RAPID TEST FOR CORROSION EFFECTS OF DEICING CHEMICALS IN REINFORCED CONCRETE

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A Report on Research Sponsored by
THE STRATEGIC HIGHWAY RESEARCH PROGRAM

UNIVERSITY OF KANSAS
LAWRENCE, KANSAS
August 1990

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ABSTRACT

Research to develop tests that can accurately predict the effects of deicing chemicals on the corrosion of steel in reinforced concrete structures is reported. The research includes the development and evaluation of a standard test specimen and the use of three deicing chemicals to determine the sensitivity of both corrosion potential and macrocell corrosion to molal ion concentrations ranging from 0.4 to 6.4. The standard test specimen consists of a No. 4 reinforcing bar embedded in a 1.18 in. (30 mm) diameter, 4 in. (100 mm) long mortar cylinder. The mortar is made using portland cement, deionized water, and standard graded Ottawa sand. Specimens cured in lime-saturated water reach a passive condition within 14 days.

The tests are easy to perform, require no special training, and can normally be completed within 60 days. Of the two tests, the corrosion potential test provides more consistent results and should prove to be a useful tool for comparing the effects of deicing chemicals on the corrosion of reinforcing steel. Additional modifications are needed in the macrocell test before it is ready for general use.

Based on limited test data using sodium chloride, calcium chloride, and calcium magnesium acetate, calcium chloride appears to be the most detrimental, followed in order by sodium chloride and calcium magnesium acetate. Corrosion in the presence of calcium magnesium acetate appears to be highly sensitive to relative concentration, with no corrosion occurring at a molal ion concentration of 0.4. In contrast, specimens exposed to both calcium chloride and sodium chloride exhibit measurable corrosion potential at a concentration of 0.4 m. At the highest concentration for which comparisons were made (6.4 m), both the CMA and the $CaCl_2$ appear to be equally detrimental, while the NaCl appears to cause somewhat less corrosion.

INTRODUCTION

The adverse effects of deicing chemicals on the corrosion of reinforcing steel and reinforced concrete structures is well known. The deicers, principally calcium chloride and sodium chloride, cause reinforcing steel to lose the passive protection which it naturally obtains in the alkaline concrete environment. The increased concentration of chloride ions directly contributes to the loss of passivity. Calcium chloride has the additional deleterious effect of reducing the pH of the pore solution within the concrete, further contributing to the loss of passivity. Some new deicing chemicals have been developed in an attempt to produce one that is noncorrosive. Calcium magnesium acetate (CMA) has received special interest (Chollar 1984, Locke, Kennelley, Boren and Luster 1987, Chollar and Virmani 1988) since it is less corrosive to exposed metals than calcium chloride and sodium chloride (Dunn and Schenk 1980, Locke et al. 1987). However, there is some indication that CMA produces a corrosive environment for reinforcing steel in concrete (Locke et al. 1987).

With any new deicing chemical, it is important to evaluate its effects on the corrosion of reinforcing steel. Ideally, that evaluation should simulate the effects of the deicing chemical on reinforcing steel in an environment similar to that in actual structures. The evaluation should also be completed in a relatively short amount of time. The most widely used test in current application, the so-called time-to-corrosion accelerated laboratory test (Pfeifer, Landgren and Zoob 1987), satisfies the first criteria but requires six to twelve months.

This report describes research to develop tests that can accurately predict the effects of deicing chemicals on reinforcing steel in actual structures in a short time period, preferably weeks rather than months. The steps taken to develop and evaluate the test specimen and the results obtained with three deicing chemicals, sodium chloride, calcium chloride, and calcium magnesium acetate, at molal ion concentrations ranging from 0.4 to 6.4, are detailed. The test procedures are described in the body of the report and, also, presented in ASTM format in Appendix A.

Additional details of the study can be found in Martinez (1990).

EXPERIMENTAL WORK

Test Specimen

The test specimen (Fig. 1) consists of a 5 in. (127 mm) long reinforcing bar, symmetrically embedded 3 in. (76 mm) into a 1.18 in. (30 mm) diameter mortar cylinder. The mortar cylinder is 4 in. (102 mm) long, and the overall specimen length is 6 in. (152 mm). This configuration was selected based, in part, on the experience obtained by Yonezewa, Ashworth, and Procter (1988) in their study of the pore solution composition and effects of chlorides on the corrosion of steel in concrete. Modifications were made to the square cross-section "lollipop" specimen used by Yonezewa et al. (1988) to provide for uniform cover and easier fabrication.

The mold for the specimen (Fig. 2) is made from standard PVC pipe and fittings (full details in Appendix A). The reinforcing steel is positioned with laboratory grade rubber stoppers to accurately maintain proper cover. The PVC mold is held together in a plexiglass/bolt fixture which allows for ease of construction and disassembly.

To prepare the specimen, the 5 in. (127 mm) long reinforcing bar is cut and tapped at one end to receive a steel screw to provide an electrical connection. The bar is then cleaned with acetone, and a 0.6 in. (15 mm) wide band of epoxy is applied around the bar, 2$^3/_4$ in. (70 mm) from the nontapped end of the bar. The purpose of the epoxy band is to prevent crevice corrosion of the steel at the interface between the steel and the surrounding mortar. The liquid epoxy coating applied around the bar (Scotchkote 309 by 3M) is mixed and applied following the manufacturer's instructions.

To cast the specimen, the bar is assembled in the mold, as illustrated in Fig. 2, by inserting the tapped end of the reinforcing bar into a hole centered in the small rubber stopper, A (widest end of the stopper first). The distance between the nontapped end of the bar and the stopper is set at 3 in. (76 mm). The rubber stopper is then inserted into a machined PVC connector, B. The widest end of the stopper is in contact with the internal surface of the connector.

The large rubber stopper, C, is inserted in the large connector, D, and positioned as shown in Fig. 2. The end of small connector, B, is then inserted into connector, D, while the tapped end of the reinforcing bar is inserted into the opening in rubber stopper, C. The 1.18 in. (30 mm) inside diameter PVC pipe, E, is then inserted into connector, B, until it is flush with rubber stopper, A. The assembled mold is inserted into the plexiglass disks, F, and the assembly is tightened using threaded rods, G. The reinforcing bar is centered in the PVC pipe, E, by controlling the tension on the threaded rods. The openings in the rubber stoppers are enlarged to match the size of the reinforcing bar, and the 1.18 in. (30 mm) pipe, E, is split longitudinally (for easy disassembly) and taped before the model is assembled.

Materials

Reinforcing Steel–ASTM A 615-87a Grade 60 No. 3, No. 4, and No. 5 bars were initially evaluated for use in the test specimen. No. 4 bars are used for the final configuration.

Mortar–The mortar mixture is made with Type I portland cement and ASTM C 778-87 graded Ottawa sand. The mixture proportions of the mortar represent the mortar constituent of concrete with a design strength of 4000 psi. The mortar has a water-cement ratio of 0.5 and a sand-cement ratio of 2.0 by weight. Both tap water and deionized water were evaluated for use in the specimens. The final design specimens use deionized water. The mortar is mixed following the procedures in ASTM C 305-87.

Specimen Fabrication

The specimens are cast in three layers. Each layer is vibrated on a vibrating table at an amplitude of 0.006 in. (0.15 mm) and a frequency of 60 cycles/sec for 15 sec, although it is likely that other consolidation methods will be satisfactory. The upper surface of the mortar is finished with a trowel. Specimens are placed in a standard laboratory curing room (ASTM C 511-85) for two days. After one day, the plexiglass disks are removed. After two days, the specimen is removed from the mold and, during this study, either left in the curing room or placed in lime-saturated water until the time of test. The final procedures require curing in lime-saturated water. Electrical cable is connected to the tapped end of the reinforcing bar using a steel screw, and the connection is covered with epoxy to prevent the formation of a corrosion cell due to the presence of dissimilar metals (steel specimen and copper wire).

Test Procedure

Corrosion Potential Test–The corrosion potential test was used to evaluate initial test specimen configurations and to determine the relative aggressiveness of deicing chemicals. The test setup is shown schematically in Fig. 3.

The test requires two plastic containers. The test specimen is placed in a 5-liter container along with crushed mortar fill and either simulated pore solution or pore solution containing a deicing chemical. A standard calomel reference electrode is placed in a second container along with a saturated potassium chloride (KCl) solution. The two containers are connected by a salt bridge, and the potential difference between the specimen and the calomel electrode is measured at selected time intervals using a digital voltmeter.

The mortar fill consists of the same mixture as used in the test specimen. The fill is used primarily to serve as a buffer and to help simulate the relative amount of cementitious material that exists in an actual structure. The fill was cast in a 1 in. (25 mm) thick layer using a metal cookie sheet as the form. The form is vibrated for 15 sec on the vibration table. The fill is cast at the same time as the test specimen. At the time of test, the mortar is broken into pieces, with nominal sizes of $^3/_4$ to $1^1/_2$ in. (19 to 38 mm). 7.75 lb (3500 g) of crushed mortar is used as fill in each test.

The 5-liter container allows 3 specimens to be evaluated at one time, with at least a 1 in. (25 mm) between specimens and under each specimen. The polymer used for the container must be insensitive to both the caustic pore solution and the deicing chemicals.

The constituents in the simulated pore solution were selected based on the analyses of expressed pore solution performed by Farzammehr (1985). Each liter of pore solution contains 0.14 g of NaCl, 18.81 g of KOH, and 17.84 g of NaOH.

To complete the corrosion cell, the two containers are connected by a salt bridge. The salt bridge is prepared, following procedures described by Steinbach and King (1950): A gel is prepared by stirring 4.5 g of agar in 100 ml of deionized water over a double boiler. After the solution becomes clear, 30 g of KCl is dissolved in the gel, while the mixture is stirred and heating continues. The gel is then poured into 5 mm inside diameter tygon rubber tubing, which serves as the salt bridge.

A standard calomel reference electrode (Fisher model 13-639-51) is used to measure corrosion potential. The electrode is submerged in a saturated KCl solution (15 g of KCl per 100 cc of water).

Laboratory grade sodium chloride (NaCl) and calcium chloride ($CaCl_2$) and commercially produced calcium magnesium acetate (CMA, 3 moles of calcium acetate per 7 moles of magnesium acetate) were used to evaluate the effects of various concentrations of deicing chemicals. The effects of the chemicals were compared on a isomolal ion basis (equal number of ions), since ion concentration in moles per unit volume of water controls ice melting capacity. Molal ion concentrations of 0.4, 0.8, 1.6, 3.2, 6.4, and 12.8 were used. The weights of materials in grams per liter of pore solution for each molal concentration and deicing chemical are presented in Table 1.

At the desired age, a specimen is taken from the curing room or the curing tank. The tapped end of the reinforcing bar is thoroughly dried using compressed air, the shielded cable is connected to the bar with a steel screw, and the connection is covered with epoxy. The cable is then passed through a hole in the lid of the container. A layer of mortar fill is placed on the bottom of the container, up to three specimens are placed, bar up, on the layer, and the balance of the fill material is added to the container. The salt bridge is placed in the container through a second hole in the lid. The other end of the salt bridge is placed in the second container. To have a good ionic path, the gel in the tubing must be continuous, without interruption by an air bubble. The respective solutions are then placed in the containers. For the tests reported here, the simulated pore solution, with or without the deicing chemical, was added until it reached a level 0.08 in. (2 mm) from the top edge of the mortar. For future tests, however, it is recommended that $^1/_2$ in. of mortar "freeboard" be left. The container with the test specimen is sealed for the duration of the test to prevent carbon dioxide from neutralizing the simulated pore solution and to prevent evaporation of the liquid.

Macrocell Test–The macrocell test is used to evaluate the relative corrosion properties of deicing chemicals by setting up an active macrocell. The elements used in this test are the same as elements described for the corrosion potential test. A schematic of the test setup is shown in Fig. 4.

In this test, two lollipop test specimens, located in separate containers, are electrically connected across a 100,000 ohm resistor. Electrical conductivity between the solutions in the two containers is provided by a salt bridge. Standard fill material is placed in both containers. One specimen is exposed to simulated pore solution, while the other is exposed to simulated pore solution containing a deicing chemical. The 100,000 ohm resistor allows corrosion to proceed while providing a measurable potential drop.

For the macrocell tests, the specimens and fill are removed from the curing tank and prepared in the same manner as the corrosion potential specimens. The pore solution is then added to one container, while the pore solution and deicing chemical are added to the other container. Both containers are sealed for the duration of the test. The potential drop across the resistor (a measure of the corrosion current) is then measured at regular intervals.

RESULTS AND EVALUATION

Specimen Evaluation

Prior to the initiation of the corrosion potential and macrocell tests using deicing chemicals, the specimens underwent a series of evaluation steps to determine the best combination of materials and preparation techniques for use in those tests. Initial evaluation of the test specimens involved determining the optimum reinforcing bar diameter, the length of curing, the method of curing, the types of sand and water to be used, and the best configuration for the epoxy coating.

Ideally, the largest bar diameter possible should be used, because it provides the minimum cover which, in turn, provides the most rapid penetration of the deicing chemicals to the bar surface. No. 3, No. 4, and No. 5 bars were evaluated.

Tests should be initiated immediately following the curing period. The length of curing must be long enough for the specimens to reach a passive condition. The shorter the time period, however, the lower the density the cement paste and the faster the test solution can reach the surface of the bar. For this reason, curing ages ranging from 3 to 28 days were evaluated.

Like the age of curing, the method of curing is important because it also must allow the reinforcing bar to reach a passive condition. Specimens were cured in both a standard moist room and in lime-saturated water.

It was considered desirable to make specimen fabrication as easy and as economical as possible: the initial specimens were fabricated using local river sand and tap water. Results from early portions of the study indicated that there were some problems with the local materials. These observations prompted a switch to ASTM C 778-87 graded Ottawa sand and deionized water for the standard test configuration. However, some additional comparisons were made using tap water in the specimen, fill material and simulated pore solution, and river sand in the fill material only, to determine if specimen passivation was specifically sensitive to these materials.

Results of Specimen Evaluation–Specimen configurations were evaluated based on the rate at which the reinforcing bars reached a passive condition. Generally speaking, there was no difference between the rate of passivation for the three size bars evaluated. The mortar in the specimens containing the No. 5 bars, however, had a tendency to crack at the end of the bar during demolding. For that reason, No. 5 bars were eliminated from further consideration. Both the No. 3 and No. 4 bars performed well. No. 4 bars were selected for the final specimen configuration because of the lower cover they provide.

The earliest test specimens were cast using tap water. Typical results are illustrated in Fig. 5 for bars cured in the moist room for 3, 7 or 28 days. As can be seen, none of the specimens had reached the passive condition, corresponding to a potential more positive than – 0.30 volts with respect to calomel, at the conclusion of curing. In fact, the longer the curing period, the less passive (the more negative) the potential. It was only after being placed in the pore solution for a period of time that the specimens attained a passive condition. At this point in the study, it was concluded that the initial corrosion state of the steel was dominated by corrosion on the exposed portion of the reinforcing bar, and for that reason, the balance of the tests used specimens that were cured in lime-saturated water.

The results for the specimens cured in lime-saturated water (Fig. 6) show that the longer the curing period, the closer the corrosion potential is to the passive condition. Specimens cured for 28 days are fully passive, while those cured for 3 and 7 days typically do not reach a passive condition until at least 10 days after casting. Based on these results, a standard curing time of 14 days was selected for the main battery of tests.

Another aspect of the tests involved the epoxy configuration, that is, the location of epoxy on the test specimen. Three configurations were considered (Fig.7). Configuration A consists of epoxy at the interface between the steel and the concrete, plus epoxy at the embedded end of the bar. This configuration was considered because of concern that the surface of the bar covered by mill scale would react differently in the presence of deicing chemicals than a surface exposed by a saw cut. Configuration B consists of a full coating of epoxy on the exterior portion of the bar, plus coverage on the embedded end of the bar. Configuration C, the one finally selected for the tests, consists of a single ring of epoxy at the exposed interface between the steel and the mortar.

Test results showed that epoxy configuration, B, full coverage of the exposed steel, results in specimens that rarely attain a passive condition and often exhibit a high negative potential instead. The reason, in all likelihood, is that small holes in the epoxy coating allow some moisture under the coating and result in crevice corrosion (Fontana 1986). Thus, for configuration B, it was impossible to evaluate the achievement of a passive condition for the portion of the bar that was in contact with the mortar. Therefore, full epoxy coverage of the exposed steel was eliminated as an option. Of the remaining epoxy configurations, specimens with configuration A, epoxy at the interface and on the embedded end of the bar, occasionally exhibited high negative corrosion potentials. Here again, crevice corrosion may have been the cause. Based on these results, configuration C was selected, since it provides the most consistent results.

The effects of using tap water in the specimen, fill and simulated pore solution and the effects of using river sand in the fill material are illustrated in Figs. 8 and 9. These figures show that, while a passive state was attained for specimens cured for 7 and 14 days, it was not consistently attained for specimens cured for 28 days. The lack of passivity at 28 days was likely due to the presence of chlorides in the tap water and river sand. Thus, standard Ottawa sand and deionized water were selected for use in all portions of the test setup. Typical curves for specimens using these materials and exposed to the simulated pore solution are illustrated in Fig. 10.

The standard specimen configuration provides only 0.08 in. (2 mm) of mortar above the top of the solution. As the corrosion potential and macrocell tests proceeded, there was some concern that the pore solution with the deicing chemical might be moving over the top of the specimen and down the epoxy interface to reach the steel, rather than diffusing through the mortar cover. To evaluate this possibility, a series of "dip" tests were carried out in which specimen corrosion potential was measured for different heights (or freeboard) of mortar above the top of the solution. Values of 2, 1 1/2, 1, 1/2 and 0.08 in. (51, 38, 25, 13 and 2 mm) were evaluated. The test solution for the dip tests consisted of the simulated pore solution with a 6.4 molal ion concentration of NaCl. Specimens with just 0.08 in. (2 mm) of freeboard attained the maximum corrosion potential by the second or third day, while the other configurations approached the maximum corrosion potential somewhat more gradually. The results, illustrated in Fig. 11, show a strong similarity between specimens with freeboards of 1/2 to 2 in. (13 to 51 mm). After 50-60 days, all specimens exhibited approximately the same corrosion potential. There is enough difference between specimens with 1/2 in. (13 mm) freeboard and specimens with 0.08 in. (2 mm) freeboard that, for future evaluations, it would appear wise to run the tests with 1/2 in. (13 mm) freeboard to insure that no portion of the solution moves over the top of the specimen and down the interface between concrete and the epoxy.

Corrosion Potential Tests

The results of the corrosion potential tests are illustrated in Figs. 12-16. Fig. 12 illustrates the response of specimens cured for 3, 7, or 28 days and exposed to a simulated pore solution with a 12.8 molal ion concentration of NaCl (saturated NaCl solution). The figure illustrates the relative insensitivity of the long-term corrosion potential to the age at which the test is initiated. The main difference observed in these tests appears to be the state of passivation at the initiation of the test. The 28-day old specimens have achieved a passive state, whereas the 7-day and 3-day specimens have not yet become passive. However, after about 10 days in the solution, there is little difference exhibited based on the age at which the test was initiated. The balance of the tests discussed in this report represent specimens that have been cured for 14 days and have, in most cases, reached a passive condition (corrosion potential more positive than – 0.30 volts) prior to the initiation of the tests.

Corrosion potential tests were run with molal ion concentrations of deicers of 6.4, 3.2, 1.6, 0.8, and 0.4 in the simulated pore solution. Figs. 10(b) and 13 illustrate results for 6 specimens placed in pore solution only. All specimens are passive or nearly passive at the initiation of the tests, and maintain the passive condition throughout the duration of the tests, 68 days after casting.

For the specimens exposed to the deicers, several clear trends can be observed (Figs. 14-16). As a general rule, the specimens exposed to NaCl and CMA exhibit a decreasing (less negative) corrosion potential with decreasing concentrations of deicing chemical, while those containing calcium chloride show only a slight drop in corrosion potential with decreasing concentration. Specimens in NaCl (Fig. 14) show a gradual drop in corrosion potential, from – 0.55 volts, at an ion concentration of 6.4 m, to – 0.35 volts, at a concentration of 0.4 m. Specimens exposed to CMA (Fig. 16) exhibit a drop from – 0.60 volts, at a concentration of 6.4 m, to a fully passive condition, – 0.25 volts, at a concentration of 0.4 m. Specimens exposed to $CaCl_2$ (Fig. 15) exhibit corrosion potentials ranging only from – 0.60 volts, at a concentration of 6.4 m, to – 0.55 volts at 0.4 m, with the exception of the 0.8 m concentration which exhibits a long term potential of about – 0.35 volts.

The corrosion potential tests provide useful insight into the effects of the three deicing chemicals evaluated in this study. When the CMA and the $CaCl_2$ are initially added to the pore solution, a precipitate is observed. The CMA causes both calcium hydroxide and magnesium hydroxide to precipitate (Locke et al. 1987), while, presumably, $CaCl_2$ causes calcium hydroxide to precipitate. In both cases, the pH of the solution is decreased, which has the effect of reducing the passive protection provided by the pore solution. Both $CaCl_2$ and NaCl provide chloride ions, which also reduce passive protection.

For the calcium chloride, the dual effect of the reduced pH and chloride ion results in a nearly uniform corrosion potential, independent of the ion concentration over the full concentration range of 6.4 m to 0.4 m, indicating that of the three chemicals, $CaCl_2$ should be the most detrimental to reinforcing steel.

At high concentrations, CMA appears to act in a similar manner to $CaCl_2$, but at lower concentrations it is less detrimental, and at the lowest concentration evaluated, 0.4 m, CMA allows a fully passive condition to be attained. This large difference in behavior as a function of concentration may explain conflicting observations (Locke et al. 1987, Chollar and Virmani 1988) as to the effect of CMA on the corrosion of reinforcing steel. The different concentrations used in these tests can be looked upon as representing the different concentrations that are attained at the surface of reinforcing bars as deicing chemicals penetrate a thick concrete cover over time. Clearly, small amounts of $CaCl_2$ rapidly change the corrosion potential of reinforcing steel, whereas low concentrations of CMA have no effect. The overall result is that in the field, reinforcing bars exposed to CMA should not corrode until the concentration reaches higher values, while bars exposed to $CaCl_2$ will begin to corrode at low concentrations.

The effect of NaCl on corrosion appears to be between the other two deicing chemicals. NaCl has little effect on the pH of the pore solution, but does expose the reinforcment to chloride ion. Overall, NaCl appears to provide reduced corrosion potential as its concentration is decreased. Low concentrations have the effect of reducing the passivity, but are not as detrimental as low concentrations of $CaCl_2$.

Considering the sensitivity of the corrosion potential to different concentrations of some deicers, it appears that a standard test should include comparisons at molal ion concentrations of 6.4, 1.6, and 0.4. NaCl appears to be a good standard for comparison, because it produces a corrosion potential that is a function of deicer concentration.

The corrosion potential versus time curves exhibit a noticeable amount of scatter. However, after 50 days the results appear to stabilize. To get a reasonably complete picture, the tests should run 60 days following the time of casting (46 days after test initiation for a 14 day cure), although useful results are obtained within 30 days of casting. The test is considerably more rapid than the time-to-corrosion test (Pfeiffer et al. 1987).

The relatively high consistency obtained with the corrosion potential tests and the general agreement of these tests with results observed in the literature (Locke et al. 1987) suggests that the use of a standard corrosion potential test using the calomel reference electrode will be useful and relatively easy to implement in the field.

Macrocell Tests

The results of the macrocell tests using simulated pore solution and molal ion concentrations of deicer of 6.4, 3.2, 1.6, 0.8 and 0.4 are illustrated in Figs. 17-19. The figures show the potential drop across the resistor which is directly related to the corrosion content. All tests were performed with two specimens. In a number of cases, the salt bridges were not functioning during the early stages of the tests, which prevented active macrocell corrosion from occurring. Cases in which this problem occurred are evident in those plots where the macrocell potentials provided by the two specimens give values that are symmetrical about 0 volts. Once the salt bridges were fixed, active corrosion resumed. Figs. 17-19 demonstrate that the effects of the deicing chemicals are qualitatively similar, but not as consistent as those observed in the corrosion potential tests. For example in Fig. 17(a), the negative potential drop across one resistor exceeds – 0.2 volts for one of the specimens exposed to the 6.4 m NaCl solution, but is essentially zero for the other specimen. For lower concentrations of NaCl [Figs. 17(b)-(e)], the potential drop across the resistor does not decrease monotonically with decreasing deicer concentration, as observed in the corrosion potential tests (Fig. 14).

The results for $CaCl_2$ (Fig. 18) are much more consistent than those for NaCl and exhibit a smooth, but nonmonotonic, variation with concentration. The negative potential drop across the resistor is greatest for the 3.2 m $CaCl_2$ solution, exceeding – 0.2 volts. The potential drop decreases for concentrations below 3.2 m, with the 0.8 m and 0.4 m concentrations [Figs. 18 (d) and (e)] producing similar results, between 0 and – 0.1 volts. The drop in corrosion with the decrease in deicer concentration differs from the apparent insensitivity to concentration observed for $CaCl_2$ in the corrosion potential tests (Fig. 15).

Like the results for NaCl, the results for CMA (Fig. 19) are erratic, with little apparent corrosion occurring for the 6.4 m solution (potential drop ≈ 0). The potential drop increases to about – 0.05 volts at 3.2 m, decreases again at 1.6 m, and then increases significantly for one specimen at 0.8 m. At 0.4 m, one specimen exhibits slight corrosion, while the other exhibits a small positive potential change, under + 0.1 volts.

Overall, $CaCl_2$ provides the greatest macrocell corrosion. NaCl causes less macrocell corrosion, and CMA, with one exception [Fig. 19(d)], causes the least corrosion.

One reason for the lack of consistency in the observed degree of macrocell corrosion could be the salt bridges that did not function during the early stages of some tests.

Another reason for the greater scatter observed in these tests may be the fact that the "reference electrode" (the specimen in the pure pore solution) is not manufactured under the same controlled conditions as is the standard calomel electrode used for the potential tests.

The results illustrated in Figs. 17-19 suggest that additional evaluation is necessary before this test procedure can be finalized. The macrocell test should ultimately prove to be more useful than the corrosion potential test, since it compares the effects of deicing chemicals on an active corrosion cell. Modifications to consider include improved methods for making the salt bridge and the use of a much lower resistance in the circuit to obtain a greater degree of corrosion in the macrocell. The very high resistance used in the current tests greatly limited the corrosion current and partially defeated the purpose of using a macrocell.

SUMMARY AND CONCLUSIONS

The results of research to develop tests that can accurately predict the effects of deicing chemicals on the corrosion of steel in reinforced concrete structures is reported. The research includes the development and evaluation of a standard test specimen and the use of three deicing chemicals to determine the sensitivity of both corrosion potential and macrocell corrosion to molal ion concentrations ranging from 0.4 to 6.4.

The standard test specimen consists of a No. 4 reinforcing bar embedded in a 1.18 in. (30 mm) diameter, 4 in. (100 mm) long mortar cylinder. The mortar is made using portland cement, deionized water, and standard graded Ottawa sand. Specimens cured in lime-saturated water reach a passive condition within 14 days.

The tests are easy to perform and require no special training. Of the two tests, the corrosion potential test appears to provide more consistent results and should prove to be a useful tool for comparing the effects of deicing chemicals on the corrosion of reinforcing steel. Additional research is needed before a similar statement can be made with regard to the macrocell test.

Based on limited test data using sodium chloride, calcium chloride, and calcium magnesium acetate, calcium chloride appears to be the most detrimental, followed in order by sodium chloride and calcium magnesium acetate. Corrosion in the presence of calcium magnesium acetate appears to be highly sensitive to relative concentration, with no corrosion occurring at a molal ion concentration of 0.4. In contrast, test specimens exposed to both calcium chloride and sodium chloride exhibit measurable corrosion potential at a concentration of 0.4 m. At the highest concentration for which comparisons were made (6.4 m), both the CMA and the $CaCl_2$ appear to be equally detrimental, while the NaCl appears to cause somewhat less corrosion.

FUTURE WORK

As pointed out in the two previous sections, additional development is necessary before the macrocell test can be applied effectively to compare the effects of deicing chemicals on reinforcing steel. However, the rapid reaction of the test specimens, as demonstrated by the corrosion potential tests, shows that significant advantages will be obtained if the specimens can be incorporated within a macrocell test system. In addition to the modifications to the salt bridge and resistor discussed earlier, it would be worthwhile to investigate the use of multiple (and perhaps longer) specimens connected in parallel to increase the surface area of the reinforcing steel and, thus, increase the measurable corrosion current. The incorporation of a zero resistance ammeter should also be considered.

Future work should include the use of deicing chemicals without simulated pore solution at the anode. The use of the straight deicing chemical solutions may cause some dissolution of the cement paste, but that should be largely mitigated by the buffering effect of the mortar fill. The use of a straight deicer solution may be more realistic than the procedure used in the current study and would, in all likelihood, be a more severe test of the deicer.

Finally, since sealed containers are used for the tests, the system should be checked to insure that the results are not affected by oxygen starvation.

ACKNOWLEDGEMENTS

This report is based on research by Sonia L. Martinez in partial fulfillment of the requirements for the M.S.C.E. degree. The research was sponsored by the Strategic Highway Research program under a subcontract from the Midwest Research Institute. The Scotchkote 305 epoxy was donated by 3M. Calcium magnesium acetate for use in this study was provided by Chevron Research and Technology Company.

REFERENCES

ASTM (1987). "Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete", (ASTM A 615-87a) *1989 Annual Book of ASTM Standards*, Vol. 4.02, American Society for Testing and Materials, Philadelphia, PA, pp. 420-424.

ASTM (1989). "Standard Specification for Portland Cement," (ASTM C 150-89) *1989 Annual Book of ASTM Standards*, Vol. 4.01, American Society for Testing and Materials, Philadelphia, PA, pp. 115-119.

ASTM (1987). "Standard Method for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency," (ASTM C 305-87) *1989 Annual Book of ASTM Standards*, Vol. 4.01, American Society for Testing and Materials, Philadelphia, PA, pp. 198-200.

ASTM (1985). "Standard Specification for Moist Cabinets, Moist Rooms and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes" (ASTM C 511-85) *1989 Annual Book of ASTM Standards*, Vol. 4.01, American Society for Testing and Materials, Philadelphia, PA, pp. 270-271.

ASTM (1987). "Standard Specification for Standard Sand," (ASTM C 787-78) *1989 Annual Book of ASTM Standards*, Vol. 4.01, American Society for Testing and Materials, Philadelphia, PA, pp. 333-334.

ASTM (1989). "Standard Specification Polyvinyl Chloride (PVC) Plastic Pipe (SDR-PR)" (ASTM D 2241-89) *1989 Annual Book of ASTM Standards*, Vol. 8.04, American Society for Testing and Materials, Philadelphia, PA, pp. 111-118.

ASTM (1989). "Standard Specification Polyvinyl Chloride (PVC) Plastic Pipe, Fitting Schedule 40," (ASTM D 2466-89) *1989 Annual Book of ASTM Standards*, Vol. 8.04, American Society for Testing and Materials, Philadelphia, PA, pp. 164-168.

ASTM (1988). "Standard Practice for Preparing, Cleaning and Evaluating Corrosion Test Specimens," (ASTM G 1-88) *1989 Annual Book of ASTM Standards*, Vol. 3.02, American Society for Testing and Materials, Philadelphia, PA, pp. 41-47.

ASTM (1989). "Standard Practice for Conventions Applicable to Electrochemical Measurements in Corrosion Testing," (ASTM G 3-89) *1989 Annual Book of ASTM Standards*, Vol. 3.02, American Society for Testing and Materials, Philadelphia, PA, pp. 62-70.

Chollar, B. H. (1984). "Federal Highway Administration Research on Calcium Magnesium Acetate, an Alternative Deicer," *Public Roads*, Vol. 47 No. 4, March, pp 113-118.

Chollar, B. H. and Virmani, Y. P. (1988). "Effects of Calcium Magnesium Acetate on Reinforced Steel Concrete," *Public Roads*, Vol. 50, No. 4, March, pp. 113-115.

Dunn, S. A. and Schenk, R. V. (1980). "Alternate Highway Deicing Materials", *Bjorstein Research Laboratory, Inc*, N. T. I. S., Springfield, Va., 17 pp.

Farzammehr, H. (1985). *Pore Solution Analysis of Sodium Chloride and Calcium Chloride Containing Cement Pastes*, Master of Science Thesis, University of Oklahoma, Norman, Oklahoma, 101 pp.

Fontana, M. G. (1986). *Corrosion Engineering*, Third Edition, McGraw-Hill, New York, 556 pp.

Locke, C. E. (1986). "Corrosion of Steel in Portland Cement Concrete: Fundamental Studies," *Corrosion Effects of Stray Currents and the Techniques for Evaluating Corrosion of Rebars in Concrete*, ASTM STP 906, V. Chaker, Ed. American Society for Testing and Materials, Philadelphia, pp. 5-14.

Locke, C. E., Kennelley, K. D., Boren, M. D. and Luster, V. (1987). "A Study of Corrosion Properties of a New Deicer, Calcium Magnesium Acetate," *Transportation Research Board Research Record* 1113, Transportation Research Board, Washington D. C., pp. 30-38.

Martinez, S. L. (1990). *Development of a Rapid Test to Measure the Corrosion Effects of Deicing Chemicals in Reinforced Concrete*, Master of Science Thesis, University of Kansas, Lawrence, Kansas, 97 pp.

Pfeifer, D.W., Landgren, J.R. and Zoob A. (1987). "Protective Systems for New Prestress and Substructure Concrete," *Report* No. FHWA/RD-86/1993 U. S. Department of Transportation. Federal Highway Administration. WJE No. 830038. Washington D.C, 133 pp.

Slater, J. E. (1983). *Corrosion of Metals in Association with Concrete.* ASTM Special Technical

Publication 818, America Society for Testing and Materials, Philadelphia, 83 pp.

Steinbach, O.F. and King, C.V. (1950). *Experiments in Physical Chemistry*, American Book Company, New York, 250 pp.

Yonezawa, T., Ashworth, V., and Procter, R. P. M. (1988). "Study of the Pore Solution Composition and Chloride Effects on the Corrosion of Steel in Concrete," *Corrosion*. Vol. 44, No. 7 July. pp. 489-499.

Table 1. Quantities of deicing chemicals in grams per liter of simulated pore solution*

Molal Ion Concentration	0.4	0.8	1.6	3.2	6.4	12.8
NaCl	11.4	22.8	45.6	91.2	182.3	364.6
$CaCl_2$	14.4	28.8	57.7	115.4	230.7	461.5
CMA**	20.8	41.7	83.4	166.7	333.4	666.9

*Simulated pore solution: 0.14 g of NaCl, 18.81 g of KOH, and 17.84 g of NaOH per liter of solution. Solvent = deionized water.

**3 moles of calcium acetate per 7 moles of magnesium acetate

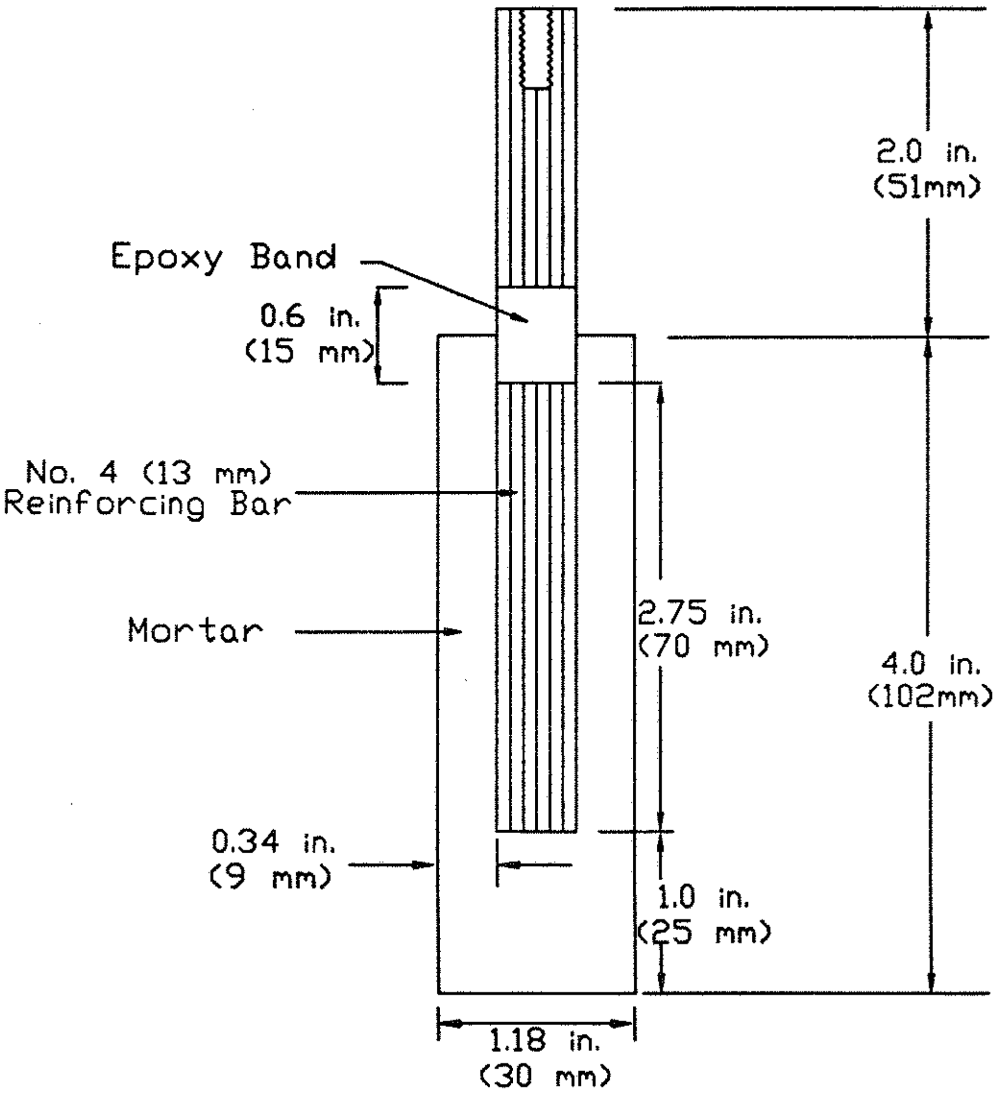

Fig. 1 Cross section of test specimen

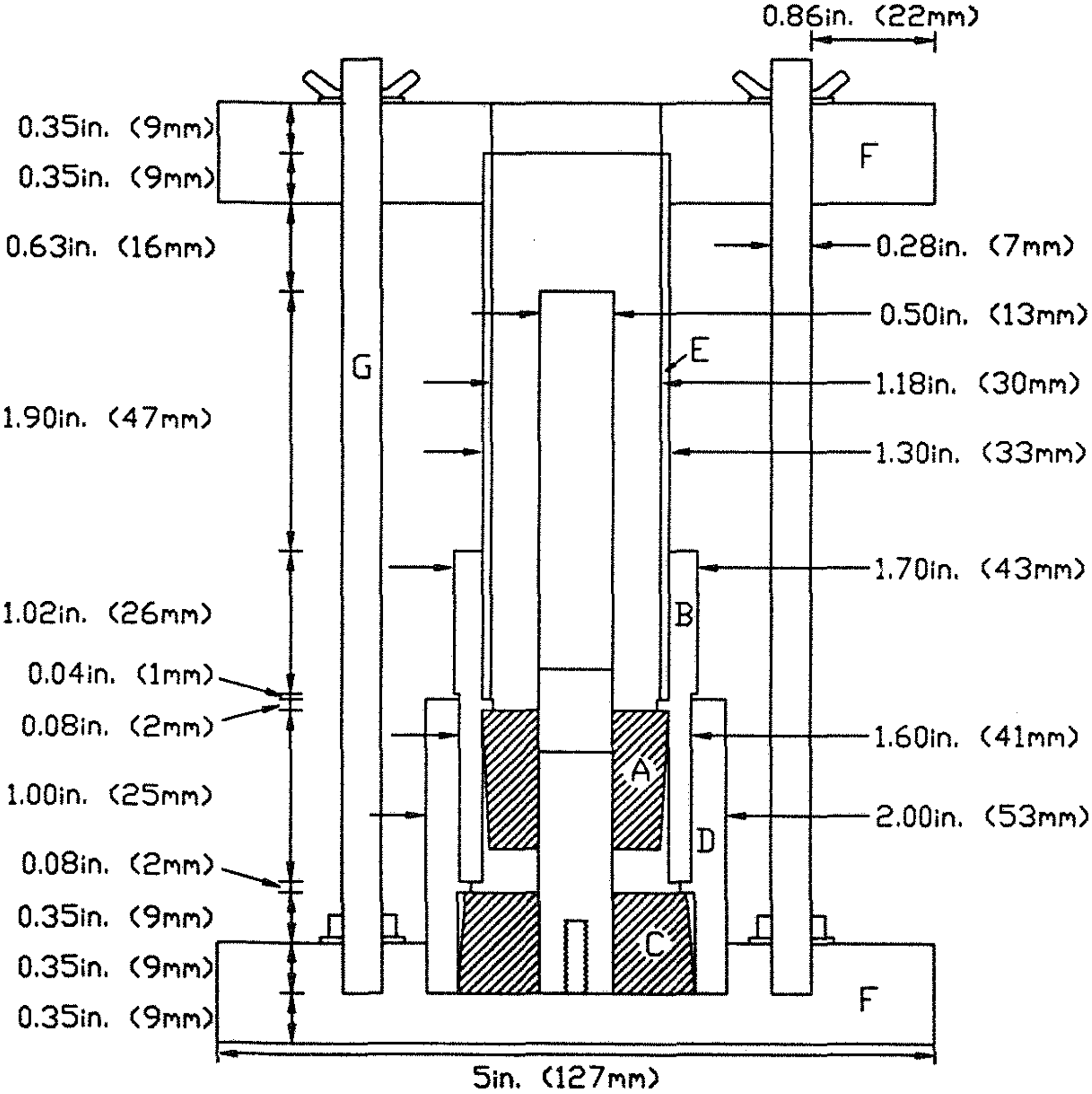

Fig. 2 Cross section of mold for test specimen

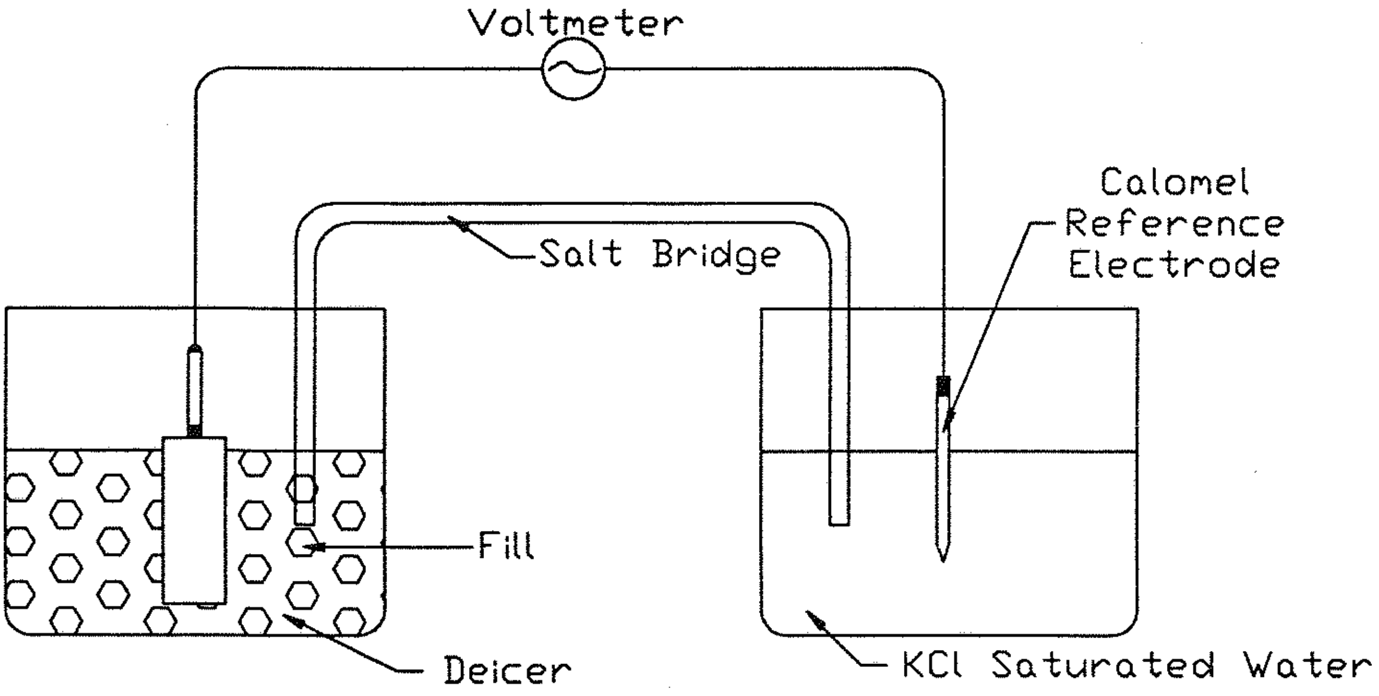

Fig. 3 Schematic of corrosion potential test configuration

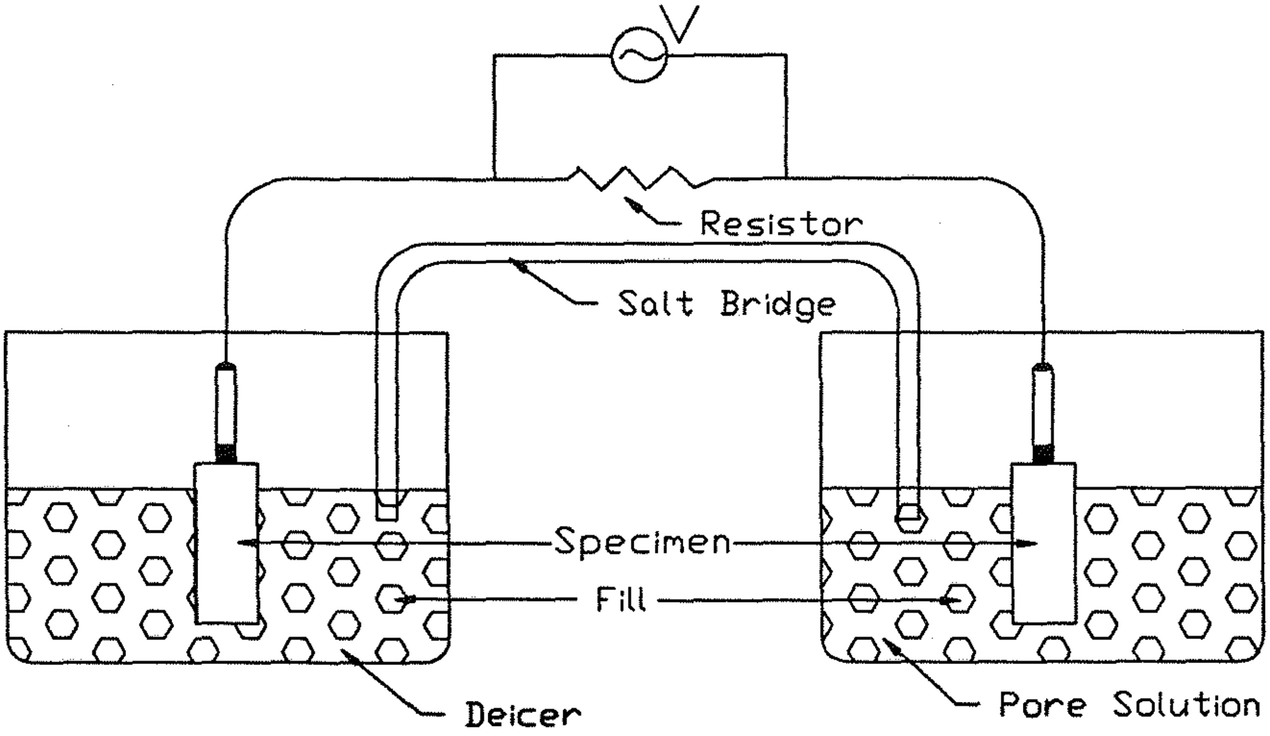

Fig. 4 Schematic of macrocell test configuration

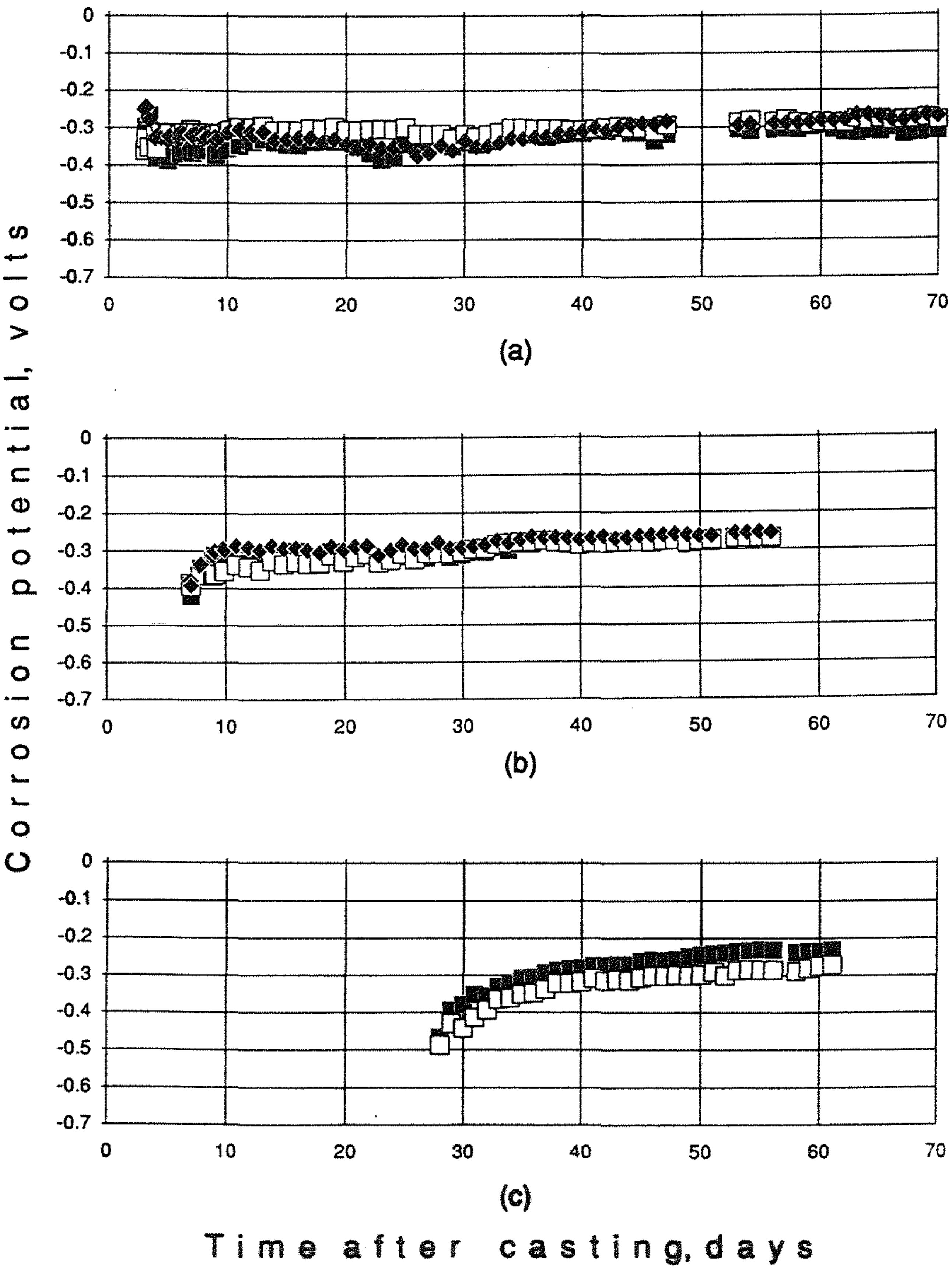

Fig. 5 Corrosion potential versus time for specimens cured for (a) 3 days, (b) 7 days, and (c) 28 days in a standard moist room and placed in simulated pore solution

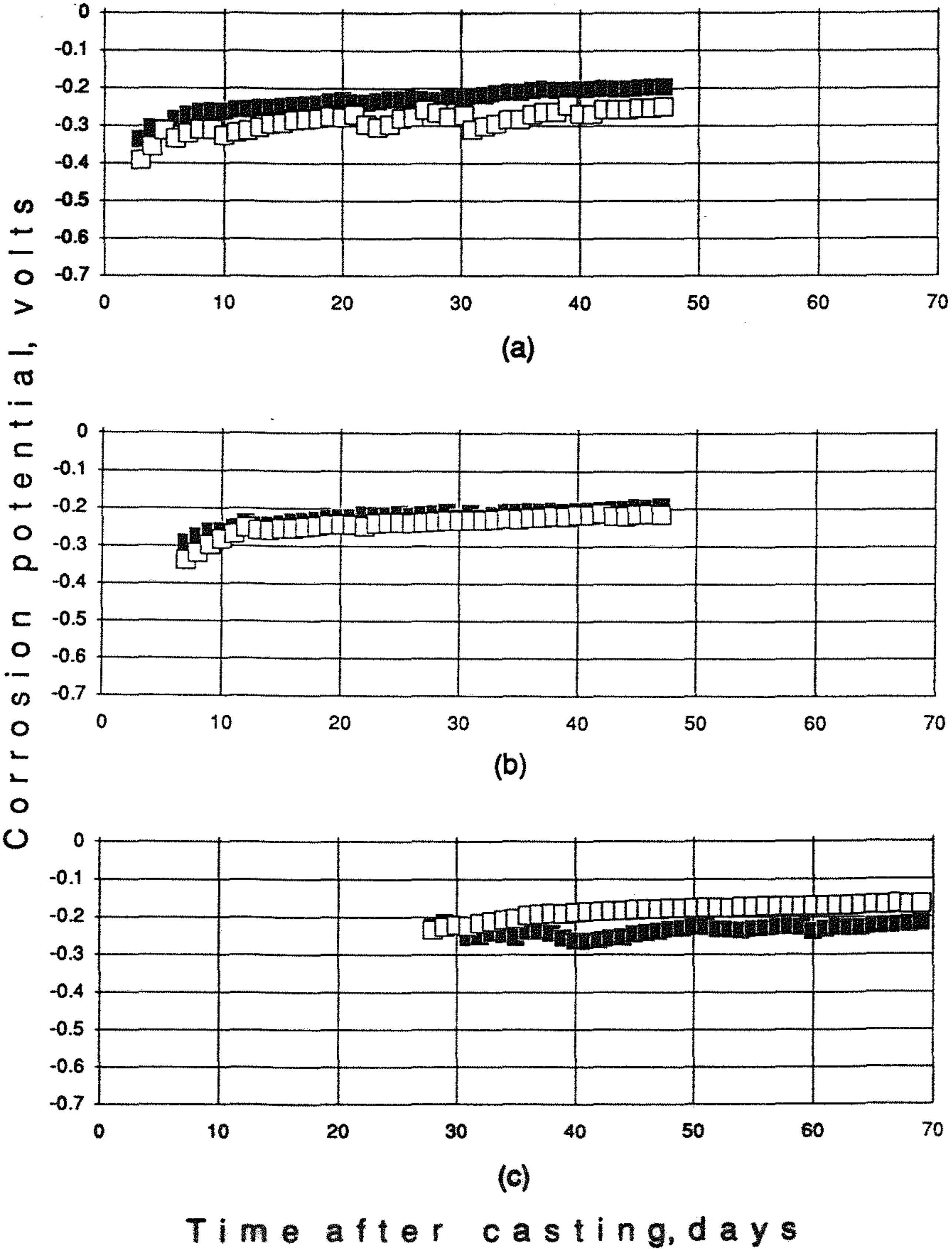

Fig. 6 Corrosion potential versus time for specimens cured for (a) 3 days, (b) 7 days, and (c) 28 days in lime-saturated water and placed in simulated pore solution

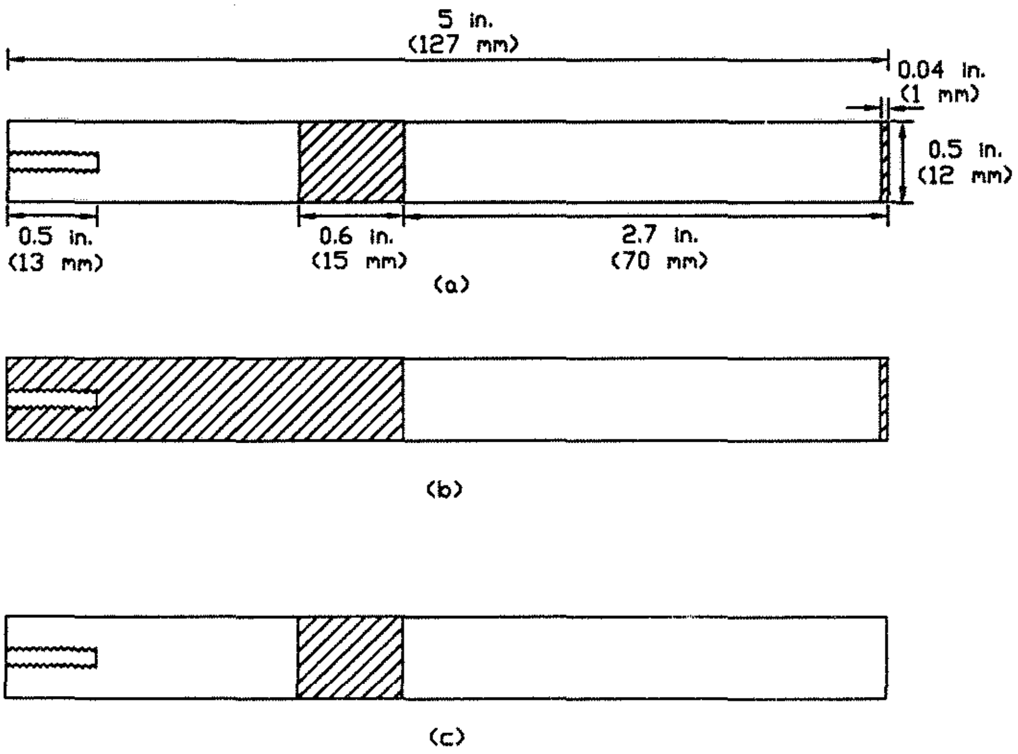

Fig. 7 Epoxy configurations. (a) Configuration A, (b) Configuration B, (c) Configuration C

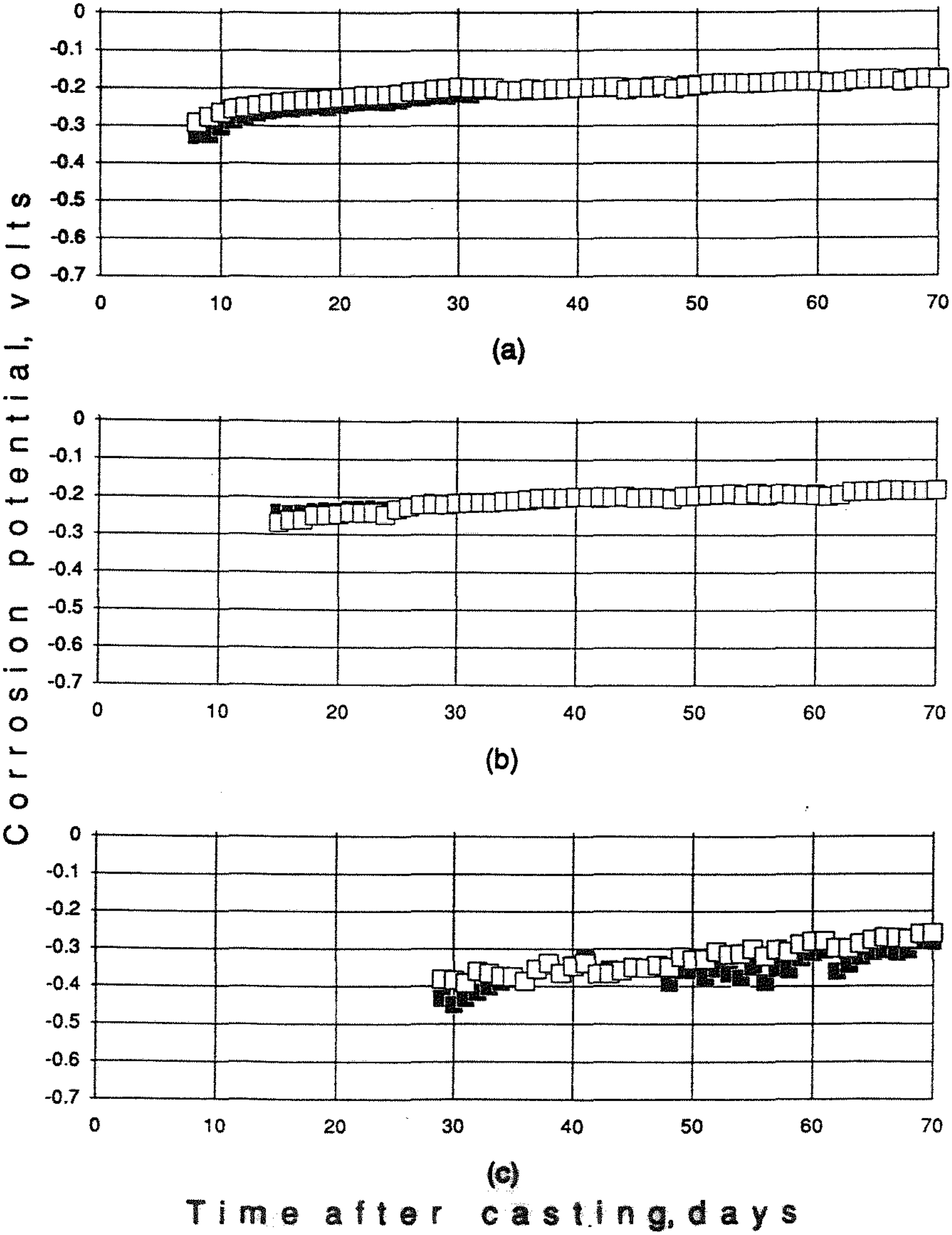

Fig. 8 Corrosion potential versus time for specimens made with tap water. Cured for (a) 7 days, (b) 14 days, and (c) 28 days

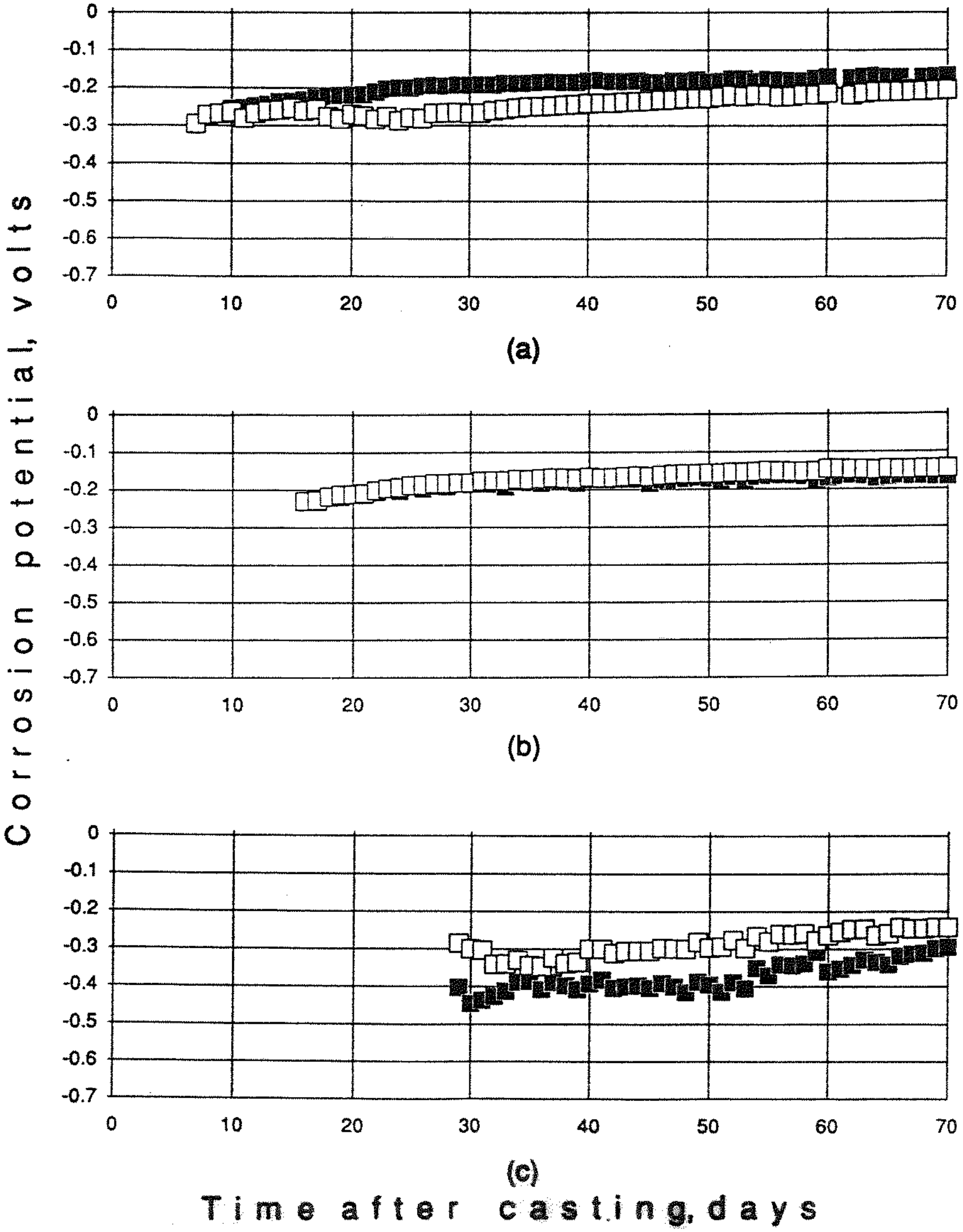

Fig. 9 Corrosion potential versus time for specimens tested with river sand in the mortar fill. Cured for (a) 7 days, (b) 14 days, and (c) 28 days

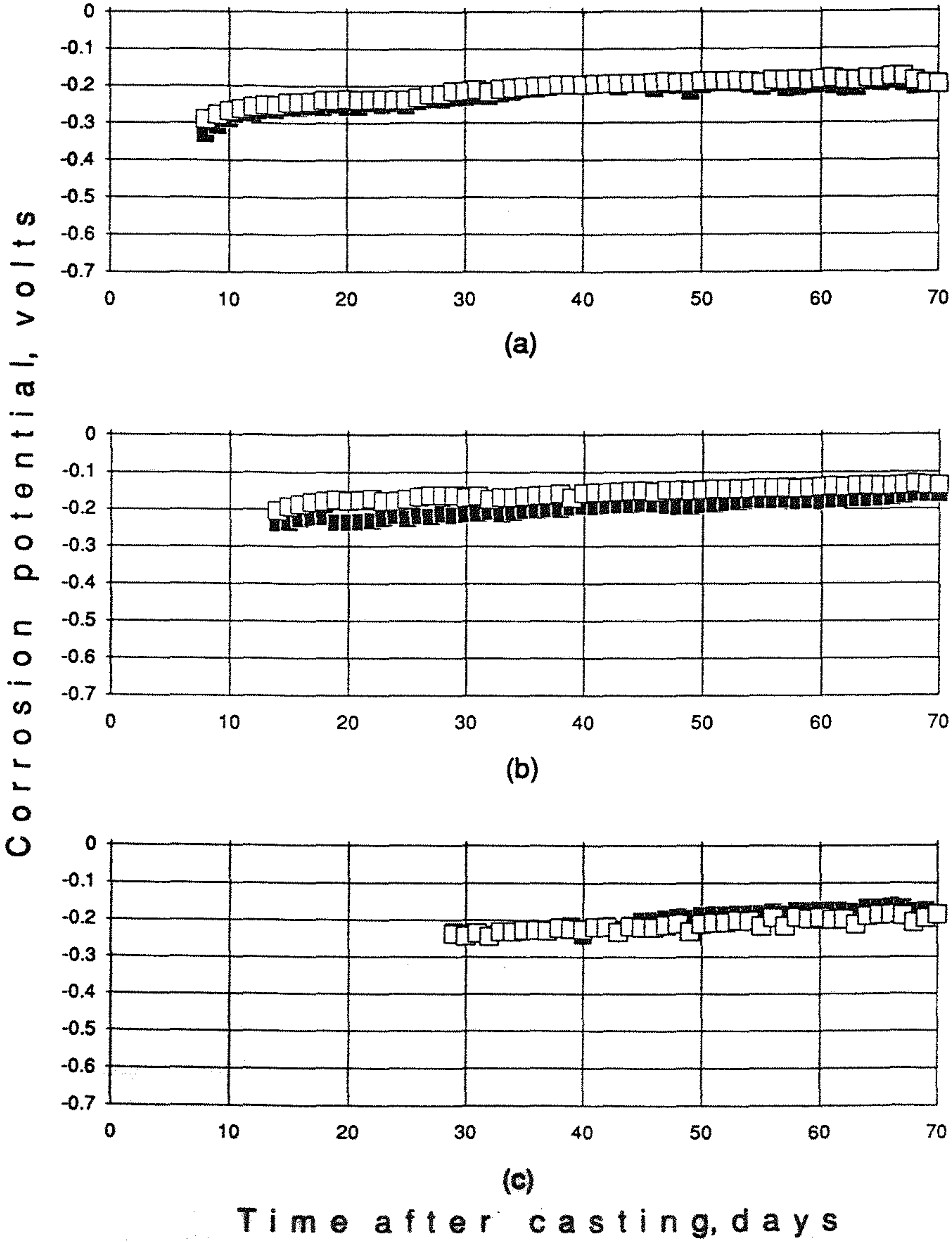

Fig. 10 Corrosion potential versus time for standard specimens. No. 4 bars, ASTM C 778 graded Ottawa sand and deionized water. Cured for (a) 7 days, (b) 14 days, and (c) 28 days

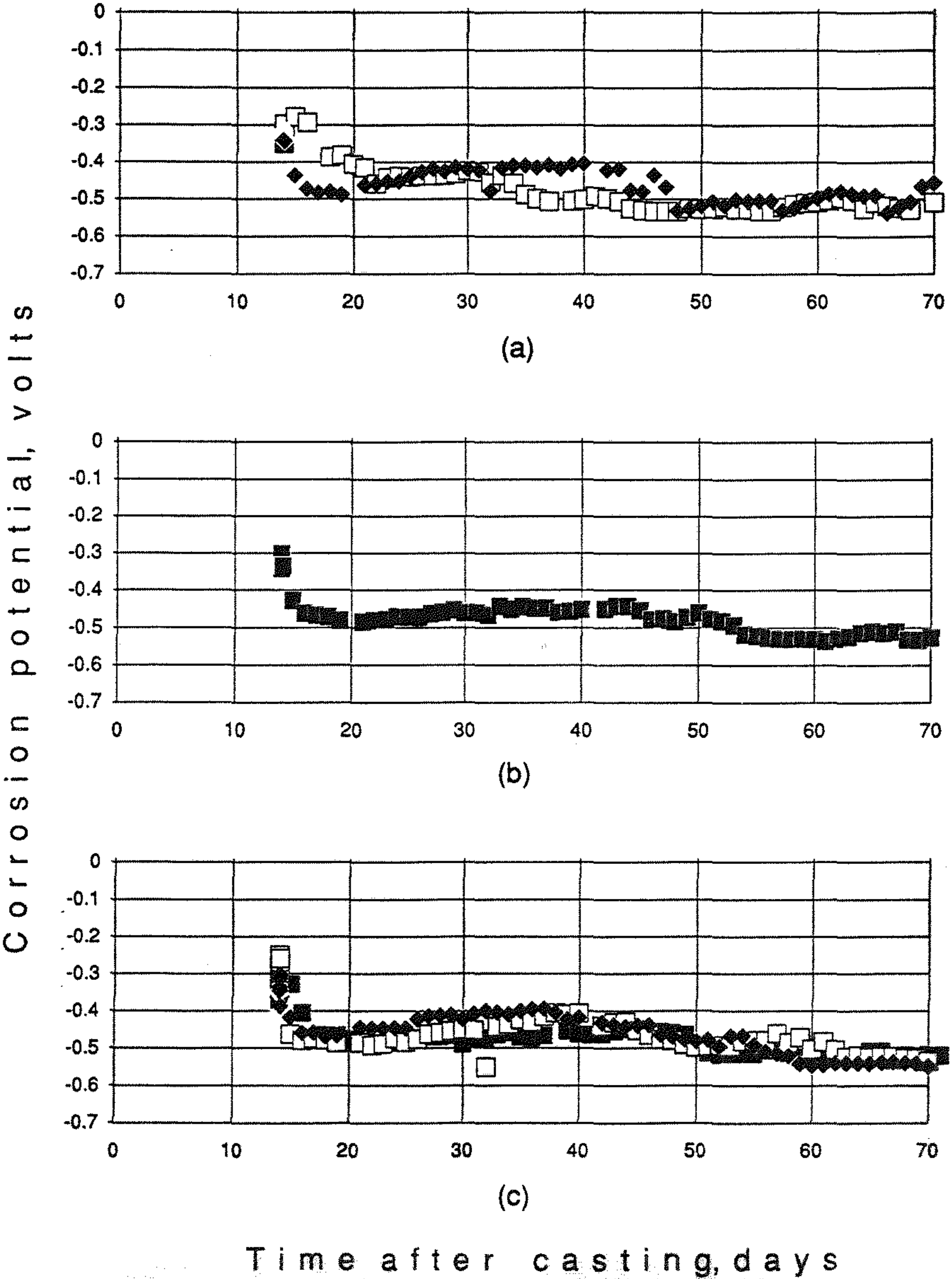

Fig. 11 Dip tests: Corrosion potential versus time for specimens cured for 14 days and exposed to 6.4 m ion concentration of NaCl in simulated pore solution. Freeboard (a) 2 in. (51 mm), (b) $1^1/_2$ in. (38 mm), (c) 1 in. (25 mm), (d) $^1/_2$ in. (13 mm), and (e) 0.08 in. (2 mm)

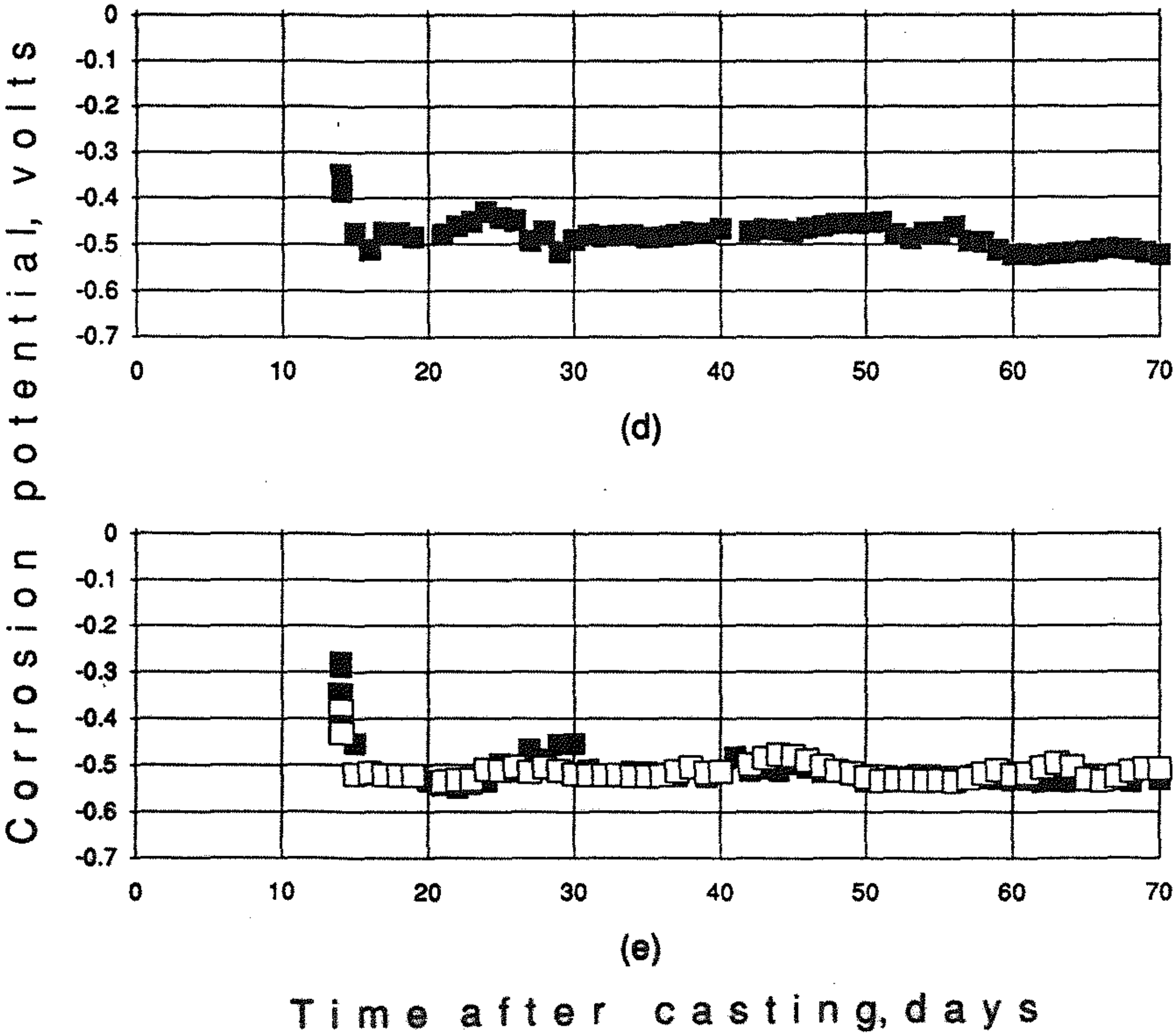

Fig. 11 (Continued) Dip tests: Corrosion potential versus time for specimens cured for 14 days and exposed to 6.4 m ion concentration of NaCl in simulated pore solution. Freeboard (a) 2 in. (51 mm), (b) $1^1/_2$ in. (38 mm), (c) 1 in. (25 mm), (d) $^1/_2$ in. (13 mm), and (e) 0.08 in. (2 mm)

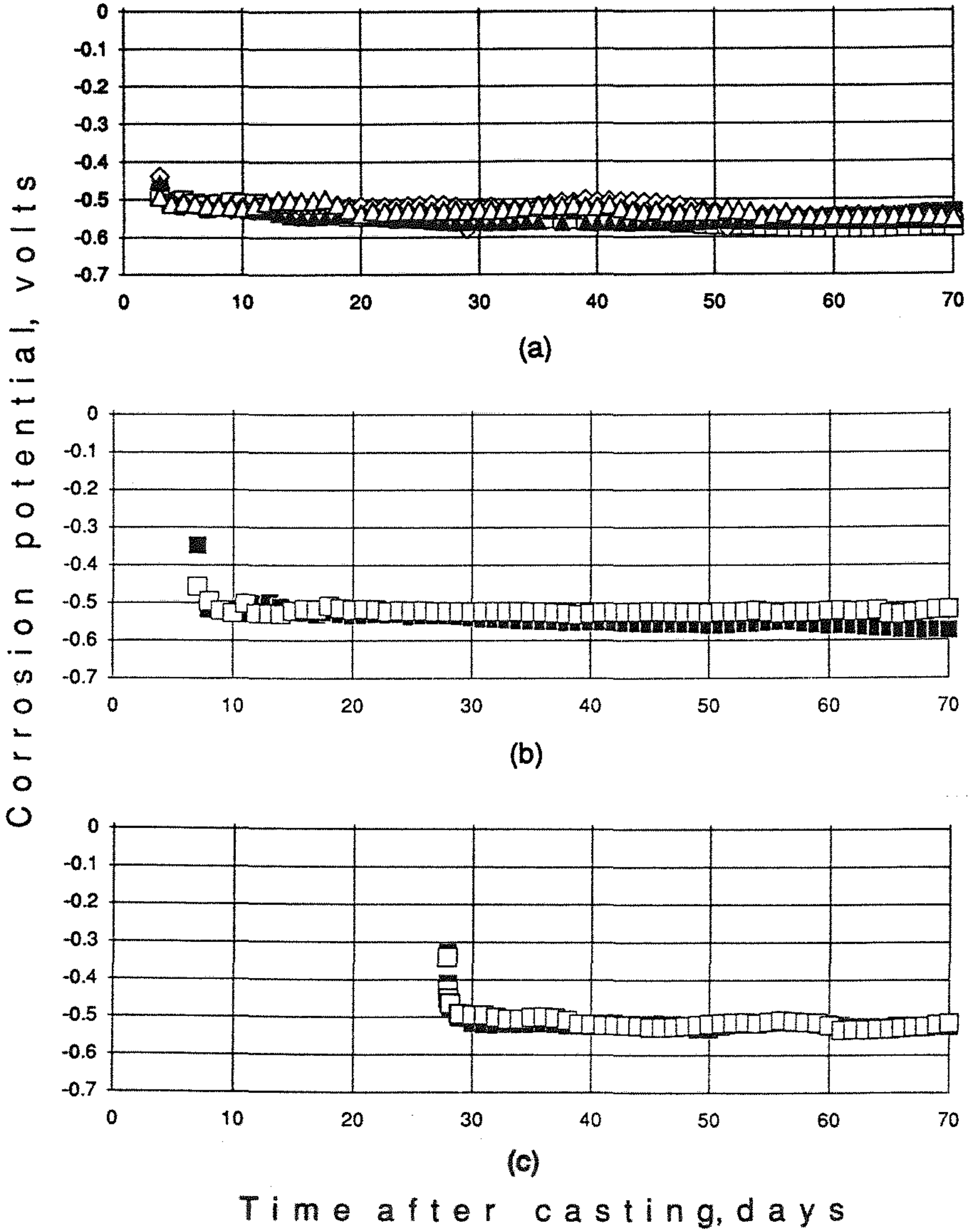

Fig. 12 Corrosion potential versus time for specimens cured for (a) 3 days, (b) 7 days, and (c) 28 days and exposed to 12.8 m ion concentration of NaCl in simulated pore solution

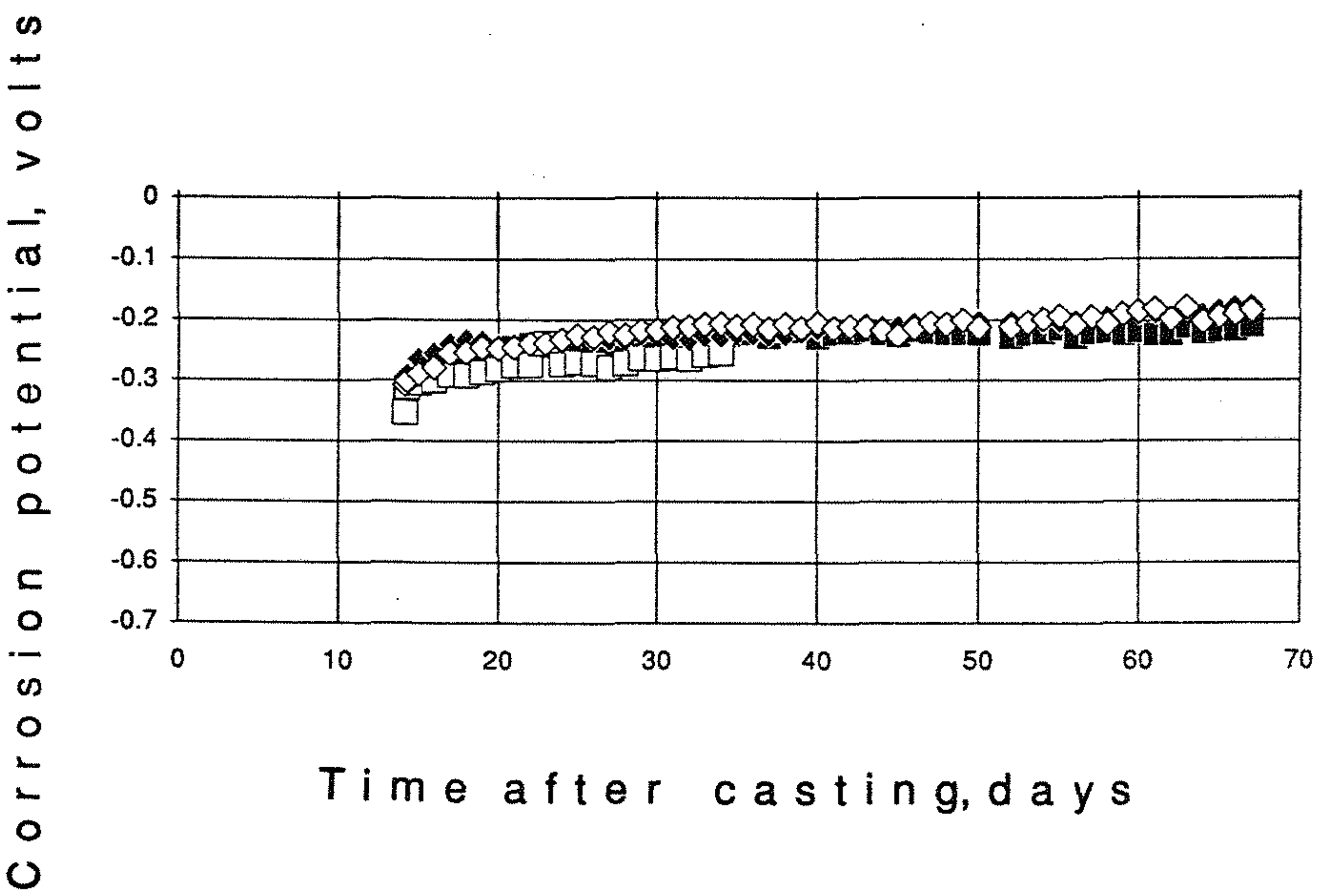

Fig. 13 Corrosion potential versus time for specimens cured for 14 days and exposed to simulated pore solution.

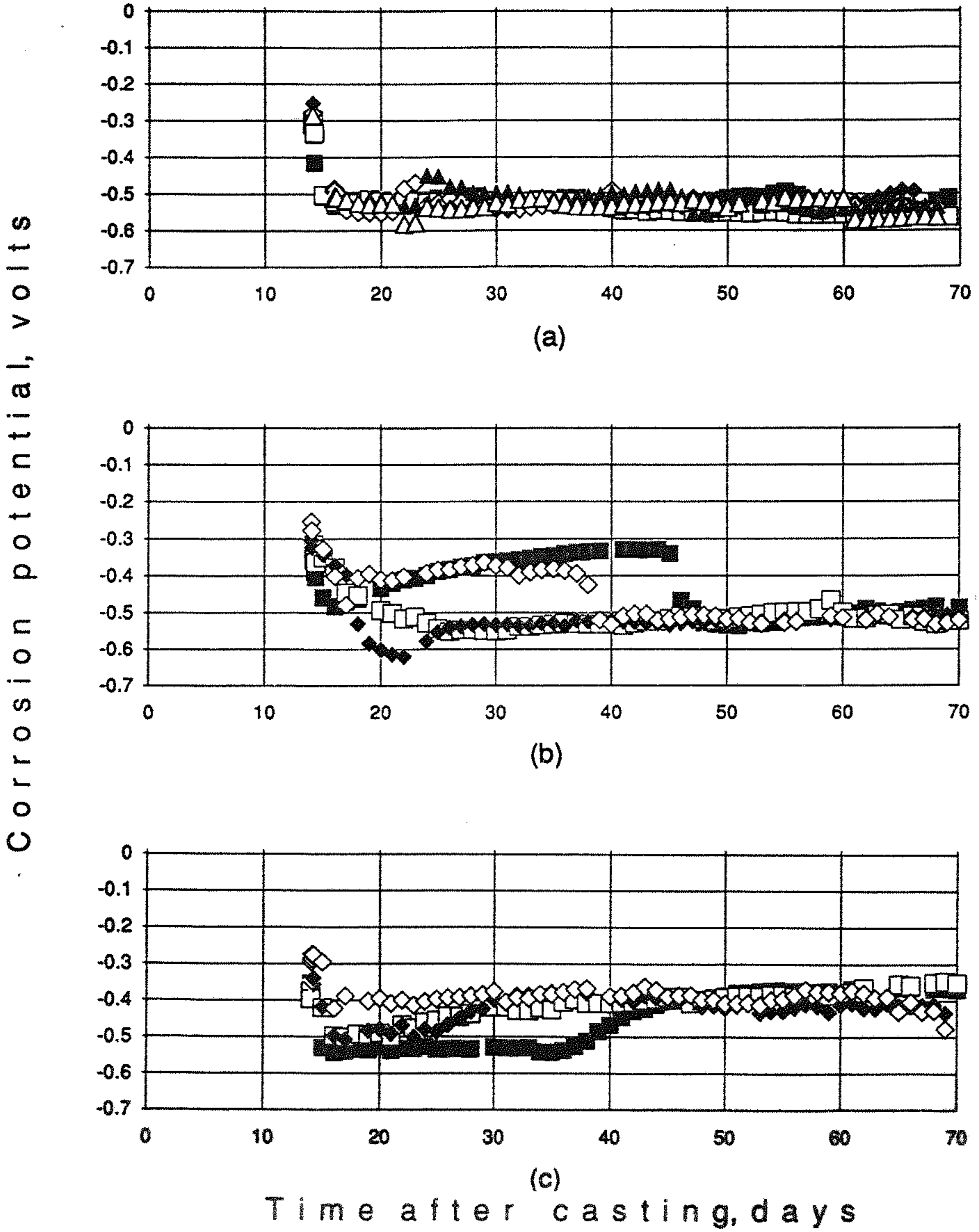

Fig. 14 Corrosion potential versus time for specimens cured for 14 days and exposed to different concentrations of NaCl in simulated pore solution. (a) 6.4 m, (b) 3.2 m, (c) 1.6 m, (d) 0.8 m, and (e) 0.4 m

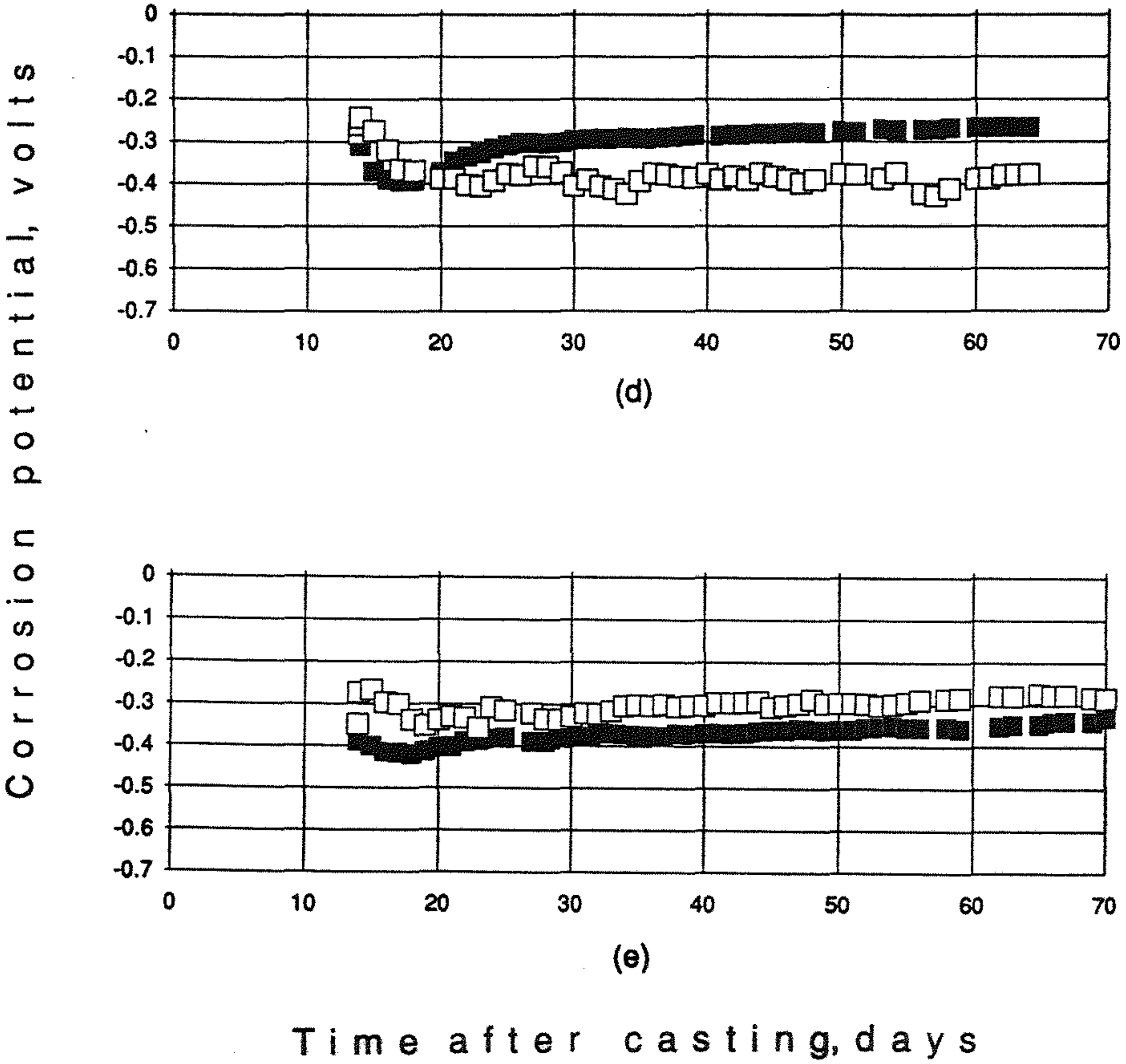

Fig. 14 (Continued) Corrosion potential versus time for specimens cured for 14 days and exposed to different concentrations of NaCl in simulated pore solution. (a) 6.4 m, (b) 3.2 m, (c) 1.6 m, (d) 0.8 m, and (e) 0.4 m

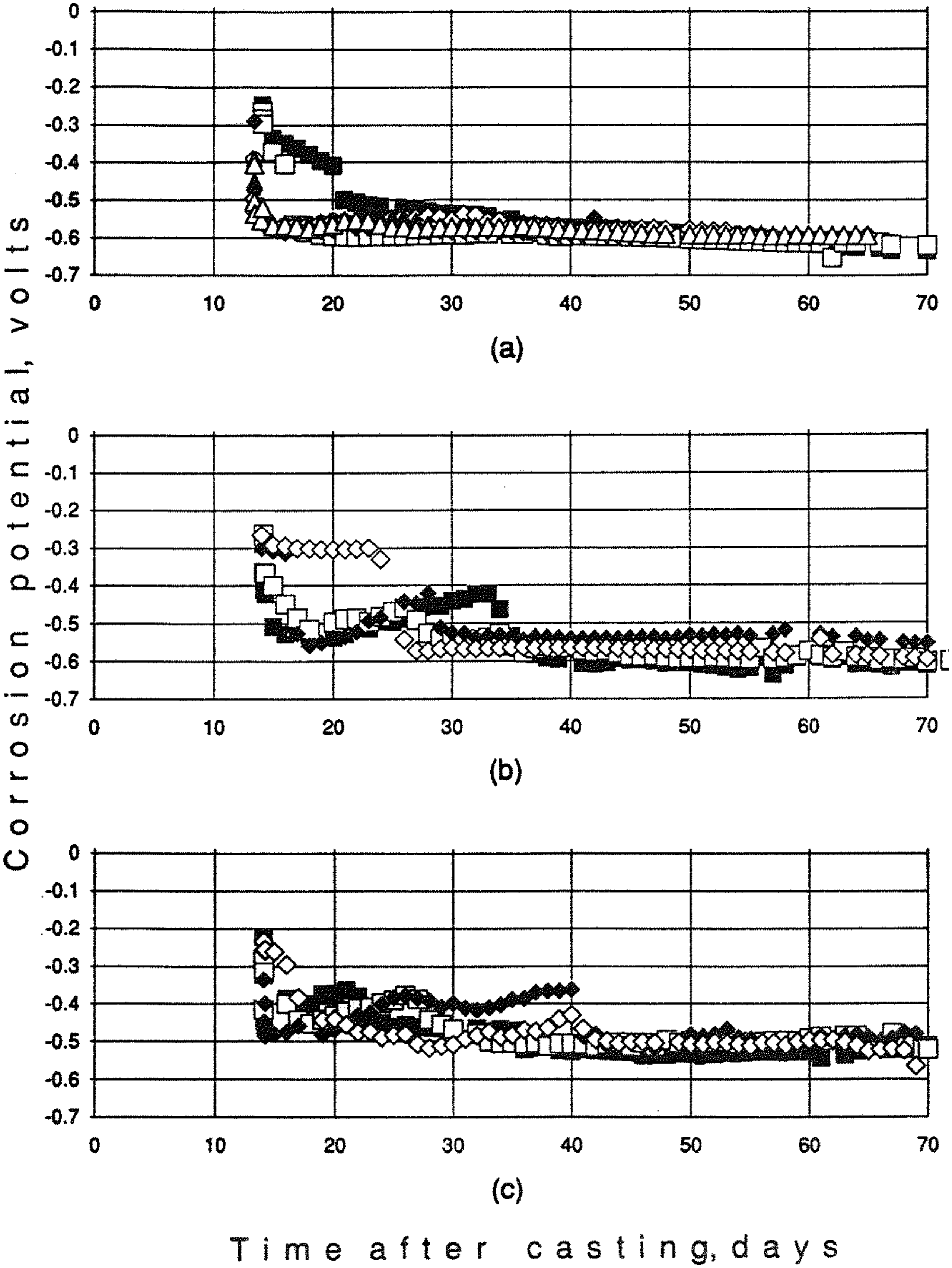

Fig. 15 Corrosion potential versus time for specimens cured for 14 days and exposed to different concentrations of $CaCl_2$ in simulated pore solution. (a) 6.4 m, (b) 3.2 m, (c) 1.6 m, (d) 0.8 m, and (e) 0.4 m

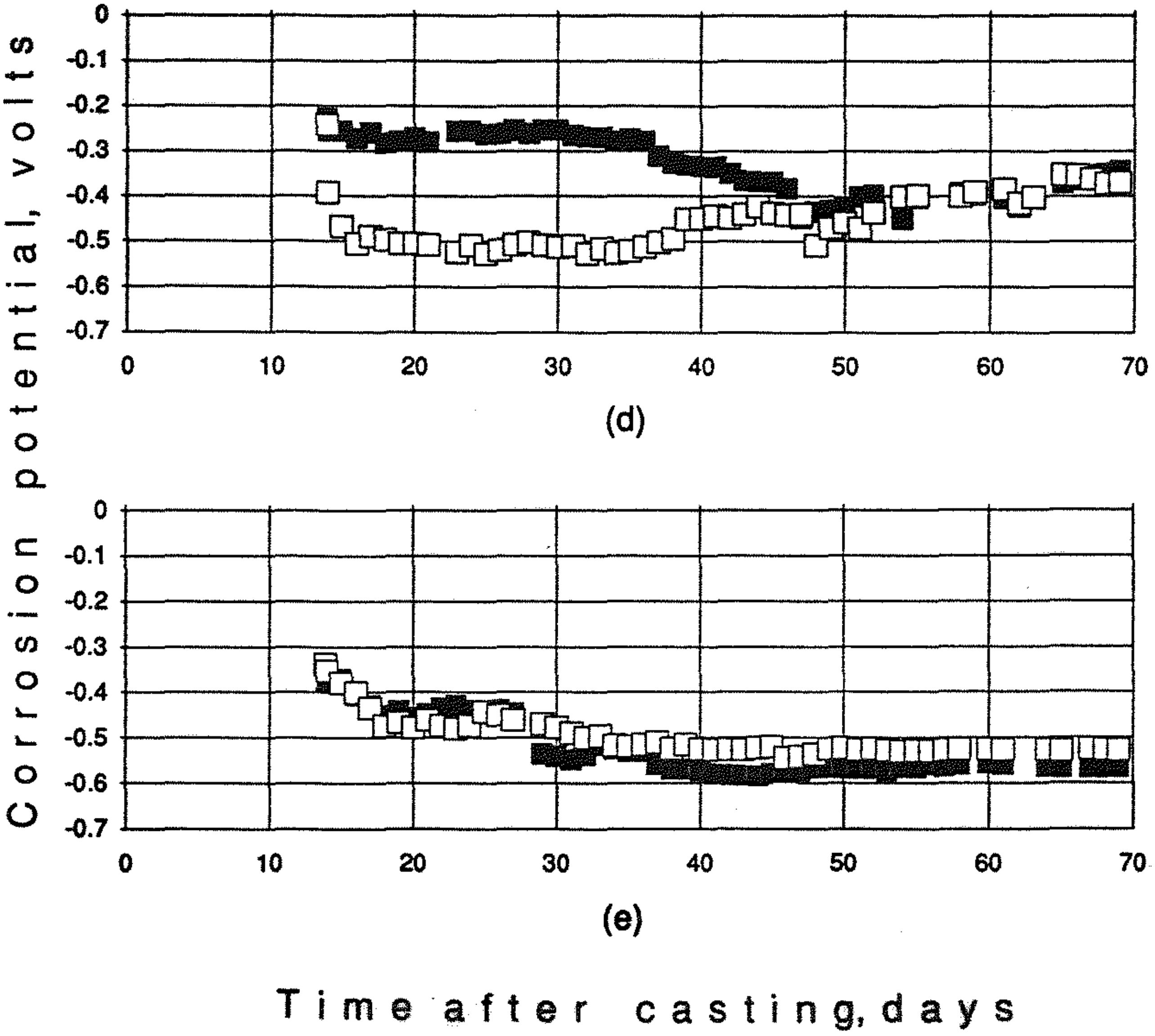

Fig. 15 (Continued) Corrosion potential versus time for specimens cured for 14 days and exposed to different concentrations of $CaCl_2$ in simulated pore solution. (a) 6.4 m, (b) 3.2 m, (c) 1.6 m, (d) 0.8 m, and (e) 0.4 m

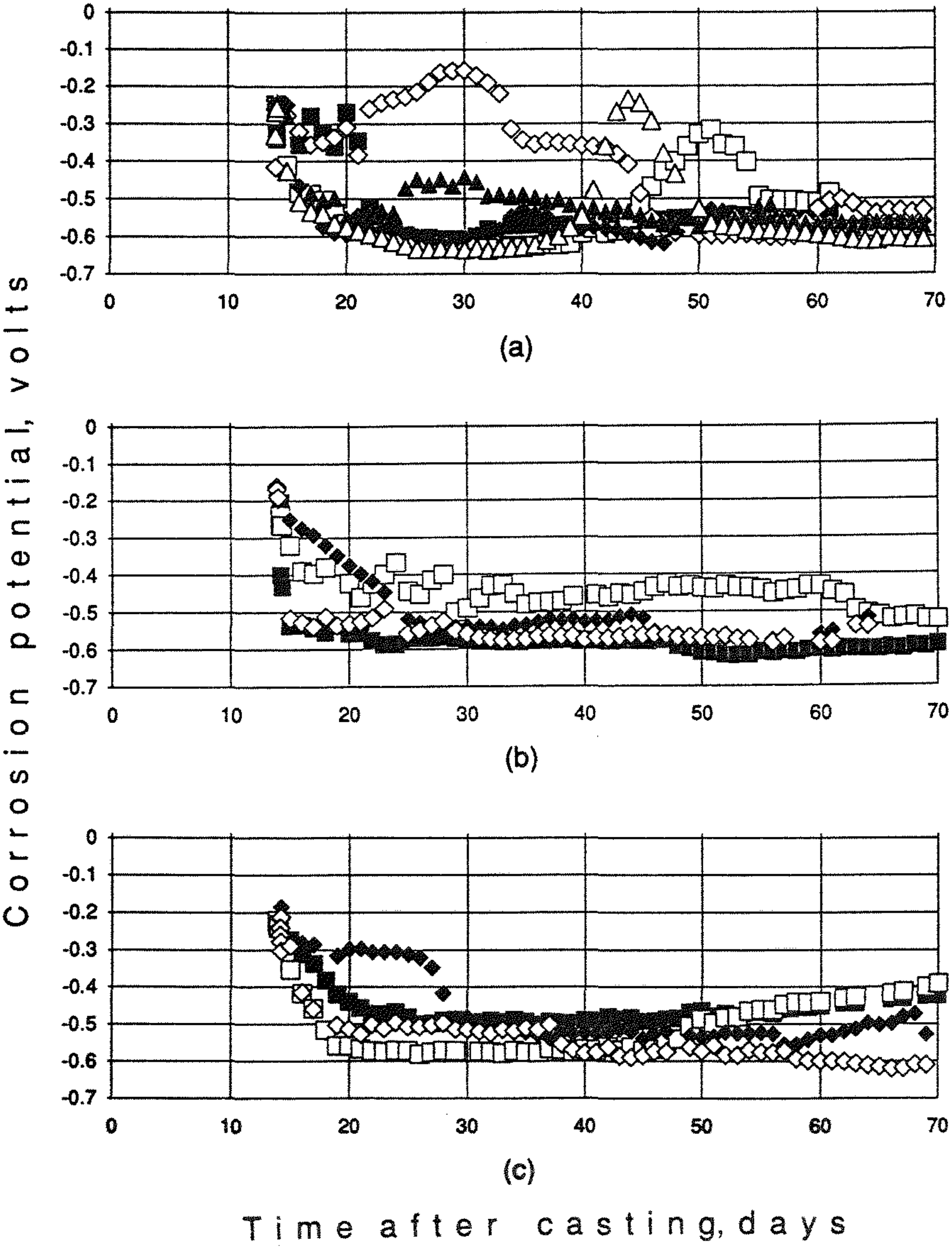

Fig. 16 Corrosion potential versus time for specimens cured for 14 days and exposed to different concentrations of CMA in simulated pore solution. (a) 6.4 m, (b) 3.2 m, (c) 1.6 m, (d) 0.8 m, and (e) 0.4 m

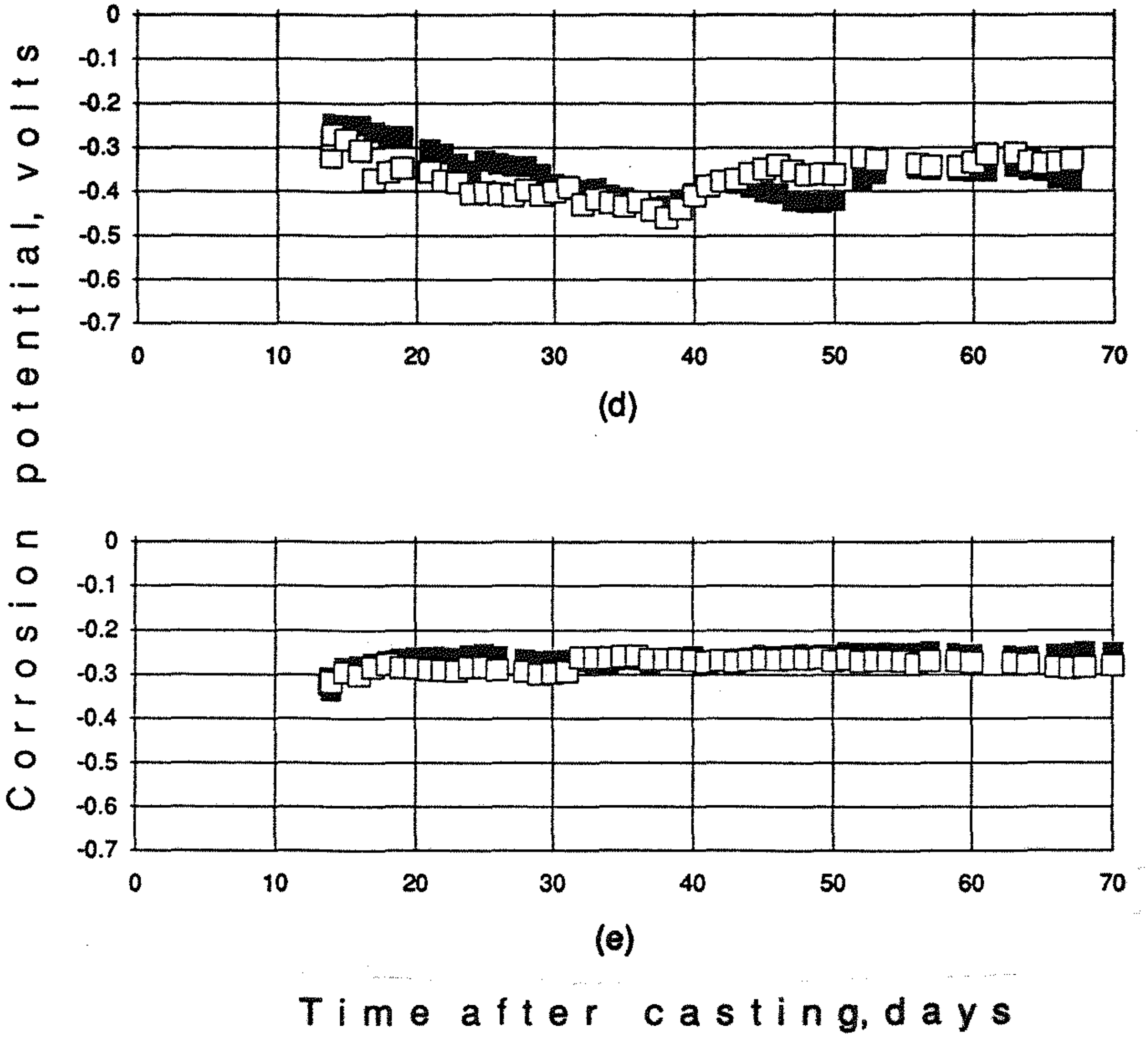

Fig. 16 (Continued) Corrosion potential versus time for specimens cured for 14 days and exposed to different concentrations of CMA in simulated pore solution. (a) 6.4 m, (b) 3.2 m, (c) 1.6 m, (d) 0.8 m, and (e) 0.4 m

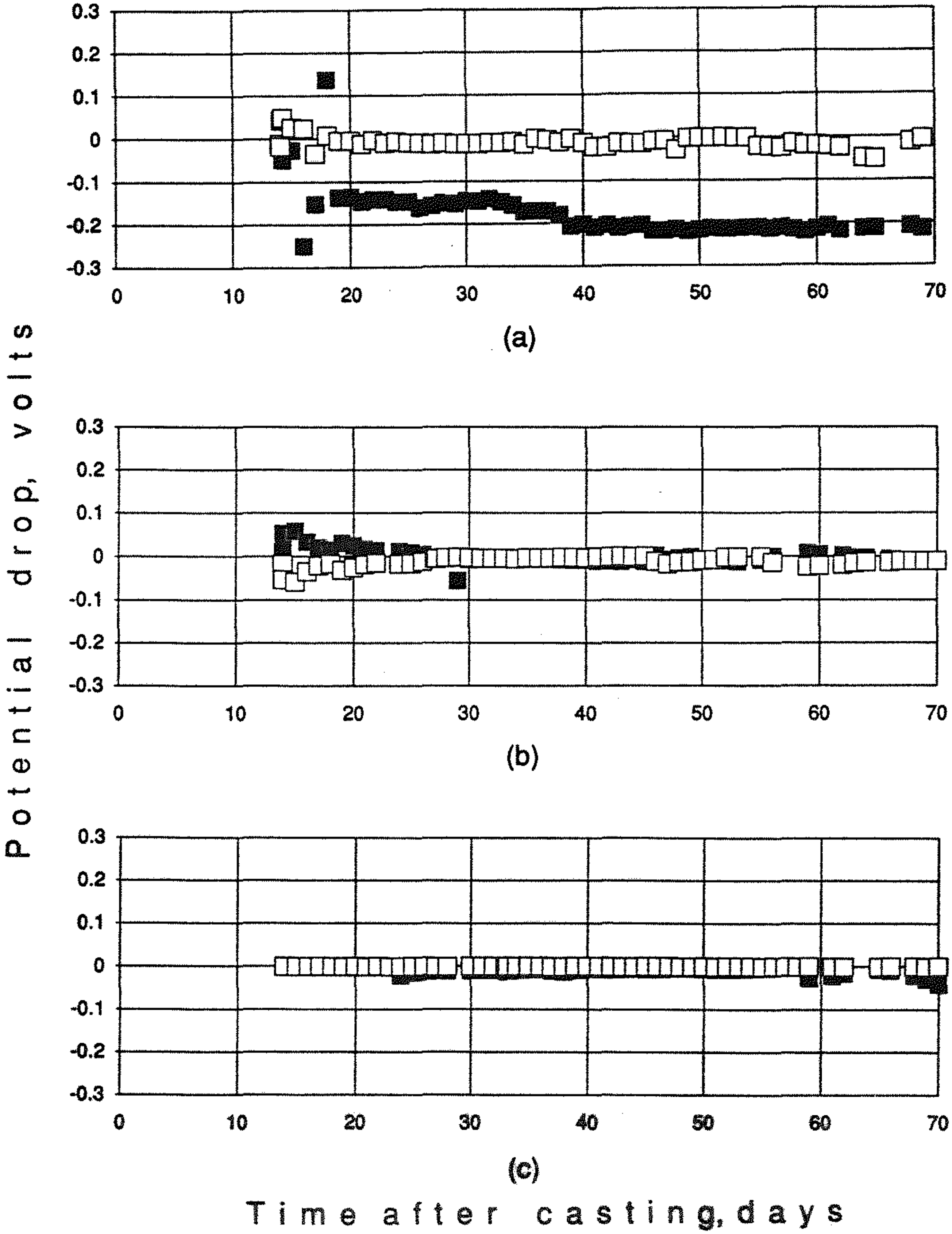

Fig. 17 Potential drop across 100,000 ohm resistor versus time for macrocells. NaCl molal ion concentrations: (a) 6.4 m, (b) 3.2 m, (c) 1.6 m, (d) 0.8 m, and (e) 0.4 m

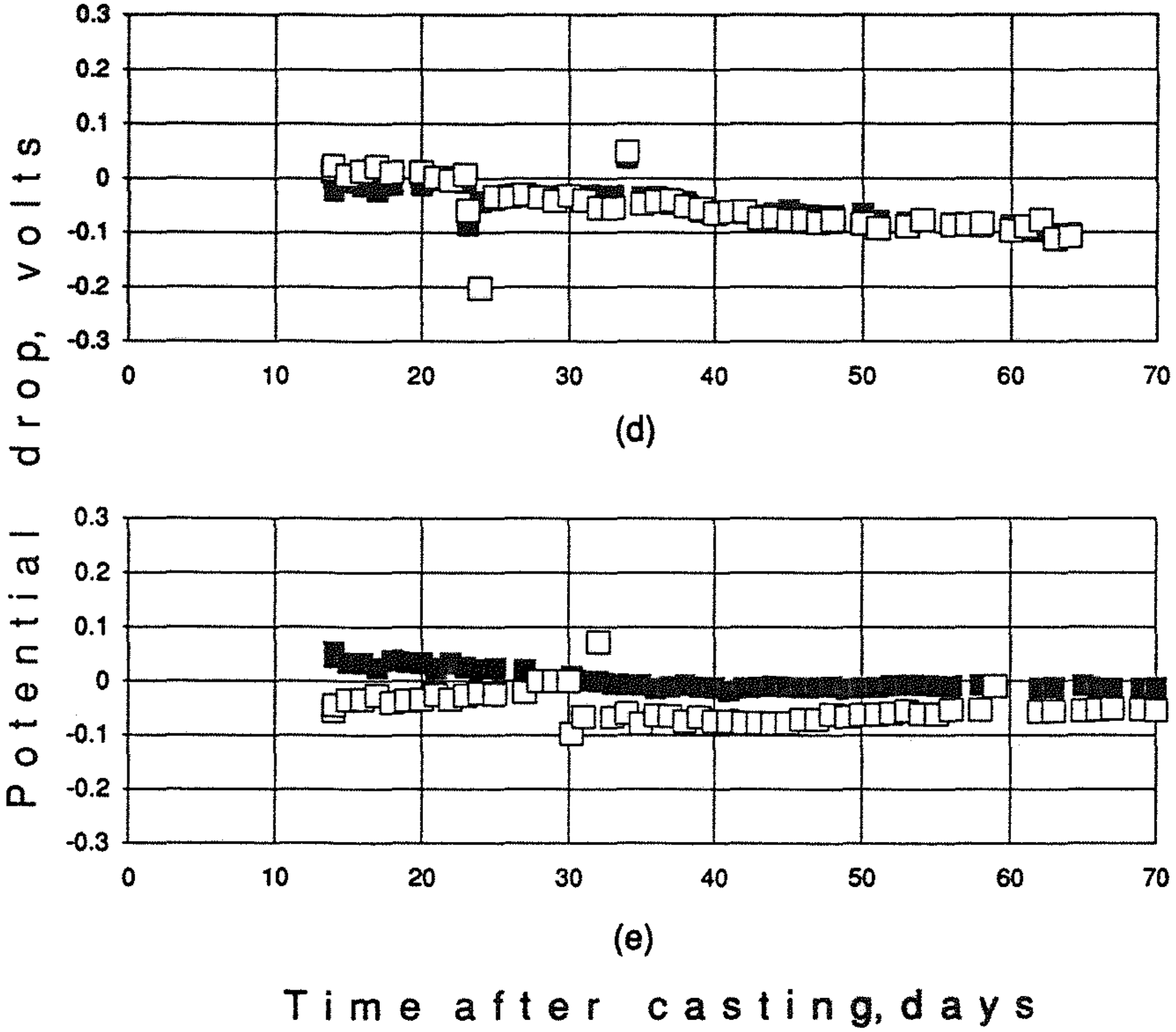

Fig. 17 (Continued) Potential drop across 100,000 ohm resistor versus time for macrocells. NaCl molal ion concentrations: (a) 6.4 m, (b) 3.2 m, (c) 1.6 m, (d) 0.8 m, and (e) 0.4 m

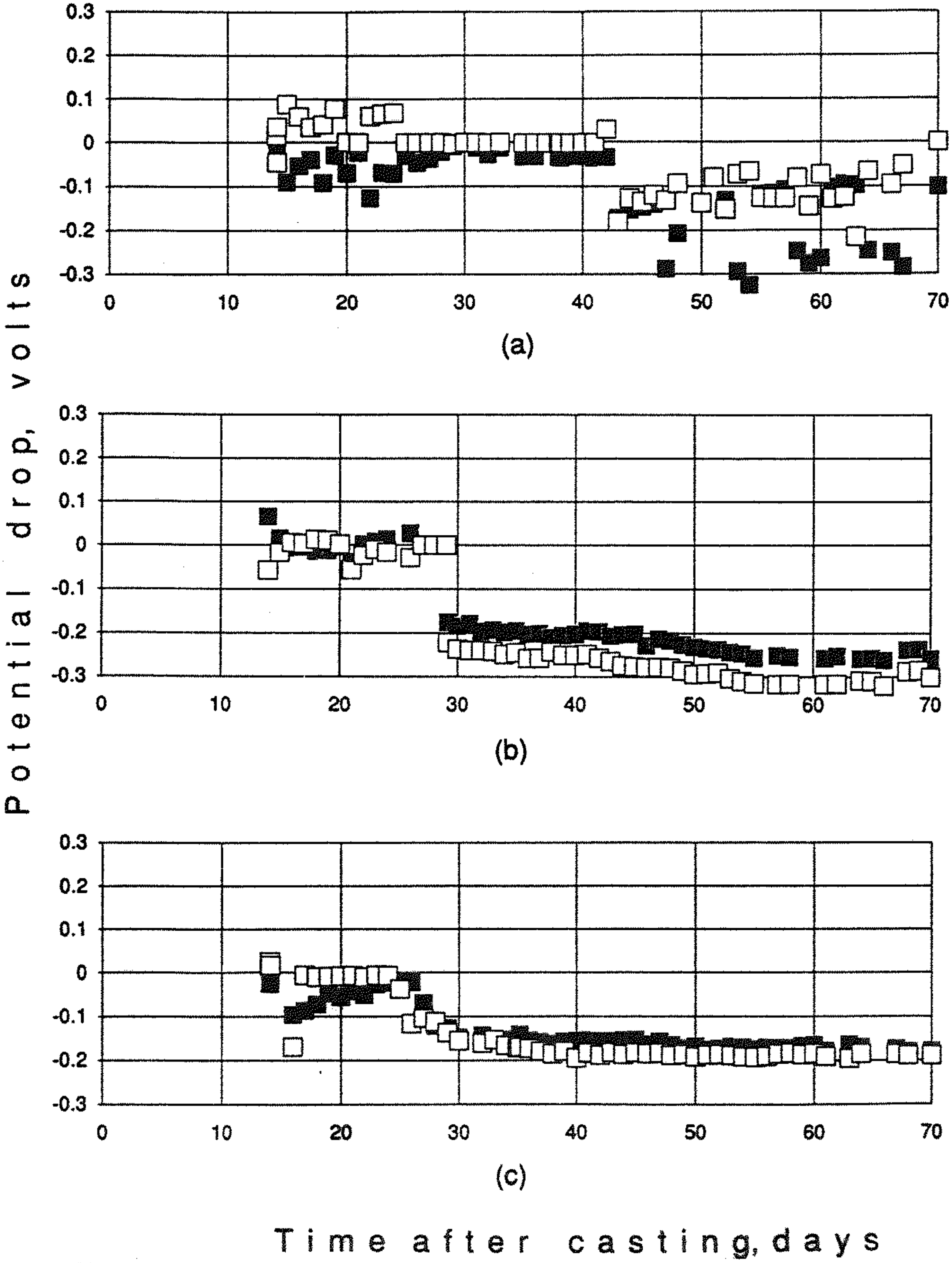

Fig. 18 Potential drop across 100,000 ohm resistor versus time for macrocells. $CaCl_2$ molal ion concentrations: (a) 6.4 m, (b) 3.2 m, (c) 1.6 m, (d) 0.8 m, and (e) 0.4 m

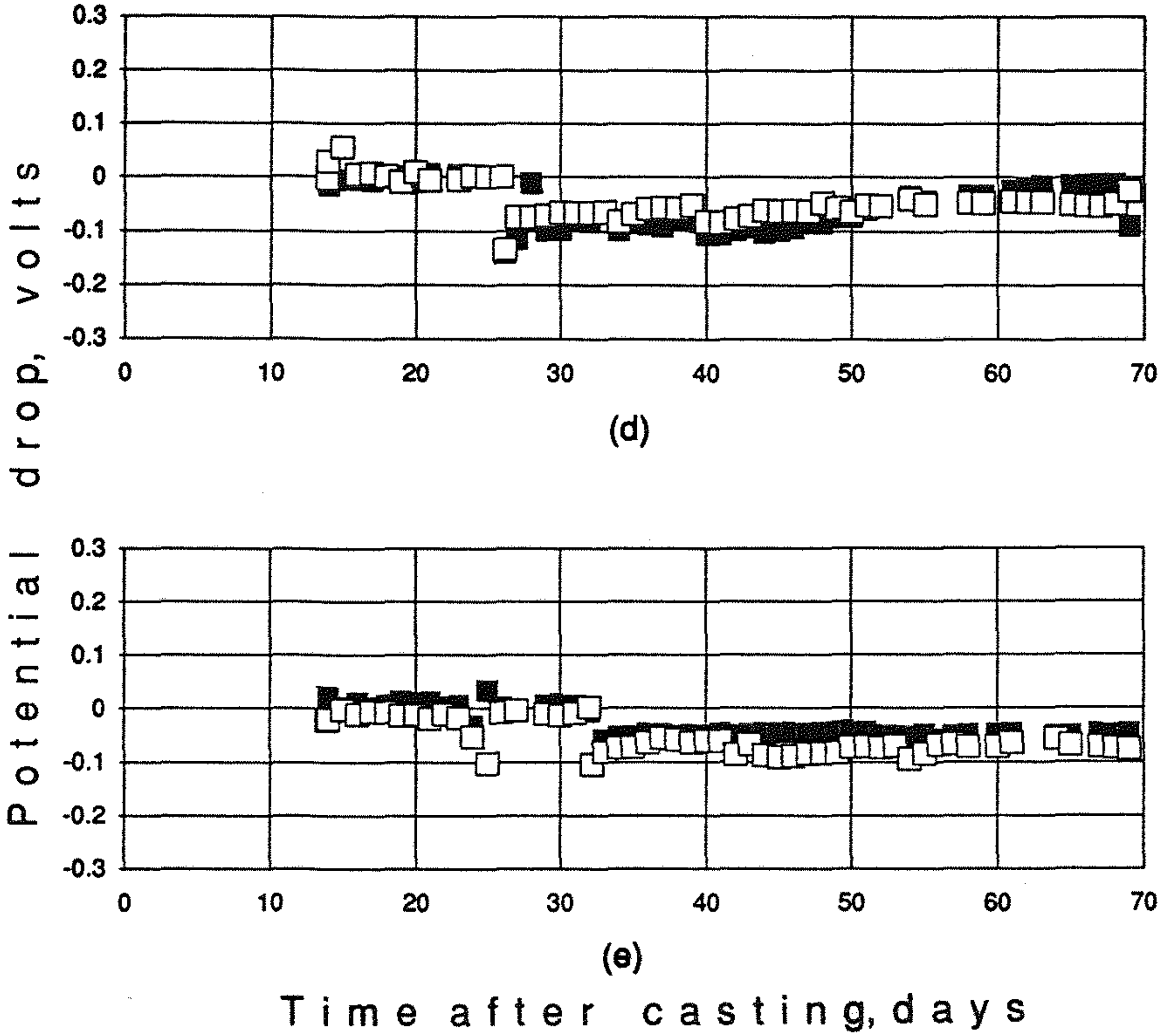

Fig. 18 (Continued) Potential drop across 100,000 ohm resistor versus time for macrocells. $CaCl_2$ molal ion concentrations: (a) 6.4 m, (b) 3.2 m, (c) 1.6 m, (d) 0.8 m, and (e) 0.4 m

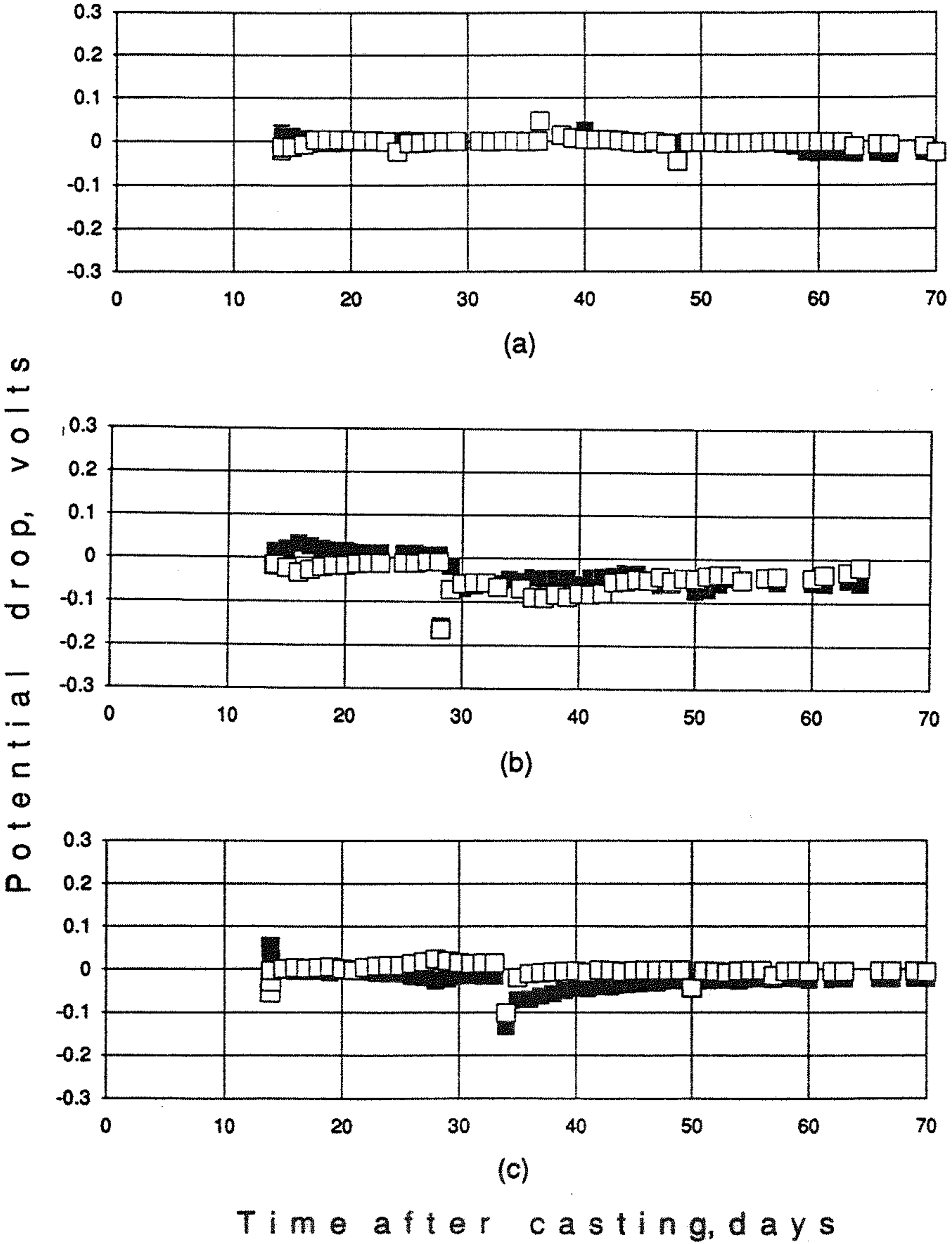

Fig. 19 Potential drop across 100,000 ohm resistor versus time for macrocells. CMA molal ion concentrations: (a) 6.4 m, (b) 3.2 m, (c) 1.6 m, (d) 0.8 m, and (e) 0.4 m

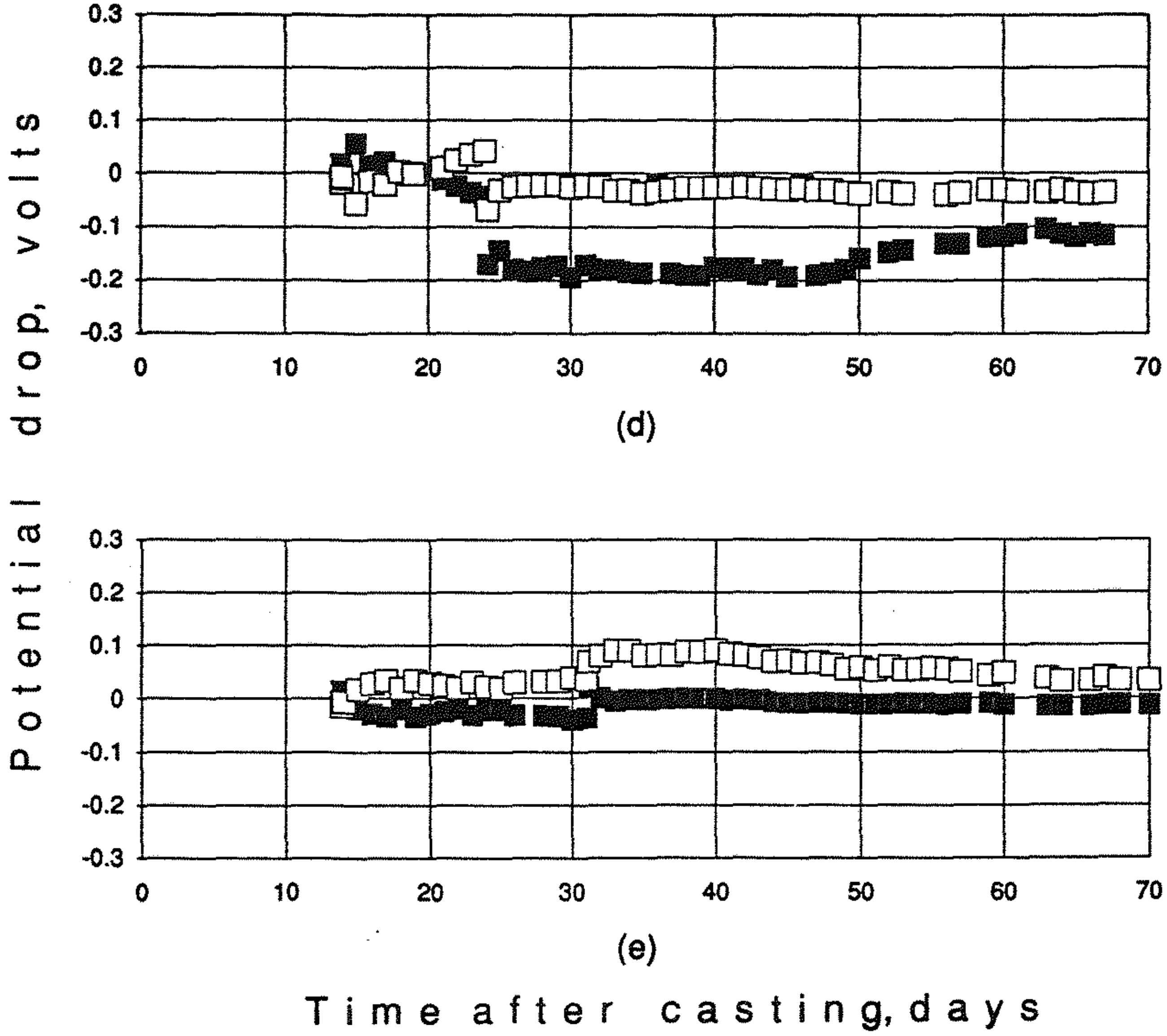

Fig. 19 (Continued) Potential drop across 100,000 ohm resistor versus time for macrocells. CMA molal ion concentrations: (a) 6.4 m, (b) 3.2 m, (c) 1.6 m, (d) 0.8 m, and (e) 0.4 m

APPENDIX A - Proposed Standard Test Method for Comparison of Effects of Deicing Chemicals on Corrosion of Reinforcing Steel

1. Scope

1.1 These test methods cover procedures for evaluating the effects of deicing chemicals on the corrosion of reinforcing steel in concrete.

1.2 The corrosion potential test and the macrocell test are described in this standard.

1.3 Annexes covering details particular to the mold, the salt bridge and the deicing chemicals are appended to this standard.

1.4 This standard may involve hazardous materials, operations and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Significance

2.1 The test methods provide rapid and simple procedures to evaluate the corrosion effects of deicing chemicals on reinforcing steel.

3. Reference Standard Documents

A 615	Standard Specifications for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement
C 150	Standard Specification for Portland Cement
C 305	Standard Method for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency
C 511	Standard Specifications for Moist Cabinets, Moist Rooms and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes
C 778	Standard Specification for Standard Sand
D 2241	Standard Specification for Polyvinyl Chloride (PVC) Plastic Pipe (SDR-PR)

D 2466	Standard Specification for Polyvinyl Chloride (PVC) Plastic Pipe, Fitting Schedule 40
G 1	Standard Practice for Preparing, Cleaning and Evaluating Corrosion Test Specimens
G 3	Standard Practice for Conventions Applicable to Electrochemical Measurements in Corrosion Testing

4. Definitions

Several definitions common to both testing methods are given:

4.1 Passive. State of low chemical reactivity under certain environmental conditions.

4.2 Pore Solution. Liquid constituent found in the pores of hardened concrete.

4.3 Potential. A unit of measurement of the electrical activity of an element, usually given in volts or millivolts, relative to the electrical activity of a reference element.

5. Test Specimen

5.1 General. The specimen described in this specification is common for corrosion testing Methods A and B, Corrosion Potential and Macrocell testing, respectively. The specimen consists of a reinforcing bar embedded in a mortar cylinder. In the test, the specimen is surrounded by crushed mortar fill to simulate the conditions found in reinforced concrete. The potential of the specimen is measured with respect to a reference electrode by connecting an electrical cable to the reinforcing bar using a steel screw inserted in a tapped hole in the exposed end of the bar.

5.2 The specimen consists of a 5 in. (127 mm) long, ASTM A 615 No. 4 (13 mm) reinforcing bar, drilled and tapped at one end to accept a screw. The solid end of the bar is symmetrically embedded 3 in. (76 mm) in a 1.18 in. diameter (30 mm), 4 in. (102 mm) long mortar cylinder (Fig. 1). The mortar mix is made with Type I portland cement, ASTM C 778 graded sand, and deionized water. The mortar has a water-cement ratio of 0.5 and a sand-cement ratio of 2.0 by weight. The mortar is mixed in accordance with ASTM C 305. The exposed mortar-steel interface is covered by a 0.60 in. (15 mm) epoxy band. The specimen is cured for 2 days in the mold and 12 days in a lime-saturated water.

5.3 Specimen Fabrication

5.3.1 Bar preparation. The 5 in. (127 mm) long, ASTM A 615 No. 4 (13 mm) reinforcing bar is drilled and tapped to accept a 10 x 24 x $1/2$ in. steel machine screw. The bar is cleaned with acetone as per ASTM G 1. A 0.60 in (15 mm) wide epoxy band is applied around the bar $2^3/4$ in. (70 mm) from the solid end of the bar (Fig. 1).

5.3.2 Mold Preparation. The mold, shown in Fig. 2, is assembled with the reinforcing bar according to the procedure in Annex 1.

5.3.3 Quantities of materials. Six specimens and the mortar fill for one container requires: 1320 g of portland cement, 2640 g of sand, and 660 g of deionized water.

5.3.4 Mixing. The mortar is mixed in accordance with ASTM C 305.

5.3.5 Molding specimens. The specimens are molded in three layers. Each layer is vibrated for 15 seconds on a vibration table with an amplitude of 0.006 in. (0.15 mm) and a frequency of 60 cycles/sec. Alternate procedures providing thorough consolidation and the removal of entrapped air are acceptable.

5.3.6 Curing Procedure. After vibration, the specimens are cured in the molds in a standard curing room (ASTM C 511) for two days. After two days, the specimens are demolded and cured in lime-saturated water until the time of test.

6. Testing Elements and Apparatus

6.1 Fill. To avoid the dissolution of the constituents of the mortar layer and to provide a buffer, the specimen is tested using a fill material. The fill material is crushed mortar, with the same proportions and age as the mortar used to fabricate the specimen. The fill is cast in a 1 in. (25 mm) deep layer on a metal form and vibrated 15 seconds on the vibration table (see 5.3.5). When the specimen reaches the age to be tested, the mortar fill is crushed to sizes between $3/4$ and $1^1/2$ in. (19 mm and 38 mm). 7.75 lb (3500 g) of crushed mortar is used in each container.

Note – A standard 10 x 15 in. (250 x 380 mm) cookie sheet serves quite well as a form for the fill material.

6.2 Containers. The container used in the test is a 5.0 liter, 8.5 in. (216 mm) high container with a lid. It is made of a plastic which does not react with any of the chemical substances to be tested.

6.3 Salt Bridge. To have a complete electrical circuit, an ionic path must be formed using a salt bridge made according Annex 2.

6.4 Simulated Pore Solution. The specimen is submerged in a simulated pore solution. The pore solution contains 0.14 g of NaCl, 18.81 g of KOH, and 7.87 g of NaOH per liter of solution and is made with deionized water. This composition represents the pore solution found in typical concretes.

6.5 Deicing chemicals. The deicing chemical, whose effects on the corrosion of reinforcing steel in concrete are going to be tested, is mixed with pore solution in the desired molal ion concentration according to Annex 3. Molal ion concentrations of 0.4, 1.6, and 6.4 are recommended. Supplementary tests may be made with molal ion concentrations of 0.8 and 3.2.

6.6 Calomel reference electrode. A standard calomel reference electrode submerged in KCl saturated water. (Required for the Corrosion Potential Test only.)

6.7 Voltmeter. The voltmeter shall have a scale that can be read to 0.001 volts without interpolation. The electrochemical measurements using the voltmeter shall be made in accordance with ASTM G 3.

7. Safety and Testing Precautions

7.1 When working with chemical products, such as the components of pore solutions, deicers, or liquid epoxy, the safety instructions for the products shall be followed.

7.2 Improper connections between the specimen and the cable may give erroneous results. Checking the connection before covering with epoxy is recommended. It is important that the tapped hole in the reinforcing bar be thoroughly dried before making the connection.

7.3 The presence of air bubbles in the salt bridge or at the salt bridge-solution interface may give incorrect results. The salt bridge should be checked during the test.

8. Test A: Corrosion Potential Test

8.1 General. This test measures the corrosion potential of the specimen with respect to a standard calomel reference electrode submerged in potassium chloride, KCl, saturated water (15 g of potassium chloride, KCl, dissolved in 100 cc of deionized water). The specimen is submerged in a deicing chemical solution, as shown in Fig. 3. The corrosion potential test indicates the corrosion state of the reinforcing bar in the specimen, determining if the bar is in a passive or active state.

8.2 Procedure. The specimen is removed from the lime-saturated water 14 days after casting, and the tapped end of the reinforcing bar is thoroughly dried. An electrical cable is securely connected to the reinforcing bar by a screw connection. The connection is then covered with epoxy. The cable is passed through a hole in the lid of the container. A layer of crushed mortar pieces is put on the bottom of the container. The specimen is placed, steel up, on the layer, and the rest of the fill is placed in the container. If several specimens are placed in the same container, at least 1 in. (25 mm) of fill should separate the specimens. The salt bridge is placed in the container through a second hole in the lid. The other end of the salt bridge and the calomel electrode are placed in saturated KCl solution. The solution with the deicing chemical is placed in the container up to a level $^1/_2$ in. (13 mm) below the top edge of the mortar cylinder. While placing the solution in the container, the corrosion potential may be read. The container must be sealed to prevent carbon dioxide in the air from neutralizing the pore solution and to prevent evaporation of the liquid during the course of the test, which is run until the potential reaches a constant value, usually 5 to 9 weeks after casting (3-7 weeks after initiation of the test). Readings should be taken at intervals of 24 hours or less.

8.3 Data presentation. The potential values should be plotted against the time in days, as depicted in Fig. 4. The deicing chemical being tested and its concentration should be identified on the plot.

8.4 Interpretation of results. The potential sign convention follows ASTM G 3. If the corrosion potential is more positive than – 0.300 V, the electrode is considered to be in a passive state. If the value is more negative, the electrode is in an active state. The more negative the potential, the more deleterious the deicing chemical.

9. Test B. Macrocell test

9.1 General. This test measures the corrosion potential of a specimen submerged in pore solution containing a deicing chemical with respect to another specimen submerged in pore solution alone, as shown in Fig. 5. Due to the pH and chloride ion level typical of concrete, the specimen submerged in simulated pore solution is in a passive condition. The specimen submerged in the solution containing the deicer, however, may reach an active state. The effect of the deicing chemical on corrosion of reinforcing steel is determined based on the potential difference read across a resistor that connects the two specimens.

9.2 Procedure. The specimen is removed from the lime-saturated water 14 days after casting, and the tapped end of the reinforcing bar is thoroughly dried. A shielded cable is securely connected to the reinforcing bar by a screw connection. The connection is then covered with epoxy. The specimen is placed, steel up, in the container with the fill in the same way as done for Test A, making sure that at least 1 in. (25 mm) of fill surrounds the specimen. A second specimen is placed in the same way in a second container. A salt bridge is used to connect the two containers through holes in the lids of the containers. The two specimens are connected by shielded cables across a 100 K ohm precision resistor. Once all of the elements are in place, simulated pore solution is placed in one container and the pore solution containing the deicing chemical is placed in the other container up to $^1/_2$ in.

(13 mm) below the top edge of the mortar cylinder. The containers are sealed for the reasons described in section 8.2. The potential change is measured across the resistor (Fig.5).

9.3 Data presentation. The potential should be plotted against the time in days, as depicted in Fig. 6. The deicing chemical being tested and its concentration should be identified on the plot.

9.4 Interpretation of results. The potential sign convention follows ASTM G 3. If the potential measured across the resistor is negative, the electrode is in an active state. The more negative the potential, the greater the amount of corrosion. If the potential values are positive, the electrode is in a more passive state than the reference electrode and no corrosion would be expected.

Annex 1. Mold Fabrication and Assembly

1. Mold Fabrication

The mold (Fig. 2) used to make the test specimen uses standard materials for ease of duplication. The mold consists of (letters preceding each item identifies the part in Fig. 2):

A. One laboratory grade No. 6 $1/2$ rubber stopper, with a centered 0.5 in. (12.5 mm) diameter hole.

B. One ASTM D 2466, 1 in. to 1 in. PVC fitting, 1.3 in. (33 mm) internal diameter. The fitting is turned on one end to 1.60 in. (41 mm) external diameter.

C. One laboratory grade No. 9 rubber stopper, shortened to 0.71 in. (18 mm), with a centered 0.5 in. (12.5 mm) diameter hole.

D. One ASTM D 2466, $1 1/4$ in. to $1 1/4$ in. PVC fitting, 1.65 in. (42 mm) internal diameter, shortened by 0.55 in. (14 mm) on one end.

E. One ASTM D 2241, SDR 21, 1 in. PVC pipe, 1.18 in. (30 mm) internal diameter, 4 in. (102 mm) long. The pipe is sliced longitudinally to allow for specimen removal. The cut in the pipe is taped on the outside with masking tape to avoid leakage during casting.

F. One 5 in. (127 mm) diameter, 0.7 in. (18 mm) thick, plexiglass disc with a centered 2.04 in. (52 mm) diameter hole through half of the thickness of the disc and four tapped holes to receive $1/4$ in. (6 mm) diameter threaded rods.

One 5 in. (127 mm) diameter, 0.7 in. (18 mm) thick plexiglass disc with a centered 1.3 (33 mm) diameter hole through half of the thickness of the disc and a centered 1.18 in. (30 mm) diameter hole through the other half.

G. Four $1/4$ in. (6 mm) diameter threaded rods with one nut, one wing nut and two washers each.

These elements are assembled as shown in Fig. 2.

2. Mold Assembly

The mold is assembled in the following fashion, as shown in Fig. 2.

a) The tapped end of the reinforcing bar is inserted in the hole of the small rubber stopper, A, through the widest end of the stopper. The distance between the nontapped end of the bar and the rubber stopper is 3 in. (76 mm).

b) The rubber stopper is inserted in the turned (lower) end of the small connector, B. The widest end of the small rubber stopper has to be in contact with the shoulder on the internal surface (see Fig. 2) of the small connector.

c) The large rubber stopper, C, is inserted beginning with the narrow end, in the cut end of the large connector, D, until coming in contact with the shoulder on the inside surface of the connector.

d) The turned end of the small connector, B, is inserted in the free end of the large connector, D, at the same time that the tapped end of the reinforcing bar is inserted in the hole of the large rubber stopper, C.

e) The cut along one side of the PVC pipe, E, is taped with masking tape. The pipe is inserted in the free end of the small connector, B.

f) The assembled mold is inserted in the holes of the plexiglass discs, F, and tightened using the threaded rods, G.

g) Once the reinforcing bar is centered in the pipe, by controlling the tension on the threaded rods, the mold is ready for the specimen to be cast.

Annex 2

1. Salt bridge.

1.1 General. The salt bridge described in this specification is used to form an ionic path between the liquid in the two containers used in the tests.

1.2 Materials. The materials used to make four 3-ft (0.9 m) long salt bridges are 4.5 grams of agar, 30 g of potassium chloride, KCl, 100 cc of distilled water, and 12 ft (3.6 m) of $^3/_{16}$ in. (5 mm) internal diameter rubber tubing.

1.3 Fabrication. The salt bridge is made by dissolving the agar in distilled or dionized water. The mix is heated to in a double boiler and stirred for 20 min. After this, the KCl is added and mixed until dissolved. The agar mix is poured into the 3 ft (0.9 m) lengths of tubing when warm. Once the agar is cold, the salt bridge can be used.

Annex 3

1. Deicing Chemicals

The quantity of deicing chemical to be added to and mixed with the simulated pore solution to provide the desired molal ion concentration is calculated using Eq. C.1.

Weight of deicing chemical added to pore solution in grams per liter of pore solution

$$= \left(\frac{974.8}{1000}\right)\left(\frac{A \times W}{N}\right) \qquad \text{(C.1)}$$

where

974.8 = the weight of the deionized water, in grams, in 1.0 liter of simulated pore solution

A = desired molal ion concentration

W = molecular weight of the deicer

N = number of ions in the molecule of deicing chemical

Sample Calculation

Deicing chemical: NaCl

Desired ion concentration: 0.4 m

Molecular weight of NaCl: W = 58.44

Number of ions in NaCl: N = 2

$$\text{Weight of deicing chemical added to pore solution} = \left(\frac{974.8}{1000}\right)\left(\frac{0.4 \text{ x } 58.44}{2}\right)$$

= 11.39 g of NaCl added to 1.0 liter of simulated pore solution

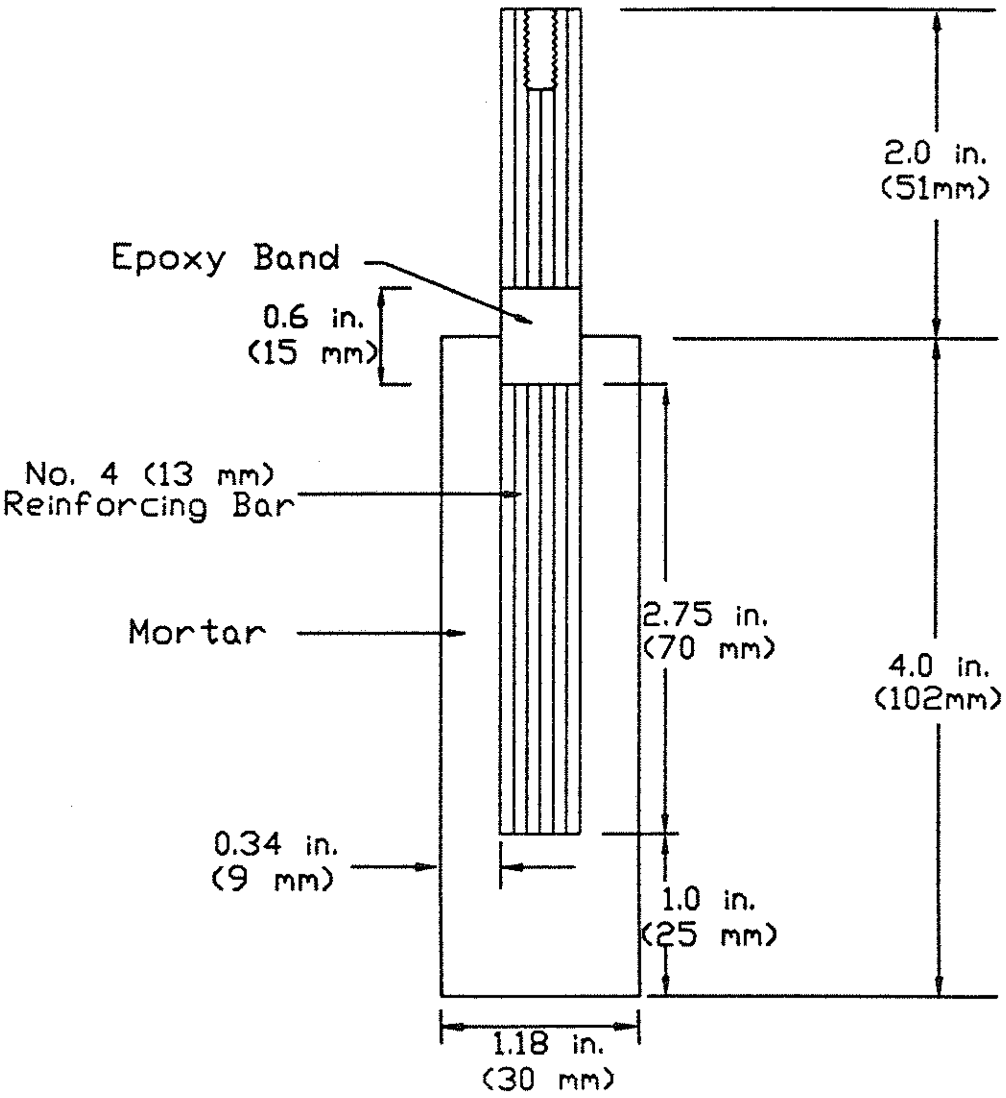

Fig. 1 Cross section of test specimen

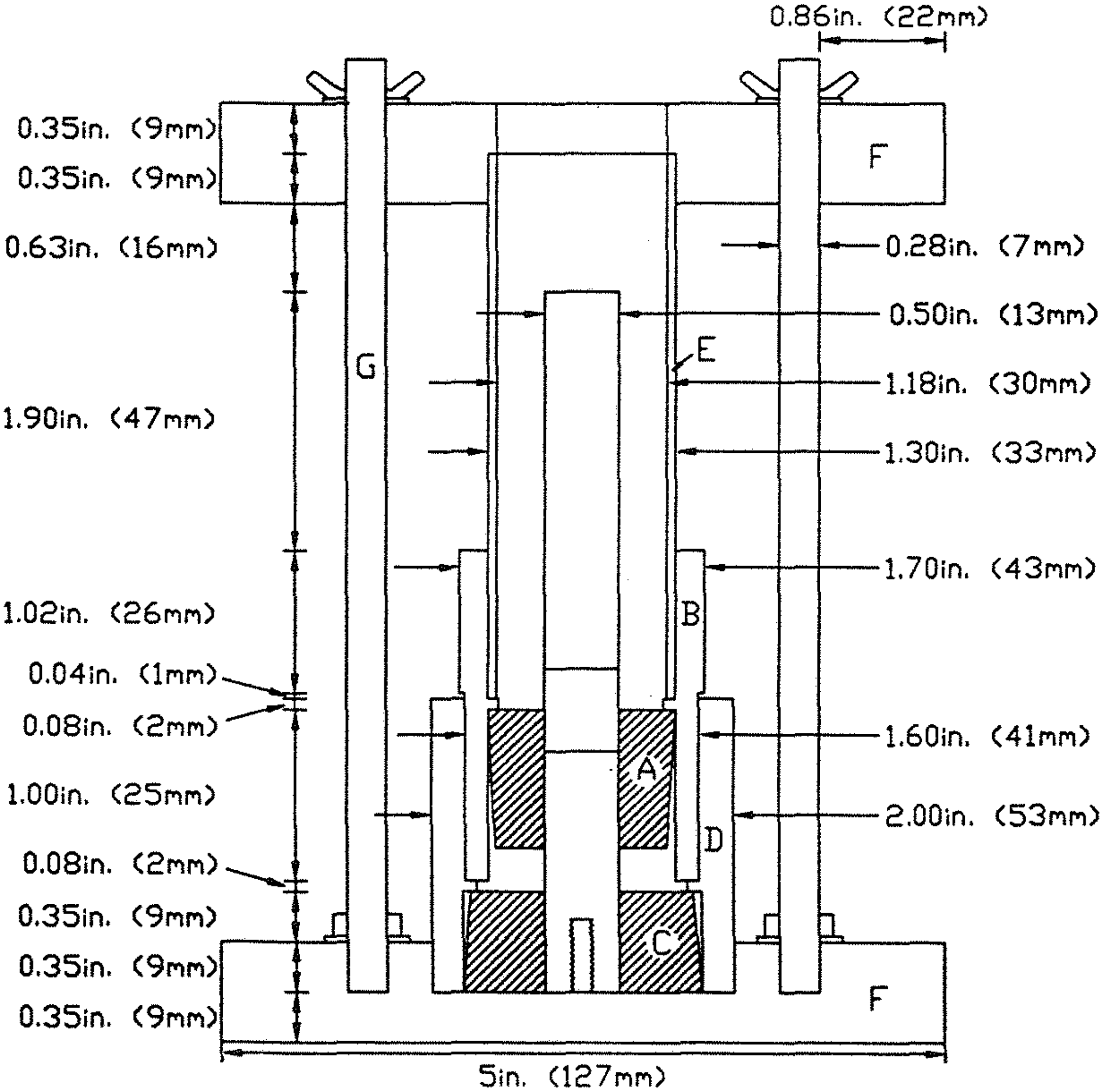

Fig. 2 Cross section of mold for test specimen

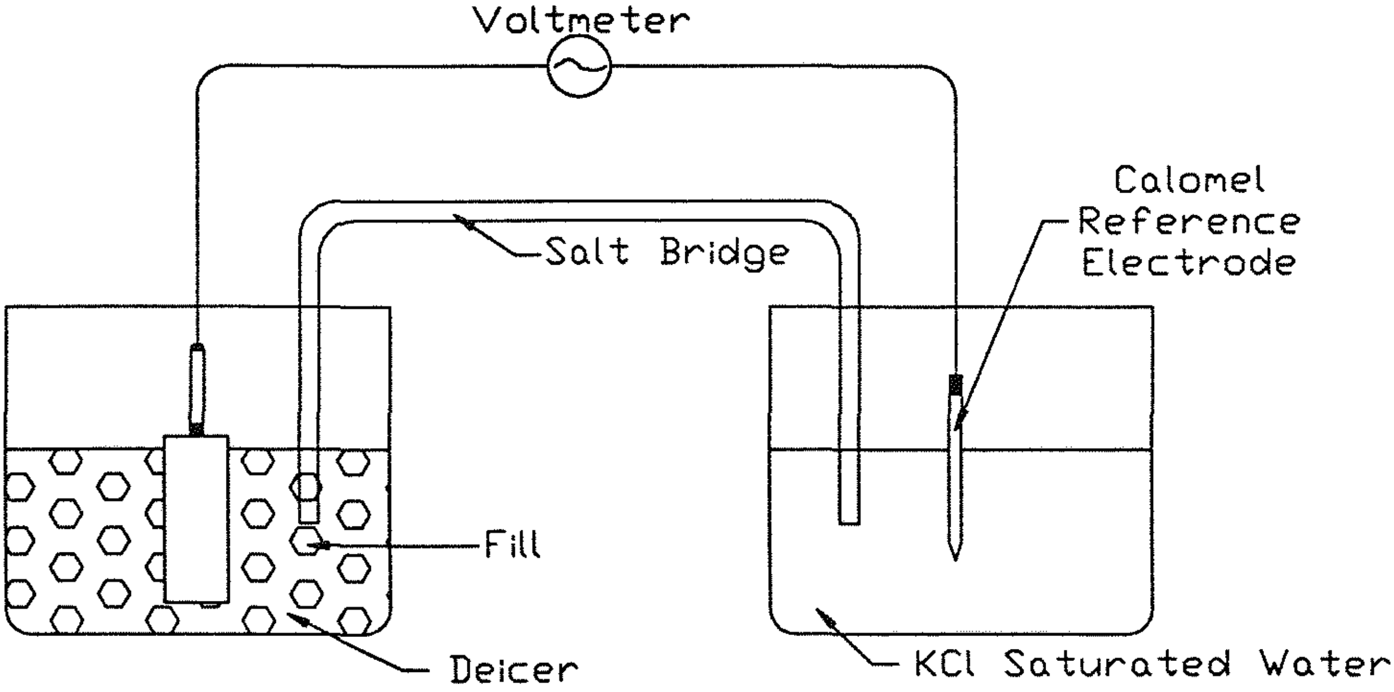

Fig. 3 Schematic of corrosion potential test configuration

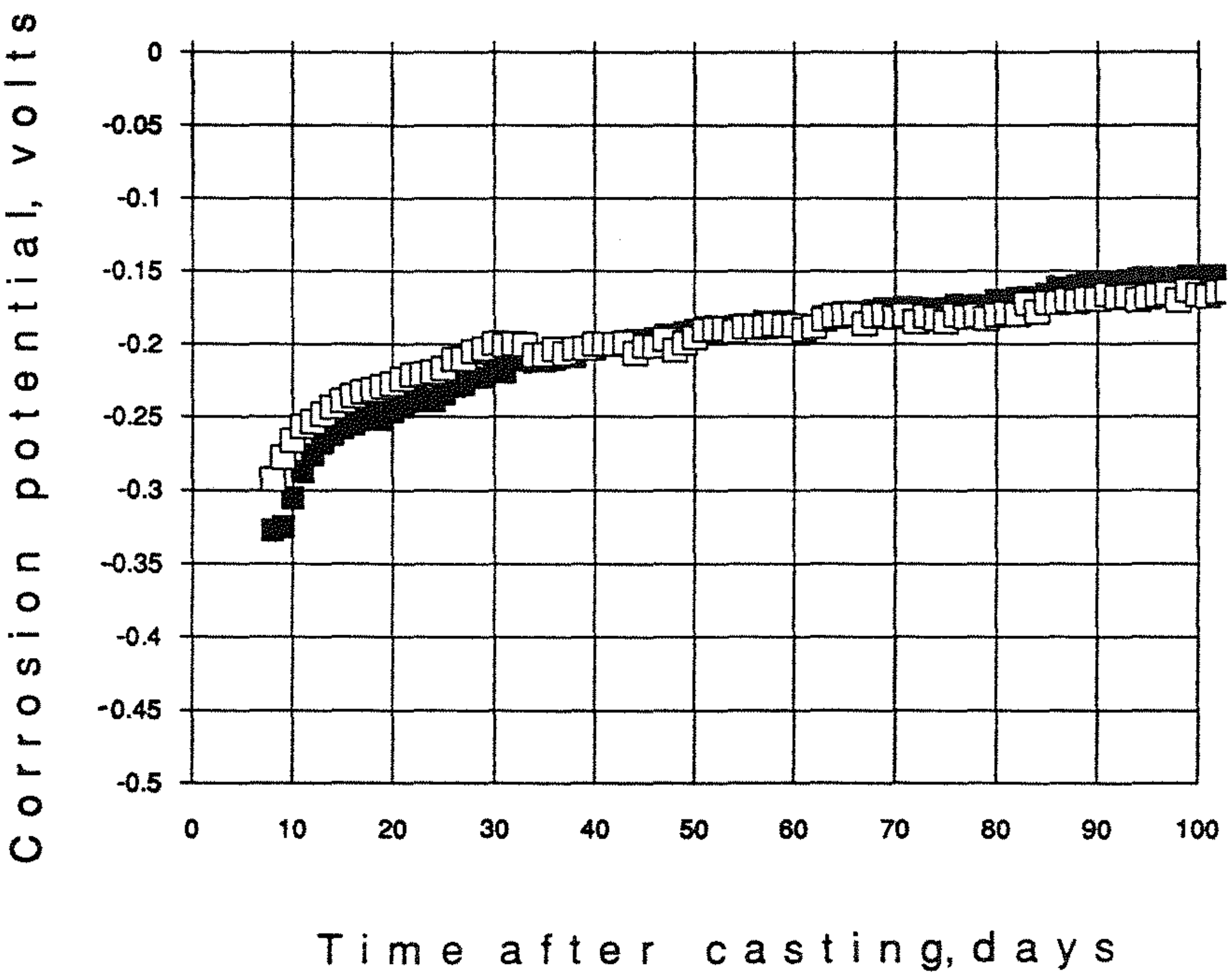

Fig. 4 Corrosion potential for specimen exposed to simulated pore solution

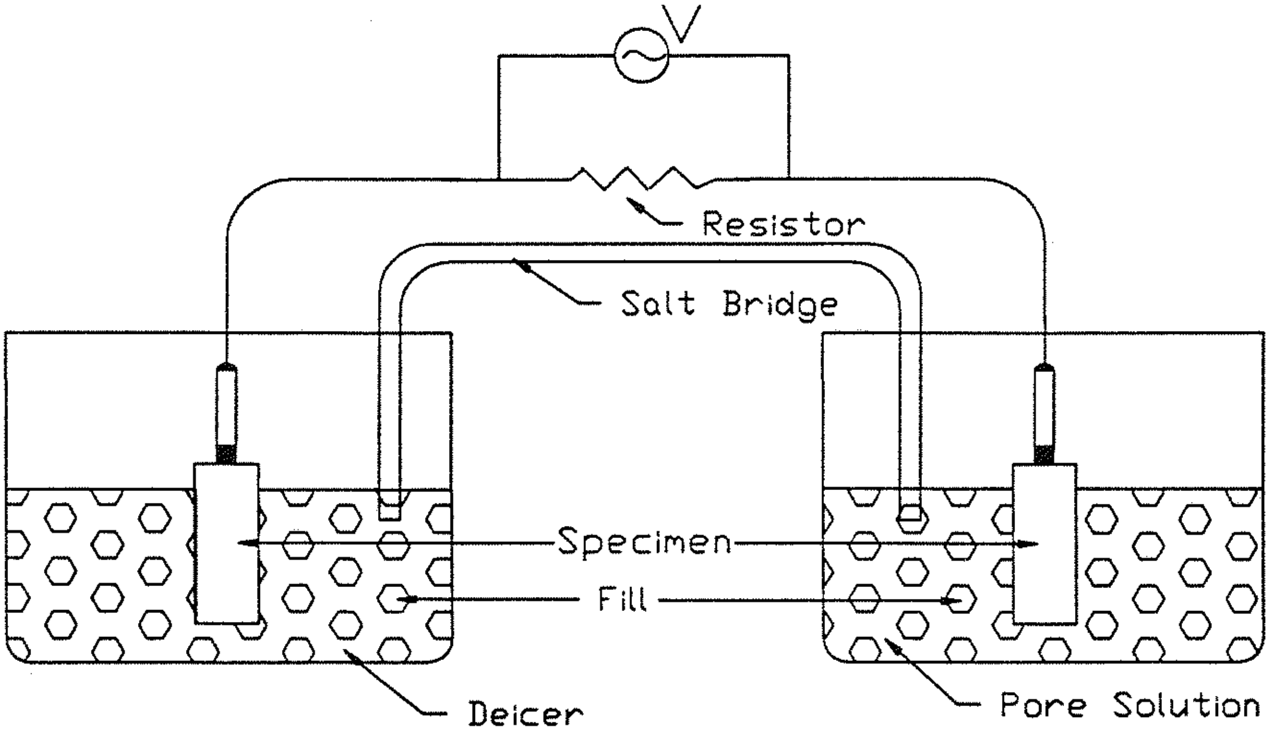

Fig. 5 Schematic of macrocell test configuration

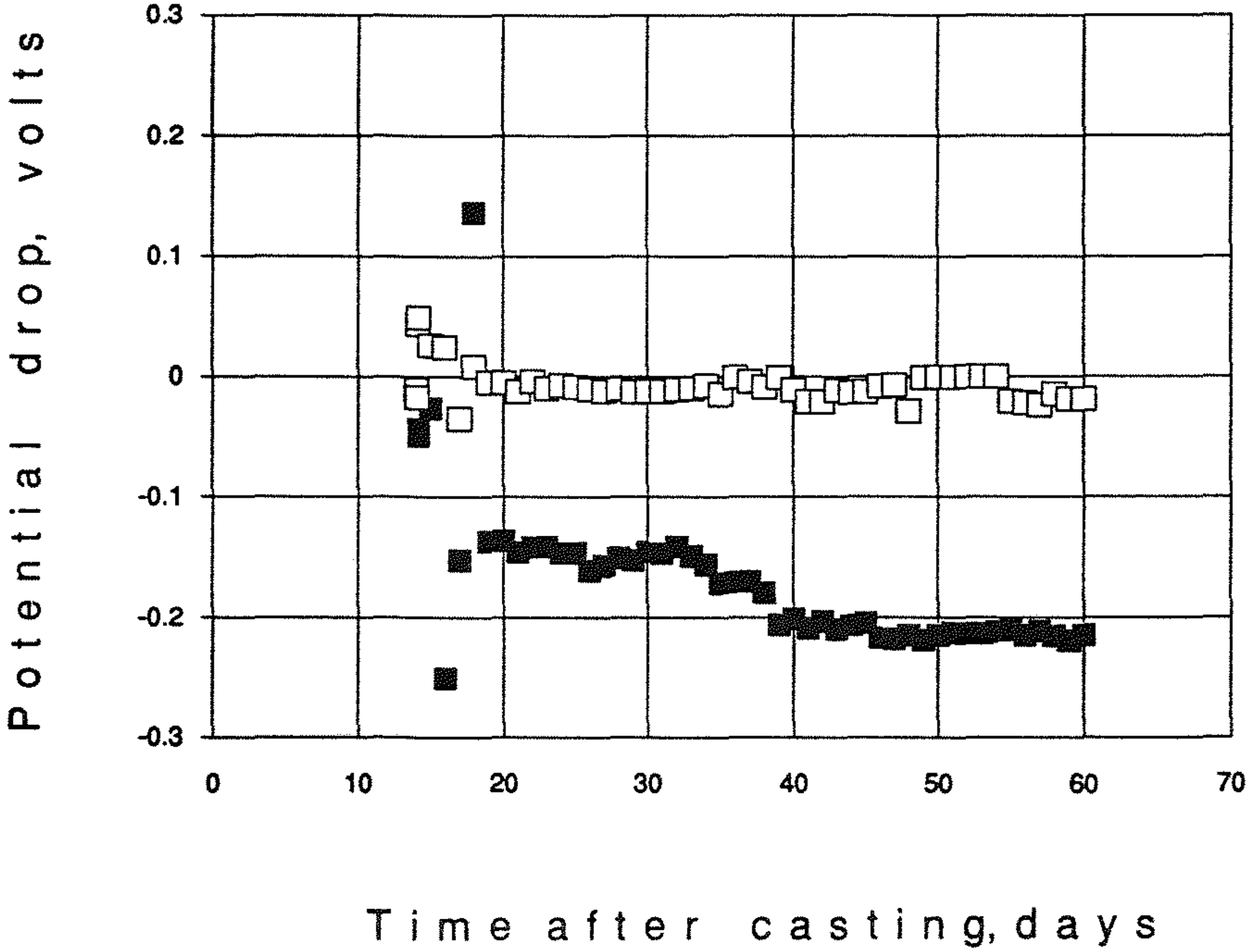

Fig. 6 Potential drop for specimen exposed to 6.4 molar ion concentration of $CaCl_2$ in simulated pore solution