

**Research and Development Laboratories
of the
Portland Cement Association**

**RESEARCH DEPARTMENT
Bulletin 198**

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Other Than Reinforcing Steel**

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Authorized Reprint from the Copyrighted
Significance of Tests and Properties of
CONCRETE AND CONCRETE-MAKING MATERIALS
STP No. 169-A, 230-238 (1966)
Published by
American Society for Testing and Materials

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CORROSION OF EMBEDDED MATERIALS OTHER THAN REINFORCING STEEL

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This paper presents a discussion of behavior of metals other than reinforcing steel, plastics, wood, and glass, which are sometimes embedded in concrete for utilitarian or esthetic purposes. Possible detrimental effects on the concrete and embedded material will be considered. These two effects are often, but not always, conjoined.

METALS

Metals other than reinforcing steel which are frequently embedded in or used in intimate contact with concrete are principally aluminum, copper, lead, and zinc. Dry concrete at normal temperature is unlikely to promote corrosion of any of these metals. However, concrete is wet when mixed and for some time after setting, depending principally on the quality of the concrete and the distance through which free water must move to an external surface where it can evaporate. The rate of drying also depends on external humidity, but even at low external humidity a long drying time may be required to lower the internal humidity to a point where corrosion is unlikely. Thus, concrete which will eventually be dry may be internally wet long enough to promote serious corrosion of susceptible metals, and, of course, concrete exposed continuously or frequently to a damp environment may remain wet enough to

support such corrosion as could occur. The free moisture in wet concrete provides an aqueous medium which facilitates transport of soluble chemical substances, such as oxygen, calcium hydroxide, alkalies, and chlorides toward the metal, and of any soluble corrosion products away from the metal. It also increases the electrical conductivity of the concrete, thus aiding any tendency for electrochemical corrosion.

The time required for concrete to dry to various internal humidity levels is not commonly appreciated. The rates of drying of 6 × 36 × 36 in. (15 × 90 × 90 cm) slabs of normal weight concrete, as determined by Abrams and Orals [*1*]² are shown in Table 1.

This table shows that at an environmental relative humidity of 50 per cent, 36 days drying time was required to lower the middepth relative humidity to 90 per cent, and 240 days drying time was required to reach 75 per cent. Additional tests showed that when the middepth relative humidity reached 90 per cent, the relative humidity at a point only $\frac{3}{4}$ in. (1.9 cm) from an exposed face was 87 per cent. The moisture condition of concrete required to support active electrochemical corrosion of aluminum and other susceptible metals is not known with any accuracy, but it seems almost certain that such corrosion could pro-

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² The italic numbers in brackets refer to the list of references appended to this paper.

ceed, other conditions being favorable, at 90 per cent relative humidity and probably at 75 per cent relative humidity, though at a lower rate.

Concrete made with lightweight aggregates dries more slowly than that made with normal weight aggregates, and thicker sections, such as beams and columns, will dry more slowly than thin sections, such as walls, or floor slabs not on the ground.

Aluminum:

Aluminum reacts in fresh concrete principally with alkali hydroxides from

TABLE 1—RATES OF DRYING 6 × 36 × 36 IN. (15 × 90 × 90 CM) SLABS OF NORMAL WEIGHT CONCRETE.^a

Environmental RH	Drying Time to Reach Various Relative Humidities in the Concrete Slab at Middepth, days		
	90% RH	75% RH	50% RH
10.....	18	80	620
35.....	30	110	840
50.....	36	240	...
75.....	36	...	...

^a From Abrams and Orals [1].

cement. One reaction product is hydrogen gas, and for this reason aluminum powder is sometimes used in concrete to form cellular or "gas" concrete, or in smaller amounts to provide a slight expansion of grout in bedding machinery base plates. Aluminum in rod, sheet, or pipe form will react much less vigorously than will the powdered metal, because of its lesser exposed area.

Tests carried out by Jones and Tarleton [2] indicate that the corrosion of aluminum embedded in plain concrete can crack the concrete under unfavorable circumstances. However, it has been shown that the situation can be worse if the concrete contains calcium chloride and much worse if it also contains steel, such as reinforcing steel which is connected (coupled) metallically to the

aluminum. Wright [3] has described a case of corrosion of sufficient severity to cause collapse of aluminum conduit in reinforced concrete containing calcium chloride, and an instance of extensive

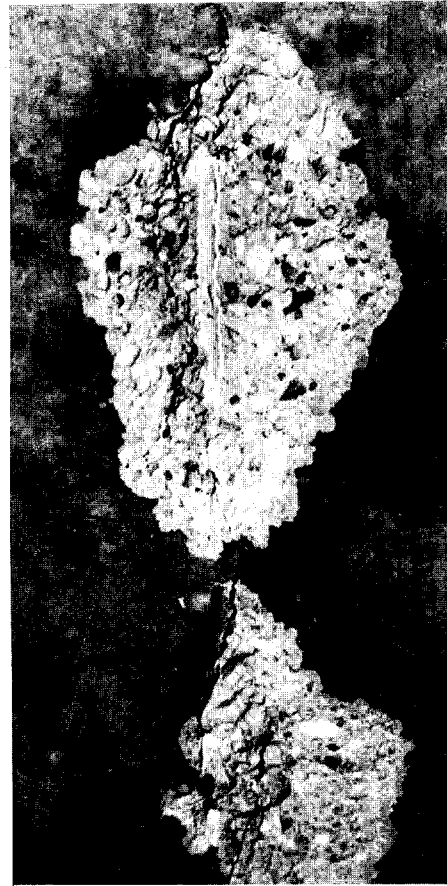


FIG. 1—Concrete spalled by corroding aluminum conduit (from Ref. 5).

concrete spalling over aluminum conduit in Washington Stadium has been published [4]. Some nine additional cases of concrete cracking over aluminum conduit in reinforced concrete have come to the attention of Portland Cement Assn. (PCA), and in every case calcium chloride was used as an admixture. An example is shown in Fig. 1.

The results of laboratory investigation by PCA have been given by Monfore and Ost [5]. Parts of that investigation will be summarized here, as they bring out the effects of concentration of cal-

aluminum conduit embedded $\frac{1}{2}$ in. from one face. Various numbers of C-shaped sheets of mild steel were also embedded in the cubes, externally connected for some tests and not connected for others.

TABLE 2—CORROSION OF 6063 ALUMINUM CONDUIT EMBEDDED IN 6-IN. CONCRETE CUBES STORED AT 50 PER CENT RELATIVE HUMIDITY FOR 28 DAYS.^a

Cement	Cement Alkalies as Na ₂ O, %	CaCl ₂ ·2H ₂ O, %	Ratio of Steel Area to Aluminum Area	Electrodes	Days to Cracking	Loss in Surface Thickness, mils ^b		
C	0.24	0	28	coupled	no crack	0.16		
		2	14	coupled	5	0.92		
		2	28	coupled	4	1.2		
		4	7	coupled	3	1.6		
		4	14	coupled	3	2.3		
		4	28	coupled	3	2.4		
		0	28	uncoupled	no crack	0.09		
		2	14	uncoupled	no crack	0.07		
		2	28	uncoupled	no crack	0.10		
		4	7	uncoupled	no crack	0.07		
		4	14	uncoupled	no crack	0.07		
		4	28	uncoupled	no crack	0.04		
		0	0	...	no crack	0.09		
		4	0	...	no crack	0.04		
		D	0.89	0	28	coupled	no crack	0.12
				1	3.5	coupled	no crack	0.54
				1	7	coupled	no crack	0.77
				1	14	coupled	no crack	1.0
1	28			coupled	no crack	0.85		
2	3.5			coupled	3	1.0		
2	7			coupled	3	1.4		
2	14			coupled	4	1.4		
2	28			coupled	4	1.6		
4	3.5			coupled	2	1.5		
4	7			coupled	2	1.7		
4	14			coupled	2	2.2		
4	28			coupled	7	3.3		
0	28			uncoupled	no crack	0.33		
2	14			uncoupled	no crack	0.06		
2	28			uncoupled	no crack	0.06		
4	7			uncoupled	no crack	0.07		
4	14			uncoupled	no crack	0.09		
4	28			uncoupled	no crack	0.08		
0	0			...	no crack	0.17		
4	0	...	no crack	0.05				

^a From Ref. 5.

^b Calculated from weight losses

cium chloride, alkali content of cement, coupling steel to aluminum, and the ratio of steel area to aluminum area. Six inch (15 cm) concrete cubes were prepared using two cements of alkali contents 0.24 and 0.89 per cent, containing pieces of nominally $\frac{1}{2}$ in. (1.25 cm)

Various amounts of calcium chloride were used. The cubes were removed from their molds at 24 hr, coated with a curing compound, and then stored at 73 F (23 C) and 50 per cent relative humidity for 28 days. They were observed regularly for cracks. After 28 days the alumi-

num pieces were removed, cleaned, and weighed. The principal results are given in Table 2.

Several important findings are to be noted in these results.

1. All cubes that cracked contained calcium chloride.

2. The cubes containing 1 per cent calcium chloride (as $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, by weight of cement) did not crack, but metal losses in these cubes were as high as, or higher than, those in other cubes which cracked. One may surmise that exposure to a damper atmosphere might have brought about sufficiently more corrosion to have caused cracking.

TABLE 3—EFFECT OF PROTECTIVE COATINGS ON CORROSION OF ALUMINUM CONDUIT EMBEDDED FOR 28 DAYS IN 6-IN. CONCRETE CUBES CONTAINING 4 PER CENT CALCIUM CHLORIDE AND STEEL COUPLED TO THE ALUMINUM.^a

Protective Coating		Days to Cracking	Loss in Surface Thickness, mils
Material	Thickness, mils		
None	.....	3	2.5
Silicone	.....	2	2.1
Lacquer B	..... 1	no crack	0.47
Lacquer C	..... 2	no crack	nil
Bitumen A	..... 5	no crack	nil
Bitumen D	..... 15	no crack	nil

^a From Ref. 5.

^b Calculated from weight losses.

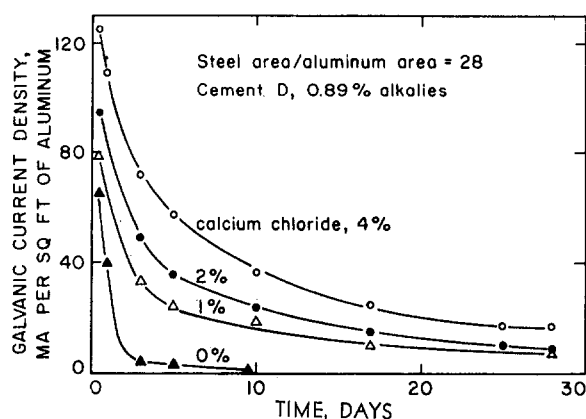


FIG. 2—Effect of calcium chloride on galvanic currents (from Ref. 5).

3. With no calcium chloride and no coupling, the corrosion was greatest with the high alkali cement.

4. With 2 or 4 per cent calcium chloride present, and with metals coupled, corrosion was a little greater with the higher alkali cement.

5. With calcium chloride present, and with metals coupled, corrosion generally increased with increasing ratio of steel area to aluminum area, and invariably increased as the amount of calcium chloride increased.

6. The cubes that cracked did so within seven days.

Additional tests were made to determine the effectiveness of several coatings applied to the aluminum before embedment in 6-in. concrete cubes made with cement of 0.89 per cent alkalis and containing 4 per cent calcium chloride by weight of cement. The results are shown in Table 3. These show that a silicone coating was ineffective and that Lacquer B prevented cracking within 28 days but permitted some corrosion. Lacquer C and bituminous coatings A and D were all effective in preventing both corrosion and cracking.

In the case of coupled metals, considerable galvanic currents were found to flow in the circuit connecting the aluminum and steel. Some measured currents as a function of time and calcium chloride content are shown in Fig. 2. The effect of increasing calcium chloride in increasing the current flow at all periods (up to end of test at 28 days) is evident. When the total electrical flow during 28 days in ampere hours per unit area of aluminum was plotted against the amount of corrosion as loss in thickness, straight lines were obtained with slopes depending on amount of calcium chloride used, the slope being greatest for the higher amounts of calcium chloride. This supports the conclusion that the corrosion observed with calcium chloride and coupled steel and aluminum is essentially galvanic corrosion, the two metals acting as electrodes of an electric cell and the calcium chloride acting as the electrolyte and probably in other ways.

Tests somewhat similar to those reported by Monfore and Ost were carried out on 12-in. (31 cm) concrete cubes by Wright and Jenks [6]. With coupled steel and aluminum (area ratio 10:1) the cubes did not crack when no calcium chloride was used, but cracked at various ages from 61 days with 1.1 per cent flake calcium chloride (70 to 80 per cent CaCl_2) to 8 days with 5.7 per cent.

The results of these various investigations and field observations show that reinforced concrete is likely to crack and spall from corrosion of uninsulated aluminum embedded therein if an appreciable amount of calcium chloride is present. Whether insulating coatings for aluminum to be used in concrete are commercially practical remains to be demonstrated.

In view of chemical similarities between calcium chloride and sodium chloride, it seems evident that the latter

would also facilitate corrosion of aluminum. Sodium chloride is the principal constituent of sea salt, and it therefore seems prudent not to use aluminum in concrete in or near sea water.

Lead:

Lead has a high resistance to certain chemical actions but, in contact with damp concrete, is attacked by the calcium hydroxide in the concrete and becomes converted to lead oxide or to a mixture of lead oxides. If the dampness persists, the attack will continue, and a lead pipe, for example, may be destroyed in a few years. If the lead is coupled to reinforcing steel in the concrete, galvanic cell action may accelerate the attack [7], in which case the rate of corrosion may be several millimeters per year. A protective coating or covering should always be used when lead pipe or cable sheaths are to be embedded in concrete. Bituminous coatings have been used successfully. Synthetic plastic coatings or sleeves which are themselves unaffected by damp concrete are suggested.

There appears little, if any, likelihood of concrete itself being damaged by corrosion of lead, because of the softness of the metal.

Copper and Copper Alloys:

In general, copper is not corroded in concrete, although it is reported that thin sheets can become perforated if soluble chlorides are present. Copper pipes are used successfully in concrete except under the unusual circumstance where ammonia is present [8]. Very small amounts of ammonia and possibly nitrates can cause stress corrosion cracking. It is reported that brass wall ties have failed by stress corrosion and that manganese bronze bolts have sheared below their ultimate strength, but as such phenomena can occur under circumstances unrelated to concrete, it is

not clear what role, if any, the concrete played in these cases. Very little systematic work has been reported on the behavior of copper and its alloys in or in contact with concrete, probably because these metals have given satisfactory service under such conditions.

Rabald [9] says that copper, brass, red brass, bronzes, aluminum-bronze, and copper-silicon alloys have good resistance to corrosion in concrete.

occasionally been recommended or used for concrete in a marine environment. Its usefulness has not been adequately demonstrated.

Galvanized corrugated steel sheets are often used as bottom forms for concrete roof or floor construction, the sheets being left in place afterwards. In general, the results have been entirely satisfactory. In some cases they have not. Figure 3 shows one instance of multiple

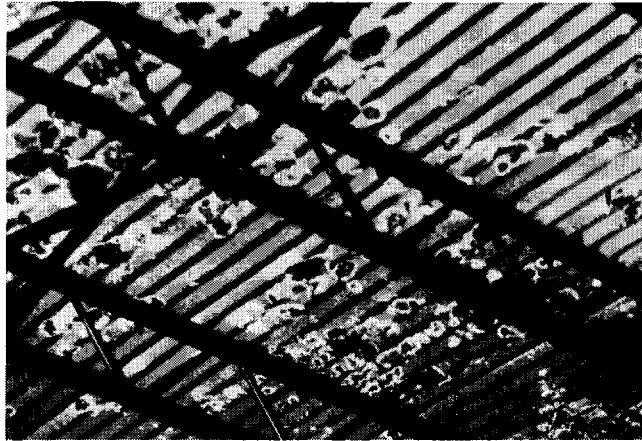
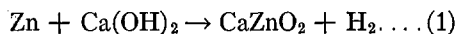


FIG. 3 — Corrosion and perforation of galvanized steel form under concrete slab (from Ref. 10)

Zinc:

Zinc reacts chemically with alkaline materials, but normally in concrete the reaction is superficial and may be beneficial to bond of zinc coated (galvanized) steel. The primary chemical reaction with calcium hydroxide is

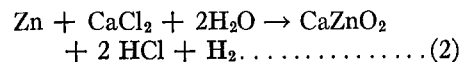


When zinc is used in concrete it is practically always as a coating for steel. The products of reaction are not voluminous and, consequently, damaging stresses are not created.

Although good concrete normally provides a nearly ideal environment for protecting embedded steel from corrosion, galvanized steel reinforcement has

perforation and corrosion of such sheets under a roof slab [10].

Most of the corroded spots were dry to the touch, but some were moist. These were found to have pH values of 2.7 to 4.8, definitely in the acid range. Analysis of the corrosion protuberances indicated the presence of iron, zinc, and chloride. Further investigation of this and other similar cases showed that in each instance calcium chloride was used in the concrete and may be presumed to have abetted the corrosion by chemical action on the zinc and by increasing the electrical conductivity of the concrete to corrosion currents. The chemical reaction is probably as follows:



As this reaction produces hydrochloric acid, it may well explain the observed acidity of the corrosion product. It is probable that this reaction could not take place at first but only after local depletion of calcium hydroxide by the reaction expressed in Eq 1.

The extent of corrosion and possible perforation of galvanized sheets used in the manner described with concrete containing calcium chloride is greatly enhanced by use of concrete with high water content and by preventing drying, as by application of a relatively impervious roof deck. Calcium chloride should not be used in concrete to be formed against galvanized steel.

Additional Metals:

Rabald [9] reports that the following metals have good resistance to corrosion in concrete: stainless steels, chrome-nickel steels, chromium-aluminum-silicon steels, cast silicon-iron, alloyed cast iron, nickel, chrome-nickel, iron-chrome-nickel alloys, monel metal, stellite, silver, and tin. It is to be noted, however, that the resistance of some of these metals to corrosion in concrete may be seriously affected by the presence of corrosion promoters such as soluble chlorides. Monel metal and stainless steel Type 316 are well known for their resistance to sodium chloride and other constituents of sea water and should work well in concrete. Special circumstances might justify the use of these more costly metals.

PLASTICS

Plastics are used in concrete as piping, shields or sheaths, chairs, and water-stops, and their compatibility with concrete is therefore important. Few, if any, results of tests of plastics in concrete have been published. However, the principal chemicals in concrete which could conceivably attack plastics are calcium hydroxide, sodium hydroxide,

and potassium hydroxide. Seymour and Steiner [11] list the following plastic groups as having excellent resistance to all three of these alkalies at 75 F:

Polyethylene
Styrene Copolymer Rubber-Resin
Blends
Polyvinyl Chlorides, Types I and
II
Polytetrafluoroethylene

Another source [12] provides the following information on the resistance of plastics to strong alkalies:

Class of Material	Resistance
Polyethylene.....	excellent
Polymethyl methacrylate.....	poor
Polypropylene.....	excellent to good
Polystyrene.....	excellent
Polystyrene acrylonitrile.....	good to excellent
Polytetrafluoroethylene.....	excellent
Polytrifluorochloroethylene....	excellent
Polyvinylchloride and polyvinylchloride vinyl acetate (rigid).....	excellent
Polyvinylchloride and polyvinylchloride vinyl acetate (plasticized).....	fair to good
Saran (monofilament grade)....	fair to good
Epoxy (unfilled).....	excellent
Melamine (formaldehyde).....	poor
Phenol (formaldehyde).....	poor
Polyester styrene-alkyd.....	poor
Urea (formaldehyde).....	poor

WOOD

Sawdust, wood pulp, and wood fibers have been incorporated in mortars and concretes, and timbers have been embedded in, or placed in intimate contact with concrete in composite constructions. The use of fresh untreated sawdust, wood chips or fibers in concrete commonly results in very slow setting and abnormally low strength because of interference with normal setting and hardening processes by carbohydrates, tannins, and possibly other substances in the wood. The amount of such substances differs with wood species and from time-to-time and place-of-origin within a

single species. Softwoods generally give less trouble in this respect than hardwoods.

Many admixtures and many wood treatments have been proposed or used to circumvent the influence of wood constituents on setting and hardening. Addition of hydrated lime to the mixture in an amount equivalent to one-third to one-half of the cement by volume has been found effective in overcoming this action [13]. The treatment is usually effective with mixed softwoods, except when a high proportion of larch or Douglas fir is present. Calcium chloride, to the amount of five per cent of the cement, is sometimes added as well as hydrated lime. With woods of high tannin or carbohydrate content the addition of lime with or without calcium chloride is not effective. Other treatments which have been suggested include soaking in sodium silicate solution, moistening the wood with 1 per cent sulfuric acid for 4 to 14 hr, then neutralizing with milk of lime; treating with 37 per cent aluminum chloride solution or 50 per cent zinc chloride solution in a rotary barrel with beater. A treatment found by Parker [13] to be effective with all woods tried consists of the following consecutive steps:

1. Boiling sawdust in water.
2. Draining and washing with water.
3. Reboiling with a solution of ferrous sulfate (2 per cent) in water.
4. Draining and rewashing.

Concrete made with wood aggregate has considerably greater volume change on wetting and drying, or simply on change in external humidity, than concrete made with mineral aggregates. If the element is restrained, drying may lead to cracking. If drying is not uniform, the element may warp. The pretreatments mentioned previously have only a small influence on these volume changes. Various methods have been employed to

lessen the changes in volume consequent upon changes in moisture. Some of these methods involve encasement of the wood particles or of the finished product in a material of low permeability to moisture, but the details of such treatments and the results achieved have not in general been revealed.

Timbers embedded in concrete have sometimes been observed to deteriorate. It is said that the harm is done by calcium hydroxide which causes dissolution of lipins and decomposition, chiefly of pentosans, to a smaller extent of lignin, and least of all of cellulose. The most suitable wood for embedment is said to be pine or fir, preferably of a type with high resinous content [14].

GLASS

Glass is sometimes embedded in mortar or concrete as artificial aggregate used for decorative or esthetic purposes, as reinforcing as a substitute for steel, as wall blocks or tile, and as frameless windows or lights. In this connection it should be observed that some glasses are expansively reactive with cement alkalis and that the resulting expansion may cause severe damage to the glass or the concrete or both [20]. If glasses are to be embedded in or used in direct contact with mortar or concrete, they should be of such character as not to react expansively. The "quick chemical test" (ASTM Test for Potential Reactivity of Aggregates (C 289)), used for the detection of aggregates which are expansively reactive with alkalis, can also be applied to glasses to be used in concrete. That test measures the extent of reaction of the sample during 24 hr immersion in 1N sodium hydroxide at 80 C. Glasses are available which exhibit very low reactivity in the test, both as to reduction in alkalinity and as to silica dissolved. Such glasses are nonexpansive in concrete.

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