Performance of Concrete at Treat Island, U.S.A.: CANMET Investigations

by V. Mohan Malhotra and Theodore W. Bremner

Synopsis: This paper deals with CANMET investigations on the performance of concrete with and without supplementary cementing materials in a marine environment. A series of more than 250 concrete prisms, 305 x 305 x 915-mm in size, were cast over a period of 16 years and installed at Treat Island, Maine, an outdoor exposure facility operated by the U.S. Army Corps of Engineers, U.S.A. The prisms of the first phase of the investigation were installed at the site in 1978 with the remaining specimens being installed at almost yearly intervals. The specimens of the latest phase were installed in 1994. The test prisms are installed at mid-tide level on a rack, and are exposed to repeated cycles of wetting and drying, and to about 100 cycles of freezing and thawing per year. The test specimens will be kept at the exposure site till at least year 2005. The test prisms are evaluated annually. The evaluation includes visual examination and rating, and ultrasonic pulse velocity testing. Also, a complete photographic record is kept.

Some of the principal conclusions based upon up to 17 years of exposure of some of the test prisms are as follows:

The use of non air-entrained concrete is not recommended for the exposure conditions experienced at Treat Island.

For the exposure conditions experienced at Treat Island, the percentage of silica fume in concrete should be limited to 10 per cent.

Both the normal-weight and semi-lightweight concretes incorporating fly ash or slag or silica fume or a combination of these materials are in good to excellent condition, provided water-to-cementitious materials ratio is kept below 0.50, and portland cement is kept at a certain minimum level.

There is no significant difference in the performance of concrete made with ASTM Types I, II, and V cements.

Keywords: Air-entraining cements; blast furnace slag; compressive strength; concretes; fibers; fly ash; freeze thaw durability; lightweight concretes; superplasticizers; underwater structures; water-reducing agents; wetting and drying tests

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INTRODUCTION

The Canada Centre for Mineral and Energy Technology (CANMET) has an ongoing program dealing with the long-term performance of supplementary cementing materials in concrete. The supplementary cementing materials being investigated include low- and high-calcium fly ashes, pelletized and granulated blast-furnace slags, silica fume, rice-husk ash, and metakaolin. In 1978, as part of this research program, CANMET initiated a study to determine the performance of concrete with and without some of the above supplementary cementing materials at Treat Island, Maine, an outdoor marine exposure facility operated by the U.S. Army Corps of Engineers, Vicksburg, Mississippi. Since then, a number of large non-reinforced concrete prisms 305 x 305 x 915-mm in size, incorporating different percentages of supplementary cementing materials have been installed at the above exposure site at almost yearly intervals. Also, a number of reinforced-concrete prisms were installed at the site in 1991.

As of August 1995, there were more than 250 prisms at the exposure site, and these prisms are being monitored yearly using visual examination and non-destructive test methods. In 1986, 1987, and 1994 reports and papers were published outlining the scope of the program and giving performance data on the conditions of the prisms (1,2,3). This paper presents a comprehensive account of the conditions of the test prisms, including the results of the last inspection which was held in August 1995. The investigations being performed by the U.S. Army Corps of Engineers at Treat Island are described elsewhere (4-11).

SCOPE

In this study, the water-to-cementitious materials ratios of the concrete, in general, ranged from 0.40 to 0.60, and the percentage replacement of portland cement by supplementary cementing materials ranged from 0 to 80 percent by mass. The details of the various phases are as follows:

Phase I:	Determination of performance of air-entrained concrete incorporating pelletized blast-furnace slag, and air-entrained and non air-entrained concretes incorporating high-range water-reducing admixtures (HRWRA) (superplasticizers). Test prisms installed at Treat Island	1978
Phase II:	Determination of the performance of air-entrained concrete incorporating fly ash and pelletized blast-furnace slag. Test prisms installed at Treat Island	1979
Phase III:	Determination of the performance of air-entrained semi-lightweight concrete incorporating pelletized blast-furnace slag. Test prisms installed at Treat Island	1980
Phase IV:	Determination of the performance of air-entrained concrete incorporating fly ash. Test prisms installed at Treat Island	1981
Phase V:	Determination of the performance of air-entrained concrete incorporating ground granulated blast-furnace slag (ggbfs), and air-entrained and non air-entrained concretes incorporating silica fume. Test prisms installed at Treat Island	1982
Phase VI:	Determination of the performance of air-entrained, semi-lightweight steel fibre-reinforced concrete incorporating fly ash and silica fume. Test prisms installed at Treat Island	1985
Phase VII:	Determination of the performance of semi-lightweight concrete incorporating silica fume. Test prisms installed at Treat Island	1986
Phase VIII:	Determination of the performance of high-volume fly ash concrete. Test prisms installed at Treat Island	1987

Phase IX:	Determination of the performance of steel reinforced concrete incorporating pelletized blast-furnace slag or fly ash or silica fume. Test prisms installed at Treat Island	1987
Phase X:	Determination of the performance of semi-lightweight concrete incorporating silica fume. Test prisms installed at Treat Island	1988
Phase XI:	Determination of the performance of semi-lightweight high-volume fly ash concrete. Test prisms installed at Treat Island	1990
Phase XII:	Determination of the performance of beams that were unreinforced, reinforced, or reinforced with epoxy-coated reinforcement. Beams installed at Treat Island	1991
Phase XIII:	Determination of the performance of high-volume fly-ash concrete (EPRI Project). Test prisms installed at Treat Island	1992
Phase XIV:	Determination of the performance of concrete containing silica fume and fly ash in controlling expansion and cracking of concrete due to alkali-silica reaction. Test prisms installed at Treat Island	1994

EXPOSURE CONDITIONS AT TREAT ISLAND, MAINE

In 1936, the Concrete Laboratory of the Passamaquoddy Tidal Power Project established an exposure site at Treat Island in Cobscook Bay near Eastport, Maine. This island is within a few kilometres of the Canadian border, and is at the entrance to the Bay of Fundy. At the site, the test prisms are positioned on a rack at mid-tide level so that they are exposed alternatively to a marine atmosphere and to immersion in sea water twice daily. The alternating condition of immersion and exposure to the air provides on an average over 100 cycles of freezing and thawing per year. By using the above facility, deterioration patterns occurring in a study can be related to the behavior of concrete in investigations performed at Treat Island over the past 50 years.

CONCRETE MIXTURES

The concrete for Phases I to XII mixtures were prepared under a CANMET contract, in the University of New Brunswick laboratory at Fredericton between 1978 - 1992 using a counter-current pan mixer; for the Phases XIII and XIV, the test prisms were made at CANMET, Ottawa, and were transported to the University of New Brunswick, Fredericton for installation at Treat Island, Maine. The details concerning the materials used and the mixture proportions are outlined below. The physical properties and chemical analysis of each of the materials used have been reported elsewhere (12-18).

Materials

Portland Cements

ASTM Types I and II cements were obtained from a plant in New Brunswick. The ASTM Type V cement was obtained from a plant in Quebec. The various types of cement used in different phases of the project are given in Table 1.

Aggregates

The characteristics of the fine and coarse aggregates used in the various phases of the investigation are described in Table 1. The fine aggregate was natural sand in all cases. In phases dealing with normal weight concretes, the coarse aggregate was either crushed limestone or river gravel with 19-mm nominal maximum size, except in phases I and II when river gravel with a nominal maximum size of 37.5 mm was used. In phases concerned with lightweight concretes, the coarse aggregate was expanded shale lightweight aggregate from various sources, with a nominal maximum size of either 12.5 or 19 mm. The gradings of the fine aggregates and the various types of coarse aggregate were within the limits of ASTM Standards.

Fly Ashes

For investigations of Phase II in 1979, the fly ash (ASTM Class F) was obtained from a plant in Detroit, MI; for the Phases IV, VA, VI, VIII, IX, XI and XIV, the fly ash was obtained from a plant in Lingan, Nova Scotia. For Phase XIII, the fly ashes were from the sources in the U.S.A.

Ground Blast-Furnace Slags

Pelletized blast-furnace slag was obtained from a plant in Hamilton, Ontario and granulated blast-furnace slag was from a plant at Sparrows Point, Maryland.

Silica Fume

The silica fume used in the various phases was of uncompacted form, and was obtained from a silicon and ferrosilicon plant in Becancour, Quebec.

Air-entraining Admixture

A sulphonated hydrocarbon air-entraining admixture was used throughout the investigations.

High-Range Water Reducing Admixture (Superplasticizer)

The high-range water reducing admixture (HRWRA) used throughout these investigations was a naphthalene-based product of Japanese or Canadian origin except for specimens SP5 and SP6 of Phase I when a melamine-based HRWRA was used.

Mixture Proportions

The mixture proportions for each phase are summarized in Tables 2 to 15. When supplementary cementing materials were incorporated into the mixtures, these were used as a direct replacement for cement by mass. All concrete mixtures without HRWRA were proportioned to give a slump of 75 ± 25 mm, whereas concrete mixtures with HRWRA were proportioned to produce slumps varying between 75 and 250 mm for the various phases. The target air content was 6 ± 1 percent for all air-entrained concrete mixtures. When lightweight aggregates were used, these were soaked in water for 24 hours prior to use in concrete. The mass of the aggregates are given in a saturated-surface dry basis with the exception of the lightweight aggregates which are given in an oven-dry basis.

PROPERTIES OF FRESH CONCRETE

The properties of the freshly-mixed concrete, i.e., temperature, slump, unit weight, and air content are given in Tables 2 to 15.

CASTING AND CURING OF TEST SPECIMENS

The large test prisms, 305 x 305 x 915-mm in size, were cast in two layers of equal depth with each layer vibrated with an internal vibrator. Upon completion of the vibration of the filled mold, the excess concrete was struck off with a wooden straight edge. As soon as the bleed water had evaporated, the concrete was floated with a wooden trowel, and the concrete covered with a sheet of plastic. The concrete prisms were demolded after 24 hours curing in the laboratory air, and then covered with a wet burlap and a plastic sheeting. After three days, the prisms were moved into the moist-curing room where they were stored on their ends. The high slag-content mixtures had a relatively slow rate of strength gain and as a result, additional moist curing was required before they could be moved. All prisms cast in 1978 were moist cured for 28 days, whereas all the subsequent prisms were moist cured for at least 90 days prior to being shipped to Eastport for subsequent transport by boat to Treat Island. A view of the concrete specimens installed at Treat Island, Maine is shown in Figs. 1 to 9.

In addition to the large prisms, a number of 152 x 305-mm cylinders were cast from each mixture for strength testing. The specimens were cast according to the ASTM procedures, and were kept in a moist-curing room until required for testing.

FREEZING-AND-THAWING RECORD FOR WINTER OF 1991/92 AT TREAT ISLAND

An XL-800 data logger was used to record temperatures at Treat Island from October 18, 1991 to March 31, 1992. Temperature sensors are located in the concrete at the centre of a 152 x 152 x 508-mm prism, and at 25 and 152 mm from the surface in a 305 x 305 x 915-mm prism. The prisms are located at mid-tide level, and subjected to repeated cycles of freezing and thawing during the winter months. The number of freezing-and-thawing cycles experienced at each of the sensors is shown in Table 16, and the temperature record in a graphical form is given in Fig. 5. The number of cycles of freezing and thawing the concrete is exposed to, is normally reported as the number of times the temperature at the centre of the 152 x 152 x 508-mm prism drops below -2.2°C. Using the above criteria, the number of freezing-and-thawing cycles was 75 for the winter of 1991/92.

TESTING OF HARDENED CONCRETE SPECIMENS

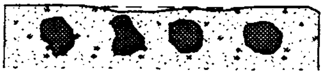
Large Prisms Installed at Treat Island

Visual Examination and Rating System

All test prisms are visually examined on an annual basis and evaluated using a rating system shown below. The detailed ratings are given in Tables 17 to 29.

RATING SYSTEM

RATING OF 0
Less than 15 aggregates are exposed



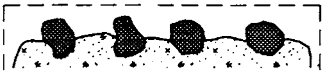
RATING OF 1
More than 15 aggregates are exposed

RATING OF 2
50% of the aggregates immediately below the surface are exposed

RATING OF 3
80% of the surface aggregates are exposed

RATING OF 4
Surface aggregates are exposed over 20% of their perimeter

RATING OF 5
90% of the surface aggregates are exposed over one half of their perimeter



RATING OF 6
95% of volume of specimen remaining

RATING OF 7
80% of volume of specimen remaining

RATING OF 8
50% of volume of specimen remaining

RATING OF 9
20% of volume of specimen remaining

RATING OF 10
Specimen disintegrated

Pulse-Velocity Measurements

Ultrasonic pulse-velocity measurements are also taken on the prisms on an annual basis using a portable digital unit. The velocities are measured between the centre of the prisms ends. The results of the pulse-velocity measurements obtained over periods up to 16 years are described elsewhere (13-15).

Laboratory Specimens

The 152 x 305-mm cylinders were tested in compression at various ages in the laboratory. The Young's modulus of elasticity E of concrete was determined on the cylinders at the age of 28 days. All tests were performed in accordance with the ASTM test procedures. The analysis of these test results will be the subject of a separate report, and only some selected results are presented in this report (Tables 2 to 15).

In terms of long-term durability of concrete, 10 to 15 years exposure is insufficient to fully evaluate the relative performance of concretes. However, given the very severe exposure conditions at Treat Island, some trends are clearly apparent even now, and these are discussed below.

DISCUSSION OF TEST RESULTS

Discussion of the test results will be limited to only those prisms which have been at the exposure site for at least 5 years. Thus the discussion will be limited to the test prisms of Phase I to X, and only passing reference will be made to the test prisms of the remaining Phases XI to XIV.

Phase I(A) - 1978

Phase I(A) was primarily concerned with the long-term performance of concrete incorporating pelletized blast-furnace slag. The percentages of the cement replacement by slag investigated were 25, 45, and 65 percent at water-to-cementitious materials ratios of 0.40, 0.50, and 0.60.

The test prisms with a water-to-cementitious materials ratio of 0.40, and incorporating 65 percent slag show very little surface deterioration. Regardless of the water-to-cement ratio, the control test prisms without slag made with either ASTM Type I or ASTM Type V portland cement, show little or no deterioration. Some slight scaling was observed for prisms with a water-to-(cement + slag) ratio of 0.50 and incorporating 65 percent slag. The test prisms with a water-to-(cement + slag) ratio of 0.60 and incorporating 45 percent slag also show slight scaling. As expected, significant scaling occurred for prisms with a water-to-(cement + slag) ratio of 0.60 and with 65 percent slag as a replacement for cement. In general, there is increasing surface

deterioration in all test prisms with increasing water-to-cementitious materials ratio, and increasing percentage replacement of cement with slag.
It is emphasized that in the extreme exposure conditions of the type being investigated, the specifications do not allow the use of water-to-cementitous materials ratios higher than 0.45. Notwithstanding the surface scaling, it can be concluded that up to 65 percent slag as a cement replacement in concrete mixtures with a water-to-cementitious ratio of 0.40 is an acceptable option. The above conclusions may have to be modified after 25 years of exposure.

Phase I(B) - 1978

The Phase I(B) investigations included a series of test prisms to examine the effect of long-term performance of both non air-entrained and air-entrained concretes.

The air-entrained prisms with or without HRWRA are in good condition after 17 years of exposure and have a visual rating of 2. The non air-entrained prisms with or without HRWRA started showing disintegration after 3 years. This, once again, stresses the importance of air-entrainment in critically water-saturated concrete exposed to repeated cycles of freezing and thawing.

Phase II - 1979

The purpose of this phase was to investigate the performance of concrete incorporating ASTM Class F fly ash and ground, pelletized blast-furnace slag. The fly ash was used as 25 percent replacement for cement in combination with the slag to replace up to 80 percent of the cement.

Control test prisms made with ASTM Type I, II, and V cements are in good to excellent conditions regardless of the water-to-cement ratio, and their visual rating ranges from 1 to 2. The effect of the cement type, if any, is not apparent.

No significant deterioration has been noticed to date on concrete prisms incorporating 25 percent fly ash; the visual rating for all of these prisms is 2.

Regardless of water-to-(cement + slag + fly ash) ratio, all test specimens containing 60 percent slag and 20 percent fly ash show unacceptable deterioration after sixteen years of exposure. Somewhat similar unacceptable deterioration but to a somewhat lesser degree, has been observed for concrete incorporating 40 percent pelletized slag and 20 percent fly ash. It appears that for the combination of the supplementary cementing materials used in this phase and for satisfactory performance under the exposure conditions at Treat Island, the air-entrained concrete must contain a minimum amount of cement, this being in the order of 200 to 250 kg/m^3 of concrete.