars in reinforced concrete prisms designed so that the top bars were in salt-contaminated concrete while the bottom bars were in salt-free concrete. The results of the previous investigation have been reported elsewhere [22,23]. Specimens from three of these mixes were chosen for encapsulation.

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The intent of the previous investigation was to include concrete mixes that are typical of mixes that might be used in practice and thus some of the mixes contained concrete admixtures. Some contained various types and amounts of fly ash while others contained superplasticizers, air entrainment, or combinations of the above.

2. Experimental procedure

2.1. Concrete with and without fibers

The experimental procedure for the present investigation involved casting and curing 76 mm diameter × 152 mm long lollipop specimens followed by cyclical exposure and measurement of E_{corr} and polarization resistance (R_p) as a function of time. In all cases, the exposure period was 3 days soaking in a salt solution followed by 4 days of drying at room temperature. The steel used was #4 (13 mm diameter) Grade 60 meeting specifications outlined in ASTM A 615. The chloride solution used for exposure was 3.5% NaCl by weight. The specimen configuration of the lollipop specimens is shown in Fig. 1. The top 5.0 cm of the bars were covered with electroplater's tape so that crevice corrosion at the concrete–steel–tape–air interface could be minimized and so that only 10.2 cm of the bars were exposed inside the concrete.

Two percent polypropylene fibers (approximately 20 mm in length) by volume were added to a concrete mix having a w/c of 0.55. After mixing, the specimens were covered and left to set for 24 h, after which they were stored in an environmentally controlled chamber under

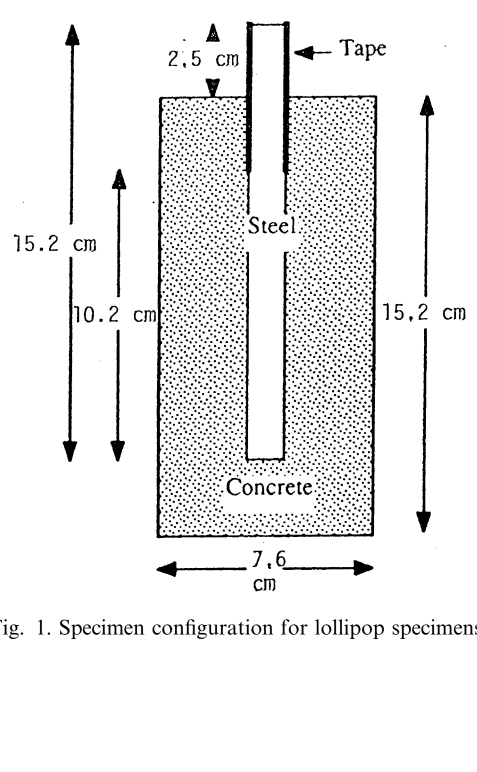

Fig. 1. Specimen configuration for lollipop specimens.

100% relative humidity and 23°C to cure for 28 days. Once the curing period was over, the specimens remained at room temperature for 1 month prior to chloride exposure. Four specimens with fibers and four specimens without fibers were monitored (on the third day of the wet period) weekly for 46 months. E_{corr} values were measured with respect to a saturated calomel electrode (SCE). After these readings were taken, R_p measurements were made using a computer-controlled potentiostat just prior to removal of the concrete specimens from the salt solution. Average values of E_{corr} and R_p for the specimens with and without fibers were recorded.

2.2. Encapsulation of concrete from previous project

For the previous project, a procedure similar to the one described above was followed. For each of the concrete mixes, eleven 76 × 152 mm^2 lollipop specimens were cast. Nine of the specimens were subjected to wet–dry cycling. E_{corr} measurements were taken on four of these specimens on the third day of every other cycle. The specimens were subjected to wet–dry cycling for 12 months. Of the five other cylinders, selected specimens were removed from the test and opened at certain times to observe the condition of the steel. This allowed comparisons to be made between corrosion data and steel surface conditions. Tables 1 and 2 show results from some of the mixes. Three mixes were chosen for encapsulation. They were Mixes 14 and 18 in which the corrosion rates were relatively low (4.2 and 10.1 $\mu S/cm^2$, respectively) and Mix 20 which had a relatively high corrosion rate (60 $\mu S/cm^2$). It should be noted that there were very fine hairline cracks on two of the lollipop specimens from Mix 20 at the time of encapsulation. While the macrocell specimens were not used for encapsulation, it should also be pointed out that average macrocell currents generated by the prisms were 6.6 μA for Mix 14, 0.1 μA for Mix 18 and 123.7 μA for Mix 20. In addition, the macrocell specimens from Mix 20 showed significant cracking. Chloride percentages by weight of cement at a depth of 13 mm in specimens made to test chloride penetration were 0.078 for Mix 14, 0.073 for Mix 18 and 0.211 for Mix 20.

The encapsulation procedure was a modified version of one that was used in another project on reinforced concrete beams that had undergone salt exposure for 2 years and is described elsewhere [12]. In that case plates and angles which were E-glass fiber reinforced composites were used to confine the beams. Plates and angles were not used for the lollipops because they were so small.

The concrete surfaces of the lollipops were prepared by grit blasting in order to provide a suitable surface for the adhesive system. A distribution medium, in the form

Table 1
Specifications for concrete mixes from previous project

Mix	Type fly ash	%	Admixture	Slump (cm)	Air (%)	w/c
1	–	–	–	11.4	3.00	0.66
10	Selected C	20	–	–	3.00	0.52
11	Selected F	35	–	10.2	3.00	0.69
12	Selected C	27.5	SUPER	7.6	3.00	0.51
13	Selected F	27.5	SUPER	8.9	3.00	0.51
14	–	–	AIR	8.3	6.50	0.45
15	–	–	AIR	14.6	9.00	0.40
16	Selected C	27.5	AIR	14.0	6.75	0.55
17	Selected C	27.5	AIR	11.4	9.00	0.55
18	Selected F	27.5	AIR	8.9	6.25	0.43
19	Selected F	27.5	AIR	7.6	8.50	0.43
20	–	–	–	18.4	3.00	0.69
23	–	–	–	11.6	3.00	0.46

Table 2
E_{corr} and $1/R_p$ (corrosion rate) data after chloride exposure for one year for concrete mixes from previous project

Mix	26 Weeks		52 Weeks	
	E_{corr} (mV vs SCE)	$1/R_P$ (μS/cm^2)	E_{corr} (V vs SCE)	$1/R_P$ (μS/cm^2)
1	−373	26.2	−520	52.2
10	−82	11.7	−288	16.2
11	−88	15.5	−107	12.9
12	−162	5.3	−231	5.4
13	−74	11.5	−69	10.1
14	−173	3.2	−360	4.2
15	−196	4	−399[a]	12.4[a]
16	−106	4.8	−295[a]	9.3[a]
17	−184	4.6	−317[a]	8.3[a]
18	−124	10.9	−103[a]	9.2[a]
19	−83	10.9	−71[a]	11.3[a]
20	−467	43.3	−476[b]	51.7[b]
23	−59	9.5	−166[b]	13.7[b]

[a] Data taken at 47 weeks.
[b] Data taken at 35 weeks.

of a fabric mesh with a relatively open weave, was wrapped around the lollipops to provide uniform resin flow. The lollipops were placed in plastic bags and the ends of the bags were sealed with tape before evacuation. After 24 h of evacuation under a vacuum to remove excessive moisture, the system was infused with an epoxy vinyl ester resin. Once the adhesive hardened, the infusion process was complete. After a 24-h curing period, the lollipops were taken out of the bags. The resulting barrier thickness was approximately 1 mm. One month after encapsulation, the lollipops were exposed to wet–dry cycling. The exposure continued for 22 months.

3. Results

3.1. Concrete with and without fibers

E_{corr} for the specimens with and without fibers were almost indistinguishable and varied from about −380 mV vs SCE at the time of initial exposure to about −660 mV vs SCE after 22 months with only small variations and a slight downward trend with time. Corrosion rates (as determined from $1/R_p$) were also very similar initially and varied between 0.02 and 0.1 μS/cm^2 for both the specimens with and without fibers for the first 6 months. Corrosion rates remained relatively stable for about 18 months and then started to increase. From the 19th month to the 26th month, the specimens with the fibers had corrosion rates between 1.7 and 4.9 μS/cm^2 while the specimens without the fibers had rates between 1.6 and 4.3 μS/cm^2. The rates were still quite similar. From the 27th month to the 42nd month, there seemed to be more distinction between the specimens. Corrosion rates for the specimens with fibers went from 5 to 170 μS/cm^2 during that period, while the rates for the specimens without fibers went from 55 to 220 μS/cm^2 during that period. The data for the last 15 months are shown in Fig. 2 where P represents the specimens without fibers and F

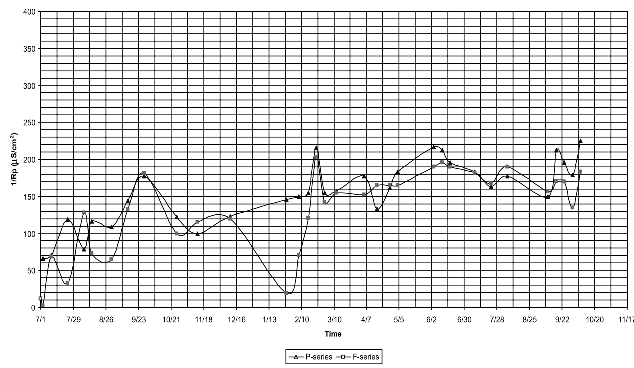

Fig. 2. Corrosion rate ($1/R_p$) data for specimens made from concrete with and without fibers during exposure to chlorides.

represents the specimens with fibers. The indications are that some reduction in corrosion rate may be observed at later times. Since the polypropylene fibers serve to minimize plastic shrinkage of concrete, it is conceivable that their effectiveness may not be exhibited until cracks begin to develop. When four of the specimens were opened, neither those with or without the fibers showed extensive corrosion. Examples are shown in Figs. 3 and 4. The corrosion that was observed was primarily associated with the concrete–steel–tape–air interface and may be associated more with crevice corrosion than corrosion along the length of the bar. Even though care was taken to minimize crevice corrosion, crevice corrosion may have been a contributor to the overall corrosion process.

3.2. Encapsulation of concrete from previous project

The E_{corr} values after initial re-exposure to chlorides and at the end of 22 months of exposure were approximately −400 mV vs SCE and −580 mV vs SCE for Mix 14, −300 mV vs SCE and −580 mV vs SCE for Mix 18, and −500 mV vs SCE and −670 mV vs SCE for Mix 20. The corrosion rates were initially low for all mixes, beginning at about 3 $\mu S/cm^2$. After 6 months, average

Fig. 3. Specimen made from concrete without fibers after 46 months of chloride exposure.

Fig. 4. Specimen made from concrete with fibers after 46 months of chloride exposure.

corrosion rates were approximately 64 μS/cm^2 for Mix 14, 33 μS/cm^2 for Mix 18 and 55 μS/cm^2 for Mix 20. After 22 months, average corrosion rates were approximately 120 μS/cm^2 for Mix 14, 42 μS/cm^2 for Mix 18, and 200 μS/cm^2 for Mix 20. Corrosion rate data for the 3 mixes for the last 15 months are shown in Figs. 5–7. When specimens were opened, corrosion was not very extensive in Mixes 14 and 18, occurring mainly at the concrete–steel–tape–air interface. On the other hand, corrosion covered about a third to one half of the bar in Mix 20. This was somewhat greater than the amount that existed after 1 year of exposure in the previous project. In addition, cracking was quite evident on the specimens removed from Mix 20 once the encapsulation material was removed, even before the specimens were opened. Examples of the specimens after exposure are shown in Figs. 8–11. One effect of the encapsulation was the tremendous confinement it provided. It was extremely difficult to remove the encapsulation material after the test. The small size of

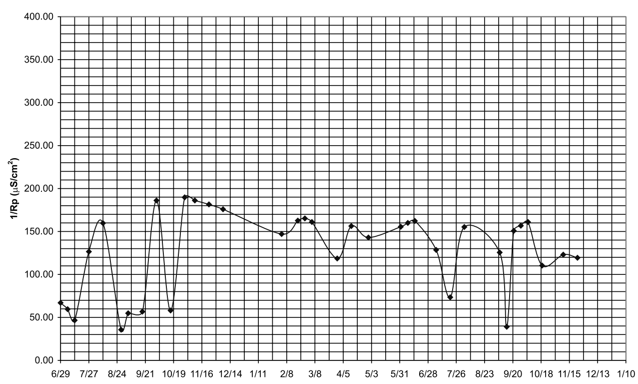

Fig. 5. Corrosion rate ($1/R_p$) data for encapsulated specimens from Mix 14 during re-exposure to chlorides (14-series).

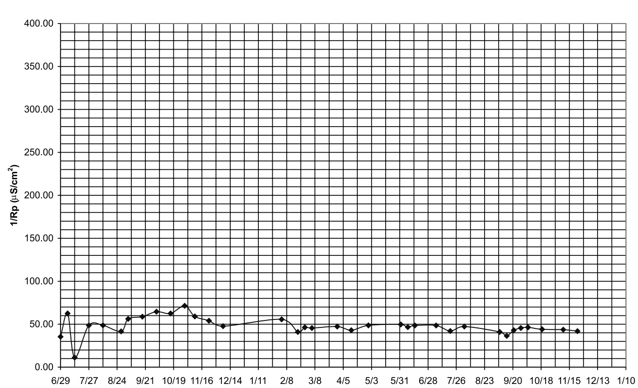

Fig. 6. Corrosion rate ($1/R_p$) data for encapsulated specimens from Mix 18 during re-exposure to chlorides (18-series).

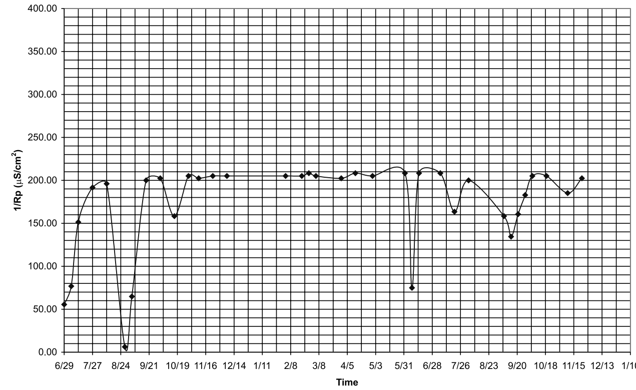

Fig. 7. Corrosion rate ($1/R_p$) data for encapsulated specimens from Mix 20 during re-exposure to chlorides (20-series).

the specimens and the difficulty exposing the steel without severely damaging the concrete prevented the determination of final chloride profiles. Chloride analysis (at specified depths) of beams encapsulated

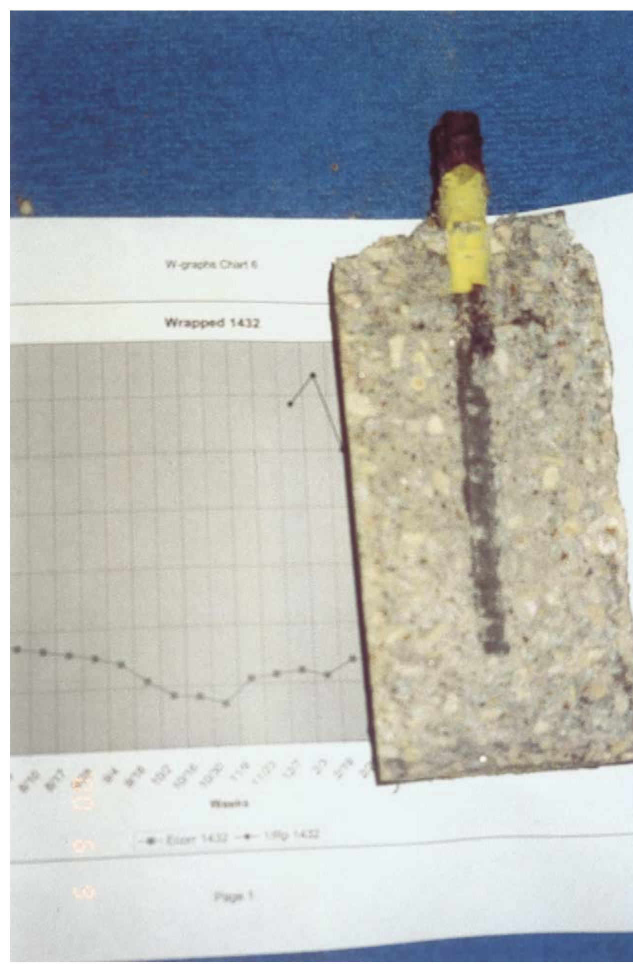

Fig. 8. Specimen made from Mix 14 after chloride exposure for 12 months, encapsulation, and re-exposure to chlorides for 22 months.

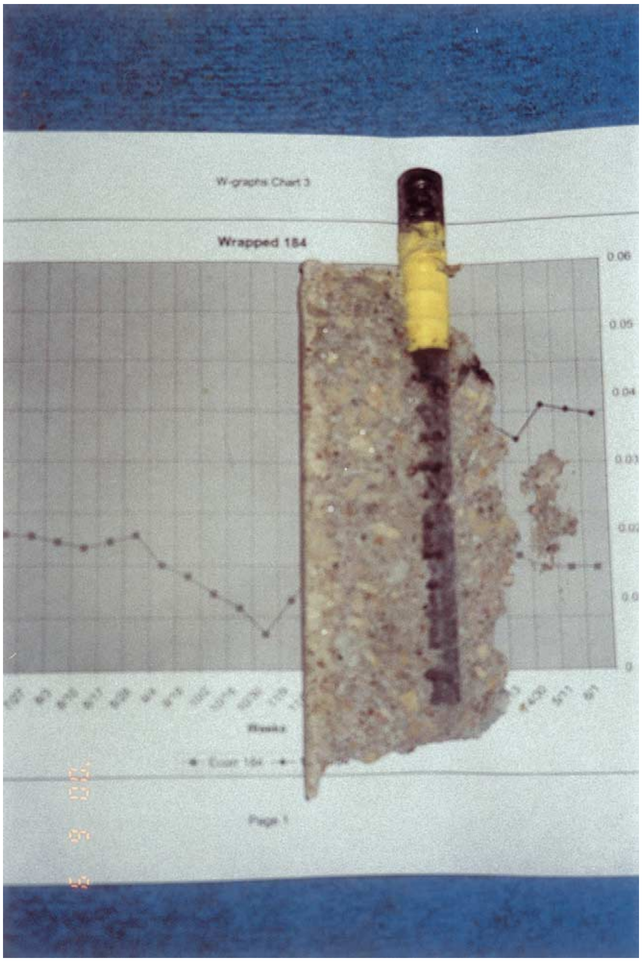

Fig. 9. Specimen made from Mix 18 after chloride exposure for 12 months, encapsulation, and re-exposure to chlorides for 22 months.

with the same procedure, however, indicated that the chloride contents were similar to or less than the values prior to encapsulation [12]. The lower values were attributed to chloride depletion due to continuing corrosion after encapsulation. This could offer a partial explanation for the visual observations in this investigation. Chloride amounts already capable of causing damage could be free to cause additional damage (as in specimens from Mix 20) even if those amounts did not increase. On the other hand, specimens containing chloride amounts which had not been sufficient to cause damage might benefit from encapsulation.

4. Conclusions

An investigation was carried out to examine the effectiveness of polymer fibers and polymer or polymer composite encapsulation in minimizing corrosion. It was assumed that as time increased, chloride transport would be reflected in changes in corrosion rates of steel in concrete as well as corrosion damage. Therefore, evaluations were made based on polarization resistance measurements (which were related to corrosion rates) made on lollipop specimens exposed to chlorides over a period of time.

The fact that corrosion rates were slightly higher for the specimens made without fibers suggests that the incorporation of fibers can be beneficial, especially as the exposure time increases and the likelihood of cracking increases.

The results of the encapsulation are not as easy to interpret. Polarization resistance values indicated that the corrosion rates decreased after encapsulation, but increased significantly after continued exposure to chlorides. However, on opening the specimens, the steel surfaces of specimens from two of the mixes exhibited conditions similar to those prior to encapsulation. This suggested that the encapsulation may have been beneficial in those cases, since it would be expected that continued exposure would result in increased damage. This is a very important consideration, because there is concern that encapsulation of salt-contaminated concrete in which corrosion has initiated and is ongoing may well accelerate the corrosion process since moisture and chlorides that are already present may be trapped [24]. This did not appear to be the case in this investigation. However, it should be pointed out that these specimens were dry at the time of encapsulation and had been dry for several years. This was probably advantageous.

Polarization resistance techniques are now used routinely to determine corrosion rates of steel in concrete. It is recognized that the rates that are determined reflect relative rates and may be influenced by factors such as localized forms of corrosion as well as varying surface areas of the corroding metal. The use of polarization resistance measurements on steel having a ribbed surface and in a concrete environment that is not homogeneous is certainly a deviation from the Stern–Geary analysis [25] on which the technique is based, and this must be kept in mind.

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Fig. 10. Specimen made from Mix 20 after chloride exposure for 12 months, encapsulation, and re-exposure to chlorides for 22 months.

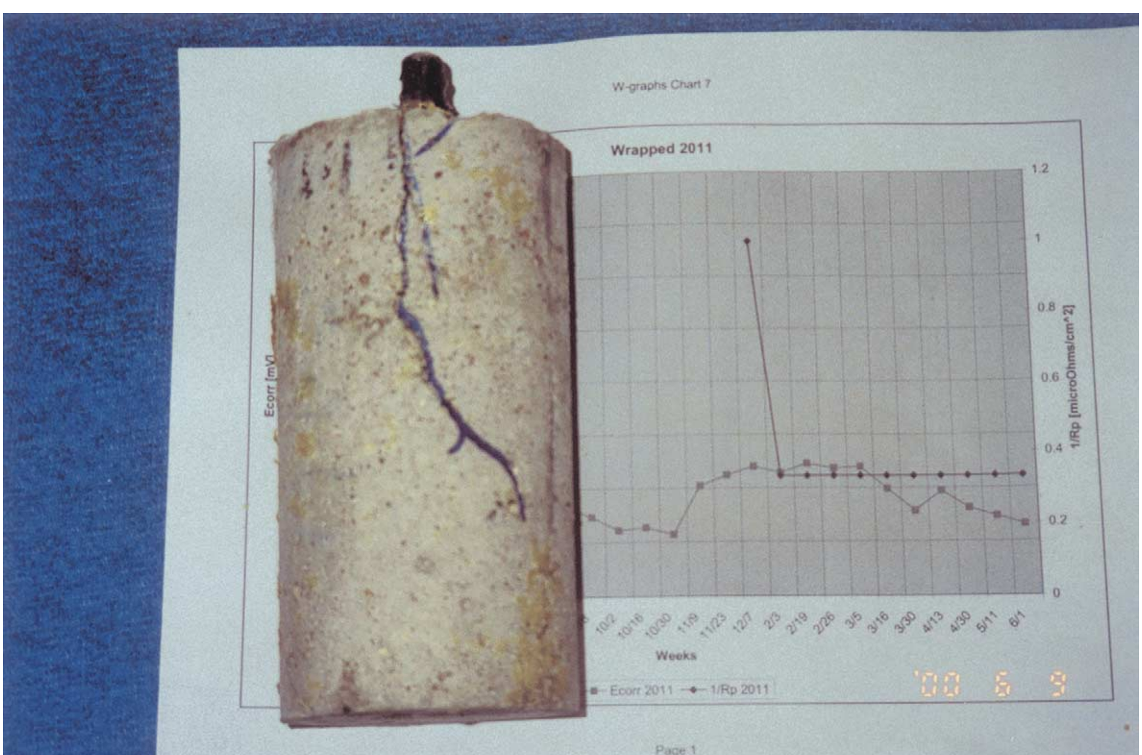

Fig. 11. Specimen made from Mix 20 after chloride exposure for 12 months, encapsulation, re-exposure to chlorides for 22 months, removal of encapsulation material prior to opening.

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