Corrosion-Inhibiting Properties of Portland and Portland-Pozzolan Cement Concretes

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Within the framework of studying properties that inhibit corrosion of concrete that contains admixtures and additives, concretes with various amounts of fly ash were tested and evaluated. Cylindrical specimens with a centrally located reinforcing bar were partially immersed in a 5 percent sodium chloride solution after various curing periods and curing procedures. An impressed-current test was used to accelerate the corrosion process. Time to cracking and current flow were measured, and total energy requirements to induce failure calculated. Other variables studied included sorption, resistivity, strength, consistency, and time to cracking failure of the specimens. Test results indicated that the use of pozzolanic material (fly ash) as an additive or an admixture improves the property of the concrete to prevent corrosion of the embedded reinforcing steel.

Large sums of money are expended anually to repair and mitigate the corrosion damage to concrete bridges and other transportation structures. In many cases, the benefits derived from such repairs may be questionable since some repairs are only for maintaining the appearance of a structure and actually intensify the corrosion process.

To serve the growing population centers along the seashores, many structures have been placed in corrosive environments. Use of concrete in such structures has increased over the last 20 years because of the large-scale use of prestressed concrete. Over this same period, changes in fabrication techniques and the quality of concrete may have influenced the corrosion problem. Coincidental with these factors has been the increased use of deicing salt on concrete bridge decks and pavements, which results in corrosion.

The research needs associated with corrosion in reinforced concrete structures may conveniently be divided into four major areas:

1. Determination of intensity, rate, and extent of corrosion in an existing structure;
2. Establishment of limiting specification values based on field corrosion tests that will assist in deciding the extent of maintenance action, i.e., whether routine repair, major replacement, or any other action is necessary;
3. Criteria for suitable repair materials and procedures; and
4. Designs for preventing corrosion of new structures.

This presentation is mainly concerned with the fourth area, but may also have application to the other areas.

Basically, there are three protective measures to mitigate the corrosion of reinforcing steel:

1. An appropriate insulator around the reinforcing steel;
2. A protective barrier applied to the concrete surface; and
3. Modification of the concrete.

This presentation discusses the last solution: the modification of concrete to achieve better protection of reinforcing steel from corrosion. A variety of admixtures and additives has been used or suggested for use in modifying concrete to inhibit corrosion of the reinforcing steel (1, 2, 3). Some measures have been used to maintain the passivity of the steel by retaining a high pH-value in the concretes.

Corrosion of major concern in reinforced concrete is of two types: galvanic, which is related to variability in characteristics of the reinforcing steel, and concentration, which is related to environmental changes in the concrete. For the activation of either type, anodes and cathodes must be present, and direct current (dc) must flow. Conducive to the electrochemical process of corrosion in reinforced concrete is the presence of water, carbon dioxide, oxygen, and chloride salt. The water acts as a carrier for salt, oxygen, and carbon dioxide. Water containing dissolved salts is an electrolyte with low electrical resistivity that favors the passage of the corrosion current.

The more permeable the concrete is, the more readily the water can move; thus the probability of corrosion increases. Therefore, an important requirement

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for protecting concrete from corrosion is a low permeability. It has been suggested (4) that the permeability of concrete is a characteristic property that assists in preventing the corrosion of embedded steel. Therefore, the use of concrete with low permeability may be a partial solution to the problem of hindering the development of corrosion in reinforced concrete.

To take remedial action after corrosion has occurred in a structure is a complicated process. Indeed, in some cases, the remedial action may intensify and promote further corrosion. Therefore, it is essential that the protective properties be built into the structure at the time of fabrication and construction through the selection of appropriate materials and design.

The primary objective of this preliminary investigation was to compare the properties that inhibit corrosion in concrete made of portland cement and with or without pozzolanic admixtures. A further objective was to determine the relative impact that curing procedures and cement content would have on inhibiting the corrosion of steel in the concrete.

A review of the literature has revealed that researchers have previously defined those variables used in mixtures of concrete that influence the protection of embedded steel against corrosion. Based on this past research, the following variables were chosen for this project:

1. Curing method and period,
2. Cement content,
3. Water to cement ratio, and
4. Cement type and pozzolanic admixtures.

In this investigation, a Florida limestone that is porous and perhaps more permeable than rock types found elsewhere in the country was used exclusively. The corrosion test procedure made use of an impressed electrical current to accelerate the corrosion process.

EXPERIMENTAL VARIABLES AND DESIGN

The independent variables are those selected in the experimental design, and the dependent variables are those measured or observed during the course of the investigation. In the analysis of data, the two sets of variables are examined to detect a possible cause-effect relationship. The independent variables selected in this investigation are shown in Figure 1. Some of the variables were combined into a factorial experiment, and other variables were studied and related to the main factorial experiment.

Cement

Studies by others (2, 3) have indicated that portland-pozzolan cement and portland cement with fly ash as a partial cement replacement may afford better protection against corrosion of reinforcing steel than a corresponding mix of only portland cement. In this investigation, commerical type I and type IP cements were used, and the corrosion protective properties of cement-pozzolan combinations were evaluated by using a single mix design.

The amount of cement has been shown to have an appreciable influence on inhibiting corrosion in concrete. In this experiment, cement contents of 334, 418, and 501 kg/m^3 of concrete (6, 7½, and 9 bags/yd^3) were used in the design of the respective mixes. In other studies (3, 5), the water to cement (w/c) ratio has been established as having a significant effect on the quality of concrete. A wide range of w/c ratios was impractical for the cement content and aggregate proportions used in this experiment. It was decided to compare the various mixes on a consistency basis that was determined by AASHTO T-119—slump tests for plastic concrete. Instead of comparison by w/c ratio, three slump values, 5.08, 10.16, and 15.24 cm (2, 4, and 6 in), were designated as the test parameters in the factorial design.

Fly Ash Admixture

Fly ash that replaced an equal amount of cement in percentages of 20 (type IP), 35, and 50 was used as an admixture.

Curing

The effect of curing procedure on permeability of concrete and its corrosion-inhibiting properties is significant and widely documented (3). One objective of this research, mentioned previously, was to determine the relative effectiveness of a variety of curing procedures by considering both curing method and curing time; therefore, six different procedures were used. These procedures along with their respective designations are as follows:

Designation	Curing Procedure
A	Stripped from mold in 1 d and moist-cured at 25°C (77°F) and 97 percent relative humidity (RH) for 6 d
B	Stripped from mold in 1 d and moist-cured at 25°C (77°F) and 97 percent RH for 27 d
C	Stripped from mold in 1 d and water-cured by submergence for 6 d at 25°C (77°F)
D	Stripped from mold in 1 d and water-cured by submergence for 27 d at 25°C (77°F)
E	Stripped from mold in 1 d and cured no further
ES	Steam-cured in mold at approximately 65.6°C (150°F) for 16 h and cured no further

Aggregates

Florida crushed limestone with a fineness modulus of 5.97, absorption capacity of 31 percent, specific gravity of 2.51, and Los Angeles abrasion coefficient of 35 was used as the coarse aggregate. The silica sand used as the fine aggregate had a fineness modulus of 2.19, specific gravity of 2.63, color number of 20, and loss on decantation of 1 percent. All aggregate properties were determined in accordance with the appropriate AASHTO procedures.

Batching of Concrete

The factorial design for the experiment was developed for cement content, cement type, curing procedure, and consistency. A single batch of concrete was made for each design mix given in Table 1. The concrete was mixed in a 0.071-m^3 (2.5-ft^3) laboratory mixer. The mixer was buttered before onset of batching operations. The batches were charged and then mixed for a minimum of 2 min.

Corrosion Specimens

Eighteen cylindrical corrosion test specimens, all 10.16 cm (4 in) in diameter by 12.70 cm (5 in) in height, were molded from each batch. The procedure used was to place and rod each specimen in a manner similar to that used for making concrete specimens of standard strength. After the cylinder was rodded, a 1.27-cm (0.5-in) diameter reinforcing bar was placed vertically in the cylinder along the centerline. The lower end of the bar was approximately 5.08 cm (2 in) from the bottom surfaces.

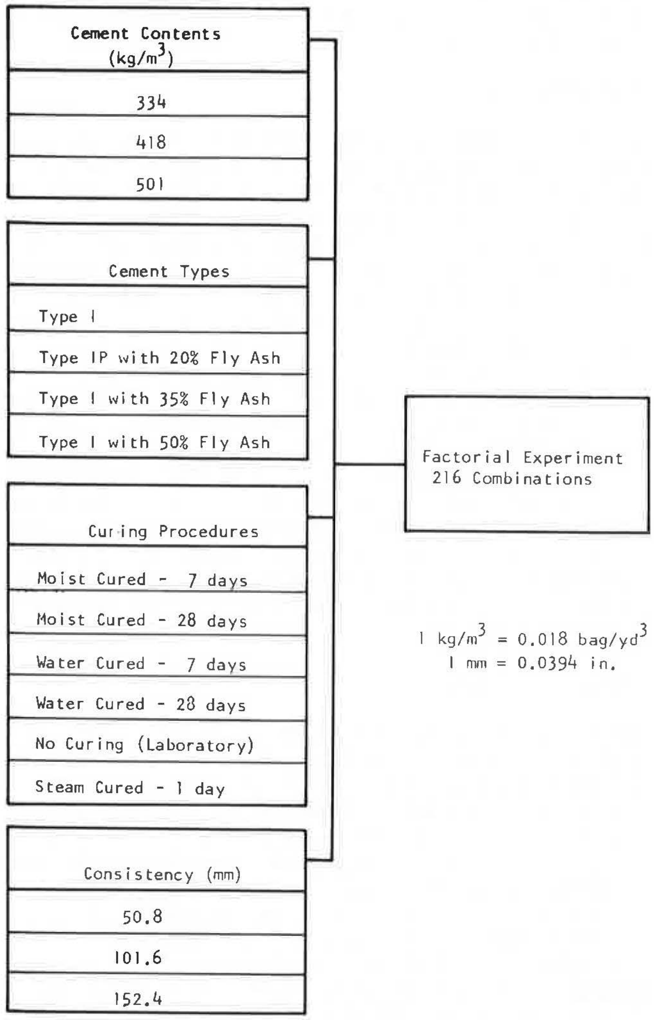


Figure 1. Experimental design.

In some cases, it was determined that the bar had settled to give less than the required cover at the bottom surface. In such instances, an epoxy was applied to the cylinder bottom.

Measured Variables

The measured variables for this research included slump, entrained air, strength, sorption, relative resistivity, and time to corrosion failure.

1. The slump test (AASHTO T-119) may not directly relate to consistency; however, it does give an indication of workability and may be easily related to current specification requirements. Slump tests were made on each batch of concrete.
2. Tests for entrained air were made on each batch of concrete in accordance with AASHTO T-196 by using a roll-a-meter. This method has been found to be preferable to the pressure method when aggregates have high porosity.
3. Since compressive strength and strength gain characteristics must be considered when pozzolanic material is used as a replacement for cement, strength specimens were made and tested in accordance with appropriate AASHTO specifications for the design mixes used. These values are shown in Figure 2.
4. Based on tests conducted in California and Texas (3, 4), it has been suggested that the basic mode of water movement through concrete is by capillary action. As such, sorption measurements were used to determine the relative permeabilities or water penetration of the design mixes used. After curing, the specimens were dried for 100 h at 110°C (230°F). The cylindrical wall was coated twice, once upon cooling and once 24 h later, and permitted to dry for 24 h. The specimens were then soaked vertically, and a 15.24-cm (6-in) hydrostatic head acted on the bottom face for 24 h. The difference between the wet and dry mass was determined, and the amount of moisture penetration was measured after the cylinders had been split open. Observed values and the split tensile strengths are given in Table 2.

Table 1. Experimental design for mixture of concrete.

	Mix Proportions							
Batch No.	Fly Ash[a] (%)	Cement (kg)	Coarse Aggregate (kg)	Fine Aggregate (kg)	Water (kg)	Slump (mm)	Air (%)	Cement Content (kg/m³)
1	0	42.68	138.5	87.6	20.1	50.8	6	334.2
2	0	42.68	137.1	86.3	21.3	101.6	5	334.2
3	0	42.68	135.3	84.0	22.6	152.4	6	334.2
4	0	42.68	101.7	64.9	18.8	50.8	4	417.8
5	0	42.68	100.3	63.6	20.1	152.4	4	417.8
6	0	42.68	104.4	61.3	19.2	76.2	4	417.8
7	0	42.68	75.8	48.6	18.8	152.4	2	501.3
8	0	42.68	77.6	49.0	18.3	101.6	4	501.3
9	0	42.68	77.6	49.5	17.9	50.8	2	501.3
10	20	42.68	148.9	79.9	18.3	50.8	4	334.2
11	20	42.68	146.6	77.2	20.5	101.6	3	334.2
12	20	42.68	136.2	82.2	22.6	152.4	4	334.2
13	20	42.68	102.6	62.7	18.8	50.8	3	417.8
14	20	42.68	104.4	59.5	19.2	101.6	4	417.8
15	20	42.68	79.5	46.3	17.9	50.8	4	501.3
16	20	42.68	79.0	46.3	18.3	101.6	4	501.3
17	20	42.68	77.6	45.6	18.8	152.4	2	501.3
18	20	42.68	102.6	59.5	20.1	152.4	4	417.8
19	33	27.69	137.1	84.0	21.2	127.0	6	334.2
20	33	27.69	104.4	59.0	19.3	101.6	4	417.8
21	33	27.69	75.8	46.3	18.9	76.2	3	501.3
22	47	21.34	137.1	81.3	21.2	101.6	5	334.2
23	47	21.34	104.4	56.8	19.3	101.6	4	417.8
24	47	21.34	75.8	44.1	18.9	127.0	5	501.3

Note: 1 kg = 2.2 lb; 1 mm = 0.0394 in; 1 kg/m³ = 0.018 bags/yd³.

[a]Batches 10 through 18 used type 1P cement containing approximately 20 percent fly ash as an additive. Batches 19 through 24 contained fly ash as an admixture.

5. The approach in the corrosion tests was to expose all specimens to the same uniform environment and to impress current in the reinforcing rod to simulate an accelerated corrosion process. During the accelerated testing, specimens were placed in a tank and immersed to three-quarters of their length in a 5 percent by mass aqueous solution of sodium chloride (NaCl), as shown in Figure 3. The tanks were lined with fiberglass and accommodated 84 specimens each. The specimens were equidistantly spaced in the tanks.

The setup for the accelerated test is shown in Figure 4. The impressed-current apparatus consisted of an air-cooled selenium rectifier, insulated wiring that connected each test specimen, and a cathodic steel bar for current return. In addition to this apparatus, shunts were used for monitoring the current impressed on each specimen. Test equipment and instrumentation used for monitoring of the current included a sensitive multimeter, shunts, and an ac electrical test meter.

TEST PROCEDURES

After fabrication and curing, the specimens were conditioned in the sodium chloride solution for a minimum of 28 d. This conditioning reduced the effect of the experimental variables for curing age and procedure. After the conditioning process, the specimens were subjected to current, as described in the following section.

Test Principles

It is recognized that reinforcing steel encased in concrete will corrode if an electrical current is present (6). Such a current may be initiated by a potential difference between two different areas of the metal. Potential difference (voltage) may be due to the nonhomogeneity of the steel, in which case the resultant corrosion is termed galvanic, or due to a difference in the environment of the metal, in which case corrosion is termed concentration. Introduction of chlorides into the concrete lowers the effective resistivity at the steel-concrete interface. Because high pH is the primary concrete property that inhibits corrosion and because the protection of steel is directly proportional to the corrosive resistance of concrete, the problem with chloride presence cannot be overstated.

The electrical current was impressed to the reinforcing bar (anode) in each specimen by using a rectifier. The current passed from the rod, through the concrete, into the water, and to a steel return rod (cathode). The use of the electrical current simulated and accelerated a natural corrosion process. As the steel corrodes, the product of the corrosion has a volume that is approximately twice the original volume of the material. Consequently, these corrosion products induce tensile stresses in the surrounding concrete and eventually result in a cracking and spalling of the concrete.

Procedures for testing remained uniform throughout the experiment. The saltwater bath (electrolyte) surrounding the test specimens was kept at a 5 percent salt concentration by mass. The water temperature varied several degrees, 21.1 to 22.8°C (37.8 to 41.0°F), but remained uniform throughout all test tanks.

Test Instrumentation

During the tests, electrical test meters monitored the alternating and direct current voltages. The latter voltages ranged from 0.1 mV to 100 V. Voltage measurements were taken across shunts to determine rectifier output and current flow to each cylinder.

Cathodic-protection rectifiers were bridged, selenium, air-cooled units with an adjustable output up to 20 V and 5 A. Connections to test cylinder reinforcing rods were made with high-pressure battery clips to ensure good conductivity.

Test Procedure

Saltwater, 5 percent sodium chloride by mass, was added to the fiberglass test tanks and was brought to a level approximately 1.91 cm (0.75 in) below the top of the concrete surface of the specimens. Electrical connections between the rectifier and specimens were then made, as shown in Figure 5. The system was energized, and the current was adjusted so that ac current of approximately 25 mA flowed to each specimen. Currents to individual specimens were monitored twice each day by measuring the voltage drop across the shunts that were installed in the respective connecting wires. Visual observations were also made twice daily to detect specimen failure. The system remained energized and adjusted without interruption throughout the testing period.

Other parameters monitored included water temperature, water salinity, and overall voltage readings at the rectifier terminals and on the specimen steel. Voltage potential readings were initially taken by using a copper sulfate half-cell but were found to add an insignificant amount of information.

Criteria for Failure

Before the initiation of the tests reported here, preliminary tests were made to determine the range in test parameters and the influence of various test methods. It was concluded that the optimum amount of dc current required to accelerate the corrosion process was approximately 25 mA. This level of current could be measured by the equipment used for monitoring and accelerated the corrosion to a desired period of time.

One criterion for specimen failure was established during the preliminary testing: Failure occurs when cracks become visible on the surface of the concrete. A before-and-after view of a failed specimen is shown in Figure 6. In such preliminary tests, the cylinders were not disconnected from the system when the initial cracks appeared, and, consequently, the cracks continued to widen until the cylinder eventually fell apart. Since the widening allowed the corrosion product to pollute the saltwater and provided no additional useful data, subsequent tests were terminated at the sight of the first crack.

A second criterion for failure was defined during the data reduction process. This criterion was based on the observance that all specimens markedly decreased in resistance, i.e., increased in current consumption, before a cracking failure. It was found that the energy applied to this point was related to the time required for visual cracking to occur.

DATA ANALYSIS AND PRESENTATION

In the first phase of data analysis, plots of current and voltage versus the time function were made. The trends established by analyzing these graphs led to the following findings.

In the initial analysis, the time of failure was when the visual crack was seen. However, after reviewing the data, such as those shown in Figure 7, it was obvious that failure was progressive and that the time to first visual crack did not correspond to the time of initial decrease in the electrical resistance of a specimen. Furthermore, it was reasonable to assume that the strength of the concrete had some effect on the time

Table 2. Permeability values for concrete.

Cement Type	Age (d)	Dry Mass (kg)	Wet Mass (kg)	Water Mass (kg)	Load[a] (kg)	Penetration (mm)
1	14	11.59	11.75	0.16	7 710	63.5 ± 3.2
1	14	11.58	11.70	0.12	9 760	63.5 ± 3.2
1P	14	11.63	11.74	0.11	11 580	57.2 ± 3.2
1P	14	11.65	11.74	0.09	12 030	50.8 ± 6.4
1	28	11.85	11.94	0.09	12 140	54.0 ± 3.2
1	28	11.87	11.97	0.10	13 620	57.2 ± 3.2
1P	28	11.90	12.00	0.10	15 660	50.8 ± 6.4
1P	28	11.98	12.06	0.08	15 430	50.8 ± 3.2

Note: 1 kg = 2.2 lb; 1 mm = 0.0394 in.
[a]Loads shown are for testing in split tension.

required for the appearance of visual cracking.

Shown in Figure 7 is the idealized plot of current flow versus time. The current flow remained approximately constant over the initial period of testing. Then a marked increase occurred in demand of current flow to the specimen. This sharp increase was designated as the time of failure. After the failure criterion was exceeded, a significant increase in current flow took place and was followed by a period of alternate decreases and increases in current flow and then by visual cracking of the specimen.

The sharp increase in current flow immediately after the failure criterion is exceeded is the result of a marked decrease in the electrical resistance of the specimen due

Figure 2. Compressive strength.

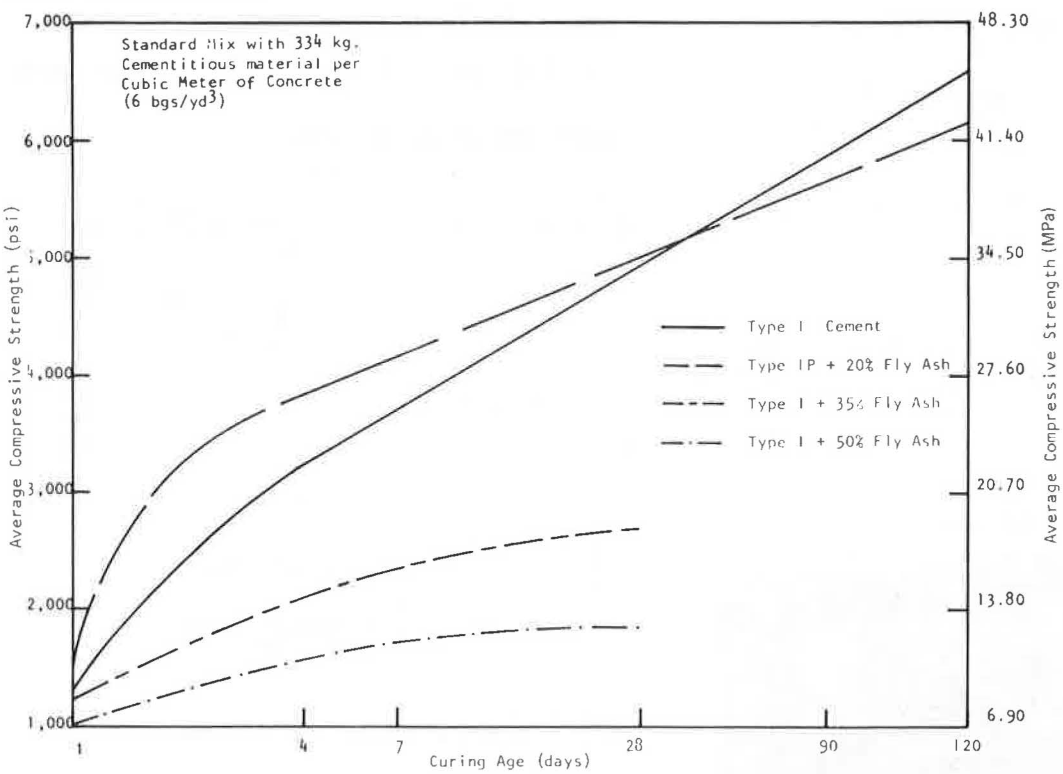
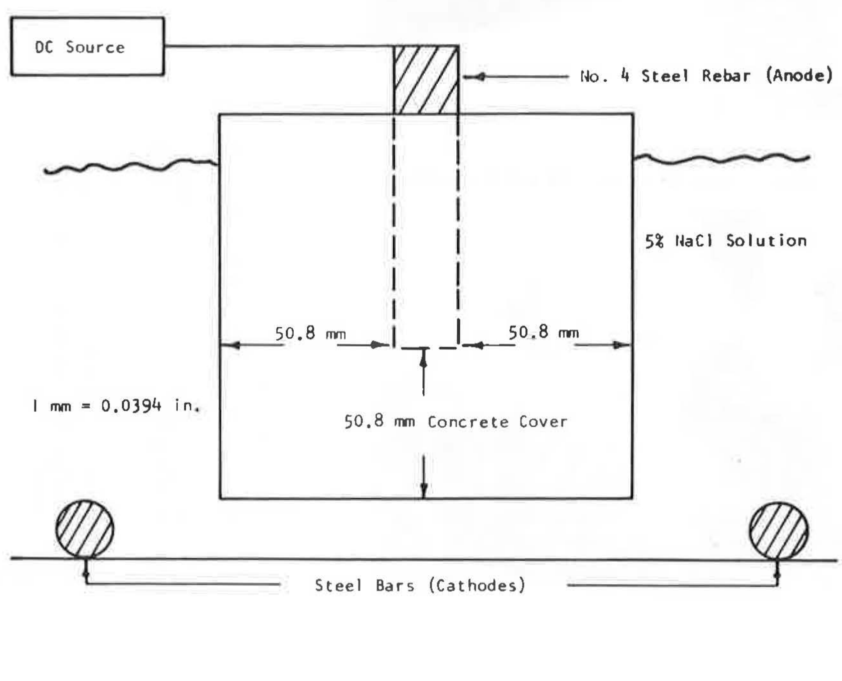


Figure 3. Components of test system.



to internal cracking. When the corrosion product begins to fill the crack, the resistance leading to decreasing the current flow is increased because of the constant voltage applied. This buildup of corrosion products results in stress in the concrete and causes further cracking and corresponding increases in current flow. A specimen may undergo several cycles of progressive cracking before visual cracks develop.

The reduced test data indicated that the best correlation between the independent and dependent variables was obtained when the dependent variables were combined in energy units required to produce failure. Such correlations are demonstrated by the test results shown in Figures 8 through 11. The electrical energy units, expressed as the product of current, of electropotential, and of time to failure, were calculated for each specimen. Although considerable variation was observed, the trends established and shown in Figure 11 lend considerable support to using the concept of energy in the data analysis. The data analysis consisted of comparing the energy consumption versus the dependent test variables. It was theorized that the energy requirement reflected the ability of the concrete to prevent corrosion.

Figure 4. Test schematic and formation of chemical compounds.

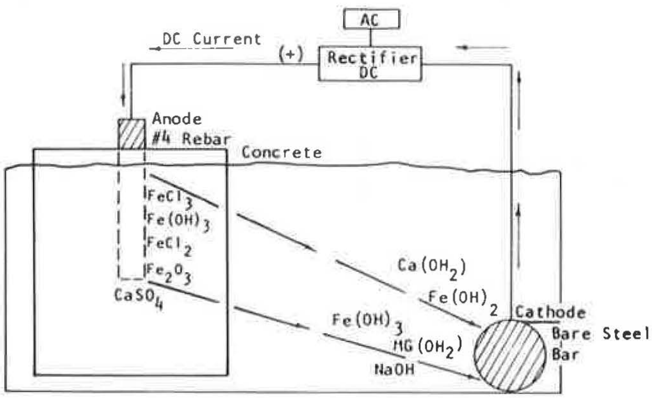


Figure 5. Overall view of typical test system.

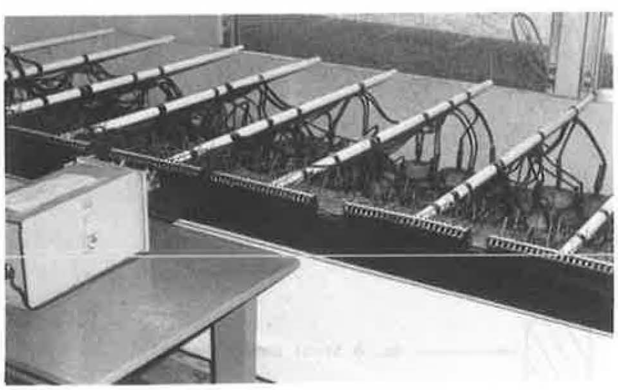
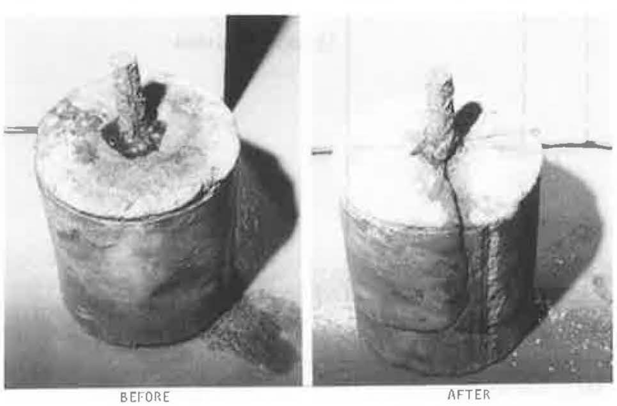


Figure 6. Before-and-after failure photographs of typical specimen.



Influence of Cement Type

The influence of cement type is shown in Figure 8 in which the energy requirements for failure are compared for specimens with type IP and type I cements. The concrete with type IP cement was superior to a corresponding concrete with type I cement.

Influence of Curing Method

Figure 8 also shows the influence of the various curing

Figure 7. Idealized trends for test data.

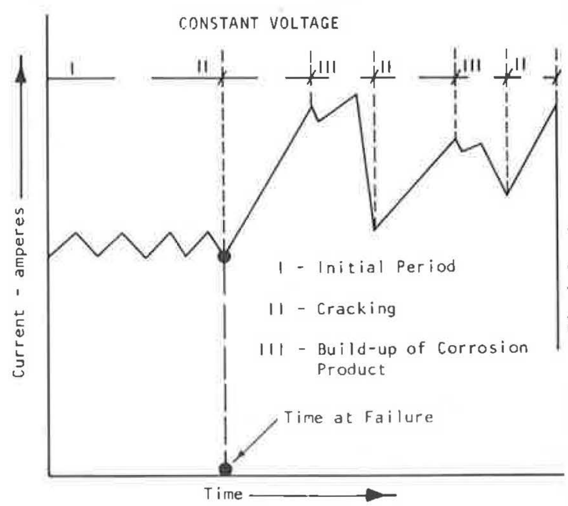


Figure 8. Influence of curing on corrosion resistance.

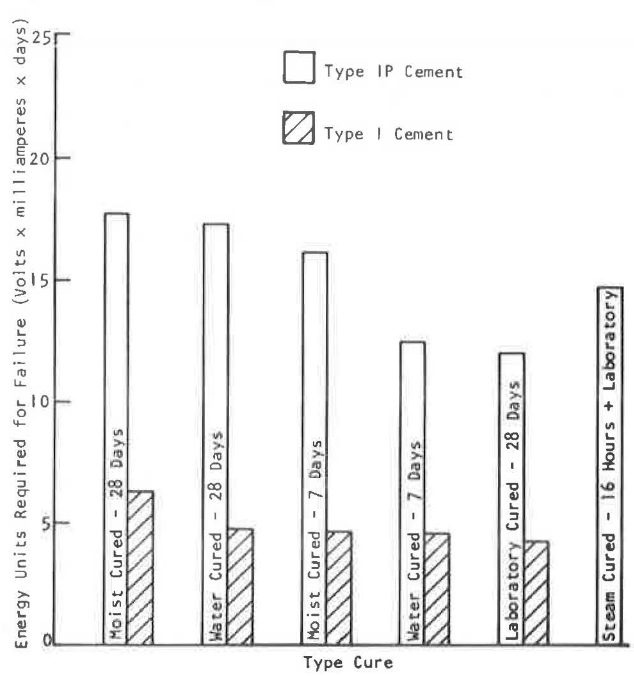
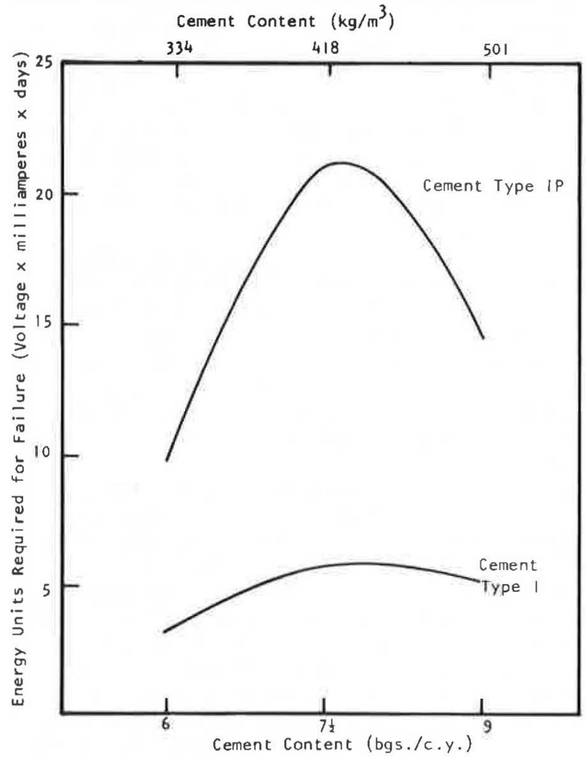


Figure 9. Influence of cement content on corrosion failure.

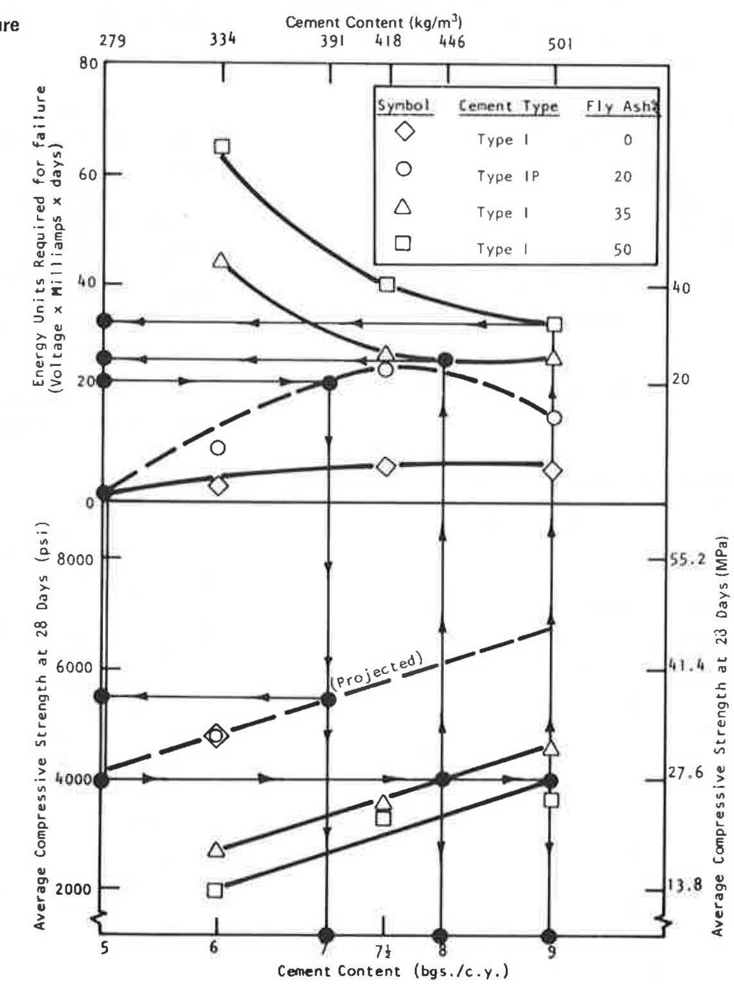


methods. The moist- and water-cured specimens with type IP cement showed similar performance for the 28-d curing period. For the 7-d curing period, the moist-cured specimens performed better than the water-cured specimens. Specimens cured under the environmental condition of the laboratory (air-cured) showed the lowest performance for both cement types. Specimens made with type IP cement, steam-cured for 16 h and then left in the laboratory environment, performed well, but exhibited a lower performance than those moist-cured or water-cured. For similar curing conditions, improvement was noted between the 7- and 28-d curing periods. Of the specimens made with type I cement, those cured for 28 d showed the best performance. For all other type I cement specimens, regardless of curing method, the energy requirements to induce failure were approximately the same.

Influence of Cement Content

The influence of cement content on the energy required to induce failure is shown in Figure 9 in which energy is plotted versus cement content. For both cement types, the performance improved as the cement content was increased from 335 to 418 kg/m^3 (6 to 7.5 bags/yd^3). Cement type IP showed a considerable decrease in performance when the cement content was increased from 418 to 502 kg/m^3 (7.5 to 9 bags/yd^3). This decrease was less marked for specimens with type I cement, and the lack of improvement was thought to be related to the mix design.

Figure 10. Influence of cement on corrosion failure and average compressive strength.



Water to Cement Ratio and Consistency

For the selected mix design, the desired range in the w/c ratio was impractical. The ratio used generally varied between 0.40 and 0.50 and showed no correlation with the energy requirement to induce failure. Because the desired range in the w/c ratio could not be attained, a variation in consistency was included for 5.08, 10.16, and 15.24 cm (2, 4, and 6 in) of slump. In the case of specimens with type I cement, the performance decreased slightly with increased slump. The reverse was true for specimens using type IP cement.

Fly Ash Content

In addition to the specimens containing type IP cement and 20 percent fly ash, a partial factorial experiment was made for specimens containing 35 and 50 percent fly ash. The data for the energy required to induce corrosion failure are shown in Figure 10. Also shown in Figure 10 are the compressive strength values and the comparative data for type I and type IP concretes.

Generally, the data demonstrate that the energy required to produce corrosion failure increased as the fly ash content increased. The energy value decreased as the cement content increased in the specimens with fly ash. This is contrary to the observations made for concretes with type I and type IP cements. Figure 10 also shows the 28-d compressive strength versus the cement content for concretes with various amounts of fly ash from 0 to 50 percent.

From the data shown in Figure 10, the deductions given in Table 3 may be made. For 27.58 MPa (4000 lbf/in²) and 28-d strength, the cement requirement is 279 kg/m³ (5 bags/yd³) for both the type I and type IP cement. Energy required to produce failure is one unit. Using 35 percent fly ash would require 341 kg/m³ (8 bags/yd³) of cement and 24 energy units, and using 50 percent fly ash would require 384 kg/m³ (9 bags/yd³) of cement and 32 energy units.

A specification may contain requirements for both the strengths and the corrosion protective properties. If the latter is specified at 20 units and the strength is better than 27.58 MPa (4000 lbf/in²), the type I cement would not meet the energy requirement. The type IP cement would require a cement content of 390 kg/m³ (7 bags/yd³) to give 37.9-MPa (5500-lbf/in²) strength and a minimum energy requirement of 20 units. For 35 percent fly ash content, 446 kg/m³ (8 bags/yd³) of cement is required to meet the minimum strength requirement. In this case, the energy required to produce corrosion failure is 24 units. When the fly ash content is increased to 50 percent, the cement content is 502 kg/m³ (9 bags/yd³) of cement to give the minimum strength requirement. The corresponding energy resistance is 32 units.

Figure 11. General trend of test data.

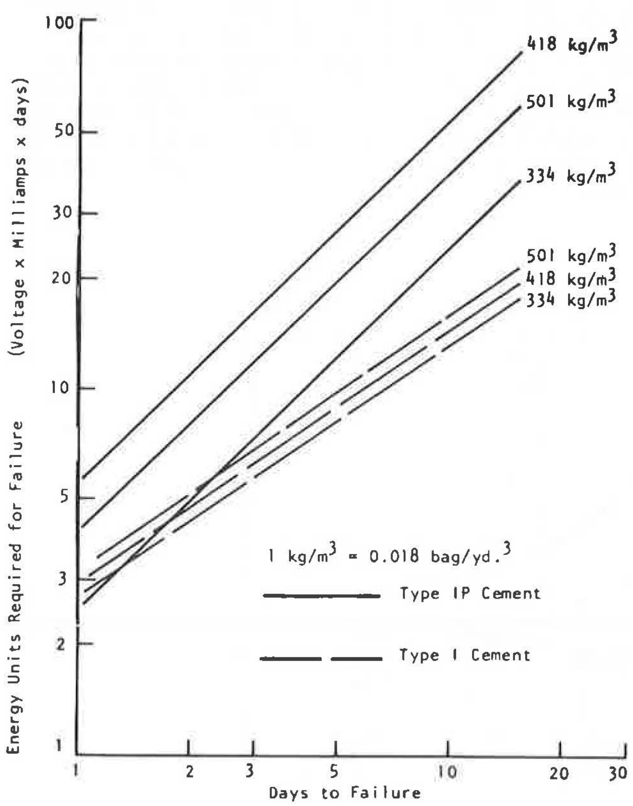


Table 3. Fly ash content and physical properties of concrete.

		Requirement		From Figure 10		
Cement Type	Fly Ash (%)	Compressive Strength (MPa)	Energy Units (V·mA·d)	Compressive Strength (MPa)	Cement Content (kg/m³)	Energy Units (V·mA·d)
I	0	27.6	0	27.5	279	1
IP	20	27.6	0	27.6	279	1
I	35	27.6	0	27.6	446	24
I	50	27.6	0	27.6	502	32
I	0	27.6	20	—ᵃ	—ᵃ	—ᵃ
IP	20	27.6	20	38.0	391	20
I	35	27.6	20	27.6	446	24
I	50	27.6	20	27.6	502	32

Note: 1 Pa = 0.021 lbf/in²; 1 kg/m³ = 0.018 bags/yd³.
ᵃNot feasible.

CONCLUSIONS

1. The compressive strengths of concrete made with type I and type IP cements do not differ significantly at an age of 28 d.
2. The consistency of concrete measured by the slump test does not appreciably influence the time to induced corrosion failure.
3. The cement content of concrete generally correlates with the corrosion protection afforded to encased steel. However, this experiment showed that no protection advantage is obtained by further additions of cement beyond 418 kg/m³ (7.5 bags/yd³).
4. The method of curing has a definite effect on corrosion-inhibiting properties of concrete. Regardless of cement type, the most beneficial methods are moist-curing and water-curing followed in order by steam-curing and air-curing.
5. The electrical energy required to induce corrosion failure is a feasible means for relating concrete parameters to the effectiveness of concrete to inhibit corrosion.
6. The permeability of concrete made with type IP cement is somewhat lower than the permeability of concrete made with type I cement.
7. The addition of fly ash increased the energy required to produce corrosion failure. However, fly ash content beyond that for type IP cement (20 percent) lowered the 28-d compressive strength.

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