CHAPTER 18

EXPOSURE RESEARCH ON CONCRETE IN SEA WATER

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INTRODUCTION

Many coastal installations are constructed entirely of concrete or contain concrete in a large part of the structure, particularly those portions which are submerged, and those portions between low and high water. It is the latter locations which are submitted to the most severe exposure.

The work done by the Corps of Engineers, on investigations of the durability of concrete in sea water, which is now being carried on by the Waterways Experiment Station, was essentially initiated by the Concrete Laboratory of the Passamoquoddy Tidal Power Project, Eastport, Maine, in 1935. While this project was never completed, a very extensive investigation of materials and the properties of various concrete mixtures was performed, including the exposure of concrete specimens to natural weathering in sea water.

Between 1935 and 1952 the Waterways Experiment Station through its Concrete Research Division and its predecessor concrete laboratories, has exposed 2556 concrete specimens to natural weathering. The principal exposure station, and the only one at which specimens have been continuously exposed since 1935, is at Treat Island (Eastport), Me. A second exposure station, which has been in use since 1940, is at St. Augustine, Fla. Other exposure stations, not now in service, have been maintained at Buzzards Bay, Mass. and at West Point and Mount Vernon, N. Y. At all but the two stations in New York, the specimens were subjected to alternate exposure to air and immersion in sea water as governed by tidal action. The geographical location of the two stations now in use are shown in Fig. 1. Detailed results of the various programs of investigation are given in laboratory reports indicated in the list of references.

The purpose of this paper is to review the results of the exposure of concrete specimens from the several essentially unrelated investigations and to summarize the major information revealed thereby as related to the durability of concrete.

DESCRIPTION OF EXPOSURE STATIONS

TREAT ISLAND EXPOSURE STATION

The exposure station at Treat Island, Me. is by far the largest and most important of the stations that have been used. The exposure rack is located at mean or half-tide elevation on a Government wharf at Treat Island, situated in Cobscook Bay at the mouth of the Bay of Fundy about midway between Eastport and Lubec, Me. The normal range in tide is 18 ft with a maximum of 26 ft and a minimum of 13 ft. The volume of tidal water is such that its temperature is remarkably uniform throughout the year; varying from a low of 34 F in April to a high of 40 F in early September. During the months of December through March the air temperature averages about 14 F with a normal low of -10 F and a normal high of 36 F.

The combination of air and water temperatures during the winter months is such that the specimens are thawed in water to a temperature of about 37 F when covered at high tide and are frozen in air to a temperature of between -10 and 28 F when out of the water at low tide. The change from the frozen to the thawed condition is very rapid, thus increasing the severity of the exposure.

The principal weathering influences to which the specimens are subjected are freezing and thawing in the winter and wetting and drying in the summer. The influence of the sulfates in the sea water on the specimens is apparently insignificant probably because the uniformly low temperature of the water is not conducive to chemical action. Further evidence of the lack of chemical action as a factor in the failure of specimens at Treat Island is the complete absence of any indication of deterioration of many comparable specimens installed in warm sea water at St. Augustine, Fla.

The original installation of specimens on the Treat Island rack consisted of 5 by 5 by 60-in. columns made in connection with concrete studies for the proposed Passamoquoddy Tidal Power Project. The specimens were originally installed in a vertical position. During the summer of 1940 an entirely new rack was constructed providing for the installation of the specimens in a horizontal position. Since 1940 all specimens at all stations have been installed horizontally.

ST. AUGUSTINE EXPOSURE STATION

The effects of mild marine weathering are evaluated at Salt Run, off Anastasia Island, near St. Augustine, Fla. The principal agent of attack at this installation is warm sea-water. The mean water temperature is about 70 F. The average tide range is 4.5 ft, with a maximum of 5.3 ft and a minimum of 3.7 ft. This station affords information on the effects of sea-water on concrete specimens, apart from the effects of freezing and thawing. Companion specimens to those exposed at Treat Island in connection with a major investigation on portland cements have been exposed here since 1940.

BUZZARDS BAY EXPOSURE STATION

The exposure station at Buzzards Bay was operated from 1938

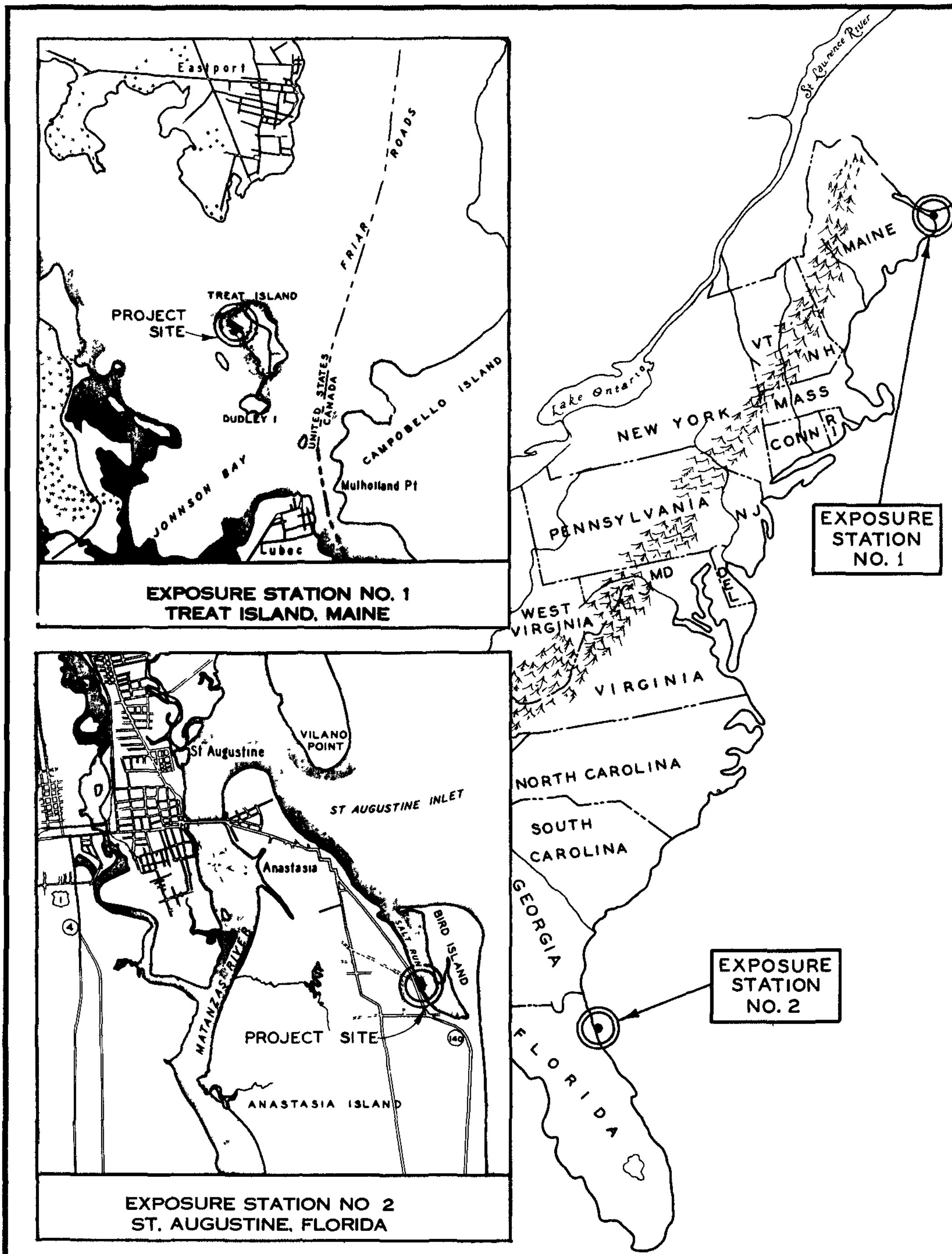

FIGURE 1. LOCATION AND VICINITY MAPS OF EXPOSURE STATIONS NOS. 1 AND 2.

through 1942. A total of 19 column specimens was exposed during this period in an investigation of blends of portland cement with certain admixtures. The exposure rack was located in the Cape Cod Canal near the shore opposite the Sandwich Coast Guard Station. The average tidal fluctuation is 9 ft. The Portland Cement Association has experimental piling exposed here also for their long-time cement studies. Because of the presence of floating ice in the Cape Cod Canal during a considerable portion of the winter season and because of the fact that the water temperature drops as low as 29 F during the late winter, this station has been abandoned for installation of concrete specimens in favor of Treat Island.

NEW YORK STATE EXPOSURE

The moderate-weathering exposure installation, not involving immersion in water, used in connection with two investigations was located out-of-doors adjacent to the Central Concrete Laboratory, at the U. S. Military Academy, West Point, N. Y., between 1940 and 1942 and in Mount Vernon, N. Y., from 1942 to 1946. Companion specimens subjected to "no-weathering" were located inside the laboratory buildings at the respective locations during the respective periods.

NUMBER OF SPECIMENS INSTALLED AT EXPOSURE STATIONS

Station	Year	Number Installed	Cumulative Total
Treat Island	1936	43	43
Buzzards Bay	1938	19	62
Treat Island	1940	271	333
St. Augustine	1940	152	485
New York (outdoors)	1940	156	641
New York (indoors)	1940	52	693
Treat Island	1941	210	903
New York (outdoors)	1941	12	915
Treat Island	1942	182	1097
Treat Island	1943	767	1864
Treat Island	1944	108	1972
Treat Island	1946	82	2054
Treat Island	1947	6	2060
Treat Island	1948	300	2360
Treat Island	1949	66	2426
Treat Island	1951	130	2556

MEASUREMENT OF EXPOSURE AND TESTING OF SPECIMENS

The basic factor in the three tidal exposures is the alternation of environment around the specimens produced by rise and fall of the tide. If the air and water temperatures at Treat Island were constant at below and above the freezing point of concrete saturated with sea water, then the only unit required for measurement of exposure would be "cycles of freezing and thawing". Since this not the case, it is necessary, in making comparisons between specimens installed at different times, to introduce a correction for variable intensity of

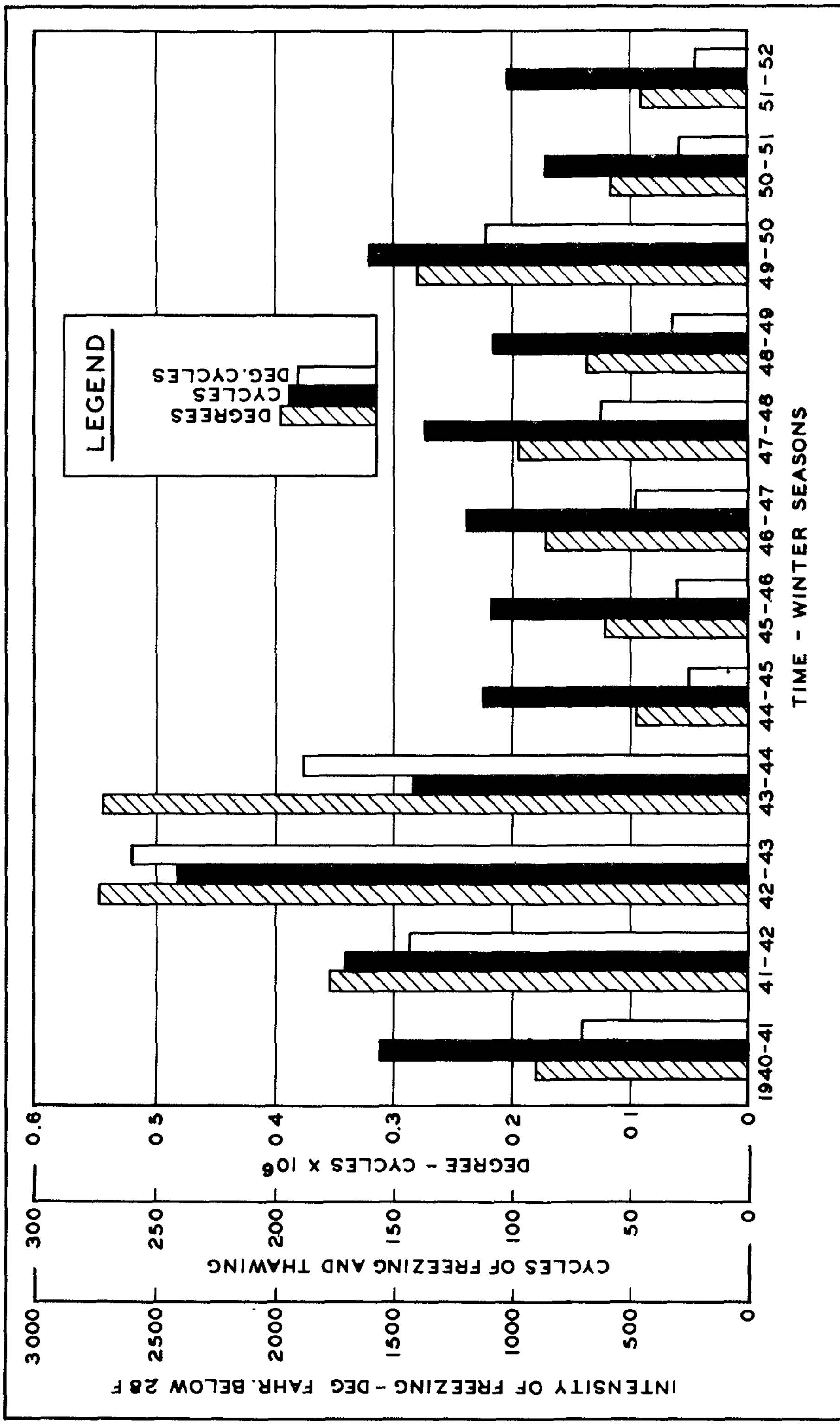

FIG. 2 ANNUAL VARIATION IN EXPOSURE OF CONCRETE SPECIMENS SUBJECTED TO FREEZING AND THAWING AT TREAT ISLAND, ME.

freezing. Fig. 2 shows a graph on which, for each winter since 1940-41, are plotted the number of freezing and thawing cycles, the cumulative total number of degrees below 28 F measured at the center of a 6 by 6 by 36-in. concrete prism at the lowest temperature reached in each freezing cycle, and the number of "degree-cycles", a value obtained by multiplying the total number of cycles by the number of degrees below 28 F. The 28 F temperature was chosen as the approximate freezing point of concrete saturated with sea water.

In all cases where the size and shape of the specimens permit its use, the method, A.S.T.M. (1952), of evaluating the effects of the exposure involves successive determinations of fundamental transverse frequency. Since this property varies directly with Young's modulus of elasticity, the evaluation is calculated as percentage change in Young's modulus. Briefly, the fundamental transverse frequency of a specimen is determined by causing it to vibrate by the action of a variable frequency driver placed in contact with the center of the surface of one side. For each specimen, the fundamental flexural frequency is that at which the amplitude of vibration is greatest. A microphone or pick-up, placed against the side of the specimen near the end, and connected to a suitable voltmeter, ammeter, or oscilloscope, is used to indicate relative amplitude of vibration. The frequency at which the maximum amplitude is indicated is noted and recorded. The actual value of Young's modulus of elasticity, or, in actual practice, the value of relative modulus expressed as a percentage of the modulus at the time of installation of the specimen are calculated as follows:

$$E = CWn^2$$

where:

E = Young's modulus of elasticity in pounds per square inch,

C and W are constants for a specimen of given dimensions and weight, and

n = fundamental transverse frequency in cycles per second.

hence:

$$P_c = \frac{n_1^2}{n^2} \times 100$$

where:

P_c = relative modulus of elasticity, per cent, after c cycles of freezing and thawing,

n = fundamental transverse frequency at 0 cycles of freezing and thawing, and

n_1 = fundamental transverse frequency after c cycles of freezing and thawing.

EXPOSURE RESEARCH ON CONCRETE IN SEA WATER

PROGRAMS OF INVESTIGATION

Concrete specimens have been exposed to natural weathering for the major programs of investigation described briefly below. Results indicated "to-date" are as of the spring of 1951. Results of the 1952 inspections were not available in time for inclusion in this paper. The results of certain programs conducted by or for other organizations are not included herein, notably 66 beams installed in December 1941 for the Portland Cement Association in connection with its long-time study, PCA (1948); 82 reinforced concrete beams for the Reinforced Concrete Research Council; and 48 beams from a joint study by the National Sand and Gravel Association and the Public Roads Administration. The latter two groups were installed in December 1951.

CEMENT DURABILITY PROGRAM

The largest single study was an investigation started in 1939 to develop data to permit the preparation of specifications for portland cement which would insure a greater durability in concrete exposed to severe weathering than provided by the existing specifications. At that time the use of air entrainment was essentially in the discovery stage. A total of 52 samples of cement and clinker from 47 mills distributed throughout the United States was included in the study and only six of these were "treated cements". It is interesting to note that so little was known about the effect of the "treated cements" that the air content of the concrete used in the exposure specimens was not determined and those engaged in the investigation believed that about every known test for cement and concrete had been included. Hence, the only data available on air content are based on unit weight tests and microscopic examination of the hardened concrete. The fact that, of the original column specimens exposed at Treat Island in 1940, the 32 containing the treated cements were the only ones showing no deterioration in 1942 was outstanding evidence that the "treatment", or as it later developed, air entrainment, contributed marked durability to portland-cement concrete. In 1951, after eleven winters' exposure (1472 cycles of freezing and thawing) 19 of the specimens remain and all are in excellent condition with values for dynamic modulus of elasticity of more than 100 per cent, except for one which is 94 per cent.

After eleven years of exposure at St. Augustine, Fla. only eleven of the 152 specimens from this same series have failed and, of these, eight contain cements with calculated tricalcium aluminate contents in excess of 12 per cent.

The specimens exposed to moderate and no-weathering in New York developed no data of significance except that the cement showing poorest durability at Treat Island showed map-cracking after 5-1/2 years of moderate weathering.

NATURAL CEMENT PROGRAM

This investigation compared the relative durability of concrete containing blends of natural and portland cement, with similar concrete containing portland cement, both with and without entrained air. Ninety-four columns representing the various test conditions were installed at Treat Island in October 1942. The results of the program to date indicate that if the natural cements contain appreciable quantities of an air-entraining addition their blending with portland cements greatly improves the durability of concrete.

AIR-ENTRAINMENT PROGRAM

It was known from the results of the cement durability program previously described, that the use of cements containing air-entraining additions materially increased the durability of concrete. The principal purpose of the air-entrainment program was to determine whether this increase in durability was due to the air-entraining addition, as such, or was due to the entrained air. In October of 1943, 182 concrete columns were installed at Treat Island. The specimens represented five plain portland cements, five portland cements with 0.03 per cent flake Vinsol resin, five portland cements with 0.01 per cent neutralized Vinsol resin, and five portland cements with 0.02 per cent neutralized Vinsol resin. All of the Vinsol resin, both flake and neutralized, was interground with the cement at the mill. Two types of coarse aggregate were used; rounded siliceous gravel, and crushed trap rock. The fine aggregate for all concrete was natural siliceous sand. Except for the concrete containing neutralized Vinsol resin, one-half of the series was mixed under normal air pressure and one-half in a vacuum of 60 mm of mercury. The purpose of the vacuum mixing was to preserve the effect of the air-entraining agent, if such effect was a factor, but to remove the entrained air. After seven winters of exposure 142 of the 182 specimens remain in sound condition. The results indicate the superior durability of concrete containing entrained air, and of concrete mixed in air, compared with that mixed in a vacuum.

CURING PROGRAM

In February 1943, 300 concrete specimens were prepared to study the effect of the method of curing on the durability of the concrete. The specimens (3-1/2 by 4-1/2 by 20 in.) were sawed from laboratory-cast slabs, at the end of the curing period. After sawing, the specimens were installed at Treat Island in 100 boxes (3 per box) in such a manner that only the finished or formed surface was exposed. The test variables were ten different liquid membrane-forming compounds, water, waterproof paper, and one integral curing material. After an exposure of four and a half winters only one of the specimens had failed. In May 1947, to intensify the exposure, the specimens were removed from the insulating boxes and exposed to weathering effects on all surfaces. Failure of specimens has not progressed to the point where any conclusive results can be drawn.

DURABILITY OF HORIZONTAL JOINTS IN MASS CONCRETE

The durability of construction joints in mass concrete as affected by the method of consolidating the upper surface of the lower lift, and the method of cleaning the top of the lower lift; the use of grout between the lifts has also been studied. Cores extracted from four projects were subjected to detailed examination in the laboratory and were exposed at Treat Island:

Project	Number of Cores Exposed	Date Installed
John Martin Dam	10	October 1942
Bluestone Dam	40	December 1943
Dale Hollow Dam	23	December 1943
Norfolk Dam	4	March 1943

While the interpretation of the results was complicated in some cases by difficulty in locating the joint, inadequate area of joint plane, or failure of the adjacent concrete coincidental or prior to joint failure, the following general conclusions were drawn:

1. The quality of the joint is governed largely by the quality of the concrete immediately below it.

2. Adequate development of the influence of type of clean-up, use of grout, and type of surface-curing was not obtained principally because the size of the cores that could practically be taken from the structures were too small in proportion to the area of the joint surface to secure true representation.

DURABILITY OF MASS CONCRETE

Several specimens of mass concrete have been exposed at Treat Island in recent years for durability testing as follows:

a. Sixty-eight 6-in. diameter cores drilled from laboratory-made mass concrete (3-1/2 and 4 bags per cu yd cement factor, coarse aggregate graded to 4 in. in size), were exposed in June, 1946. Surfaces were formed against oiled wood, and against absorptive form lining. Each core was encased, except for the formed face, in a 2-in. thickness of mortar. All of the cores are sound to-date, the surfaces formed against absorptive form-lining being generally in better condition than those formed against wood forms.

b. Six 8 cu ft concrete cubes representing concrete with 2.0, 3.0, and 4.0 bags of cement per cu yd, Type II and Type IV cement, entrained air, and aggregate proposed for use in the Pine Flat Dam, were exposed in September, 1947. All of the cubes are in good condition showing no deterioration except for minor raveling of the edges and some spalling. Three 10-in. cores from concrete of similar cement factors, all containing Type IV cement and the aggregate actually being used on the Pine Flat project were exposed in the fall of 1949. In the spring of 1951 all of the cores had relative dynamic moduli of elasticity of more than 100 per cent.

c. In the fall of 1949, nine 10-in. diameter cores taken from a 70-cu-yd test block of Prepakt concrete were exposed at Treat Island. All have relative E values in excess of 100 per cent.

d. Thirty-six 10-in. diameter cores and ten 8-in. diameter cores representing mass concrete with vacuum-treated surfaces were installed at Treat Island in the fall of 1949. These cores also are still in excellent condition.

e. Eleven 10-in. diameter cores drilled from mass concrete in the Mt. Morris Dam were installed at Treat Island in the fall of 1949. These also had relative E values in excess of 100 per cent in 1951. Exposure of all of the above specimens has not been sufficient to permit the drawing of any comparisons or particular observation except that it is interesting to note that the blocks containing only 2.0 bags of cement per cubic yard, exposed in 1947, are still in good condition.

PASSAMOQUODDY TIDAL POWER PROJECT

The purpose of this installation was to find a cement-aggregate combination which would give the greatest assurance of durability for the proposed concrete structures. In connection with the study 43 concrete columns were installed in 1935. After approximately 600 cycles of freezing and thawing, six of the most durable specimens were installed on the new rack in October, 1940. Three of these columns contained plain portland cement similar to the present Type II but manufactured by a mill which permitted introduction of crusher oil by leakage. The other three specimens were made with aluminous cement. After approximately 1200 cycles of freezing and thawing the three plain concrete specimens were removed due to severe deterioration. The three columns containing aluminous cement are still sound after more than 1850 cycles of freezing and thawing.

ST. LAWRENCE SEAWAY

The purpose of this investigation was to find an aggregate that would give the greatest assurance of durability in concrete for the proposed structures. Twelve columns representing twelve test conditions involving four aggregates were exposed at Treat Island in October 1941. The results of the exposure indicated the relative durabilities of the aggregates in question and indicated that neither the presence of entrained air nor the use of absorptive form-lining are sufficient to protect concrete containing definitely unsound aggregate even though the use of such precautions greatly improves the durability of concrete made with sound aggregate. The specimens were discarded in April 1946 to provide needed space on the rack.

ADMIXTURE PROGRAMS

A series of investigations was made to determine the relative effect of several commercial admixtures on the durability of concrete. The first series of 12 columns exposed at Treat Island in March, 1942, studied the effect of a non-air-entraining admixture when used in concrete made with plain and with air-entraining portland cement. The second series (specimens made by the National Bureau of Standards) consisted of 116 columns exposed in October, 1943, represented another commercial admixture, not basically air-entraining in nature, with 13 cements. The third series, represented by 90 columns exposed in November, 1944, included specimens representing eight commercial admixtures, seven of which were air-entraining in nature, and plain cement. The general indications are that air-entraining admixtures greatly improve the durability of concrete. Non-air-entraining admixtures tested in general showed little improvement in durability over plain portland-cement concrete, but did not adversely affect the improvement in durability shown by air-entraining admixtures when used in conjunction with them.

COMPARATIVE FIELD AND LABORATORY DURABILITY PROGRAM

This investigation will attempt to correlate the field exposure condition at Treat Island with laboratory freezing and thawing in the standard accelerated freezing-and-thawing equipment used in the laboratory, Wuerpel and Cook (1945).

For this program 300 specimens were installed at Treat Island in December, 1948. Half the specimens were 3-1/2 by 4-1/2 by 16-in. beams and half were 6 by 6 by 30-in. beams duplicating the smaller specimens. One-hundred and fifty 3-1/2 by 4-1/2 by 16-in. companion beams were frozen and thawed in the laboratory. Six coarse and eight fine aggregates were used.

It is felt that at least one more winter of exposure is necessary before definite trends can be developed and any positive correlation established. It may well be that no definite correlation exists and if so it also should be understood that any correlation with this particular exposure condition does not imply any correlation with any other natural weathering. However, a few general observations of indications to date may be of interest. Twenty-six aggregate combinations in the smaller beams and 35 aggregate combinations in the larger beams had relative moduli of over 90 per cent as of May, 1951, at Treat Island. The larger specimens appear to stand the exposure somewhat better than the smaller ones. Comparing the two exposures on a cycle basis, the laboratory test appears to be more severe, however, on a degree-cycle basis the Treat Island exposure appears more severe. Nine of the 48 aggregate combinations in the smaller specimens, of which six were with quartzite coarse and three with non-chert gravel coarse aggregates, showed greater deterioration at Treat Island after 355 cycles than did their companions after 300 cycles in the laboratory apparatus. A statistical analysis is now being made to determine the degree of correlation that may exist.

MISCELLANEOUS PROJECTS

Beam specimens from the Rome Air Depot, Rome, New York, and the Syracuse Air Depot, Syracuse, New York, with and without air-entrainment were exposed at Treat Island in 1941 and 1942. In both instances the plain cement concrete failed during the first winter and the air-entrained specimens are in sound condition. Some of the sound specimens have been removed to make room for additional specimens on the rack. Also, 42 specimens from the John Martin Dam, Caddoa, Colorado, were installed on the Treat Island rack in 1941. Twenty-four were columns made from wet-screened job concrete and 24 were cores from the downstream face of the dam. The purpose of the installation was to observe the influence of method of surface preparation on the durability of concrete. The columns were cast against oiled wood forms, and against two different types of absorptive form-lining. The cores represented surfaces cast against oiled wood forms, cast against one type of absorptive form-lining, and produced by screeding. The cores were exposed in boxes and were surrounded by fine gravel, only the formed or screeded surfaces being exposed to weathering. All specimens had either failed or were discontinued after two winters. The results indicated that the surfaces cast against absorptive form-linings tested were of appreciably greater durability than those obtained by the use of oiled wood forms or by screeding.

CONCLUSIONS

The results obtained from the exposure of more than 2500 concrete specimens to natural weathering over a 16-yr period are the basis for the following statements:

1. The entrainment of properly regulated quantities of air is the most important factor in the improvement of the durability of concrete under severe weathering conditions that has been developed by these investigations. At Treat Island well-made concrete of good quality materials will not ordinarily withstand the exposure for more than one winter unless the concrete contains the proper amount of entrained air.

2. The use of various non-air-entraining admixtures did not appear to be of material benefit in increasing the durability of plain concrete but were not harmful in that they did not appear to decrease the durability of air-entrained concrete.

3. The use of air entrainment does not protect concrete which contains unsound aggregate.

4. The blending of natural cement with plain portland cement greatly improves the durability of concrete if by so doing the proper amount of entrained air is produced in the concrete.

5. No definite trends in the effect of curing conditions on

durability have been revealed.

6. Aluminous cement produced highly durable concrete.

7. The use of absorptive form-lining improves the durability of concrete surfaces.

8. The quality of horizontal construction joints appears to be governed primarily by the quality of the concrete at the top of the lower lift.

9. The use of cement with a tricalcium aluminate content in excess of 12 per cent has resulted in concrete that is non-durable in warm sea water. The use of Type II cement with a tricalcium aluminate content less than 8 per cent appears warranted for such exposure.

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