

# Effects of Seawater on Concrete

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Concrete exposed to seawater is wetted by a solution of salts—principally sodium chloride and magnesium sulfate. Damage to concrete, if it occurs, usually results from failure to use good practices in concrete construction, and often is the result of freezing and thawing or wetting and drying, as much as or more than the results of the effects of seawater as such. Magnesium sulfate may attack most, if not all, of the constituents of hardened portland cement paste, especially the aluminate constituent; chlorides may promote corrosion of steel; alkalis may participate in alkali-aggregate reaction. Thus, concrete exposed to seawater should be made with cement of controlled aluminate content and with nonreactive aggregate, embedded steel should be well covered by concrete of low permeability, and good construction practices should be followed.

•FOR AS LONG as concrete has been used, it has been employed in construction exposed to the action of seawater. Examples of concrete used by the Romans 2,000 years ago in structures exposed to seawater on the shores of the Mediterranean Sea are still intact. When concrete is to be employed under conditions in which it will be exposed to the effects of seawater, cognizance should be taken of these effects and appropriate precautions taken. Generally, these precautions are not drastic and do not involve the selection and use of unusual materials or procedures nor cause any significant increase in cost of production (12).

The effects of seawater on concrete may conveniently be examined by considering: (a) the factors characteristic of the seawater exposure that can affect concrete; (b) the elements of the specific concrete involved that may be affected by these factors; (c) the consequences of the interaction of seawater with the concrete; and (d) the precautions that should be taken to avoid undesirable performance of the concrete due to its interaction with seawater.

## PERTINENT FACTORS IN A SEAWATER EXPOSURE

Concrete exposed to seawater will be subjected to wetting by an aqueous solution containing principally dissolved sodium chloride and magnesium sulfate. The oceans contain, on the average, about 35 parts per thousand (3.5 percent) dissolved salts. The major cations,  $\text{Ca}^{++}$ ,  $\text{Mg}^{++}$ ,  $\text{Na}^+$ , and  $\text{K}^+$ , exist in seawater largely as uncomplexed species. The major anions include  $\text{Cl}^-$ , which is also not strongly complexed, and  $\text{CO}_3^{=}$ ,  $\text{HCO}_3^-$ , and  $\text{SO}_4^{=}$ , which are. Expressed as milligrams per liter of seawater, the principal elements present in solution are chlorine, 19,000; sodium, 10,600; magnesium, 1,300; sulfur, 900; calcium, 400; and potassium, 380. All other elements are probably present, but no others make up more than 65 mg/l. The six elements mentioned make up 99 percent of the dissolved salts in seawater. Although the concentration of dissolved solids has been found to vary from place to place, the ratio of any one of the major constituents to the total dissolved solids is nearly constant everywhere. The foregoing information, taken from a recent report (2), can be compared with an analysis (Table 1) of a specific sample reported by Forrest and Worthley (4).

TABLE 1  
ANALYSIS OF SEAWATER FROM  
ST. VINCENT GULF,  
SOUTH AUSTRALIA<sup>a</sup>

Ion	Concentration (g/100 ml)	Ion	Concentration (g/100 ml)
Na <sup>+</sup>	1.22	Cl <sup>-</sup>	2.19
Mg <sup>++</sup>	0.145	SO <sub>4</sub> <sup>=</sup>	0.32
Ca <sup>++</sup>	0.056	HCO <sub>3</sub> <sup>-</sup>	0.014
K <sup>+</sup>	0.044	Br <sup>-</sup>	0.008

<sup>a</sup>Specific gravity of seawater (25°C), 1.03.

Thus, the factors inherent in seawater exposure that should be considered for their effects on concrete are wetting and drying and chemical reaction of chlorides, sulfates, alkalies (sodium and potassium), and, in some instances, dissolved carbon dioxide.

The elements of concrete that may be affected by wetting or by chemical reaction with chlorides, sulfates, or alkalies include the cement, the aggregates, and reinforcing steel or other metal, if present.

## EFFECTS OF CONTINUOUS IMMERSION OF CONCRETE IN SEAWATER

Concrete that is totally and continuously immersed in water, even if the water contains dissolved salts such as are found in seawater, generally may be regarded as being in a protected exposure. Continuous immersion usually provides a uniformity of environment with respect to temperature and moisture content that prevents the immersed concrete from being subjected to such deteriorating influences as frost action, volume change due to wetting and drying, and differential volume change due to moisture content differences between the surface and the interior. Continuous immersion also tends to reduce the potential for chemical reaction by removing changes in the degree of saturation as a mechanism for the flow into and out of the concrete of solutions containing ions capable of attacking constituents of the concrete, and leaving only concentration gradients as the means of ingress of such ions. Locher and Pisters (11) note that, under equal conditions of exposure, the aggressiveness of water increases with increasing concentration of the relevant substances, but that aggressiveness is also increased by higher temperatures, higher pressures, wetting and drying, or mechanical abrasion by fast-flowing or turbulent waters.

## EFFECTS OF INTERMITTENT IMMERSION OF CONCRETE IN SEAWATER

Most concrete structures exposed to seawater are partially or wholly situated so that they are sometimes immersed in seawater and sometimes exposed to the air. If the structure is located where the temperatures fall below freezing, the concrete exposed to the air with falling tide is probably subjected to as severe frost action as is any concrete in natural exposure. The realization that concrete exposed in the tidal zone in a region of low winter temperatures would be subjected to very severe frost action resulted in the selection of the mean-tide elevation at Treat Island, Cobscook Bay, Me., as the location for the U. S. Army Corps of Engineers severe natural weathering station. This location has been used since 1936 by the Corps of Engineers to develop information rapidly on the relative resistance of concretes to frost action (8). Since effects of frost action on concrete are not within the scope of this symposium, this subject is not developed further here.

The second important effect on concrete related to wetting and drying is the volume change relations due to changes in, or changes in uniformity of, moisture content. These phenomena, often referred to as drying shrinkage effects, are also not within the scope of this symposium, and hence are not discussed further here.

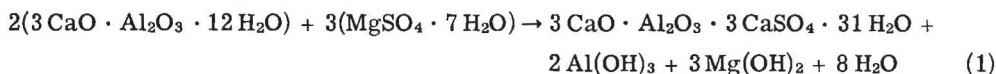
In localities such as Treat Island, the mean temperature of the seawater is low and chemical reactions take place relatively slowly. Concretes relatively deficient in resistance to frost action seldom survive long enough to manifest any readily observable effects of chemical attack; hence, it can be argued that there is a general tendency for the severity of chemical attack to be reduced when that of physical attack increases, and vice versa (8).

## CHEMICAL ATTACK OF SEAWATER ON CONCRETE

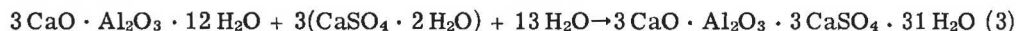
The potentially aggressive constituents of seawater with respect to concrete are the sulfate, chloride, carbonate, bicarbonate, alkali metal, and magnesium ions. The aggressive action of the sulfate ion on concrete is discussed by other contributors to this symposium (22). However, since in seawater the sulfate component is magnesium sulfate rather than sodium or calcium sulfate, as is more often the case in sulfate-attack situations not involving seawater, the various chemical reactions of magnesium sulfate with several of the constituents of hydrated portland cement are noted subsequently. These comments are based on the discussion by F. M. Lea (9) who pointed out that, initially, magnesium sulfate has a similar action to that of other sulfates in attacking calcium aluminate hydrate, but that later it can induce a significantly different and more far-reaching effect because of its ability—as distinguished from other sulfates—to attack and decompose the calcium silicate hydrate. This reaction (Eq. 4) proceeds to completion because of the low solubility of magnesium hydroxide.

### Magnesium Sulfate

Magnesium sulfate initially reacts with calcium aluminate hydrate ( $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 12\text{H}_2\text{O}$ ) to form calcium aluminum sulfate hydrate (ettringite,  $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 31\text{H}_2\text{O}$ ) magnesium hydroxide, and aluminum hydroxide:



Magnesium sulfate also reacts with calcium hydroxide to form calcium sulfate (gypsum) which, in turn, reacts with calcium aluminate hydrate to form additional calcium aluminum sulfate hydrate (ettringite):

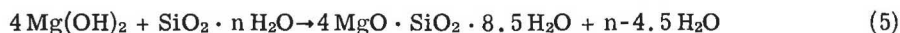


Magnesium sulfate also can react with calcium silicate hydrate ( $3\text{CaO} \cdot 2\text{SiO}_2 \cdot n\text{H}_2\text{O}$ ) to form calcium sulfate, magnesium hydroxide, and silica gel ( $\text{SiO}_2 \cdot n\text{H}_2\text{O}$ ).



The calcium sulfate formed in Eq. 4 may then react with calcium aluminate hydrate according to Eq. 3.

Finally, the magnesium hydroxide formed in the reactions indicated by either Eqs. 1 or 4 can react with silica gel, as produced by the reaction indicated in Eq. 4 or otherwise, to form a magnesium silicate hydrate ( $4\text{MgO} \cdot \text{SiO}_2 \cdot 8.5\text{H}_2\text{O}$ ):



A soft white material having the approximate composition  $4\text{MgO} \cdot \text{SiO}_2 \cdot 8.5\text{H}_2\text{O}$  was found by Cole and Hueber (3) in a deteriorated concrete seawall.

### Carbonate and Bicarbonate

The carbonate and bicarbonate ions may participate in the reaction of carbonation of calcium ion or calcium hydroxide formed during hydration of cement. In a discussion (16) of deterioration of concrete in the shipways at Newport News, Va., in 1948, Mrs. Terzaghi concluded that two processes were at work, one involving sulfate attack that caused internal expansion and cracking, and the other involving carbon dioxide dissolved in the water as carbonic acid that caused local softening and disintegration. The water samples taken from relief wells in these shipways were regarded as containing from 30 to 60 percent seawater, based on chloride content, and had free  $\text{CO}_2$

contents of 7 to 99 mg/l; the highest  $\text{CO}_2$  content was found in the sample of lowest seawater content which had 57 mg/l aggressive  $\text{CO}_2$  and a pH of 6.9.

### Alkalies

The alkali metal ions may participate in any of several reactions with reactive silica or reactive carbonate constituents of the aggregates. Stanton (15) in 1937 listed among structures adversely affected by alkali-silica reaction, sections of seawalls in Ventura and Santa Barbara Counties in California. Recently it was suggested that expansion of concrete in certain dry docks in New York had resulted from the alkali-carbonate reaction. The available data, however, indicated that the aggregates in these structures are natural siliceous sand and gravel. Hence, as far as is known, there have as yet been no documented cases of alkali-carbonate reaction which have caused deterioration of concrete structures exposed to seawater. Kennedy and Mather (8) found that in concrete containing a crushed limestone aggregate that had been exposed to seawater at Treat Island, there was evidence of the formation of reaction rims on certain limestone coarse-aggregate particles. The particular limestone studied contained about 4 percent of a montmorillonitic clay which undergoes greater swelling when wetted with a solution containing sodium ion than when sodium ion is not present. They showed that this material, processed as manufactured fine aggregate, exhibited two to three times as much increase in volume when immersed in seawater as when immersed in fresh water or in a saturated solution of calcium hydroxide.

### Chlorides

The chloride ion may participate either in chemical reactions similar to those involving the sulfate ion—so as to yield such products as chloraluminates that are analogous to sulfoaluminates—or in reactions involving the corrosion of reinforcing or other embedded metal. In this latter connection, Halstead and Woodworth (6) reported that reinforced concrete structures exposed under coastal conditions (within 10 mi of the seacoast) in South Africa have, in some cases, shown deterioration believed caused by electrochemical corrosion of the steel. In the discussion of their paper, it was noted that the South African Railway Administration has adopted the policy of using reinforced concrete structures in preference to steel because of difficulties in maintaining steel structures. This agency also has attempted to design structures for a minimum of reinforcing steel. The performance of such structures has generally been good, and such deterioration as has occurred is believed related to insufficient concrete cover over reinforcing steel that permitted corrosion to occur.

The role of chlorides in seawater in chemical interaction with concrete is twofold. Chlorides act independently to do those things that chlorides are capable of doing, and they also tend to retard or inhibit the action of sulfates. The presence of chlorides, as in seawater, retards or inhibits the expansion of concrete by sulfate solutions, but not the degree of reaction. Lea (9) cited the work of Batta, who attributed this effect to the greater solubility of gypsum and calcium aluminum sulfate in chloride solutions, and it is the reason why failure arising from chemical attack by seawater is not preceded by swelling to the same degree as in solutions of sodium or magnesium sulfate.

Griffin and Henry (5) studied, separately, the effects of sodium chloride and seawater salts in concrete. Their purpose was to determine the effect of sea-salt spray on concrete and the permissible amounts of salt in concrete when it is mixed. They found that the optimum salinity of mixing water for maximum compressive strength was from 18 to 36 g/kg when sodium chloride was used and up to 88 g/kg when sea salt was used. They also found that, when sodium chloride was used, the rate of moisture migration through concrete from a region of higher to one of lower relative humidity decreased with increasing salinity of mixing water to a salinity of about 70 g/kg and then remained relatively constant with further increases in salinity. When sea salt was used, the rate of moisture migration also decreased with increase in salinity, but leveled off at about 25 g/kg.

They concluded that some salt may be beneficial to concrete in some respects. With a mixing water salinity of about 25 g/kg, strength was improved, the rate of moisture



movement was reduced, and corrosion of mild steel in the low-strength concrete used in their investigation was negligible. With sodium chloride, the maximum corrosion of mild steel appeared to take place at a salinity of about 70 g/kg. It should perhaps be emphasized that Griffin and Henry were studying the "permissible amounts of salt" that could be tolerated; it is not, I believe, their intent to suggest that one would deliberately add salt to reinforced concrete if it could readily be avoided.

Work done in connection with studies of the action of chloride salts used to remove ice from concrete pavements, insofar as it concerns the effect of chloride ion, may be considered relevant to the action of seawater. Hartmann (7) has noted that the reaction of sodium chloride solutions with tricalcium aluminate or tricalcium aluminate hydrates produces either or both the calcium chloroaluminate hydrates,  $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCl}_2 \cdot 10\text{H}_2\text{O}$  or  $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCl}_2 \cdot 18\text{H}_2\text{O}$ . However, she concluded that, although chemical effect of chloride de-icing salts on concrete was a possible cause of damage, it did not seem to be a probable cause.

#### FACTORS AFFECTING RESISTANCE OF CONCRETE TO CHEMICAL ATTACK

Results of experiments in which mortars and concrete specimens have been exposed to seawater are in general agreement that the attack occurs to the extent that hydrated calcium aluminate is available and accessible to the sulfates in the seawater. The more permeable the concrete and the higher the  $\text{C}_3\text{A}$  content of the cement, the sooner will evidence of sulfate attack be manifested and the greater will be the degree of attack.

The use of pozzolans in concrete to be exposed to seawater has long been advocated because of observations that their use increases the resistance of the concrete to chemical attack of the seawater. Lea (9) reviewed the various explanations that have been offered for this effect, and concluded that many or all of them sound reasonable. However, he also concluded that no one by itself provides an adequate explanation, and that all of them taken together fail to give the complete story. The explanations include: (a) reduction in amount of free calcium hydroxide by reaction with pozzolan, thus reducing the degree to which the reaction of sulfates and calcium hydroxide can occur; (b) increased solubility of hydrated calcium aluminates with decreased concentration of calcium hydroxide, and hence greater likelihood that the sulfate-aluminate reaction will take place through solution rather than in the solid state and thus produce less expansion; (c) decreased tendency of the low-sulfate calcium aluminum sulfate to convert to the high-sulfate form (ettringite) as the concentration of calcium hydroxide in solution decreases, due to the higher sulfate concentration required to effect the conversion as such decrease occurs; (d) decreased permeability of the concrete with reduced rate of entry of sulfate solution; (e) formation of lime-pozzolan reaction product films that protect the hydrated calcium aluminate; and (f) decomposition of lime-pozzolan reaction products by seawater to leave silica and alumina gel which are more stable products.

Satisfactory concrete for exposure to seawater will be obtained if reasonable precautions are followed in the selection and use of the materials of which it is composed. The 1963 ACI Standard Building Code (1) requires that concrete to be exposed to freezing while wet have a water-cement ratio not exceeding 6 gal/sk and contain entrained air. It references ACI 613-54 (1) for requirements for seawater exposure, Table 4 of which requires that water-cement ratios not exceed  $4\frac{1}{2}$  gal/sk for thin members and 5 gal/sk for thicker members in contact with seawater. The cement should meet the requirements for Type II, specifically in that it should not contain more than 8.0 percent tricalcium aluminate ( $\text{C}_3\text{A}$ ) as calculated from the chemical analysis. Reinforced concrete members should be designed and inspected continuously during construction to ensure that no steel is closer than 3 in. from the exposed faces and 4 in. from corners, unless special precautions are taken to prevent corrosion.

Special treatments and materials may, in certain cases, prove advantageous. Wakeman et al. have described (17) the successful use of asphalt impregnation of precast concrete piling to improve resistance to seawater exposure. Li (10) has called attention recently to the potential benefits of expansive cements for concrete construction in marine exposures. Portions of his statement indicate that concretes

made with expansive cement may be controlled to achieve shrinkage compensation, resistance to cracking, reduced permeability, and wear resistance. Such properties may help to render wharf decks crackproof, waterproof and, hence, more wear-resistant. Expansive-cement concrete should further enhance the resistance to seawater of both reinforced and prestressed concrete piles for waterfront applications.

Neville (14) notes that portland blast-furnace slag cement is frequently used in seawater construction because of the fairly high sulfate resistance of concrete made with it. He also notes that concrete made with aluminous cement stands up extremely well in seawater, but points out that seawater should not be used as mixing water when aluminous cements are used.

The performance of portland cement concrete when used in service involving exposure to seawater has often been excellent, usually adequate, but sometimes exceedingly poor. It is believed that, when poor performance has occurred, the cause was poor concrete, the inferior nature of which was perhaps revealed more rapidly by the somewhat more severe exposure than might have been the case in a less severe situation. Mention was made earlier of concrete which has been exposed to Mediterranean Sea water for 2,000 years and is in rather good shape.

#### EXAMPLES OF PERFORMANCE OF REINFORCED CONCRETE IN MARITIME EXPOSURES

Wentworth-Shields (21) described the first maritime reinforced concrete structure in Great Britain, constructed at Southampton in 1899, and noted that very few failures have occurred. The 1899 structure was a jetty consisting of a 100- by 40-ft deck on piles. In 1902, Town Quay, a reinforced concrete structure 360 by 20 by 34 ft high, was built at Southampton. A few years later longitudinal cracks appeared above the mean-tide level along lines of reinforcement, due to rusting of steel. Repairs were made with pneumatically applied mortar. The rusting of the steel has been ascribed to the permeability of the concrete, but in the case of Town Quay electrolytic action was, if not the sole cause, a very important contributory cause. The 1899 structure, which is still in excellent condition, was made with dry, low water-cement ratio concrete; the 1902 one was made with a "rather wet" mixture.

Not only is the first maritime reinforced concrete structure built in Great Britain still in excellent condition, but most concrete structures in seawater exposures are in good condition when good practice was used and care was taken in their design and construction. For example, the concrete ship "Atlantus," the first constructed by the United States Government, was launched in 1918. It was brought to Cape May, N. J., to serve as a terminal for a ferry line and in 1927 became stranded on a sandbar. It was inspected at various times between 1918 and 1930. A report on its trial run in 1919 from Brunswick, Ga., to Charleston, S. C., states that the concrete was "in a practically perfect state of preservation with no important rust stains visible, although there could be traced in certain places on the hull the faint markings of hairline cracks which paralleled the system of reinforcing closest to the outer surface." Walter in 1929 (18) published a photograph of a specimen of concrete taken from the ship in 1928 showing the imprint of a square bar  $\frac{13}{16}$  in. and a round bar  $\frac{5}{16}$  in. from the outer exposed surface of the concrete, and stated that the steel was not corroded. After an examination of the ship in 1928, it was reported that a very pronounced rust stain had developed in the bulkhead enclosing the afterquarters, and in one spot the bars parallel to the deck were clearly outlined for a space of 2 or 3 ft each way. A close inspection of this area showed that there was almost no concrete coverage. In some places the intended depth of coverage was  $\frac{1}{4}$  in.; in some cases the actual coverage was less than  $\frac{1}{16}$  in. A disc of concrete 3 in. in diameter and 0.7 in. thick was cut from a fragment collected in 1928, tested in the laboratory, and found to have very low water permeability (13).

Similar inspection reports have been recorded on other concrete ships built during World War I. The "Selma," now stranded near Galveston, Texas, was inspected and reported on by Rogers at the 1953 Regional Meeting of the American Concrete Institute. The "Selma" was a tanker built in Mobile in 1918 and sunk at Galveston in about 1923.

Samples of the concrete tested in 1953 showed a compressive strength of about 10,000 psi. No corrosion of steel was observed, even though less than 1 in. of cover was provided. Another of these vessels, the "Palo Alto," is exposed on the Pacific coast at Seacliff Beach State Park, 6 mi south of Santa Cruz, Calif., where it is used as a fishing pier. It was built as a tanker during World War I and is 435 ft long. It remained anchored in the Oakland Estuary, where it was built, until 1930 when the Cal-Nevada Stock Company purchased it and had it towed to Seacliff on Monterey Bay, about 100 mi to the south. The sea cocks were opened and it now rests on a sandstone shelf. It was later acquired by California when the state park was created. The ship has broken its back, but a gangway across the fracture permits both parts to be used. It is probably the most accessible of the remaining World War I concrete ships (20).

#### CONCLUDING STATEMENT

The conclusions of the 18th Congress of the Permanent International Association of Navigation Congresses\* as summarized by Warren (19) are quoted as a closing statement:

It was agreed that the deterioration of concrete in warm sea-water is mainly due to chemical action, namely, the change in composition of the cement caused by the chlorides and sulphates present in the water. Little can be done to protect poor concrete, the remedy being to select a suitable type of cement and good sound aggregates in the first place, and to take steps to ensure that the finished product is as dense and impermeable as possible. In colder water, chemical action is less severe and the main damage is done by temperature changes. There are other causes of deterioration, such as abrasion and acids deposited by lithofagous organisms.

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\*Much useful data on performance of structures exposed to seawater are contained in the publications of the Permanent International Association of Navigation Congresses (General Secretary, 155 Rue de la Loi, Brussels, Belgium) (23).

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### *Discussion*

G. M. IDORN, Concrete Research Laboratory, Karlstrup, Karlslunde, Denmark—For about the last 250 years it has been possible to calculate structures, with due regard to their safety, by the development of static methods. The absolute basis for this was Newton's Principia, published in 1687, which brought about acknowledgment of universal gravitation, the fact that the force of gravity is constant. The immeasurable value of this acknowledgment to static and other calculations is possibly one reason why civil engineers so often tend to tabulate, and reckon on, and introduce constant values or ratios, even when a design problem calls for consideration of chemical or physical processes. Another reason for this tendency to tabulate is perhaps that many structural engineers are not educated to apply chemistry and physics.

However, unlike the situation with respect to static calculations, it is gradients and accumulations that characterize the conditions under which chemical and physical forces can have a deleterious effect on concrete. One is tempted to recall the words of Leonardo da Vinci: "To understand motion is to understand the universe." For example, it is sometimes considered probable that the climate on the coast of Denmark is more severe for concrete than the climate inland. However, in the moor regions or post-glacial sands of Jutland, for instance, the climate has a definite continental character, with 100 to 200 days of frost per year against only 70 to 80 on the west coast of Jutland. Similarly, frost starts about 1 month earlier and ends about 1 month later than on the west coast. The rate of freezing must vary correspondingly inland, and this factor is decisive in controlling the degree to which deleterious hydraulic pressures develop during the formation of ice in the capillary system of hardened con-



crete. In seawater and near the coast, the temperature variations generally are relatively slight. Even in the case of shallow water there is hardly any place in the world with a greater variation per 24 hr than 5 C, and the annual variation in Denmark is at any rate between -1 C and +20 C (and considerably less in both polar and tropical zones). The relative humidity of the air also generally varies less at the coast than inland. However, topographical, geological, and industrial conditions, for example, may cause considerable variations from place to place, frequently of such a magnitude as to render a broad geographical classification quite illusory. Discussion of these matters is in any case difficult because no comprehensive compilation and treatment of observations seem to exist.

A further illustration of the mistake in tabulating chemical conditions in standard specifications is the requirement that when groundwater contains more than 300 mg/l sulfate, precautions must be taken against sulfate reactions, for instance by the use of special cements for concrete exposed to the action of groundwater.

This requirement or a similar one is known from a number of countries and is considered useful in regions of completely uniform and constant geochemical conditions. Considering Denmark, however, it must not be forgotten that the aggressive action of sulfates on concrete is dependent on many other conditions than the concentration determined by chemical analysis of samples of water. It depends, for instance, on the cations with which the sulfates are able to combine, on the possibility of oxidation or reduction in the milieu in question, on the presence of suitable conditions for the accumulation of sulfates whereby the concentrations might locally or temporarily increase, and on whether the surroundings are such that a future increase in sulfate production must be expected. Industrial and urban development is thus frequently a source of considerable increase in the sulfate content of the soil and groundwater. Dewatering of bogs or marshes is another important source of sulfates.

The physical and chemical conditions touched on here can be denoted a part of the "milieu description" of a concrete structure or building area. The provision of data for such descriptions, their interpretation and an evaluation of their effect on the characteristics of concrete, especially its durability, will in future years become an important, although at the same time a difficult, field of research.

The statistical nature of the phenomenon of deterioration is also insufficiently recognized, and methods have not, therefore, been developed for quantitative treatment of the problems of durability touched on here for guidance in practice. For example, up to the present time, the main stress has been laid on describing and analyzing "average" results from laboratory tests, whereas stress should, in reality, be laid on the extremes encountered in practice. Therefore, correlations can rarely be established between test data and practical precautions. The data most often collected cannot be used for this purpose and they are, moreover, from a statistical point of view, encumbered with much greater uncertainty than usually dealt with in concrete technology. These remarks tend to support the opinion that attempts should not be made to govern the durability of concrete by standard specifications. Moreover, as experience has shown that the deterioration of concrete is not a problem of safety but a question of choice between initial and maintenance expenditure, the choice must juridically remain a private matter, and socially lead to the most economical practice by distributing the responsibility rather than centralizing it.

Many of those responsible for the practical production of concrete will perhaps be shaken by the consequences of these comments. Is one not being deprived of vital, unambiguous rules of law that one has been accustomed to having or assumed to have in previous standards? Will it not be necessary, for each individual project, to carry out a much more thorough analysis of the problems of concrete technology (as is traditionally done with the problems of stress calculation and design) before stipulating special conditions? Does not the average engineer lack the necessary technological insight?

The answer to the first question is a clear NO. Standard specifications have never been the only juridical basis in contracts. Both ordinary and special conditions are also included. The latter may refer to any supplementary requirement and instructions on which the contractual parties may agree.

The answer to the next question is also NO provided we invest not only in research but also in the preparation of the results of such research for the purposes of practical guidance. This is probably the point where there have not been sufficient advances in recent years, especially in certain fields in which an overwhelming quantity of research results are being produced. In this work there is still a need both for the more theoretical instructions, which also give assumptions for and explanations of the recommended methods and modes of execution, and for the highly condensed tabular form, which gives short and unambiguous instructions on methods. The former category of recommendations and directions provides a valuable contribution to the practical training of engineers, and the latter has proved a powerful instrument in forced production.

The answer to the third question is undoubtedly YES. There is a very great need for new concepts, especially in the training of engineers.

There is thus quite definitely a very great social task to be undertaken in the critical preparation of the results of research for instruction purposes and in the continued revision of technological training with special reference to the advances made in research and the main trends of the coming development in concrete construction practice.

**BRYANT MATHER, Closure**—Mr. Idorn's discussion of the necessarily different approach to durability as contrasted with that that is taken with respect to load-bearing capacity in specifications for concrete structures is very welcome and a very important addition to the remarks contained in my paper. Mr. Idorn speaks of the choice between initial and maintenance expenditures as an important concept employed in dealing with the problems of durability in specifications for concrete work. In many instances, the degree to which precautions are properly required to be taken in the selection of materials, dimensions, and construction practices will depend on the degree to which the owner desires to provide himself with assurance of freedom from deterioration and the degree to which he is willing to pay for such assurance. If the structure is to be a monument where aesthetic considerations are of great importance and cost need not be kept to a minimum, it may well be that the use of precautions is justified, even though the eventualities that they are intended to preclude are extremely remote. In other cases, where initial cost is the dominant consideration and anticipated service need is relatively shorter in duration, precautions may be not taken, even though the phenomena whose effects might be mitigated by the taking thereof are quite likely to manifest their effects. In any case, the desirability of greater understanding of these considerations by all concerned is a goal that should be sought far more diligently than it often is at present.