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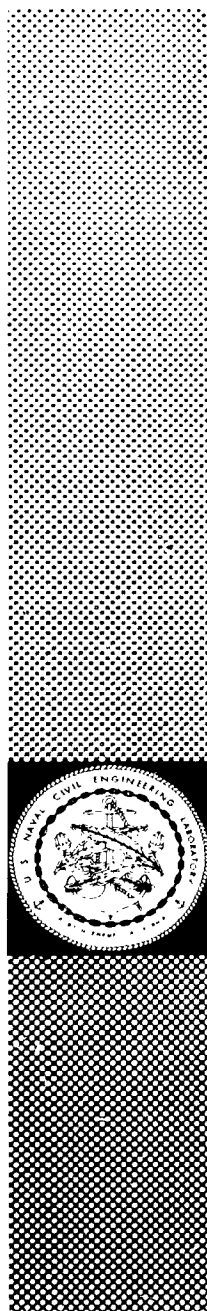
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294 576

Technical Report

294 576

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THE EFFECT OF SALT IN CONCRETE
ON COMPRESSIVE STRENGTH, WATER
VAPOR TRANSMISSION, AND CORROSION
OF REINFORCING STEEL

12 November 1962

NOV 1963

U. S. NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

THE EFFECT OF SALT IN CONCRETE ON COMPRESSIVE STRENGTH, WATER VAPOR TRANSMISSION, AND CORROSION OF REINFORCING STEEL

Y-R007-05-012

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by

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ABSTRACT

The information reported herein represents basic data about the effects of salt in concrete on compressive strength, water vapor transmission (WVT), and corrosion of the reinforcing steel. Variables included in the study are: (1) water-cement ratio, (2) diameter of specimen, (3) thickness of specimen, (4) percent concentration of salts — either sodium chloride or sea-water salts, and (5) environment of specimen — 20, 50, or 75 percent relative humidity at 73.4 F.

The investigation, partially carried out utilizing the NCEL-developed wet cup, has been in progress for approximately 1-1/2 years. An additional study of experimental walls subjected to sea-water spray was begun about one year ago and will continue for several years.

Sea-water salts at one time were thought to be detrimental to reinforced concrete, but this study shows that, if controlled, some salt is beneficial. A gain in strength, lower values of WVT, and no significant corrosion of mild steel are realized when a salinity of 25 grams of salt per kilogram of solution is established in the mixing water. Other results reveal that an electrical-resistance corrosion-rate detection probe appears to be a reliable device for measuring the degree of corrosiveness of any concrete environment to reinforcing steel; with or without salts, WVT varies directly with the water-cement ratio; thinner concrete specimens have somewhat higher WVT rates than thicker concrete specimens; with increasing salinities the effect of thickness upon WVT becomes more pronounced.

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The Laboratory invites comment on this report, particularly on the
results obtained by those who have applied the information.

INTRODUCTION

The purpose of the present investigation was to determine the effect of salt spray on portland-cement concrete and to determine the permissible amount of salt in the concrete mix. Specifically, it was desired to develop information about the effects of sodium chloride and of sea water on the strength and water vapor transmission of concrete, and the corrosive effect on the reinforcing steel. A previous investigation of water-vapor transmission of plain concrete utilizing the wet-cup system has been described by the authors both in a Naval Civil Engineering Laboratory report¹ and in a Journal of the American Concrete Institute.² Although more specific details about assembling wet cups with concrete specimens are given in References 1 and 2, the reader may obtain a good idea of the wet-cup system by referring to Figures 11 and 14. In all cups, the water in the liquid phase of the cup was distilled water. All saline waters referred to are the mixing waters for the concretes. Initially, the vapor phase portion of each cup was flushed out with ambient air.

The previous study employed concrete specimen disks of one diameter and one thickness. In contrast, the study reported herein includes disks of two diameters and of several thicknesses and involves a specimen series with varying concentrations of sodium chloride and a specimen series with varying concentrations of sea water in the mixing water. Also included is a unique but direct method for estimating the degree of corrosiveness of any concrete to reinforcing steel.

A collateral study of small, experimental reinforced-concrete walls to measure their durability to marine exposure, particularly as related to corrosion of the reinforcing steel, was initiated in May 1961 and will extend for several years. A description of this phase of the investigation and the observations to date are included in this report as a related study.

The figures and tables follow the text.

CONCRETE MIX PROPORTIONS

The concrete mixes were proportioned according to the mix design data of Table I. San Gabriel aggregate (described in Table I) was used in every case except where other aggregates are specified. Except for the reinforced-concrete walls, all

batches had a volume of 2.25 cubic feet, and were mixed in a pan-type mixer, with the following sequential operations:

1. Add gravel, sand, and cement.
2. Mix dry for 30 seconds.
3. Add water (73 F) in shortest time possible with mixer running.
4. Mix for 150 seconds, for a total mixing time (Items 2-4) of 3 minutes.
5. Take slump test: designed for 3 inches; actual slump . . . inches.
6. If slump is too low, add water and mix for 30 seconds.
7. Repeat slump test; final slump . . . inches.
8. Place concrete in molds in ASTM standard manner, except vibrate with spud vibrator.
9. Smooth off tops with wooden float.
10. Cover with metal plates and place in fog room.
11. After 24 hours, strip molds, number cylinders, and place in fog room.

Every effort was made to treat every batch and specimen in identical ways. The fresh concrete was vibrated with a 1-inch spud vibrator in three lifts, instead of rodding. Each lift was vibrated approximately 2.5 seconds.

Concrete for the walls was mixed in a revolving-drum mixer using a batch of approximately 6.0 cubic feet. The mixing procedure was similar to that used above except that the coral aggregate was saturated-surface-dry when placed in the mixer.

COMPRESSIVE STRENGTH

Sodium Chloride Series

Previous attempts to determine the compressive strength of concrete as a function of sodium chloride content were not as conclusive as required and made use of data for batches of concrete made at widely varying times for different purposes.¹ Series

of data, such as those shown in Tables II-a and II-b, can be satisfactorily obtained only by having an adequate supply of uniform materials and by batching in an orderly manner on successive days using the same personnel for each operation.

Figures 1-a and 1-b show graphically, for two different water-cement ratios, how compressive strength varies with increases in the sodium chloride content of the mixing water.* There is a pronounced and unmistakable optimum sodium chloride content for maximum compressive strength for each of the water-cement ratios. It is interesting to note that the optimum sodium chloride content for the two water-cement ratios is not a function of the ratio of NaCl to cement, as might be expected, but is more nearly a function of salinity (grams of salt per kilogram of solution, ‰) of the mixing water. The optimum salinity for maximum strength seems to be within the range of 30-36 ‰ for the two water-cement ratios.

Mixing water of the least salinity used (about 9 ‰) increased the slump from a design of 3 inches to a value of 5 inches. With increasing salinities, the slump increased to 8 inches. A constant slump of 3 inches undoubtedly would have required less mixing water, with consequently higher compressive strengths.

The rather sharp, abrupt changes in the curves of Figures 1-a and 1-b may be questioned; however, these changes are what the data indicate as the result of careful quality control in the fabrication and care of the concrete, which in turn is reflected by the low standard deviations for the 14-day strengths. Other natural phenomena showing such abrupt changes in relationships are not unknown.

Compressive strengths for the data in Tables II-a and II-b may also be expressed by the following data model involving the various factors observed to affect strength:

$$\begin{aligned} S = & 7929.7 + 863.7N - 1428.7N^2 + 326.2N^3 - 6327.2 W/C \\ & + 1029.1T - 248.9NT + 12.1N W/C - 1031.3T W/C \\ & + 379.0NT W/C \end{aligned}$$

where S = compressive strength, psi

N = sodium chloride by weight of fresh concrete

T = natural logarithm of age in days

W/C = water-cement ratio

* Sodium chloride, U.S.P. granular; F.W. = 58.45, dissolved in the mixing water.

This data model was obtained by a least-squares fit to the data in Tables II-a and II-b. As an example of the meaning of this formula, consider a case where N is 0.6, T is 2.639 for 14 days age, and W/C is 0.444. For this combination of factors, S may be calculated to be 6577 psi and compared with the observed value of 6640 psi. Curves for this data model are compared with observed data plotted in Figure 1-c.

The presentation of this data model is not a rejection of the peaked curves of Figures 1-a and 1-b. On the contrary, this model should be used only to approximate compressive strength as a function of the factors given and only within the range of the data and under the conditions specified for this experiment.

Sea Water Series

The chemical composition of hypothetical sea water is as follows:

Composition of Sea Water ³		Combinations of Ions in Sea Water ⁴	
<u>Ion</u>	<u>‰</u>	<u>Salt</u>	<u>‰</u>
Cl ⁻	18.980	NaCl	23.477
SO ₄ ⁻⁻	2.649	MgCl ₂	4.981
HCO ₃ ⁻	0.140	Na ₂ SO ₄	3.917
Br ⁻	0.065	CaCl ₂	1.102
F ⁻	0.001	KCl	0.664
H ₃ BO ₃	0.026	NaHCO ₃	0.192
Na ⁺	10.556	KBr	0.096
K ⁺	0.380	H ₃ BO ₃	0.026
Mg ⁺⁺	1.272	SrCl ₂	0.024
Ca ⁺⁺	0.400	NaF	0.003
Sr ⁺⁺	0.0085	Total	34.482

Note: ‰ = grams per kilogram of sea water. The salinity (‰) of this hypothetical sea water is 34.325, as shown in Reference 3.

On the basis of work by the International Commission (Torch, Knudson, and Sorenson, 1902), salinity is defined as the total amount of solid material in grams contained in one kilogram of sea water when all the carbonate has been converted to oxide, the bromine and iodine replaced by chlorine, and all organic matter completely oxidized.⁵

Table III and Figure 2 show compressive strengths of concrete versus different concentrations of sea water in the mixing water. Sea water from the NCEL sea-water well, with a salinity of 31.32‰ (determined by chemical analysis), and distilled water were proportioned by weight. For example, in a 20 percent sea-water concentration, 20 percent of the mixing water by weight is sea water.

Sea-Rite salt was added to sea water in order to obtain concentrations in excess of 100 percent. Sea-Rite salt is a simulated sea-salt mix containing elements found in natural sea salt in quantities greater than 0.004 percent. It is a granular, colorless salt.

Figure 2 shows a general increase in strength of concrete with age and with increases in concentration of sea water up to 200 percent strength. Data for 546 days age became available after Table III was made up. The values for this age for batches 1 through 10 are respectively 5250, 5350, 5600, 5410, 5440, 5840, 5560, 5440, 5440, and 5690 psi. In general, these figures show that compressive strength has continued to increase after 364 days age. Unlike sodium chloride water, sea water had virtually no effect on slump of fresh concrete even with a salinity up to 63‰ (See Note to Table III).

The characteristics of the curves in Figure 2 are somewhat unusual. In view of the rather pronounced characteristics of curves in Figures 1-a and 1-b, the authors believe there is a certain justification for the peculiar curves of Figure 2. The low values for standard deviation in Table III lend some support to this belief. Moreover, the peak condition in Figure 2 occurs at nearly the same salinity as it does in Figures 1-a and 1-b. To determine if Sea-Rite salts alone in the mixing water would have the same effect, concrete cylinders were fabricated for strength determinations employing Sea-Rite salts in distilled water without the use of sea water (Table IV and Figure 3). Figure 3 shows that the data are similar in magnitude and general trend to the data in Figure 2; however, the trends are much more nearly linear in Figure 3.

Depth-of-Cover Series

Concretes with two different water-cement ratios were fabricated for studies of water vapor transmission and steel corrosion. The compressive strengths in psi of these concretes for various ages in days (d) without additives or admixtures are as follows:

Batch No.	W/C	7d	14d	28d	Std Dev	56d	112d	224d	364d
					28d				
S4L-2	0.702	2280	2820	3680	95	4310	4890	5050	5200
S4H-2	0.444	4630	5630	6470	175	7520	8070	8570	8950

The above compressive strength values are for 4-inch-diameter by 8-inch cylinders. Each value represents the average for three cylinders except for tests at 28 days, for which nine cylinders were used. Cement was Colton Type II; average slump was 3 inches. All cylinders were cured in 100 percent relative humidity (RH) at 73.4 F. (Tolerances for all controlled environmental rooms were ± 2.0 percent RH and ± 2.0 F.)

Wall Specimens

Twelve small reinforced-concrete walls were cast using concrete described in Table I. The walls are described further on in this report under "Corrosion of Steel." Table V and Figure 4 show the results of compressive strength versus age for two water-cement ratios for each of three aggregates, the characteristics of which are presented in Table I. Except for 28-day specimens, cylinders for compressive strength were field-cured on concrete pads on either side of the walls (land side and sea side). The values in Table V shown for the land side received no sea-water spray; the ones shown for the sea side received sea-water spray. Values for the sea side and land side generally were in such close agreement through 224 days age that average values were plotted in Figure 4.

It should be noted in Table V that for 448 days age, in general there are significant differences in compressive strengths for storage conditions (land side versus sea side). At this age, compressive strengths of cylinders receiving sea-water spray are all lower than corresponding cylinders protected from sea spray. For earlier ages, no strong pattern was established.

The effect of poor-quality aggregate on strength of concrete is shown by a comparison of strength of concrete incorporating Guam reef coral with the concrete incorporating superior aggregates such as San Gabriel and Eniwetok reef coral.

WATER VAPOR TRANSMISSION

Sodium Chloride Series

Table VI shows water vapor transmission (WVT, grains per square inch per day) values for concrete disks containing varying percentages of sodium chloride. The data are also shown graphically in Figure 5. It may be observed that there is a rapid decrease in WVT with increasing salinity of mixing water. WVT reaches a minimum value at a salinity of about 70‰; however, with further increasing salinity, the WVT values remain virtually constant.

Table VII shows WVT values for specimen thickness studies and relative humidity studies for low-strength concrete ($W/C = 0.702$) containing 1.5 percent sodium chloride by weight of fresh concrete. This percentage of sodium chloride has significance because a large number of cores drilled from concrete structures on Pacific Ocean atolls contained chloride salts in this equivalent amount.¹ For the structures sampled, there was no mix design information available and it was therefore not possible to determine the amount of salts on a salinity basis or on a salt-cement ratio basis.

Table VIII is similar to Table VII, except that the concrete is high strength ($W/C = 0.444$), and there is no salt in the concrete. Data for both tables are plotted as Figure 6. Comparison of Figures 6-a and 6-b shows that the effect of the salt in the low-strength concrete is to reduce its WVT values close to the level of those for the high-strength concrete without salt at the same respective ambient relative humidities.

Table IX shows WVT values for specimens made in connection with a depth-of-cover corrosion study. Table VIII and Table IX-b are comparable and show similar results. Data of Tables VII, VIII, and IX show slightly increasing rates of WVT with decreasing thicknesses of specimens. Table IX also shows that WVT varies directly with water-cement ratio; i.e., high water-cement-ratio concrete has higher WVT values than does low water-cement-ratio concrete.

Sea Water Series

WVT values for concrete disks containing varying percentages of sea water are shown in Table X. Figure 7 shows variations in WVT versus salinity. From a comparison of Figures 7 and 5, it may be observed that the nearly horizontal portion of the curves begins at a salinity of only 25.06‰ for sea water and of 70.5‰ for sodium chloride. Figure 7 also shows the effect of thickness of specimen. At zero salinity, the thicker specimens show only slightly lower WVT rates than do the thinner specimens; however, with increasing salinity, the thicker specimens show much lower WVT.

Although not conclusively resolved, Figure 8 shows some limited evidence to indicate that specimens with larger cross-sectional areas have somewhat lower WVT rates than similar specimens with smaller areas.

Figure 9 shows WVT as a function of ambient relative humidity. This figure shows that if no sea water is present in the mixing water, WVT is virtually independent of specimen thickness, and if it is present, the thicker specimens show a greatly reduced WVT rate compared to the thinner specimens. The dotted lines are assumed to be reasonably correct (refer to Table X, for Figures 7, 8, and 9).

Kwajalein Coral Concrete

Table XI shows WVT rates for two 6-inch-diameter concrete cylinders made by the Corps of Engineers on 19 September 1960 (PST). These cylinders were field-cured at Kwajalein for 24 hours at an average relative humidity of 73 percent. They were then sealed in cardboard containers and delivered by air to NCEL on 26 September 1960 and placed in a 100 percent RH, 73.4 F room until 17 October 1960, when they were cut into disks and emplaced in wet cups in a 20 percent RH, 73.4 F room. A 2-inch-thick disk and a 4-inch-thick disk were cut from each of the cylinders. The pair of 2-inch specimens show remarkably close WVT rates; however, they are higher than any values obtained at NCEL for other concretes. WVT rates for the 4-inch specimens agree reasonably close and are in line with values for other concretes. Portions of ground concrete samples from each of the two specimens were dried, weighed, extracted in a soxhlet apparatus for 96 hours, and analyzed spectrophotometrically for sodium chloride. The average sodium chloride content was found to be 0.09 percent by weight of hardened concrete.

The coral aggregate was hard reef coral with a maximum particle size of 1.5 inches. The aggregate was washed with fresh water to reduce the salt content to a minimum. The concrete incorporated an air-entraining agent and was made with Lion Type II cement from Japan. The water-cement ratio was 0.554 and the slump was 3 inches. Air entrainment was 3.5 percent. The mixing water was fresh potable water.

WVT of Wall Specimens

Table XII shows WVT rates for specimens fabricated at the time the walls were cast. The specimens were fabricated from closely controlled batches mixed in the pan-type mixer (see p 2). Values for the SG aggregate specimens are slightly greater than for other NCEL specimens of the same aggregate. Values for the ENR high-quality coral aggregate specimens are the lowest of the three different aggregates. The GMR poor-quality coral aggregate specimens show distinctly higher WVT rates than either the ENR or SG, apparently reflecting its poor quality in high WVT values as well as in low comparative-strength values.

WVT Curve Characteristics

Wet-cup specimens (disks) in this study were cut from fog-cured cylinders using a masonry saw. From the time the concrete was taken from the fog room until it was emplaced in a wet cup and stored in a constant-humidity room, not more than two days elapsed. Consequently, the initial weight loss of a wet cup was of the same nature as the weight loss of any saturated concrete specimen during drying in a constant RH. As water evaporates from the specimen to some unknown value, the specimen begins to pick up water vapor from inside the cup and eventually transmits it out the drier side. Naylor⁶ has shown that the water from the cup does not pass through concrete as a gas in any significant amount.

After some transitional period of water flow, a steady-state transmission rate of water is established. Generally speaking, this steady state of water transmission versus time was found to be a straight-line relationship. A very few specimens located in the 20 percent as well as in the 75 percent RH (73.4 F) room exhibited a slightly curvilinear relationship in the so-called steady-state flow range, with the slope of the tangent to the curve decreasing with time. Almost all specimens in the 50 percent RH room in the present study showed this slightly curvilinear relationship. The reason for this is not completely clear. A new 50 percent RH room was used in this study, and one possible explanation is the precipitate on the surface of the specimens from the extremely hard water used to maintain humidity in this room. Over a period of 18 months, all horizontal surfaces were covered with a significant coating of white powder. This coating was definitely traceable to the water used to maintain ambient relative humidity. It is quite possible this substance has acted to lower the WVT rates of the specimens in the 50 percent RH room in the same way that NaCl or sea water in the concrete did. The WVT graphs nearly all show that these values are lower than might be expected in relation to values for the 20 and 75 percent RH rooms. The WVT values for the 50 percent RH room were obtained by taking a chord of the relatively steady-state flow portion of each of the curves. This is believed to be a realistic compromise.

An empirical equation of the relationship of water loss versus time which appears to fit the data, such as that illustrated in Figure 12, is:

$$w = (a + bt)(1 - e^{-ct})$$

where w = weight loss of wet cup

a = intercept value on w -axis

b = slope of linear portion of curve

t = time

$e = 2.718$

c = coefficient accounting for early curvilinear portion of relationship of w and t

Asymptotically as time goes on (i.e., as t becomes quite large), this equation is well approximated by:

$$w = a + bt$$

so that $b = dw/dt$ is the asymptotic WVT rate.

In the previous study,^{1, 2} water vapor transmission was defined by the formula:

$$WVT = \frac{lW}{At}$$

where l = length of flow path or thickness of specimen, inches

W = weight of vapor transmitted, grains

A = area of cross section of specimen, square inches

t = time during which vapor transmission occurred, days

This expression seemed reasonable at the time; however, this study shows that WVT is virtually independent of specimen thickness and therefore, l , must be deleted in the above equation so that

$$WVT = \frac{W}{At}$$

Excluding vapor and ice as significant modes of moisture migration through concrete in the tests described herein, there remain four possible modes of moisture migration: chemical compound, adsorbed, liquid, and dissolved. If the true mechanism of moisture migration could be disclosed, a great deal of understanding about the behavior of concrete would result.

WVT Hysteresis

Hysteresis is herein defined as a reduction in WVT caused by aging or a previous exposure of the specimen.⁷ For example, a number of specimens were first allowed to dry naturally in each of the three RH rooms to nearly constant weight. These specimens, at equilibrium with their ambient environments, were then emplaced in wet cups, and water loss versus time was determined. Although insufficient time has passed to provide conclusive data, an example is shown in Figure 10. To date, the three specimens show WVT values of 0.128, 0.095, and 0.086 grains per square inch per day respectively for 20, 50, and 75 percent RH. If these values are compared with Figure 7, it may be noted that they are considerably lower than the curves of Figure 7 indicate for a salinity of 6.26 ‰.

Vented Cups

With the exception noted below, all of the wet cups in the present as well as in the previous study^{1, 2} were unvented. That is, there was no opening directly into the vapor phase portion of the cup. Consequently, as water was transmitted from the cup through the concrete, partial vacuums may have developed and altered the vapor pressure.

According to Sears,⁸ a change in total pressure changes the vapor pressure. For example, an increase in the total pressure always increases the vapor pressure; if more of an inactive gas is pumped into a container, more of the liquid in the container evaporates, contrary to what might be expected. The change in vapor pressure is very small compared with the change in total pressure.

In order to assure equal total pressures internal to and external to the cup, vents were installed in two cups as shown in Figure 11. Companion specimens were placed in the vented cups and in unvented cups. The curves of weight loss versus time for these four cups are shown in Figure 12. This figure shows that for the first 100 days there are no significant differences between the vented and unvented cups. Also, it shows no significant differences between specimens 1 inch and 2 inches thick. Additional time may be required to verify this. A control vented cup with acrylic top (instead of concrete) showed no significant weight loss.

CORROSION OF STEEL

Corrosion-Detection Probe

The use of a Corrosometer, an electrical-resistance corrosion-rate detection probe and metering device, to measure directly the degree of corrosive environment of reinforcing steel occurred to the authors. The efficacy of the Corrosometer and probes as a corrosion-detection device had been investigated previously.⁹ Consequently, probes fabricated of mild steel of the type shown in Figure 13 were obtained for this purpose. The phenolic-resin potting cylinder shown in this figure was made just long enough to extend about 1/2 inch into the concrete. The probes were inserted into the fresh concrete through a hole in the wall of the cylindrical steel mold of the concrete cylinder. In order to do this, a cap was fastened across the top of the cylinder immediately after the concrete was cast. The cylinder was laid on its side, the plug unscrewed from the hole, and the probe inserted. The cylinder was then replaced in its as-cast position and placed in the fog room. The exterior end of the probe was protected by a small rubber sheet fastened around it.

The operation of the Corrosometer is based on the fact that the electrical conductivity of most metals is very great, while the conductivity of nonmetals is negligible by comparison. As the corrosion process converts metal into nonmetal, the electrical resistance of a piece of metal thus increases. The Corrosometer circuit utilizes this change of resistance to indicate the extent of penetration in an exposed metal specimen as corrosion proceeds on its surface.

The resistance of this exposed specimen is not measured directly by the Corrosometer circuit. Instead, a second specimen, made from the same metal or alloy, is connected in series with the first and the two specimens are made part of a bridge circuit. The second specimen is covered with a highly corrosion-resistant coating and so retains its original cross section and resistance. The ratio of the resistance of the exposed specimen to that of the covered specimen is then determined. Changes in this resistance ratio are translated directly into units of corrosion by the meter circuit.

By using a circuit which measures only the ratio of the two resistances, the measurements are made essentially independent of the current used to energize the bridge. Likewise, because temperature changes affect the resistance of both exposed and covered elements in the same manner, the resistance ratio and the meter reading are independent of the temperature of the environment. It is this self-compensating feature of the bridge arrangement that permits the high degree of precision and sensitivity attained by the Corrosometer.

Sodium Chloride Series

Cylinders with probes were fabricated for concretes with different percentages of sodium chloride. Two-inch-thick disks were cut with the probe in the middle and emplaced in wet cups as shown in Figure 14. In order to place the disk with probe in an acrylic cup, a vertical strip was removed from the wall of the tube and cemented in place after the disk had been placed in the cup. The joint above the probe may be seen in Figure 14. The cups were stored in 20 percent RH at 73.4 F.

Table XIII and Figure 15 show results of the cups with concrete containing sodium chloride. Figure 15 shows that a salinity of 70.5‰ is most favorable for the maximum rate of corrosion. The pattern of corrosion versus salinity is very similar to that shown on page 131 of Reference 10, and is thus verified.

Sea Water Series

A similar set of concrete disks with probes incorporating varying percentages of sea water in the mixing water was also prepared and emplaced in wet cups stored in 20 percent RH at 73.4 F. Table XIV and Figure 16 show corrosion rates for these probes. Figure 16 indicates that no significant corrosion occurs up to a salinity of 25‰; thereafter, the corrosion rate increases markedly. The most favorable salinity in sea-water solutions for the maximum corrosion rate is evidently beyond 63‰ (200 percent sea water).

Depth-of-Cover Series

A series of 6-inch-diameter by 6-inch-thick concrete specimens for each of two different water-cement ratios (0.444 and 0.702) were prepared with corrosion-detection probes. No salt was used in the concrete. The specimens were emplaced in wet cups and stored in 50 percent RH at 73.4 F. Measuring from the bottom surface of the specimen, the probes had depths of concrete cover of 1, 2, 3, 4, and 5 inches. A single probe was placed in each concrete disk, and each concrete disk was made in duplicate (each series had 10 cups). A time period of 400 days has shown no measurable corrosion in any of the 20 cups involved. WVT values of these cups are represented by cup No. U750 and cup No. U758 in Table IX.

Experimental Walls

In order to simulate a marine environmental exposure such as that encountered by a building on a tropic atoll, small walls of reinforced concrete were built and sea-water spray was applied daily. The details of the concrete mixes and their ingredients are shown in Table I.

The variables to be investigated are shown in Table XV. The three types of aggregate described in Table I and two water-cement ratios (0.444 and 0.702) were used, and two different reinforcing-steel arrangements were employed. Each of the steel arrangements had the same grid spacings. The only difference in arrangement was that in one case the mild-steel bars were insulated from each other with electrician's plastic tape and tied together with nylon fishing cord, as shown in detail in Figure 17. In the other arrangement all steel bars were tack-welded together at the point of contact. These arrangements were to permit the investigation of corrosion of individual steel bars as compared to the corrosion of an interconnected grid of steel bars. Two depths of steel cover were also included as variables, the depth being measured from the outer surface of the concrete to the nearest surface of the steel. It was desired to eliminate all external entries, such as tie-wire and bolt holes, through the concrete to the steel as unknown variables; therefore, concrete blocks for the particular kind of concrete to encase the steel grids were precast with wire loops embedded in each block for securing the steel grids. These are shown in Figure 18. In this way there were no steel wires going from the steel grid through the concrete to the outside. The use of spacer blocks was avoided for the same reason, and the grids were held in place vertically by means of temporary holding devices which may be seen in Figure 19.

It was desired to hold the water-cement ratio for the high-strength concretes equal throughout and that for the low-strength concretes equal throughout. It was further desired to design all concretes for identical consistencies as measured by the slump test. This required a greater amount of water and cement for the coral aggregate concretes than for the San Gabriel aggregate concrete.

While the slump test has for a number of years appeared to be an excellent measure of consistency for San Gabriel aggregate concrete, coral aggregate concretes do not respond quite so uniformly to the slump test. Although distribution of aggregate by percentage was approximately the same for all batches, the coral concretes appeared too harsh, compared with the San Gabriel aggregate concrete. The slumps in inches for the various concretes used in the walls are tabulated below:

<u>Wall No.</u>	<u>Min</u>	<u>Avg</u>	<u>Max</u>	<u>W/C</u>	<u>Aggregate</u>
6, 9	4-1/2	6-1/2	8	0.702	GMR
2, 8	1	2	3	0.702	SG
3, 10	1-1/2	5	6-1/2	0.702	ENR
1, 11	1/2	1-1/2	3	0.444	GMR
4, 12	3	3-1/2	4-1/2	0.444	SG
5, 7	3	4-1/2	6	0.444	ENR

The apparent harshness of the coral concretes was further demonstrated in the construction of walls when the forms were stripped at 7 days age. For example, Figure 20 shows a typical San Gabriel concrete wall immediately after the forms were stripped and Figure 21 shows a typical coral concrete wall after the forms were stripped. Although the apparent consistencies were the same, the coral concretes did not flow down into the foundation of the wall as well as did the San Gabriel concrete. This occurred even though the spud vibrator was applied internally to the concrete as well as externally to the form.

During the first 7 days of curing, the forms of each wall remained in place, and burlap was placed across the top of the walls for moisture retention. The burlap was kept wet by means of water spray. On the 7th day, after the forms were stripped from each wall, the voids, as shown in Figure 21, were filled in with appropriately designed fresh concrete. On the 8th day each wall was rubbed down with mortar employing the same fine sand that had been used in the concrete mix for each particular wall. The walls were then completely wrapped in burlap, which was kept soaking wet. On the 28th day after placing, the walls were stripped of burlap, and 3-inch-diameter by 6-inch concrete cylinders for determining compressive strength were placed along the walls as shown in Figure 22. When the last walls to be cast (GMR) had achieved an age of 30 days, the first application of sea water was made to the seaward side of each wall on 15 June 1961 for a 5-minute interval once each day at 0830. The sea water was obtained from the NCEL sea-water well.

When the GMR walls were 29 days old, the first set of monthly photographs was taken for the purpose of a statistical evaluation of time-dependent deterioration. On 7 July 1961, considerable efflorescence was noted on walls 6, 9, and 11. Outside of this, no deterioration of the walls has been noted as of June 1962. The tests will continue.

GENERAL DISCUSSION

Strength

A contributing factor to deterioration of concrete structures on tropical atolls is believed to be the presence of foreign salt. When hardened concrete is chemically analyzed, the chloride content is usually expressed in combination with sodium. For this reason, the effect of sodium chloride was of interest. The actual combination of chloride ions with other metals in concrete is very difficult to estimate accurately.

In a marine environment, sea water is the source of a significant amount of foreign salt found in concrete. There may be sea-water salts in the aggregate, and sea water may be used in the mixing water. Also, in tropical atolls, sea spray on

concrete structures continuously adds salt to the hardened concrete. This salt may be carried into the concrete by the penetrating saline solution. A satisfactory external water-repellant coating on the concrete would prevent sea-spray salts from penetrating the concrete.

For the average maximum of 1.5 percent sodium chloride by weight of hardened concrete found in tropical concrete, the corresponding salinity for concretes in this study is 159‰. Roughly this would be equivalent to the salts in 4 kilograms of sea water reduced to 1 kilogram of saline solution. It is very difficult to see how this concentration of salt could get into the concrete at the time of mixing; however, a concrete structure exposed to sea spray might accumulate this concentration of salts over a period of years. Since the latter can be prevented, interest is mainly in the amount of salt permissible at the time of mixing.

Neither sea water with a salinity up to 63‰ nor sodium chloride water with a salinity up to 36‰ have adverse effect on compressive strength of concrete up to one year as determined in this study. The general conclusion of Lea and Watkins,¹¹ emerging from their study of reinforced-concrete piles exposed to sea-water action for up to 23 years, was that the primary cause of deterioration of the piles was corrosion of the reinforcement and not the disintegration of the concrete from chemical or physical effects of the salts in the sea water. The senior author (Griffin) of the present study, from his own observations in the islands of Canton, Eniwetok, Kwajalein, and Midway, found no reason to disagree with this thesis.

Lea outlines prime essentials for sea-water concrete on page 552 and 553 of Reference 12. He states that sea water may be used for mixing plain concrete for sea-water structures except for high-alumina cement. However, high-alumina cement concrete made with fresh water has greater durability when exposed to sea water than does portland cement. The durability of pozzolanic cements was lower than for high-alumina cement and higher than for portland cement under the same conditions.¹¹

Water Vapor Transmission

The use of lower water-cement ratios decreases WVT rates. The use of sodium chloride water with salinities up to 70‰ and of sea water with salinities up to 25‰ decreases WVT values.

Corrosion of Steel

For either sodium chloride water or sea water in concrete, salinities up to 25‰ do not produce highly significant corrosion rates. For sodium chloride water, salinities in excess of about 160‰ do not produce highly significant corrosion rates. Salinities between 25‰ and 160‰ of sodium chloride solutions in concrete do produce highly significant corrosion rates. This pattern may be true for sea-water concentrations also; however, the full pattern was not developed in this study.

Summary

It is apparent that some salt is beneficial to reinforced concrete. Concrete with mixing water with a salinity of 25‰, corresponding to 80 percent sea water and 20 percent fresh water by weight, shows a gain in strength, lower values for water vapor transmission, and no significant corrosion of mild steel. Additional salt gain in marine structures from sea spray should be prevented by use of water-repellant exterior coatings.

The experimental walls should reveal the extent of salt gain from sea-water spray and the length of time for corrosion of the reinforcing steel to manifest itself either by an appearance of rust stains or by cracking of concrete caused by a formation of corrosion products on the reinforcing rods.

FINDINGS

A. Compressive Strength

1. Concrete incorporating sodium chloride in the mixing water shows an optimum salinity of about 36‰ for maximum compressive strength.
2. Depending upon age of concrete, relatively high concentrations of NaCl are permissible before strengths less than those for zero salinity result.
3. Natural sea water does not deteriorate plain concrete nor does it cause any reduction in strength. On the contrary, strength is generally increased with up to double the normal concentration of salts in sea water.

B. Water Vapor Transmission

1. With increasing sodium chloride salinity of mixing water up to 70‰, and of sea-water salinity up to 25‰, WVT is reduced to its minimum. With further increasing salinities, WVT is almost constant.
2. With increasing salinities, the effect of the thickness of the specimen becomes much more pronounced, with thicker specimens showing much greater reductions in WVT than do thinner specimens.
3. With or without salts, WVT varies directly with the water-cement ratio. Concretes with higher water-cement ratios have higher WVT values.

4. Without salts, thinner concrete specimens have somewhat higher WVT rates than do thicker specimens. Indications are that 6 inches may be a limiting thickness beyond which greater thicknesses do not further decrease WVT significantly.
5. Concrete made with poor-quality aggregate (GMR) shows higher WVT values than concrete made with high-quality aggregate (SG and ENR), other factors being equal.
6. The present study does not confirm nor — probably because of the situation described for the 50 percent RH room — does it completely negate an earlier finding¹ that an ambient relative humidity of 20 or 50 percent at 73.4 F has no significant effect on WVT compared with experimental variability.
7. No mathematical relationship could be established to predict water vapor transmission for specimens of identical concrete but with different thicknesses.

C. Corrosion

1. The electrical-resistance detection probe appears to be a reliable device for measuring the corrosiveness of concrete to reinforcing steel.
2. Concrete incorporating sodium chloride in the mixing water shows an optimum salinity of 70‰ for maximum corrosion of steel.
3. Sea water with a salinity of 25‰ or less in the concrete mixing water does not significantly corrode steel.

GENERAL CONCLUSION

A small amount of sea-water salts is beneficial to concrete. At a mixing-water salinity of 25‰, strength is improved, WVT is minimized, and corrosion of mild steel is not significant.

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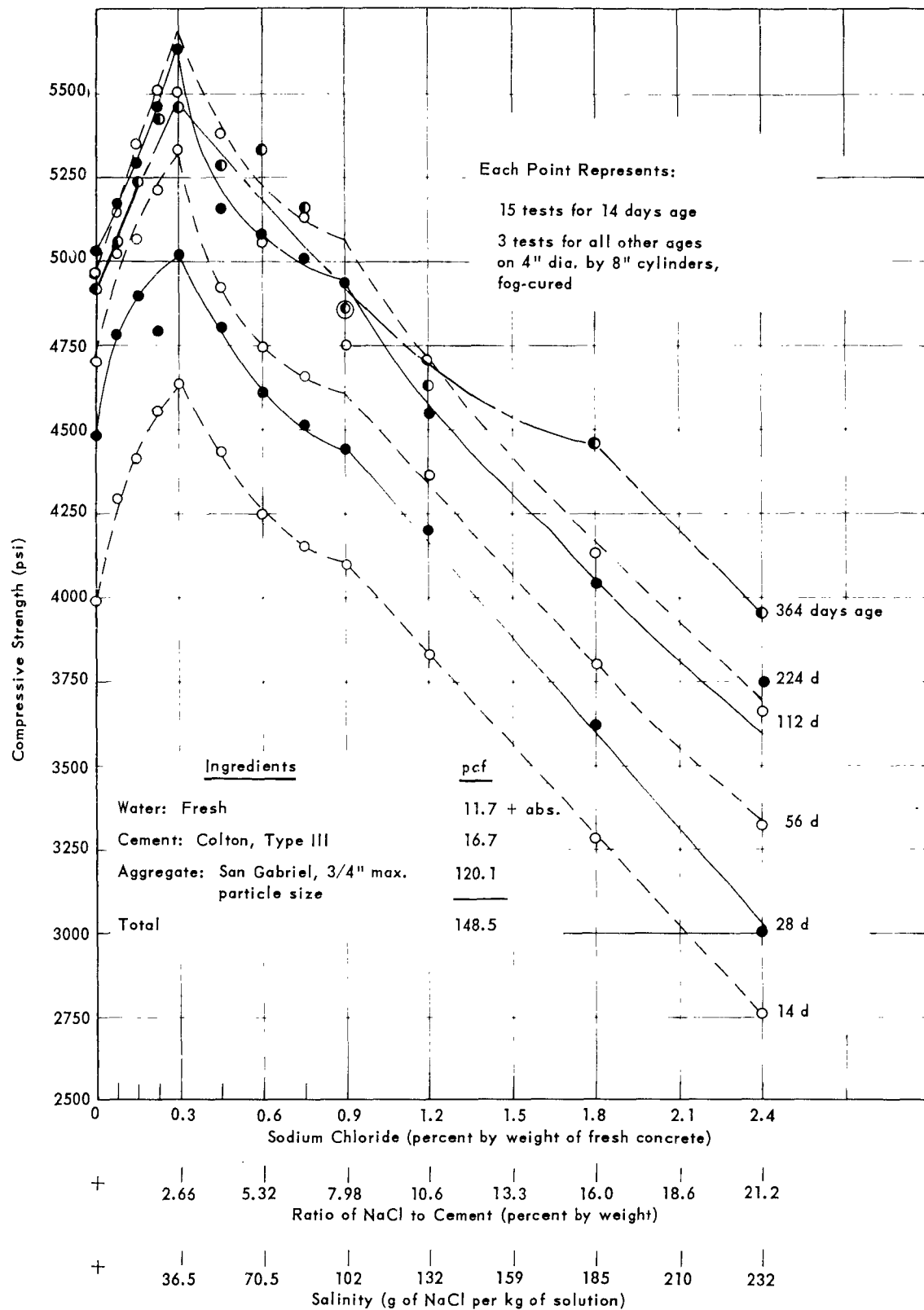


Figure 1-a. Compressive strength versus sodium chloride content for W/C = 0.702.

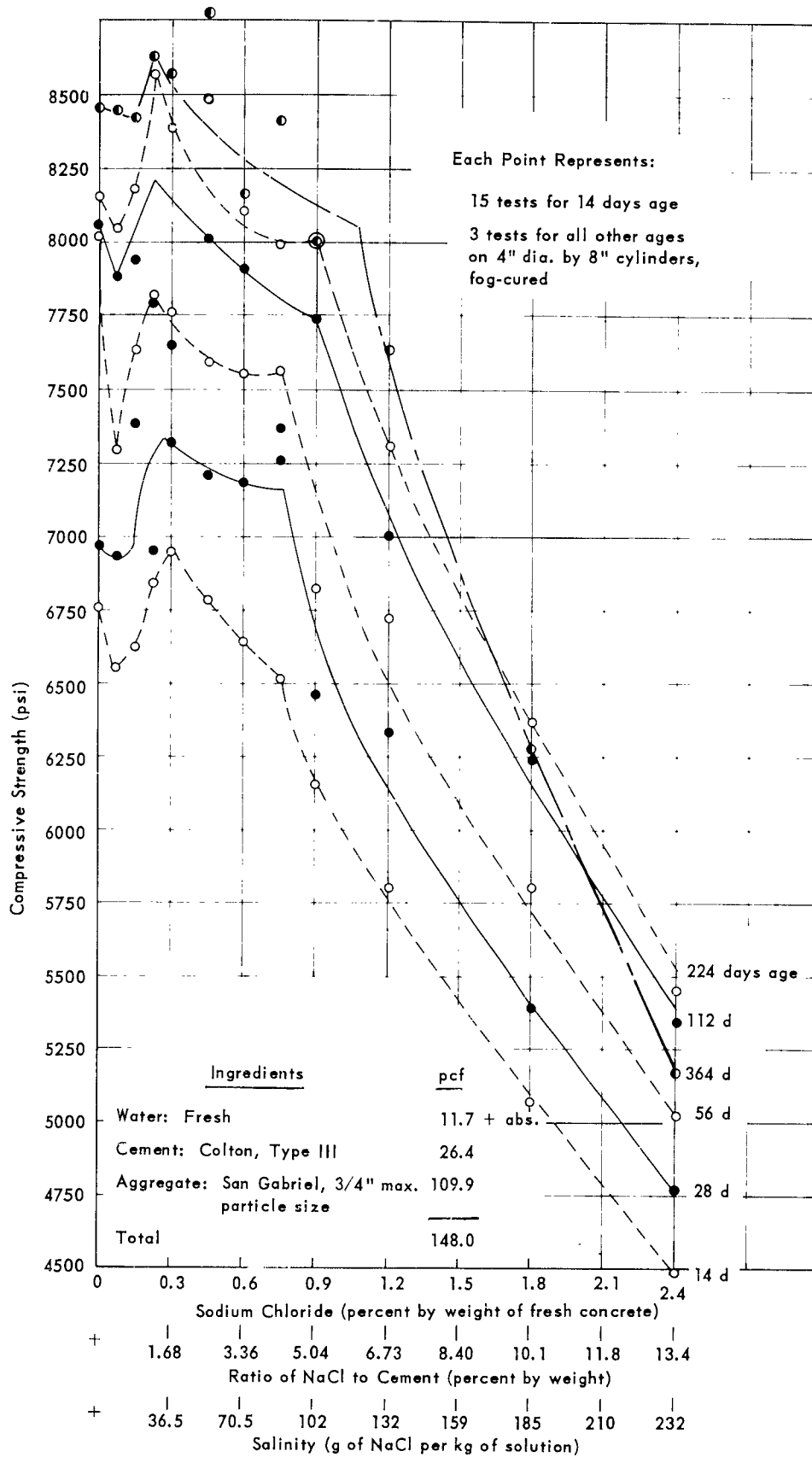


Figure 1-b. Compressive strength versus sodium chloride content for W/C = 0.444.

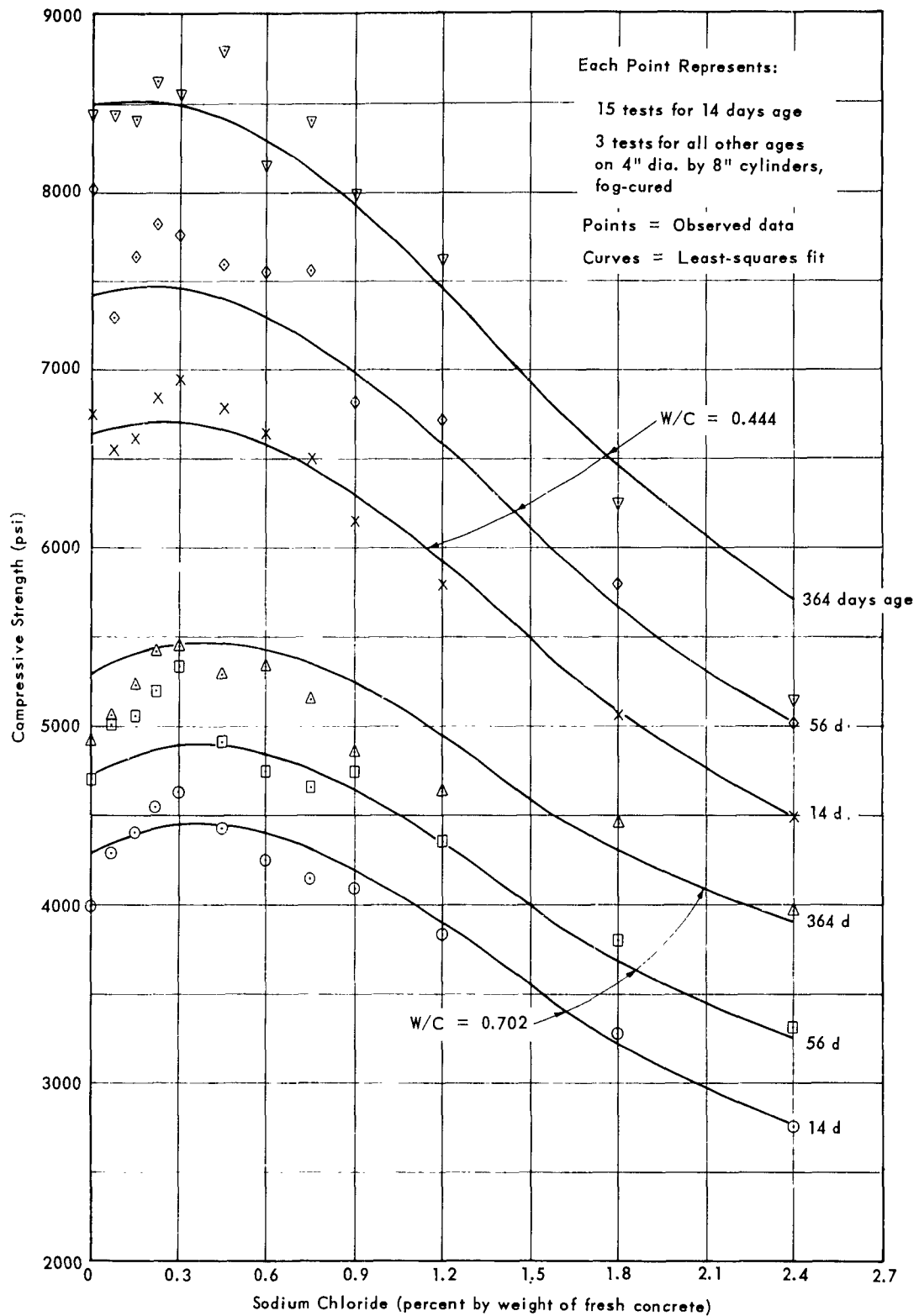


Figure 1-c. Compressive strength versus sodium chloride content — Least-squares fit.

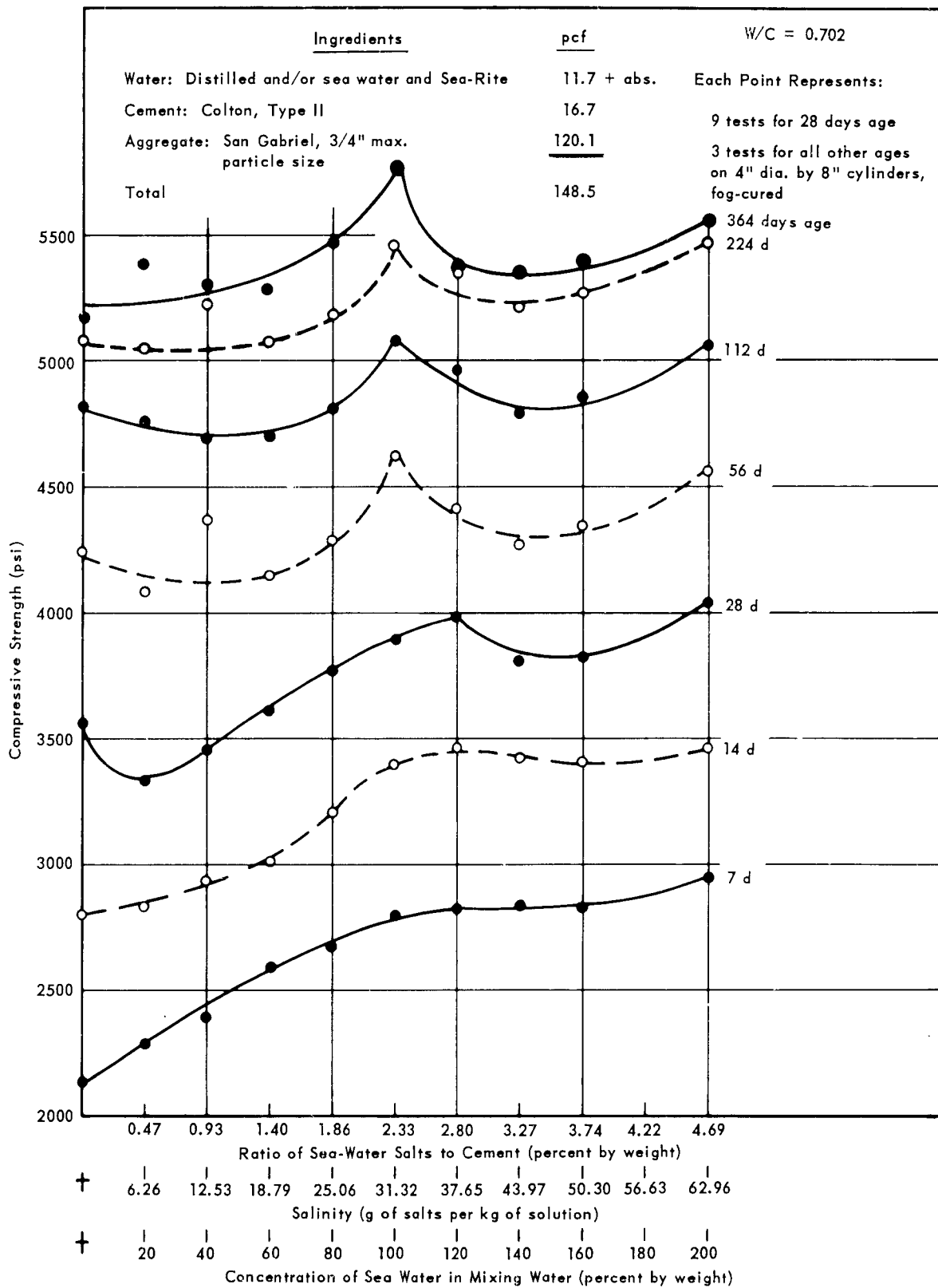


Figure 2. Compressive strength versus sea-water concentration.

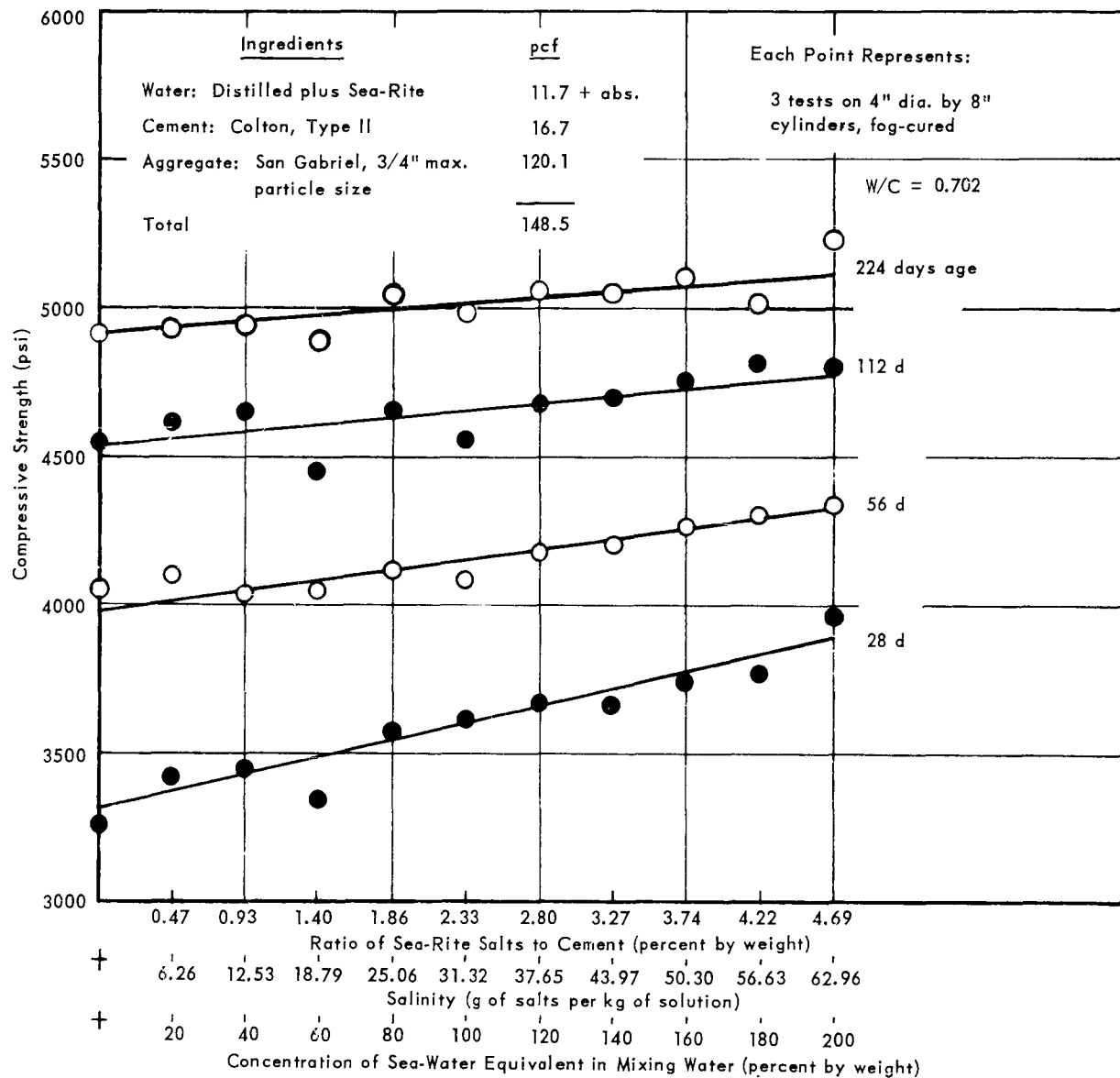


Figure 3. Compressive strength versus Sea-Rite concentration.

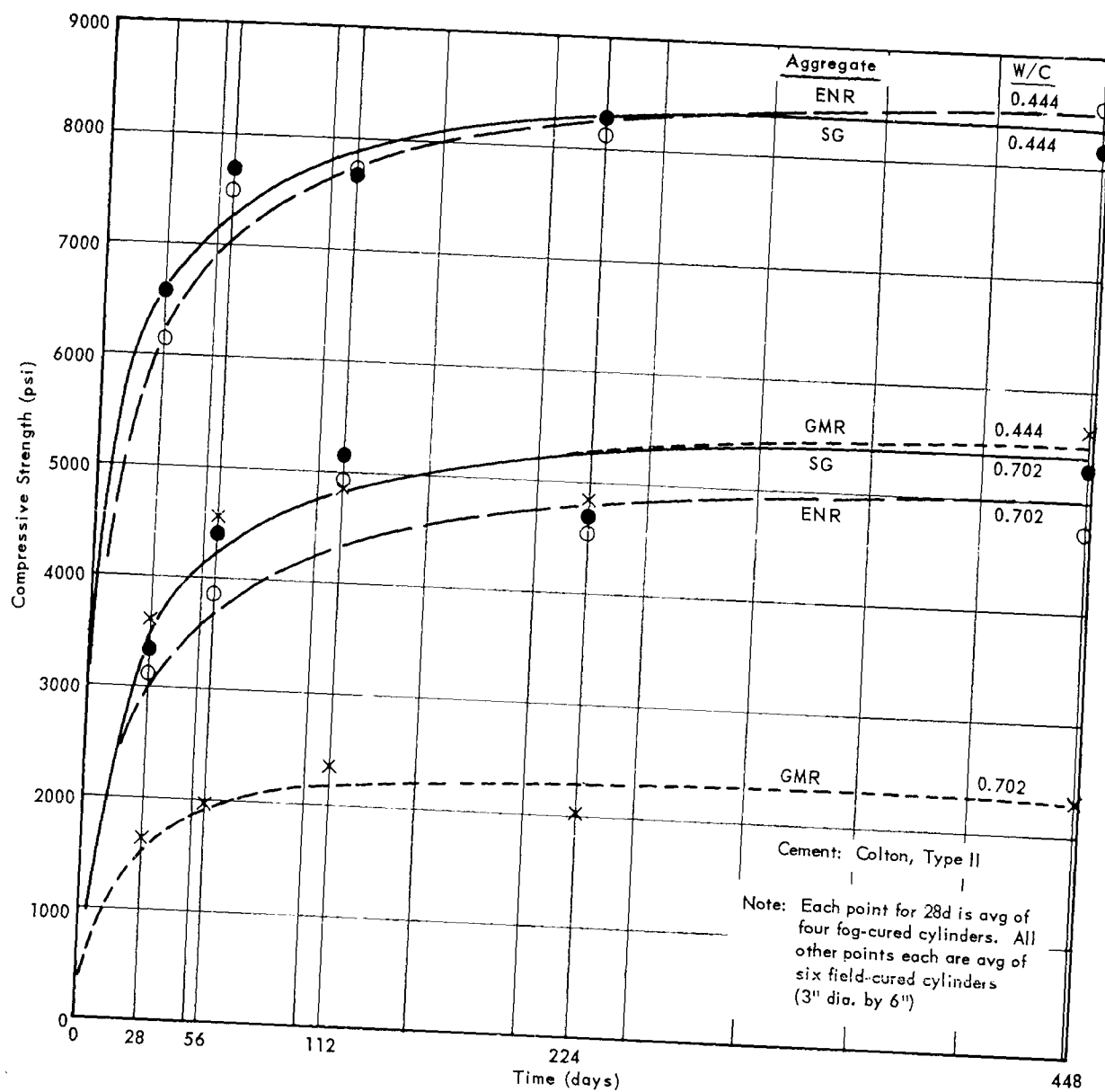


Figure 4. Compressive strength versus age of walls.

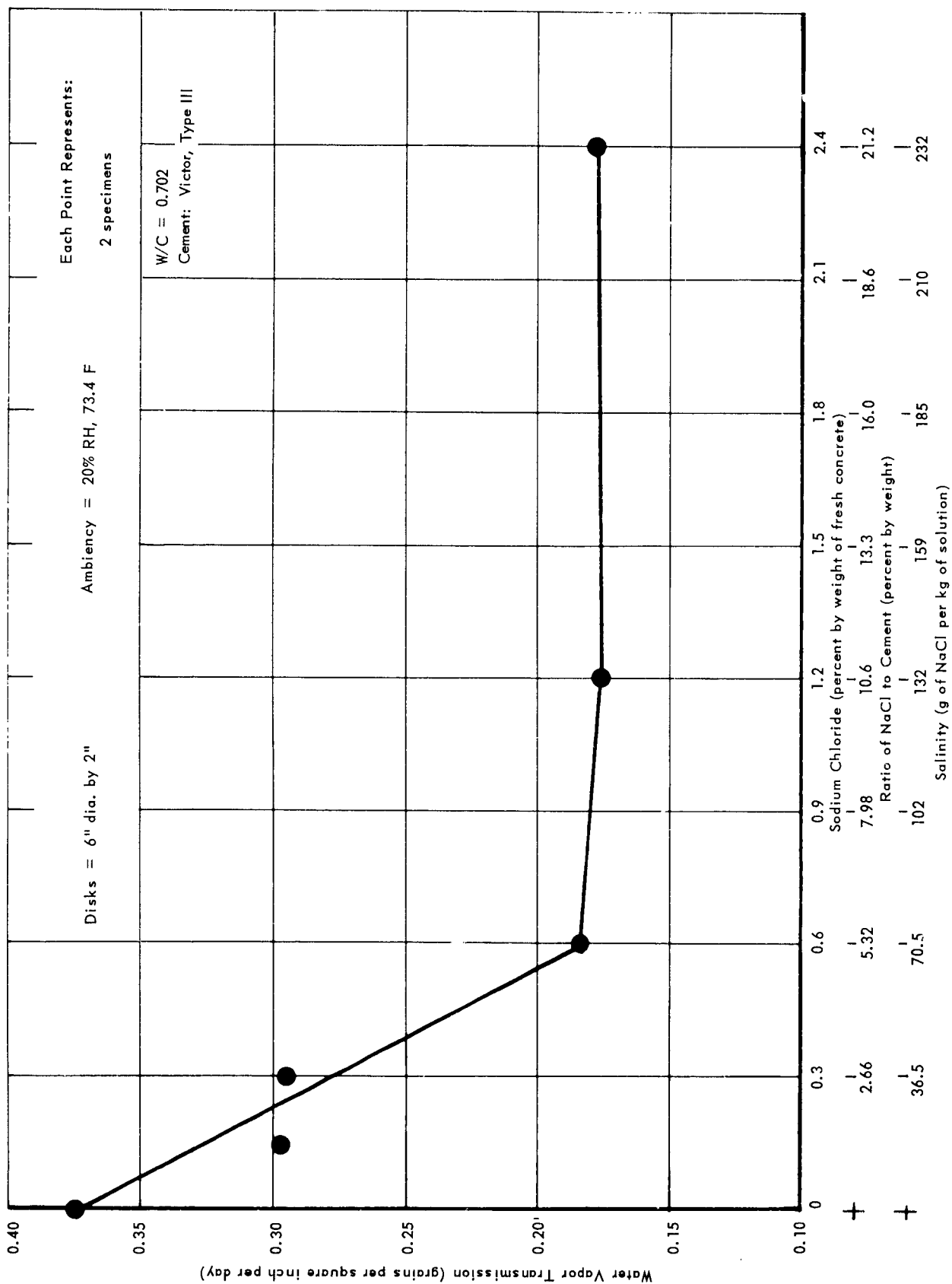


Figure 5. Water vapor transmission versus sodium chloride content.

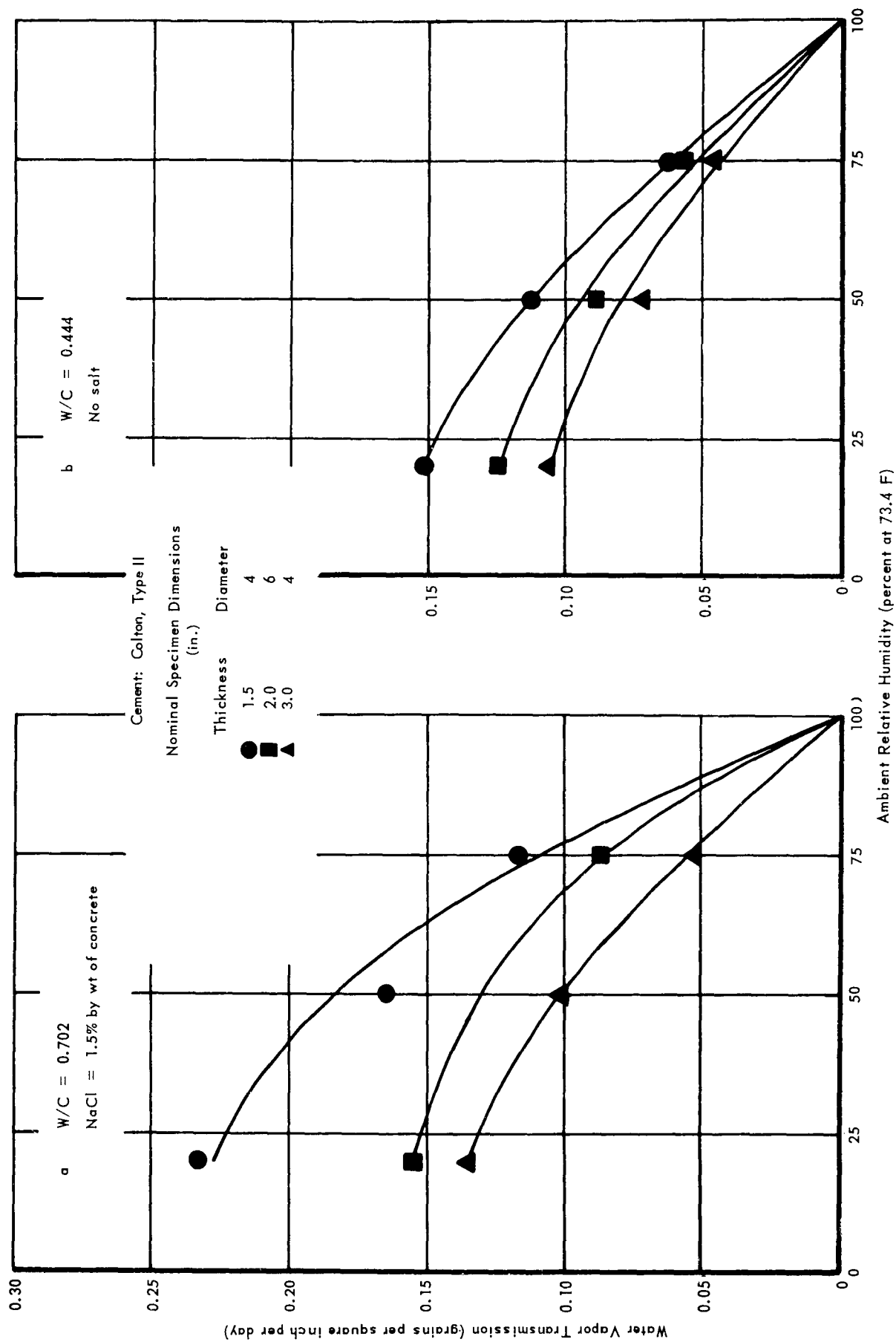


Figure 6. Water vapor transmission versus ambient relative humidity — with and without NaCl.

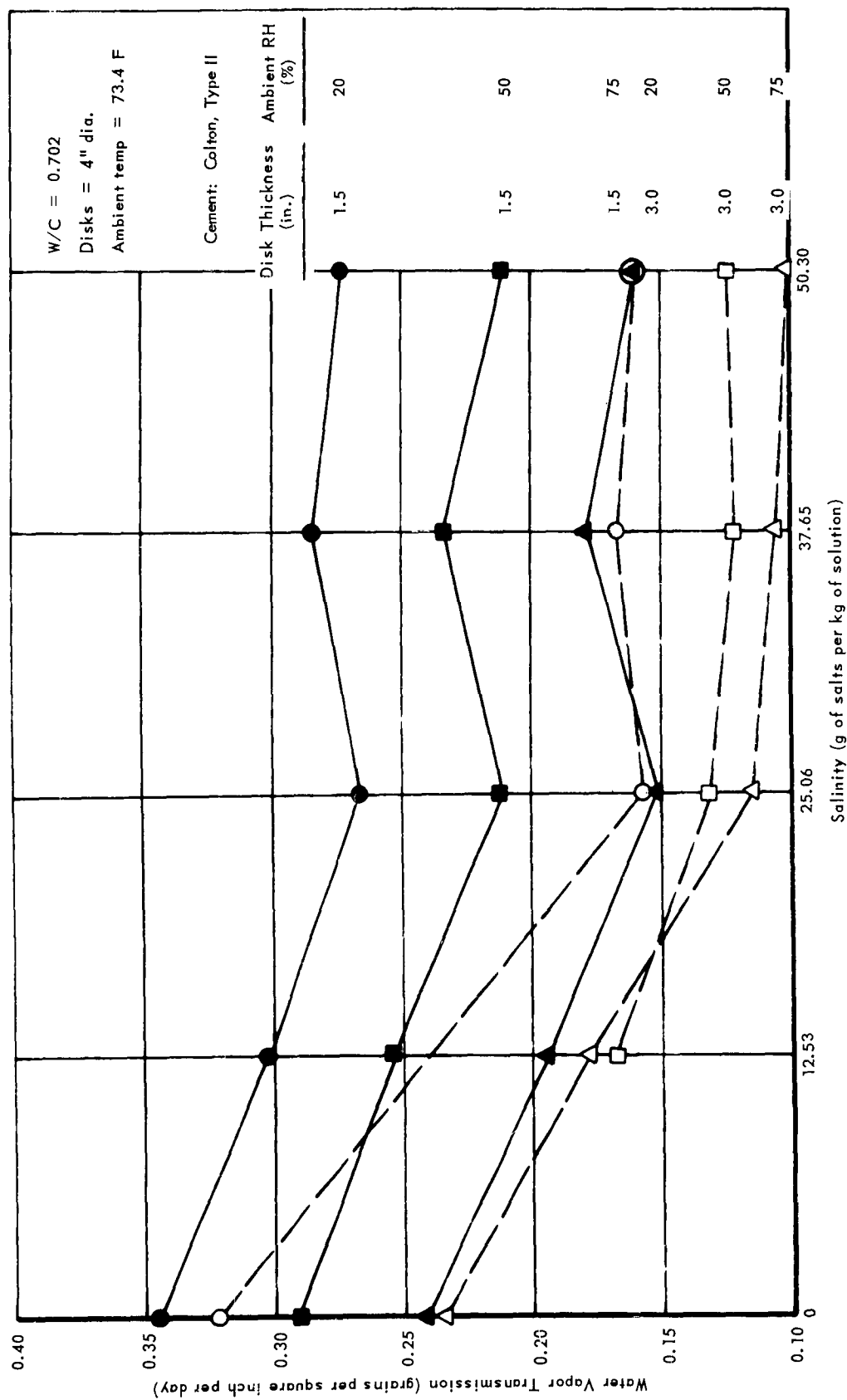


Figure 7. Water vapor transmission versus sea-water concentration — Thickness effect.

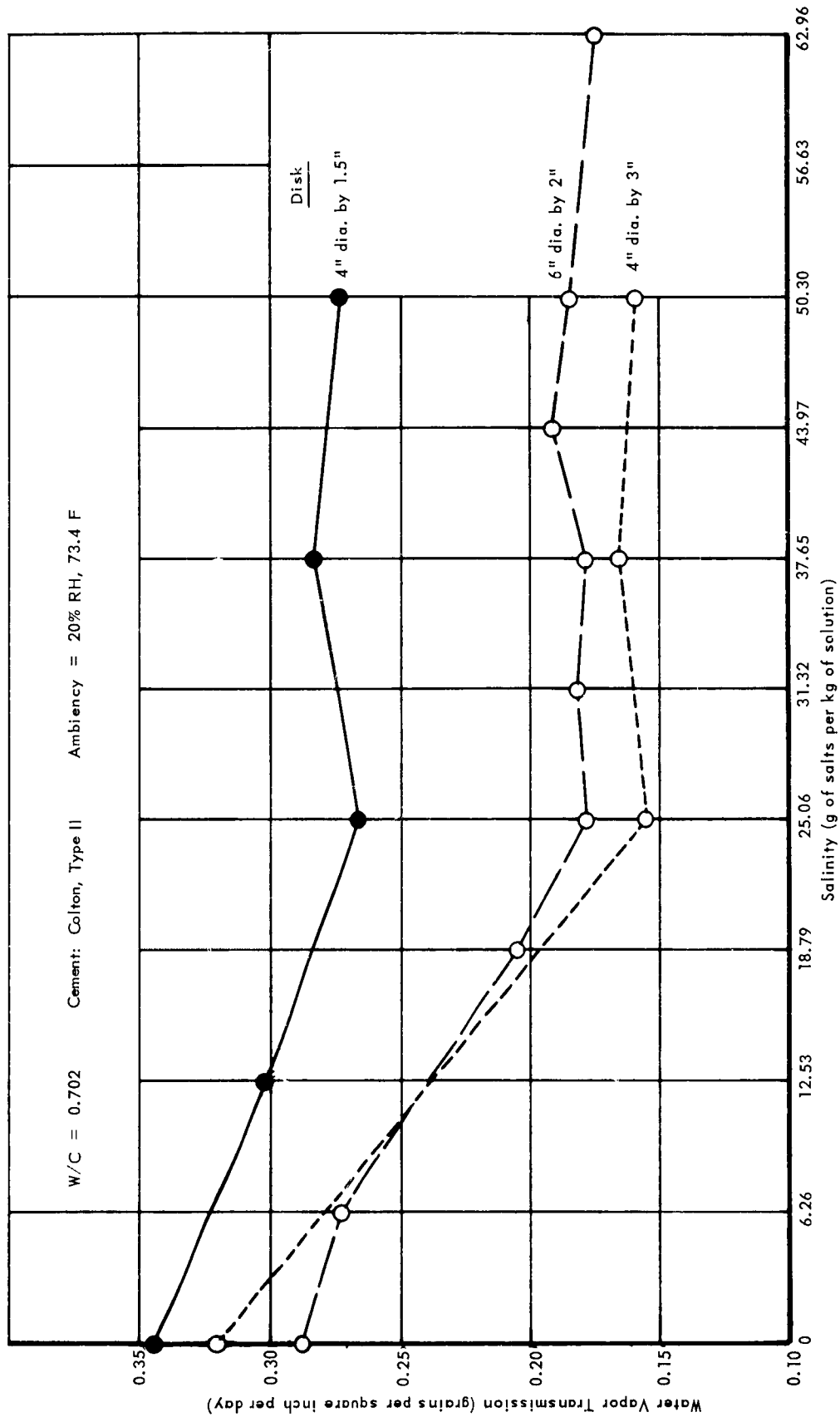


Figure 8. Water vapor transmission versus sea-water concentration — Diameter effect.

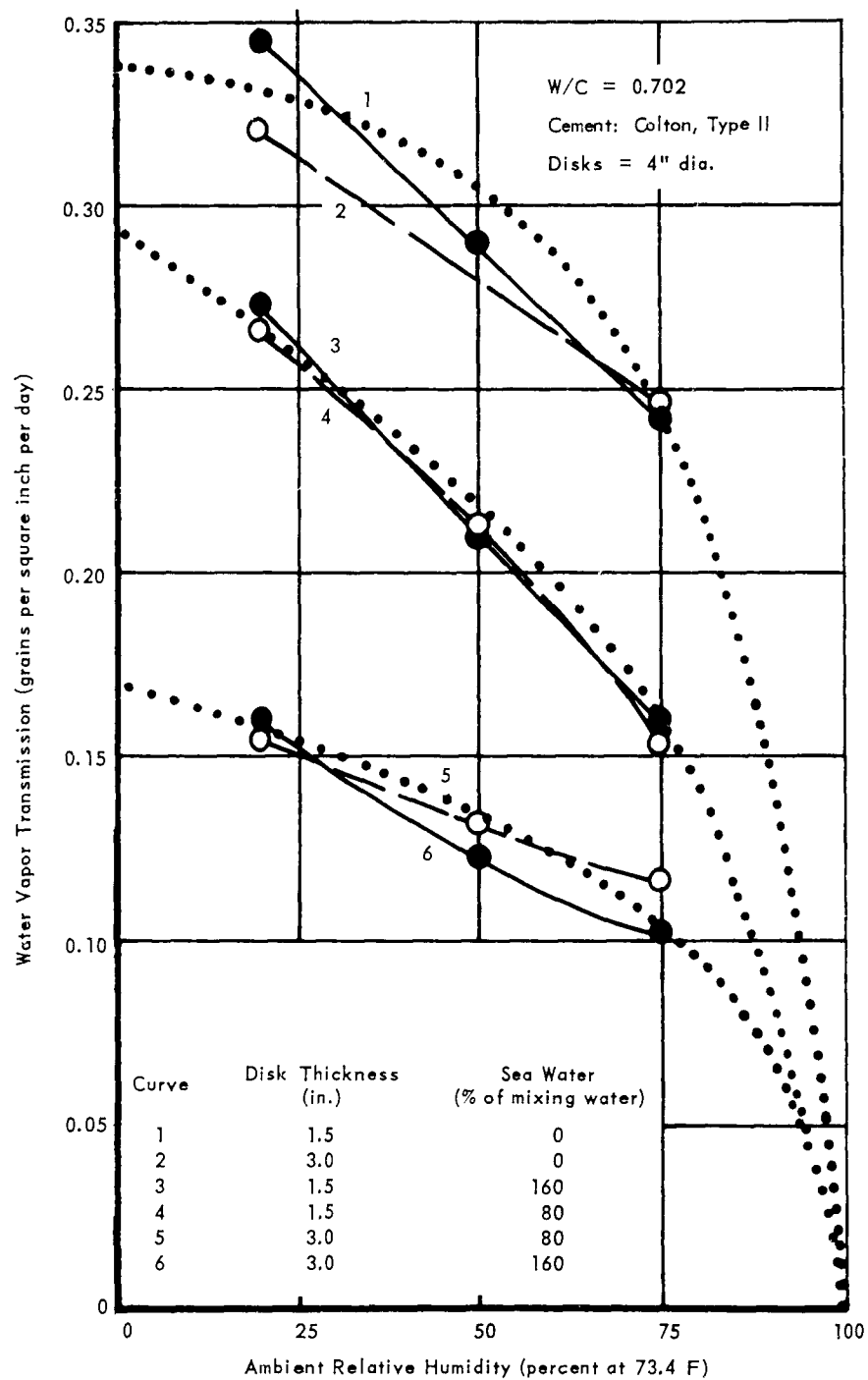


Figure 9. Water vapor transmission versus ambient relative humidity — With and without sea-water.

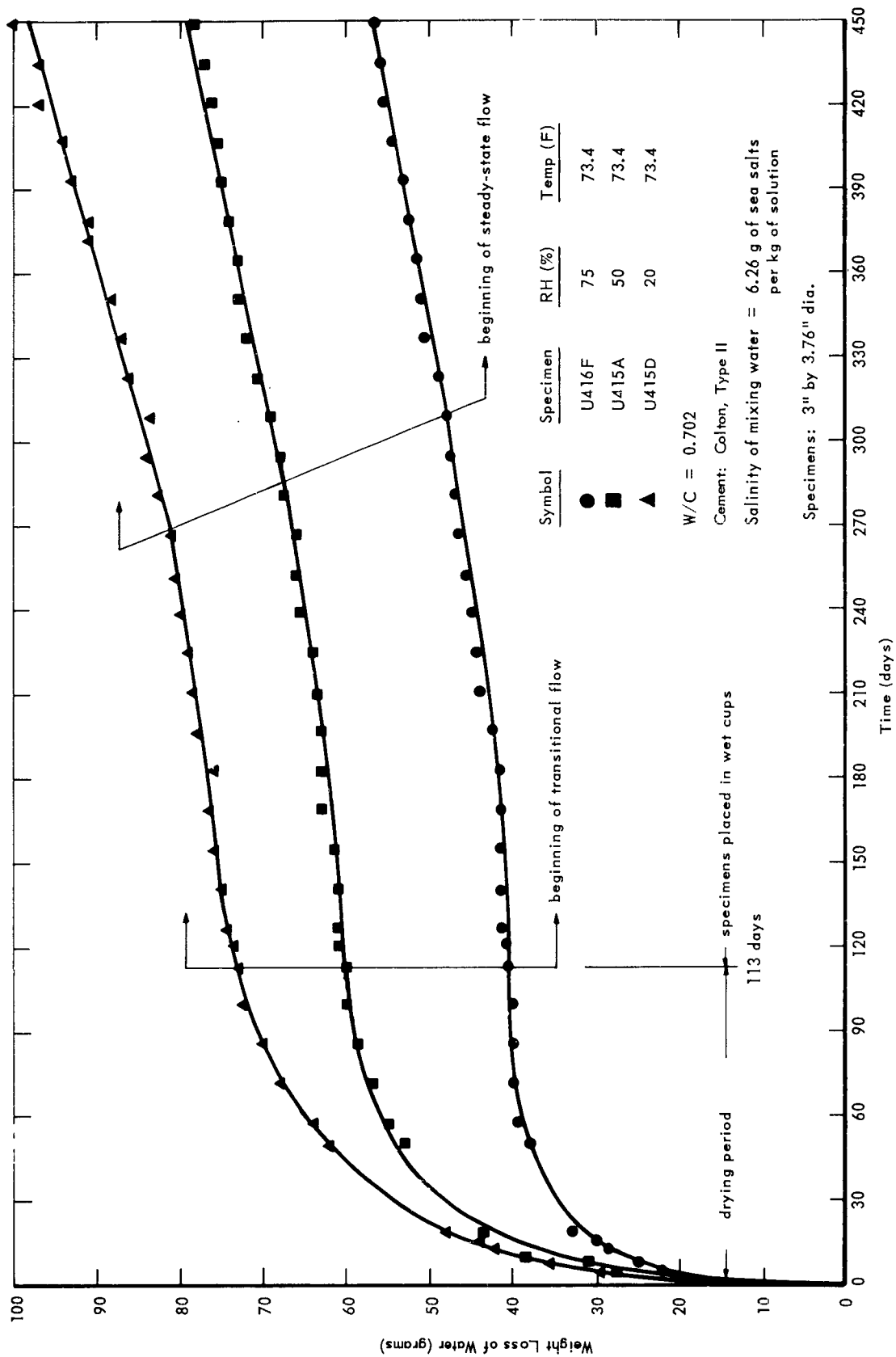


Figure 10. Effect of drying period on water vapor transmission rates.

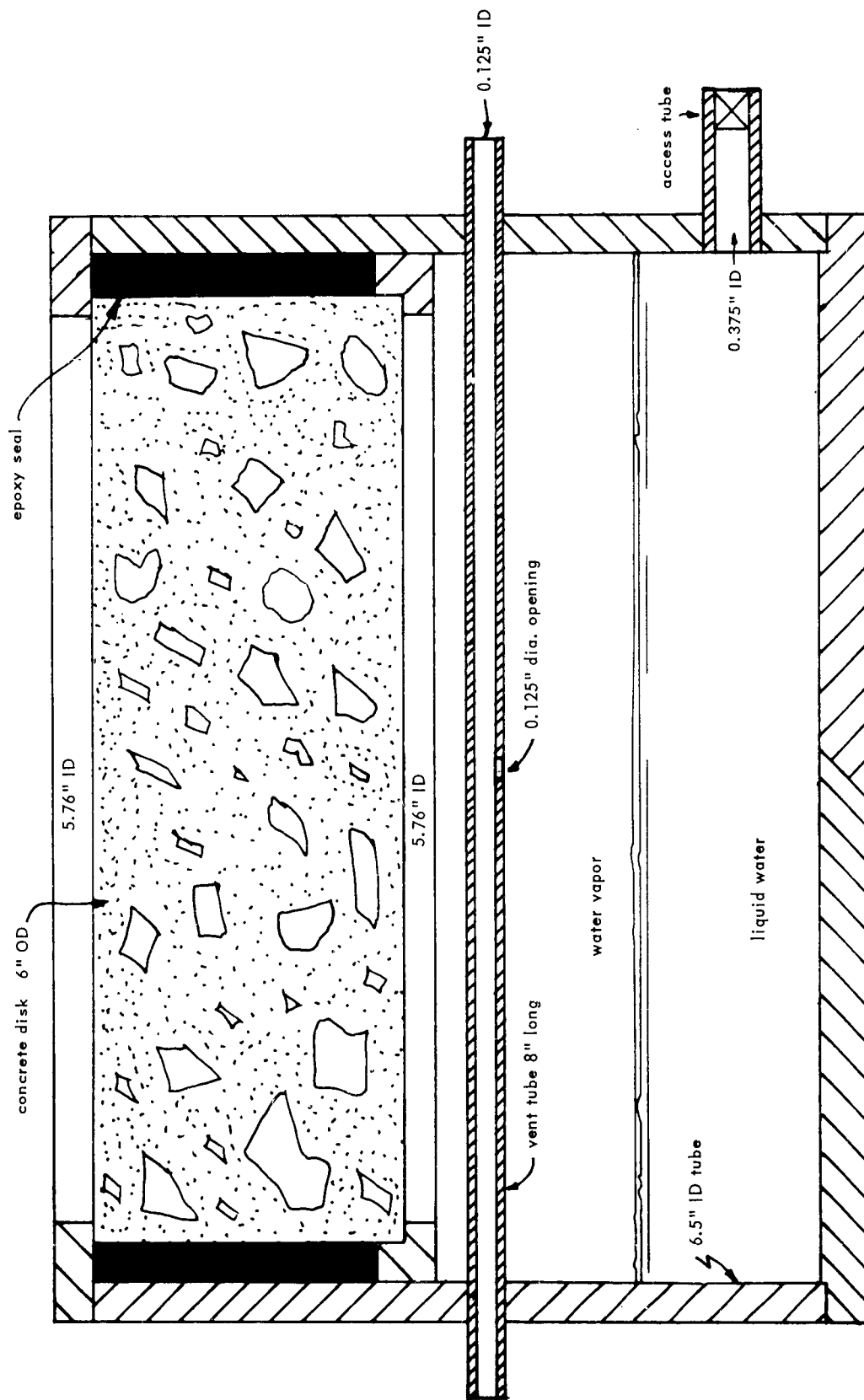


Figure 11. Half-section of assembled acrylic wet cup with vent.

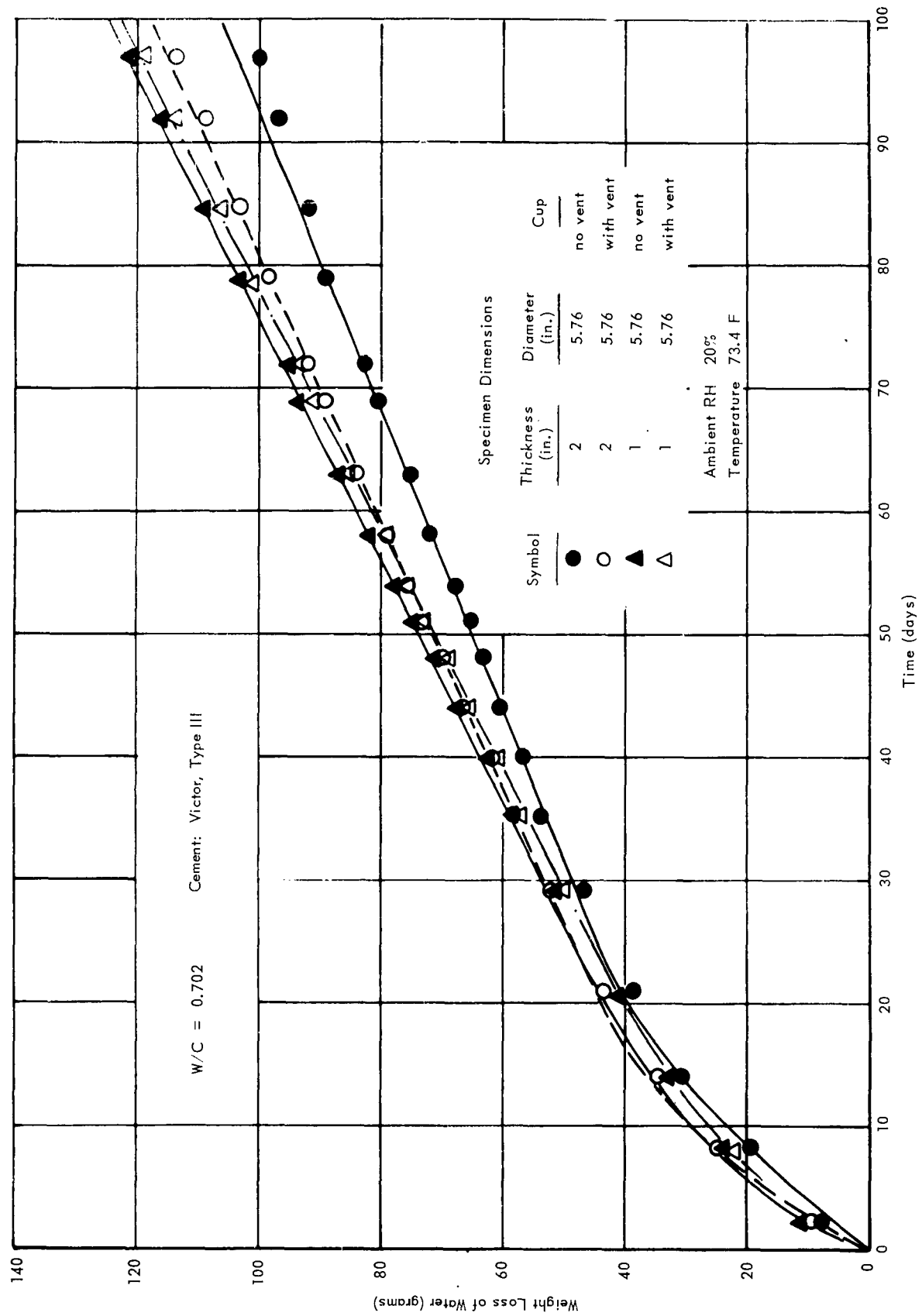


Figure 12. Effect of vent in wet cup on water vapor transmission.

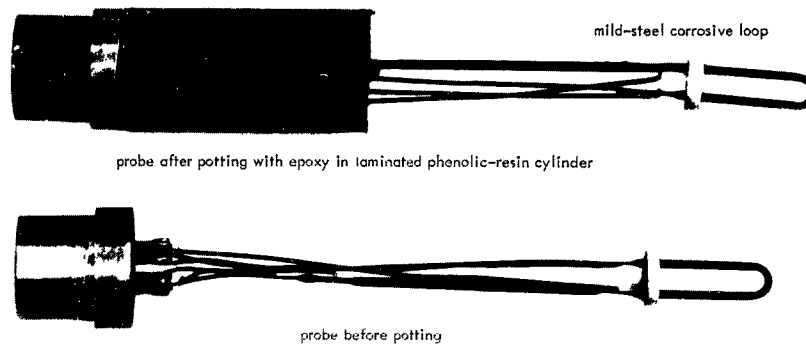


Figure 13. Electrical-resistance corrosion-rate detection probe.



Figure 14. Wet cup assembled with corrosion probe.

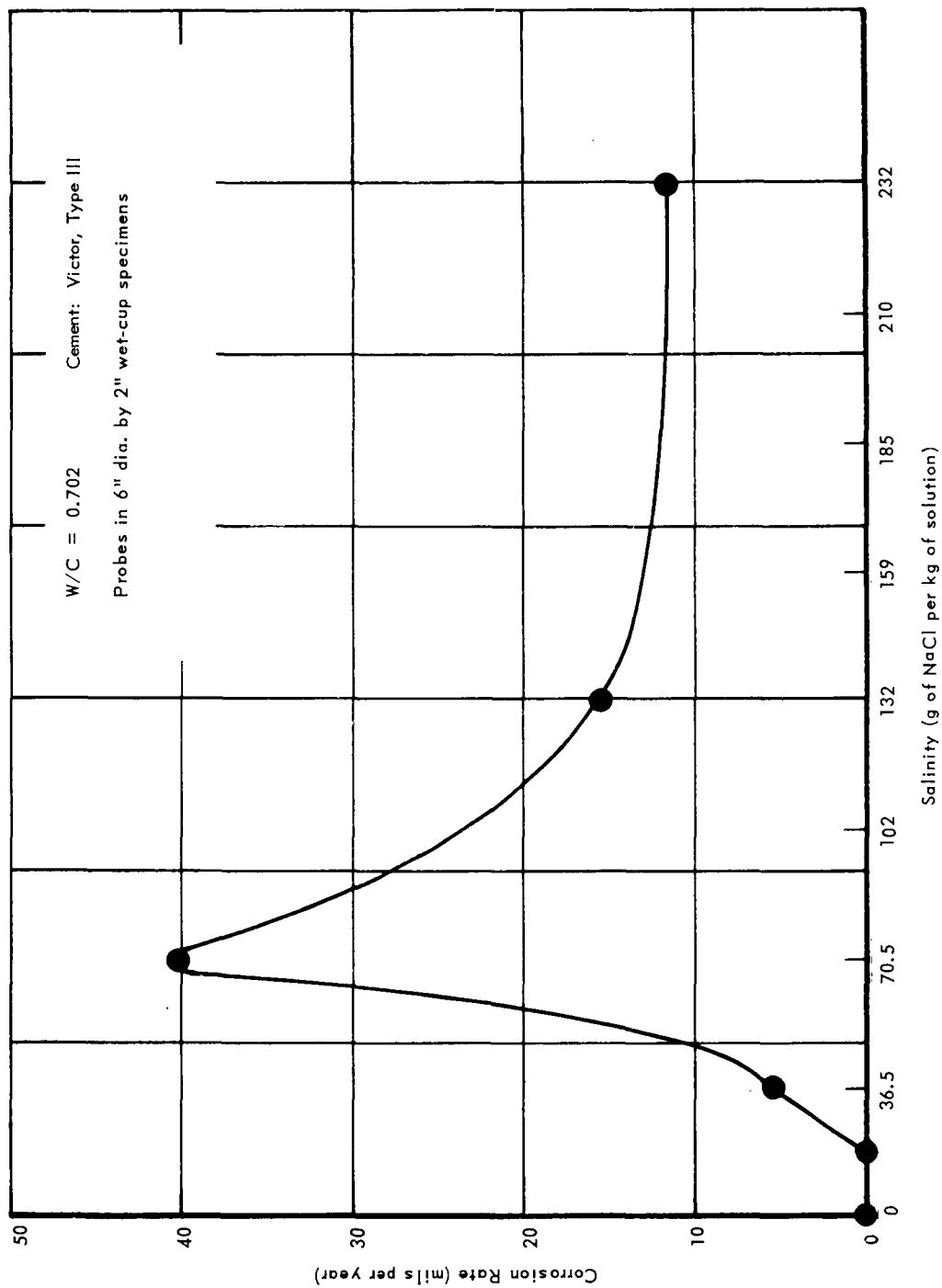


Figure 15. Corrosion versus salinity using NaCl.

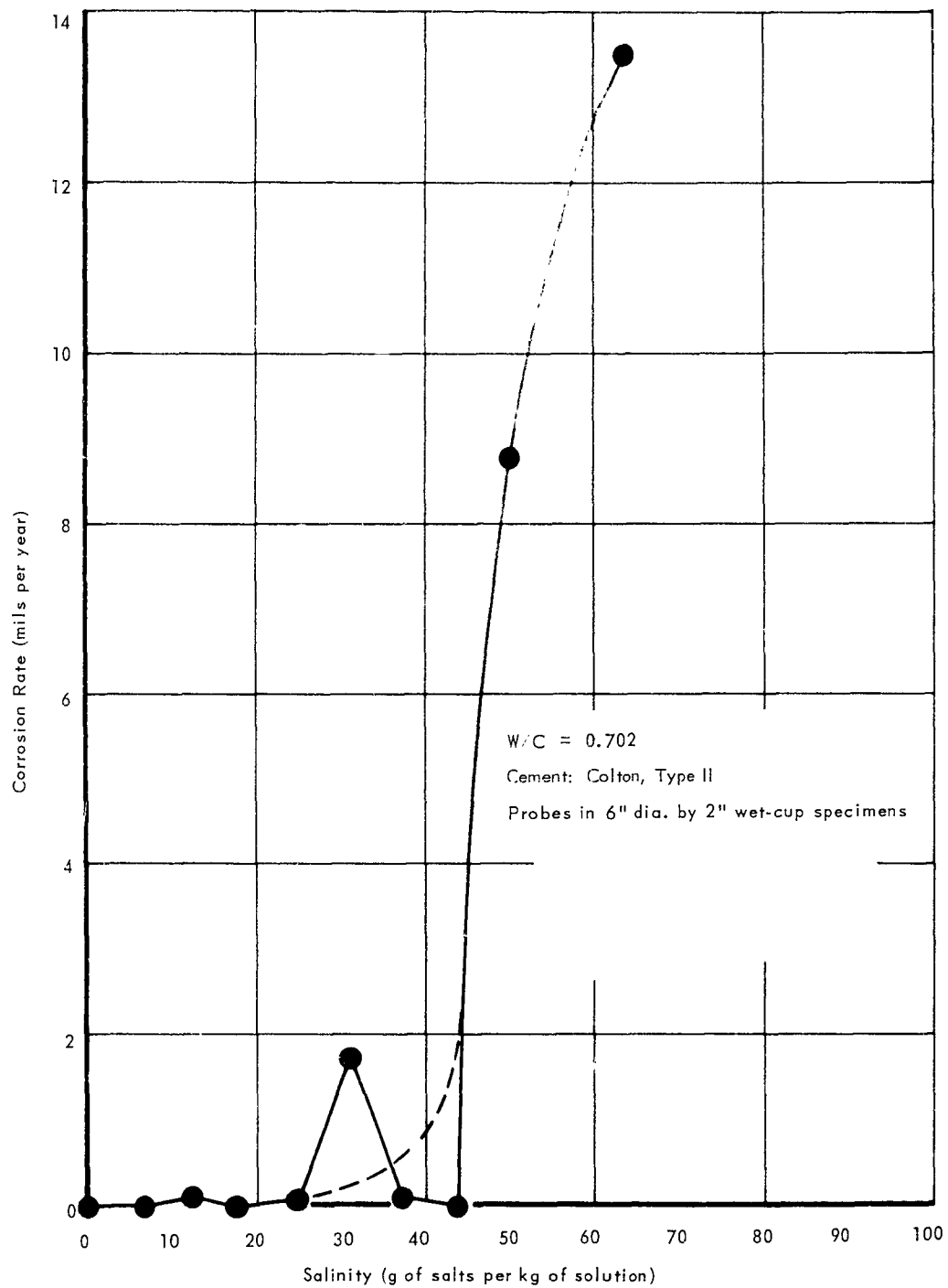


Figure 16. Corrosion versus salinity using sea water.



Figure 17. Details of steel insulation.

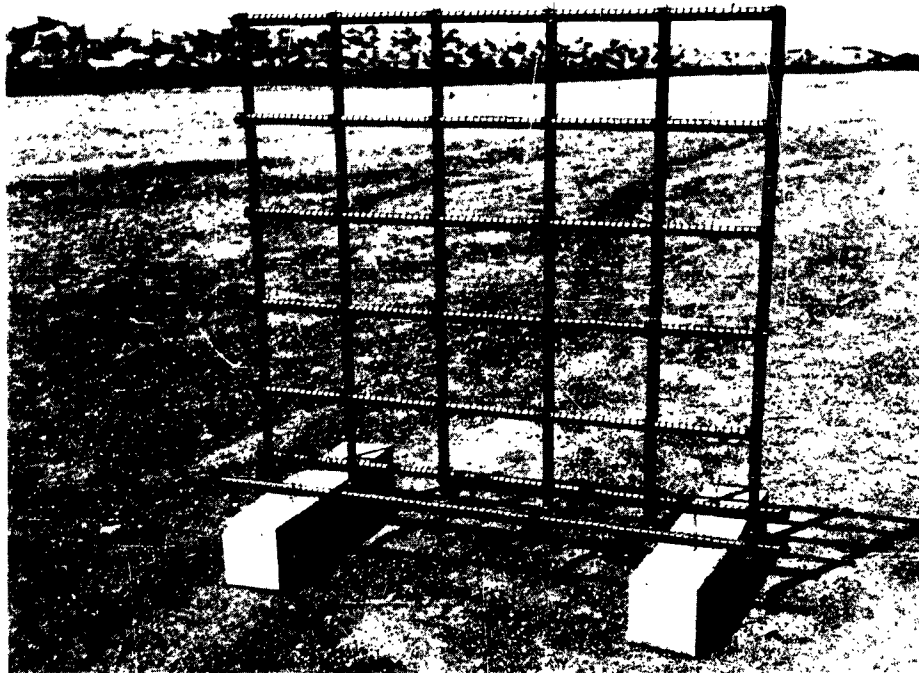


Figure 18. Concrete supports for steel grids.

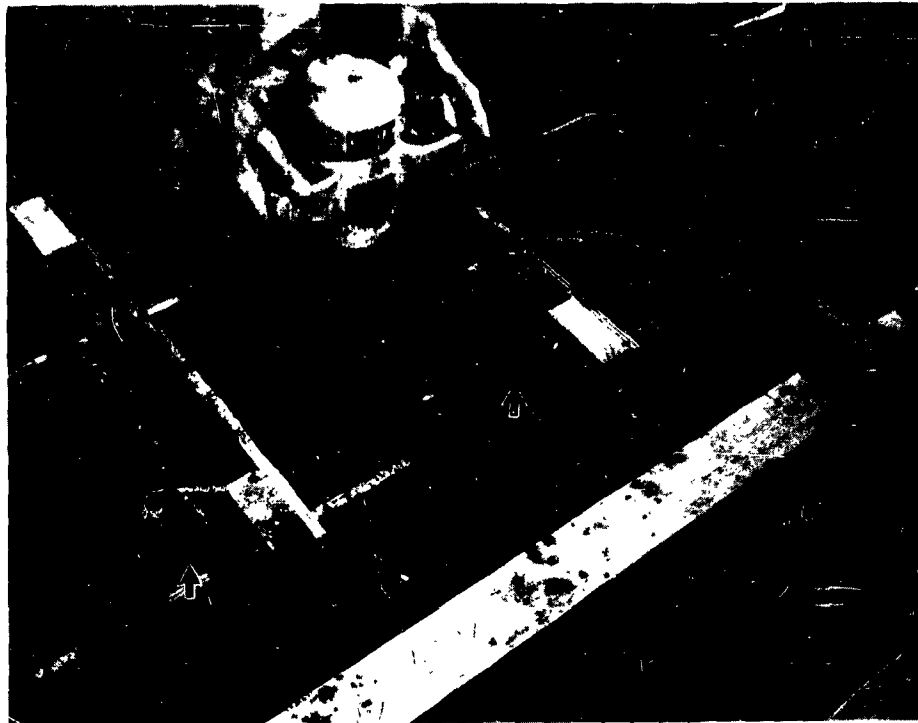


Figure 19. Temporary devices for holding steel grids in forms.

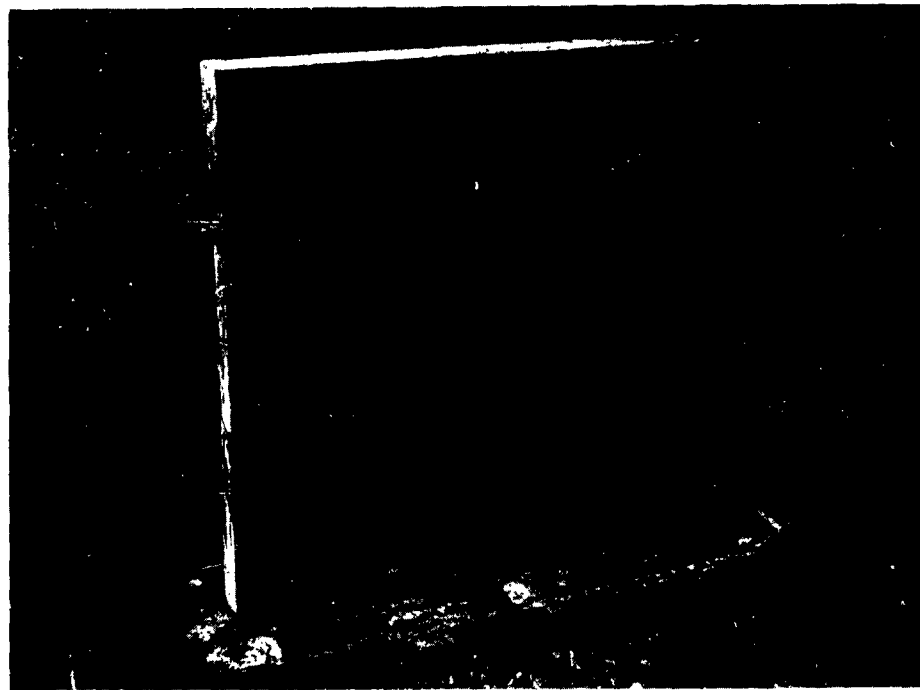


Figure 20. San Gabriel wall after stripping forms.

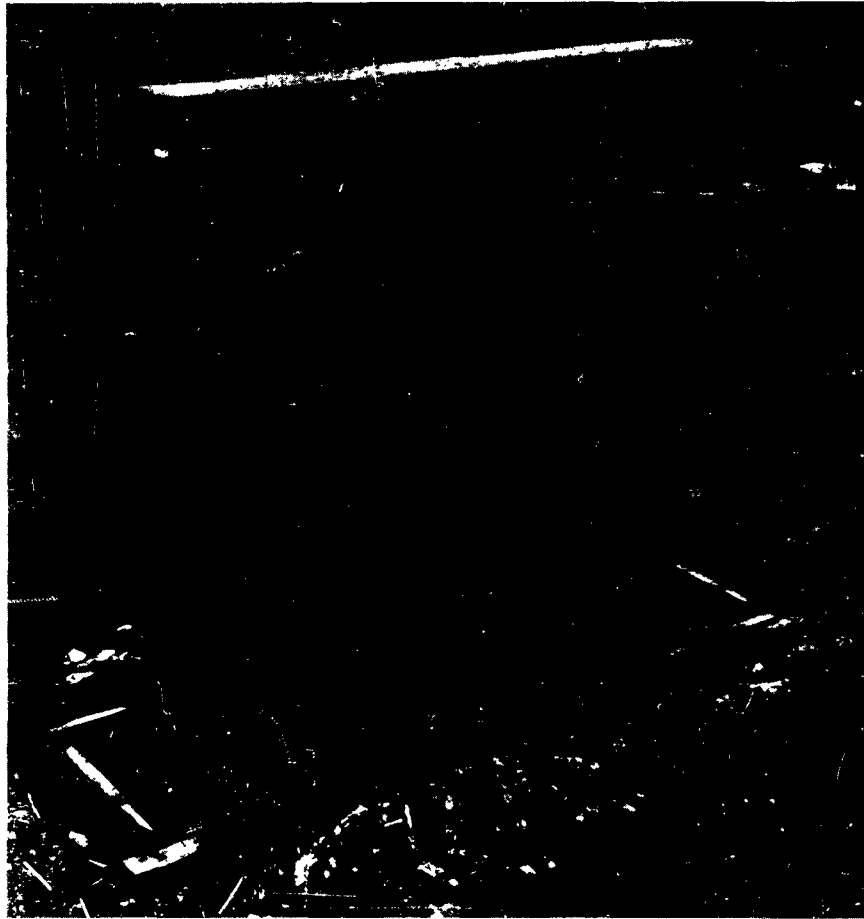


Figure 21. Coral concrete wall after stripping forms.



Figure 22. Overall view of experimental walls.

Table 1. Summary of Concrete Mix Design Data

A. Characteristics of Materials

Cements: Colton, Type II; Colton, Type III; Victor, Type III.

Aggregates: 1. SG or San Gabriel, a reference aggregate from the Irwindale Pit of Consolidated Rock Products Co., Calif.

2. ENR or Eniwetok Atoll reef coral from Eniwetok Islet, Marshall Islands; a good-quality coral consisting of 95 percent coralline limestone.

3. GMR or Guam reef coral from Apra Harbor, Guam, the Marianas; a poor-quality coral consisting of 96 percent cellular coral or porous coralline rock.

4. Specific characteristics:

Item	SG		ENR		GMR	
	C	F	C	F	C	F
Bulk Sp Gr (oven-dry)	2.66*	2.63*	Overall Avg 2.49 2.49		Weighted Avg L: 2.16 H: 2.11**	
24-hr abs, percent	1.6*	1.8*	2.32	2.32	20.0*	7.6*
Comparative general physical condition, percent by weight	Reference aggregate, approx. 100 percent good		73 Good 25 Fair 2 Poor	73 25 2	49 Good 45 Fair 6 Poor	45 45 10

* Determined by Task Engineers.

Data without (*) taken from NCEL TN-335A.

** L = W/C ratio of 0.702.

H = W/C ratio of 0.444.

Note: San Gabriel aggregate was used unless otherwise indicated.

Table I. Summary of Concrete Mix Design Data (Cont'd)

5. Grading: Pounds retained on each sieve per $6.0 \pm$ cu-ft batch

Sieve	SG		ENR		GMR	
	H	L	H	L	H	L
3/4	19.7	16.5	0	0	0	0
3/8	197.6	196.6	202.0	193.8	179.6	172.4
No. 4	125.1	121.0	116.4	110.0	103.4	98.0
No. 8	72.5	85.9	67.2	77.8	59.8	69.6
No. 16	65.9	82.9	61.2	75.2	54.4	67.0
No. 30	72.5	83.5	67.2	76.0	59.8	67.6
No. 50	59.2	76.2	55.2	69.4	49.0	61.8
No. 100	33.1	38.7	30.6	35.4	27.2	31.2
Pan	13.3	18.7	12.2	17.0	10.8	15.2
Total	658.9	720.0	612.0	654.6	544.0	582.8

Water: Port Hueneme tap water at 73.4 F.

Chemical analysis (ppm): hydroxide (0.0); carbonate (0.0);
bicarbonate (137.0); chlorides (62.0); calcium (38.0); magnesium (14.6);
sulphate (465.0); sodium and potassium (219.0).

Slump: Designed for 3 in.

B. Batch of $1.0 \pm$ cu ft consisted of the following:

Mix Design Factors	SG		ENR		GMR	
	H	L	H	L	H	L
W/C	0.444	0.702	0.444	0.702	0.444	0.702
Water (lb) ^{a/}	11.7	11.7	13.4	13.8	13.4	13.8
Cement (lb)	26.4	16.7	30.1	19.7	30.1	19.7
Cement Factor ^{b/}	7.62	4.81	8.65	5.66	8.65	5.66
Aggregate (lb)	109.9	120.0	102.0	109.0	90.7	97.2

^{a/} The quantity of water added at the mixer was corrected for moisture present in the aggregate and moisture required for absorption.

^{b/} Sacks per cu yd of concrete.

Table IIa. Compressive Strength Versus Sodium Chloride Content for W/C = 0.702

Batch No.	NaCl ^{a/}	Compressive strength after various days of cure in 100 percent RH at 73.4 F (psi) ^{b/}						
		14d	Std Dev 14d	28d	56d	112d	224d	364d
SIL-1	0	3990	95	4480	4700	5030	4970	4910
SIL-2	0.075	4290	100	4780	5020	5170	5150	5060
SIL-3	0.150	4410	95	4890	5070	5290	5350	5230
SIL-4	0.225	4550	115	4790	5210	5460	5510	5420
SIL-5	0.300	4630	115	5020	5330	5630	5500	5450
SIL-6	0.450	4430	95	4800	4920	5160	5380	5280
SIL-7	0.600	4250	95	4610	4740	5080	5060	5330
SIL-8	0.750	4150	100	4510	4660	5010	5130	5150
SIL-9	0.900	4090	105	4440	4750	4930	4860	4850
SIL-10	1.200	3830	100	4200	4360	4540	4710	4630
SIL-11	1.800	3280	85	3620	3800	4040	4130	4450
SIL-12	2.400	2760	65	3000	3320	3750	3660	3960

^{a/} Percent by weight of fresh concrete.

^{b/} Three cylinders (4-in.-dia. by 8-in.) for each age for each salt concentration except for 14d age: 15 cylinders for each were used.

Note: C-Type III cement; slump: 3 in. with no salt; with salt, slump ranged from 5 to 8 in. as salt content was increased.

Table IIb. Compressive Strength Versus Sodium Chloride
Content for W/C = 0.444

Batch No.	NaCl ^{a/}	Compressive strength after various days of cure in 100 percent RH at 73.4 F (psi) ^{b/}						
		14d	Std Dev 14d	28d	56d	112d	224d	364d
SIH-1	0	6760	200	6970	8020	8060	8150	8450
SIH-2	0.075	6550	185	6930	7290	7880	8040	8440
SIH-3	0.150	6620	180	7380	7630	7940	8180	8420
SIH-4	0.225	6840	180	6950	7820	7800	8570	8630
SIH-5	0.300	6940	125	7320	7760	7650	8380	8570
SIH-6	0.450	6780	185	7210	7590	8010	8480	8800
SIH-7	0.600	6640	150	7180	7550	7910	8100	8160
SIH-8	0.750	6510	130	7260	7560	7370	7990	8410
SIH-9	0.900	6150	185	6460	6820	7740	8000	8000
SIH-10	1.200	5800	160	6330	6720	7000	7310	7630
SIH-11	1.800	5070	125	5390	5800	6240	6370	6260
SIH-12	2.400	4480	65	4770	5020	5340	5450	5150

^{a/} Percent by weight of fresh concrete.

^{b/} Three cylinders (4-in.-dia. by 8-in.) for each age for each salt concentration except for 14d age: 15 cylinders for each were used.

Note: C-Type III cement; slump: 3 in. with no salt; with salt, slump ranged from 5 to 8 in. as salt content was increased.

Table III. Compressive Strength Versus Sea-Water Concentration
for W/C = 0.702

Batch No.	Sea-Water Concentration ^{a/}	Compressive strength after various days of cure in 100 percent RH at 73.4 F (psi) ^{b/}							
		7d	14d	28d	Std Dev 28d	56d	112d	224d	364d
S3L-1R	0	2130	2800	3560	150	4240	4820	5080	5160
S3L-2	20	2290	2830	3330	45	4080	4770	5030	5370
S3L-3	40	2390	2930	3460	45	4370	4690	5220	5290
S3L-4	60	2590	3010	3610	45	4150	4700	5060	5280
S3L-5	80	2670	3210	3770	70	4280	4810	5180	5460
S3L-6	100	2800	3400	3890	100	4620	5080	5440	5760
S3L-7	120	2820	3470	3980	65	4410	4950	5330	5350
S3L-8	140	2840	3420	3810	110	4270	4780	5200	5340
S3L-9	160	2830	3410	3820	100	4350	4860	5260	5390
S3L-10	200	2950	3460	4040	90	4560	5070	5460	5540

^{a/} Percent by weight of mixing water; Sea-Rite added to sea water to obtain concentrations greater than 100 percent.

^{b/} Three cylinders (4-in.-dia. by 8-in.) for each age for each sea-water concentration except for 28d age: 9 cylinders for each were used.

Note: C-Type II cement; slumps: 3 in. and nearly constant for all batches.

Table IV. Compressive Strength Versus Sea-Rite Water Concentration for W/C = 0.702

Batch No.	Sea-Rite Water Concentration ^{a/}	Compressive strength after various days of cure in 100 percent RH at 73.4 F (psi) ^{b/}			
		28d	56d	112d	224d
SR-1L	0	3270	4060	4550	4920
SR-2L	20	3420	4100	4610	4930
SR-3L	40	3460	4040	4660	4940
SR-4L	60	3350	4050	4460	4890
SR-5L	80	3580	4120	4650	5040
SR-6L	100	3610	4090	4560	4990
SR-7L	120	3680	4180	4690	5060
SR-8L	140	3680	4200	4700	5040
SR-9L	160	3740	4270	4770	5100
SR-10L	180	3780	4300	4810	5010
SR-11L	200	3870	4340	4800	5220

^{a/} Concentration of sea-water equivalent in mixing water, percent by weight.

^{b/} Three cylinders (4-in. -dia. by 8-in.) for each age for each Sea-Rite water concentration.

Note: C-Type II cement; slumps: nearly constant; minimum = 2.75 in., maximum = 3.25 in.

Table V. Compressive Strength of Wall Specimens

Aggregate Type ^{a/} and W/C	Compressive Strength (psi) Age of 3-in. -dia by 6-in. concrete cylinders (days)				
	28d ^{b/}	56d	112d	224d	448d
SG, 0.702					
Land Side	3330	4420	5250	4450	5990
Sea Side		4390	5060	4940	4600
SG, 0.444					
Land Side	6590	7990	7990	8140	8500
Sea Side		7410	7390	8460	7880
ENR, 0.702					
Land Side	3120	4490	4600	4510	4780
Sea Side		3240	5230	4550	4670
ENR, 0.444					
Land Side	6150	7410	7820	8150	8850
Sea Side		7600	7610	8110	8280
GMR, 0.702					
Land Side	1630	1990	2230	2040	2400
Sea Side		1960	2430	1980	2190
GMR, 0.444					
Land Side	3610	4670	4550	4840	6050
Sea Side		4460	5180	4880	5240

^{a/} See Table I.

^{b/} Each value is average of four fog-cured cylinders; other values are averages of three field-cured cylinders.

Note: C-Type II cement.

Table VI. Water Vapor Transmission Versus Sodium Chloride Concentrations in Mixing Water for W/C = 0.702 (also see Table XIII)

Batch No.	Cup No.	NaCl Content ^{a/}	t (in.) ^{b/}	W/t ^{c/}	WVT ^{d/}	Avg WVT ^{d/}
S2L-1	T483	0	1.992	0.625	0.370	0.375
S2L-1	T484	0	1.972	0.642	0.380	
S2L-2	T500	0.15	1.986	0.500	0.296	0.298
S2L-2	T501	0.15	1.902	0.505	0.299	
S2L-3	T547	0.30	1.987	0.504	0.298	0.295
S2L-3	T548	0.30	1.975	0.494	0.292	
S2L-4	T580	0.60	1.928	—	—	0.182
S2L-4	T581	0.60	2.160	0.308	0.182	
S2L-5	T597	1.20	1.983	0.291	0.172	0.176
S2L-5	T598	1.20	2.022	0.305	0.180	
S2L-6	T646	2.40	1.971	0.303	0.179	0.179
S2L-6	T647	2.40	1.986	0.301	0.178	

a/ NaCl content, percent by weight of fresh concrete; V-Type III cement.

b/ Length of flow path (or thickness of specimen).

c/ Slope of straight-line portion of graph of water loss in grams versus time in days; 520 days of record; 20 percent RH at 73.4 F.

d/ Grains per sq in. per day (1 gram = 15.43 grains). Area of cross section of flow path is 26.06 sq in. All specimens have a nominal diameter of 6 in.

Table VII. Water Vapor Transmission of Concrete With 1.5 Percent Sodium Chloride by Weight of Fresh Concrete (Salinity of 159‰) for W/C = 0.702

Cup No.	RH at 73.4 F (percent)	l (in.) ^{a/}	Nominal Dia (in.)	W/t ^{b/}	WVT ^{c/}
U827A	20	1.504	4	0.167	0.232
U827B	20	3.039	4	0.097	0.135
U828A	50	1.480	4	0.118	0.164
U828B	50	3.049	4	0.073	0.101
U829A	75	1.516	4	0.084	0.117
U829B	75	3.007	4	0.038	0.053
U822B	20	1.996	6	0.261	0.155
U822M	50	2.044	6	—	—
U822T	75	2.059	6	0.149	0.088

^{a/} Length of flow path (or thickness of specimen).

^{b/} Slope of straight-line portion of graph of water loss in grams versus time in days; 400 days of record.

^{c/} Grains per sq in. per day (1 gram = 15.43 grains). Effective cross-sectional area of 4-in.-diameter specimens = 11.12 sq in., and of 6-in.-diameter specimens = 26.06 sq in.

Note: S5L-1 series, C-Type II cement.

Table VIII. Water Vapor Transmission of Concrete Without
Admixtures for W/C = 0.444

Cup No.	RH at 73.4 F (percent)	ℓ (in.) ^{a/}	Nominal Dia (in.)	W/t ^{b/}	WVT ^{c/}
U871A	20	1.506	4	0.109	0.151
U871B	20	3.067	4	0.077	0.107
U872A	50	1.498	4	0.081	0.113
U872B	50	3.056	4	0.052	0.072
U873A	75	1.538	4	0.045	0.062
U873B	75	3.060	4	0.034	0.047
U874A	20	2.004	6	0.210	0.124
U874B	50	2.050	6	0.151	0.089
U874C	75	2.039	6	0.098	0.058

a/ Length of flow path (or thickness of specimen).

b/ Slope of straight-line portion of graph of water loss in grams versus time in days; 400 days of record.

c/ Grains per sq in. per day (1 gram = 15.43 grains). Effective cross-sectional area of 4-in.-diameter specimens = 11.12 sq in., and of 6-in.-diameter specimens = 26.06 sq in.

Note: S5H-1 series, C-Type II cement.

Table IX. Water Vapor Transmission — Depth-of-Cover Series (No Salt)

Cup No.	RH at 73.4 F (percent)	l (in.) ^{a/}	W/t ^{b/}	WVT ^{c/}
Table IXa - S4L Series, W/C = 0.702, C-Type II cement				
U744A	20	1.993	—	—
U741A	20	4.066	0.447	0.265
U740	20	6.015	0.417	0.247
U750A	50	2.098	0.445	0.264
U747A	50	4.008	0.375	0.222
U750	50	5.979	0.307	0.182
U746A	75	1.998	0.420	0.248
U745A	75	4.009	0.324	0.192
U740A	75	6.018	0.278	0.164
Table IXb - S4H Series, W/C = 0.444, C-Type II cement				
U753A	20	2.056	0.204	0.121
U752A	20	3.995	0.138	0.082
U751	20	6.041	0.144	0.085
U757A	50	2.020	0.164	0.097
U758A	50	4.020	0.095	0.056
U758	50	6.004	0.086	0.051
U755A	75	2.002	0.120	0.071
U756A	75	4.033	0.060	0.036
U751A	75	5.998	0.048	0.028

^{a/} Length of flow path (or thickness of specimen).

^{b/} Slope of straight-line portion of graph of water loss in grams versus time in days; 400 days of record.

^{c/} Grains per sq in. per day (1 gram = 15.43 grains). Area of cross section of flow path is 26.06 sq in. All specimens have a nominal diameter of 6 in.

Table X. Water Vapor Transmission Versus Sea-Water Concentrations in Mixing Water for W/C = 0.702 (also see Table XIV)

Batch No.	Cup No.	Sea-Water Concentration ^{a/}	RH at 73.4 F (percent)	Nominal Dia (in.) ^{b/}	ℓ (in.) ^{c/}	W/t ^{d/}	WVTe ^{e/}
S3L-1	U306	0	20	6	2.000	0.488	0.289
S3L-2	U414	20	20	6	2.001	0.460	0.272
S3L-3	U447	40	20	6	2.006	—	—
S3L-4	U480	60	20	6	1.960	0.348	0.206
S3L-5	U514	80	20	6	1.996	0.302	0.179
S3L-6	U569	100	20	6	2.034	0.308	0.182
S3L-7	U605	120	20	6	2.009	0.303	0.179
S3L-8	U638	140	20	6	2.033	0.325	0.192
S3L-9	U671	160	20	6	2.043	0.313	0.185
S3L-10	U704	200	20	6	2.000	0.296	0.175
S3L-1	U307C	0	20	4	1.476	0.248	0.344
S3L-1	U307D	0	20	4	3.029	0.231	0.321
S3L-3	U448C	40	20	4	1.506	0.218	0.303
S3L-3	U448D	40	20	4	3.069	—	—
S3L-5	U515C	80	20	4	1.494	0.192	0.266
S3L-5	U515D	80	20	4	3.031	0.112	0.155
S3L-7	U606C	120	20	4	1.489	0.204	0.283
S3L-7	U606D	120	20	4	3.056	0.118	0.164
S3L-9	U672C	160	20	4	1.513	0.196	0.272
S3L-9	U672D	160	20	4	3.061	0.114	0.158
S3L-1	U307A	0	50	4	3.060	—	—
S3L-1	U307B	0	50	4	1.512	0.209	0.290
S3L-3	U448A	40	50	4	3.072	0.121	0.168
S3L-3	U448B	40	50	4	1.526	0.184	0.255

Table X. Water Vapor Transmission Versus Sea-Water Concentrations in Mixing Water for W/C = 0.702 (also see Table XIV) (Cont'd)

Batch No.	Cup No.	Sea-Water Concentration ^{a/}	RH at 73.4 F (percent)	Nominal Dia (in.) ^{b/}	ℓ (in.) ^{c/}	W/t ^{d/}	WVTe ^{e/}
S3L-5	U515A	80	50	4	3.054	0.094	0.131
S3L-5	U515B	80	50	4	1.503	0.153	0.212
S3L-7	U606A	120	50	4	3.053	0.088	0.121
S3L-7	U606B	120	50	4	1.497	0.168	0.233
S3L-9	U672A	160	50	4	3.078	0.089	0.123
S3L-9	U672B	160	50	4	1.492	0.152	0.211
S3L-1	U308E	0	75	4	1.506	0.174	0.242
S3L-1	U308F	0	75	4	3.020	0.177	0.246
S3L-3	U449E	40	75	4	1.529	0.140	0.194
S3L-3	U449F	40	75	4	2.994	0.128	0.178
S3L-5	U516E	80	75	4	1.500	0.110	0.153
S3L-5	U516F	80	75	4	3.030	0.083	0.115
S3L-7	U607E	120	75	4	1.494	0.129	0.179
S3L-7	U607F	120	75	4	3.025	0.076	0.105
S3L-9	U673E	160	75	4	1.491	0.115	0.160
S3L-9	U673F	160	75	4	2.936	0.073	0.101

^{a/} Concentration of sea water in mixing water, percent by weight.

^{b/} Area of cross section of flow path for 6-in. cups is 26.06 sq in.; for 4-in. cups, area is 11.12 sq in.

^{c/} Length of flow path (or thickness of specimen).

^{d/} Slope of straight-line portion of graph of water loss in grams versus time in days; 440 days of record.

^{e/} Grains per sq in. per day (1 gram = 15.43 grains).

Note: C-Type II cement.

Table XI. Water Vapor Transmission of Kwajalein Coral Concrete

Cup No.	l (in.) ^{a/}	W/t ^{b/}	WVT ^{c/}
S684M	2.017	0.374	0.221
S685M	1.995	0.376	0.223
S684T	4.081	0.203	0.120
S685B	4.098	0.224	0.133

^{a/} Length of flow path (or thickness of specimen).

^{b/} Slope of straight-line portion of graph of water loss in grams versus time in days; 570 days of record; 20 percent RH at 73.4 F.

^{c/} Grains per sq in. per day (1 gram = 15.43 grains). Nominal diameter of cups is 6 in.; effective cross section of flow path is 26.06 sq in.

Note: Japanese Type II cement.

Table XII. Water Vapor Transmission of Wall Specimens

Type of Aggregate ^{a/}	Cup No.	l (in.) ^{b/}	W/t ^{c/}	WVT ^{d/}	Avg WVT ^{d/}
W/C = 0.444					
ENR	V84A	2.018	0.166	0.098	0.100
ENR	V84B	2.031	0.170	0.101	
SG	U997A	2.080	0.212	0.126	0.135
SG	U997B	1.999	0.241	0.143	
GMR	V170A	1.994	0.453	0.268	0.272
GMR	V170B	2.000	0.467	0.276	
W/C = 0.702					
ENR	V41A	1.976	0.270	0.160	0.158
ENR	V41B	2.055	0.264	0.156	
SG	U954A	2.021	0.492	0.291	0.302
SG	U954B	2.012	0.527	0.312	
GMR	V127A	2.004	0.580	0.343	0.335
GMR	V127B	2.032	0.550	0.326	

^{a/} See Table I.

^{b/} Length of flow path (or thickness of specimen).

^{c/} Slope of straight-line portion of graph of water loss in grams versus time in days; 360 days of record; 50 percent RH at 73.4 F.

^{d/} Grains per sq in. per day (1 gram = 15.43 grains). Nominal diameter of cups is 6 in.; effective cross section of flow path is 26.06 sq in.

Note: C-Type II cement.

Table XIII. Sodium Chloride Content Versus Corrosion of Steel in Concrete for W/C = 0.702 (also see Table VI)

Cup No.	Percent NaCl ^{a/}	Time to Begin Corrosion (days)	Corrosion Rate (mills per year)
T484	0	—	0
T501	0.15	—	0
T548	0.30	60	5.4
T581	0.60	20	40.2
T598	1.20	16	15.5
T647	2.40	69	11.5

^{a/} Percent by weight of fresh concrete. See Figure 1-a.

Table XIV. Sea Water Concentration Versus Corrosion of Steel in Concrete for W/C = 0.702 (also see Table X)

Cup No.	Percent Sea Water	Salinity of Water ^{a/}	Time to Begin Corrosion (days)	Corrosion Rate (mills per year)
U306	0	0	none	—
U414	20	6.26	none	—
U447	40	12.53	25	0.1
U480	60	18.79	none	—
U514	80	25.06	193	0.1
U569	100	31.32	360	1.7
U605	120	37.65	60	0.1
U638	140	43.97	none	—
U671	160	50.30	25	8.8
U704	200	62.96	315	13.5

^{a/} Grams of salts per kilogram of sea water.

Table XV. Variables for Experimental Walls

Wall Configuration (Plan View)													
Statistical Factors													
Wall Number		1	2	3	4	5	6	7	8	9	10	11	12
Aggregate ^{a/} Strength ^{b/}	GMR	SG	ENR	SG	ENR	ENR	GMR	ENR	SG	GMR	ENR	GMR	SG
Steel Arrangement ^{c/}	Hi	Lo	Lo	Hi	Hi	Hi	Lo	Lo	Lo	Lo	Lo	Hi	Hi
Depth of Steel (cover)	T	W	T	W	T	W	W	W	T	T	W	W	T
Wall Thickness	1"	1"	6"	6"	1"	6"	1"	6"	6"	6"	1"	6"	1"
Casting Date (1961)	3-1/2"	3-1/2"	13-1/2"	13-1/2"	3-1/2"	13-1/2"	3-1/2"	13-1/2"	13-1/2"	13-1/2"	3-1/2"	13-1/2"	3-1/2"
Cylinder Test Dates	15 May	8 May	11 May	8 May	11 May	15 May	15 May	11 May	8 May	15 May	11 May	15 May	8 May
	10 Jul '61	3 Jul '61	6 Jul '61	3 Jul '61	6 Jul '61	10 Jul '61	6 Aug '62	2 Aug '62	30 Jul '62	6 Aug '62	2 Aug '62	6 Aug '62	30 Jul '62
	5 Sep '61	28 Aug '61	31 Aug '61	28 Aug '61	31 Aug '61	5 Sep '61	15 May '63	11 May '63	8 May '63	15 May '63	11 May '63	15 May '63	8 May '63
	26 Dec '61	18 Dec '61	21 Dec '61	18 Dec '61	21 Dec '61	26 Dec '61	15 May '64	11 May '64	8 May '64	15 May '64	11 May '64	15 May '64	8 May '64

^{a/} See Table I

^{b/} Hi = High W/C = 0.444
Lo = Low W/C = 0.702

^{c/} T = Tied (and steel contacts insulated)
W = Welded

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