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ELECTROLYSIS IN CONCRETE

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ELECTROLYSIS IN CONCRETE

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I. INTRODUCTION

During the last few years attention has been called to the possibility of damage to reinforced-concrete structures by stray currents from electric railways and other power sources. The laboratory experiments of Toch,[1] Knudson,[2] and Langsdorf[3] in 1906 and 1907 showed clearly that under certain circumstances the passage of electric currents from the reinforcing material into the concrete gave rise not only to serious corrosion of the reinforcing material, but also to cracking and splitting of the surrounding concrete. Since then numerous laboratory experiments have been carried out by various investigators, all tending to confirm the earlier observations in regard to the cracking of the concrete, but giving rise to various conflicting theories as to the cause of the phenomena observed. Following the early demonstrations of the possibility of damage to concrete by electric currents, reports of serious damage to certain concrete buildings and bridges became current and considerable apprehension has been aroused in some quarters that great damage may be in progress due to this cause. The subject was brought directly before the Bureau of Standards by letters of inquiry from engineers, contractors, and corporations requesting information in regard to the probable extent of the damage and the most practicable methods of preventing it.

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[1] Max. Toch: The Electrolytic Corrosion of Structural Steel, J. Am. Electro-Chem. Soc., 9, p. 77; 1906.

[2] A. A. Knudson: Electrolytic Corrosion of Iron and Steel in Concrete, Trans. A. I. E. E., 26, p. 231; 1907.

[3] A. S. Langsdorf: Electrolysis in Reinforced Concrete, J. Assn. of Eng. Soc., 42, p. 69; 1909.

Although a good deal of work had been done showing that under certain conditions, readily producible in the laboratory, blocks of reinforced concrete could be split and broken up by electric currents, there remained a wide diversity of opinion as to the cause of the observed phenomena. Nothing had been published showing to what extent and under what circumstances damage might be expected under practical conditions, or how trouble from this source might best be prevented. Recognizing the great practical importance of the subject the Bureau of Standards has undertaken a thorough investigation into the nature and cause of the phenomena observed in concrete under the influence of electric currents, the extent to which damage has occurred or is likely to occur in practice from this cause, and the best methods of mitigating the trouble under practical conditions. The work was begun during the summer of 1910 and certain phases of the investigation are still in progress, but enough work has been completed to justify the publication of a report of progress at this time.

At the time the present work was undertaken the following facts had seemingly been established by the work of other investigators:

1. That, as far as the experiments went, the passage of an electric current of whatever magnitude from embedded iron to concrete in the presence of moisture resulted in cracking of the concrete and rusting of the embedded iron. These cracks extended radially from the iron and opened out gradually as the test progressed until the block in which the iron was placed would go to pieces or could be easily broken.

2. The passage of an electric current from concrete to embedded iron resulted in no damage whatever to the block, except in one or two extreme cases, where the voltage used was very high. This led to the conclusion that no damage is to be expected where current is found flowing from concrete to iron—that is, where the iron is cathode.

3. The specimens of concrete showed a tendency to protect the iron contained in them by virtue of a large increase of resistance as the test proceeded. This increase is not entirely permanent,

as is evidenced by measurements taken before shutting off the current and again some time after stopping the current and is found in greatest degree where embedded iron is anode—that is, where the current passes from iron to concrete. Where the iron is cathode, the rise of resistance occurs, but is not nearly so great. There is, however, no instance in any previous investigation of this increase of resistance being sufficient to reduce the current to a negligible value.

4. The voltage apparently had nothing to do with the phenomena observed beyond affecting the magnitude of the current and consequently the rapidity of the action.

Beyond these four points there appeared to be little agreement among the various investigators. Especially contradictory were the theories advanced to explain the phenomena observed. As the result of experimental evidence of record, at least five different theories had been advanced to account for the destruction of the concrete. These were: (1) *Gas pressure.*[4] When an electric current passes between electrodes in an electrolyte, more or less gas is evolved at the electrodes, and it was held that this gas, liberated within the mass of the concrete, escaped with such difficulty that sufficient pressure was developed to crack the concrete. (2) *Heating.*[5] The passage of an electric current through concrete generates heat therein, and if the current density is high the concrete may become quite hot. It was shown that local heating by a flame or other means would produce cracking, and the conclusion was therefore drawn that the cracking of the concrete under the influence of the electric current was due to its heating effect. (3) *Electrochemical deterioration of the concrete.* The early observations of Toch, Langsdorf, and others led them to believe that the concrete underwent a marked chemical or physical change, whereby it became soft and fragile and that this apparent decay of the concrete was in large measure responsible for the cracking observed. (4) *Mechanical pressure.* When a current passes from iron into the concrete, corrosion of the iron results with the ultimate production of insoluble compounds of

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[4] A. J. Nicholas: Tests on Effect of Electrolysis in Concrete, Eng. News, **60**, p. 710.

[5] O. L. Eltinge: Tests on Effect of Electrolysis in Concrete, Eng. News, **63**, p. 373.

iron, largely the oxides. These form near the surface of the iron and occupy about 2.2 times as much space as the original iron from which they were formed. It is evident, therefore, that considerable mechanical pressure might be developed in this way between the surface of the iron and the concrete, possibly sufficient to produce the cracking observed. This theory had perhaps been most widely accepted, but it was directly opposed by Upson and Barker[6] as a result of their experiments with collapsible electrodes. These experimenters used hollow electrodes made by rolling thin sheet iron into cylindrical forms, the idea being that they would collapse readily, and thus relieve any radial pressure that might be developed at the surface of the electrode. When these electrodes were used, the concrete was found to crack in very much the same manner as when solid electrodes were employed, and it was therefore concluded that there was no appreciable pressure developed on the surface of the electrode. Upson and Barker advanced the theory that the cracking was due to *the formation of deposits of iron compounds*, chiefly hydrates, *within the pores of the concrete*, and these on oxidation developed the forces which are responsible for the cracking of the concrete. These various theories will be discussed in detail hereafter in connection with the description of the experimental work carried out at the Bureau of Standards.

In addition to the laboratory investigations discussed above, a number of cases had been reported in the technical press in which damage of a serious nature had occurred to certain concrete buildings, bridges, and other structures in which the damage was attributed to stray currents from power circuits. Whether or not the problem was as serious from a practical viewpoint as these reports led many to believe, the possibility of trouble having been established, a thorough investigation of the subject became imperative. Such an investigation was authorized by act of Congress June 17, 1910, and a special appropriation made for carrying on the work.

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[6] Barker and Upson: Experimental Studies of the Electrolytic Destruction of Reinforced Concrete, Eng. News, 66, p. 10.

As mentioned above the investigation has consisted of three parts, as follows:

I. Laboratory investigations relating to the nature and cause of the phenomena produced by the passage of electric currents through concrete.

II. Investigations in the field with the view of establishing the probable extent of the danger in practice and the circumstances under which trouble is most likely to occur.

III. A study of the various possible means of mitigating trouble from this source, leading to specific recommendations.

II. INVESTIGATIONS RELATING TO THE NATURE AND CAUSE OF THE PHENOMENA RESULTING FROM THE PASSAGE OF ELECTRIC CURRENTS THROUGH CONCRETE

1. FORM AND COMPOSITION OF TEST SPECIMENS

At the outset of the investigation a number of the experiments described by previous experimenters were repeated in order to verify their results and also to afford an opportunity for studying at first hand the phenomena previously observed. At the same time numerous modifications of these experiments, as well as many radically different ones, designed to throw light on particular phases of the subject, were instituted. In this preliminary work one general type of specimen was adhered to as far as practicable. A number of well-known brands of Portland cement, all of which conform to the requirements of the standard specifications for Portland cement, were selected, together with sand and stone similar to those used in large quantities by builders in the city of Washington for reinforced concrete construction work. Using filtered Potomac River water, these ingredients were made into a 1:2½:4 concrete, proportions which gave a fairly dense aggregate. In many experiments, especially where chemical analyses were to be made, quartz sand and distilled water were used, as noted later. The specimens were molded into cylinders 6 inches in diameter and 8 inches long, with an electrode embedded in the axis of each cylinder, as shown in Fig. 1.

The specimens were allowed to remain in the molds until set sufficiently for handling and then removed and buried in wet sand for approximately 20 days. At the end of this time they were taken out of the sand and placed in an inclosed case, where they were wet down occasionally until used.

Where iron served as material for the embedded electrode it was cleaned of scale and rust by pickling in dilute sulphuric acid. After the pickling process was completed the iron was removed from the acid, dipped in limewater and immediately embedded in the specimen, after being numbered and weighed.

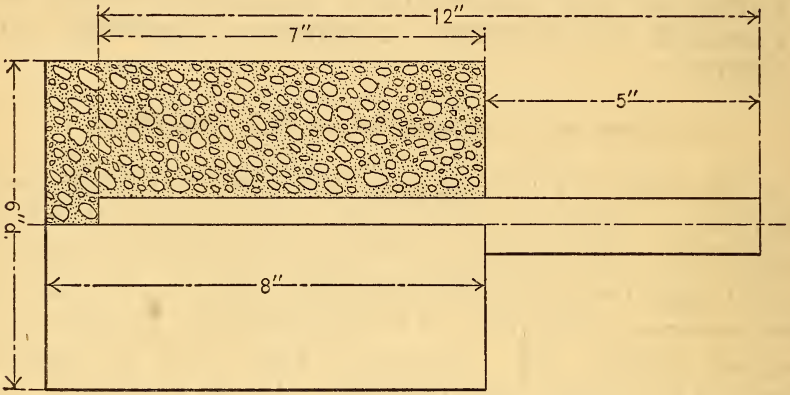

Fig. 1.—*General type of specimen used in electrolysis tests*

This insured the entire absence of rust to begin with. Electrodes other than iron were sandpapered or otherwise cleaned to a bright surface before embedding. In the report of each experiment the type of electrode used is given as well as any departure from the procedure described above.

2. ELECTRICAL CIRCUITS

Direct electric current for the experiments was obtained from two sources. One of these was the 115-volt power circuit of the bureau and the other the 15-volt circuit of a small motor-generator set. The wires from these circuits were led into cases containing the specimens under test and terminated in binding posts at convenient points. Intermediate voltages were obtained by connecting a small storage battery in the circuit of the 15-volt generator and tapping it at suitable points, or by connecting a metallic resistance across the 15-volt or 115-volt circuit, as the case demanded, and shunting a certain portion of it with the specimen. The currents used by the specimens were all very small. Still another way of getting intermediate and equal voltages on specimens was to connect two specimens in series, and, in parallel with the one having the highest resistance, place a water rheostat. These water rheostats were made by filling a glass jar with distilled water and placing two movable sheet-iron electrodes in the jar. The resistance of these rheostats could be varied from 200 to 5000 ohms and they served the purpose very satisfactorily.

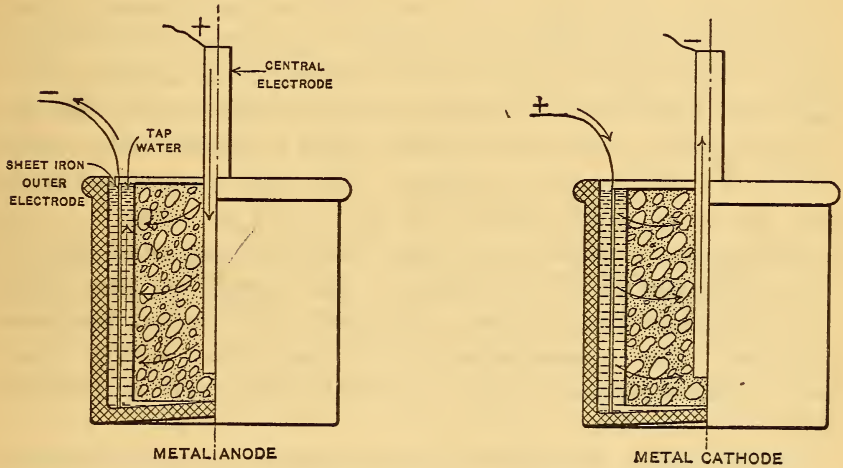

Fig. 2.—*Showing method of making connections to specimens*

3. ARRANGEMENT OF SPECIMENS IN VESSELS

Each specimen under test was placed in an earthenware jar 8½ inches in diameter and 9 inches deep. For an outer electrode an 8 by 24 inch piece of No. 24 gauge sheet-iron was rolled into a cylinder 7 inches in diameter by 8 inches long and placed around the specimen. The arrangement is shown in Fig. 2. The jar, with the exception of cases otherwise designated, was filled to about 1 inch from the top of the specimen with tap water. Rubber-covered wire leads were soldered to the outer sheet-iron electrode and to the projecting end of the embedded metal. By connecting these wires to the proper poles of the electric circuits the embedded metal could be made either anode or cathode. The jars were set on shelves in a case provided with glass doors. The shelves were fitted with drip pans connected to a common drain pipe. Two cases had spaces for 180 jars.

4. ELECTROLYTE

The term "tap water" as here used means Potomac River water after being filtered for domestic use in the city of Washington. The use of this water for electrolyte in all but a few cases was justified by a chemical analysis which shows that its principal foreign ingredient is lime, which is present only to the extent of a few parts in a million. The water evaporated from each jar at an approximate rate of 100 cc per week. A test extending over a period of 50 weeks would, consequently, permit a total evaporation of water about twice during that time, since the jar contained nearly 3000 cc of liquid when the specimen was immersed. The concentration of the impurities in the water used would therefore be very low in the electrolyte at the end of the test.

In none of the tests recorded in the section on anode effects or in the section dealing with cathode effects, was a complete change of electrolyte made. As the water evaporated the jars were refilled to the proper amount; the electrolyte retained, in addition to the impurities of the water, the compounds diffused from the immersed specimen and those absorbed from the atmosphere above it.

5. MISCELLANEOUS CONDITIONS OF TESTS

The description of the phenomena observed is given under two heads, viz, (1) anode effects, or those effects observed where the current flows from the embedded iron into the concrete, and (2) cathode effects, or those occurring when the current flows from the concrete to the embedded iron. In each case experiments were carried out both under high and low voltage, and as the results were radically different in the two cases, they are discussed below under separate heads. In the high-voltage tests the specimens were subjected to voltages varying from about 50 to 70 volts, and the current flow was continuous, except for infrequent and irregular intervals when work was being done on the specimens under test or on the electric circuits to which they were connected. The time during which they were disconnected amounted to less than 1 per cent of the total time. In the low-voltage tests the current was maintained for 7½ hours each working day for the first 8 weeks, after which the current was on for 24 hours each day, with the exception of Sundays and holidays and an occasional short interval when the machine was shut down for repairs. In calculating the number of hours of a test only the time during which current flowed was considered.

6. ANODE TESTS ON HIGH VOLTAGE

Only a comparatively small number of specimens were tested on high voltage, because such conditions are abnormal and would rarely, if ever, be encountered in practice. A few of these were made, however, to check the observations of previous experimenters, and the results noted in these tests are recorded briefly below. In the preliminary tests on high voltage, in which iron served as the anode, 11 specimens were used. They were all of like proportions, viz, 1:2½:4, and were connected two in series on 115 volts direct current. Condensed data on these tests are given in Table 1. All of the specimens behaved in substantially the same manner. During the first few hours there was an appreciable rise in the external temperature. In most cases this rise amounted to from 12° to 25° C above room temperature as measured by a thermometer placed within the electrode if hollow, or against the electrode at the point of emergence from the concrete and covered with cotton waste if the electrode was solid. This rise of temperature usually reached its maximum and diminished very considerably before any damage to the concrete was apparent. After a few hours of current flow bubbles of water containing iron rust began to appear around the anode and cracks soon developed in the concrete. The manner in which the cracking occurred was the same in all specimens. First there appeared a very fine crack, beginning at the iron and extending outwardly in practically a radial direction. This crack soon extended to the outer surface of the concrete cylinder, and then gradually widened, while at the same time two or three other smaller cracks would appear on the opposite side of the anode from the initial crack, also radiating from the center.

The manner in which these cracks occur and develop is strongly suggestive of a wedge-like action slowly applied at the center of the specimen. After the first crack has extended from the center to the outer surface of the concrete, the specimen can readily be pried open with a screwdriver and separated into several pieces. The individual pieces of concrete thus obtained are, however, to all appearances as strong as similar specimens of concrete that have not been subjected to the influence of electric currents and are broken with a hammer with the same difficulty. There is no indication whatever that the cement decayed or deteriorated in any way, as reported by some earlier investigators, but, on the contrary, the appearance of the concrete and its mechanical properties both indicate very strongly that there has been no such action. This is fully substantiated by special experiments described in a later section, which appear to show quite conclusively that in the body of the concrete remote from either electrode the current has no apparent effect on the concrete.

As shown in Table 1, most of the specimens cracked in about the same time, the first eight specimens containing Old Dominion cement having shown cracks at the end of 23 hours. Nos. 10 and 11, containing Alpha cement, required 72 hours, while No. 9, made with Medusa White Portland cement, required 96 hours to develop a fracture. In the latter case, however, it will be noted that the voltage at starting was only 24.5 volts, this gradually rising to 54 volts at the time of cracking. This low voltage at the start was caused by the placing of a rheostat in series with the specimen in order to prevent an unduly rapid rise of temperature. As the specimen warmed up the resistance of the rheostat was cut out by steps until full voltage was on.

The variation of the electrical resistance of the specimen with time is of particular interest. In Table 1 the resistances of the test specimens at three stages are given, viz, at starting, at the time of cracking, and at the conclusion of the test. It will be noted that the first eight specimens containing Old Dominion cement show a fair degree of uniformity in initial resistance, the average of the eight being 68 ohms. At the end of 23 hours, when cracks first appeared, this had increased somewhat, the average then being 133 ohms. At the end of the test this average had risen to 2194 ohms, or over 32 times its initial value. This enormous rise in resistance with time is of the greatest importance, particularly from the practical standpoint, and is referred to again in another part of this paper.

On breaking open the specimens the embedded iron was found to have been very badly corroded, thick layers of scale consisting largely of the oxides of iron having formed all over the surface and to some extent in the voids in the concrete adjacent to the iron. In those specimens which were left in circuit for a long period after cracks developed, the deposit of oxides spread for some distance out into the cracks, but in specimens 10 and 11, which were removed and opened immediately after cracking, this was not the case. Upon breaking open the solid portions of the concrete it was found that the discoloration due to the products of corrosion had not penetrated into the body of the concrete more than an eighth of an inch or so.

The general appearance of the specimens is shown in Fig. 3, which is a photograph of two specimens, one exhibiting the initial crack as caused by the passage of the current and the other showing the appearance of a similar specimen after having been pried open to expose the embedded iron. They form very striking examples of what may happen to reinforced concrete when subjected to comparatively high voltages. They should not, however, be assumed to represent a condition that is liable to be of frequent occurrence in practice, as will presently appear.

TABLE 1

High Voltage Tests of Reinforced Concrete, Using Iron Electrodes

Specimen number	Volts at beginning of test	Volts at cracking	Average current to cracking (amps.)	Total ampere hours.	Ampere-hour density per sq. in.	Resistance at beginning of test (ohms)	Resistance at cracking	Resistance at end of test	Hours to cracking	Hours of test	Cement used	Electrode used	Age of specimen at test
1.....	55. 0	38. 0	0. 75	17. 25	1. 04	64	90	1766	23	1128	Old Dom.....	¾-inch round iron	40 days
2.....	59. 0	78. 0	0. 75	17. 25	1. 04	70	171	2100	23	1128	.....do........	.....do..........	Do.
3.....	59. 5	63. 0	0. 57	13. 20	0. 86	79	157	2330	23	1128	.....do........	.....do..........	Do.
4.....	54. 5	53. 0	0. 57	13. 20	0. 86	72	132	1530	23	1128	.....do........	.....do..........	Do.
5.....	56. 5	77. 0	0. 74	17. 02	0. 63	66	140	2700	23	1200	.....do........	1-inch pipe......	56 days
6.....	55. 5	69. 5	0. 79	18. 10	0. 67	69	124	2400	23	1200	.....do........	.....do..........	Do.
7.....	55. 0	53. 5	0. 57	13. 00	0. 48	58	119	1920	23	1200	.....do........	.....do..........	Do.
8.....	62. 0	70. 0	0. 74	17. 02	0. 63	71	132	2810	23	1200	.....do........	.....do..........	Do.
9.....	24. 5	54. 0	0. 144	13. 80	0. 83	122	275	5250	96	3068	Medusa white Portland	¾-inch round iron	Do.
10.....	58. 0	57. 0	0. 42	30. 96	1. 08	100	140	140	72	72	Alpha.........	1-inch pipe......	9 months
11.....	58. 0	57. 0	0. 39	28. 20	1. 00	100	163	163	72	72	.....do........	.....do..........	Do.

7. ANODE TESTS ON LOW VOLTAGE

Tests on specimens subjected to 15 volts and less were carried out in much greater number than those on high voltage. At the outset of the investigation 90 specimens containing iron electrodes were placed in circuit and watched for a period of about 5500 hours (7½ months), during which time careful records were kept of voltage and current flow. Now and then a few specimens were broken open to give an idea of what was taking place. At the end of the time mentioned a large number of specimens were broken open and examined, the amount of the corrosion determined, and the general condition of the concrete noted. A most conspicuous feature of the results of this test, and a very surprising one in view of the results previously obtained at higher voltages, is the fact that cracking almost universally failed to occur. Of the 90 specimens under test only 3 had cracked at the end of 5500 hours. One of these was made of a white Portland cement, a cement which is shown later to give much larger amounts of cor-

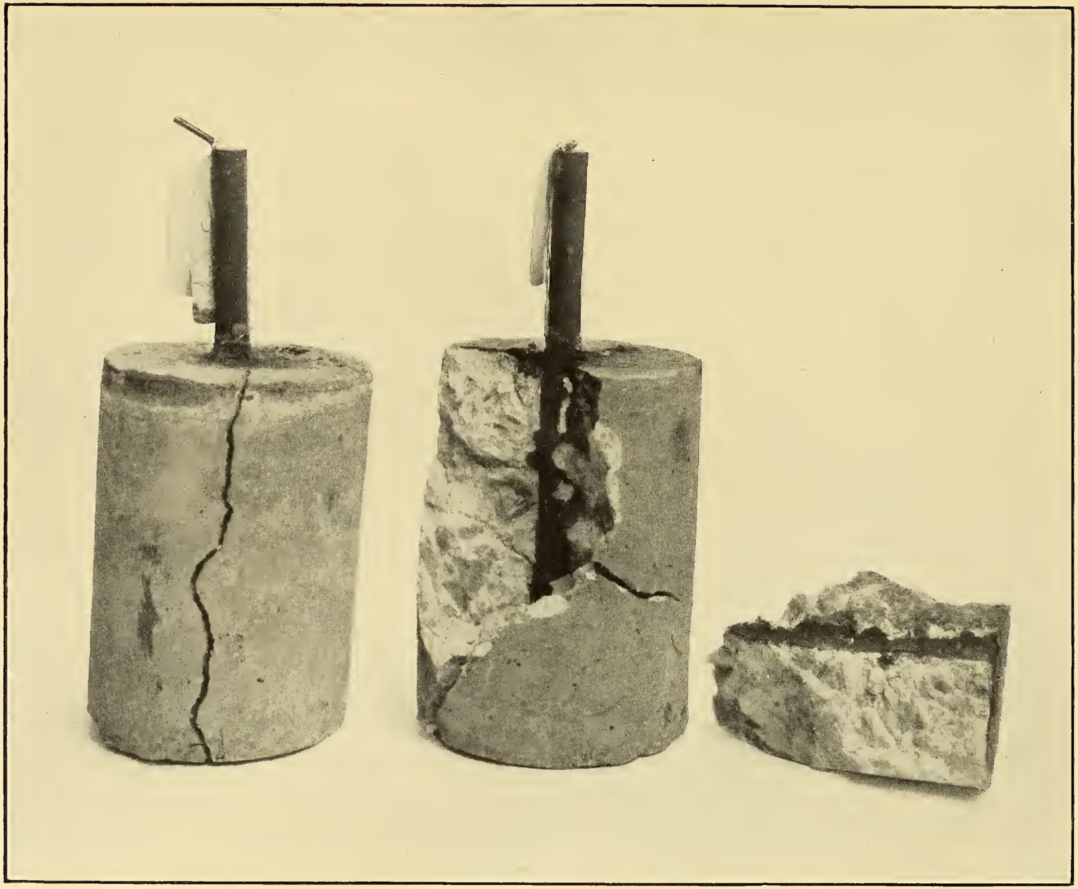

Fig. 3.—*High voltage anode specimens*

rosion under certain circumstances than most of the ordinary brands of Portland cement under similar conditions, and the other two of Old Dominion cement, to one of which a foreign ingredient (20 per cent of paraffin-gasoline solution) had been added. Both of the specimens of Old Dominion cement which cracked possessed rather unusual characteristics and behaved very differently from their fellows of the same composition, inasmuch as their resistances at starting were normal, but at cracking the resistance of the one to which no foreign ingredient had been added (No. 30, Table 2) had increased only two times, while the other had increased three times (see No. 3, Table 15). The time of cracking was 1000 hours and 2100 hours, respectively. At the end of the test the resistance of the first specimen was 4 times as great as at starting, while that of the second was 10 times as great. These values are but a small fraction of those ordinarily observed at corresponding periods in the life of similar specimens, as will later appear. This eccentricity seems sufficient to exclude these two specimens from consideration as normal specimens. Since white Portland cement has been found, in general, to differ very materially from the ordinary run of Portland cements in its electrochemical characteristics it should doubtless be considered in a class by itself.

It seems allowable, therefore, to say that not one of 87 normal specimens made of ordinary Portland cement and put under test on 15 volts or less had cracked at the end of 5500 hours. Of the specimens which were then opened for examination it was found that in every case the concrete was broken with difficulty and appeared to be as sound as that of similar specimens made at the same time and not subjected to the action of electric currents. In practically all cases there was more or less corrosion around the anode at the point where it entered the concrete and in some instances for an inch or so below the surface. In some cases, also, where there were voids in the concrete next to the iron there was some rust and slight pitting, but in nearly all cases where the concrete was in actual contact with the iron the corrosion was quite small, and in many cases the iron was practically as bright and clean as when placed in the concrete. Condensed data of the tests on a few representative specimens broken open to date are given in Table 2. It is important to note that the total number of ampere-hours per square inch of embedded electrode surface carried, on the average, is considerably larger than the corresponding figures for the high-voltage specimens at the time they cracked, the average being 2.6 for the low-voltage specimens, as against 0.83 required to crack the high-voltage specimens. It is evident, therefore, that the quantity of electricity that passes through a specimen does not alone determine the amount of damage that it may do, but that the rate at which the current flows is also an important factor. Moreover, it must be evident from these observations that the rate at which damage occurs decreases with decreasing voltage much more rapidly than the voltage is lowered, since in the present instance a reduction of the voltage to one-fourth of the value used in the high-voltage tests enabled the specimens to run with little or no damage for a period over 200 times as long as was required to crack and split open the specimens on the higher voltage.

The resistances given in Table 2 are also instructive. It will be seen that the average resistance of the specimens at the beginning of the test was 91 ohms, and at the end of the test it had risen to 12 500 ohms, or about 137 times its initial value. It is obvious that the rise of resistance, and therefore the tendency toward self-protection, is much more marked in the case of the low-voltage specimens than in those run on the higher voltage. As this matter is discussed at length later it is simply mentioned here.

TABLE 2

Low-Voltage Tests on Reinforced Concrete Using Iron Anodes

Specimen number	Voltage	Total ampere-hours	Ampere-hour density per sq. in.	Resistance in ohms at beginning of test	Resistance at end of test	Hours of test	Cement used	Electrode used	Age of specimen at test	Corrosion
12	15	49.5	1.81	75	10000	5508	Atlas	1-inch pipe	30 days	None
13	15	44.0	1.61	85	9370	5508	do	do	do	Do.
14	15	105.6	4.20	64	3300	5500	Dragon	do	do	Slight
15	15	53.4	1.95	75	21000	5500	do	do	do	Do.
16	15	45.4	1.66	94	3000	5500	Alpha	do	34 days	Do.
17	15	34.9	1.28	81	50000	5500	do	do	do	Do.
18	15	55.0	2.10	75	12500	5500	Lehigh	do	24 days	Do.
19	15	62.3	2.30	69	15000	5500	do	do	do	Do.
20	15	74.3	2.73	100	5000	5500	Pennsylvania	do	23 days	Severe
21	15	91.0	3.30	92	7500	5500	do	do	do	Do.
22	15	35.5	2.10	141	8800	5300	Giant	¾-inch round iron	46 days	None
23	15	35.2	2.10	133	15000	5300	do	do	do	Do.
24[7]	15	93.0	5.60	127	1875	4400	White Portland	do	57 days	Severe
25	15	66.0	4.00	134	5000	4400	do	do	do	Very severe
26	15	26.6	0.97	107	7500	1800	Alpha	1-inch pipe	9 months	Slight
27	15	47.6	1.74	88	7500	1800	do	do	do	Do.
28[8]	15	52.4	1.90	75	5000	5691	Old Dominion	do	57 days	Medium
29[8]	15	54.6	2.00	75	5000	5691	do	do	do	Do.
30[9]	15	121.9	4.50	81	469	2477	do	do	do	Very severe
31	5	11.7	0.43	126	5200	5300	do	do	80 days	None
32	5	13.7	0.50	137	5700	5300	do	do	do	Do.

[7] Hours to cracking, 732. Resistance at cracking, 470 ohms. Ampere-hours per square inch to cracking, 2.4.

[8] Electrolyte distilled water.

[9] Hours to cracking, 1000. Resistance at cracking, 260 ohms. Electrolyte distilled water.

8. TESTS ON MATERIALS OTHER THAN IRON AS ANODE

(*a*) COPPER, BRASS, CARBON, AND COPPER-CLAD STEEL

A number of specimens were made up with Old Dominion cement in a 1 : 2½ : 4 mixture, but using copper, brass, carbon, and copper-clad steel as electrodes. Part of these were placed in circuit with the metal or carbon as anode, and subjected to voltages ranging from 15 to 60 for periods varying from a few days to 10 months. The data obtained from the tests on copper, brass, carbon, and copper-clad steel are summarized in Table 3. Nos. 33 and 34 were in series, as also were 35 and 36, and 37 and 38. The action in the cases of 33, 37, and 38 was much the same for each one as far as appearance went. The resistances at the end were very different, however. There was no cracking whatever in any case, nor was there any disintegration of the concrete apparent upon breaking. The outside surfaces of the blocks were not changed in appearance except for the deposit of calcium carbonate usually found beneath the water. The action in Nos. 34, 35, and 36 was somewhat different. A good deal of water was forced out around the electrode which, evaporating, deposited calcium carbonate, forming at the same time a path for the current over the top of the specimen which caused deep pits to be formed in the brass rods where they entered the concrete. On breaking open the specimens the appearance of Nos. 33 to 38 was much the same, there being a layer of red copper compound next to the metal, a black layer over this, and what was apparently $CuSO_4$ diffused for some distance into the concrete. Nos. 39 and 40 were the same in appearance as 33 to 38, but were not corroded to as great a degree. Nos. 41 and 42 were in no way different from the rest.

TABLE 3

Anode Effects in Concrete using Brass, Copper, and Carbon Electrodes

Specimen number	Volts at beginning of test	Volts at end of test	Total ampere hours	Ampere-hour density per sq. in.	Resistance in ohms at beginning of test	Resistance at end of test	Hours of test	Electrode used	Age of specimen at test	Anode loss in grams
33	52.5	8.0	108.0	10.1	55	920	3988	½-inch copper	24 days	8.6
34	60.5	104.0	108.0	10.1	63	11900	3988	½-inch brass	do	11.1
35	57.0	57.0	58.8	5.3	112	15000	1836	do	7 months	7.5
36	57.0	57.0	53.6	4.8	112	15000	1836	do	do	5.1
37	57.0	57.0	103.0	9.4	112	8142	1836	½-inch copper	do	9.8
38	57.0	57.0	95.6	8.3	112	8142	1836	do	do	10.0
39	15.0	15.0	31.6	3.9	250	9370	5643	⅜-inch brass	50 days	1.0
40	15.0	15.0	42.6	5.3	103	3750	5643	⅜-inch copper	do	......
41	15.0	15.0	33.3	2.0	115	3000	1808	½-inch brass	9 months	2.0
42	15.0	15.0	53.4	3.3	115	3000	1808	½-inch copper	do	3.5
43	57.0	57.0	75.4	9.1	120	2110	1302	⅜-inch copper-clad steel	26 days	10.9
44	57.0	57.0	75.4	9.0	116	2110	1302	do	do	11.6
45	58.0	57.0	80.5	7.3	96	613	450	½-inch carbon	10 months	......
46	58.0	57.0	58.0	5.2	83	613	450	do	do	......
47	57.0	57.0	73.5	6.7	44	295	714	do	5 days	......
48	57.0	57.0	64.9	5.9	40	375	714	do	do	......
49	15.0	15.0	32.3	3.0	75	1875	3229	do	50 days	......
50	15.0	15.0	52.6	4.8	79	3750	1919	do	10 months	......
51	15.0	15.0	32.3	2.9	101	3750	1919	do	do	......

In Nos. 43 and 44, containing anodes of copper-clad steel, the greatest amount of corrosion occurred at the bottom of the electrodes and the points where they entered the concrete. The iron seemed to corrode very rapidly where it was exposed in cutting. Gas forming at the anodes forced water out on top of the concrete and made an electrolytic path across the top of the specimen to the water in the jar and caused the corrosion where the electrodes entered the concrete. There were no pits reaching to the iron below the surface of the concrete, except where the iron was exposed in cutting. The surfaces of the rods were much corroded and roughened by the action of the current, thereby tending to increase the bond between the concrete and the rod. There was no cracking or disintegration of the concrete notwithstanding the high ampere-hour density. On the whole, these specimens acted much the same as copper anode specimens, having the same layers of oxides in regions outside the exposed area of the iron. Specimens 45 to 51 all acted very much the same. The carbon disintegrated and appeared as a thick black liquid around the electrode to a degree which seemed to depend on the voltage and rate of current discharge. There was no disintegration of the concrete, nor any sign of cracks in any of these tests, although heating was considerable in specimens 45 to 48. The fact that the concrete did not crack in any of the above cases is significant, and it is interesting to note in this connection that in the case of the metals used there is a tendency for the formation of soluble salts as the end products of corrosion. Since these salts remain in solution to some extent, they diffuse through the concrete and thus do not give rise to the local mechanical pressure found in the case of iron, where the insoluble oxides are precipitated near the surface of the anode. This phenomenon supports the theory that the cracking of the concrete is due to a mechanical pressure developed by the formation of oxides at the anode surface. This is referred to again in a later section dealing in detail with the causes of fracture in the concrete.

(*b*) TESTS ON ALUMINUM ANODES

The possibility that the protective film formed over the surface of an aluminum-covered rod, when embedded in concrete and made anode, might serve as a preventive of electrolysis in concrete was first suggested by Magnusson and Smith,[10] and the fact that the experimental results published by them tended to show that aluminum would not suffer deterioration as iron does when maintained anode in concrete led to the following investigation.

The tests were made on aluminum rods with voltages ranging from 5 to 115, the embedded metal being made anode, and, although the number of specimens used in each case is rather limited, the results may be taken as a fairly reliable indication of what may be expected of this metal in service. The specimens

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[10] Magnusson and Smith: The Electrolysis of Steel in Concrete, Proc. A. I. E. E., 30, p. 939.

were all made with Old Dominion cement, the mixture being 1 : 2½ : 4 and all tests were made in tap water.

The test of specimen No. 52, Table 4, on 115 volts was purposely made very severe, in order to see whether the anode film would form on aluminum when made anode in concrete, and whether it would stand up under the high voltage. The current was very high at first, but dropped off rapidly. There was a considerable amount of heating in the immediate vicinity of the electrode and this may have been primarily responsible for the cracking which followed within a few hours. On removal from the jar the specimen fell in pieces and a large amount of white aluminum products was found around the embedded metal. These products appeared to occupy a great deal larger volume than the original metal. The concrete was not disintegrated and there was no dissemination of aluminum products through the concrete other than that which took place along the cracks.

Specimen No. 53, made anode on 60 volts, was of somewhat faulty construction, as the electrode came to about three-eighths inch from the bottom of the cylinder. The film formed, as shown in the data in Table 4, but the concentration of current flow at the bottom of the rod caused severe corrosion there. The resulting pressure from below pushed the rod upward about one-sixteenth of an inch and at the same time broke the entire bottom half of the specimen into several pieces. The formation of salts was of the same nature as in specimen No. 52, but was confined to the bottom of the rod.

Specimen No. 54, made anode on 30 volts, did not crack nor was there a marked formation of aluminum salts. The loss by corrosion was very low, as shown in the table, but this was in the form of pits which were rather deep, but not of very great area. Some of them were one-sixteenth inch in depth and about the same diameter.

Specimen No. 55, made anode on 15 volts, acted almost the same as No. 53, except that the loss by corrosion was not so great. The construction was the same, however, and such an action might be expected.

None of the specimens tested for any appreciable length of time was free from corrosion of the metal, and where aluminum products formed they occupied a much larger volume than the metal from which they originated.

An examination of Table 4 shows that the resistance rises very quickly at the beginning of the test when aluminum anodes are used. This is doubtless due to the formation of the high-resistance film on the surface of the aluminum just as in other forms of aluminum cells. This resistance is not altogether permanent, however, as there was a considerable diminution of resistance in most of the specimens as the test proceeded, although it never returned to its initial value. It is not sufficient, however, to protect the metal as the large amount of corrosion observed shows.

TABLE 4

Aluminum Anodes in Concrete

Specimen number	Voltage of test	Hours of test	Resistance at beginning of test	Resistance after 20 minutes	Resistance at end of test	Age of specimen at test	Loss in weight of electrode	Hours to cracking
						Days	Grams	
52	115	20	57	1045	287	9	7.136	10
53	60	1440	50	8000	7500	40	9.2	192
54	30	1248	130	1700	8571	36	.853	(11)
55	15	1248	100	3000	3750	40	2.4	192
57	5	2709	143	10000	20000	36	(12)	(11)

[11] No cracks.

[12] Slight pitting.

9. CATHODE EFFECTS USING IRON, BRASS, COPPER, CARBON, AND ALUMINUM ELECTRODES

In the preceding section the phenomena noted are those resulting when current flows from the embedded iron or other metal out into the concrete. When the direction of current flow is reversed, making the iron cathode, very different effects are produced. In this case there is no tendency for the iron to corrode because of the current flow, but on the contrary the iron is protected from any natural corrosion that might tend to take place. In the published work of previous investigators no mention is made of any injurious effects, either to the iron or the concrete in those specimens in which the current flowed from concrete to iron, except in a single instance in which the specimen cracked. The cracking in this isolated instance was beyond doubt merely incidental, since all other investigators have failed to note any tendency to crack when the iron is made cathode. The conclusion has therefore been widely accepted that when the current flows from concrete to iron no effects are produced, and at the time these experiments were begun there appeared to be no substantial ground on which to question this conclusion. It was deemed advisable, however, to confirm these observations, and accordingly a number of specimens were made exactly similar to those used in the anode tests above described, using not only iron, but also brass, copper, carbon, and aluminum as electrodes. These were placed in circuit with the current flowing from the concrete to the electrode. Both high and low voltages were used, and the conditions in general were kept exactly the same as with the anode tests except for the direction of current flow. Condensed data on these tests are given in Table 5.

TABLE 5

Cathode Effects

Specimen number	Voltage at beginning of test	Voltage at end of test	Resistance at beginning of test (ohms)	Resistance at end of test	Total ampere-hours	Ampere-hour density per sq. in.	Hours of test	Electrode used	Age of specimen at test	Cement used
[13] 56	15.0	15.0	130.0	150	....	......	144	$\frac{1}{2}$-inch aluminum	36 days	Old Dominion
58	57.5	20.0	67.0	800	407.0	25.4	8900	$\frac{3}{4}$-inch round iron	40 days	Do.
59	58.5	30.5	73.0	950	395.0	24.7	8900	do	do	Do.
60	59.0	17.0	61.0	1650	415.0	25.7	8900	do	do	Do.
61	52.0	45.0	60.0	2100	422.0	26.2	8900	do	do	Do.
62	56.0	96.0	56.0	1170	387.0	36.8	3988	$\frac{1}{2}$-inch copper	21 days	Do.
63	57.0	16.0	57.0	195	387.0	36.8	3988	$\frac{1}{2}$-inch brass	do	Do.
64	15.0	15.0	53.6	357	330.6	12.2	5508	1-inch pipe	34 days	Atlas
65	15.0	15.0	53.6	384	345.0	12.8	5503	do	do	Dragon
66	15.0	15.0	57.6	405	215.0	8.0	5508	do	33 days	Alpha
67	15.0	15.0	57.0	300	387.8	14.3	5808	do	do	Lehigh
68	15.0	15.0	82.0	468	263.5	35.1	6200	$\frac{3}{8}$-inch copper	50 days	Old Dominion
69	15.0	15.0	88.0	500	279.4	36.0	6200	$\frac{3}{8}$-inch brass	do	Do.
70	15.0	15.0	75.0	208	219.0	20.7	3229	$\frac{1}{2}$-inch carbon	do	Do.

[13] Resistance after 20 minutes, 300 ohms; loss in weight of electrode, 5 grams; hours to cracking, 216.

It will be noted that there is a rise in resistance as the test proceeds very similar to that which occurs in the anode specimens, but this rise is less marked, the average ratio of increase being about 10 to 1. The first four specimens represented in the table (58 to 61) contained iron electrodes. Each one was started in series with an anode specimen, and the voltage went down to about 9 volts at the end of 1200 hours, due to the relatively greater rise of resistance of the anode specimens. The four were then connected in series on 115 volts, and the voltage for the remaining 7700 hours of the test remained practically constant at the values given in the table for the voltage at the end of the test. Throughout the test water was forced out around the embedded iron and kept the top of the specimen wet. This forcing out of water was evidently due to the formation of gas at the cathode, which on escaping forced the water through the pores of the concrete to the surface. This water carried calcium hydroxide in solution, and as evaporation took place calcium carbonate was deposited in rings surrounding the cathode on the surface of the concrete. The greater part of the gas evolved was hydrogen. As the test proceeded the mortar on the top surface of the specimen immediately surrounding the cathode became quite soft. This softening extended in the surface to a distance of about three-fourths inch from the cathode, and in this region the concrete was darker, particularly while wet, than elsewhere. After the expiration of several months, and at intervals thereafter, certain of the specimens were broken open for examination. In every case the concrete blocks were broken with difficulty, the main body of the concrete being apparently as sound as in similar specimens not subjected to the action of electric currents. On laying the specimen open it was found that the embedded metal was in a perfect state of preservation, but the entire region surrounding the cathode for a distance of one-sixteenth inch to one-fourth inch from the surface of the metal was considerably darker in appearance than the main body of the concrete and was very soft, like the concrete immediately surrounding the cathode at the surface. The cement here could be shaved off with a knife like soft soapstone.

In specimens Nos. 62 and 63, having copper and brass cathodes, respectively, the same phenomena were observed, except that in specimen No. 63 no water was forced out at the surface surrounding the cathode. Both cathodes were quite slippery when first removed from the concrete. Nos. 64 to 67 contained iron cathodes as above, but were subjected to only 15 volts throughout the test. The results were the same as described above, except that they had not advanced quite as far. Specimens Nos. 68 and 69, containing copper and brass electrodes, respectively, behaved exactly the same as Nos. 62 and 63, except that the resulting effects were less pronounced. Specimen No. 70 contained an electrode consisting of a piece of arc-light carbon. The carbon itself disintegrated badly, and after the bond had been destroyed it was forced out of the concrete by the formation of gas underneath. The mortar near the carbon was found to be disintegrated in the same manner and to about the same extent as in the case of metal cathodes on 15 volts.

In all of the above specimens there was a rather sharp line of demarcation between the softened area and the remainder of the concrete, the soft portion being in every case readily distinguishable by its darker color. Outside this darkened zone the concrete appeared to be as sound as in specimens not carrying current, and no physical change of any kind could be detected therein. After the specimens had been broken open for some time and allowed to dry, the darkened zone became somewhat lighter in shade, but there always remained a distinct difference readily detectable by the eye. The softening also diminished greatly as the specimen became drier, and after becoming thoroughly dry it became nearly as hard as the unaffected mortar, but remained distinctly more friable.

Radically different results were obtained from the test on specimen No. 56, in which aluminum was made cathode on 15 volts. The specimen cracked at the end of 144 hours, and when opened the metal was found to be very badly pitted and corroded, but the corrosion was different from that found in the anode tests on aluminum. The products were black, forming a hard shell around the electrode, from which they were separated very readily. This corrosion was doubtless due to a secondary action of products formed by the electrolysis. In the light of the results of experiments described further along in this section, it seems quite probable that the action is the result of a concentration of alkali metals (Na and K) near the cathode by the current with the resulting formation of sodium and potassium aluminates. The dark color described is doubtless due to the presence of iron as impurity. A check specimen made at the same time as specimen No. 56, and kept in water without current flow, showed no corrosion whatever with the exception of a slight reaction between the metal and the cement forming a hard layer on the surface of the metal. There was no loss of weight in the case of the check specimen.

10. BOND TESTS OF CATHODE SPECIMENS

The disintegration of the mortar in the immediate vicinity of the cathode, as described above, led to tests on the relative strength of the bond where current had passed with embedded iron cathode and where it had not. For this test, specimens 58 to 61 of Table 5 were used, together with four identical specimens through which no current had passed. In order to carry out this mechanical test the bottoms of the saturated specimens were ground over a surface perpendicular to the axis of the embedded iron rods until the lower ends of the rods were exposed. The projecting ends of the rods were then sawed down to a length of about 2 inches and the specimens placed, one at a time, in an Olsen testing machine, which pushed the rods through the blocks sufficiently to give the maximum bond strength and also the friction load after the bond was broken. The test was carried out in the usual way, care being taken to see that the rod was perpendicular to the platform of the machine, and the load gradually applied until the beam dropped and slipping commenced. The load at which the beam dropped was taken as the maximum load of the bond and a succeeding reading made while the rod was slipping through the block was taken as the friction load. The rod was pushed through the block a distance of about 0.1 inch.

The results are given in Table 6. It is there seen that the passage of current under the conditions of the test carried out on specimens 58 to 61 reduced the bond to about one-fifth of its original value.

The electrical test here was quite severe, but the other specimens which were run at voltages ranging from 5 to 15 as described, showed on examination that the same disintegrating action was going on, and the extent of the softened area, while somewhat irregular and slightly indefinite, indicated that at least during the first few months of a test the amount of the disintegration is probably roughly proportional to the quantity of electricity that has passed through the concrete, and is thus but indirectly affected by the voltage used, at least within the range of voltages used in these tests. In this respect it is in marked contrast to the anode effects previously described, which appear to diminish much more rapidly than the voltage, until at voltages of 5 to 10 in the specimens used they practically disappear.

TABLE 6

Bond Tests

[Numbers correspond with numbers in electrical-test record sheet]

BOND TEST OF CATHODE SPECIMENS, TESTED ON HIGH VOLTAGE (50 VOLTS)

Specimen number	Total load	Friction load	Maximum strength of bond in pounds per square inch	Friction strength of bond in pounds per square inch	Area of embedded iron.
	Pounds	Pounds			Sq. ins
58	2170	1200	127	70	17.0
59	2640	1500	157	90	16.8
60	2550	1270	155	77	16.4
61	1300	1000	79	61	16.4
Average			129	74	

BOND TESTS ON SPECIMENS THROUGH WHICH NO CURRENT HAD PASSED

58	14500	7000	800	400	17.5
59	9600	3800	585	231	16.4
60	10850	8800	711	516	15.1
61	8340	6000	496	357	16.8
Average			648	376	

11. CAUSE OF SOFTENING ACTION AT CATHODE

In order to throw some light on the nature and cause of the phenomena which gives rise to the softening of the concrete near the cathode, a number of experiments were carried out in which hollow concrete cylinders were used, made from 1 : 2½ : 4 concrete, using Old Dominion cement, sand, and crushed trap. These hollow cylinders were filled with distilled water and immersed in distilled water in a manner illustrated in Fig. 9. One electrode was immersed in the water within the cylinder and the other electrode was immersed in the water outside. The cylinders were electrolyzed under different conditions, as described below, under the various experiments. After the flow of current had continued for some time the water was drawn off and analyzed. In all cases the water contained within the cylinder was taken after the current was stopped, and filtered to remove suspended matter before analyzing. The total amount of solution available was about 200 cc, and of this one-fourth was used in all cases in each group so that the results are directly comparable.

Sample 1.—Anode solution from interior of concrete cylinder, which had been electrolyzed with an iron anode for 28 hours, with 15 volts, and a current which averaged about 0.045 amperes. This solution contained a light brown precipitate in suspension, due to the oxidation of the iron anode. This was filtered off and the solution was analyzed for SO_3, with the following results: SO_3, 0.042 g.

Sample 2.—Cathode solution from interior of concrete cylinder which had been electrolyzed with an iron cathode for 28 hours, with 15 volts, and a current which averaged 0.110 amperes. This solution was practically clear, with a few suspended particles, which were filtered off, and the solution was then analyzed for SiO_2, Al_2O_3, and CaO, alkalies, and SO_3. The solution was strongly alkaline. The results of the analysis were as follows:

	Gram
SiO_2	0. 006
Al_2O_3 and Fe_2O_3	. 005
CaO	. 003
K_2O	. 446
Na_2O	. 196
SO_3	None.

Sample 3.—Water from interior of concrete cylinder, the same as samples 1 and 2, except that no current passed. The water remained in the cylinder 28 hours, after which it was practically clear, with a few suspended particles, which were filtered off. The solution was then analyzed for SO_3, SiO_2; Cl_2O_3 and Fe_2O_3, CaO, and the alkalies, with the following results:

	Gram
SO_3	0.006
SiO_2	None.
Al_2O_3 and Fe_2O_3	None.
CaO	None.
K_2O	.011
Na_2O	.006

Sample 4.—Anode solution from interior of concrete cylinder, which had been electrolyzed with an iron anode for 28 hours, with 110 volts, and a current which averaged 0.82 ampere. This solution contained a dark brown precipitate in suspension in considerable amount, caused by the oxidation of the iron anode. This was filtered off and the solution was diluted to 250 cc and analyzed for SO_3, and CaO, with the following results:

	Gram
SO_3	0.061
CaO	None.

Sample 5.—Cathode solution from interior of concrete cylinder, which had been electrolyzed with an iron cathode for 28 hours, with 110 volts, and a current which averaged 1.8 amperes. This solution was strongly alkaline and was practically clear, except for a few suspended particles, which were filtered off. The solution was analyzed for SiO_2, Al_2O_3 and Fe_2O_3, CaO, alkalies, and SO_3, with the following results:

	Grams
SiO_2	0.027
Al_2O_3 and Fe_2O_3	.022
CaO	None.
K_2O	1.944
Na_2O	.852
SO_3	.014

The solution contained CO_2.

Sample 10A.—Cathode solution from interior of concrete cylinder, which had been electrolyzed with a carbon cathode 5 hours, with 110 volts and about 1 ampere. The solution was analyzed for SiO_2, Al_2O_3, and Fe_2O_3, CaO, alkalies, and SO_3, with the following results:

	Gram
SiO_2	None.
Al_2O_3 and Fe_2O_3	None.
CaO	0.018
K_2O	.349
Na_2O	.036
SO_3	None.

Sample 10B.—Anode solution from the exterior of the concrete cylinder from which sample 10A was taken. A carbon anode was used. This solution was very dark brown, with black suspended particles, due to the disintegration of the carbon anode. After filtering the solution was analyzed for SO_3 and with the following result: SO_3, 0.112 gram.

The results of these water analyses show that the constituents of concrete which are affected by the passage of the electric current are the water-soluble constituents, namely, the alkali salts, and probably the water-soluble calcium salts, and that the migrations of the ions is the same as in any water solution; that is, the positive ions, sodium, potassum, and calcium, move toward the cathode, and the negative ions move toward the anode. Thus, in samples 1, 4, and 10B, which were the solutions taken from around the anode, the SO_3 ions are present in very much larger amounts than in sample 3, which was the solution through which no current passed, or in samples 2, 5, and 10A, which were solutions taken from around the cathode; and, further, that the SO_3 content was greater in sample 4 than in sample 1, on account of the larger current which was employed in the former case.

In examining the results obtained from the solutions which were taken from around the cathode, namely, samples 2, 5, and 10A, it is found that the solutions were all strongly alkaline and that the alkali concentration was very much greater than in the case of sample 3, which was the solution in which the concrete soaked without the passage of the current. It is also seen by comparing samples 2 and 5 with each other that the alkali concentration was much greater in the latter, due to the greater current which was employed. The presence of silica and aluminum in these cathode solutions is doubtless to be explained by the solvent action of the potassium and sodium hydroxides on the combined silica and alumina of the concrete, as will appear later. It is seen that more silica and alumina were found in sample 5 than in sample 2, the former solution being more strongly alkaline than the latter. It would be expected that calcium would be found in rather large amount in the cathode solutions, as some of the calcium is doubtless present in concrete in a water soluble condition, so as to be affected by electrolysis; and it will be noticed that a slight amount of calcium was found in the cathode solutions 2 and 10A, while none was found in solution 3 or in the anode solution 4. The reason for there being no calcium in the cathode solution 5 is probably found in the fact that any calcium which may have been present originally would have been converted to the insoluble carbonate, since the solution contained considerable amounts of carbon dioxide, probably absorbed from the air, and the same explanation may apply to the other cathode solutions, although carbon dioxide was not especially noticeable in those solutions. Furthermore, the concrete specimens used in these tests had been exposed to the air in the laboratory for more than a year before the above tests were made, so that it is possible that a large proportion of the calcium occurred as insoluble carbonate, and hence would not have been affected by the current to an appreciable degree.

Other experiments were carried out along the same line on specimens made up with neat cement, and after they had been subjected to the action of an electric current for several months with the embedded iron cathode, samples of cement were taken at three points, viz, near the cathode where the cement was soft, midway between the anode and cathode, and near the anode, and subjected to chemical analysis, the results of which are summarized in Table 6A. The table also contains the results of alkali determinations on the cement used in making up the specimens.

TABLE 6A

Specimen from—	CaO	K_2O	Na_2O
	Per cent	Per cent	Per cent
Interior around cathode	57.74	6.41	1.75
Between anode and cathode	62.20	.83	.48
Near anode	62.70	.39	.18
Original unset cement	62.40	.87	.38

The analyses of both waters and cement, taken as a whole, show that potassium and sodium are present in the cement in appreciable amounts and that there is a decided tendency for the concentration of these to increase in the vicinity of the cathode. An examination of the results in Table 6A seems to show that at the same time there is a decrease in the concentration of the calcium near the cathode. This, however, is only apparent. The percentage of calcium is expressed in terms of total solids, and since there has been an increase in the percentage of potassium and sodium in the cathode region the calcium constitutes a relatively smaller portion of the total solids in this region than elsewhere in the specimen.

Since the alkalies are known to react chemically with silicates and aluminates, it appeared probable that in such action lay the explanation of the effect of the electric current in causing the disintegration of the concrete near the cathode. Additional experiments were therefore carried out for the purpose of showing whether or not such chemical action might occur in the case of Portland cements and what, if any, might be the difference in the action of sodium and potassium hydroxides on concrete. For these experiments quantities of 1 : 3 mortar and of neat cement were ground to pass a 20-mesh sieve and 5-g samples of each were allowed to stand in solutions of sodium hydroxides and potassium hydroxides of equivalent strengths for varying lengths of time, as given below in detail. The suspended material was then filtered off and washed, and the solution was analyzed for SiO_2, Fe_2O_3 and Al_2O_3, CaO, and MgO, in order to determine what had been dissolved out by the alkali hydroxides and to compare the solvent action of sodium hydroxide and potassium hydroxide.

The results are tabulated below:

A.—50 CC OF NORMAL SOLUTION STANDING FOR 18 HOURS

	NaOH		KOH	
	Cement	Mortar	Cement	Mortar
	Gram	Gram	Gram	Gram
SiO_2	0.0005	0.0003	0.0011	0.0008
$Al_2O_3+Fe_2O_3$	None	.0009	.0008	.0004
CaO		Not determined		
MgO		do.		

B.—50 CC OF DOUBLE NORMAL SOLUTION STANDING FOR 72 HOURS

SiO_2	0.0023	0.0016	0.0026	0.0023
$Al_2O_3+Fe_2O_3$	.0001	.0006	.0006	.0008
CaO	.0234	.0207	.0163	.0349
MgO	None	None	None	None

C.—50 CC OF 4 NORMAL SOLUTION STANDING FOR 40 HOURS

SiO_2	0.0126	0.0091	0.0131	0.0090
$Al_2O_3+Fe_2O_3$	.0026	.0010	.0033	.0032
CaO	.0521	.0440	.0684	.0653
MgO	None	None	None	None

D.—50 CC OF 10 NORMAL SOLUTION STANDING FOR 6 DAYS

SiO_2	0.0992		0.1003	
$Al_2O_3+Fe_2O_3$	.0211		.0283	
CaO	.4654		.4336	
MgO	Not determined		Not determined	

E.—50 CC OF NEARLY SATURATED SOLUTION, STANDING 6 DAYS (18 NORMAL NaOH AND 15 NORMAL KOH)

SiO_2	0.2413		0.2224	
$Al_2O_3+Fe_2O_3$	.0674		.0668	
CaO	.4756		.4542	
MgO	Not determined		Not determined	

These results show that there is a considerable solvent action on the silica and alumina in ground mortar and cement by both sodium hydroxide and potassium hydroxide, especially in the case of the stronger solutions, and that the extent of this solvent action increases progressively as the concentration of the alkali increases. But there does not appear to be any great difference in the solvent action of sodium hydroxide and potassium hydroxide solutions which are nearly saturated. The action may be a replacement of the calcium silicates and aluminates by sodium or potassium with the formation of soluble sodium or potassium silicates and aluminates, and formation of calcium hydroxide. It is doubtful, however, if, in the above determinations, all the calcium which was originally converted to the hydroxide was found in the solutions analyzed, because during the prolonged washing which was required to get the calcium hydroxide into solution, owing to its rather limited solubility in water, some of it was very probably converted to the insoluble carbonate by the carbon dioxide of the air.

In another experiment along the same line cylindrical concrete blocks, each weighing about 9 kilograms, were allowed to stand in solutions of potassium hydroxide and sodium hydroxide of various strengths and at the end of three months 50 cc samples of the solution were taken from each specimen and analyzed in order to determine the relative solvent action that had taken place. The strengths of the solutions used and the amounts of silica alumina and calcium oxid which were found in solution after three months, are given below:

Solution used	Amounts dissolved in 50 cc of solution		
	SiO_2	Al_2O_3	CaO
	Grams.	Grams	Grams.
One-half per cent KOH	0.2	Trace	None
1 per cent KOH	.3	Trace	None
4 per cent KOH	.8	Trace	None
7 per cent KOH	1.3	Trace	None
10 per cent KOH	1.9	0.4	Trace
45 per cent KOH	15.5	1.1	3.4
45 per cent NaOH	5.0	1.5	.4

These results also show an appreciable solvent action on the silica in the concrete even by the weaker solutions of potassium hydroxide, the solvent action becoming greater in the case of the stronger solutions; and that slight amounts of alumina were also dissolved by the stronger solutions. On comparing experiments 6 and 7, in which 45 per cent solutions of potassium hydroxide and sodium hydroxide, respectively, were used, it is seen that there was a markedly greater solvent action on the silica by the potassium hydroxide than by the sodium hydroxide. Furthermore, an examination of the concrete block in experiment 6 showed that it had been very much disintegrated by the strong solution of potassium hydroxide to a depth of about one-half to 1 inch and could be crumbled off very easily; on the other hand, in the concrete block of experiment 7, in which sodium hydroxide of still greater strength had been used, no such disintegration was apparent on superficial examination. It thus appears that potassium hydroxide of great strength has a stronger solvent action on the silicia in cement than sodium hydroxide of the same per cent composition does, but as the strengths of the solutions decrease the solvent actions approach the same value. It is probable that the apparent lack of disintegration reported in experiment 7 came about as a result of comparison of the two specimens by physical examination of the surface. It should not therefore be taken as indicating that the solvent action of sodium hydroxide does not result in disintegration of the concrete. That the opposite is true seems to be borne out by the results of experiments on cathode specimens to which NaOH had been added, which are described below.

Another series of experiments was carried out in order to find if any reaction took place which resulted in leaving the sodium or the potassium in the insoluble portion after finely ground neat cement had been immersed in sodium hydroxide or potassium hydroxide. To this end the alkalies were determined in a 0.5-g sample of finely ground neat cement; another 0.5-g sample of the same cement was placed in 25 cc of 4n NaOH for six days, after which it was filtered off and thoroughly washed and the alkalies determined; and another 0.5-g sample was placed in 25 cc of 4n KOH for six days, after which it was filtered off and thoroughly washed, and the alkalies also determined. The results obtained were as follows:

	Original sample	Sample after being placed in 4n NaOH	Sample after being placed in 4n KOH
	Per cent	Per cent	Per cent
K_2O	0. 19	0. 10	0. 12
Na_2O	. 03	. 01	. 01

The cement used in this test had been exposed outdoors for several months, which may account for the small alkali content present. The soluble portion was analyzed for SiO_2 Al_2O_3 and Fe_2O_3, and CaO with the following results:

	25 cc 4n NaOH and 0.5-g cement	25 cc 4n KOH and 0.5-g cement
	Gram	Gram
SiO_2	0. 0076	0. 0082
Al_2O_3 and Fe_2O_3	. 0019	. 0016
CaO	. 0938	. 0911

The results of the alkali determinations on the insoluble portions show that there are no appreciable quantities of insoluble compound formed between the sodium or potassium and any of the constituents of the cement, since no more alkalies were present in the samples which had been placed in sodium and potassium hydroxides than in the original sample. The results of the analysis of the soluble portion were similar to those which were obtained before in the other series.

Another experiment was conducted as follows: A number of mortar cylinders 3½ inches in diameter by 4½ inches long were made up with one-half-inch iron rods embedded to a depth of 4 inches on the axes of the cylinders in a manner similar to that shown in Fig. 1. The mortar used was a 1 : 2 mix containing Old Dominion cement and quartz sand which had been thoroughly washed. Distilled water was used in the mixing. A number of these cylinders were made up with nothing added, while to others potassium hydroxide, sodium hydroxide, and a mixture of equal parts by weight of sodium and potassium hydroxides were added in various percentages by weight of the cement. After the mortar

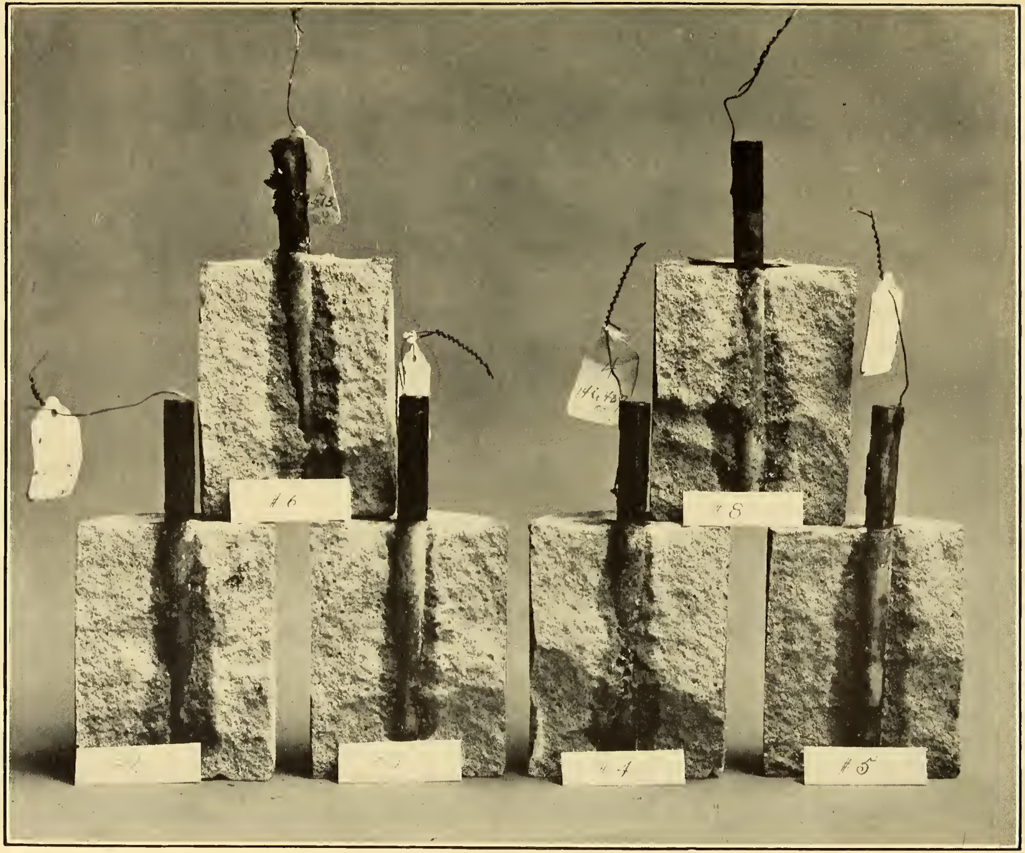

Fig. 4.—*Cathode specimens showing disintegrated mortar about electrode*

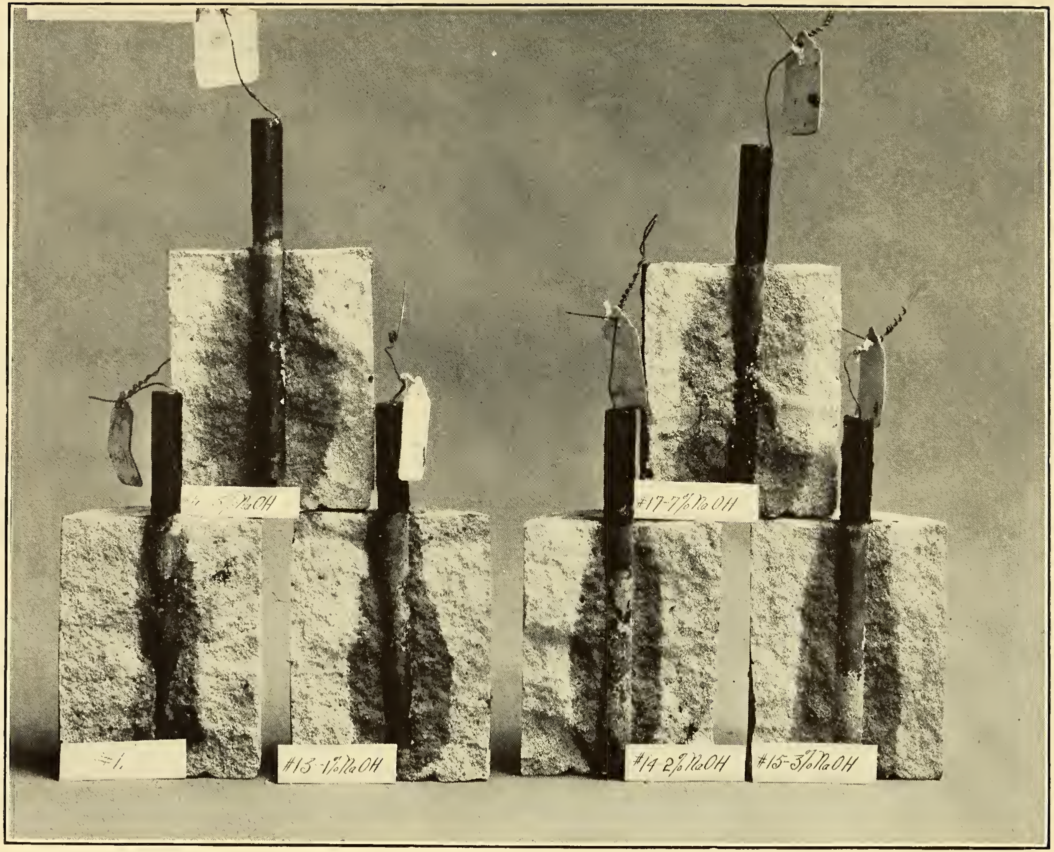

Fig. 5.—*Cathode specimens showing increase of disintegration due to addition of sodium*

had set the specimens were placed in jars and connected up with the embedded iron cathode (see Fig. 2) and current allowed to flow during a period of 62 days. The average current flow was about 0.080 ampere under a pressure of 15 volts for each specimen. Distilled water served as the electrolyte. At the end of the time mentioned above the specimens were all removed from the jars, broken open, and photographs taken. Figs. 4, 5, 6, and 7 show with remarkable clearness the zone of disintegration and its variation with varying percentages of the hydroxides as indicated by the accompanying cards. By measurement there is, roughly, three times as much disintegration where 1 per cent of KOH or NaOH is added as where no addition is made. This is approximately the same ratio as existed between the percentages of alkali in the two cases.

A test was also carried out on some specimens similar to those described in the preceding paragraph, from which the sodium and potassium contained in the cement had been removed by electrolysis. This electrolytic removal of the sodium and potassium was effected by connecting the specimens up with the embedded metal anode and allowing a current of about 20 mil-amperes to flow during an extended period of time. Since the electrode placed around the specimen was cathode the sodium and potassium which took part in the conduction of the current would in time appear in the electrolyte around the cathode as hydroxides or carbonates and by changing the electrolyte at suitable intervals all or nearly all of the sodium and potassium could be removed. When tests for alkalinity of the electrolyte showed that almost no sodium or potassium was coming off the current was reversed, making the metal embedded in the specimens cathode and carrying a current of about 0.050 ampere under a pressure of 30 volts. This condition was maintained about three months. At the end of that time the specimens were broken open for examination. Fig. 7a shows the condition of the mortar about the cathode in four of them. All of the specimens shown in Fig. 7a were in series while anodes, and it is probable that the removal of the sodium and potassium was quite complete in the smaller specimens while the larger specimens still contained some of the alkali. The quantity of disintegrated mortar in the case of the larger specimens is but a fraction of that found in the specimens shown in Fig. 4, to which no additions of alkali had been made however, while in the case of the smaller specimens no disintegration was evident. The conditions under which this result was obtained were practically the same as those under which the result shown in Fig. 4 was obtained as far as quantity of electricity is concerned.

It seems fully established, therefore, that the disintegration of the mortar at the cathode is due to an accumulation there of sodium and potassium by the current and there appears to be a consequent liberation by them of the silicates and aluminates of the set cement with a formation of soluble products. It is obvious that this action would continue until all of the sodium and potassium in the path of the current had been drawn to the cathode. On the other hand, cement free from any appreciable quantities of sodium and potassium would not show the disintegration at the cathode described above.

12. EFFECT OF ELECTRIC CURRENTS ON THE MECHANICAL STRENGTH OF NONREINFORCED CONCRETE

While the foregoing experiments appear to show quite clearly that no effect is produced by the passage of an electric current through the main body of the concrete remote from the electrodes, it was deemed advisable to corroborate this with a series of mechanical tests on specimens so designed as to eliminate the electrode effects. The only mechanical test of this sort that has been published was conducted by Magnusson and Smith.[14] Although their test was continued but a short time it appeared to show that under the conditions of the test there was no appreciable decrease in the crushing strength of the mortar.

In order to secure further information on this subject a test was carried out using concrete cylinders 6 inches in diameter and 8 inches long with no iron embedded. These cylinders were made of 1 : 2½ : 4 concrete, using Old Dominion cement for part of them and Alpha for the rest. Sand and crushed trap rock constituted the aggregate. After the concrete had become thoroughly set 18 of the cylinders were provided with electrical connections by

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[14] Magnusson and Smith: The Electrolysis of Steel in Concrete, Proc. A. I. E. E., **30**, p. 939.

Fig. 6.—*Cathode specimens showing increase of disintegration due to addition of potassium*

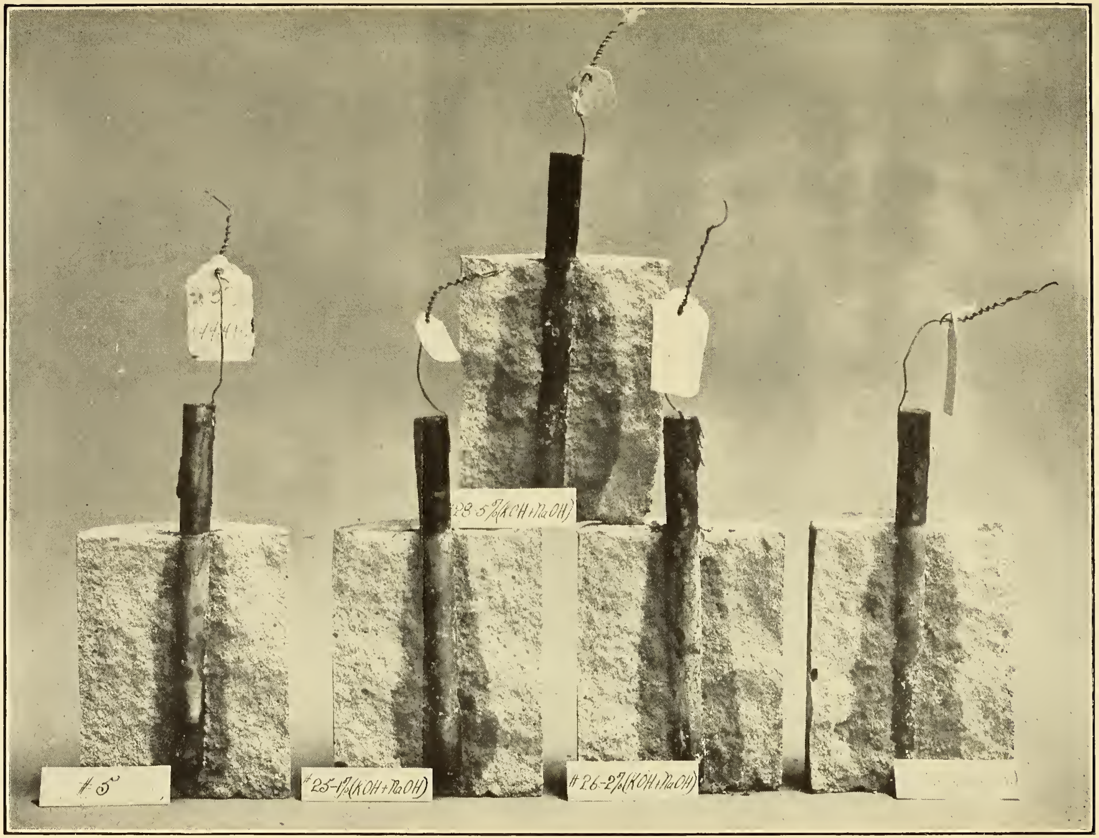

Fig. 7.—*Cathode specimens showing increase of disintegration due to addition of sodium and potassium*

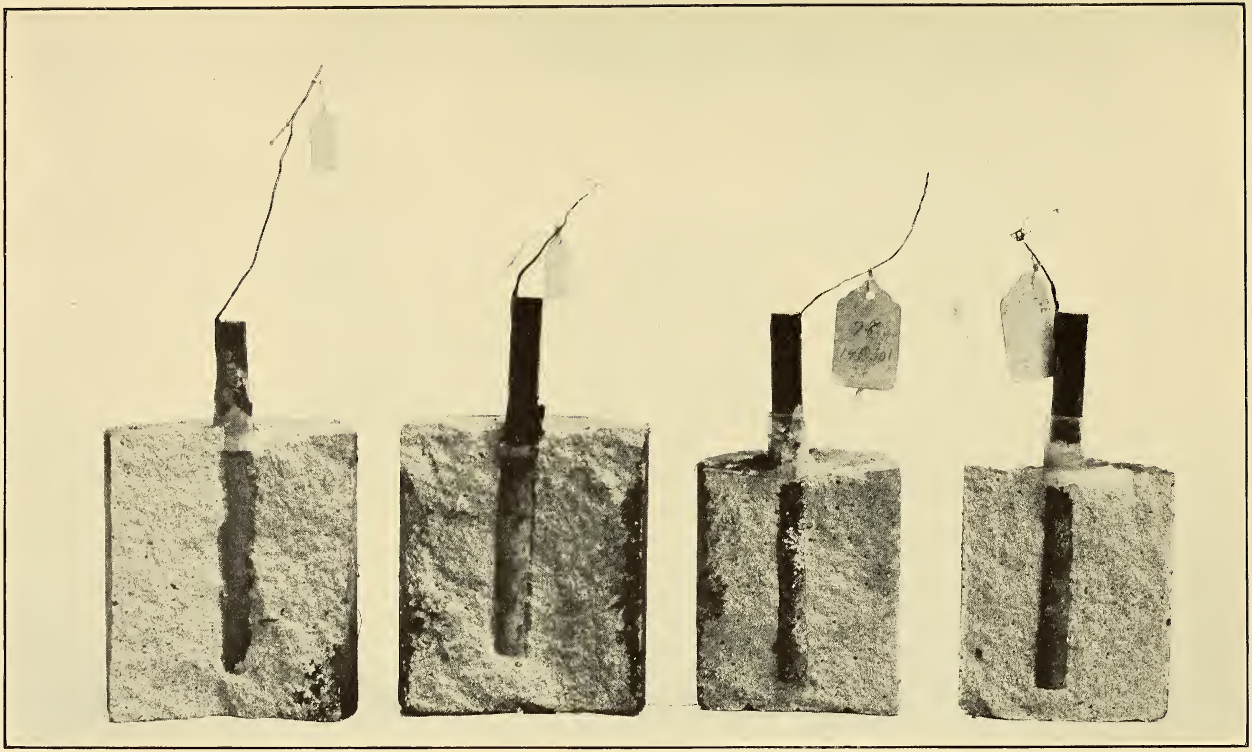

Fig. 7a.—*Cathode specimens showing absence of disintegration where alkalies had been removed by electrolysis*

plastering a 3 by 3 inch carbon plate to the ends of each cylinder with cement mortar. A copper lead was attached to each carbon plate. The general scheme of the connection is illustrated in Fig. 8. When the mortar which held the electrodes on had set the cylinders were laid on 2 by 2 inch strips of wood and the copper leads connected to the terminals of the 115-volt circuit. The potential gradient impressed on these specimens was therefore 172 volts per foot and the test was extremely severe. Check specimens were placed in the immediate vicinity and all of them were thoroughly wet down each day with tap water so that both the check specimens and those carrying current were under the same moisture conditions. Current flowed continuously for 14 months and averaged 0.009 ampere for each specimen. This means that approximately 75 ampere-hours of electricity passed through each specimen under a potential gradient of a little more than 14 volts per inch. The current density averaged about 0.0003 ampere per square inch of cross-sectional area of the specimen.

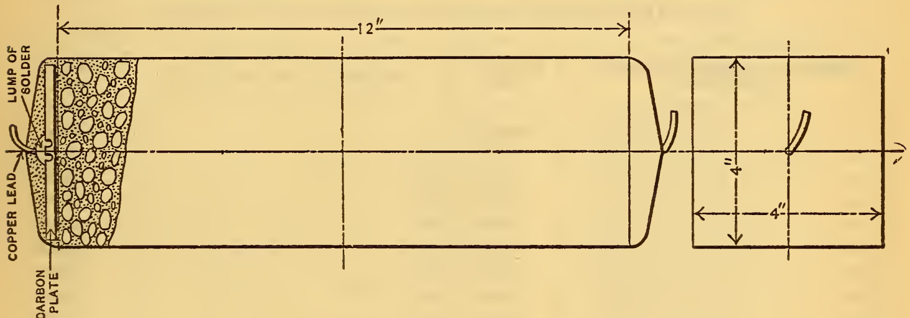

Fig. 8.—*Concrete brick with carbon plates plastered on ends.*

At the end of the period of 14 months the specimens were removed from the circuit and tested for their crushing strength. The specimens which had been subjected to current were prepared for the test by simply splitting off the plaster which adhered to the ends. No grinding was required. The testing was done with a 200 000-pound Olsen testing machine. Blotting paper of 7 or 8 thicknesses was placed on the bottom and top of each specimen in order to insure more uniform distribution of pressure, and the load was run up to a maximum shown by the dropping of the beam when the specimen failed. Nearly all of the failures were of such a character as to show the usual 45° shear. The results are given in Table 7. There is no indication there that the passage of current affected the crushing strength of the concrete. It will appear from the first series of tests on specimens made with Old Dominion cement that the averages show a slight difference in favor of the specimens which carried no current. In the second series, however, using Alpha cement, the reverse is the case, the difference being in favor of the specimens carrying current. The differences are negligibly small, however, in view of the wide variation between individual specimens subjected to the same treatment.

TABLE 7

Effect of Current on Mechanical Strength of Concrete

SPECIMENS MADE WITH OLD DOMINION CEMENT

Specimens through which current had passed	Crushing load	Specimens not carrying current	Crushing load
	Pounds		Pounds
173	60 630	185	73 270
174	69 210	186	75 840
175	66 910	187	51 000
176	64 060	188	80 890
177	69 700	189	56 210
178	53 650	190	57 050
179	41 100	191	63 020
180	66 300	192	53 490
181	69 850	193	65 250
182	73 450	194	55 310
183	92 900	195	86 110
184	31 350	196	67 100
		197	51 210
Average	63 260	198	88 630
		Average	66 020

SPECIMENS MADE WITH ALPHA CEMENT

Specimens through which current had passed	Crushing load	Specimens not carrying current	Crushing load
199	47 400	205	42 000
200	46 000	206	35 440
201	31 450	207	38 550
202	50 750	208	45 040
203	45 660		
204	49 300		
Average	43 400	Average	40 250

The effect of the passage of current on the mechanical strength of concrete is further shown to be negligible by a test on specimens similar to the one represented in Fig. 9. Six of these specimens which were made of 1:2½:4 concrete consisting of Old Dominion cement, sand, and crushed trap rock were put under the electrical test in the manner indicated in Fig. 2 with the exception that the inner iron electrode was placed loosely in the hole in the cylinder. Two of the specimens tested were connected up with the inner electrode anode, two of them cathode, and the remaining two carried no current. The connection was made to the 15-volt circuit. Tap water served as electrolyte and care was taken to keep the hole on the axis of each cylinder full of water. After 454 days of current flow the specimens were removed from the circuit, the ends ground off parallel with each other, and the specimens tested in the same way as the specimens described in connection with Table 7. Condensed data are given in Table 8. There is no indication in the results that the passage of current affected the crushing strength of the concrete to an appreciable degree. This test was a severe one, the potential gradient being about 7 volts per inch and the concrete in a condition of saturation. The conditions were also such that the electrode products were free to act on the concrete and the absence of any appreciable depreciation in the crushing strength of these specimens is very significant.

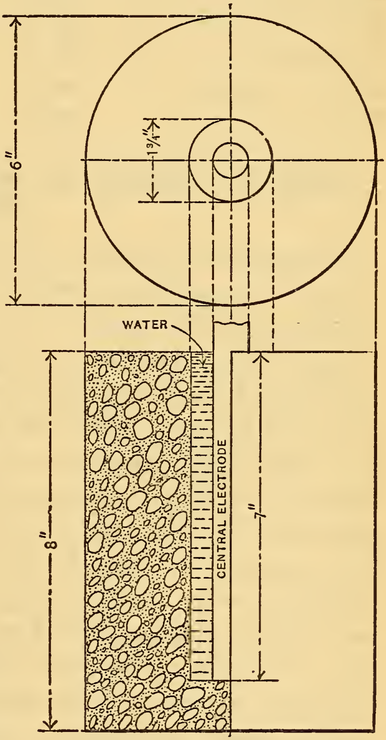

Fig. 9.—*Specimen with loose electrodes used in tests to show the location of the rise of electrical resistance of concrete specimen, due to flow of current*

TABLE 8

Effect of Current on Mechanical Strength of Concrete

Specimen number	Time of test in days	Average current in amperes	Ampere-hours passed	Total crushing load
209	454	0.013	144.0	36 000
210	454	.014	151.3	36 780
212	454	.054	591.7	35 370
213	454	.043	468.0	47 080
214	454	0	0	36 430
215	454	0	0	50 000

13. CAUSE OF CRACKING OF REINFORCED CONCRETE BY ELECTRIC CURRENTS

As regards the various theories that have been advanced as to the cause of cracking of reinforced concrete which were previously mentioned in this paper, the first, that of gas pressure, appears to have little evidence to support it. In all cases it has been found that a much greater volume of gas is liberated at the cathode than at the anode, and if the pressure due to any accumulation of gas within the concrete were an important factor in causing the cracking, we should expect to find even greater damage in cathode specimens than in anode specimens. On the contrary, however, the cracking is found to be peculiarly an anode effect, and it therefore seems certain that gas pressure at most plays but a very minor part in causing the damage. As for the second theory, that of heating, the same objection applies, because the heat developed in the cathode specimens is substantially the same as in the anode specimens under similar conditions. Moreover, cracking has been repeatedly produced in anode specimens in which the external temperature rise was but a few degrees (12° to 15° C), whereas equal and much greater heating in cathode specimens (100° C in one case) failed to cause fracture. It must be admitted that heating of the embedded iron, if sufficiently great, is capable of developing cracks in concrete, but with the ordinary circumstances under which cracking has occurred in the laboratory this is not sufficient to contribute materially to the damage, as the cathode experiments show.

The third theory, that of electrochemical decomposition of the cement, also appears to rest on very uncertain ground. The fact that the main body of the concrete remains unaffected, and at the anode where cracking always originates, no deterioration of the concrete is evident, argues strongly against this theory. It is seen that the concrete is unquestionably weakened by chemical action in the region very near the cathode, but the fact that no cracks develop there, even under the weakened conditions, is proof positive that the immediate cause of the cracking resides elsewhere than in a chemical action similar to that which occurs at the cathode. The results of the chemical analyses given in the section immediately preceding this one show that the products formed by the reactions at the cathode are soluble and hence could not give rise to an internal pressure which could cause cracking similar to that observed in anode specimens. Moreover, the disintegration of concrete by an increase in volume through chemical reactions within the mass with resultant insoluble products always takes place by crumbling. The cracking of anode specimens is in marked contrast to this as described heretofore. It appears inevitable therefore that we must conclude that the cracking is a direct result of some process occurring at the surface of the anode, and hence we must look to the anode phenomena for the true explanation of the damage. The explanation previously advanced that the cracking is due to the deposition of oxides of iron between the surface of the iron and the concrete, which, occupying a larger volume than the original iron, produces a mechanical pressure sufficient to crack the surrounding concrete, appears on the surface to be well founded. There are, however, no published data showing that such pressures actually develop or indicating what magnitudes they may attain. On the contrary, the results of experiments by Barker and Upson[15] of the University of Vermont with so-called collapsible electrodes, in which cracking of the concrete was observed, have caused those investigators to oppose this theory and to hold that no pressure of any considerable magnitude is necessary at the surface

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[15] Barker and Upson: Experimental Studies of the Electrolytic Destruction of Reinforced Concrete, Eng. News, 66, p. 10.

of the iron anode in order to produce cracking of the concrete. There appears, however, to be some question in regard to the strength of these collapsible electrodes, made by rolling sheet iron into cylindrical form. Certain electrodes of this type used in the present investigation showed somewhat surprising rigidity, due either to the open edges becoming bound by the concrete or by cementation of overlapping surfaces accompanying corrosion of the iron. It was therefore deemed advisable to carry out additional experiments with a view of furnishing further information.

(a) EXPERIMENTS WITH SPECIMENS CONTAINING LOOSE ELECTRODES

In order to determine whether cracking would occur without actual contact between the anode and the concrete some specimens were made up as shown in Fig. 9. These are substantially of the same form as those previously used except that the anode instead of being cast solidly in the concrete is inserted loosely in a cylindrical hole in the center of the concrete cylinder, there being a space of about half an inch between anode and concrete on all sides. This space was filled with water to complete the electrical circuit, and the specimens were then connected to the circuit in the usual way, the iron being anode. In this case we have all the possibilities for chemical action, heating, and the formation of deposits of oxides within the mass of the concrete, but it is impossible for any mechanical pressure to develop between the iron and concrete. Specimens of this kind were put under test on 15 and 110 volts, the former being in circuit for more than a year, without the least trace of cracking or other deterioration having developed. This affords strong additional evidence, if any were needed, that heating or chemical action have no important part in the destruction of the concrete in anode specimens under ordinary conditions. Its chief value in this connection, however, lies in the fact that it shows that in the absence of direct mechanical pressure between the iron and the concrete the cracking does not take place.

(b) EXPERIMENTS WITH CARBON ELECTRODES

Experiments with carbon electrodes in which there can be no secondary reactions to cause swelling of the anode also confirm this view. (See also Table 3, specimens 45 to 48.) Some specimens were made up with carbon electrodes as shown in Fig. 8. Rectangular blocks of concrete 4 inches square by 8 inches long were made and after being allowed to set small plates of brush carbon with copper leads attached were plastered on each end by means of neat cement. These specimens were then connected to the 115-volt circuit and after having been in circuit for more than 14 months showed no sign of fracture. Here, again, all conditions such as gas pressure, heating, and chemical action, and in fact all the conditions which have been supposed to contribute to the destruction of the concrete are present, with the single exception of the possibility of the development of mechanical pressure, and the failure to occur of cracking or disintegration of the specimens is significant.

(c) EXPERIMENTS WITH COLLAPSIBLE ELECTRODES

It is not sufficient, however, to show merely that cracking does not take place in those cases where mechanical pressure is absent. It is necessary to show that a mechanical pressure actually is developed when cracking occurs, and that this pressure is of sufficient magnitude to produce the phenomena observed. In order to definitely demonstrate this point the following experiments were carried out:

The first test was made on a standard size specimen of 1:2 mortar made up with a collapsible electrode such as is shown in Fig. 10. The sheet iron of this electrode was rolled to as true a cylinder as possible under the circumstances and wrapped at intervals with fine copper wire. When the electrode was embedded in the specimen the mortar worked into the seam at *a* thus forming a brace for the edge of the sheet iron at that point. After setting the specimen was placed in circuit on 50 volts, carrying a current which varied from 1.2 to 0.37 amperes as the test proceeded.

After 96 hours the specimen was found to be cracked. The crack formed at *c* and extended radially to the edge of the specimen. The sheet iron was forced away from the mortar about one thirty-second inch from *a* in a clockwise direction around to *c*, making it evident that there had been some pressure developed between the concrete and the iron. The iron being braced at *a*, however, would not yield in the other direction, and since any further relaxation would have to take place completely around the electrode, it is probable that the friction became too great and the specimen cracked.

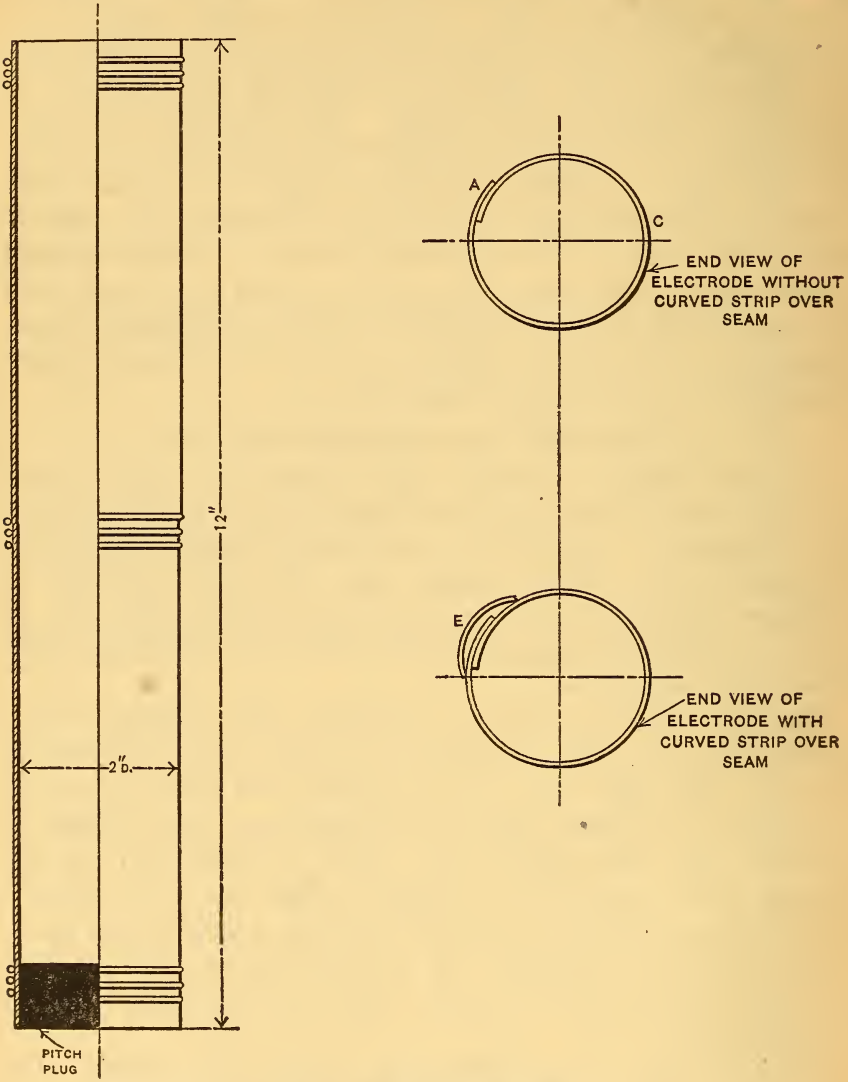

Fig. 10.—*Collapsible electrode.*

Fig. 11.—*Specimens used in tests to determine the force produced by the corrosion of iron in concrete*

In order to test this matter further two more specimens were made up with collapsible electrodes of the same material as the first, but with a curved strip of sheet iron covering the seam, as shown at *e*, in order to prevent binding of the edges by the concrete. These two specimens were placed in series on 115 volts and continued in circuit for three months. The current was never greater than 1 ampere nor less than 0.045 ampere during that time. There was evidence of a great deal of corrosion, but no cracks appeared in either of the specimens, although the voltage was about 60 to 70 volts for one specimen and 45 to 55 volts for the other.

These conditions are so severe that similar specimens with solid electrodes would inevitably have cracked within a day or two. A thick layer of oxide was deposited between the sheet-iron cylinder and the cement, which caused considerable shrinkage of the cylinder, and it was without doubt this yielding of the cylinder which relieved the pressure and prevented cracking of the concrete.

(*d*) MEASUREMENT OF FORCE PRODUCED BY CORROSION OF IRON IN CONCRETE

Another and more striking experiment to demonstrate the existence of a mechanical pressure and at the same time to give an idea of the order of magnitude of the forces developed was made with the apparatus shown in Fig. 11. Several sections of 4-inch cast-iron pipe about 5 inches long were cut through on one side with a hack saw, making slits about one-sixteenth inch in width. These sections of pipe were then filled with concrete and an iron rod embedded in the center of each to serve as one electrode. After being properly aged, the specimens were connected in circuit, with the outer cast-iron sleeves as anodes. In that case corrosion would take place on the inner surface of the cast iron and produce a layer of oxide between the iron and the concrete. If any considerable pressure were produced it would result in a tendency to expand the cast-iron sleeve, with consequent widening of the slit. This actually proved to be the case. Fig. 11 shows on the right one of these cylinders as it first appeared and on the left one that has undergone considerable expansion. The increase in the width of the slit in this instance is about three thirty-seconds inch. As the cast-iron sleeve was about one-half inch thick and possessed considerable rigidity, a very appreciable mechanical pressure is here made evident. Calculation showed that the natural expansion of the concrete could not have produced more than a few per cent of the effect observed.

A modified form of the last experiment was next carried out, in which provision was made for actually measuring in a rough way, the magnitude of the pressure developed. A hollow cast-iron cylinder shown in Fig. 12 of 1 inch internal diameter and 2 inches external diameter, and 1½ inches in height was cut through on one side with a hack saw, making a slit one-sixteenth inch in width. On either side of the slit three thirty-seconds-inch holes were drilled three-sixteenths inch deep and iron pins inserted with projections of one-eighth inch. These were placed opposite each other and filed flat on the outside with such a pitch that if the cylinder opened out appreciably there would be no difficulty in measuring the distance between the outside of the bases of opposite pins with a flat vernier caliper.

To find the radial pressure required to produce a given amount of spreading of the slit in the cylinder, two piano wires were wrapped once around the cylinder and a varying load applied to one end of the wires while the system was suspended from the other end. The cylinder was greased and although the friction between the wires and the cylinder would doubtless still be quite great a little agitation seemed to cause the deflection, or narrowing of the slit, to be almost directly proportional to the load as shown in the curve in Fig. 13. Also the external radial load required to produce a given narrowing of the slit would be nearly the same as the internal radial load required to produce the same widening.

A three-fourths-inch solid iron cylinder was placed in the hole in the cast-iron cylinder and the space between them filled with 1 : 1 cement mortar made up with a 1 per cent NaCl solution. The object of adding the salt was to increase the rate of corrosion and shorten the time required to make the test. The bottom of the

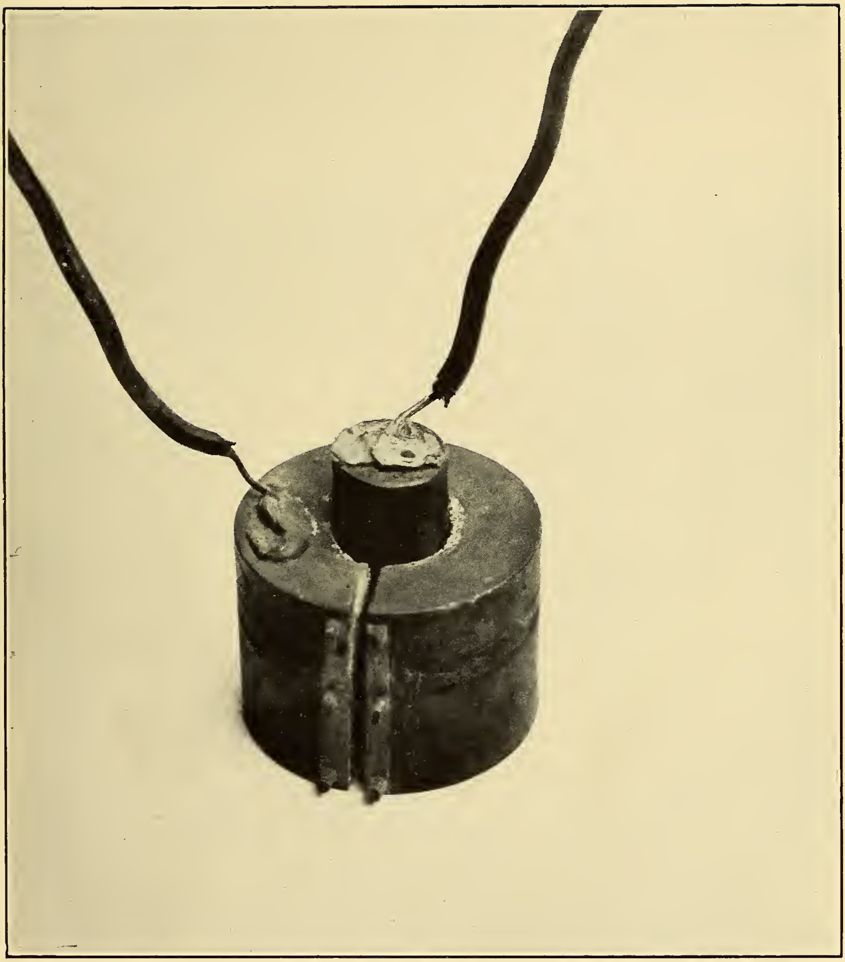

Fig. 12.—*Specimen used in test to determine the force produced by the corrosion of iron in concrete*

specimen was covered with two layers of asphalt and felt to keep the current from shunting around the mortar while under test the test being made in a crystallizing dish filled to one-eighth inch from the top of the shell with lime water to prevent the mortar from drying out and at the same time keep the pins from rusting seriously.

The specimen was put in circuit on 15 volts January 2, 1912, with the iron cylinder as anode, the distance between the bases of the pins having previously been measured. On January 12 the specimen was removed from circuit, measured for total deflection of the pins, and the central electrode removed. The measurements were then taken again to obtain the permanent set. The difference between the total deflection and the permanent set represents the true deflection over which the ratio of deflection to load or internal radial pressure is probably constant. As seen from the calibration curve of Fig. 13, the load required to give a deflection of 0.0022 cm is 30 pounds. This load corresponds to a

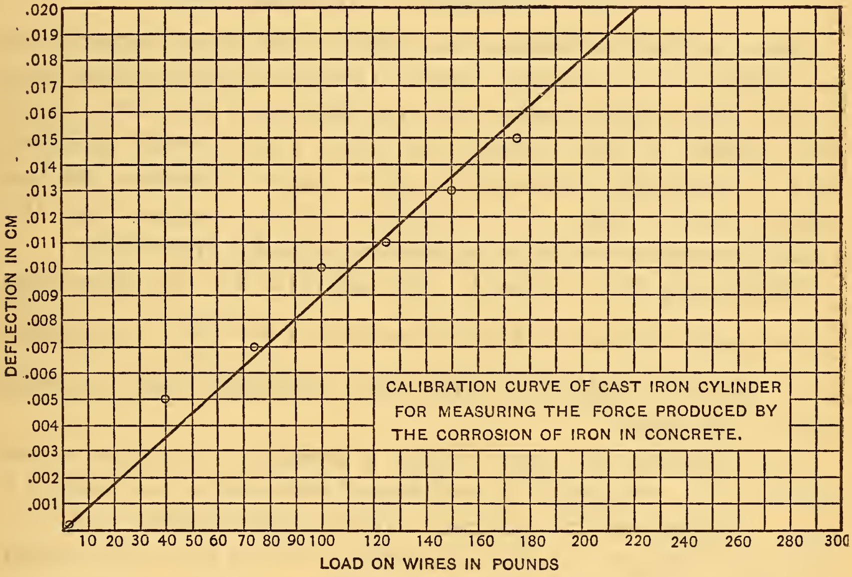

Fig. 13

radial pressure of 40 pounds per square inch on the interior of the shell where the diameter is 1 inch. This is obtained from the formula $Pdl = 2\ LN$, or external load equals internal load, and where

P = internal radial pressure,
d = interior diameter of shell,
l = length of shell,
L = load on wires and
N = number of wraps of wire around shell.

This is neglecting friction, but since in the actual experiment the friction of the rough, corroded surface on the mortar was beyond doubt much greater than the friction of the wires on the oiled surface of the cylinder, the error, if any, would probably tend to make the calculated pressure due to oxidation too low rather than too high. It is therefore safe to assume that the actual pressure developed is as great as the value given below.

Substituting $L = 30$ pounds, and the value for the dimensions of the shell in the above formula we have $P = \frac{2 \times 30}{1 \times 1.5} = 40$ pounds. $N = 1$ since in reality the two wires constitute but one wrap around the shell.

The deflection of 0.0022 cm for a pressure of 40 pounds per square inch corresponds to an internal diameter of the shell of 1 inch. Making up the specimen with the three-fourth inch electrode and filling the space surrounding it in the bore with mortar as described above had the effect of increasing the radial pressure per square inch required for the same deflection in the ratio of 1 to three-fourths. The pressure at the surface of the electrode would be, therefore, 53 pounds per square inch. That is, 53 pounds per square inch over the surface of the three-fourths inch electrode would produce the same deflection as 40 pounds per square inch exerted upon the walls of the tube.

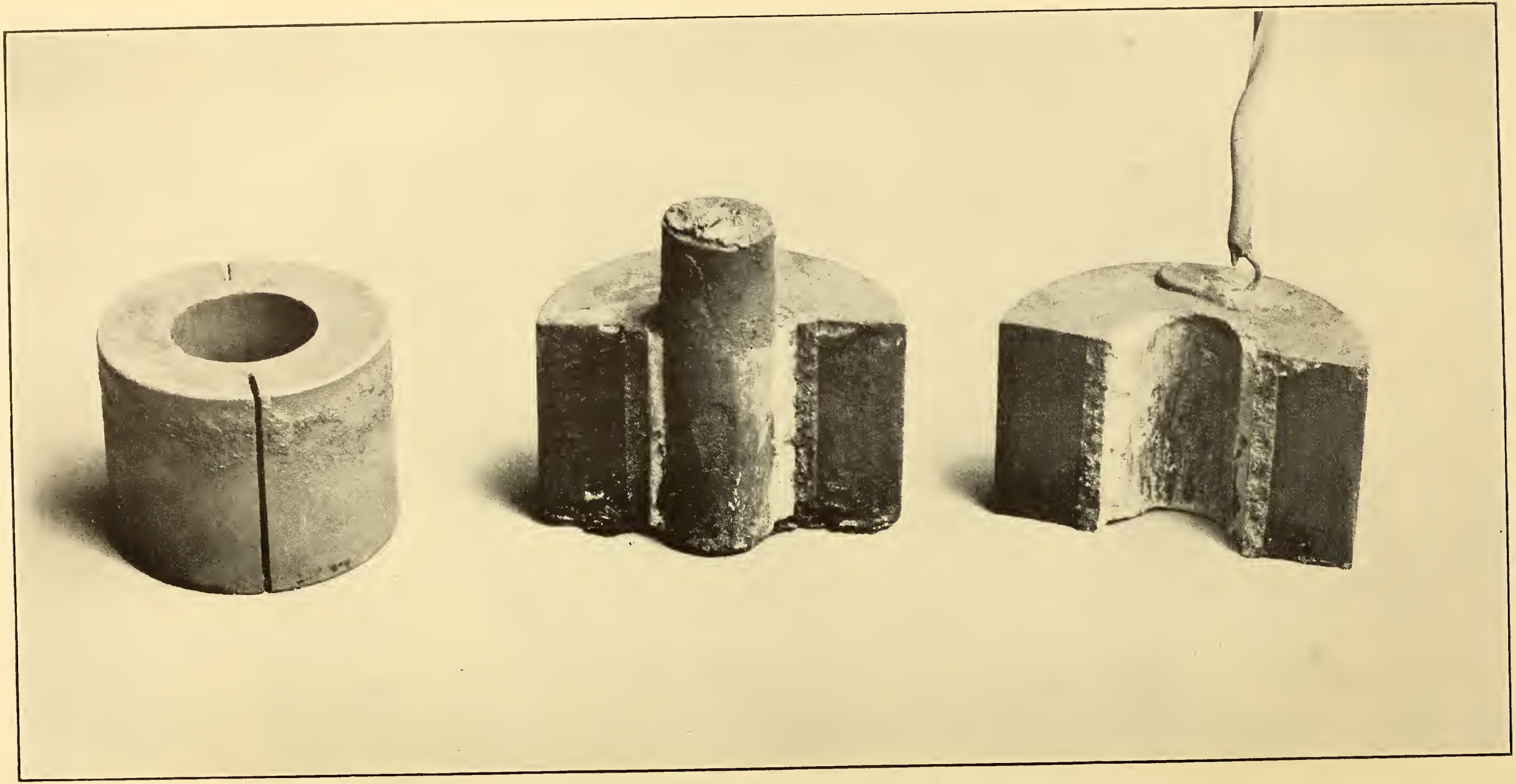

Fig. 14.—*Form of specimen used to determine the force produced by the corrosion of iron in concrete*

TABLE 9

Calibration and Test Data on Cylinder for Measuring Pressure Caused by Corrosion of Iron

Load.	Deflection in set of pegs No. 1	Deflection in set of pegs No. 2	Deflection in set of pegs No. 3	Average
First calibration:	cm	cm	cm	cm
0	0	0	0	0
33	0.004	0.005	0.006	0.005
59	.006	.007	.008	.007
86	.008	.007	.010	.008
110	.010	.011	.012	.011
Second calibration:				
0	0	0	0	0
40	.006	.006	.004	.006
74	.008	.008	.006	.007
100	.010	.010	.010	.010
125	.012	.012	.010	.011
149	.013	.014	.012	.013
172	.014	.014	.016	.015
			Permanent set	.002
Test data:	cm bet. pins	cm bet. pins	cm bet. pins	cm def.
Jan. 2, 9:00	0.268	0.947	0.986	0
2, 4:00	.872	.990	1.028	0.043
3, 9:00	.916	1.034	1.072	.088
4, 9:00	.952	1.068	1.106	.122
6, 4:00	1.011	1.124	1.162	
8, 4:00	1.012	1.127	1.168	
9, 9:00	1.020	1.134	1.174	
12, 1:00	1.068	1.180	1.220	Current 0.045 amp.
				cm
After removal of central electrode	.960	1.076	1.116	True def. .105

The data of Table 9 show a true deflection of 0.105 cm, which corresponds to a radial pressure of 2400 pounds per square inch at the surface of the electrode, mostly due to the formation of rust.

As a check on the foregoing experiment a similar cast-iron shell, 1½ inches in external diameter, was made up as shown in Fig. 14. This cylinder was slotted lengthwise at opposite extremities of a diameter to a depth one-sixteenth inch less than the thickness of the shell. The thickness of the shell was one-fourth inch in this case, so the cuts were each three-sixteenths inch deep, leaving a thickness of one-sixteenth inch of cast iron holding the two halves of the shell together on either side. The object in making slots of this character in the shell was to cause practically all of the elongation of the iron due to an internal pressure to take place in the slot. The smaller cross sectional area of iron there would then reach its elastic limit sooner than the thicker portion and lead to a quick break in the event of the pressure becoming great, while a shell one-sixteenth inch in thickness throughout might expand to such an extent that a break would not occur. A three-fourths-inch solid-iron electrode was cemented in the bore of the shell with 1:1 mortar made up with a 3 per cent NaCl solution. After the mortar had set the shell was put in circuit on 15 volts with the central electrode anode. In about three days the two halves of the shell were found to be broken apart by the formation of rust on the surface of the anode. By measuring the length of the shell and the width at different points of the broken portion on the side which evidently yielded first, data were obtained from which a curve was plotted and integration showed the area of the broken section of iron to be 0.106 of a square inch. The formula which expresses the relation between the internal load due to radial pressure within a cylinder which is required to rupture it and the resistance of the cylinder against the rupture is $Pdl = 2\,AF$ where

P = internal radial pressure per unit area,
A = cross-sectional area of iron on one side of cylinder,
d = internal diameter of cylinder,
l = length of shell and
F = breaking strength of cast iron.

As in the former case the internal diameter of the shell is to be taken as the diameter of the electrode and for the same reason. Assuming F to be 20 000 pounds per square inch ($d = \frac{3}{4}$ inch) we have, solving for the internal radial pressure,

$$P = \frac{2 \times 0.106 \times 20\,000}{0.75 \times 1.5} = 3\,760 \text{ pounds per square inch.}$$

In a similar specimen tested in the same way, but having an area of iron on each side of 0.131 square inch holding the two halves of the shell together, the break occurred at 4700 pounds pressure per square inch, calculated in the same way.

While, of course, the above measurements are only approximate, a higher degree of accuracy does not appear to be necessary, since we are not chiefly concerned with the actual pressure developed, but desire only to know whether or not it can become of sufficient magnitude to destroy concrete. The above experiments are sufficient to show that the force developed due to the corrosion of iron in concrete by electric currents may reach a value of at least several thousand pounds per square inch, which is amply sufficient to produce the fractures observed in reinforced concrete blocks under the influence of electrolysis.

14. RISE OF ELECTRICAL RESISTANCE OF REINFORCED CONCRETE DUE TO FLOW OF CURRENT

The electrical resistance of concrete is a factor of great importance, but one which varies so greatly with varying physical conditions, especially with varying moisture content, that it is difficult to give any reliable numerical values except in the case of approximately saturated specimens. An average figure for representative specimens of thoroughly wet concrete may be taken as varying from 4000 to 6000 ohms per centimeter cube, depending somewhat on the proportions. With reduced moisture content the resistance rises rapidly, the concrete becoming a fairly good insulator when thoroughly dry.

(*a*) RISE OF RESISTANCE OF ANODE SPECIMENS

In the published work of previous investigators mention is frequently made of the fact that when electric current passes through reinforced concrete, under the conditions usually imposed upon it in the laboratory, there is a gradual increase of resistance with time, regardless of the direction of flow of current. Nothing definite has been said as to the probable cause of this rise of resistance, nor does it appear that its importance as a factor in minimizing trouble from electrolysis in reinforced concrete has been fully appreciated. With a few exceptions, which are considered later, such a rise of resistance occurred in all of the specimens tested in the course of this work. When the specimens were first placed in circuit the resistance was a minimum, but upon the application of the electric current the resistance began to rise. In the low-voltage specimens the first apparent increase in resistance may have been more or less affected by polarization, but in the higher voltage tests at 15 to 100 volts polarization effects are negligible. The resistance at first increased quite rapidly, but the rate of increase usually commenced to diminish after about 1000 to 1200 hours. The rise of resistance continued for a period varying from several days to several months, according to circumstances as described later, until an approximately constant condition was reached. In the case of higher voltages the increase of resistance was the more rapid at first, but the rate of increase was not maintained in proportion to the voltage applied, so that a greater ampere-hour flow of current was required to produce a given rise of resistance in the case of high-voltage specimens than where the voltage was low. Typical curves showing the resistance as a function of time and also as a function of the ampere hour flow of current are shown in Figs. 17, 18, and 19. The relative magnitude of the initial and final resistances varied very much under different conditions, but the general tendency was the same whether the specimens were run as anode or cathode on high or low voltage. The results of the tests for anode effects on low voltage, which are summed up in Table 2, show an average increase of resistance to 137 times the original value at the end of 5500 hours. The results of the tests for cathode effects on all voltages, which are summed up in Table 5, show an average increase to 14 times the original resistance at the end of about the same period. The anode tests on high voltage do not show such a large increase of resistance as the anode tests on low voltage, but this is due, no doubt, to the fact that, owing to the early destruction of the specimens on high voltage, these tests were of comparatively short duration.

(*b*) DETERMINATION OF LOCATION OF RISE OF RESISTANCE

A rise of resistance of sufficient magnitude to cause the reduction of current through a specimen of reinforced concrete to less than 1 per cent of its original value was recognized as a phenomenon of great importance and was therefore given special consideration. The first step taken in determining its nature was the very obvious one of finding its location; that is, ascertaining whether it is an anode or a cathode effect, or both, or is distributed throughout the specimen. After the first unsuccessful attempts in this direction, the following experiment was devised and carried out. Fig. 15 shows the general form of the specimen used. It was of standard type, made of 1:2 mortar, with a three-fourths inch round-iron electrode embedded in the axis of the cylinder. The contact piece shown embedded at B in the figure consisted of two concentric sheet-iron cylinders which were perforated with a large number of one-half-inch holes. These holes were so spaced as to remove about one-third of the area of the iron and when the cylinders were in place, one within the other, the holes were opposite. Rubber covered copper wire leads were soldered to each cylinder. The inside of the outer cylinder and the outside of the inner cylinder were painted with an alkali resisting metal preservative having considerable temporary insulating value so that when the cylinders were shoved together the outer and inner faces of the arrangement were conducting but were insulated from each other. The whole was embedded concentrically with the central iron rod and mortar worked into the holes. When current was made to flow through the specimen from the central to the outer electrode the mortar in the holes provided a path for it in passing out of the cylinder B.

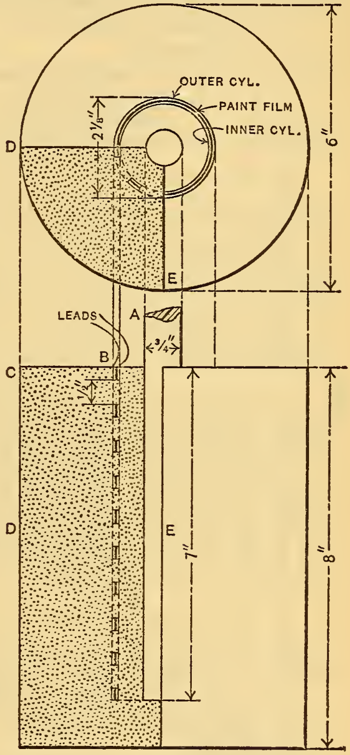

Fig. 15.—*Specimen used in experiments to determine the location of the rise of resistence of concrete specimens due to flow of current.*

No current could flow through B itself. The purpose of this was to prevent corrosion of the sheet iron and a consequent

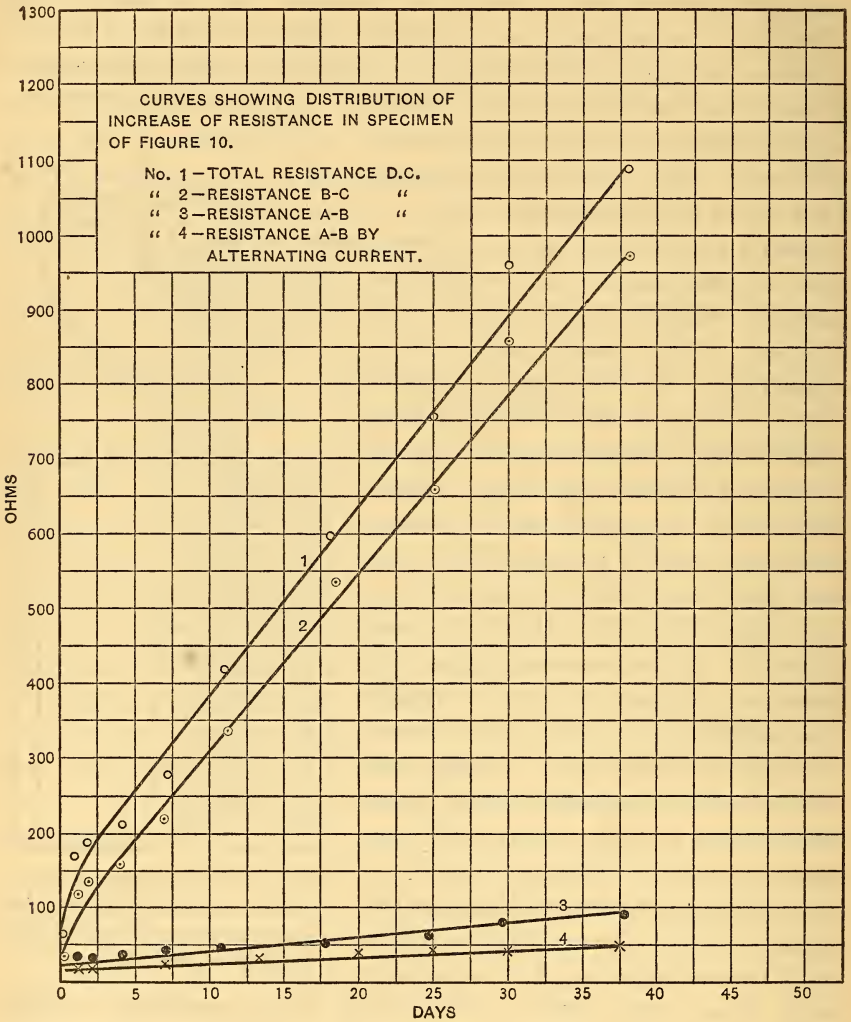

Fig. 16

possible changing of the resistance between the faces of the contact piece and the concrete and also to prevent polarization of the surface of the cylinder B.

When the mortar had set the specimen was placed in tap water, allowed to stand until its resistance became fairly constant, and then connected up on 15 volts, direct current, with the central electrode anode, using the usual sheet-iron cylinder for the outer electrode C. Current was allowed to pass continuously except for about 33 hours each week. The following measurements were made at regular intervals:

(1) Total current and voltage from A to C in the figure.

(2) Potential fall by potentiometer from A to B and B to C. The inner face of the contact piece B was used for the measurements A–B and the outer face for B–C.

(3) Resistance by alternating current from A to C. Calculating the resistances A–B, B–C, and A–C from the observed data, and plotting the values obtained in each case as a function of time, gives the curves of Fig. 16. The result indicates that in this type of specimen at least the rise of resistance occurs almost wholly in the neighborhood of the cathode.

The next step taken was to select specimens from those under test which had been in circuit for a year or more, and thoroughly stir the electrolyte in which they were immersed. That finished, the outsides, i. e., the surface adjoining the cathode of the specimens, were scraped with a sharp-edged tool. The results are given in Table 10.

TABLE 10

Effect on the Resistance of Anode and Cathode Specimens of Scraping the Outside Surface of the Concrete

Specimen number	Proportions of concrete	Cement used	Added	Hours in circuit	Voltage	Resistance at beginning of test	Resistance before disturbing water
71........	1:2.5:4	Old Dominion..	20% crude oil No. 4147	5600	15	131	17400
72........	1:2.5:4	.....do...........	20% oil par. sol....	5600	15	160	25820
73........	1:2.5:4	.....do...........	20% oil No. 4147...	5600	15	208	861
74........	1:2.5:4	Atlas...........	....	5500	15	76	8000
75........	1:2.5:4	Old Dominion ..	....	0	0	157	157
76........	1:2.5:4	.....do...........	....	6000	15	75	5000

TABLE 10—Continued

Specimen number	Resistance after stirring water with current on	Resistance after scraping outer surface	Resistance after standing in air nine days	Polarity of embedded electrode	Electrolyte	Age of specimen at test
71	12000	380		Positive	Tap water	60 days
72	14000	1026		do		Do.
73	861	861		Negative	Tap water	Do.
74	Not stirred	Not scraped	1400	Positive	do	46 days
75				Neutral	do	8 months
76		196		Positive	do	57 days

As shown by this table, specimen No. 71 lost about 30 per cent of its resistance on stirring the electrolyte, and returned nearly to its original resistance after scraping the outside to a depth of about one thirty-second inch. The indications are that by sufficiently diligent scraping the resistance could have been reduced still more. No. 72 lost about 50 per cent of its resistance on stirring the electrolyte. It was not scraped to as great a depth as No. 75, but was worked down with a hoe-shaped tool while in the jar with current flowing. No. 73, in which the central electrode was cathode, was not changed in resistance in the least by stirring, scraping, or otherwise disturbing it. No. 74 was removed from the jar after measuring its resistance and allowed to stand in air for nine days. At the end of that time it was returned to the electrolyte, allowed to become saturated, and another measurement made of its resistance which was found to have fallen to about one-sixth of its maximum value. Specimen No. 75 had been standing in water for eight months with no current passing. Measurement showed that there had been no appreciable increase of resistance. No. 75 was tested in distilled water, but did not act differently from the rest. Scraping had the same effect on its resistance as on that of Nos. 71 and 72.

(c) CAUSE OF RISE OF RESISTANCE

The results given above indicate quite clearly that the greater part of the rise of resistance in specimens with embedded anodes takes place near the cathode and it is quite probable that it is due to several causes. Analysis of the concrete scraped from the surface of an anode test specimen after having been in circuit a year shows that there is a large accumulation of calcium carbonate at this point which undoubtedly has its share in the increase of resistance. This accumulation takes place as a result of a concentration of $Ca(OH)_2$ near the cathode surface by the current where it comes in contact with CO_2 absorbed by the water from the air with the resulting precipitation of $CaCO_3$ within the pores of the concrete near the surface of the specimen, thus plugging up these pores and forming a nearly impermeable wall. If a specimen is made anode for a considerable time, it shows a tendency to decrease in weight while the resistance is increasing, whereas, if the current is reversed, it regains a considerable portion of the loss. This indicates that electrical endosmose, or the carrying of the water bodily toward the cathode through the pores of the concrete by the current, may also have something to do with the increase of resistance by drying out the specimen in this way. If the current is reversed rapidly, say at a rate of two reversals per second, an action is observed that is much like the rectifying action of an aluminum cell but is much slower because at 120 reversals per second it disappears entirely, no reading being obtained on a direct-current instrument placed in the circuit. The larger current flows when the embedded metal is cathode. The difference between anode and cathode resistance with two reversals of current per second may be as great as 30 per cent in a new specimen, decreasing very much, however, with a specimen which has been in circuit long enough to attain a high resistance. No explanation is offered for this action. It is probable that the three phenomena above mentioned all contribute to the rise of resistance, but to what extent each contributes, and what other actions may also occur, can not be stated at present.

(*d*) RISE OF RESISTANCE OF CATHODE SPECIMENS

In case the embedded electrode is made cathode a rise of resistance occurs which is, however, much less than when the embedded electrode is anode. This might be expected from the fact that CO_2 has very little access to the $Ca(OH)_2$ at the surface of the embedded electrode, and hence the tendency to produce a dense precipitate of $CaCO_3$ would be very slow. Moreover, electrical endosmose would have a tendency to fill the pores with water instead of drying them out. In fact, there is good reason to believe that the rise of resistance which takes place at the embedded cathode is due chiefly to the liberation of gases at that point by the electrolysis of water; and since these gases are necessarily slow in escaping through the pores of the concrete, the electrolyte is largely excluded from the pores near the cathode surface with consequent rise in resistance. This is indicated by bubbling and forcing out of water around the cathode, by variations of the resistance of such specimens of as much as 10 to 20 per cent while current is flowing, and also by the fact that the resistance drops back quite close to its original value when the current is discontinued for a few days and the gas permitted to diffuse. Specific instances are given below as examples: A standard type specimen of 1:2.5:4 concrete, made up with Alpha cement and containing a 1-inch pipe for an electrode, had an initial resistance of 60 ohms. After being in circuit on 15 volts with the central electrode cathode for 2200 hours, the resistance had reached a value of 300 ohms. On leaving the current off for a week the resistance decreased to 136 ohms. Another specimen of the same character as the above, with the exception that it was made up with Giant cement, had been in circuit 1000 hours as cathode on 15 volts. The resistance had risen from 120 to 240 ohms. The current was left off for about a week and the resistance decreased to 125 ohms, or practically to its original value. A third case was that of four cathode specimens in series on 116 volts. These specimens were of 1:2.5:4 concrete, made up with Old Dominion cement, and containing three-fourths-inch round-iron electrodes. The resistance of the four specimens in series at the beginning of the test was 256 ohms. After 4162 hours the resistance had increased to 2700 ohms. The current was then cut off for about four days. When it was resumed the resistance was found to be 865 ohms, or about four times the original resistance.

Some very interesting curves are shown in Figs. 17, 18, and 19. One of the curves of Fig. 17 is a plot of the current values as a function of time for a high voltage anode specimen, and the other the same for a low voltage anode specimen. These curves cover the first 1000 hours of each test. It is seen that the greatest drop of current occurs during the first 200 hours. If the current is then discontinued for a considerable time the resistance decreases almost to its original value; this is partially shown in the curve of the high-voltage specimen at the point where the current is indicated as having been off for a short time—an hour or two at most. Beyond the 200-hour point the curves are both comparable with a straight line and nearly parallel. This is also shown to some degree in the curves of Fig. 18. These show plots of resistance as a function of time for a high and a low voltage anode specimen, respectively. The high-voltage specimen was continued in circuit but a short time in comparison with the low-voltage specimen, but there is an indication that the curves would be very nearly parallel if they had both been continued in circuit indefinitely. Fig. 19 shows plots of increase of resistance as a function of ampere hours for high and low voltage specimens. If the continued increase of resistance after the initial rapid

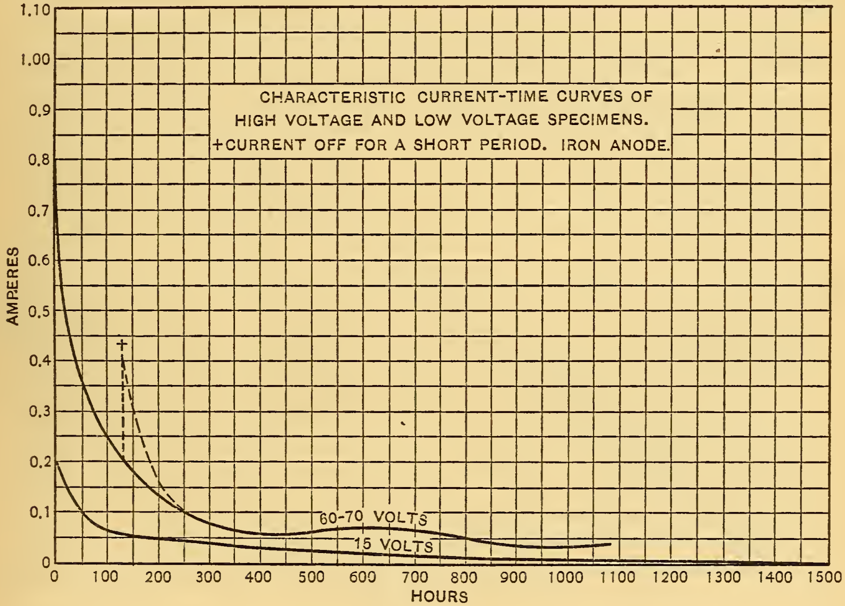

Fig. 17

increase were wholly an electrical effect and its rate of increase depended on the rate of ampere hour discharge we should expect the two last-named curves to practically coincide. There is a wide divergence, however, showing that the increase of resistance is not wholly an electrical effect. A much larger amount of electricity passes on the high voltage for a given rise of resistance than on the low voltage. It would thus appear that lapse of time is an important factor in the rise of resistance noted. As seen from the results obtained on specimen No. 75, however, the mere passage of time without current flow has but little effect, a fact which is proved more fully by measurements made on a number of other specimens in the course of the work. The foregoing phenomena are entirely in accord with the explanation of the rise of resistance set forth above.

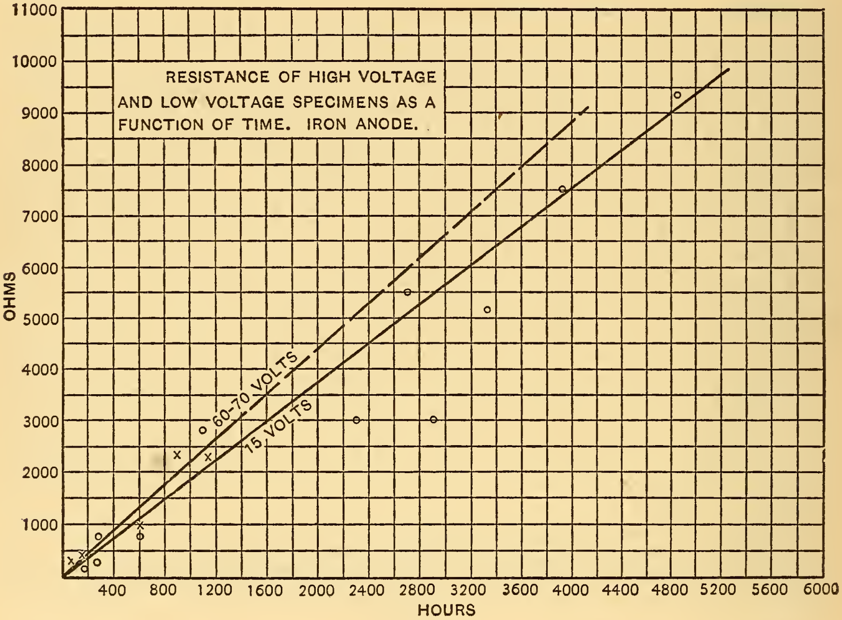

Fig. 18

(*e*) EFFECT OF THE ADDITION OF SALTS ON THE RESISTANCE OF CONCRETE

A notable exception to the practically general rule with regard to the increase of resistance of reinforced concrete when current flows through it will now be considered. A not uncommon practice in connection with the placing of concrete in cold weather is to dissolve 2 or 3 per cent of common salt (NaCl), or calcium chloride ($CaCl_2$), in the water which is used in making the mortar. This is of material benefit in lowering the freezing point of the mixture while setting. It is not definitely known that it has any detrimental effect upon the concrete itself. The effect of this addition of salt to concrete upon its electrical properties appeared very important, and hence several tests were made in the usual manner with salt added in various ways. In all cases where such specimens were tested as anodes the damage was not only found to be very much hastened, but instead of the usual increase of resistance with passage of current, the resistance actually decreased in some cases as the test proceeded. Two specimens in particular which were made up with no addition of salt, but which were tested in a 3 per cent salt solution decreased from 115 ohms to 80 ohms

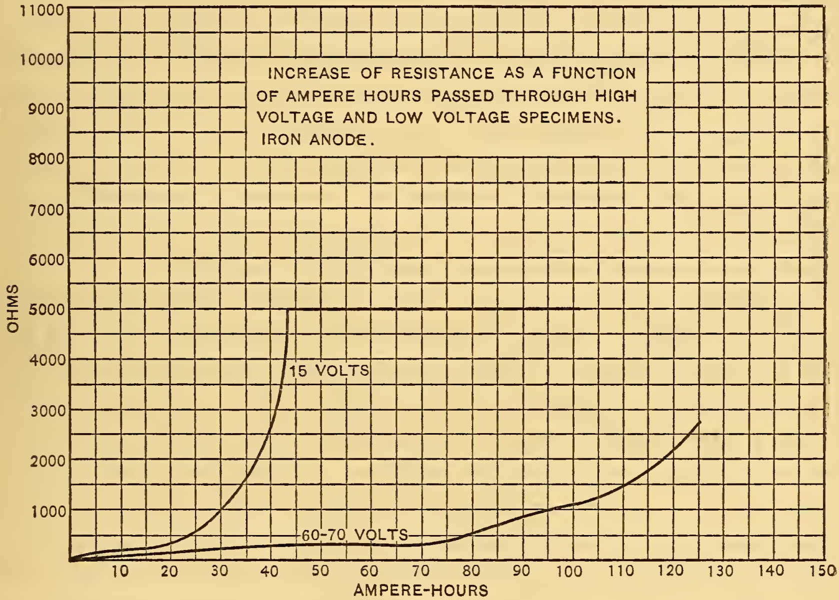

Fig. 19

and from 130 ohms to 60 ohms at the end of 410 hours and 1490 hours, respectively. (See specimens 126 and 127, Table 15.)

A second test, in which the concrete was made up with a 10 per cent salt solution and tested as anode on 15 volts over a period of five days, showed a decrease of resistance of 25 per cent. Cathode specimens tested in a manner similar to the tests on the first two specimens mentioned showed an increase of resistance of 20 to 25 per cent in the same length of time. This marked difference in character from that of all the other specimens tested in this work must be attributed chiefly to the salt, or rather to the presence of an excessive amount of the acid radical chlorine. The currents taken by the specimens were rather high in most cases, and hence heating may have had something to do with the decrease of resistance instead of an increase, but it can not account for all of it. In tests on specimens to which no salt was added the temperature rise was nearly as great, but the rise of resistance never failed to occur.

The failure of the resistance of the concrete to rise when a large amount of sodium chloride is added may be explained in part by the fact that, owing to the relatively great concentration of the sodium ions as compared with the calcium ions in this case, the greater part of the current is carried by the sodium, and hence little calcium is carried to the surface. A more important factor, however, is that the presence of sodium chloride in a solution tends to prevent the precipitation of calcium carbonate at ordinary temperatures, and thus the plugging up of the pores can not occur. This phenomenon is, therefore, corroborative of the explanation above given for the rise of resistence of specimens of normal concrete.

(f) RISE OF RESISTANCE OF CONCRETE BURIED IN DAMP EARTH

It is evident that a rise of electrical resistance of reinforced concrete takes place under all the conditions of the electrolysis experiments conducted in the laboratory except when an appreciable amount of chlorine, or perhaps other acid radical, is present in the cement. These laboratory conditions provide a liquid electrolyte in all cases. In practice wet soil would more often be the electrolyte if conditions were favorable to electrolysis. Current would also be likely to flow between sections of reinforcement without leaving the concrete. In order to determine whether or not a rise of resistance would occur in the case of concrete in soil, two blocks of concrete containing embedded iron were molded in holes dug in the earth so that about 3 inches of the block projected above the surface. The blocks were of 1:25:4 concrete, 3.5 feet square by 2.5 feet deep. Four electrodes were embedded perpendicularly to a depth of 2 feet in each block, with 4 or 5 inches of each one projecting for electrical contact purposes. These electrodes consisted of 1-inch iron rods, 1-inch iron pipe, and a length of 4-inch wrought-iron pipe. The blocks were placed about 2 feet apart. Three of the eight electrodes were connected to the negative terminal of the 15-volt circuit and the remaining five to the positive terminal. Current flowed continuously except for about 33 hours each week. Part of the current which flowed to the positive electrodes flowed out through the surface of the blocks to the soil and to a large ground plate near by, which was connected to the negative terminal of the 15-volt circuit. The rest returned by way of the electrodes which were connected to the negative terminal of the 15-volt circuit. Current readings were taken on each electrode from time to time. The values of the current on each electrode are plotted as a function of time in Figs. 20 and 21, the first figure being for the anodes and the second for cathodes. A rise of resistance was found to take place, but it is a longer time in appearing than in the case of specimens tested in jars.

(*g*) RISE OF RESISTANCE OF CONCRETE SETTING IN AIR

A similar test was carried out by passing current through three reinforced concrete beams 5 inches square by 5 feet long. These beams were made up of 1:2½:4 concrete and reinforced with one-fourth-inch rods. Four rods were embedded about 1½ inches from the bottom of each beam and came to within 1½ inches from the ends. In two of the beams 1 foot of length on the end of each rod was bent up until the end of the rod came to about 1½ inches from the top surface of the concrete. In the other two the rods were laid flat. The four beams were placed with their ends on planks so they were insulated from the earth. Holes 5 inches square were cut in the sides of a number of sheet-iron cylinders and the ends of three of the beams inserted, the fourth being used as a check. The cylinders were then filled with wet earth and connected to the 15-volt circuit, so that each beam, with the exception of the check specimen, was under 15 volts pressure over its full length with wet earth conducting the current

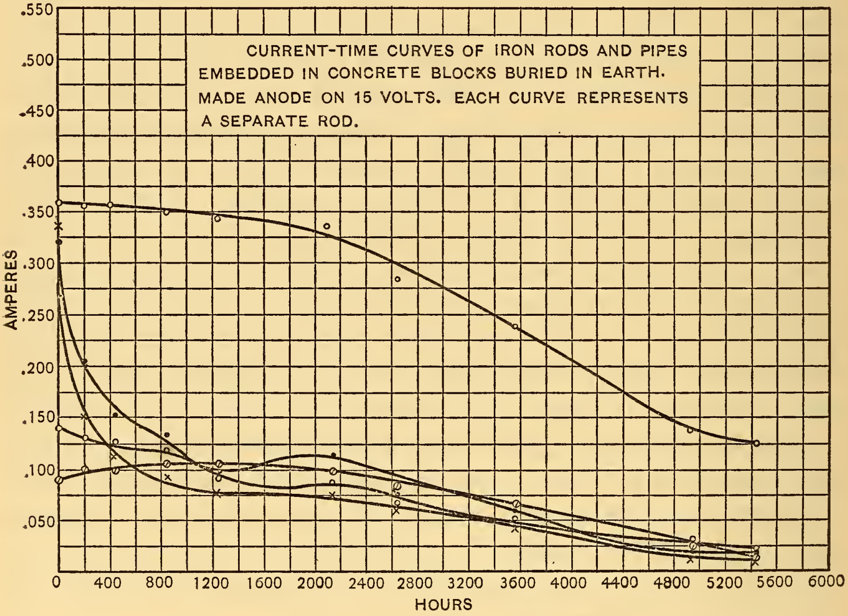

Fig. 20

from the sheet-iron cylinder to the end of the beam. Current readings were taken from time to time and the values obtained are plotted as a function of time in Fig. 22. The rise of resistance occurs in much the same manner as in the blocks buried in the earth.

In order to gain some information as to the specific resistance of concrete while setting in air without current flowing, eight 1 : 2½ : 4 concrete specimens were made in the form of rectangular blocks similar to the one shown in Fig. 28. In each of the specimens two perforated sheet-iron plates were embedded transversely at a distance of 8 inches from each other and 2 inches from the ends of the block. These plates were used as contact pieces for measuring the resistance of the portion of the concrete block between them. The dimensions of the plates were equal to those of the cross-sectional area of the block in which they were embedded. The perforations mentioned above constituted about one-third of the area of the plates and enabled the mortar of the different parts of the block to unite through the plate, thus holding the parts firmly together. When the blocks were removed from the molds the electrical resistances between the plates were measured by alternating current, using the Kohlrausch bridge.

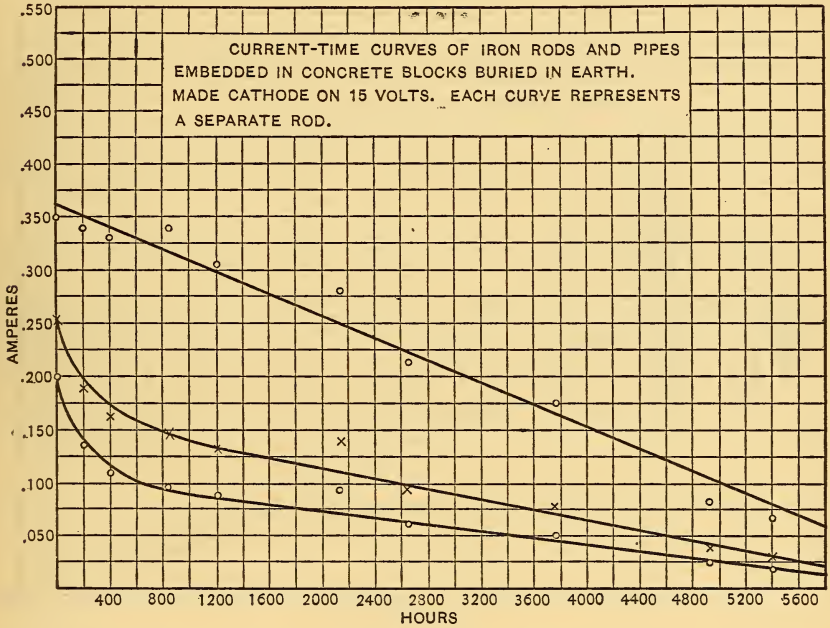

Fig. 21

The specimens were then buried in damp sand for about eight weeks. On removal from the sand the resistances were measured again, after which the specimens were placed in air in the laboratory and the measurements repeated from time to time. The average results are plotted as a function of time in Fig. 23. The points do not fall on a smooth curve, but this can doubtless be attributed to the state of the atmosphere with regard to moisture content at the time the measurements were made. The weight of the specimens remained nearly constant from the time of removal from the sand to the end of the test. This can best be accounted for, in view of the large increase of resistance noted, by the fact that with the slow-setting process which goes on during the first few months of the life of concrete a considerable amount of water is taken up by hydration, enough, possibly, to counteract the drying effect of the atmosphere.

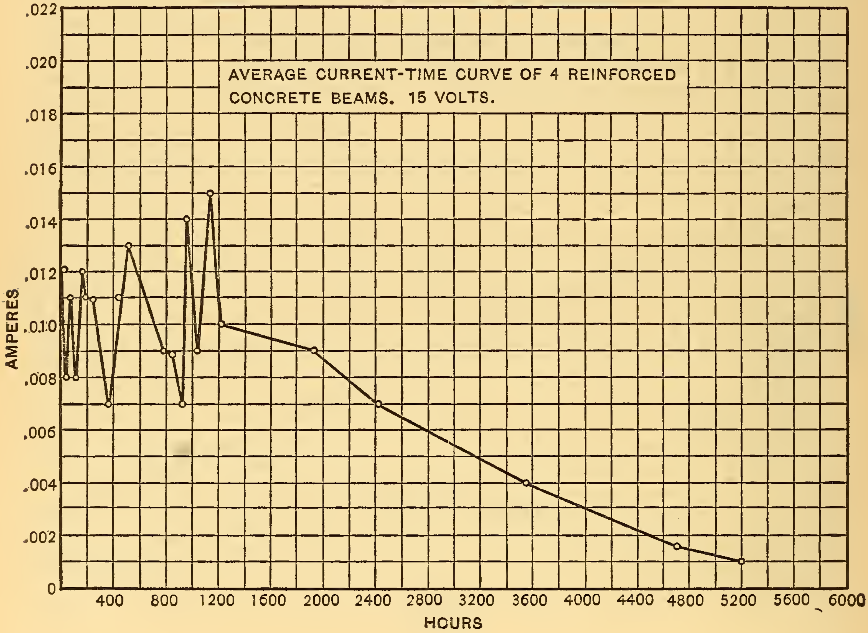

Fig. 22

It is therefore seen that a great rise of resistance takes place under conditions practically identical with those occurring in practice, and it is, therefore, an important factor in reducing damage to concrete structures, and particularly so in the case of moderate or low voltages, as a few volts or less, such as would almost invariably be met with under actual conditions. Its magnitude is such as to increase by many times the life of a structure over what it would have if subjected to severe electrolysis conditions and the rise of resistance did not occur.

15. VARIATIONS IN THE MAGNITUDE OF ELECTROLYTIC CORROSION OF IRON IN CONCRETE

It is well known that in cases of corrosion by electric currents the total amount of corrosion does not in general correspond with Faraday's law, but is in many cases considerably less than the theoretical amount. In particular, in the case of concrete, it was to be expected that the actual amount of corrosion would be less than that expected from Faraday's law, because of the alkalinity of the electrolyte. This obviously has an important bearing on the subject of electrolysis in reinforced concrete, because the extent of the reduction in the amount of corrosion determines the damage which will result to the reinforcing material by a given ampere discharge, and also determines in greater or less degree the extent of the injury to the concrete itself. This subject is here

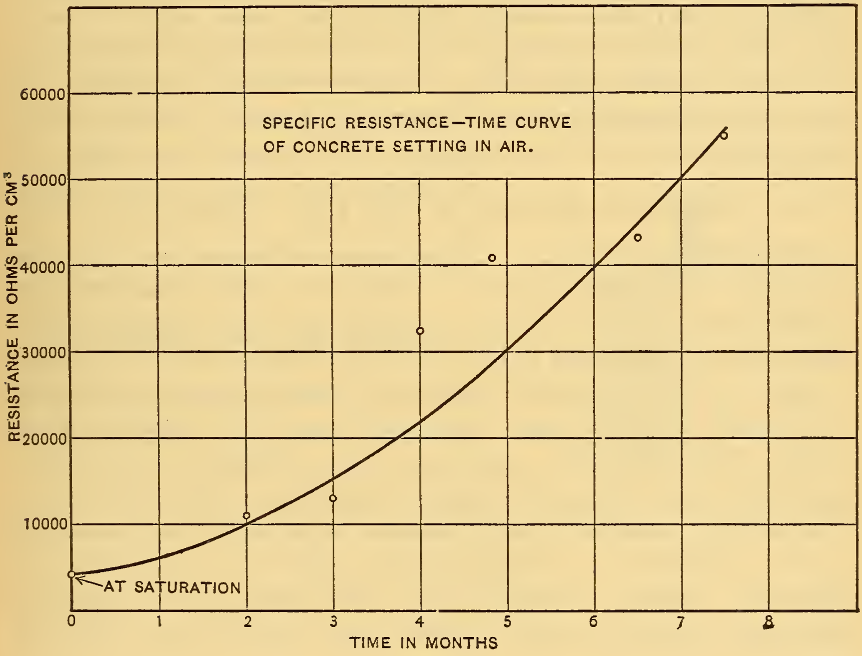

Fig. 23

discussed under two heads, i. e.: (1) Corrosion of iron in normal concrete, and (2) Corrosion of iron in concrete to which certain foreign ingredients had been added.

The first data on electrolysis of iron in concrete that admitted of comparing the theoretical amount of corrosion which should have occurred at the anode with that which actually did occur were obtained by Glauber and reported on by Prof. Langsdorf[16] in 1909. The results were very indefinite but showed that the amount of corrosion actually obtained and that which should have been obtained according to Faraday's law did not agree, the observed corrosion being only a fraction of the theoretical. In the terms of Faraday's law the theoretical amount of metal which will dissolve from an iron anode in an electrolyte, a solution of ferrous sulphate, for instance, is $\frac{2.090}{n}$ g per ampere-hour where n is the change of valency. If the change of valency is 2, as it is in nearly all ordinary cases, the amount of iron dissolved per ampere-hour would be 1.045 g. However, if the proper conditions are not maintained in the cell while the process of electrolysis is going on, or if an alkaline solution is used, a quantity of metal considerably less than the theoretical may be dissolved, that portion of the electricity passed in excess of what is used in dissolving the iron being consumed in breaking up the electrolyte. The quantity of metal actually dissolved divided by the theoretical amount according to Faraday's law is called the "efficiency of corrosion," which, as stated above, was shown by the data in Langsdorf's report to be in certain cases at least but a few per cent.

The next work along this line was done by Burgess[17] two years later. The data obtained by him were more definite and confirmed the earlier observations. Iron pipe was used in the experiments and the corroded metal was "scratch bushed" after removing it from the concrete in order to free it from rust and ascertain the loss in weight. The greatest efficiency of corrosion shown in any case not involving the addition of chemicals to the cement or

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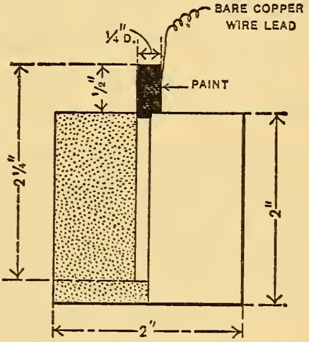
[16] A. S. Langsdorf: Electrolysis of Reinforced Concrete, Jour. Assn. of Eng. Soc., 42, p. 69; 1909.

[17] Abstract of paper by C. F. Burgess: Electrolytic Corrosion of Iron in Concrete, Eng. Record, 63, p. 272; 1911.

electrolyte was 6.88 per cent. From this value it varied downward to 1.05 per cent, depending in some degree, apparently, upon the mixture of the concrete and also on whether it was made "moist" or "wet" in mixing. The latter conditions would undoubtedly affect the percentage of voids. Testing some specimens in a 3 per cent salt (NaCl) solution gave the rather surprising result of increasing the efficiency of corrosion to percentages varying from 55 to 80. The exactness of the results in general was open to some question, however, because a considerable amount of natural corrosion could easily have taken place on the interior of the pipe during the test and the method used for cleaning the pipes, which was by brushing, would necessarily give rise to some uncertainty. The experiments were of great value, however, for the purpose for which they were intended, viz, to point out the general tendencies involved.



2"MORTAR CUBES USED IN EFFICIENCY OF CORROSION TESTS.

Fig. 24

(*a*) CORROSION TESTS USING DIFFERENT CEMENTS

By way of verification of the foregoing results a number of tests were carried out using different cements, and every effort was made to have the conditions of the tests as nearly uniform as possible. The specimens used consisted of 2-inch cubes of 1:2 mortar made up wet with standard Ottawa sand and distilled water. A round iron electrode, one-fourth inch in diameter by 2¼ inches long, was embedded 1¾ inches deep in each cube, as shown in Fig. 24. Before embedding these electrodes they were filed to a bright surface and a short bare copper wire soldered to each one. This was followed by weighing them on a balance having a sensibility of 0.0005 g, the average weight of the anodes being about 14 g. In order to prevent natural corrosion of the exposed portion of the electrode while the specimen was immersed in distilled water undergoing the setting process, this exposed portion was painted with two coats of an alkali-resisting preservative paint.

After the setting process had continued for approximately two weeks the test was commenced. Each specimen was placed in a crystallizing dish 5 inches in diameter by 2 inches deep and surrounded by a sheet-iron cylinder, which served as the cathode. The dish was then filled to within one-fourth inch of the top of the cube with distilled water, and the specimen put in circuit on 15 volts with the central electrode anode. The current density averaged about 0.025 ampere per square inch of anode surface at the beginning and gradually decreased to about 0.005 ampere per square inch at the end of the test. Current flowed continuously with the exception of 33 hours each week, current readings being taken at intervals, which increased as the test proceeded. When cracking occurred, or, if cracking did not occur, as soon as a sufficient number of ampere-hours had passed to give a reliable indication of the efficiency of corrosion, the specimens were removed from the circuit and broken open. The corroded electrodes were cleaned by a process hereafter described and then weighed and the losses determined. The current readings were plotted as a function of time, and the area included between the axes and the curve integrated by means of a planimeter. The area of the curve and the scale to which it was drawn gave the number of ampere-hours which had passed through the specimen; multiplying by 1.045 gave the amount of corrosion which would have occurred if the iron had dissolved in accordance with Faraday's law. Dividing the theoretical amount into the amount observed gave the efficiency of corrosion as defined above. Table 11 contains the condensed data.

TABLE 11

Efficiency of Corrosion in Various Cements

Specimen number	Name of cement	Voltage	Ampere-hours	Ampere-hour density	Anode loss	Theoretical loss	Efficiency of corrosion	Hours to cracking
					Gram		Gram	
77	Alpha	15	3.95	3.1	0.085	4.11	2.07	202
78	do	15	2.72	2.1	.032	2.84	1.12	202
79 (check)[19a]	do	0	0	0	.001	0		
80	Dragon	15	2.44	1.92	.047	2.54	1.85	202

TABLE 11—Continued

Efficiency of Corrosion in Various Cements—Continued

Specimen number	Name of cement	Voltage.	Ampere-hours	Ampere-hour density	Anode loss	Theoretical loss	Efficiency of corrosion	Hours to tracking
					Gram		Gram	
81	Dragon	15	1.94	1.53	.040	2.03	1.97	202
82 (check)[19a]	do	0	0	0	0	0	....	....
9	Old Dominion	15	7.7	1.3	.046	8.0	0.5	No cracking
10	do	15	7.7	1.3	.068	8.0	0.85	Do.
11	do	15	7.7	1.3	.118	8.0	1.47	Do.
12	do	15	7.7	1.3	.223	8.0	2.80	Do.
83	do	15	0.99	0.78	.054	1.03	5.20	42
84	do	15	1.16	0.91	.079	1.22	6.40	66
85 (check)[19a]	do	0	0	0	.003	0	....	....
86	Lehigh	15	1.57	1.23	.084	1.64	5.10	90
87	do	15	1.54	1.21	.061	1.61	3.70	90
88 (check)[19a]	do	0	0	0	.004	0	....	....
89	Universal[18]	15	0.43	0.34	.073	.455	16.00	24
90	do	15	0.42	0.33	.058	.437	13.20	24
91 (check[19a])	do	0	0	0	.004	0	....	....
92	Vulcanite	15	4.83	3.80	.017	5.04	0.33	No
93	do	15	5.74	4.52	.023	6.00	0.38	Cracks
94 (check)[19a]	do	0	0	0	0	0	....	....
95	Erz cement[19]	15	1.52	1.20	.237	1.58	15.00	193
96	do	15	1.58	1.24	.160	1.65	9.70	193
97 (check)[19a]	do	0	0	0	.001	0	....	....

[18] Containing 0.3 per cent SO_3.
[19] Manufactured in Hemmoor, Germany.
[19a] These specimens carried no current.

The test of each cement was made on a set of three cubes, one being kept without current as a check on natural corrosion and the other two tested electrically, as described. The results obtained from specimens of Old Dominion cement include those of four 3 by 4 inch cylinders of 1.2 mortar with one-half inch rods embedded.

The check specimens showed very little natural corrosion, the losses in these cases being hardly greater than the errors which would be expected to occur in weighing. The efficiencies of corrosion compare very well with those obtained by Burgess, and show beyond a doubt that under the conditions of these experiments but a small fraction of the current passing through a specimen of reinforced concrete is effective in dissolving the iron. The variations in efficiency of corrosion between different cements are quite marked; the corrosion efficiency of some specimens of Old Dominion and Lehigh being three or four times that of Alpha and Dragon. The Vulcanite shows a remarkably low efficiency of corrosion, but while under test the resistance of the specimens was less than half that of the other specimens. The Universal cement contained only 0.3 per cent SO_3, no calcium sulphate being added in grinding the particular batch from which the specimens were made. The Erz cement shows a comparatively high efficiency of corrosion. This cement contains a relatively large percentage of iron, the iron replacing part of the aluminum which enters into the composition of ordinary Portland cement.

An examination of the chemical analyses of these cements shows that there is apparently no relation whatever existing between the variations in the efficiency of corrosion and the SO_3 content of a cement.

(*b*) EFFECT OF TEMPERATURE ON EFFICIENCY OF CORROSION

One of the most important facts to be noted in connection with the efficiency of corrosion in concrete is the great change in the efficiency of corrosion attendant upon a change of the voltage through a wide range of values and the consequent accompanying change of current density at the surface of the electrode. There is evidence of this change in the efficiency of corrosion in the results of the anode tests described in the first part of this paper. The high voltage tests recorded in Table 1 show that cracking of the specimens occurred after an ampere-hour density of 0.83 per square inch had passed through them. Specimens Nos. 10 and 11 of Table 1 were in such a condition at the end of the test with regard to natural corrosion of the exposed iron as to permit cleaning and weighing to determine the loss by electrolysis. No. 10 showed an efficiency of corrosion of 37 per cent and No. 11 of 40.8 per cent. There is a marked contrast between these values and those found in Table 2, where the results of testing specimens on 15 volts are recorded. The 15-volt specimens passed an average of 2.6 ampere-hours per square inch of anode surface with no sign of cracking, excepting 3 isolated instances out of 90, the characteristics of which were such as to exclude them from consideration as normal specimens. The electrode of specimen No. 25 of Table 2 was undoubtedly corroded more than that of any specimen recorded there. It was cleaned and weighed and the efficiency of corrosion found to be 10 per cent. From this extreme value of 10 per cent for a 15-volt specimen the efficiencies of corrosion for this voltage varied downward, decreasing nearly to zero in many cases. Specimens Nos. 31 and 32 of Table 2 were tested on 5 volts. At the end of 5300 hours 0.43 and 0.53 ampere-hours per square inch of anode surface had passed. When broken open there was no sign of corrosion whatever. For specimens of the same form the various current densities were in practically the same ratio as the voltages at like periods of the tests. The decrease in the efficiency of corrosion therefore does not take place in the same proportion as the decrease in current density. For the type of specimen used in these tests and for the conditions of the tests it seems that corrosion practically ceases at a voltage somewhat below 15 volts.

An additional experiment, which shows the effect on the efficiency of corrosion of varying the voltage and current density was carried out on specimens from the same group of 2-inch mortar cubes as 87 and 88 of Table 11. These specimens were tested in the same way as those of Table 11, excepting that the voltages on the different specimens varied from 1 to 15 volts. Condensed data of the tests are given in Table 12.

TABLE 12

Efficiency of Corrosion with Various Current Densities

Specimen number	Name of cement	Voltage	Ampere-hours	Anode loss	Theoretical loss	Efficiency of corrosion	Average amperes per square inch
				Gram		Per cent	
98	Lehigh	1	0.00034	0.002	0	0	0
99	do	1	.00034	.001	0	0	0
100	do	4	1.15	.015	1.20	1.25	0.0022
101	do	6	1.74	.031	1.82	1.70	.0034
102	do	9	2.28	.085	2.38	3.50	.0049
103	do	11	1.40	.116	1.46	8.00	.0075
104	do	15	1.57	.084	1.64	5.10	.013

Fig. 25 is a curve showing the efficiencies of corrosion as a function of current density. On comparing the results of these tests with those previously described, it is seen that while an increase of voltage from 4 to 15 volts in the case of the 2-inch tubes caused an increase in efficiency of corrosion from 1 per cent or a little more to about 5 per cent, an increase of voltage from 15 volts to 50 volts on the 6 by 8 inch cylinders caused an increase in the efficiency of corrosion from 2 or 3 per cent to about 40 per cent.

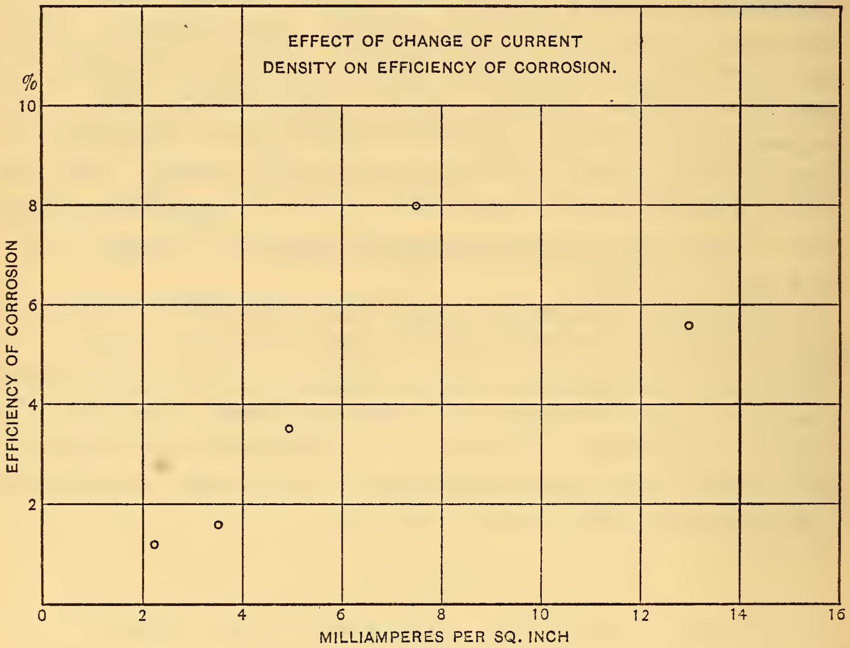


Fig. 25

The comparison of these results, together with the fact that where the high efficiencies of corrosion prevailed there was always high temperature, led to other tests which were designed to show the effects of temperature on the efficiency of corrosion.

For the purpose of carrying out the temperature tests a number of cylindrical specimens 4 inches in diameter by 4½ inches long were made up of a 1:2 mortar consisting of quartz sand and Old Dominion cement mixed with distilled water, the sand having been washed with tap water before using. A one-half inch round iron electrode was embedded to a depth of 4 inches in the axis of each cylinder. Before embedding the iron electrodes they were filed to remove all scale and rust and bare copper-wires leads soldered to them. They were then carefully weighed, and the exposed portion well coated with paint to prevent natural corrosion. When the electrodes were placed in the mortar a piece of glass tubing 1 inch in length and having an internal diameter of about seven-sixteenths inch was placed around the electrode, the lower end of the piece of tubing being embedded in the mortar to a depth of one-fourth inch. The object of this was to prevent leakage of current from the electrode above the mortar if the top of the specimen became wet while under test. After being removed from the molds, the specimens were allowed to set in a damp closet two weeks before testing.

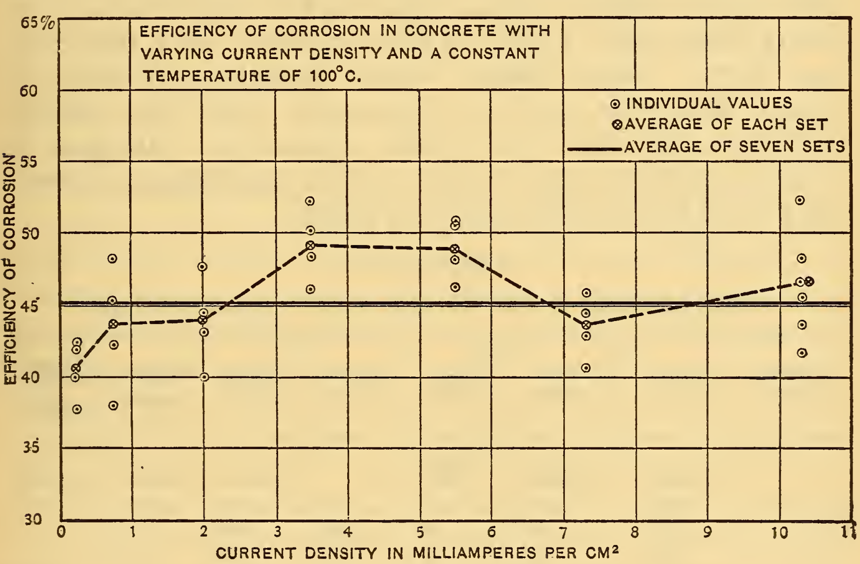


Fig. 26

In order to test the specimens, they were inclosed in metal vessels with wooden tops which could be screwed down tight, to prevent the rapid evaporation of water, and placed in an electrically heated bath of transformer oil. To obtain a fair average result for each value of the temperature and current density at the anode surface, the specimens were tested in sets of four, the four specimens being connected in series, so that the current density might be the same in each. Distilled water served as the electrolyte and the metal vessel answered for a cathode.

The first series of tests was carried out, using varying current density and constant temperature. The object of this test was to ascertain whether or not any variation in efficiency of corrosion might be directly due to a change in the current density over the surface of the electrode. The only temperature which could be relied on for constancy with all values of I^2R in the specimen was boiling temperature, which, for the electrolyte, was a trifle more than 100° C. Seven different current densities were used, the current density for each set of specimens being kept constant throughout the test. The results obtained are tabulated in Table 13, while the curve of Fig. 26 shows the efficiency of corrosion plotted as a function of current density.

TABLE 13

Corrosion tests at 100° C with various current densities

Specimen number.	Time of test	Total current	Current density	Ampere-hours	Loss by corrosion	Efficiency of corrosion	Average efficiency of corrosion
	Hours	Amperes	$\frac{\text{M. A.}}{\text{CM}^2}$		Grams	Per cent	Per cent
105	148.5	0.010	0.25	1.48	0.586	37.8	
105A	148.5	.010	.25	1.48	.653	42.1	
115	148.5	.010	.25	1.48	.626	40.3	
111	148.5	.010	.25	1.48	.657	42.3	40.6
100	49.0	.030	.78	1.47	.714	46.3	
104	49.0	.030	.78	1.47	.583	38.0	
103	49.0	.030	.78	1.47	.654	42.4	
102	49.0	.030	.78	1.47	.743	48.2	43.7
83	24.0	.072	2.0	1.728	.780	43.3	
80	24.0	.072	2.0	1.728	.727	40.0	
84	24.0	.072	2.0	1.728	.796	44.2	
97	24.0	.072	2.0	1.728	.861	47.8	44.3
85	12.6	.120	3.5	1.51	.760	48.4	
82	12.6	.120	3.3	1.51	.724	46.1	
79	12.6	.120	3.4	1.51	.820	52.2	
75	12.6	.120	3.4	1.51	.788	50.2	49.2
96	6.75	.200	5.12	1.35	.655	46.3	
86	6.75	.200	5.55	1.35	.679	48.1	
94	6.75	.200	5.40	1.35	.715	50.7	
87	6.75	.200	5.40	1.35	.711	50.5	48.9

TABLE 13—Continued

Specimen number	Time of test	Total current	Current density	Ampere-hours	Loss by corrosion	Efficiency of corrosion	Average efficiency of corrosion
	Hours	Amperes	$\frac{\text{M.A.}}{\text{CM}^2}$		Grams	Per cent	Per cent
76	7.0	.265	7.3	1.85	.786	40.7	
74	7.0	.265	7.7	1.85	.886	45.9	
77	7.0	.265	7.3	1.85	.831	43.0	
92	7.0	.265	7.3	1.85	.860	44.5	43.5
91	3.66	.37	9.7	1.35	.643	45.6	
88	4.0	.37	10.6	1.48	.805	52.2	
89	4.0	.37	10.3	1.48	.742	48.1	
73	4.0	.37	10.3	1.48	.645	41.8	
95	6.5	.35	10.3	2.27	1.106	46.6	
93	7.25	.35	10.3	2.53	1.156	43.7	46.5

It is seen that increasing the current density in the ratio of 1 to 40 causes no material change in the efficiency of corrosion. For a given current density there are variations in the efficiencies of corrosion between individual specimens, but these variations may be attributed to variations in the concentrations of the dissolved substances of the electrolyte. A slight variation in the concentration of one of the solvents could easily cause a marked change in the efficiency of corrosion. This is especially true at the boiling point, because at that temperature calcium hydroxide is but about one-half as soluble as at room temperatures and its passivating action would therefore be greatly reduced, giving any dissolved salts of marked corrosion tendencies a much greater opportunity to act in proportion to their concentrations.

A second series of tests, the purpose of which was to show the effect of variation of temperature on the efficiency of corrosion, was conducted in a manner similar to that of the preceding series of tests. The range of temperature was from 3° to 100° C, the temperature of the electrolyte being the one measured and recorded. In order that the heating effect of the current on the interior of the specimen might be nearly the same at all temperatures the current was kept constant and equal to 0.030 ampere through the four specimens of each set in series. The total average voltage required for this was about 26 volts. The power expended in all four specimens was therefore 0.78 watt. Dividing this by 4 x 4.189 gives 0.047 calorie of heat liberated in each specimen per second. Since heat was being constantly lost from the specimen through evaporation of water, such a rate of heat liberation, distributed as it was between positive and negative electrodes, could not result in a material increase of the temperature of the interior of the specimen over that of the electrolyte. If such an

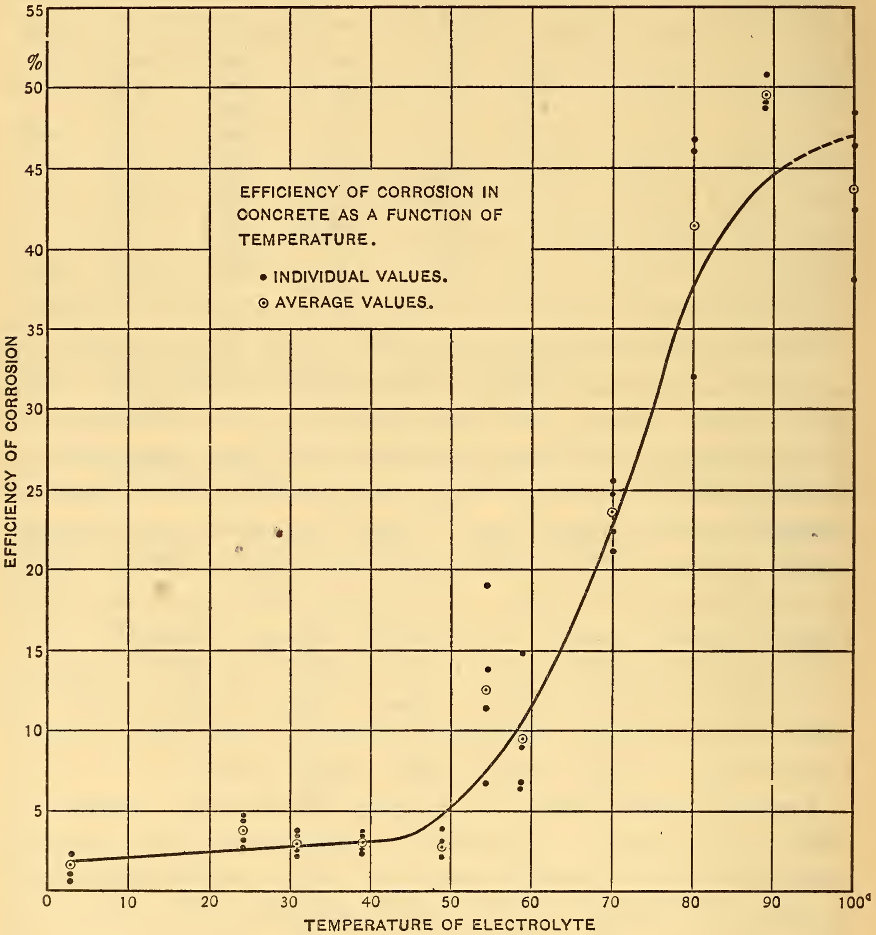


Fig. 27

increase took place, however, it would only mean that the curve showing the efficiency of corrosion as a function of temperature would be displaced a certain amount toward the right if the temperature at the surface of the electrode were known and plotted in place of the temperature of the electrolyte. The shape of the curve would not be changed. The condensed data of the test are given in Table 14. Fig. 27 shows a plot of efficiency of corrosion as a function of temperature, the temperature of the electrolyte being the one used, as mentioned above.

TABLE 14

Efficiencies of Corrosion

Specimen number	Time of test	Ampere-hours	Loss by corrosion	Temperature of electrolyte	Efficiency of corrosion	Average efficiency of corrosion
	Hours		Grams	°C	Per cent	Per cent
142	51.5	1.54	0.026	3.0	1.60	
150	51.5	1.54	.037	3.0	2.31	
146	51.5	1.54	.017	3.0	1.06	
141	51.5	1.54	.012	3.0	.75	1.43
99	48.5	1.45	.069	24.8	4.54	
108	48.5	1.45	.044	24.8	2.90	
110	48.5	1.45	.068	24.8	4.47	
113	48.5	1.45	.053	24.8	3.42	3.84
109	47.8	1.43	.048	31.0	3.20	
107	47.8	1.43	.051	31.0	3.40	
116	47.8	1.43	.041	31.0	2.73	
106	47.8	1.43	.039	31.0	2.60	2.98
132	48.2	1.45	.038	39.5	2.51	
114	48.2	1.45	.042	39.5	2.76	
101	48.2	1.45	.054	39.5	3.57	
112	48.2	1.45	.046	39.5	3.04	2.97
132	48.0	1.44	.031	49.3	2.06	
122	48.0	1.44	.058	49.3	3.86	
137	48.0	1.44	.038	49.3	2.53	
139	48.0	1.44	.041	49.3	2.73	2.79
144	48.0	1.44	.206	54.5	13.70	
135	48.0	1.44	.102	54.5	6.80	
143	48.0	1.44	.285	54.5	19.00	
136	48.0	1.44	.174	54.5	11.50	12.7
124	48.0	1.44	.103	59.9	6.86	
121	48.0	1.44	.138	59.9	9.20	
123	48.0	1.44	.218	59.9	14.53	
119	48.0	1.44	.102	59.9	6.80	9.35
125	48.3	1.45	.384	70.0	25.40	
121	48.3	1.45	.343	70.0	22.70	
128	48.3	1.45	.375	70.0	24.80	

TABLE 14—Continued

Specimen number	Time of test	Ampere-hours	Loss by corrosion	Temperature of electrolyte	Efficiency of corrosion	Average efficiency of corrosion
	Hours		Grams	°C	Per cent	Per cent
118	48.3	1.45	.322	70.0	21.30	23.50
140	48.0	1.44	.692	79.8	46.10	
126	48.0	1.44	.479	79.8	32.00	
129	48.0	1.44	.702	79.8	46.80	41.60
130	48.0	1.44	.740	89.5	49.30	
134	48.0	1.44	.733	89.5	48.80	
133	48.0	1.44	.763	89.5	50.80	49.6
102	49.0	1.47	.743	100.0	48.30	
103	49.0	1.47	.654	100.0	42.40	
104	49.0	1.47	.583	100.0	38.00	
100	49.0	1.47	.714	100.0	46.30	43.7

The most prominent characteristic of the curve of Fig. 27 is the sharp bend upward which occurs in the neighborhood of the temperature of 50°. Below 50° the efficiency of corrosion is very small. Since current density has been shown to have no direct effect on efficiency of corrosion, the great difference in efficiency of corrosion between high and low voltage specimens must therefore be attributed to the heating effect of the current. If the heating effect of the current is sufficient to raise the internal temperature of the specimens to 50° C or more, active corrosion occurs. Below 50° the iron remains passive, or nearly so. This has been found to be strictly true, however, only for normal concrete specimens to which no foreign ingredient of marked corrosive tendencies has been added, as will presently appear.

(c) CORROSION OF IRON IN CONCRETE CONTAINING FOREIGN INGREDIENTS

In building concrete structures it is not uncommon to add certain ingredients to the mortar in mixing. One of these ingredients is sodium chloride, and in adding it the purpose is to lower the freezing point of the mixture while it is setting in cold weather. Calcium chloride is also used for the same purpose. Another ingredient commonly added to mortar is hydrated lime, the function of which is to reduce the percentage of voids in the concrete and thus render it more than ordinarily impermeable to water. A large number of proprietary compounds are also used with the same object in view. These consist of powders, pastes, and liquids, and are usually added in a way calculated to affect their thorough and uniform distribution throughout the mass. The effect of these additions upon the efficiency of corrosion and other electrical properties of concrete has not heretofore been investigated. A number of specimens were therefore made up and tested, using as many of these ingredients as were at hand when the tests were instituted.

(*d*) EFFECT OF WATERPROOFING COMPOUNDS

The specimens used were of standard type, 1:2½:4 concrete, made up in the way described at the beginning of this paper, with the exception that the integral compounds were included in the mixture.

These were added to the cement and did not replace any of it. Table 15 contains the condensed data of these tests as far as they have been carried out to date. All of the specimens were connected up with the embedded electrode anode, the electrical connections being the same as shown in Fig. 2. Tap water was used for electrolyte unless otherwise designated in the table.

TABLE 15

Effect of Addition Integral Compounds to Concrete upon the Efficiency of Corrosion

Specimen number	Voltage	Total ampere-hours	Ampere-hour density per square inch	Resistance in ohms at beginning of test	Resistance at cracking	Resistance at end of test	Hours to cracking	Hours of test	Cement used	Electrode used	Age of specimen at test	Integral added	Corrosion
													Per cent
37	15.0	7.7	1.1				No cracks	233	Old Dominion	½-inch round iron	69 days	0.001 % $CaCl_2$	0.46
38	15.0	7.7	1.1				do	233	do	do	do	0.005 % $CaCl_2$	1.11
39	15.0	10.0	1.4				do	111	do	do	84 days	0.010 % $CaCl_2$	2.30
40	15.0	10.0	1.4				do	111	do	do	do	0.02 % $CaCl_2$	9.10
41	15.0	6.5	0.94				72	72	do	do	93 days	0.05 % $CaCl_2$	15.3
42	15.0	8.4	1.20				72	72	do	do	do	0.10 % $CaCl_2$	10.8
105	15.0	25.3	0.92	131	No cracks	18750	No cracks	5631	do	1-inch pipe	60 days	20% oil No. 4147	(20)
106	15.0	35.3	1.30	119	do	37500	do	5631	do	do	do	15% oil No. 4147	(21)
107	15.0	39.2	1.40	120	do	1150	do	5631	do	do	do	10% oil No. 4147	(22)
108	15.0	36.2	2.26	487	do	7500	do	5696	Dragon	¾-inch round iron	do	do	(22)
109	15.0	56.9	3.50	92	do	4687	do	5696	do	do	do	do	(20)
110[28]	15.0	80.2	2.94	160	do	25000	do	5631	Old Dominion	1-inch pipe	do	20% paraffin-gasoline solution	(20)
111[24]	15.0	188.8	7.30	141	326	1000	2000	5631	do	do	do	do	(22)
112	15.0	38.4	2.38	226	No cracks	10700	No cracks	5832	Atlas	¾-inch round iron	46 days	15% lime	(20)
113	15.0	32.7	2.04	191	do	9000	do	5832	do	do	do	do	(22)
114	15.0	42.4	2.72	160	do	18750	do	5832	do	do	do	10% lime	(20)
115	15.0	49.0	3.00	142	do	16600	do	5832	do	do	do	do	(20)
116	15.0	60.9	3.74	166	do	21400	do	5832	do	do	do	5% lime	(22)
117	15.0	67.1	4.00	150	do	12500	do	5832	do	do	do	do	(22)
118	15.0	38.7	2.40	186	do	10700	do	5718	do	do	do	6% Medusa	(20)
119	15.0	41.9	2.60	181	do	10000	do	5718	do	do	do	do	(20)

120...	15.0	36.8	2.30	186	.....do......	11500	.....do......	5718	.....do.......	.....do...........	...do.....	4% Medusa....	(20)
121...	15.0	61.8	3.80	160	.....do......	21400	.....do......	5718	.....do.......	.....do...........	...do.....	.....do.........	(22)
122...	15.0	53.0	3.30	128	.....do......	7500	.....do......	5718	.....do.......	.....do...........	...do.....	2% Medusa....	(22)
123...	15.0	36.6	2.35	137	.....do......	5000	.....do......	5718	.....do.......	.....do...........	...do.....	.....do.........	(20)
124...	15.0	60.8	3.80	100	.....do......	7500	.....do......	4425	Alpha.........	.....do...........	33 days..	3% Harrison's compound.	(22)
125...	15.0	58.1	3.60	120	.....do......	7500	.....do......	4425	.....do.......	.....do...........	...do.....	.....do.........	(22)
126...	57.5	12.1	0.77	115	90	8.0	19	216	Giant.........	.....do...........	29 days..	Tested in 3% NaCl sol.	Very severe
127...	31.0	23.9	0.88	248	64	6.0	46	1490	Pennsylvania .	1-inch pipe........	90 days..	.....do.........	Do.
128...	15.0	171.5	5.40	10	7.5	7.5	120	120	Old Dominion	4-5 x ½ inch round iron rods	6 months	15% NaCladded	87.4
129...	15.0	144.7	4.60	9	7.0	7.0	120	120	.....do.......	.....do...........	...do.....	.....do.........	70.6
130...	15.0	87.6	2.80	12	8.0	8.0	120	120	.....do.......	.....do...........	...do.....	.....do.........	72.4
131[25].	15.0	0.60	0.47	....	....	....	....	....	Lehigh........	¼-inch round iron..	5 days...	0.33% NaCl	80.0
132[25].	15.0	0.73	0.57	....	....	....	....	....	.....do.......	.....do...........	...do.....	.....do.........	63.0

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[20] Corrosion confined to spots and small pits. Rest of iron bright.

[21] No corrosion.

[22] Iron coated with a thin layer of rust.

[23] Solution consisted of 18 per cent paraffin and 82 per cent gasoline.

[24] Ampere-hour density to cracking = 4.

[25] Specimens 131 and 132 were of the same form as those described in connection with Table 10.

The addition of integrals to specimens 105 to 125, inclusive, did not result in a very material increase in corrosion in any case if specimen 111 is excepted. As mentioned in the first part of this paper, this specimen seems to have been abnormal in respect to its resistance and hence the results obtained on it should perhaps not be considered as representing what would happen in any considerable number of cases if an addition of the character designated under specimen 111 were made to concrete. All but one of the other specimens of this number were corroded very badly. But one specimen gave evidence of no corrosion at all, which is a small percentage of the whole number in comparison with the percentage of those showing no corrosion which is found in Table 2.

(*e*) EFFECT OF SALT AND CALCIUM CHLORIDE

The effect of sodium chloride and calcium chloride proved to be in every way as remarkable as indicated by the work of Burgess. The addition of 0.02 per cent of $CaCl_2$ to the cement resulted in a very marked increase in the efficiency of corrosion. Below that percentage the addition of chlorine in the form of $CaCl_2$ did not seem to have an appreciable effect. One-third of 1 per cent of sodium chloride was found to be sufficient to destroy passivity of the iron almost entirely. Such a result might have been anticipated from the work of Hayden on the electrolytic corrosion of iron by direct current[26] in which it was found that the addition of ammonium chloride to a potassium bichromate solution (to the amount of 4 per cent of the potassium bichromate) destroyed the passivity of iron when made anode in the solution. With potassium nitrate solution the addition of ammonium chloride to the amount of 2 per cent of the potassium nitrate was required to destroy the passivity of the iron. The same work also shows the addition of sulphates to be much less destructive than chlorides to the passivity of iron anodes in solutions which normally produce passivity of iron. Specimens 126 and 127 had no salt added in making, but were tested in 3 per cent NaCl solution.

It thus appears that great care should be exercised in selecting an ingredient to add to reinforced concrete for any purpose what-

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[26] Hayden: Electrolytic Corrosion of Iron by Direct Current, J. Franklin Inst., 172, p. 295.

soever, provided there is any likelihood that the structure will later be subjected to the action of electric currents. In such cases the addition of chlorine should be avoided entirely, and before using it an integral waterproofing should be carefully examined for the presence of any soluble salt having a marked tendency to increase corrosion of the iron.

16. ELECTROLYTIC CLEANING OF RUSTED IRON

In cleaning a specimen of corroded iron preparatory to weighing great care must be exercised in order to insure the removal of all corroded iron and at the same time not remove any of the pure metal. Numerous mechanical methods have often been employed, but their use often leads to serious errors. In the course of the present investigation it was early recognized that such methods could not be relied upon, and after considerable experimenting they were abandoned.

Electrolytic methods were then developed for cleaning corroded wrought iron and cast iron which have proven entirely satisfactory. The first attempt to clean wrought iron of rust electrolytically was made by connecting it up as cathode in a 2.5 per cent H_2SO_4 solution, using iron for the anode. The rusted iron was cleaned, but iron apparently dissolved from the anode and plated out at the cathode, causing an increase of weight which was too great to be neglected. The fact that the iron plated out at the cathode was ascertained by running a clean check specimen in parallel with and close to a rusted specimen and also by running a clean specimen as cathode with no rusted specimen accompanying it. Increase of weight occurred with the check specimens in both cases and seemed to be proportional to the time provided the current was constant. Pieces of one-fourth-inch round iron rod 2½ inches long, weighing about 15 g, were used as check specimens. The increase in weight of the check specimen in one case was 0.016 g after two hours with 1 ampere of current flowing. This was the greatest increase of weight noted in any case, but several other check specimens were run for one-half hour, one hour, and one and three-fourths hours, and increases in weight of 0.004 to 0.012 g occurred.

The solution of the problem thus seemed to depend upon finding a material for the anode which would be noncorrodable by electrolysis in a dilute solution of sulphuric acid. With this in mind a piece of magnetite ore (Fe_3O_4) was tried in the same way as the iron anode. Contact was made with the magnetite above the solution with mercury-solder amalgam, care being taken to keep the amalgam out of the electrolyte. The resistance of the cell was considerably increased over that with the iron anode, but no difficulty was encountered in making the current density at the cathode great enough for rapid action. A number of rusted specimens were cleaned with check specimens beside them and several check specimens were run for periods varying from one-half hour to seven or eight hours. In 10 or more trials there was no change of weight that could not be attributed to errors in weighing. The greatest change noted was 0.002 g and the most of them were 0.001 g or less. The magnetite anode lost some weight during the progress of the tests, which probably was due to impurities in it that were attacked by the acid. Exposure to the action of the acid for a number of days resulted in disintegration of the magnetite. The cleaning action was all that could be desired, however, the iron being left perfectly free from rust.

The magnetite anode in the acid seemed to work perfectly, but the difficulty of obtaining an anode of this type of very great size led to the use of lead in place of magnetite. The results of the first tests with a lead anode were not very satisfactory. The iron was cleaned of rust but was blackened. Continued use of the same lead anode, however, seemed to give rise to a passive condition of the lead which gave very good results as far as cleaning was concerned. The blackening of the iron while being cleaned ceased entirely and for a period of two hours in a fresh solution of acid check specimens gave no sign of an appreciable change in weight. The passive condition of the lead doubtless came about by the formation of a layer of difficultly soluble lead sulphate on its surface during the first hours that the current was passed from it. It was found necessary, however, to change the solution periodically. After about four hours of current flow lead would begin to plate out and blacken the cathode, causing a change in weight. This rule held for a cell containing 1000 cc of solution and a lead anode surface of about 70 cm². The current used was 3 amperes or a little more. When the precautions of running the lead as anode until the passive condition was reached and changing the solution often enough were observed, however, the cleaning action was perfect and the change in weight of the cleaned iron negligible.

It was found that in all cases where wrought iron was cleaned in acid by the electrolytic method the current flow must take place over the entire surface of the iron. Neglect of this important point resulted in action by the acid. In order to ascertain what current density was necessary to completely protect the iron from corrosion by the acid while the cleaning process was going on a number of tests were carried out using various current densities. It was found that for different specimens of wrought iron the current density necessary for protection varied a good deal. In no case, however, did the specimens lose weight when the current was equal to or in excess of 0.0003 ampere per square centimeter, and it was therefore concluded that a current density of that value would be a safe one to assume for the purpose.

An attempt to clean rusted cast iron by this method resulted in a total failure. The iron lost weight very rapidly even when the current density was very high. With a current density of 0.01 ampere per cm² a specimen of clean cast iron lost 3.82 g in six hours. Continuing the specimen in circuit longer resulted in a plating out of lead at the cathode. Smaller current densities permitted much greater losses than the above. A trial was then made with a 1 per cent KOH solution (ordinary lye), using a piece of cast iron for the anode. A run on a check specimen of clean iron weighing 292 g, lasting 24 hours, with a current density of about 0.0003 ampere per cm², resulted in a gain in the weight of the cathode of 0.02 g. Rusted cast iron was then tried and the cleaning action was found to be very good. A black deposit was left on the surface of the iron but it washed off quite readily. The iron was blackened slightly but was otherwise in good condition. For small pieces of rusted wrought iron the method using the lead anode is perhaps best and most convenient, while for large pieces of either cast or wrought iron the latter method is to be preferred. The latter method is also safest when close attention can not be given the cell while in action. If the current is stopped no corrosive action can take place in the latter case while in the former the acid attacks the iron.

The cleaning action at the cathode seems to be due to the liberation on the surface of the iron of hydrogen. The liberation seems to occur on the surface of the iron rather than on the rust, and the resulting sudden expansion probably pries or knocks the rust particles loose while at the same time the iron itself is protected against corrosion.

17. LABORATORY EXPERIMENTS WITH PROPOSED METHODS FOR MINIMIZING ELECTROLYSIS IN REINFORCED CONCRETE

A number of methods have been proposed by various investigators for preventing or reducing damage in reinforced concrete by electrolysis. Little has been known as to the efficacy of these proposed remedies, however, and in order to throw further light on the questions regarding their practical value a number of laboratory experiments were instituted. These methods are, in general, only applicable to structures which are in process of erection.

(a) REDUCING THE EFFICIENCY OF CORROSION OF THE IRON BY CHEMICAL MEANS

Up to the date of this writing the attempts toward reducing the efficiency of corrosion by chemical means have met with very indifferent success. In an endeavor to contrive some means for reducing the efficiency of corrosion of iron when made anode in concrete a number of substances known to retard the natural corrosion of iron in their aqueous solutions were tried out. The names of the materials used were taken from the published work of Heyn and Bauer[27] and are indicated in Table 16, which gives the condensed data of the test. The type of specimen used for the test was the same as that described in connection with Table 11 and illustrated in Fig. 24. The specimens were of 1 : 2 mortar, made up of Old Dominion cement, quartz, sand, and distilled

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[27] Heyn and Bauer: Mitteillungen K'gl'n Materialprufungsamt, p. 45, 1908.

water. In order to insure the uniform distribution of the chemicals throughout the mass they were dissolved in the water used in making the mortar. They were used in varying concentrations, and the specimens of a set containing a single chemical were connected in series while under test in order to have the same current density in each one as far as practicable. Eight specimens constituted a set and were connected to the 115-volt circuit, thus making the drop across each specimen about 14 volts. Several specimens to which no additions had been made were also tested. Distilled water served as the electrolyte. The current density at the surface of the electrode varied from approximately 20 mil-amperes per square inch at the beginning of the test to about 0.8 of a mil-ampere at the end. After the specimens had been in circuit a sufficient length of time to give reliable results, they were removed and the loss of iron by electrolysis determined. The resulting efficiencies of corrosion are seen to be extremely small in all cases, while the differences between those obtained with the chemicals added and those without any added are not of a magnitude which would suggest their use in practice as preventives of electrolytic damage.

TABLE 16

Efficiency of Corrosion in Mortar with Various Chemicals Added

Specimen number	Substance used	Per cent of substance by weight of cement	Per cent solute in gaging water	Concentration in block in mols. per liter	Ampere-hours	Loss of iron by corrosion	Efficiency of corrosion (per cent)
						Gram	
133.........	....	....	....	....	2.46	0.012	0.47
134.........	Chromium trioxide....	1.8	3.6	0.0955	2.46	.000	.00
135.........	.....do................	.18	.36	.00955	2.46	.013	.51
136.........	.....do................	.09	.18	.00478	2.46	.012	.47
137.........	.....do................	.0018	.036	.000955	2.46	.017	.66
138.........	.....do................	.009	.018	.000478	2.46	.005	.20
139.........	.....do................	.0018	.0036	.0000955	2.46	.013	.51
140.........	.....do................	.00018	.00036	.00000955	2.46	.002	.08
141.........	Potassium dichromate.	1.72	3.44	.0351	2.22	.005	.22
142.........	.....do................	.172	.344	.00351	2.22	.018	.78
143.........	.....do................	.086	.172	.00176	2.22	.008	.35
144.........	.....do................	.0172	.0344	.000351	2.22	.002	.09
145..... ...	.....do................	.0086	.0172	.000176	2.22	.004	.17

TABLE 16—Continued

Specimen number	Substance used	Per cent of substance by weight of cement	Per cent solution in gaging water	Concentration in block in mols. per liter	Ampere-hours	Loss of iron by corrosion	Efficiency of corrosion (per cent)
						Gram	
146	Potassium dichromate	.00172	.00344	.0000351	2.22	.035	1.56
147	do	.000172	.000344	.00000351	2.22	.030	1.30
148	Potassium chromate	1.785	3.57	.0546	2.22	.034	1.47
149	do	.1785	.357	.00546	4.51	.030	.65
150	do	.01785	.0357	.000546	4.51	.057	1.24
151	do	.00895	.0179	.000273	4.51	.029	.63
152	do	.00445	.0089	.000137	4.51	.048	1.04
153	do	.001785	.00357	.0000546	4.51	.029	.63
154	do	.0001785	.000357	.00000546	4.51	.017	.37
155	do				4.51	.014	.30
156	Potassium iodate	1.785	3.57	.0496	4.51	.003	.00
157	do	.1785	.357	.00496	3.80	.015	.37
158	do	.0895	.179	.00248	3.80	.013	.32
159	do	.01785	.0357	.000496	3.80	.052	1.30
160	do	.00895	.0179	.000248	3.80	.018	.45
161	do	.001785	.00357	.0000496	3.80	.021	.52
162	do	.0001795	.000357	.00000496	3.80	.182	4.55
163	Potassium bromate	1.7850	3.57	.0656	3.80	.152	3.80
164	do	.1785	.357	.00654	3.80	.023	.57
165	do	.0895	.179	.00329	2.30	.022	.91
166	do	.01785	.0357	.000651	2.30	.031	1.30
167	do	.00895	.0179	.000327	2.30	.006	.25
168	do	.001785	.00357	.0000654	2.30	.030	1.25
169	do	.0001785	.000357	.00000649	2.30	.022	.91
170	do				2.30	.041	1.70
171	Potassium permanganate	1.785	3.57	.0670	2.30	.048	2.00
172	do	.1785	.357	.00675	2.30	.027	1.12

It is well known that the presence of sulphates in even comparatively small amounts tends to destroy the passive state which iron generally assumes in strongly alkaline solutions, and, accordingly, a trial was made with barium hydrate added to the cement in the form of a fine powder. It was believed that by precipitating the SO_4 ions as practically insoluble barium sulphate, leaving the cement comparatively free from SO_4, the extreme alkalinity of the solution in the pores of saturated concrete would then allow the current to pass from the iron to the concrete with little or no corrosion of the iron. That is, the iron anode would become passive as it does in highly concentrated alkaline solutions.

The tests were carried out on 2-inch cubes of 1 : 2 mortar made up in the same way as the cubes described in connection with Table 11. The tests were also conducted in the same manner. The only difference between the two sets of tests lay in the addition of the barium hydrate, which was made by percentage of weight of the cement. A quantity more than chemically equivalent to the SO_4 present was added in every case. Condensed data are given in Table 17. A column showing the efficiencies of corrosion obtained with the same cements with no $Ba(OH)_2$ added is also given to aid comparison. The SO_4 was precipitated as $BaSO_4$ and, as was to be expected, with the exception of the trial with the ore cement, the treated cements "flashed," or set very quickly when mixed with water after the manner of unplastered cement. The ore cement did not flash, and it was thought that by mixing $Ba(OH)_2$ with this slow-setting cement that a practicable application might be made of the scheme.

TABLE 17

Effect of $Ba(OH)_2$ on Efficiency of Corrosion

Specimen number	Ampere-hours	Ampere-hour density	Anode loss	Theoretical loss	Efficiency of corrosion	Hours to cracking	Added $Ba(OH)_2$	Efficiency of corrosion, same cement, no addition
			Grams	Grams	Per cent		Per cent	Per cent
216	1.35	1.06	0.068	1.41	4.9	75	5	1.85
217	1.22	.96	.065	1.27	5.1	75	5	1.97
218	0	0	.003	0	....	....	5	....
219	1.72	1.35	.025	1.79	1.4	No cracks.	10	....
220	1.77	1.40	.036	1.85	1.9	...do......	10	....
221	0	0	.005	0	....	....	10	....
222	1.76	1.40	.060	1.83	3.2	47	10	15.0
223	2.20	1.76	.038	2.30	1.6	23	10	9.7
224	0	0	.005	0	....	....	10	....

An examination of the results presented in Table 17, however, does not reveal any evidence from which we can conclude that the addition of barium hydroxid is of any material value in reducing the efficiency of corrosion. In the case of the iron-ore cement there appears to have been a decrease in the corrosion, but in the case of other cements the reverse is the case.

It should perhaps be noted in this connection that the barium hydrate added to the cement would have no effect on the activity of any soluble chlorides that might be present.

Under ordinary conditions and at usual temperatures the efficiency of corrosion of iron in normal concrete is very low; and in the light of the above results it seems that efforts along the line suggested under heading (a) might most profitably be directed toward keeping it low by preventing the addition to the concrete of any acid radical of marked corrosive tendencies in a form which is readily dissolved and ionized. The wisdom of such a precaution is indicated in the section dealing with electrolytic corrosion of iron in concrete and should be taken, not only with reinforced concrete in the process of making, but at every stage of its existence, Concrete takes up a very appreciable amount of water, and when a salt or an acid in solution comes in contact with its surface the chemical may diffuse throughout the mass. The resulting damage by electrolysis may be as great as if the chemical had been added in making the concrete. Evidence of this fact is found in a comparison of the results obtained on specimens 126 to 132, inclusive, in Table 15.

(b) PAINTING OR COATING THE IRON BEFORE EMBEDDING IT IN THE CONCRETE

Painting or otherwise treating the iron before embedding it in the concrete has not as yet been tried thoroughly, the tests being held up to await the outcome of some experiments with a large number of preservative paints for iron as preventives of natural and electrolytic corrosion in the presence of air and moisture. Three standard size specimens were made up for one test along this line, however, using three-fourths-inch round iron electrodes which had been dipped in melted pitch before embedding them. They were connected up as anode on 15 volts and left in circuit more than one year. The currents in two of the specimens were inappreciable at all times. The third carried a current which varied a great deal, but the highest current reading at any time was only 20 mil-amperes. It is evident, therefore, that the pitch had considerable effect in preventing current flow, but in common with all paints used in this manner it has the disadvantage that no bond forms between the concrete and iron when the concrete sets.

This limits the application of such a method of protection to structures where the strength of the bond is not an important matter.

(c) SPECIFIC RESISTANCE OF CONCRETE, TESTS OF INTEGRAL WATERPROOFING, AND RESISTANCE MEASUREMENTS OF GRANITE AND LIMESTONE

The judicious distribution about a structure of courses of masonry or concrete of high specific resistance offers large possibilities as a contributory means at least toward minimizing electrolysis in reinforced concrete in those cases where electrolysis might be expected to occur. Investigations were accordingly undertaken to ascertain the specific resistance of very wet concrete of different proportions, methods by means of which its specific resistance might be increased, and also the specific resistances of samples of the two commonly used building materials, granite and limestone, in both wet and dry condition.

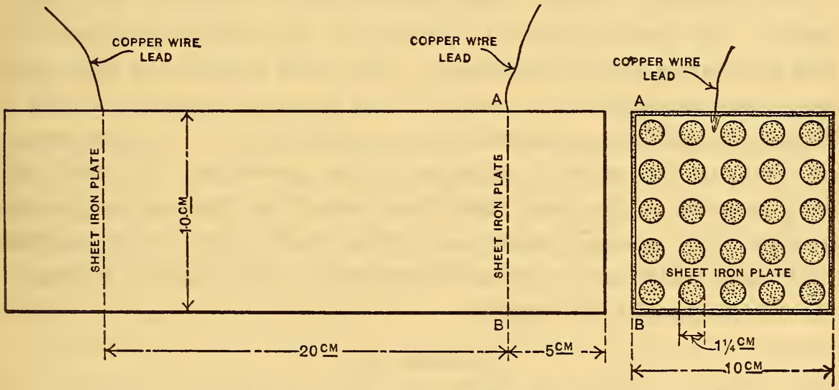

Fig. 28.—*Specimens used in measuring the specific resistance of concrete.*

The measurements of the specific resistance of wet concrete were conducted on 4 by 4 by 12 inch bricks made up in a manner illustrated in Fig. 28. Table 18 gives the results of the measurements, and also the characteristics of the concrete with regard to proportions. Old Dominion cement, river sand, and crushed trap constituted the aggregate. The perforated sheet-iron plates shown embedded in the concrete in Fig. 28 were found to act as very satisfactory contacts for the purpose of electrical measurements.

The concrete was 9 months old when the measurements were made. For three months previous to the time of making the measurements the bricks had been immersed in water, weighings being made from time to time until it was evident that no more water was being taken up. The specimens were then removed from the water, allowed to drain for a few minutes, and the resistance between the plates measured by alternating current using the ammeter-voltmeter method. In making calculations the contact error which would be introduced by the perforated plate was neglected because it would be but a very few per cent of the total resistance of the specimen. The result given for each proportion is the average obtained from measurements made on five specimens. The results show a decrease in the specific resistance as the amount of sand is increased. With the addition of both sand and stone an increase is noted. This peculiar variation seems to be most plausibly explained by a consideration of the percentage of voids in the mass in relation to the percentage of sand and rock present. The sand and stone would in themselves possess a very high specific resistance, while voids filled with calcium hydroxide solution, or other electrolyte, would have a comparatively low specific resistance.

TABLE 18

Specific Resistance of Concrete[28]

Proportions of concrete	Resistance in ohms cm^3	Proportions of concrete	Resistance in ohms cm^3
Neat cem	3500	1:2½:4	8000
1:2	2300	1:3:5	8200
1:4	2100	1:4:7	9900
1:2:3	6300		

[28] The resistance of concrete will of course vary greatly with the aggregate, method of making, etc., and the above values are indicative only of the order of magnitudes of resistances that may be expected.

The one would probably counteract the other; that is, with the first additions of sand the increase in the percentage of voids filled with calcium hydroxid solution having a low specific resistance would more than counteract the increase of specific resistance due to the lengthening of the path of the current by the presence of the sand grains. A continued increase in the proportion of sand, or sand and rock, would finally bring about an opposite result.

In a search for a solution for the problem of increasing the specific resistance of concrete a trial was made of a number of integral waterproofings for concrete which are commonly sold in the market. These integral compounds are sold in the form of powders, pastes, and liquids and are designed for incorporation within the mass of the concrete while mixing the aggregate and their intended function is to reduce the porosity of the mass or otherwise render it impermeable to water. The method of application varies with the character of the compound; the procedure generally being to mix the powders with the dry cement, the pastes and liquids with the water used in making the concrete.

The concrete specimens used for the tests were of the type shown in Fig. 1. They were made of a 1:2½:4 mixture, with three-fourths inch round iron electrodes embedded in them. Each compound was added to the concrete in the manner prescribed by its manufacturer. After the specimens had been taken out of the moulds they were allowed to set in water or wet sand for 8 or 10 weeks before testing.

The concrete containing the compounds first tested was treated as follows: The damp specimens were placed in an oven and dried at a temperature of about 100° C, until no more water was given off, which was shown by the constant weight of the specimens. The dry specimens were then immersed to about one-half inch from the top of the concrete in water, the arrangement electrolytically and otherwise being the same as that shown in Fig. 2. The conductivity between the embedded and outer electrodes was measured from time to time by alternating current, using the ammeter-voltmeter method. The weights of the specimens were also obtained at the time the conductivity measurements were made. When the weight and conductivity each became practically constant the test was considered finished. The results of this test are given in Table 19, Nos. 2 to 11, inclusive, the value of the conductivity at the end of the test being the one recorded. The values of the conductivity and absorption given in the table for each particular integral are the averages obtained from four specimens. The absorption is expressed as a percentage of the dry concrete, the water absorbed by the dry specimen during the test being used in the calculation. The results obtained on a set of specimens to which no integral had been added are also given to aid comparison. The untreated set is No. 1 in the table.

Realizing that the test as above described might be open to criticism because of the temperature used in drying it was modified in the cases of the remaining integrals which were tested, and in order to ascertain what effect might have been caused by the drying temperature a check test in the modified form was run on a powder and a paste, Nos. 4 and 6 in Table 19, both of which had been tested before. In the modified test the specimens were weighed and their conductivities measured while they were still saturated with the water in which they had been placed, after which they were placed in air in the laboratory where they were allowed to dry for two months. At the end of the period of two months they were again immersed in water and weight and conductivity measurements made in the same manner as described in the preceding paragraph. When the measurements were finished the specimens were dried at 100° C, in order to obtain the amount of absorption. The absorption in this case was taken as the difference in weight between approximate saturation and complete dryness of the specimens and is expressed as a percentage of the dry concrete. The results of these tests are given in Table 19, Nos. 13 to 17, inclusive.

TABLE 19

Effect of Various Integrals on the Specific Resistance of Concrete

Compound number [29]	Absorption in per cent of dry concrete	Conductivity before specimens were dried	Conductivity at end of test
	Per cent		
1[29]	3.3		0.015
2	2.9		.0092
3	2.9		.0091
4	3.0		.0110
5	2.3		.0080
6	3.2		.0045
7	3.8		.0019
8	5.9		.0070
9	4.9		.0030
10	2.2		.0023
11[29]	1.6		.00004
12		0.0219	
13		.0134	.0089
14		.0135	.0087
15		.0077	.0062
16		.0100	.0076
17		.0112	.0065

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[29] Specimens containing compounds 2 to 11 were dried at 100° C. before testing. No. 1 gives the results obtained on a set of untreated specimens which had been dried at 100° C. Specimens containing compounds 13 to 17 were air dried as described. No. 12 was a set of untreated specimens which had been air dried.

On comparing the different results obtained it was seen that drying at 100° of specimens made up with No. 4 and No. 6 resulted in a decrease in the conductivity and amount of absorption in the case of No. 6, while No. 4 seemed to have been changed but little. In view of these facts no check tests were run on the other integrals which had been dried at 100°, with the exception of No. 11, which was the only one giving results which warranted further investigation. In the case of No. 11 tests were instituted to ascertain how long and how well it would protect against electrolysis and under what conditions the change in the specific resistance of the concrete was brought about.

For these electrolysis tests five specimens were used, four of which had served for the absorption and conductivity tests. All of the specimens had been dried at 100° C, and contained 40 per cent of the compound by weight of the cement. The electrolysis tests were conducted in the usual manner, three of the specimens being connected with embedded iron anode on 115 volts and the remaining two cathodes on the same voltage. Tap water served as the electrolyte. The currents on the anode specimens were from 0.005 to 0.003 ampere in value and the cathode specimens carried currents of from .007 to 0.016 ampere. After two and one-half months in circuit there were no marked detrimental effects to be seen upon the concrete. Two of the specimens were broken open, one a cathode and the other an anode. There was no apparent corrosion on the anode iron with the exception of a slight ring of rust around the rod where it emerged from the concrete. There was but slight evidence of decomposition of the mortar in the vicinity of the cathode.

In order to ascertain what conditions were required for compound No. 11 to affect materially the specific resistance of the concrete a number of cylinders were made up in the usual manner using 20 per cent of the compound in some cases and 40 per cent in others. The tests on these specimens were conducted as follows: Six specimens were made up and allowed to set in water three and one-half months. They were then measured for conductivity in the manner described above. The results are given in Table 20, specimens 381 to 386. Four of the specimens were then dried in an oven at 100° C, and two were dried in air in the laboratory for two months. When the drying was finished they were placed in jars and allowed to take up water until the conductivity became constant. The results of these measurements are also given. Eight other specimens were then made up using 20 per cent of the compound. When removed from the molds four of the specimens were placed in air to set. The others were placed in a damp closet. After six weeks conducivity measuremens were made with results as shown under specimens 452 to 459. A comparison of the results of the conductivity measurements shows that drying at a high temperature is essential to the attainment of a high specific resistance by concrete treated with this compound. Ais drying is not sufficient and it seems, therefore, that in practical work this compound can be regarded as of value in causing an increase in the specific resistance of concrete only in cases where the concrete can be subjected to a high temperature after it has set.

TABLE 20

Conductivity of Specimens Treated with Compound No. 11 After Setting Three and One Half Months in Water

Specimen number	Per cent of compound	Conductivity	Dried in—[30]	Loss in weight [30]	Conductivity [30]
				Per cent	
381	40	0.0123	Oven	7.1	0
382	40	.0123	do	6.4	0.000052
383	40	.0123	Air 2 months	3.3	.004
384	20	.0106	Oven	6.1	.000052
385	20	.0106	do	6.0	.00021
386	20	.009	Air 2 months	3.2	.005

Specimen number	Per cent of compound	Set in air	Conductivity	Specimen number	Per cent of compound	Set in damp closet	Conductivity
		Weeks				Weeks	
452	20	6	0.0079	454	20	6	0.0080
453	20	6	.0079	455	20	6	.0074
456	20	6	.0078	457	20	6	.0075
458	20	6	.0074	459	20	6	.0072

In making an interpretation of the results of these tests on integral waterproofings the tendency of normal reinforced concrete to protect itself against the effect of electric currents should be considered. In the section dealing with the rise of resistance of reinforced concrete due to flow of current it is seen that when saturated specimens are subjected to the action of current the rise of resistance is sufficient within a few weeks to prevent damage unless the conditions of electrolysis are extremely severe. (See No. 1, Table 22.) Therefore, unless a waterproofing integral causes a decrease in the conductivity of concrete under the conditions of application in practice to an amount comparable with that observed in connection with the flow of current through normal reinforced concrete its use would not be justified merely on the ground of preventing electrolysis. That is, in order to be efficient in the prevention of electrolysis the addition of the waterproofing agents should cause a reduction in the conductivity of wet concrete to 1 or 2 per cent of its normal value instead of to 50 per cent, as

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[30] Conductivity measurements after drying and being reimmersed.

most of them do. The reason for this is found in the fact that the effect of the compound on the conductivity of the concrete is only additive. Speaking in terms of resistance, the statement that the effect is additive may be made clear by the following: Suppose two specimens of reinforced concrete to be made up in exactly the same manner excepting that to one a waterproofing integral is added. When both are thoroughly set and saturated with water the resistance of the untreated specimen will probably be about 100 ohms, while that of the treated specimen will be, say, 200 ohms. If both are put in circuit with embedded metal anode and current allowed to flow for three months or so the resistance of the untreated specimen will rise to about 10 000 ohms. At the same time the resistance of the treated specimen will be found to have increased to about 10 100 ohms, both specimens having been subjected to the same conditions of voltage, showing practically no advantage in favor of the latter. A comparison of the ultimate resistances of the specimens of Table 2 with the ultimate resistances of specimens 112 to 125, inclusive, of Table 15 shows the above numerical example to be a fair illustration of what will occur. From this it appears that the mere fact that the addition of a waterproofing agent increases the initial resistance by a considerable amount should not be construed as evidence of its value as a permanent protection against electrolysis.

The specific resistance measurements of granite and limestone were conducted on a total of seven specimens, six of granite and one of limestone. Two kinds of granite were represented, one gray and the other red. In preparing the specimens for testing parallel faces were ground on them and the edges ground off to a more or less regular geometrical outline in each case. The specimens were then dried at a temperature of 100° C for two weeks. No losses of weight were recorded in the case of the granite because they were too small to be of consequence, but the limestone specimen showed rather remarkable absorptive qualities, the 2-inch cube of limestone losing 13.1 g in weight in passing from approximate saturation to dryness. This is about 4 per cent in weight and shows that the particular limestone specimen used contained pores to the extent of nearly 10.5 per cent of its volume.

The electrical measurements were made with alternating current, using the ammeter-voltmeter method. Contact was made to the parallel faces of the specimens with mercury-solder amalgam. A high resistance ammeter (831 ohms, 0.050 ampere total scale reading) was placed in series with the specimen and the voltage applied in steps up to 750 volts. The voltage was measured by means of a voltmeter connected across the terminals of the primary coil of the 1:10 ratio transformer used in stepping up the voltage. A current of about 1 mil-ampere gave a perceptible deflection of the ammeter needle and the results given for the dry granite and limestone in Table 21 are calculated on the assumption that 1 mil-ampere was the smallest reading that could be obtained.

After the measurements on the dry granite and limestone were completed the specimens were immersed in a saturated solution of calcium-hydroxide and allowed to soak for two months. At the end of this period they were removed from the solution, the water which clung to the surface wiped off and the resistance measurements repeated while the surfaces of the specimens were still damp. Table 21 gives the results of the two sets of measurements, the specific resistances being calculated from the resistance of each specimen and its dimensions.

TABLE 21

Resistance Measurements of Dry and Saturated Specimens of Granite and Limestone

DRY SPECIMENS

Specimen number	Kind of stone	Average area of specimen	Average thickness	Voltage applied	Current	Total resistance	Specific resistance
		cm^2	cm		ampere	ohms	ohms/cc
225	Gray granite	95.3	5.8	750	< 0.01	> 75 000	>1 200 000
226	do	79.6	7.6	750	< .01	> 75 000	>1 200 000
227	do	61.1	5.8	750	< .01	> 75 000	>1 200 000
228	do	77.5	5.5	750	< .01	> 75 000	>1 200 000
229	Red granite	35.1	3.4	750	< .01	> 75 000	>1 200 000
230	Gray granite	14.0	3.3	750	< .01	> 75 000	>1 200 000
231	Limestone	25.0	5.0	750	< .01	> 75 000	>1 200 000

TABLE 21—Continued

SATURATED SPECIMENS—SURFACES DAMP

Specimen number	Kind of stone	Average area of specimen	Average thickness	Voltage applied	Current	Total resistance	Specific resistance
		cm^2	cm		ampere	ohms	ohms/cc
225	Gray granite	95.3	5.8	600	0.015	39 200	642 880
226	do	79.6	7.6	710	.009	77 700	809 000
227	do	61.1	5.8	600	.015	39 200	411 600
228	do	77.5	5.5	710	.015	46 600	657 000
229	Red granite	35.1	3.4	710	.001	710 000	7 100 000
230	Gray granite	14.0	3.3	700	.003	233 000	978 600
231	Limestone	25.0	5.0	250	.019	12 300	61 500

The value of the specific resistance of the water-soaked specimens is the most important, and a comparison of the values given in Table 21 with the specific resistance of saturated concrete already given shows that the resistance of the limestone ranges about six or eight times that of concrete and the resistance of granite is of the order of a hundred times that of concrete. The latter value particularly is sufficient to warrant its use in many instances in the footings and foundations of buildings in order to reduce the tendency of electric currents to flow between them and the earth.

(*d*) TESTS ON WATERPROOFING PAINTS AND MEMBRANES FOR CONCRETE

In a search for an effective and durable insulating coating which might be applied to the surface of concrete some tests were made of a number of waterproofing and damp-proofing paints and membranes. For the purpose of testing these paints and membranes they were applied to concrete cylinders of the same description as those used in testing for the effect of integral waterproofing, with the exception that the integrals were omitted in mixing the aggregate. After the concrete had set thoroughly the cylinders were dried at 100° C until no more water was given off and the application of the paint followed when the cylinders had cooled.

In applying the paints great care was exercised to obtain continuous and flawless films as far as the character of the paints would permit. The directions of the manufacturers were followed closely, and after the finishing coat had been applied the specimens were set aside for a period varying from four to six weeks before testing. In order to avoid bruising the coating on the bottom of the cylinder where it came in contact with the floor in handling the coating was there treated with a layer of melted paraffin. This prevented sticking, and as far as the tests were conducted it seemed to have no detrimental effect on the paints. Trial showed that there is a vast difference between painting over a paraffined surface and putting a layer of paraffin over dried paint. In the first instance the paint never dries, but in the second no sign of deterioration ever appeared in the 40 or more paints tested in the course of this work.

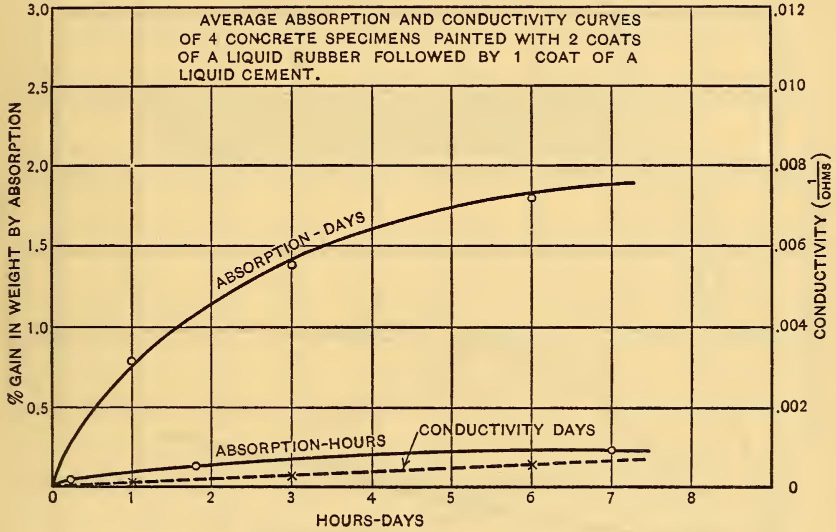


Fig. 29

The test on the paints was conducted in much the same way as the tests for the effect of integral waterproofings; that is, the dry, painted specimens were weighed, then immersed to about one-half inch from the top of the concrete in water as shown in Fig. 2 and the conductivity between the embedded iron and the outer electrode measured in each case by alternating current, using the ammeter-voltmeter method. After 15 to 30 minutes immersion, according to the characteristics of the coatings, the specimens were again measured for conductivity, then removed from the jars, allowed to drain two or three minutes, and weighed. This operation was repeated at increasing intervals during the next seven days, a period of time which was usually long enough to give definite results. If a paint showed signs of holding out indefinitely the cylinders which had been treated with it were put aside in water and the measurements continued at intervals of several weeks.

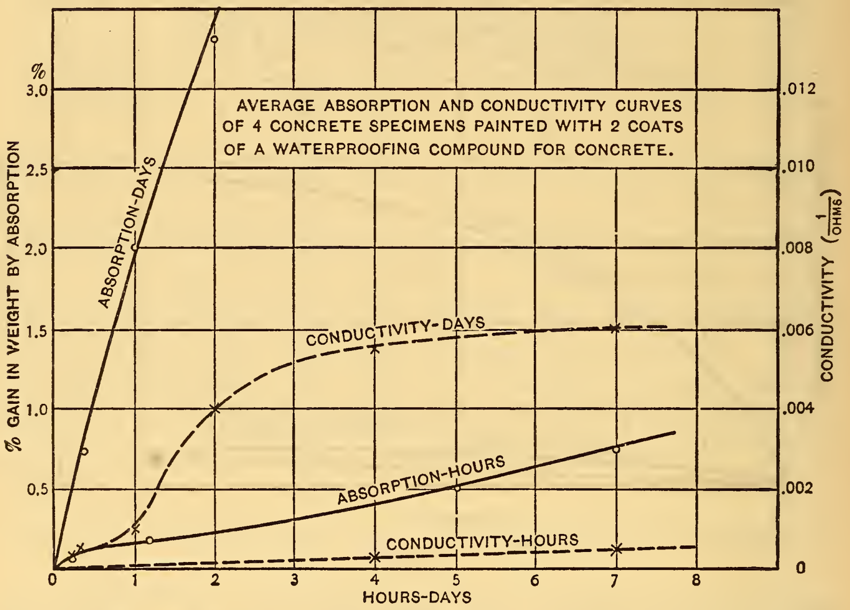


Fig. 30

For the test of each paint a set of four specimens was used and the average results were plotted in the form of curves showing increase of weight by absorption of water, and increase of conductivity, with time. Examples of these curves are shown in Figs.

29, 30, and 31. Calculations were made from each set of absorption curves to show the rate of absorption of water near the beginning of the test, the area covered by the paraffin being subtracted from the total submerged area in so doing because such a coating was found to be almost absolutely waterproof during the time of the test. The rate of absorption near the beginning of the test was taken as the true measure of the efficiency of the coating as a waterproofer because at any subsequent time the specimens had become more or less saturated with water with a consequent decrease in the rate of absorption, which was not due to any property of the coating. Table 22 gives the condensed data of the specimens and the results of the tests.

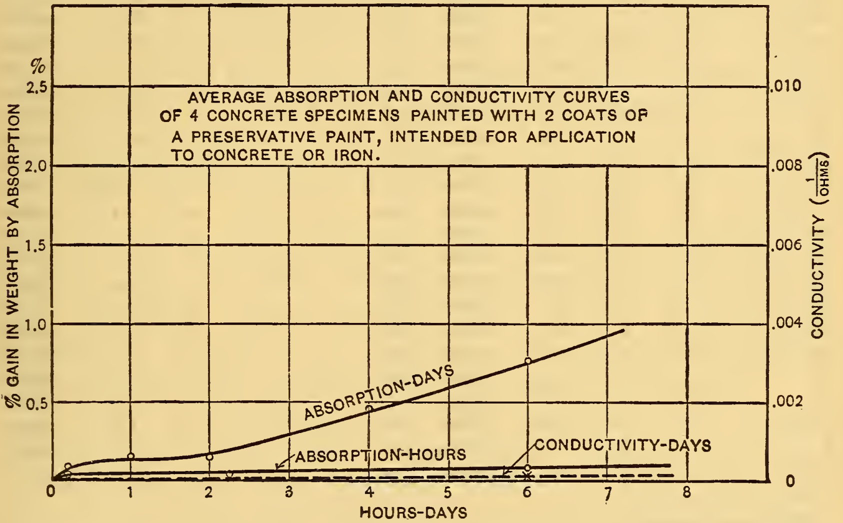


Fig. 31

TABLE 22

Results of Tests on Paints for Waterproofing Concrete

Number of paint or coating	Coats	Rate of absorption (c c per square foot per hour)	Conductivity at end of seven days	Number of paint or coating	Coats	Rate of absorption (c c per square foot per hour)	Conductivity at end of seven days
1[1]	....	375.0	0.015	23	2	30.0	0.002400
2	2	1.0	.000018	24	2	37.0	.004500
3	2	1.8	.000300	25	4	30.0	.006500
4	2	13.0	.004800	26	5	50.0	.015000
5	2	35.0	.005300	27	2	7.0	.007200
6	1	1.0	.000050	28	3	150.0	.014000
7	3	2.0	.000050	29	2	18.0	.012000
8	3	.67	.000300	30	1	150.0	.016000
9	3	2.8	.000900	31	3	18.0	.011000
10	2	2.5	.001000	32	2	.57	.000040
11	2	24.0	.003800	33	2	2.9	.000490
12	2	1.27	.000600	34	2	25.0	.007000
13	2	1.65	.001500	35	1	6.0	.002600
14	2	8.2	.005500	36	2	13.0	.002800
15	2	4.1	.001700	37	2	52.0	.008100
16	2	3.2	.002000	38	2	7.0	.000800
17	2	31.0	.007000	39	2	7.0	.000300
18	2	5.6	.005500	40	2	7.5	.000350
19	2	12.1	.004000	41	2	2.0	.000150
20	2	2.0	.000500	42	2	1.0	.000000
21	2	1.2	.000000	43	2	1.0	.00015
22	2	3.0	.000580	44	2	100.0	.0031

[1] Specimens not coated.

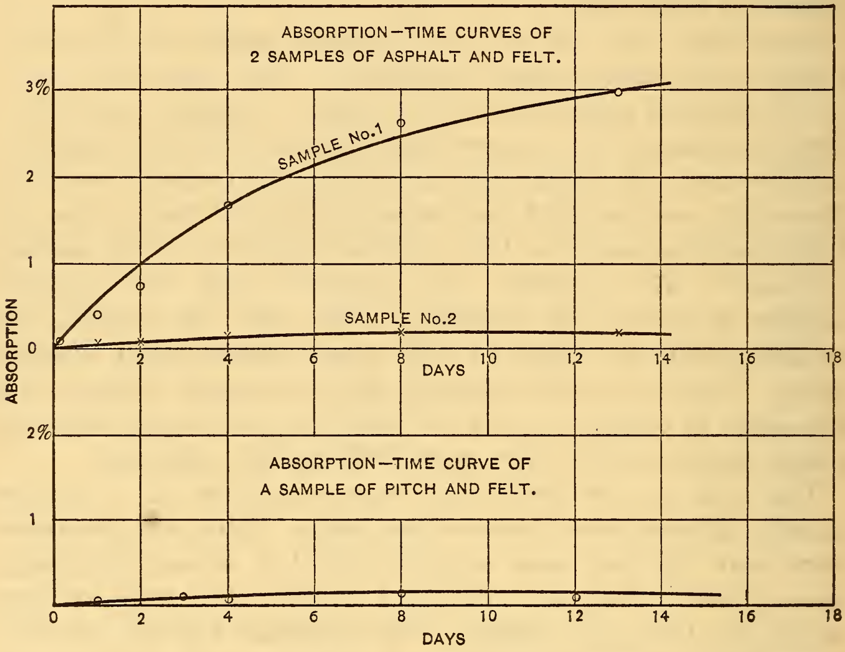
NOTE.—1a, Conductivity by direct current of untreated specimens after current flow for one month on 15 volts=0.0046. 1b, Conductivity by direct current of untreated specimens after current flow for three months on 15 volts=0.00028. 1c, Conductivity by direct current of untreated specimens after current flow for nine months on 15 volts=0.000093.

The results include the average rate of absorption of water in cubic centimeters per square foot per hour near the beginning of the test and the average conductivity of the specimens at the end of seven days. A comparison of these results with those obtained on a set of untreated specimens gives an indication of the efficiency of each coating as a waterproofer and an insulator. The most important figures in Table 22 in relation to the work dealt with in this paper are those of the conductivity. The greater portion of the coatings show conductivities at the end of seven days which are too large to allow them to be considered as insulating. There are others, however, which show very favorable results in comparison with untreated normal specimens after being three months under test on 15 volts and their use where occasion demands it might be desirable if a life test on them should indicate that their insulating power is not too short lived. Life tests were not run in connection with the present work, partly because of lack of time.

Some tests were also run on specimens similar to the above treated with waterproofing membranes. These membranes consist of alternate applications of hot pitch, or asphalt, and fabric. They are designed for waterproofing against hydrostatic pressure, underground. In placing the membranes the concrete was first thoroughly swabbed with the melted compound, then a layer of fabric rolled on and it in turn swabbed with more of the melted compound. The operation was repeated until the required number of layers were obtained. Great care was exercised in breaking joints and filling all holes where leakage might possibly occur. The tops of the specimens did not come in contact with the water in testing, so were not laid over with fabric but were simply painted with a thick coat of the melted compound.

The tests on the membranes were conducted in a manner slightly different from those on the paints. After the specimens were made up they were weighed, placed in a tank containing water 7 inches deep and connected up with the embedded iron anode on the 15-volt circuit. The potential was left on continuously. At intervals of a month or two current readings were made and the specimens were removed from the tank and weighed. Two different brands of membranes were tested in this way, using from two to five layers. Four specimens constituted a set in each case and the results given in Table 23 are the averages of the several sets. The tests were continued for 14 months and the electrical readings are those obtained at the end of that time. The effectiveness of these coatings as preventives of electrolysis in the manner for which they are adapted is unquestionable, provided, of course, that the membrane is applied with sufficient care.

A test which throws further light on the comparative values as insulators of the membranes mentioned above is one a description of which follows. The test included pitch and felt as well as asphalt and felt. Five alternate layers of melted compound and felt were laid on one side of a piece of glass 3½ inches wide by 5 inches long, making up three specimens of this kind in the case of each product tested. The top layer of felt was thoroughly swabbed over with the melted compound.



Figt 32

The specimens were then carefully weighed and two of each set immersed in water, while the other was left in air for a check. From time to time the specimens were weighed, those in the water first being removed and wiped of water clinging to their surfaces. This operation was continued for about two weeks. The check specimens showed no appreciable change in weight. Fig. 32 gives the results obtained on the specimens subjected to water in the form of curves showing increase of weight with time. Each curve is the average result obtained on the two specimens.

TABLE 23

Tests on Waterproofing Membranes

Number of product	Layers used	Rate of absorption of water (cc per square foot per hour)	Conductivity of coating
1	5	0.021	0
1	3	.015	0
1	2	.011	0
2	5	.028	0
2	3	.030	0.000001
2	2	.042	.00004

III. POSSIBILITIES OF TROUBLE FROM ELECTROLYSIS IN CONCRETE STRUCTURES UNDER PRACTICAL CONDITIONS

As mentioned in the introduction to the present paper, reports have become current from time to time during the last few years that more or less serious trouble has occurred in concrete structures as a result of electrolysis, and in some cases serious damage has been reported. Since the reports of such trouble have in some instances been made in leading technical papers by reputable engineers, it became imperative that a thorough investigation of the practical aspect of the problem be made. In connection with the investigations described in the preceding section, the matter has been studied from the practical standpoint also, in order to determine, as far as possible, to what extent the conditions under which concrete can be injured in the laboratory may be expected to obtain in practice.

18. CONDITIONS NECESSARY FOR DAMAGE TO OCCUR

A careful study of the data presented in the preceding pages shows conclusively that while there are conditions under which reinforced concrete may be seriously injured, such conditions are nevertheless exceptional rather than the rule. These exceptional conditions occur, however, with sufficient frequency to make the problem one of great importance, and fortunately most of these conditions are amenable to control. It has been seen that the most important essentials to the injury of concrete by electrolysis are moisture and a difference of potential between electrodes in contact with the mass of the concrete. At first thought it might appear that these two conditions are almost omnipresent, since perfectly dry concrete, especially below grade, is seldom if ever found; while, as every electrical engineer knows, there are few places in our cities at the present time where appreciable differences of potential can not be found between any two points more than a few yards apart. The statement in regard to the rarity of dry concrete is made advisedly, since only the most minute quantities of moisture are necessary in order to impart to concrete a considerable conductivity. On the other hand, the concrete has to be made very wet in order to impart to it a maximum of conductivity, and any reduction of the moisture content below the saturation point causes an increase in its resistance and a consequent decrease in the current which will flow through the concrete under a given potential gradient. As indicated by data already presented, the resistance of ordinary air-dried concrete, while extremely variable, is usually of the order of about ten times that of wet concrete, and for this reason concrete above grade is much less susceptible to electrolytic damage than if so located as to be permanently wet. It is not to be inferred, however, that air-dried concrete is immune from electrolysis troubles, but rarely would the voltage be high enough to produce trouble; and, in general, in the absence of special conditions to be mentioned in the next section, electrolytic damage to concrete above grade will be extremely rare.

The condition mentioned above, that the electric current must flow between electrodes in contact with the concrete, should be emphasized. The conduction being electrolytic, the reactions take place only at the electrodes, and in the absence of such electrodes no reactions occur within the concrete. The only effect, therefore, would be the slow removal of the water-soluble constituents, and hence the effect on the concrete would not be essentially different from that of slow water seepage.

19. SOURCES OF STRAY CURRENTS

If there be electrodes embedded within the concrete, as in the case of reinforced concrete structures, the electrode effects described in the foregoing section may be expected provided the voltage is sufficient. The sources of potential differences in concrete structures may be classed under two heads, (1) those due to direct contact between the conductors of lighting or power circuits, and some part of the building and (2) those which have their origin in stray currents from railways or other grounded power lines. The former may happen in any building containing electric wires, through defective insulation. It is not necessary, of course, that both sides of the line be grounded in the building itself, since if one side of the line is grounded on the building and the other grounded in some remote quarter of the system those portions of the building itself near the grounded wire will be subjected to a considerable difference of potential. If the wire be grounded directly on the concrete and not on the reinforcement, the comparatively small cross section of the path of the current near the point of contact between the concrete and the wire will result in most of the total drop of potential to ground occurring within a restricted region near the wire, and it is only here that any damage may be expected, and since the current will be small the damage, if any, will be small. Ultimately, of course, any current that leaks off from the wire would pass out into the earth through the footings and foundations and through pipe systems entering the building. As a rule, the cross section of these paths is so large in the aggregate that the potential gradients would not be sufficient to raise the temperature appreciably, and hence no appreciable damage is likely to occur. If the current be reversed, flowing to the building from outside, there would in time be some softening of the concrete in a thin layer under and around the steel structure terminating in the footing, but this would be under compression and not subjected to shear along the surface of contact between steel and concrete, so that failure here is extremely improbable. The only places where trouble is to be expected due to grounding of power wires directly on the concrete inside of a building is in the region close to the point of ground.

If, however, the power wire be grounded directly on a portion of the reinforcing material, the condition will be more serious, and the extent of the danger will be greater if there is a large quantity of the reinforcing material in metallic contact with the electric circuit. If this comprises a large part of the total reinforcement of the building, the condition might be serious irrespective of whether the positive or negative side of the line is grounded. If the ground is on the positive side, the potential gradient near the reinforcement may become high enough to cause rapid corrosion and consequent destruction of the reinforcing material. If, on the other hand, the reinforcing material be negative, there would develop a softened condition of the concrete near the surface of the iron which would practically destroy the bond, and this would probably be the more serious condition of the two, since the latter would not manifest itself by producing local cracks in the concrete, and might not become known until a large portion of the building has become weakened. However, while such a condition as this might occur, and if neglected become very serious, it is nevertheless a trouble that can be readily guarded against, as will be pointed out below.

The other source of current that might possibly give rise to trouble under certain circumstances is the ground return of railways. The current may enter a building in two different ways. First, if the foundations under the two opposite sides of the building are at different potentials, there would be a tendency for a certain amount of current to flow up through the foundation on the one side, through the walls and floors of the building and out through the foundation on the other side. This condition may be said to exist to a very small extent in practically all concrete buildings, but it is not one that need cause any alarm. In the course of numerous electrolysis surveys that we have carried out in various cities we have found that a potential difference exceeding a few volts due to stray currents between any two parts of a building is extremely rare, and this would almost inevitably be distributed over so great a distance that the potential gradient would not be sufficient to cause any appreciable trouble, in view of the experimental results set forth in the first section of this paper, which show that under ordinary conditions comparatively large potential gradients are required before any material damage is likely to occur.

The second way in which stray currents may enter a building is through water or gas pipes, lead cable sheaths, and similar structures. In this case considerably larger differences of potential may be brought about between different portions of the building and between parts of the building and the earth. If the pipe systems come in contact only with the concrete and not with the reinforcing material, any damage that may occur will be slight and will be confined chiefly to the immediate vicinity of the pipes or cables; but if the pipes come into metallic contact with the reinforcing material, the latter comes to the same potential as the pipes and may become either anode or cathode, according to the condition of the pipes. Cases may arise in practice where differences of potential of serious magnitude may be produced in this way, some instances having been brought to our attention in which the reinforcing material was from 5 to 15 volts above or below the earth. Under most conditions damage would proceed very slowly under such differences of potential as these, but nevertheless wherever voltages of this magnitude exist it should be regarded as a dangerous condition and should be remedied at once.

20. INCREASED DANGER DUE TO PRESENCE OF SALT

The above statements in regard to the liability of damage under low or moderate differences of potential are intended to apply only to concrete which contains no appreciable quantities of salt. The data given in the preceding section show that if a small quantity of sodium chloride or calcium chloride be added to the concrete the rate of deterioration proceeds many times faster, and under such circumstances much lower voltages should be regarded as dangerous. Even a small fraction of 1 per cent of chlorine in concrete is capable of increasing the electrolytic corrosion of the iron manyfold, and if salt has been added to the concrete during construction, or if it comes into contact with salt water afterwards, much greater precautions are necessary in order to prevent damage.

In the course of our investigations we have examined a considerable number of cases in which damage to concrete structures has been attributed to electric currents. Some of these have been reinforced structures and some have been without reinforcement. Among these we have not found any nonreinforced structures in which the conditions indicated that electric currents could in any way be responsible for the damage. Among the reinforced structures which have been called to our attention there are some in which electrolysis has been at least a contributing cause of the damage. We have not, however, seen any case in which serious damage has occurred in which there was not also present a considerable quantity of salt in the concrete, either from having been put there during construction or from contact with salt water in service. This is in accord with the results of our laboratory investigations, which show that under low or moderate voltages the rate of damage, in the absence of chlorine, is so slow as to be almost negligible, but that when salt is present rapid deterioration at both electrodes may be expected even on comparatively low voltage.

21. SOME SPECIFIC CASES OF TROUBLE

In making an examination of these cases the condition of the concrete was carefully noted and compared with that of specimens known to have been injured by electric currents in the laboratory. Potential measurements were made between different parts of the structure, and also between the structure itself and surrounding structures, although the latter are as a rule not important since the electrical resistance between different structures is usually unknown, and hence the voltage readings give no idea of the current flow. By comparing the potential gradients observed with those used in the laboratory and considering also the age of the structure and any special conditions which may have influenced it, we are enabled to judge as to whether it is possible for the damage to have been caused by electric currents, and this judgment is further confirmed by studying the character of the damage and noting whether it is in any way similar to the damage that can be caused by electrolysis. One or two specific cases may be mentioned here as instances. The concrete foundations of a small bridge across the Gowanus Canal at Hamilton Avenue, South Brooklyn, developed large cracks in a number of places, and the damage had been attributed by some to electrolysis. On the strength of the first reports we were inclined to attribute the trouble to electrolysis, since a trolley line passed over the bridge, and it seemed quite probable that conditions might have arisen whereby a sufficiently high potential gradient had been produced to corrode the reinforcing material and crack the concrete. On making an examination of the bridge, however, it was found that those portions in which failure had occurred did not contain any reinforcing material, and the cracks were not so located that they could have been caused by corrosion of iron, nor could there have been a weakness due to a cathode effect, since there were no electrodes near the cracks and the concrete nowhere showed evidence of softening. In short, there was no similarity between the damage found here and any of the effects which we have noted in the laboratory. Further, potential measurements showed that the maximum potential difference to be found was 1.6 volts, while potential gradient measurements between points 2 feet apart near some of the cracks showed values ranging from 0.01 to 0.05 volts per foot. In our experiments at the Bureau of Standards we have impressed on wet concrete blocks potential gradients of about 100 volts per foot, continuously for a year and a half using noncorrodible electrodes, without producing any cracking such as observed in this bridge. It seems inconceivable that such small potential gradients as found here could have been responsible for the cracking of the unreinforced portions of the structure, when potential gradients in the laboratory 2000 times greater failed to produce any damage at all, except such as noted in the foregoing chapters and which was always closely associated with the reinforcement in the concrete. Further, there was evidence that the foundations of the structure were unstable, as shown by the fact that they had moved several inches toward the canal since they were built. We are informed that somewhat similar trouble has been experienced in a number of buildings in this vicinity, indicating that the earth in this locality does not afford a stable support for the foundations. This alone would seem to be capable of causing trouble of the nature that has actually occurred here, whereas as just indicated the damage is not of a nature that has been observed to result from the passage of electric current.

One other instance may be cited here because of its importance. Some concrete-lined railway tunnels had suffered considerable damage due to disintegration of the concrete and in some instances within a few months after the work had been completed. A number of engineers had pronounced the trouble due to electrolysis, and the engineers of the Bureau of Standards were asked to make an investigation. A voltage survey throughout the tunnels was made, potential measurements being taken between points on the tunnel walls in both a vertical and horizontal direction, and in some cases holes were drilled in the wall and voltage measurements made in a direction at right angles to the surface. Some measurements were also made between walls on opposite sides of the tunnel, and in two or three cases between the tunnel wall and the rails. The measurements taken were classified under three heads, viz, those taken where the concrete was very badly disintegrated, those taken where there was but slight disintegration, and those taken where the concrete was perfectly sound. A comparison of the magnitudes of the voltage showed first that there is no definite relationship between the magnitude of the potential gradients observed and the physical condition of the concrete. The average voltage per foot in the first group where the concrete was very badly damaged was 0.017 volt. In the second group where there was no damage whatever the average potential gradient was 0.027 volt per foot. These figures do not support the view that the trouble is caused by stray electric currents. It should be noted that in a number of places measurements were obtained where the concrete was very wet and yet in perfect condition, and in which the potential gradients were of the same order as those in the first group, where the concrete was badly damaged.

In taking the readings the usual method of making contact at points between which measurements were to be taken could not be used, because the high resistances at the contact points would absorb the major part of the total voltage. Special terminals were designed, consisting of brass cups 2 inches in diameter, in each of which was compressed a sponge saturated with a solution of copper sulphate. Inside the cup and below the sponge was a brass piston, which was used as the instrument terminal. When readings were to be taken, the cups were placed against the concrete wall at points between which the voltage was to be measured with the piston pressing the sponge firmly against the wall. This gave a large surface of contact and therefore a relatively low resistance. Even in this case, however, it was found that the resistance of the contacts was still too high to permit of using a voltmeter, and therefore a special high sensibility portable galvanometer connected in series with a megohm resistance was used. Careful tests in the laboratory showed that the accuracy of the measurements was within 3 per cent, even on nearly dry concrete, and considerably higher when the concrete was wet.

The fact that there is no definite relationship between the voltages observed and the condition of the concrete is not surprising, particularly in view of the low values of most of the readings. In our experiments at the Bureau of Standards we have subjected blocks of wet concrete to potential gradients varying from very low values up to several thousand times the average values observed in the tunnels mentioned above, for a period of one and one half years, without producing any appreciable diminution in the crushing strength of the main body of the concrete, and there is no evidence of any other action except in the immediate vicinity of the electrodes. We wish to emphasize the fact that in concrete, as in all other electrolytic conductors, all chemical reactions which take place as a result of the current are essentially electrode effects, and they do not, except by progressive action from the electrodes, affect the mass of the concrete.

In the region of the cathode there is a softening of the concrete, but as pointed out above it begins as a thin film on the surface of the cathode and very slowly progresses outward. There is a sharp line of demarkation between the injured and uninjured area, the main body of the concrete being unaffected. The rate at which this softened region progresses outward from the electrode is so slow that it could not possibly give rise to the phenomena observed in the tunnels in question. In our experiments with normal concrete in which we have used potential gradients up to about 5000 times those found in these structures, we have found that the rate at which the softened region moves outward from the cathode is not over about an inch per year, and the concrete outside this very restricted area always remains perfectly sound. In the light of these experiments and considering the relatively low potential gradients existing in and around these concrete structures the theory that damage of this nature could have spread over such vast areas in so short a time is absolutely untenable. After a careful study of the conditions existing in these tunnels we were forced to the conclusions that electrolysis has played no appreciable part in the damage which has been experienced.

22. PROCEDURE IN MAKING VOLTAGE MEASUREMENTS ON CONCRETE STRUCTURES

We desire to say a word in regard to the proper method of taking electrical measurements that are intended to show whether or not a structure is being affected by stray currents. The apparatus which we have used successfully has already been described. It is not only important to read the voltages correctly, but it is equally important to take the measurements between the proper points and to properly interpret them. We have known cases where damage has been attributed to stray currents on the strength of potential measurements taken between the structure and the rails of a near-by steam railroad. The rails near the structure and for a half mile or so on either side were supported out of contact with the soil on wooden ties, so that the potential measurement that was being taken was between the structure and a point several thousand feet distant. It seems almost needless to say that a potential measurement of this kind is worse than worthless as an indication of the electrical condition of the structure under examination. If we are to get an idea of the extent to which currents may be flowing in a building by means of potential measurements, it is necessary that we take the potential readings between two points within or on the building itself and not between the building and some other structure more or less insulated from it. Similarly, if we wish to determine whether current is flowing into or out of a building, we should make the potential measurement between points on the building and thoroughly grounded points near by. Failure to keep these facts in view appears to have been responsible for a good many erroneous reports of damage to concrete structures by stray currents.

IV. PROTECTIVE MEASURES

In the following discussion of means of reducing or preventing electrolysis troubles it is to be understood that the measures recommended are to be regarded as necessary only in those cases in which there is reasonable probability that the electrical conditions may become dangerous. In considering measures that may be taken to prevent damage or to cure electrolysis troubles it is not necessary to consider structures which have no metal imbedded in them, since, as pointed out above, these are immune from electrolysis effects. As regards reinforced-concrete buildings (or concrete buildings with metal conduits imbedded in the concrete) there are two cases to consider—(1) new structures in process of building and (2) structures already completed.

23. EXCLUSION OF SALT

In the case of new structures of reinforced concrete salt should be omitted altogether if there is the slightest probability that they may ever be subjected to the action of electric currents. Calcium chloride is quite as bad as sodium chloride, it being the chlorine that does the harm. Since the addition of even a fraction of 1 per cent of chlorine is sufficient to increase the rate of damage a hundredfold, it is impossible to use a sufficient quantity of salt to lower the freezing point of concrete perceptibly without making the structure decidedly more vulnerable to the action of electric currents.

24. WATERPROOFING BELOW GRADE

A good deal can be accomplished also by proper construction of the basement, foundations, and footings of the building. If beneath the foundations and outside the basement walls a layer of insulating material be placed, it will prevent the access of electric currents through the building foundations. While such insulating materials can readily be made that will give permanent increase of resistance, we have yet to see one that will, in the presence of water, remain completely insulating over a period of years. We have tested a great many waterproofing membranes, but in the presence of water all have sooner or later begun to acquire considerable conductivity and show gradual deterioration. It is, of course, not necessary that such insulation should be perfect in order to be of value, since any considerable increase in the resistance which it may produce in the path of current flow will be useful. For this reason a waterproofing medium, such, for instance, as one made up of multiple layers of fabric treated with pitch, will have sufficient insulating value to be quite effective in preventing the passage of electric currents, and would probably be of considerable value even after the waterproofing has ceased to be perfect.

25. ADDITION OF WATERPROOFING COMPOUNDS

Attempts to increase the resistance of concrete by the addition of so-called waterproofing compounds to the cement before mixing have uniformly failed to give satisfactory results. As pointed out in the first section of this report, none of these compounds or mixtures that have been brought to our attention are of great value in this connection, and reliance should not be placed on them as a means of protecting structures against electrolysis.

26. CONSTRUCTION OF FOUNDATIONS

A good deal can be done in the way of increasing the resistance between the building and ground by a proper selection of materials for the foundations. Blocks of granite, frequently used in such work, have a much higher resistance than concrete, a number of specimens tested by us showing, in the water-soaked condition, a resistance approximately one hundred times as great as that of wet concrete, and hence if granite blocks be interposed between the footings and the soil the tendency of the building to pick up stray currents will be greatly reduced. We regard this matter in most cases as of secondary importance if the potential differences in the region of the building are as small as usual, since any currents which a building may pick up in this way will be too small to do any appreciable harm. In some cases, however, the use of granite footings may be justified as a measure of precaution.

The foregoing statements are not applicable to structures already built, but the following preventive measures may as a rule be applied to old as well as new structures.

27. ELECTRIC WIRING

In wiring a concrete building with direct-current circuits it is of the greatest importance that the construction be such as to preclude the possibility of either side of the circuit coming in contact with the concrete. The insulation should be of the best grade and the wires should be inclosed in continuous metal conduit. When practicable periodic tests should be made on the insulation and any defect remedied. This can usually be done in the case of large structures, but in small structures generally it can not be considered practicable. If the power supply is a private plant belonging to the building the installation of ground detectors is desirable. If these precautions are taken it will not be necessary to insulate the conduits from the building as has been sometimes proposed.

28. INSULATION OF PIPE AND CABLES

By far the most important path of entry of electric currents into concrete structures from outside sources is through the pipes and lead cable sheaths which enter the building, and it is only through these paths, as a rule, that sufficiently high potential differences can be produced to result in damage to the structure. The most effective remedy, therefore, and at the same time a comparatively simple one, is to introduce insulating joints into the pipes before they enter the building. Such joints can easily be made, and are in fact now used in many places, although not so far as we are aware in this particular connection. The only condition to guard against is the possibility of developing too high a difference of potential across the joint which might give rise to electrolytic injury to the pipes; but this can be obviated by proper construction of the joint, as by giving it a long leakage path and by putting several insulating joints in series.

When a pipe line passes through a building it will be necessary, if insulating joints are used at all, to use them on both sides of the building. To use them on one side only would result in making the building more strongly positive or negative to the earth than it would be without such joints and thus the danger would be increased. If the insulating joints are put on both sides, however, there will be no likelihood of currents entering the structure to any apppreciable extent, except in special cases where the difference of potential between the broken sections of pipe becomes very high, say of the order of 10 or 15 volts or more. When this condition occurs, however, it can be alleviated by shunting around the insulated section of pipe within the building by means of a copper cable, preferably an insulated one.

It was stated above that lead-covered cables also form a possible source of entry of stray currents into buildings. It is, of course, possible to break up the continuity of lead cable sheaths by inserting insulating joints, but there are more serious objections to doing this than in the case of water or gas pipes. Nevertheless in some instances this is to be recommended; but it would be usually better simply to insulate the cable from the building, since only a very low degree of insulation would be necessary, such as would be obtained by carrying the cable on wooden supports and keeping it out of actual contact with the concrete and reinforcing material.

29. MAKING THE REINFORCING MATERIAL NEGATIVE

A method of protecting reinforced concrete structures that has frequently been proposed, viz, by making the reinforcing material continuous throughout the building and connecting it to the negative terminal of a low-voltage generator, should be referred to here, but only to point out the danger attending it. While there is no question but that corrosion of the reinforcing material might be prevented in this way, the experiments described in the first section of this paper show that under ordinary low voltages there is greater danger in having the iron negative than positive on account of the destruction of the bond in the former case. Any condition, therefore, which may cause the reinforcing material to become negative to the concrete should be carefully avoided.

30. IMPROVING THE NEGATIVE RETURN OF RAILWAYS

In discussing means of preventing damage to buildings due to stray currents, we should not lose sight of the fact that, after all, the most effective way of reducing damage due to stray currents is by removing, as far as practicable, the cause of such currents. This means a proper design, construction and maintenance of the railway distribution system, whereby potential gradients in the earth are not permitted to reach such high values as to give rise to serious trouble. The protective measures against stray currents mentioned above are rather to be regarded as precautionary ones, rendered necessary only on the failure of the railway companies to provide adequate means for returning their currents to their source. If the negative return systems of the electric railways of this country were uniformly as good as those maintained in the principal countries abroad, the problem of damage to buildings by stray currents would practically disappear.

31. GROUNDING OF METALLIC CONDUITS

The practice at present followed in many instances, and made compulsory in some city ordinances, of grounding all metallic conduits in contact with the concrete, is not to be recommended as a general rule. There are, of course, many cases under which such grounding would not bring about a condition dangerous to the concrete, but in some cases at least the results of such grounding might be serious.

The above recommendation against the grounding of conduits is based on several considerations. If the ground were made on water pipes without insulating joints to prevent flow of current between the pipe system and the building as is commonly done, and if the district were one in which the pipes were at a higher or lower potential than the earth, the conduits would be made either anode or cathode, a condition which in general should be regarded as unsafe, and this condition would in fact be worse than the unrestricted entry of pipe systems into the buildings, which should be guarded against as pointed out above.

If, on the other hand, the ground is made through a ground plate under or near the building this would bring all of the conduit system to the same potential as the ground plate, and this being of small area compared to that covered by the building the footings of the building remote from the ground plate may show a considerable difference of potential against the ground plate and consequently against the conduit of the building, thus giving rise to flow of current between the conduit and the structure itself. That this may be the case is quite evident from the fact that voltage surveys made in several cities in the course of this investigation show that in a great many instances large potential differences are found between two points in the earth that might easily fall within the space covered by a large building. This is particularly true if the measurements are taken over distances at right angles to the electric railway tracks and very close thereto, in either the positive or negative areas. Places were found quite frequently where a difference of potential of several volts would be noted between points not over 100 feet apart. If a building were placed in such a locality, the different footings and different parts of the foundation would be at a considerable difference of potential with respect to each other and this would give rise to a tendency for the current to flow in at some of the footings and out at others. The resistance opposing this current flow would be mainly that of the footings themselves and the earth immediately beneath and such resistance would be encountered at both the entrance and exit of the current. If, however, ground plates be placed under the building at one locality and connected to the metal structure of the building the resistance in the current path would be reduced and larger currents would flow through the building, producing either anode or cathode effects in the footings remote from the ground plate, according to the direction of current flow. While such voltages as would be likely to occur here would probably not give rise to any considerable trouble from anode effects, the cathode effects might be serious not only here but elsewhere in the building. The point to be emphasized is that a ground at one point does not assure relief from differences of potential, because of possible high local potential gradients in the earth. Of course, if the vertical walls and columns of the building were of nonreinforced concrete, and fairly dry, then the resistance would no doubt be sufficient to guard against trouble from this cause, but with any considerable amount of iron in the walls, either as reinforcement, piping, etc., such would not be the case and a local ground would have a tendency to increase the danger from this source. A ground covering the entire basement of the building, or a separate plate under each footing and under the foundation walls, all interconnected, would of course relieve this danger, but the desirability of attempting such extensive grounding is questionable, partly because of the cost and the lack of permanence of such grounds and their connection, and partly because grounding of this character would tend to increase danger from other sources, as described below.

Another argument sometimes advanced in favor of grounding the metal work of a building, including the electrical conduits, to a ground plate, is that in case one of the power wires comes in contact with the conduit the grounding of the conduit would prevent any difference of potential between the building and the earth. An extensive study of electrical grounds in general, which was made incidental to this work shows that such is not the case. In the first place, it is practically impossible to make a ground through a metal plate that will have a sufficiently low resistance to prevent such differences of potential from arising due to a contact between wires and conduit. Tests conducted on grounds made at the Bureau of Standards, and also of those commercially used on low voltage secondaries and other places, show that these grounds are invariably of comparatively high resistance. The best grounds tested have been those made at the bureau and the results of these tests are instructive. These were made with plates 8 feet by 12 feet laid in wet ground with a bed of crushed coke below the plates and a layer of the same above, the whole being heavily salted and thoroughly flooded. In wet weather, when the ground is everywhere saturated with water, the resistance of these grounds is about 15 ohms, as shown by measurements against each other and against the water-pipe system of the city of Washington. During a dry period the resistance is much higher. Consider, now, that the metal work of a building, including the electrical conduit, is connected to such a ground and that the wires become grounded on the conduit. The current can go to ground both by way of the ground plates and also through the footings and foundations, the two paths being in parallel and independent of each other. If the circuit be 110 volts, several amperes may flow through the ground plate, but this, under usual conditions, would not cause any disturbance in the system and would probably go unnoticed except in a very small building using but little power. This parallel circuit through the ground plate would have no more effect on the potential of other parts of the building than the throwing of a load of several amperes in parallel with a lamp on an ordinary lighting circuit would have on the potential of the lamp. It would not, therefore, have any tendency to protect the structure from damage due to contact between a power wire and its conduit. On the other hand, it is extremely difficult to insure that all parts of the conduit shall be at all times in perfect electrical connection with the other metal parts of the building, because considerable resistance may be developed at joints, so that the portion of the conduit in contact with the wire may be but imperfectly connected to the ground plate. If at the same time the reinforcing material be connected to a ground plate there would be a great tendency for current to flow from conduit to reinforcing material or the reverse. Owing to the close proximity of conduit and reinforcement in many places, a comparatively low resistance joint sufficient to take up 2 or 3 per cent only of the voltage of the line (which would require but a fraction of an ohm in the case being considered, viz, a 15-ohm resistance in the ground plate) would give rise to a potential difference of several volts between conduit and reinforcement, which might do great harm, especially if the reinforcement is cathode.

While, of course, it would be possible, by going to considerable expense to make a ground of lower resistance than those just considered, it does not seem that it would be practicable to make and maintain permanently a sufficiently low resistance to give the protection sought.

It is desirable, however, to connect the metal work of the building together as far as practicable, provided such metal work is not in turn connected directly to pipe lines and cables entering the building. In other words, it is recommended that conduits, and such pipes as are separated from their mains by means of insulating joints, be interconnected electrically, but that this group of interconnected metal work should not be grounded directly to earth for the reasons given above. In addition, it may be said that if the low-voltage side of alternating-current circuits be grounded at the neutral point there is no material advantage to be gained by grounding the conduit.

V. CONCLUSIONS

The following conclusions are drawn from the investigations:

1. The observations of previous investigators that the passage of current from an iron anode into normal wet concrete caused the destruction of the test specimen by cracking the concrete were only partly confirmed. This effect was found not to occur in most of the specimens tested when the potential gradient was less than about 15 volts through a distance of 3 inches, or about 60 volts per foot. These figures must be considered as but roughly approximate as they depend much on conditions.

2. Of the numerous theories that have been advanced for the cracking of reinforced concrete due to electric current that one which attributes it to oxidation of the iron anode following electrolytic corrosion has been fully established. The oxides formed occupy 2.2 times as great a volume as the original iron, and the pressure resulting from this increase of volume causes the block to crack open.

3. Metals which do not form insoluble end products of corrosion and all noncorrodable anodes never cause cracking of the concrete as a result of the passage of an electric current.

4. The mechanical pressure developed at the iron anode surface by corrosion of the iron has been measured in a number of cases

and has been found to reach values as high as 4700 pounds per square inch, a value more than sufficient to account for the phenomena of cracking that have been observed.

5. Suggestions of some engineers[31] that copper-clad steel or aluminum be used as reinforcing material have been shown to be impracticable, since the copper coating is readily destroyed and the aluminum is attacked by the alkali in the concrete.

6. Corrosion of iron anodes even in wet concrete is very slight at temperatures below about 45° C (113° F).

7. For any fixed temperature the amount of corrosion for a given number of ampere-hours is independent of the current strength.

8. The lack of corrosion of the iron at temperatures below 45° C is due to the inhibiting effect of the $Ca(OH)_2$ and possibly other alkalies in the concrete.

9. The rapid destruction of anode specimens of moist concrete at high voltages (60 to 100 volts or more) is made possible mainly by the heating effect of the current, which raises the temperature above the limit mentioned above. If the specimen be artificially cooled no appreciable corrosion occurs, and no cracking results.

10. The potential gradient necessary to produce a temperature rise to 45° C with consequent corrosion, in the specimens used, was about 60 volts per foot. For air-dried concrete it is much higher. This shows that under actual conditions corrosion from stray currents may be expected only under special or extreme conditions as noted below. These figures are but roughly approximate since they will vary greatly with the conditions, such as the size, form, and composition of the specimen, but they serve to show the order of magnitude of the voltage required to produce trouble.

11. Since the passivity of iron in concrete is due chiefly to the $Ca(OH)_2$ present it appears probable that old structures in which the $Ca(OH)_2$ has been largely converted into carbonate will be more susceptible to the effects of electric currents than comparatively new concrete with which the foregoing experiments have been made. The increase in the efficiency of corrosion would, however, be at least partly offset by the increase in the resistance of the concrete which would accompany the change.

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[31] Magnusson and Smith: The Electrolysis of Steel in Concrete, Proc. A. I. E. E., 30, p. 939.

12. The addition of a small amount of salt (a fraction of 1 per cent) to concrete (as is frequently done to prevent freezing while setting) has a twofold effect, viz, it greatly increases the initial conductivity of the wet concrete, thus allowing more current to flow, and it also destroys the passive condition of the iron at ordinary temperatures, thus multiplying by many hundreds of times the rate of corrosion and consequent tendency of the concrete to crack. Salt should, therefore, never be used in structures that may be subjected to electrolytic action. Further, reinforced concrete structures built in contact with sea water, or in salt marshes, are more susceptible to electrolysis troubles than concrete not subjected to such influences.

13. Specimens of normal wet concrete carrying currents increase their resistance a hundredfold or more in the course of a few weeks, which fact still further lessens danger of trouble.

14. The rise of electrical resistance is probably due to a number of causes among which are the precipitation of $CaCO_3$ within the pores of the concrete thus plugging them up. A slight amount of salt tends to prevent this precipitation and interferes with the rise of resistance, thus still further emphasizing the detrimental effect of salt.

15. Contrary to the observations of previous investigators there was a distinct softening of the concrete near the cathode. This begins at the cathode surface and slowly spreads outward, in some cases as far as one-fourth inch or more. After exposure to the air this softened layer becomes very hard again, but remains brittle and friable.

16. The softening effect at the cathode noted above, caused under the conditions of the experiments, practically complete destruction of the bond between reinforcing material and the concrete, reducing it to a few per cent of its normal value.

17. Unlike the anode effect which becomes serious in normal concrete only on comparatively high voltages, the cathode effect develops at all voltages used in the experiments, the rate being roughly proportional to the voltage in a given specimen.

18. In general the cathode effect occurs under conditions which may not infrequently occur in practice and is therefore

probably a more serious matter practically than the anode effect about which so much has been written. This trouble is unlikely to be serious, however, except where the concrete is wet and the potential differences rather large.

19. The softening of the concrete at the cathode is due chiefly to the gradual concentration of Na and K near the cathode by the passage of electric current. In time the alkali becomes so strong as to attack the cement.

20. Softening at the cathode is increased by increasing the Na and K content of the cement, and reduced by diminishing this content, at least within the range below 10 per cent of the total salts.

21. The softening of the concrete has never been observed, except very close to the cathode, the main body of the concrete remaining perfectly sound. Numerous tests show conclusively that the crushing strength of the main body of the concrete is not reduced even when the potential gradient is maintained at 175 volts per foot for over a year.

22. Because of the cathode effect noted above, the proposal to protect reinforced concrete buildings by maintaining the reinforcing material cathode as by a battery or booster would be much more dangerous than no protection at all.

23. Aside from slight heating, which is usually negligible, the only effect which an electric current has on unreinforced concrete is to cause a migration of the water soluble elements. Consequently, in the absence of electrodes, the ultimate effect of current flow on the physical properties of the concrete is not materially different from that of slow seepage, which also removes the water soluble elements. Nonreinforced concrete buildings are therefore immune from trouble due to stray earth currents. They might, however, be injured by the grounding of power wires within the structure since these or the inclosing conduits would then act as electrodes.

24. Conditions arise in practice which give rise to damage due to stray currents, but the danger from this source has been greatly overestimated. While precautions are necessary under certain conditions, there is no cause for serious alarm.

25. If reinforced concrete could be thoroughly waterproofed, it would greatly increase its resistance and diminish accordingly the danger from either the anode or cathode effects. It should be emphasized, however, that waterproofing to prevent electrolysis is a much more difficult matter than waterproofing to maintain a moderate degree of dryness, because of the much higher degree of waterproofing required in the former case. It has been found that practically all of the waterproofing agents now on the market that are intended to be mixed with the concrete, are of little value as preventives of electrolysis. Waterproofing membranes, etc., applied to the surface can be made more effective and when properly applied may have considerable effect in preventing the entry of earth currents into the concrete.

26. Painting or otherwise coating iron with an alkali resisting metal preservative before embedding it in concrete may serve to minimize the dangers of electrolysis, but no such coating has been found that does not prevent the proper formation of the bond between the concrete and iron when the concrete sets.

27. In order to insure safety of reinforced concrete from electrolysis the investigation shows that potential gradients must be kept much lower in structures exposed to the action of salt waters, pickling baths, and all solutions which tend to destroy the passive state of iron.

28. All direct current electric power circuits within the concrete building should be kept free from grounds. If the power supply comes from a central station the local circuits should be periodically disconnected and tested for grounds and incipient defects in the insulation. In the case of isolated plants ground detectors should be installed and the system kept free from grounds at all times.

29. All pipe lines entering concrete buildings should, if possible, be provided with insulating joints outside the building. If a pipe line passes through a building and continues beyond, one or more insulating joints should be placed on each side of the building. If the potential drop around the isolated section is large, say, 8 or 10 volts or more, the isolated portion should be shunted by means of a copper cable.

30. Lead-covered cables entering such buildings should be isolated from the concrete. Wooden or other nonmetallic supports which prevent actual contact between the cable and the concrete will give sufficient isolation for this purpose. Such isolation of the lead-covered cable is desirable for the protection of the cable as well as the building.

31. The interconnection of all metal work within a building is an advantage where practicable, provided that all pipe lines entering the building are equipped with insulating joints and lead cables are taken care of as indicated in the preceding paragraph, but the grounding of such interconnected metal work or any part of it to ground plates or to pipe lines outside of the insulating joints is to be strictly avoided.

32. In making a diagnosis of the cause of damage in any particular case, the fact that a fairly large voltage reading may be obtained somewhere about the structure should not be taken as sufficient evidence that the trouble is due to electrolysis. The distance between the points, and particularly the character of the intervening medium, are of much greater importance than the mere magnitude of the voltage reading. As a precautionary measure, however, all potential readings about a reinforced concrete structure should be kept as low as practicable.

WASHINGTON, March 19, 1913.

APPENDIX.—BIBLIOGRAPHY OF ELECTROLYSIS IN CONCRETE

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