Paper No. 1

The three main causes of deterioration in concrete, freezing and thawing, reinforcement corrosion, and chemical attack by sea water, are discussed on the basis of the fundamental concept that these causes can be generally minimized if watertight concrete is attained.

CONCRETE IN MARINE ENVIRONMENTS

By Ivan L. Tyler

THERE ARE THREE MAIN CAUSES OF deterioration in concrete marine structures: (1) freezing and thawing attack on the concrete, (2) corrosion of reinforcing steel and disruption of concrete by the resulting expansion, and (3) chemical attack on concrete by sea water.

Deterioration from these main causes could be greatly minimized or completely eliminated if the concrete was watertight. Most other concrete structures would also last indefinitely if impermeability could be attained, but in marine construction it is of utmost importance. Most exposures have seasonal drying periods; tidal structures do not and so may become saturated after a few years of exposure.

It seems evident that watertightness should be the first concern of builders of marine structures. The extent to which watertight construction can be achieved is probably the best measure of the structure's potential lasting qualities. However the hope of building completely impermeable structures is remote because of the nature of portland cement concrete.

Since permeability is of such overriding importance, an examination of permeability curves may be worthwhile. Fig. 1 shows curves of permeability for two concretes. The top curve has a water-cement ratio of 6.5 gal. per sack, the bottom curve has 4.5 per sack. Both concretes contain entrained air. The determinations were made on moist cured 6 x 12-in. cylinders by measuring the rate of penetration of tap water under different pressures.

Moist curing for 7 days did not produce anywhere near the potential of either mix so far as permeability is concerned. It is worth noting that after 7 days of moist curing neither concrete mix is exactly watertight. Consider the right end of the lower curve showing permeability after 28 days of moist curing. It appears to be pretty good concrete so far as permeability is concerned. But is it?

According to the method of test used in establishing the curves shown in Fig. 1, it would take non-air-entrained concrete with a permeability coefficient of $K = 30 \times 10^{-12}$ about ¾ hr for a 1-in. penetration of water under 500 psi. With $K = 1 \times 10^{-12}$, represented by the better concrete of the lower curve, it would take 20 hr for 1-in. penetration.

Assuming an average hydraulic head of 1 ft against a concrete structure, it should take a little over a year for a 1-in. saturation of a well-cured concrete of the water-cement ratio indicated, and a little less than 5 years for a 2-in. saturation with the higher grade concrete represented by the lower curve. With air-entrained concrete the rate of penetration would be somewhat slower with K remaining the same as for non-air-entrained concrete. Clearly, if the coefficients quoted could be depended on, these rates of penetration are close to the point of complete saturation at the reinforcement. A lower water-cement ratio is desirable to prevent salt water from getting at reinforcement having 2 in. of cover.

Many things affect the dependability of permeability coefficients found by experiment. These data are presented only to indicate that what is normally considered good concrete is still within the danger area if moisture penetration alone is taken as a criterion. As will be emphasized later, the presence of oxygen is necessary for corrosion to proceed. The foregoing data should be kept in mind for the more specific problems to be discussed: freezing and thawing attack, corrosion of reinforcing steel, and chemical attack on cement paste.

FREEZING AND THAWING

The severest natural exposures in the United States are along the New England seacoast where the principal deteriorating agent is frost. There is little air-entrained concrete with a sufficiently long service record to provide reliable data. Judging from the performance of 12 x 12-in. test piling, the life of well-made 7-sack air-entrained concrete should be more than 20 years for this size specimen. The useful life of 5-sack concrete is much less. These results were from test piling of relatively small dimensions with reinforcement embedded only 1 to 1.5 in. It has been most difficult to distinguish the effects of freezing and thawing from those of steel corrosion in this exposure. However, the effects of mix proportions are entirely clear.

Lyse[1] explains at some length the problems faced in Norway in producing frost resistant concrete for marine structures. His recommendation, based on laboratory results, was to use a low water-cement ratio with what would normally be considered an excessive amount of entrained air (10 to 12 percent) in the concrete intended for exposure.

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However, there are questions about the validity of laboratory tests by freezing and thawing, particularly as applied to the performance of concrete in marine construction. Such tests, to be useful, must be accelerated with respect to time, and at least one of the factors involved, that of degree of saturation, does not lend itself well to controlled acceleration. As an example, drying the specimen before test generally increases its resistance to freezing and thawing during the relatively short period of an accelerated test but any effect of continual soaking, perhaps for 25 years or more, is lost. The proposal of Powers to measure the soaking time required before freezing produces dilation of the specimen, seemingly useful for other exposures, is hardly applicable, either, because the test cycle would have to be as long as the probable life of the structure.

Laboratory tests do not tell the complete story about the probable life expectancy of continuously wet concrete under freezing conditions. But one item is apparent—completely saturated cement paste (with air voids filled) will not stand freezing without disruption.

The aggregates must also be considered. Some may become susceptible to freezing damage when embedded in concrete before the cement paste becomes saturated, and in cases of frost-damaged concrete it is not always apparent which is at fault, the cement paste or the aggregate.

To summarize the state of knowledge on concrete for marine construction in severe climates, it seems best to first admit a considerable area of

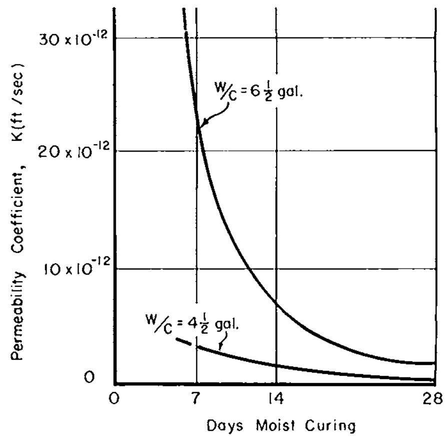

Fig. 1—Permeability of moist cured concrete

ignorance, particularly in the field of moisture content. A few items are of particular importance and should be emphasized in connection with frost resistance in sea water construction, the most severe exposure likely to be encountered by structural concrete.

1. It is assumed that all of the procedures of good workmanship, including mixing, placing, and curing, are being followed to the letter.

2. Aggregates must be "good." A good aggregate is probably best defined by its performance record in sea water construction but something of its suitability may be estimated from its physical properties. Ideally, it would be nonporous, but a porous material having a pore structure that would not become saturated might be just as satisfactory.

3. The concrete must be air-entrained.

4. The quality of the cement paste must be high, perhaps 4½ gal. of water or less per sack of cement to keep the rate of water penetration low.

CORROSION OF REINFORCING STEEL

Reinforcing steel rusts when it is exposed to moisture and oxygen. The presence of chloride speeds the reaction. In the process, the volume of corrosion products formed is more than twice the original volume of the affected steel and produces expansive forces much higher than the tensile strength the best concrete can withstand. This somewhat simplified picture of reinforcing steel corrosion will do for most engineers concerned with the practical side of concrete performance.

Concrete with a pH of 12 to 13 normally provides a favorable environment for reinforcing steel. The presence of chloride alters this greatly by diminishing the passivity of the normal environment.

The main problem is to keep moisture, chloride, and oxygen away from the reinforcing steel. The first move is to avoid putting chloride into the concrete in the first place, as it will get there soon enough from the sea water. Extensive corrosion of reinforcement at some installations in the Pacific as a result of sea water penetration of concrete has been privately reported.

Earlier in this report, mention was made of the rate of penetration of water under pressure into concrete. An example cited 1 year to penetrate 1 in. of concrete at 1 ft head and somewhat less than 5 years to get 2 in. of penetration. Moisture may also move within the concrete by a diffusion process, and, by a similar mechanism, chloride may move from an area of high concentration to one of low concentration. Cracks, bleeding channels, and other defects may affect moisture penetration. Laboratory experiments and field investigation show that moisture and chloride can penetrate rapidly enough to cause disruptive steel corrosion in a relatively short time—a few years, in some cases, in all but the best of concrete.

When moisture, chloride, and oxygen do get to the reinforcing steel, complex reactions can result. Corrosion cells are set up and the steel rusts and expands. Differences in salt concentration may cause conditions of severe corrosion and differences in temperature and in moisture content may contribute greatly to corrosion. One investigator in South Africa has gone so far as to recommend using salt in the concrete mix so that differences in salt concentration are less likely to occur after concrete has time to take up sea water. However, this recommendation seems highly questionable.

Out of this confusing picture of corrosion cells and factors that affect them, the builder of marine structures has one comforting fact to rely on: there is little to fear from corrosion if moisture, chloride, and oxygen are kept out.

CHEMICAL ATTACK ON CONCRETE BY SEA WATER

For the most severe exposures, deterioration of concrete by the forces of weathering is often so severe that chemical attack on cement paste by sea water is at least partly obscured. Furthermore, chemical attack is slowed considerably by low temperatures. It is in the warm climates that chemical attack assumes its greatest importance and it is here that chemical composition of cements has become of most concern. As with other problems of concrete durability, permeability of concrete is of utmost importance. It should be stated that a great many of the reported cases of sea water attack could have been averted if a high quality concrete had been used in the construction.

Even so, there are well documented cases of sea water attack, some of this in concrete in the high quality bracket. In the author's experience, cements that are susceptible to sea water attack are usually vulnerable to sulfate exposure though the rates of attack may not be the same. In all of the known cases, the vulnerable cements were those of high C_3A content but with only a general relationship between C_3A content and performance.

Not all concretes made with high C_3A cements have performed badly in sea water. Old structures in San Francisco Bay and others reported from South America have performed in an entirely satisfactory manner. In fact, much of the evidence against high C_3A cements rests on the performance of relatively small test specimens which cannot be expected to represent fairly the performance of full size structures.

It appears that chemical attack by sea water on concrete is a most complex subject. Much of the writing on the subject assumes that sea water attack is much the same as sulfate attack except that it is slower. It has been indicated that the presence of chloride in sea water should reduce the sulfate attack on C_3A to some extent at least. Perhaps this explains why the more than 2000 parts per million of sulfate in sea water is not more destructive. There is some basis for a belief that sulfate may attack the calcium hydroxide released during the hardening of cement as well as tricalcium aluminate. This would support a view long held by several authorities who do not favor high lime cements for sulfate exposure. As of now it cannot be substantiated by field observations.

As in the case of frost attack, a considerable area of ignorance must again be admitted concerning chemical attack on marine structures. However, there are several statements that can be made with confidence.

1. Chemical attack is more severe in warm exposures than in cold exposures.
2. Some cements are more susceptible to sea water attack than others (cements of Type II composition supply ample resistance if used in good quality concrete).
3. Permeability of the concrete is probably the most important factor involved.

MISCELLANEOUS PROBLEMS

Besides the three major considerations that must be given to the performance of concrete in marine structures, there are some minor ones. Although not usually encountered, they appear with sufficient frequency to warrant mentioning here.

One of these would be acid contamination sometimes found in harbor areas. Unfortunately for portland cement concrete, there is no known remedy and the best that can be done is to make the concrete as watertight as possible to delay the acid attack. The use of limestone aggregate has been advocated in this connection.

The alkali aggregate reaction is known to be aggravated by sea water exposure. Again, the use of highly impermeable concrete will greatly increase the time required for sodium from the salt to get at reactive particles.

What does prestressing do to the lasting properties of concrete in marine construction? At least it should prevent some of the structural cracking that may lead sea water directly to the reinforcement and to this extent it should be beneficial. On the other hand, it should have little or no effect on permeability, and the high tensile steel is usually more susceptible to corrosion than mild steel. Overall, any major effect seems doubtful.

SUMMARY AND CONCLUSIONS

In addition to the usual recommendations for producing high quality concrete, there are three items that should receive special consideration by the designer of marine structures, and a fourth that has been known to come into play on occasion:

1. Permeability is the property of concrete that should be of most concern. In freezing climates high impermeability delays saturation of the cement paste and to some extent it does the same for the aggregate and thus reduces damage due to frost. In mild climates it reduces the rate of chemical attack on cement paste and corrosion of reinforcing steel.

2. Air entrainment, a necessity in freezing climate, is also an aid in mild climate by slowing the rate of sea water penetration.

3. Depth of cover over reinforcing steel, important in all climates, should never be less than 2 in. Cover of 3-in. is preferred.

4. To avoid the occasional highly susceptible cement of high C_3A content, it is recommended that the cement have moderate sulfate resistance equivalent to that of ASTM Type II.

Careful adherence to the generally accepted recommendations for high quality concrete, with particular consideration for the four admonitions given above will insure sound, long lasting marine structures.

REFERENCES

1. Lyse, Inge, "Durability of Concrete in Sea Water," ACI JOURNAL, *Proceedings* V. 57, No. 12, June 1961, pp. 1575-1584.

2. Stanton, Thomas E., and Meder, Lester C., "Resistance of Cement to Attack by Sea Water and by Alkali Soils," ACI JOURNAL, *Proceedings* V. 34, No. 4, Mar.-Apr. 1938, pp. 433-464.

3. Hadley, Homer M., "Concrete in Sea Water; A Revised View Point Needed," *Transactions,* ASCE, V. 107, 1942, pp 345-358.

4. Stanton, Thomas E., "Durability of Concrete Exposed to Sea Water and Alkali Soils—California Experience," ACI JOURNAL, *Proceedings* V. 54, No. 9, May 1948, pp. 821-847; Discussion, No. 4, Part 2, Dec. 1958, pp. 848-1–848-18.

5. Cook, Herbert K., "Experimental Exposure of Concrete to Natural Weathering in Marine Locations," *Proceedings,* ASTM, V. 52, 1952, pp. 1169-1181.

6. Halstead, S., and Woodworth, L. A., "Deterioration of Reinforced Concrete Structures under Coastal Conditions," *Transactions,* South African Institution of Civil Engineers, V. 5, No. 4, Apr. 1955, pp. 115-134; Discussion, V. 5, No. 10, Oct. 1955, pp. 353-372.

7. "Factors affecting Durability of Concrete in Coastal Structures," *Technical Memorandum* No. 96, Beach Erosion Board, Office, Chief of Engineers, Department of the Army, June 1957.

8. Wakeman, C. M., Dockweiler, E. V.; Stover, H. E.; and Whiteneck, L. L., "Use of Concrete in Marine Environments," ACI JOURNAL, *Proceedings* V. 54, No. 10, Apr. 1958, pp. 841-856.

9. Tremper, Bailey; Beaton, John L.; and Stratfull, R. F., "Corrision of Reinforcing Steel and Repair of Concrete in Marine Environment: Fundamental Factors Causing Corrosion," *Bulletin* 182, Highway Research Board, 1958, pp. 18-41.

10. Gewertz, M. W., "Corrosion of Reinforcing Steel and Repair of Concrete in Marine Environment: Method of Repair," *Bulletin* 182, Highway Research Board, 1958, pp. 1-17.

11. Shalon, R., and Raphael, M., "Influence of Sea Water on Corrosion of Reinforcement," ACI JOURNAL, *Proceedings* V. 55, No. 12, June 1959, pp. 1251-1268.

12. Lea, F. M., and Watkins, C. M., "The Durability of Reinforced Concrete in Sea Water," *Research Paper* No. 30, National Building Studies, Department of Scientific and Industrial Research, London, 1960, 42 pp.

13. Tyler, I. L., "Concrete Exposed to Sea Water and Fresh Water," ACI JOURNAL, *Proceedings* V. 56, No. 9, Mar. 1960, pp. 825-836.

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Paper No. 2

Presents some of the rules and lessons learned from experience, as well as analyzing a few of the difficulties and problems encountered, in the placement of high quality concrete under water by the tremie method.

PLACEMENT OF TREMIE CONCRETE

By Ben C. Gerwick, Jr.

TREMIE CONCRETE IS CONCRETE placed underwater through a tube called a tremie pipe.* The lower or discharge end of the tremie pipe is kept embedded in fresh concrete, so that washing and segregation are substantially prevented. With proper mixes and placement, extremely high quality concrete can be obtained.

Tremie concrete is used for the following purposes:

1. Cofferdam or caisson seal
2. Mass underwater concrete
3. Underwater structures (bridges piers, drydocks, etc.)
4. Repairs to underwater concrete
5. Joining tunnel sections

Tremie concrete for structural purposes frequently is reinforced. It may be used in conjunction with precast concrete elements and with structural steel. It may be placed through any liquid lighter than fluid concrete, e.g., water or a bentonite suspension.

Principle

The aim is to introduce plastic concrete under the surface of the fresh concrete previously placed. Studies show that tremie concrete flows outward, pushing the existing surface outward and upward. As long as flow is smooth and the surface is not physically agitated, high quality concrete will result.

Mix

The proper mix is essential. The following are the author's recommendations:

Coarse aggregate—Use gravel, not crushed rock. For large masses, use 1½ in. maximum size. For smaller

*Placement of underwater concrete by buckets, which sometimes also is called tremie concrete, is not covered in this paper.

size, or where reinforcement or H-piles are to be embedded, use ¾ in. maximum size. For repairs, joints, etc., use pea gravel.

Fine aggregate—Use enough sand to insure workability; 42 to 45 percent, with 40 percent minimum.

Cement—A rich mix is essential; 7 sacks per cu yd for an average placement. Use an 8-sack mix for a small or complex placement; 6½ sacks per cu yd minimum on large masses.

Slump—The recommended slump is 6 to 7 in. with a 5 in. minimum and an 8 in. maximum.

Admixture—In many specific cases, use of a retarding and plasticizing admixture has given excellent results with and without entrained air.

Equipment

The tremie pipes are generally eight times the size of the coarse aggregate. Pipes 10 to 12 in. in diameter are most common, but tremie grout has been placed through a 2½-in. hose under pressure.

A hopper is attached to the upper end of the pipe (Fig. 1). The entire assembly is lowered and raised during placement so means for this must be provided. For thin seals (3 ft), the pipe assembly may be set with a crane and supported on a frame or blocking under the hopper. For thicker seals, the pipe assembly may be handled by a derrick or crane. A stand or frame with air hoists to raise the pipes gives the best control and eliminates jerks.

Engineers have invented, developed, and written about foot valves, cone valves, deflector valves, compressed-air rotary valves, and deflector plates at the bottom of the tremie pipe. These are neither necessary nor desirable. They generally cause plugs and laitance and have been abandoned in practice. The lower end of the pipe should be open. The object of these inventions was to prevent the sudden discharge of the concrete, but proper techniques give better control.

Tremie pipes on deep placements are long and, when raised, are hard to fill. As they are raised, sections are usually removed. The most common method is to use 10-ft sections which are unbolted and removed one by one as the pipe is raised. Good gaskets are essential. A quick, watertight coupler should be developed for this purpose. Telescoping tremie pipes and pipes with side gates also have been used with success.

The tremie pipe must be strong enough to withstand handling and lateral current pressures. Tremie pipes are usually made heavy enough to prevent floating even when empty.

CONSTRUCTION TECHNIQUE

Spacing of pipes

One tremie pipe usually serves to place about 300 sq ft of concrete surface. The spacing is usually 15 ft on centers, but this varies depending on the thickness of the placement, the congestion from piles and reinforcement, and the configuration of the structure. One pipe in a 34 ft diameter caisson and two in a 35 x 90 ft cofferdam have proven entirely satisfactory but must be considered special cases. Recent trends have been to increase the spacing, and this is made more

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practicable by admixtures. When such a large area is to be covered that it is impracticable to set enough tremies for simultaneous concreting, pipes may be leap-frogged ahead into the advancing slope. The pipe should not be dragged through the concrete.

Starting the placement

Since the tremie pipe must be initially filled with concrete, the pipe must be sealed. The best method is to use a wood plug with rubber gasket fastened on with light wire. As the pipe is lowered to rest on the bottom, the water pressure seals the gasket and the pipe is kept dry. Concrete is now placed in the pipe. To start the concrete flow, the pipe is raised about 6 in. off the bottom. The weight of concrete pushes out the plug, and the concrete flows out to form a mound around the end of the pipe. More concrete is fed into the pipe and is maintained at a suitable height in the pipe to balance the rate of flow.

For structural concrete, grout of the same mix, less the coarse aggregate, often is used for the first few batches. This grout also lubricates the pipe.

For deep placements (over 70 ft) where the buoyancy of the empty pipe may be a problem, a go-devil may be used. The pipe is set on the bottom, with the bottom open and filled with water. The go-devil, which is a traveling plug, enters at the top, and is pushed down with first loads of concrete. It must not move too fast or the rush of water out the tube will scour the bottom or displace reinforcing steel or forms. An inside wire line has been used to control the fall; many experienced contractors, however, prefer to control the fall by having the go-devil fit tightly and adding concrete at the proper rate to control its descent. An inflated rubber ball makes an excellent go-devil and is recoverable.

The tremie pipe should be kept buried in the fresh concrete from 1½ to 5 ft depending on the rate of flow and the head of concrete in the tremie pipe. Deeper embedment gives a flatter slope provided initial set has not taken place. Here again, retarding admixtures help.

The depth of concrete in the pipe should be just enough to balance the water head and maintain flow. On deep placements, this means the concrete surface in the pipe will be deep, and continuous sounding will be necessary for control.

Batches of concrete should not be dumped suddenly into the hopper. Buckets should be opened gradually to provide a smooth, continuous flow. Stops of over 5 min are undesirable.

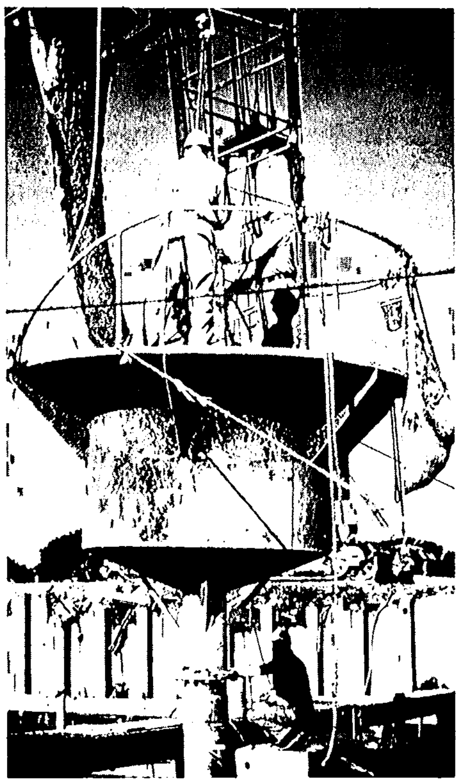

Fig. 1—Hopper attached to the upper end of the tremie pipe