
1996

**THIRD
CANMET/ACI**

INTERNATIONAL • CONFERENCE • INTERNATIONALE



**PERFORMANCE OF
CONCRETE IN
MARINE
ENVIRONMENT**

**COMPORTEMENT DU
BÉTON EN
ENVIRONNEMENT
MARIN**

EDITOR • V.M. MALHOTRA • RÉDACTEUR EN CHEF

Documents

Document Sharing Hub

CANMET



Concrete in Marine Environment

Proceedings
Third CANMET/ACI International Conference
St. Andrews by-the-Sea, Canada
1996

SP-163
V. M. Malhotra
Editor

*Front cover: Northumberland Strait crossing bridge
under construction between Prince Edward Island
and New Brunswick, Canada in 1996.
Photo courtesy of Alain and Marlene Bailly*



Documents
Document Sharing Hub

DISCUSSION of individual papers in this symposium may be submitted in accordance with general requirements of the ACI Publication Policy to ACI headquarters at the address given below. Closing date for submission of discussion is February 1, 1997. All discussion approved by the Technical Activities Committee along with closing remarks by the authors will be published in the May/June 1997 issue of either ACI Structural Journal or ACI Materials Journal depending on the subject emphasis of the individual paper.

The Institute is not responsible for the statements or opinions expressed in its publications. Institute publications are not able to, nor intended to, supplant individual training, responsibility, or judgment of the user, or the supplier, of the information presented.

The papers in this volume have been reviewed under Institute publication procedures by individuals expert in the subject areas of the papers.

Copyright © 1996
AMERICAN CONCRETE INSTITUTE
P.O. Box 9094, 38800 International Way
Farmington Hills, Michigan 48333

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by any electronic or mechanical device, printed or written or oral, or recording for sound or visual reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietors.

Printed in the United States of America

Editorial production—Anne Sharp

Library of Congress catalog card number 96-85195

PREFACE

The Canada Centre for Mineral and Energy Technology (CANMET) of Energy, Mines, and Resources Canada, Ottawa, has played a significant role in Canada for over 20 years in research on durability of concrete. In August 1980, CANMET, in association with the American Concrete Institute, the U.S. Army Corps of Engineers, the University of New Brunswick, and several other professional organizations sponsored a five-day international conference at St. Andrews-by-the-Sea, New Brunswick, Canada, on the performance of concrete in marine environment. The purpose of the conference was to bring together representatives of the cement and concrete industries to exchange information on the effects of marine environment on plain and reinforced concrete, and to explore new areas of needed research and development. The proceedings of the conference containing 33 papers from more than 10 countries were published as ACI SP-65.

In 1988, CANMET, in association with the American Concrete Institute, University of New Brunswick, U.S. Army Corps of Engineers, and the Institute for Research in Construction (National Research Council), sponsored the Second International Conference on Performance of Concrete in Marine Environment. The conference was held August 21-26 at St. Andrews-by-the-Sea. ACI SP-109 is a record of the proceedings of the conference.

In 1996, CANMET, in association with the American Concrete Institute, the Institute for Research in Construction (National Research Council), Ottawa, the University of New Brunswick, Fredericton, NB, and the Canadian Portland Cement Association, sponsored the Third CANMET/ACI International Conference on the subject of Performance of Concrete in Marine Environment. The conference was held August 4-9 at St. Andrews-by-the-Sea. More than 35 papers from 10 countries were presented at the conference, and the proceedings were published in ACI SP-163.

As an integral part of the conference, a special symposium to honor Prof. Odd E. Gjrv of the Norwegian University of Science and Technology, Trondheim, Norway, was held on Tuesday, August 6. The symposium recognizes Prof. Gjrv's long-term contributions to the durability of concrete in marine environment. The symposium was chaired by Prof. P. K. Mehta of the University of Berkeley, California, and the proceedings of this symposium were published as a separate volume.

Thanks are extended to the members of the paper review panel which met in Las Vegas in 1995 to review the manuscripts.

The assistance of H. S. Wilson, consultant, Ottawa, Gordon D. Brearley,

and Maria Venturino of CANMET is gratefully acknowledged for administrative work associated with the conference, and for processing of the manuscripts both for the ACI proceedings and the supplementary volume. Thanks are also extended to A. Bilodeau (chairman) and Messrs. B. Fournier and R. Chevrier (members) of the Slide Review Panel for their services to insure that the slides met the CANMET/ACI criterion.

The support of Bryant Mather, Director, Structures Laboratory, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, and his associates in making it possible for the conference participants to visit the Natural Weathering Exposure Station at Treat Island, ME is gratefully acknowledged.

Thanks are also extended to Helayne Beavers, Managing Editor, Journals and Special Publications, ACI, and her staff for the work associated with the publication of the conference proceedings.

V. M. Malhotra, PEng
Chairman, Third CANMET/ACI
International Conference on Performance
of Concrete in Marine Environment
St. Andrews-by-the-Sea
August 1996

**Committee for the Organization of the Third CANMET/ACI
International Conference on Performance of Concrete
in Marine Environment**

**August 4-9, 1996
St. Andrews-by-the-Sea
New Brunswick, Canada**

V. M. Malhotra
Chairman

H. S. Wilson
Secretary-Treasurer

Members

T. W. Bremner
H. L. Isabelle
W. S. Langley
V. S. Ramachandran

Dedicated to members of the "Paper Review Panel" who assisted in the review of the manuscripts.

Review Panel Members—St. Andrews Conference—August 1996

N. Carino
National Institute of
Standards and Technology
Bldg. 226, Room B158
Gaithersburg, MD 20899
U.S.A.

J. T. Dikeou
American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48331
U.S.A.

G. Hoff
Mobil Research &
Development Corp.
P.O. Box 819047
Dallas, TX 75381
U.S.A.

Henri Isabelle
Lafarge Canada, Inc.
6150 Royalmount Ave.
Montréal, PQ
H4P 2R3

Joseph F. Lamond
3410 Southampton Dr.
Jefferson, VA 22724
U.S.A.

V. M. Malhotra
CANMET/NRCan
405 Rochester St.
Ottawa, Ontario
Canada K1A 0G1

Bryant Mather
Structures Laboratory
WES-SV-Z
3909 Halls Ferry Rd.
Vicksburg, MS 39180-6199
U.S.A.

P. K. Mehta
Civil Engineering Dept.
University of California
723 Davis Hall
Berkeley, CA 94720
U.S.A.

G. J. Osborne
Head of Concrete Durability
Section
Building Research
Establishment
Garston, Watford WD2 7JR
U.K.

P. Seabrook
Levelton Associates
Consulting Engineers
#1-12791 Clarke Place
Richmond, BC
Canada V6V 2H9

CONTENTS

PREFACE	iii
PERFORMANCE OF CONCRETE AT TREAT ISLAND, U.S.A.: CANMET INVESTIGATIONS by V. Mohan Malhotra and Theodore W. Bremner	1
FIRE RESISTANCE OF HIGH-STRENGTH CONCRETES FOR OFFSHORE CONCRETE PLATFORMS by George C. Hoff	53
CORROSION OF STEEL IN MARINE CONCRETE: LONG-TERM HALF-CELL POTENTIAL AND RESISTIVITY DATA by Daksh Baweja, Harold Roper, and Vute Sirivivatnanon	89
DEVELOPMENT OF APPARATUS FOR TESTING THE WASHOUT RESISTANCE OF UNDERWATER CONCRETE MIXTURES by Michal Ceza and Peter J. M. Bartos	111
CORROSION OF REINFORCING STEEL IN CONCRETE STRUCTURES SUBMERGED IN SEAWATER by L. Coppola, R. Fratesi, S. Monosi, P. Zaffaroni, and M. Collepardi	127
CONCRETE SHIPS—LESSONS LEARNED by Theodore W. Bremner, Thomas A. Holm, and Dudley R. Morgan	151
LONG-TERM DURABILITY OF CONCRETE BREAKWATERS IN COLD MARINE ENVIRONMENT by T. Horiguchi, N. Saeki, and H. Kudoh	171
THE EFFECT OF CRACKS ON REINFORCEMENT CORROSION IN HIGH-PERFORMANCE CONCRETE IN A MARINE ENVIRONMENT by Karin Pettersson, Oddny Jørgensen, and Per Fidjestøl	185
MARINE EXPOSURE OF CONCRETE UNDER SELECTED SOUTH AFRICAN CONDITIONS by James R. Mackechnie and Mark G. Alexander	201

A NEW CLASS OF CORROSION INHIBITORS FOR REINFORCED CONCRETE by U. Maeder	215
FIELD STUDIES OF CHLORIDE TRANSPORT INTO HIGH-PERFORMANCE CONCRETE by Paul Sandberg, Karin Pettersson, and Oddny Jørgensen	233
BEHAVIOR AND PROTECTION OF HYDROGEN EMBRITTLEMENT ON TENDONS OF PC MEMBERS by K. Ikawa, K. Ishii, T. Fukute, and H. Seki	255
PERFORMANCE CHARACTERISTICS OF AN ACRYLIC RUBBER PROTECTIVE COATING SYSTEM FOR CONCRETE DURABILITY IN A MARINE ENVIRONMENT by Shin Tanikawa, R. Narayan Swamy, and Tony Laiw	275
CHLORIDE ION PENETRATION AND FROST RESISTANCE OF HIGH-ALUMINA CEMENT (HAC) AND HAC/GROUND GRANULATED BLAST FURNACE SLAG CONCRETES IN MARINE ENVIRONMENTS by G. J. Osborne and B. Singh	295
CHLORIDE PENETRATION AND REINFORCEMENT CORROSION IN FLY ASH CONCRETE EXPOSED TO A MARINE ENVIRONMENT by M. D. A. Thomas and J. D. Matthews	317
DETERMINATION OF CHLORIDE DIFFUSION COEFFICIENT OF HIGH-PERFORMANCE CONCRETE BY ELECTRICAL POTENTIAL TECHNIQUE by T. Sugiyama, Y. Tsuji, Theodore W. Bremner, and C. Hashimoto	339
PERFORMANCE OF CORROSION PROTECTION SYSTEMS FOR REINFORCED CONCRETE EXPOSED TO MARINE CONDITIONS OF THE UNITED ARAB EMIRATES by Adnan Sharafi, Abdulghafoor Qasimi, and S. M. K. Chetty	355
OBSERVATIONS AND TESTING OF POST-TENSIONED BEAMS EXPOSED TO SEVERE WEATHERING FOR 33 YEARS by Morris Schupack and Edward F. O'Neil	383
INFLUENCE OF ACCELERATING ADMIXTURES ON THE DURABILITY OF DRY-MIX SHOTCRETE USED FOR REPAIRS IN A MARINE ENVIRONMENT by Michel Pigeon, Ann Lamontagne, and Caroline Talbot	409
DURABILITY OF CEMENTITIOUS MIXTURES USED FOR SEALING VOIDS IN RUBBLE-MOUND BREAKWATERS AND JETTIES by L. Z. Hales and D. E. Wilson	423
EFFECT OF TYPE OF SURFACE TREATMENT AND EPOXY COATING ON CORROSION ACTIVITY by Irina L. Kondratova, Theodore W. Bremner, and Şakir Erdoğan	447

FIELD PERFORMANCE OF PORTLAND CEMENT AND FLY ASH CONCRETE SUBJECTED TO FLOWING SEAWATER by Vute Sirivivatnanon, P. Marsh, and P. Nelson	463
INFLUENCE OF DIRECT ELECTRICAL CURRENT ON SPECIFIC VOLUME OF MORTAR IN SEAWATER by A. Le Floch and W. Hartt	481
HIGHLIGHTS OF THE SAPPORO INTERNATIONAL CONFERENCE ON CONCRETE UNDER SEVERE CONDITIONS—1995 by Koji Sakai	501
SI (Metric) TABLES	515
INDEX	517

SP 163-1

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

2 Malhotra and Bremner

ACI Honorary Member V. Mohan Malhotra is Program Principal, Advanced Concrete Technology Program, CANMET, Ottawa, Canada. He is a former member of the ACI Board of Direction and has served on numerous ACI committees. He is a prolific author, editor, and researcher, and has received many awards and honors from ACI and other institutions throughout the world.

ACI Fellow Theodore W. Bremner, P.Eng., is Professor of Civil Engineering, University of New Brunswick, N.B., Canada and is past-president of the Atlantic Chapter of the ACI. Professor Bremner is very active on the CSA and ACI technical committees, and is a member of the Fédération Internationale de la Précontrainte Commission on Lightweight Concrete. He has published numerous technical papers in ACI journals and proceedings. Currently, he Chairs the ACI Technical Committee on Lightweight Concrete.

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 |

4 Malhotra and Bremner

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

10 Malhotra and Bremner

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-cementitious 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/m³ of concrete.

Phase III - 1980

The purpose of this phase of the investigation was to determine the performance of air-entrained, semi-lightweight concrete incorporating up to 65 percent pelletized slag, with expanded shale as the coarse aggregate.

The air-entrained semi-lightweight concrete had a total cementitious material content ranging from 240 to 480 kg/m³ and the slag was used at cement replacement levels of 25, 45 and 65 percent. In general, regardless of the slag content, the concrete incorporating 480 and 360 kg/m³ of cementitious material has shown excellent performance and has a visual rating of 1 to 2. For concretes with total cementitious material content of only 240 kg/m³, the concrete prisms show significant deterioration which increases with an increase in the slag content.

In general, the pattern of deterioration for the semi-lightweight concrete seems to be different from that of normal-weight concrete. With normal-weight concrete, there appears to be a potential for the mortar over the aggregates to come off in a sporadic fashion indicating a plane of weakness at the aggregate-cement paste interface. With semi-lightweight concrete this is not noted, and deterioration occurs by a uniform loss of the surface layer. After 15 years, the lowest strength semi-lightweight concrete prisms show losses of up to 8 mm of mortar.

The quality and the type of slag used may have contributed to the poor performance of the above concretes at low cementitious material factors.

Phase IV - 1981

The phase was undertaken to monitor the long-term performance of concrete incorporating normal-weight aggregates and ASTM Class F fly ash. The water-to-cementitious materials ratios were 0.40, 0.50, and 0.60, and fly ash was used at 25 percent replacement level for cement.

After 14 years of exposure, the test prisms with a water-to-(cement + fly ash) ratio of 0.40 and 0.50 are in good to excellent conditions with a visual rating of 1 to 2. However, the test prisms with a water-to-cementitious materials ratio of 0.60 and incorporating fly ash show unacceptable surface deterioration with a visual rating of 4. This investigation, once again, stresses the need for low water-to-cementitious materials ratio for the type of exposure conditions encountered at Treat Island exposure site, especially in the case of concrete incorporating supplementary cementing materials.

Phase V(A) - 1982

This phase involved the evaluation of the performance of air-entrained concrete incorporating large volumes of blast-furnace slag from a U.S. source. The water-quenched, ground granulated slag, used as a replacement for cement was 80 percent, and the water-to-cementitious materials ratio investigated were 0.40, 0.50, and 0.60.

After 13 years of exposure, the test prisms with water-to-cementitious materials ratio of 0.40 and 0.50 are in excellent condition, and have a visual rating of 1. The prisms with water-to-cementitious materials of ratio 0.60 show some surface scaling, and have a visual rating of 3. The performance of the test prisms in this phase is superior to the performance of slag concrete investigated in Phases I, II and III, and is probably due to the different types of slags used. Previous CANMET studies have indicated that these slags have very different physical and mechanical properties such as fineness and compressive-strength development (14). Further research is needed in this direction.

Phase V(B) - 1982

This phase involved the determination of the long-term durability of air-entrained and non air-entrained concrete incorporating silica fume either as a direct replacement for cement or as an addition to cement. In either case, the percentages of silica fume used were 0, 10, 15, and 20 by mass of portland cement.

After 13 years of exposure, the air-entrained test prisms incorporating up to 10 percent silica fume either as a direct replacement or as an addition are in good to excellent condition with visual rating of 2. Beyond this percentage of silica fume, there is significant surface scaling of test prisms, and this increases with the increasing percentage of silica fume used.

All non air-entrained concrete prisms show serious damage regardless of the manner in which silica fume is used, and the visual rating of these prisms is 7. This confirms previously CANMET published data (18). It is recommended that all silica fume concretes must be air-entrained to resist severe frost action and the type of exposure at Treat Island; it is further recommended that the percentage of silica fume in concrete should not exceed 10 percent.

Phase VI - 1985

This phase was undertaken to evaluate the performance of air-entrained, semi-lightweight concrete incorporating 50-mm long steel fibres. The nominal cementitious material content of the mixtures investigated were 375, 500, and

625 kg/m³ including 13.5 percent fly ash and 6.5 percent silica fume. The steel fibres were used at the rate of 2.5 percent by mass of concrete.

After ten years of exposure, all concretes, regardless of the cementitious material factors, are in good to excellent condition, and show no distress. In general, the visual rating of the prisms is 2.

Phase VII (Ready-mixed Concrete) - 1986

This phase dealt with the evaluation of high-strength semi-lightweight concrete incorporating silica fume as an addition. The air-entrained concrete was made at a commercial ready-mixed plant, and the cementitious material factors used were 530 and 430 kg/m³ including 6 and 7.5 percent silica fume, respectively.

Regardless of the cementitious materials content, and irrespective of the amount of silica fume used, the test prisms are in excellent condition after nine years of exposure, with a visual rating of 1.

Phase VIII - 1987

This phase involved the evaluation of high-volume fly-ash concrete. Typically, in this low cement-content concrete, large volumes of ASTM Class F fly ash (56 percent by mass of cement) are incorporated into concrete, and the water-to-cementitious materials ratio is kept at about 0.30. The high slumps are achieved with the use of large dosages of a superplasticizer. In this investigation, air-entrained concretes were made incorporating 56 percent of fly ash by mass of cement and with water-to-cementitious materials ratios of 0.31 and 0.35. The nominal cement and fly ash contents were 155 and 200 kg/m³ respectively, in both cases.

After eight years of exposure, the concretes with a water-to-cementitious ratio of 0.31 are in excellent condition but concretes with water-to-cementitious ratio of 0.35 show considerable scaling. The visual ratings are 1 and 3, respectively. Based upon the laboratory experience, it is recommended that for the type of exposure at Treat Island, the water-to-cementitious materials ratio of high-volume fly ash concrete must not exceed 0.30 ± 0.02 .

Phase IX - 1987

This phase involves the evaluation of steel-reinforced, normal-weight concrete with a water-to-cementitious materials ratio of 0.50 and incorporating 50 percent slag, or 25 percent fly ash or 10 percent silica fume as a replacement for cement. The steel reinforcing bars were 20 mm in diameter, and the concrete cover was 20, 30, 40, 50, 60, and 70 mm. The slag was from a source

in southern Ontario, the fly ash was from a source in Nova Scotia, and the silica fume was from a source in Quebec.

The air-entrained control test prisms are performing well after eight years of exposure. The concrete prisms incorporating supplementary cementing materials are showing some slight surface scaling.

Phase X - 1988

This phase was undertaken to determine the comparative performance of semi-lightweight silica-fume concrete made with lightweight aggregates from sources in Canada, Germany, and the U.S.A. All three aggregates were of the expanded shale type and in each case, the nominal maximum size was 12.5 mm. The water-to-cementitious materials ratio was 0.40 with cement and silica fume content of 415 and 30 kg/m³, respectively. The concrete was air-entrained and contained a HRWRA.

Notwithstanding that the test prisms are in good condition, the short duration of seven years of exposure is insufficient to draw any conclusions as to the comparative performance of the concrete incorporating different types of lightweight aggregates. All specimens show some loss of surface mortar.

Phase XI - 1990

This phase was undertaken to determine the comparative performance of semi-lightweight, high-volume fly-ash concrete made with aggregates from sources in Canada, Germany, and the U.S.A. As in Phase X, all three aggregates were of the expanded shale type with a nominal maximum size of 12.5 mm. The concrete was air-entrained, and a high dosage of HRWRA was used to obtain high slumps (175 mm).

The short duration of two years of exposure does not allow any conclusions to be drawn.

Phase XII - 1991

This phase is a joint CANMET/3M Canada Ltd. project, and deals with the relative performance of air-entrained concrete beams reinforced with uncoated steel reinforcement and epoxy-coated steel reinforcement. Also, unreinforced plain concrete beams were cast for reference purposes. The water-to-cement ratios for the concrete were 0.45 and 0.60 with cement factors of 380 and 275 kg/m³, respectively. No supplementary cementing materials were incorporated into the concrete.

The duration of exposure is too short to draw any conclusions.

Phase XIII - 1992

This phase is a joint CANMET/Electric Power Research Institute (EPRI, Palo Alto, U.S.A.) undertaking, and deals with the performance of air-entrained, high-volume fly ash concrete incorporating ASTM Class F fly ash from eight different sources in the U.S.A. The water-to-cementitious materials ratio was 0.30 with nominal cement and fly ash contents of 150 and 210 kg/m³, respectively. Large dosages of HRWRA were used to achieve high slumps.

The duration of exposure is too short to draw any conclusions.

Phase XIV - 1994

This phase is a part of research program undertaken by CANMET for the CANMET/Industry Research Consortium on Alkali-Aggregate Reactivity. The main objective of this work is to evaluate the long-term effectiveness of silica fume and fly ash in controlling expansion and cracking of concretes incorporating an alkali-reactive greywacke from Nova Scotia. The fly ash and silica fume were incorporated into the concrete at cement replacement levels of 20 and 30% and 10 and 15%, respectively. The water-to-cementitious materials ratio of the concrete was 0.40.

The duration of exposure is too short to draw any conclusions.

CONCLUDING REMARKS

The following conclusions are based on the visual evaluation of the performance of concrete after periods up to a maximum of 17 years at Treat Island. Some of these conclusions may have to be reconsidered after the specimens have been at the site for more than 25 years.

Phase I

Concretes made with ASTM Types I and V perform equally well at the Treat Island exposure facility.

Concrete prisms incorporating up to 65 percent pelletized blast-furnace slag as replacement for portland cement show satisfactory performances provided the water-to-cementitious materials ratio is of the order of 0.40.

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

16 Malhotra and Bremner

Phase II

Concrete incorporating high volumes of supplementary cementing materials shows considerable degree of deterioration. It appears that, for the combination of the 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 of the order of 200 to 250 kg/m³.

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

Phase III

Semi-lightweight concrete made with expanded-shale aggregate and having a cementitious material content of 360 kg/m³ or greater shows excellent performance after 13 years of exposure.

Phase IV

For the exposure conditions experienced at Treat Island, concrete incorporating 25 percent fly ash as replacement for cement must have a water-to-cementitious materials ratio of 0.50 or lower.

Phase V

After 13 years of exposure, concrete prisms incorporating 80 percent ground granulated blast-furnace slag as replacement for cement and with water-to-cementitious materials ratio of 0.50 or lower show excellent performance; however, prisms with water-to-cementitious materials ratio of 0.60 show some surface scaling.

It is recommended that all silica-fume concretes be air entrained to resist freezing-and-thawing in the type of exposure at Treat Island; and it is further recommended that the percentage of silica fume in concrete be limited to 10 percent.

Phase VI

Regardless of the cementitious material factors, the semi-lightweight steel fibre- reinforced concrete prisms with and without supplementary cementing materials, show good to excellent performance after ten years of exposure.

Phase VII

After nine years of exposure, the semi-lightweight concrete prisms incorporating up to 7.5 percent silica fume and having a cement factor of 430 kg/m³ and higher, show excellent performance with little or no deterioration.

Phase VIII

After eight years of exposure, high-volume fly-ash concrete with a water-to-cementitious materials ratio of 0.31 is shown to perform well. However, at higher water-to-cementitious materials ratio, it has started to exhibit considerable scaling.

Phase X to XIV

The duration of exposure for these phases is considered too short to allow any conclusions to be drawn.

ACKNOWLEDGEMENTS

The support of the U.S. Army Corps of Engineers in allowing the use of the facilities at the Treat Island Natural Weathering Exposure Station is gratefully acknowledged.

REFERENCES

1. Malhotra, V.M., Carette, G.G., and Bremner, T.W. "Durability of Concrete Containing Supplementary Cementing Materials in Marine Environments" ACI Special Publication SP 100, 1987, pp. 1227-1258, 1987. (Editor: John M. Scanlon).
2. Malhotra, V.M., Carette, G.G., and Bremner, T.W. "CANMET Investigations Dealing with the Performance of Concrete Containing Supplementary Cementing Materials at Treat Island, Maine". Proceedings, P.K. Mehta Symposium on Durability of Concrete, Nice, France, pp. 291-335, 1994.
3. Malhotra, V.M., Carette, G.G., and Bremner, T.W. "Current Status of CANMET's Studies on the Durability of Concrete Containing Supplementary Cementing Materials in Marine Environment"; ACI SP 109, 1988, pp. 31-72 (Ed. V.M. Malhotra).

4. Kennedy, T.B., and Mather, K. "Correlation Between Laboratory Accelerated Freezing and Thawing and Weathering at Treat Island, Maine"; ACI Journal, Proc. Vol. 50, 1953, pp. 141-172.
5. Cook, H.K. "Experimental Exposure of Concrete to Natural Weathering in Marine Locations"; ASTM Proc. Vol. 52, 1952, pp. 1169-1180.
6. Thornton, Henry J., Jr. "Natural Weathering Exposure Station for Concrete and Concreting Materials--Treat Island, Maine"; ACI SP 65, 1980, pp. 83-94 (Ed. V.M. Malhotra).
7. Scanlon, John M., Jr. "Current Program and Future Corps of Engineers Plans for the Treat Island Exposure Station"; ACI SP 65, 1980, pp. 95-101 (Ed. V.M. Malhotra).
8. Mather, K. "Concrete Weathering at Treat Island, Maine"; ACI SP 65, 1980, pp. 101-112 (Ed. V.M. Malhotra).
9. O'Neil, Edward F. "Study of Reinforced Concrete Beams Exposed to Marine Environment"; ACI SP 65, 1980, pp. 113-132 (Ed. V.M. Malhotra).
10. Schupack, M. "Behaviour of 20 Post-Tensioned Test Beams Subject to Up To 2200 Cycles of Freezing and Thawing in the Tidal Zone at Treat Island, Maine"; ACI SP 65, 1980, pp. 133-152 (Ed. V.M. Malhotra).
11. Lamond, J. and Lee, M.K. "Field Exposure of Concrete to Severe Natural Weathering"; ACI SP 122, 1990, pp. 201-212.
12. Malhotra, V.M., Carette, G.G. and Bremner, T.W. "CANMET Investigation Dealing With the Performance of Concrete Containing Supplementary Cementing Materials at Treat Island, Maine"; CANMET Division Report MSL 92-69 (OP&J) Draft, 1992, Energy, Mines and Resources Canada, Ottawa.
13. CANMET contract report 016SQ.23440-5-1044, Annual Testing of Concrete Specimens at Treat Island, Maine, 1995.
14. CANMET contract report 003SQ.23440-3-9326, Annual Testing of Concrete Specimens at Treat Island, Maine, 1994.
15. EPRI TR-103151 Project 3176-06 Final Report, Investigation of High-Volume Fly Ash Concrete System, October 1993.

16. CANMET/Industry Research Consortium on Alkali-Aggregate Reactions: Second Progress Report, Spring 1995, CANMET, Natural Resources Canada, Ottawa.
17. Malhotra, V.M. "Comparative Evaluation of three Different Granulated Slags in Concrete"; Report MSL 87-50 (OP), CANMET, Energy, Mines and Resources Canada, Ottawa.
18. Malhotra, V.M. "Mechanical Properties and Freezing and Thawing Resistance of Non Air-entrained and Air-entrained Condensed Silica Fume Concrete using ASTM Test C 666, Procedures A and B"; ACI Special Publication SP-91, 1986, pp. 1069-1094. (Editor: V.M. Malhotra).

TABLE 1—TYPES OF MATERIALS USED IN CANMET RESEARCH PROGRAM

Phase	No. of Prisms	Year	Cement Type (ASTM)	Fine Aggregate	Coarse Aggregate	Fly Ash	Slag	Silica Fume	Others
I(A)	30	1978	I, V	natural sand	gravel, 37.5-mm nom. max. size	-	x	-	-
I(B)	6	1978	I	natural sand	gravel, 37.5-mm nom. max. size	-	-	-	superplasticizer
II	33	1979	I, II, V	natural sand	expanded shale 25-mm nom. max. size	x	x	-	-
III	30	1980	I, V	natural sand	crushed dolomitic limestone 19-mm nom. max. size	-	x	-	-
IV	15	1981	I, V	natural sand	crushed dolomitic limestone 19-mm nom. max. size	x	-	-	-
V(A)	12	1982	I	natural sand	expanded shale, 25-mm nom. max. size	x	-	-	-
V(B)	12	1982	I	natural sand	expanded shale, 25-mm nom. max. size	-	-	x	-
VI	15	1985	I	natural sand	expanded shale, 25-mm nom. max. size	x	-	x	steel fibres
VII	6	1986	I	natural sand	expanded shale, 25-mm nom. max. size	-	-	x	-
VIII	8	1987	I	natural sand	gravel, 19-mm nom. max. size	x	-	-	-
IX	8	1987	I	natural sand	gravel, 19-mm nom. max. size	x	x	x	steel reinforcement
X	6	1988	I	natural sand	expanded shale, N.B. expanded shale, N.Y. expanded shale, Germany	-	-	x	-
XI	6	1990	I	natural sand	expanded shale, N.B. expanded shale, N.Y. expanded shale, Germany	x	-	-	-
XII	16	1991	I	natural sand	crushed limestone	-	-	-	steel reinforcement
XIII	28	1992	I	natural sand	crushed limestone	x	-	-	-
XIV	12	1994	I	natural sand	crushed greywacke	x	-	x	see note below

Note: A naphthalene-based HRWRA was used in concrete mixtures incorporating silica fume.

TABLE 2—MIX PROPORTIONS AND PROPERTIES OF FRESH AND HARDENED CONCRETE, PHASE I

Mixture Series	w/(C+BS)*	ASTM Cement Type	Batch No.	Batch Quantities [†] , kg/m ³							Properties of Fresh Concrete			Compressive Strength of Test Cylinders, MPa			
				Water	Cement	Slag	Fine agg.	Coarse agg.	A.E.A., mL/m ³	HRWRA, mL/m ³	Slump, mm	Density, kg/m ³	Air content, %				
A	0.40	Type I	1	158	396	0	590	1196	360	-	70	2340	5.6	32.0			
			2	160	292	97	576	1176	580	-	55	2300	7.0	29.8			
			3	178	318	97	553	1138	480	-	90	2290	6.6	29.3			
			5	176	443	0	558	1146	430	-	90	2320	6.5	29.0			
			6	176	243	199	556	1141	870	-	75	2320	6.8	28.6			
			7	175	243	199	554	1138	860	-	55	2310	6.4	30.5			
			9	177	445	0	558	1147	370	-	90	2330	5.8	30.3			
			10	176	154	287	553	1137	1130	-	55	2310	6.0	29.5			
			11	179	155	290	536	1102	1120	-	75	2250	6.4	27.2			
			13	157	392	0	600	1196	490	-	70	2350	6.2	33.6			
			B	0.50	Type I	1	161	329	0	641	1168	280	-	90	2300	6.5	27.2
						2	161	244	82	638	1162	380	-	100	2290	6.7	27.1
						3	161	247	82	644	1173	340	-	90	2310	5.9	27.9
5	161	320				0	608	1224	260	-	85	2370	5.5	24.4			
6	166	183				150	629	1179	450	-	75	2310	6.4	25.6			
7	166	183				150	629	1178	450	-	70	2300	6.8	28.1			
9	167	335				0	656	1184	350	-	75	2340	6.5	27.1			
10	166	116				215	634	1173	590	-	75	2300	7.0	22.7			
11	167	117				217	640	1165	540	-	65	2320	5.6	23.5			
13	157	314				0	659	1203	350	-	85	2330	6.2	32.0			
C	0.60	Type I				1	170	282	0	688	1222	270	-	90	2360	5.8	24.0
						2	167	209	70	674	1209	320	-	100	2330	6.4	25.7
						3	168	209	70	676	1210	300	-	100	2330	5.5	24.8
			5	160	276	0	650	1248	260	-	75	2320	5.7	26.5			
			6	160	147	120	650	1249	390	-	75	2330	5.2	26.2			
			7	158	145	119	641	1231	440	-	90	2290	6.5	25.5			
			9	160	266	0	647	1243	260	-	90	2320	5.4	22.7			
			10	160	94	174	638	1250	380	-	90	2320	5.5	19.5			
			11	160	93	173	636	1246	380	-	90	2310	6.2	19.8			
			13	163	272	0	656	1270	260	-	100	2370	5.4	25.4			
			SP	0.50	Type I	1	167	334	-	654	1182	280	0	80	2340	5.6	28.0
						2	166	332	-	649	1172	280	4720**	collapse**	2320	6.3	24.2
						3	174	348	-	682	1232	0	6580**	collapse**	2440	0.9***	34.9
4	174	349				-	683	1233	0	0	60	2440	1.5***	34.7			
5	165	335				-	647	1169	280	9730***	collapse**	2310	6.2	29.4			
6	172	345				-	675	1219	0	16550***	collapse**	2410	0.3***	33.7			

* Water/(cement + slag) by weight.
 ** Naphthalene-based HRWRA was used.
 *** Melamine-based HRWRA was used.
 † Note that A.E.A. and HRWRA are in mL/m³.

TABLE 3—MIX PROPORTIONS AND PROPERTIES OF FRESH AND HARDENED CONCRETE, PHASE II

Mixture Series	W/(C + BFS + F)*	ASTM Cement Type	Batch No.	Batch Quantities†, kg/m³							Properties of Fresh Concrete			Compressive Strength of Test Cylinders, MPa
				Water	Cement	Slag	Fly ash	Fine agg.	Coarse agg.	A.E.A., mL/m³	Slump, mm	Density, kg/m³	Air content, %	
D	0.40	Type I	1	158	395	0	0	611	1256	390	55	2420	6.0	33.0
			2	150	281	0	94	580	1192	960	75	2290	6.2	24.0
			3	150	281	0	94	580	1192	960	60	2290	6.4	26.0
			5	164	411	0	0	586	1198	370	55	2350	5.3	33.7
			6	160	161	161	80	563	1152	1290	50	2270	6.4	26.4
			7	160	161	161	80	564	1152	1290	65	2270	5.8	24.3
			9	164	411	0	0	582	1198	420	80	2350	5.7	29.2
			10	165	83	247	82	564	1161	2130	55	2300	6.2	18.6
			11	168	84	252	84	554	1138	1910	60	2270	5.5	19.1
			13	153	384	0	0	551	1245	310	100	2340	6.6	32.3
			16	148	370	0	0	530	1319	270	85	2370	5.4	29.9
	0.50	Type I	1	160	320	0	0	664	1208	160	100	2350	5.2	29.7
			2	160	240	0	80	662	1211	590	95	2340	5.2	24.0
			3	154	231	0	77	637	1213	640	100	2310	6.6	20.1
			5	149	298	0	0	657	1260	150	100	2370	5.0	27.3
			6	160	128	128	64	686	1163	640	85	2320	6.9	22.2
			7	152	122	122	61	652	1185	610	100	2290	6.3	22.0
			9	148	297	0	0	656	1257	180	85	2350	5.6	26.6
			10	143	57	171	58	611	1246	770	95	2290	6.9	16.2
			11	147	59	176	59	628	1241	680	85	2310	6.2	17.3
			13	152	304	0	0	657	1258	290	50	2370	5.5	28.6
			16	149	297	0	0	629	1233	320	55	2310	6.8	24.5
	0.60	Type I	1	148	246	0	0	724	1247	140	80	2370	5.3	23.2
			2	145	182	0	61	713	1229	440	100	2340	5.2	18.9
			3	139	174	0	58	743	1179	490	90	2290	6.7	15.7
			5	139	233	0	0	744	1179	210	19.3	2310	6.5	19.3
			6	146	97	97	49	745	1166	540	95	2310	6.5	19.6
			7	145	98	98	49	666	1239	490	100	2290	6.5	17.0
			9	137	226	0	0	767	1147	190	75	2270	6.5	17.9
			10	138	46	137	46	775	1160	540	85	2310	6.4	12.6
			11	136	46	136	45	770	1152	500	75	2290	6.5	12.7
			13	135	225	0	0	745	1230	170	60	2340	6.0	20.3
			16	126	209	0	0	729	1203	200	75	2270	6.9	19.6

* Water/(cement + slag + fly ash) by mass.

† Note that A.E.A. is in mL/m³.

TABLE 4—MIX PROPORTIONS AND PROPERTIES OF FRESH AND HARDENED CONCRETE, PHASE III

Mixture Series	(C+BFS)* kg/m ³	ASTM Cement Type	Batch No.	Batch Quantities ¹ , kg/m ³					Properties of Fresh Concrete			Compressive Strength of Test Cylinders, MPa	
				Total water	Cement	Slag	Fine agg.	Coarse agg. ²	A.E.A. ³ , mL/m ³	Slump ⁴ , mm	Density, kg/m ³		Air content, %
G	0.40	Type I	1	212	240	0	866	583	70	70	1910	6.5	17.9
			3	215	183	61	869	589	78	75	1920	6.5	19.0
			4	219	184	62	870	589	75	85	1920	5.2	21.5
			6	210	241	0	871	585	71	65	1910	6.1	18.7
			7	210	135	111	877	596	92	55	1940	5.4	20.5
			8	207	133	109	864	587	94	70	1910	6.5	17.4
			10	204	239	0	864	581	78	65	1890	6.6	19.3
			11	207	84	157	856	583	99	90	1890	7.0	12.8
			12	209	85	158	868	592	94	75	1910	5.7	15.9
			14	202	241	0	871	586	125	90	1910	5.6	20.8
		Type V											
H	0.50	Type I	1	215	356	0	777	589	102	75	1940	5.6	29.4
			3	222	268	90	764	590	121	75	1940	6.0	33.3
			4	226	263	88	751	580	119	95	1910	7.0	30.2
			6	221	353	0	771	585	113	75	1940	6.0	31.0
			7	220	198	162	750	587	155	90	1920	6.7	35.6
			8	221	199	163	753	589	140	85	1920	6.8	34.6
		Type V	10	217	355	0	774	588	113	75	1940	6.8	29.4
			11	209	129	239	747	592	191	75	1920	6.8	32.5
			12	215	128	238	761	598	167	70	1940	6.0	30.3
			14	200	352	0	759	595	194	80	1910	7.0	35.5
I	0.60	Type I	1	222	473	0	661	571	151	85	1920	5.8	36.5
			3	224	360	129	653	574	195	85	1940	6.3	39.4
			4	225	363	121	659	578	178	75	1940	5.8	45.7
			6	247	474	0	646	568	198	65	1920	5.7	37.4
		Type V	7	247	261	214	616	565	231	75	1910	5.5	39.9
			8	243	261	214	616	565	252	85	1910	5.6	42.6
			10	221	469	0	655	567	173	90	1910	7.0	33.2
			11	214	166	307	628	565	266	95	1870	6.0	32.7
Type V	12	220	169	314	641	577	272	85	1920	5.5	36.6		
	14	211	465	0	648	576	351	75	1910	6.9	36.6		

* Nominal content of (cement + slag)

¹ (lightweight)

² Note that A.E.A. is in mL/m³

TABLE 5—MIX PROPORTIONS AND PROPERTIES OF FRESH AND HARDENED CONCRETE, PHASE IV

Mixture Series	W/(C + FA)*	ASTM Cement Type	Batch No.	Batch Quantities [†] , kg/m ³						Properties of Fresh Concrete			Compressive Strength of Test Cylinders, MPa	
				Water	Cement	Fly ash	Fine agg.	Coarse agg.	A. E. A., mL/m ³	Slump, mm	Density, kg/m ³	Air content, %	28-day	90-day
J	0.40	Type I	1	178	440	0	586	1128	415	90	2320	6.6	36.7	38.5
			2	178	440	0	586	1128	376	85	2330	6.6	33.6	41.8
			4	170	318	106	529	1140	832	100	2260	7.0	31.1	35.0
			5	163	305	101	507	1239	683	80	2310	6.8	31.4	38.0
			7	171	429	0	605	1214	367	80	2420	5.0	39.9	46.9
K	0.50	Type I	1	174	348	0	639	1211	306	75	2370	5.5	30.8	35.0
			2	173	346	0	635	1204	333	80	2360	6.2	29.9	33.9
			4	163	244	81	625	1249	519	70	2360	5.2	30.0	38.2
			5	160	240	80	632	1244	590	65	2350	6.1	25.8	33.6
			7	156	311	0	688	1226	337	95	2380	6.0	29.6	32.8
L	0.60	Type I	1	159	263	0	730	1217	229	75	2370	6.0	26.9	29.1
			2	160	260	0	737	1201	226	100	2360	6.0	23.3	27.4
			4	148	183	61	742	1225	425	80	2360	6.1	20.4	24.7
			5	149	184	61	760	1226	426	65	2380	5.8	18.9	25.4
			7	147	244	0	777	1241	255	65	2410	5.3	24.9	27.7

* Water/(cement + fly ash) by mass

† Note that A. E. A. is in mL/m³

TABLE 6—MIX PROPORTIONS AND PROPERTIES OF FRESH AND HARDENED CONCRETE, PHASE V

Mixture Series	W/(C+BFS) or W/(C+SF)*	ASTM Cement Type	Batch No.	Batch Quantities [†] , kg/m ³							Properties of Fresh Concrete			Compressive Strength of Test Cylinders, MPa		
				Water	Cement	Slag	Silica fume	Fine agg.	Coarse agg.	A.E.A., mL/m ³	HRWRA,** mL/m ³	Slump, mm	Density, kg/m ³	Air content, %	28-day	90-day
M	0.40	Type I	1	174	435	0	-	581	1120	435	0	95	2310	6.5	29.2	39.5
			2	177	443	0	-	590	1137	407	0	90	2350	5.9	36.9	35.5
			3	179	89	357	-	571	1146	1193	849	80	2340	5.8	36.8	38.1
			4	177	88	354	-	567	1137	1906	1183	95	2320	6.2	34.7	38.6
N	0.50	Type I	1	164	329	0	-	729	1147	246	0	90	2360	6.3	30.4	35.5
			2	163	327	0	-	726	1143	235	0	70	2360	5.6	32.1	37.7
			3	162	65	259	-	710	1130	661	333	80	2320	6.0	28.8	32.3
			4	160	64	256	-	701	1115	1031	343	100	2290	6.7	26.5	30.5
O	0.60	Type I	1	154	260	0	-	751	1148	143	0	90	2350	5.2	28.0	31.2
			2	155	257	0	-	754	1194	177	0	75	2360	5.5	26.1	31.0
			3	151	50	202	-	724	1159	456	0	110	2290	6.3	19.9	23.8
			4	153	51	204	-	733	1174	389	0	100	2320	6.1	22.9	26.1
P	0.60	Type I	1	157	260	-	0	802	1101	203	0	80	2320	6.4	26.5	30.1
			2	155	257	-	26	767	1087	368	957	75	2290	6.5	33.5	36.6
			3	158	262	-	39	764	1105	468	2248	80	2330	5.3	35.7	36.4
			4	157	259	-	52	742	1095	776	2894	90	2300	6.3	38.4	44.0
Q	0.60	Type I	1	146	243	-	0	804	1125	196	0	75	2310	6.3	25.4	28.2
			2	146	218	-	26	799	1125	417	1572	65	2320	6.3	34.6	35.9
			3	146	206	-	39	790	1125	540	2525	85	2300	6.5	36.2	41.6
			4	147	196	-	52	791	1135	672	2674	70	2330	6.0	38.9	41.8
R	0.60	Type I	1	167	278	-	0	838	1129	0	0	50	2410	1.5	36.0	39.8
			2	171	256	-	28	848	1159	0	3250	90	2460	1.1	43.7	47.9
			3	170	240	-	43	837	1149	0	4236	100	2430	0.9	44.8	48.3
			4	170	226	-	56	834	1149	0	4409	85	2430	1.1	44.9	42.1

* Water/(cement + slag) by weight or water/(cement + silica fume) by mass.

** Naphthalene-based superplasticizer was used.

† Note that A.E.A. and HRWRA are in mL/m³.

TABLE 7—MIX PROPORTIONS AND PROPERTIES OF FRESH AND HARDENED CONCRETE, PHASE VI

Mixture Series	Nominal Cement Content, kg/m ³	ASTM Cement Type	Batch No.	Batch Quantities [†] , kg/m ³								Properties of Fresh Concrete			Compressive Strength of Test Cylinders, MPa	
				Water	Cement	Fly Ash	Silica Fume	Fibre	Fine agg.	Coarse agg.	A.E.A., mL/m ³	HRWRA, mL/m ³	Slump, mm	Density, kg/m ³		Air content, %
S	630	I	1	238	492	84	39	0	527	561	2410	5360	Collapse	1950	5.5	53.9
			2	243	502	85	40	0	493	573	1684	2882	"	1950	5.7	54.6
			5	244	632	0	0	0	508	577	652	2740	"	1960	6.0	49.9
			6	253	501	85	40	50	403	584	958	5196	"	1920	6.4	56.8
			7	252	505	86	40	51	407	589	912	5990	"	1940	5.0	56.8
			1	227	408	70	33	0	587	606	594	2716	"	1940	5.5	53.0
			2	228	408	69	32	0	582	601	657	2712	"	1920	5.5	49.1
T	510	I	5	230	509	0	0	0	612	600	361	2462	"	1950	6.1	46.2
			6	245	391	66	31	49	570	598	518	3710	"	1960	5.0	50.0
			7	237	394	67	32	48	563	590	630	4770	"	1940	6.6	47.5
			1	225	303	51	24	0	692	596	448	3792	"	1890	7.0	45.6
			2	236	308	52	25	0	704	616	232	2533	"	1930	5.6	47.2
			5	235	375	0	0	0	799	590	210	2146	"	2000	6.2	34.8
			6	228	307	52	25	51	658	591	297	3165	"	1920	6.1	49.6
U	375	I	7	221	303	52	24	51	668	600	292	3736	"	1920	5.5	46.6

† Note that A.E.A. and HRWRA are in mL/m³

TABLE 8—MIX PROPORTIONS AND PROPERTIES OF FRESH AND HARDENED CONCRETE, PHASE VII

Mixture Series	Nominal Cement Content, kg/m ³	ASTM Cement Type	Batch No.	Batch Quantities [†] , kg/m ³							Properties of Fresh Concrete			Compressive Strength of Test Cylinders, MPa
				Water	Cement	Silica Fume	Fine agg.	Coarse agg.	A. E. A., mL/m ³	HRWRA, mL/m ³	Slump, mm	Density, kg/m ³	Air content, %	
V	500	I	1	140	500	30	700	550	800	4000	120	1950	7.0	48.2
			2	140	500	30	700	550	800	4000	120	1950	7.0	48.2
			3	140	500	30	700	550	800	4000	120	1950	7.0	48.2
W	400	I	1	145	400	30	660	635	750	2500	80	2025	4.0	59.5
			2	145	400	30	660	635	750	2500	80	2025	4.0	59.5
			3	145	400	30	660	635	750	2500	80	2025	4.0	59.5

† Note that A. E. A. and HRWRA are in mL/m³

TABLE 9—MIX PROPORTIONS AND PROPERTIES OF FRESH AND HARDENED CONCRETE, PHASE VIII

Mixture Series	Water cement + fly ash	ASTM Cement Type	Batch No.	Batch Quantities [†] , kg/m ³							Properties of Fresh Concrete			Compressive Strength of Test Cylinders, MPa
				Water	Cement	Fly Ash	Fine agg.	Coarse agg.	A.E.A., mL/m ³	HRWRA, mL/m ³	Slump, mm	Density, kg/m ³	Air content, %	
X	0.38	I	1	132	347	0	864	1039	78	10800	200	2390	6.0	59.2
	0.39	I	2	134	345	0	860	1034	78	11300	180	2370	7.0	58.0
	0.31	I	3	109	157	199	827	1152	200	13500	180	2450	6.8	67.6
	0.31	I	4	107	157	199	827	1153	200	15200	190	2450	6.5	63.1
Y	0.46	I	1	139	306	0	835	1074	134	6600	210	2360	7.0	45.3
	0.46	I	2	139	304	0	830	1068	89	6700	220	2340	7.0	48.7
	0.35	I	3	123	154	195	768	1129	174	6200	220	2370	7.0	51.6
	0.35	I	4	124	156	197	775	1141	176	5500	195	2390	6.0	47.8

[†] Note that A.E.A. and HRWRA are in mL/m³

TABLE 10—MIX PROPORTIONS AND PROPERTIES OF FRESH AND HARDENED CONCRETE, PHASE IX

Mixture Series	Water-C + SCM*	ASTM Cement Type	Batch No.	Batch Quantities [†] , kg/m ³									Properties of Fresh Concrete			Compressive Strength of Test Cylinders, MPa
				Water	Cement	Slag	Fly Ash	Silica Fume	Fine agg.	Coarse agg.	A.E.A., mL/m ³	HRWRA, mL/m ³	Slump, mm	Density, kg/m ³	Air content, %	
Z	0.50	I	1	164	328	0	0	0	789	1048	152	0	60	2330	6.0	33.3
			2	170	339	0	0	0	781	1048	157	0	70	2340	6.0	33.0
			3	155	233	0	78	0	781	1053	307	0	65	2300	6.6	27.0
			4	152	228	0	76	0	764	1030	309	0	65	2250	6.6	25.9
			5	164	295	0	0	33	772	1030	270	890	60	2290	6.1	37.1
			6	163	291	0	0	33	762	1017	334	1250	65	2270	6.9	38.2
			7	159	159	159	0	0	758	1051	187	0	85	2290	7.0	30.8
			8	160	160	160	0	0	763	1057	184	0	90	2300	6.6	30.9

* Water-to-(cement + supplementary cementing materials) ratio.

† Note that A.E.A. and HRWRA are in mL/m³.

TABLE 11—MIX PROPORTIONS AND PROPERTIES OF FRESH AND HARDENED CONCRETE, PHASE X

Mixture Series	Nominal Cement Content, kg/m ³	ASTM Cement Type	Batch No.	Batch Quantities [†] , kg/m ³							Properties of Fresh Concrete			Compressive Strength of Test Cylinders, MPa
				Water	Cement	Silica Fume	Fine agg.	Coarse agg.	A.E.A., mL/m ³	HRWRA, mL/m ³	Slump, mm	Density, kg/m ³	Air content, %	
AA	415	I	1	177	411	30	672	617	274	2658	130	1910	5.5	52.3
			2	176	417	30	683	628	342	4768	150	1940	5.0	53.3
			3	177	416	30	681	625	214	3072	140	1930	5.1	48.2
			4	179	414	30	678	623	339	3567	140	1930	5.6	50.8
AB	435	I	1	160	435	31	773	509	367	4764	140	1910	5.1	53.1
			2	165	433	31	770	507	331	4689	140	1910	5.5	51.8
			3	156	434	31	772	508	341	5044	150	1900	5.1	50.3
			4	164	434	31	771	508	426	6915	140	1910	5.0	53.6
AC	410	I	1	158	411	30	660	644	362	4340	145	1900	5.4	63.6
			2	158	411	30	660	644	362	4340	160	1910	5.7	60.6
			3	158	411	30	657	642	367	3151	140	1900	6.5	60.7
			4	158	414	30	663	648	332	3803	155	1910	5.5	54.4

† Note that A.E.A. and HRWRA are in mL/m³

TABLE 12—MIX PROPORTIONS AND PROPERTIES OF FRESH AND HARDENED CONCRETE, PHASE XI

Mixture Series	Nominal Cement Content, kg/m ³	ASTM Cement Type	Batch No.	Batch Quantities [†] , (kg/m ³)						Properties of Fresh Concrete			Compressive Strength of Test Cylinders, MPa	
				Water	Cement	Fly Ash	Fine agg.	Coarse agg.	A.E.A., mL/m ³	HRWRA, mL/m ³	Slump, mm	Density, kg/m ³		Air content, %
BA 01	150	I	1	130	152	191	772	698	190	1813	160	1950	5.0	25.7
BA 02			2	129	148	189	749	677	184	959	130	1890	6.0	21.6
BA 03			3	132	152	191	771	698	189	1319	125	1950	5.5	25.1
BA 04			4	132	152	191	768	698	189	1314	160	1940	5.0	27.1
BB 01	150	I	1	135	153	192	752	607	185	2092	125	1840	6.0	20.2
BB 02			2	136	153	192	755	609	178	1858	125	1850	5.5	20.5
BB 03			3	136	151	190	748	599	151	1588	155	1820	6.0	15.9
BB 04			4	137	151	190	746	601	167	1674	160	1830	6.0	16.0
BC 01	150	I	1	131	153	192	757	726	131	1615	130	1960	5.0	31.2
BC 02			2	142	153	192	756	725	145	1612	170	1970	4.0	34.3
BC 03			3	151	146	188	736	709	128	1837	128	1930	4.5	23.4
BC 04			4	137	152	191	751	721	144	1603	150	1950	5.0	28.6

† Note that A.E.A. and HRWRA are in mL/m³

TABLE 13—MIX PROPORTIONS AND PROPERTIES OF FRESH AND HARDENED CONCRETE, PHASE XII

Mixture Series	Water/Cement	ASTM Cement Type	Batch No.	Batch Quantities [†] , kg/m ³						Properties of Fresh Concrete			Compressive Strength of Test Cylinders, MPa
				Water	Cement	Fine agg.	Coarse agg.	A.E.A., mL/m ³	HRWRA, mL/m ³	Slump, mm	Density, kg/m ³	Air content, %	
CA 01	0.45	I	1	171	381	678	989	353	0	85	2220	6.0	30.6
CA 02			2	172	382	680	992	354	0	90	2220	6.0	31.0
CA 03			3	171	381	678	989	370	0	90	2220	6.5	31.8
CA 04			4	171	381	678	989	353	0	90	2220	6.0	31.3
CA 05			5	168	373	669	1008	302	0	70	2250	6.2	33.2
CA 06			6	172	383	682	995	347	0	80	2230	5.8	31.5
CA 07			7	171	381	678	989	353	0	100	2220	6.0	31.9
CA 08			8	172	382	680	992	172	0	95	2230	6.0	32.0
CB 01	0.60	I	1	166	278	786	1018	148	0	100	2250	6.5	27.3
CB 02			2	164	276	781	1012	138	0	95	2230	6.5	27.2
CB 03			3	164	274	778	1003	137	0	105	2220	7.0	25.0
CB 04			4	166	277	788	1016	121	0	90	2250	6.5	26.9
CB 05			5	166	280	804	1025	122	0	80	2280	6.0	30.9
CB 06			6	165	278	799	1019	122	0	95	2260	6.5	26.8
CB 07			7	165	278	799	1019	122	0	100	2260	6.5	26.1
CB 08			8	165	279	802	1023	122	0	90	2270	6.0	27.9

* All prisms are reinforced either with uncoated or epoxy-coated reinforcing bars.

† Note that A.E.A. and HRWRA are in mL/m³.

TABLE 14—MIX PROPORTIONS AND PROPERTIES OF FRESH AND HARDENED CONCRETE, PHASE XIV

Mixture Series	Water-cement	Nominal Cement Content, kg/m ³	ASTM Cement Type	Batch No.	Batch Quantities [†] , kg/m ³							Properties of Fresh Concrete			Compressive Strength of Test Cylinders, MPa
					Water	Cement	Fly ash	Fine agg.	Coarse agg.	A.E.A., mL/m ³	HRWRA, L/m ³	Slump, mm	Density, kg/m ³	Air content, %	
EPH 01	0.33	150	I	1	120	154	213	645	1198	330	4.2	160	2330	5.9	31.7
EPH 02				2	118	149	207	631	1173	415	5.4	180	2280	7.5	38.2
EPH 03				3	118	150	207	625	1167	1050	3.9	180	2270	7.4	26.7
EPH 04				4	120	152	211	636	1186	595	4.5	150	2305	6.3	35.2
EPH 05				5	119	152	209	642	1197	95	1.2	115	2320	6.4	37.7
EPH 06				6	119	152	211	645	1203	70	2.1	85	2330	6.4	37.0
EPH 07				7	118	152	209	642	1197	400	3.6	115	2320	6.2	33.1
EPH 08				8	119	152	211	645	1203	210	3.4	100	2330	6.3	34.8
EPH 09				9	119	152	211	647	1203	210	1.8	145	2330	6.7	34.9
EPH 10				10	120	154	212	650	1209	90	1.9	100	2345	6.2	37.1
EPH 13				13	120	153	212	646	1200	320	2.5	120	2330	6.3	28.8
EPH 14				14	119	152	209	638	1187	245	4.0	110	2305	7.3	33.2
EPH 15				15	119	151	209	638	1188	245	2.7	125	2305	6.0	35.1
EPH 16				16	118	151	209	639	1188	165	3.2	145	2305	6.2	39.2
EPI 01	0.33	150	I	1	120	153	212	641	1192	365	4.2	165	2320	6.2	31.3
EPI 02				2	119	151	209	638	1186	435	5.5	150	2305	7.0	37.6
EPI 03				3	120	153	212	639	1193	1175	4.1	205	2320	6.1	29.1
EPI 04				4	118	151	209	632	1180	615	4.4	150	2295	6.5	35.2
EPI 05				5	119	152	209	642	1197	95	1.3	165	2320	6.8	36.8
EPI 06				6	117	150	207	634	1183	70	2.4	115	2295	7.0	36.3
EPI 07				7	117	150	207	635	1184	360	3.2	115	2295	6.8	32.0
EPI 08				8	118	151	208	638	1189	215	3.6	125	2305	6.9	35.3
EPI 09				9	120	154	212	650	1209	210	1.9	145	2345	6.1	35.0
EPI 10				10	120	154	212	650	1209	90	2.1	100	2345	6.0	40.2
EPI 13				13	120	153	212	645	1200	330	2.6	110	2330	6.3	29.5
EPI 14				14	119	152	209	638	1186	235	4.1	110	2305	7.2	31.6
EPI 15				15	118	150	208	634	1181	305	3.1	180	2295	6.6	33.9
EPI 16				16	117	151	208	635	1182	170	3.2	180	2295	6.6	39.9

[†] Note that A.E.A. and HRWRA are in mL/m³

TABLE 15—MIX PROPORTIONS AND PROPERTIES OF FRESH AND HARDENED CONCRETE, PHASE XIV

Mixture Series	Water/ cementitious	Nominal Cement Content, kg/m ³	ASTM Cement Type	Batch Quantities [†] , kg/m ³								Properties of Fresh Concrete			Compressive Strength of Test Cylinders, MPa
				Water	Cement	Fly ash	Silica fume	Fine agg.	Coarse agg.	A.E.A., mL/m ³	HRWRA, L/m ³	Slump, mm	Density, kg/m ³	Air content, %	
CONLM72	0.40	430	I	172	431	--	--	699	1049	304	--	90	2345	6.3	42.3
CONM73	0.40	430	I	172	431	--	--	699	1049	281	--	90	2345	6.9	34.7
CONF A20M74	0.39	350	I	136	348	87	--	705	1056	268	--	125	2359	6.4	31.3
CONF A30M75	0.38	300	I	114	301	129	--	697	1047	341	--	130	2331	7.5	25.3
CONF E7.5M76	0.41	400	I	165	402	--	33	696	1043	353	1.8	110	2345	6.2	40.4
CONF S10.0M77	0.41	400	I	159	387	--	43	687	1030	440	2.7	140	2317	7.2	43.3

† Note that A.E.A. and HRWRA are in mL/m³

TABLE 16—FREEZING AND THAWING CYCLES OF CONCRETE AT TREAT ISLAND, 1994-95

Freezing Pt.	Prism, (305 x 305 x 915 mm)		* Prism, (152 x 152 x 510 mm)		
	@ 25 mm cover	@ 152 mm cover	1991	1994	1995
0.0	128	119	149	155	155
-1.0	101	82	107	127	123
-2.0	70	53	79	103	104
-2.2*	62	49	75*	97*	102*
-3.0	56	41	54	83	80
-4.0	42	32	46	71	64
-5.0	31	28	39	64	46
-6.0	24	22	32	55	34
-7.0	19	14	27	47	29
-8.0	11	8	17	35	19
-9.0	7	6	13	26	14
-10.0	4	4	7	22	9
-11.0	4	3	6	18	6
-12.0	1	1	3	14	3

* Nominal number of freezing and thawing cycles per year is based upon the number of times the temperature at the centre of 152 x 152 x 510-mm prism drops below minus 2.2°C. In the above case, the total number of freezing and thawing cycles is 75.

TABLE 17—VISUAL RATING OF TEST SPECIMENS, PHASE I

Prism	ASTM Cement Type	W/(C+BFS)	Slag Content, %	Visual Rating (See rating scale on page 7)																	
				1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
A01	I	0.40	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	2	2
A02	I	0.40	25	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	2	2
A03	I	0.40	25	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	2	2
A05	I	0.40	0	0	0	0	0	0	0	0	0	0	0	0	1	2	2	2	2	2	2
A06	I	0.40	45	0	0	0	0	0	0	0	1	1	1	1	1	2	2	2	2	2	2
A07	I	0.40	45	0	0	0	0	0	0	0	1	1	1	1	1	2	2	2	2	2	2
A09	I	0.40	0	0	0	0	0	0	0	0	0	1	1	1	1	2	2	2	2	2	2
A10	I	0.40	65	0	0	0	0	0	0	0	1	1	1	1	1	2	2	2	2	2	2
A11	I	0.40	65	0	0	0	0	0	0	0	1	1	1	1	1	2	2	2	2	2	2
A13	V	0.40	0	0	0	0	0	0	0	1	1	1	1	1	1	2	2	2	2	2	2
B01	I	0.50	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
B02	I	0.50	25	0	0	0	0	0	0	0	0	0	0	0	1	2	2	2	2	2	2
B03	I	0.50	25	0	0	0	0	0	0	0	0	1	1	1	1	1	2	2	2	2	2
B05	I	0.50	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	2	2
B06	I	0.50	45	0	0	0	0	0	0	1	2	2	2	2	2	2	2	2	2	2	2
B07	I	0.50	45	0	0	0	0	0	0	0	1	2	2	2	2	2	2	2	2	2	2
B09	I	0.50	0	0	0	0	0	0	0	0	0	1	1	1	1	2	2	2	2	2	2
B10	I	0.50	65	0	0	1	1	1	1	1	2	3	3	3	3	3	3	3	3	3	3
B11	I	0.50	65	0	0	1	1	1	1	1	2	3	3	3	3	3	3	3	3	3	3
B13	V	0.50	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	6	6	6
C01	I	0.60	0	0	0	0	0	0	0	1	1	2	2	2	2	2	2	2	2	2	2
C02	I	0.60	25	0	0	0	0	0	0	0	1	1	1	1	1	2	2	2	2	2	2
C03	I	0.60	25	0	0	0	0	0	0	1	2	3	3	3	3	3	3	3	3	3	3
C05	I	0.60	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
C06	I	0.60	45	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2
C07	I	0.60	45	0	0	0	0	0	0	1	2	2	2	2	3	3	3	3	3	3	3
C09	I	0.60	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	2	2	2
C10	I	0.60	65	0	1	2	2	2	2	3	3	4	4	4	4	4	4	4	4	4	4
C11	I	0.60	65	0	1	2	2	2	2	3	3	4	4	4	4	4	4	4	4	4	4
C13	V	0.60	0	0	0	0	0	0	0	0	0	1	1	2	2	2	2	2	2	2	2
SP1	I	0.50	0	0	0	0	0	0	0	1	1	1	1	2	2	2	2	2	3	3	3
SP2	I	0.50	0	0	0	0	0	0	0	0	0	1	1	1	1	2	2	2	2	2	2
SP3	I	0.50	0	0	0	0	0	0	0	1	2	6	7	8	8	9	10	10	10	10	10
SP4	I	0.50	0	0	0	0	0	0	0	1	2	6	7	7	8	8	8	8	10	10	10
SP5	I	0.50	0	0	0	0	0	0	0	1	1	1	1	1	2	2	2	2	3	3	3
SP6	I	0.50	0	0	0	0	0	0	0	6	7	8	9	9	10	10	10	10	10	10	10

TABLE 18—VISUAL RATING OF TEST SPECIMENS, PHASE II

Prism	ASTM Cement Type	W/(C+BFS+FA)*	Slag Content, %	Fly ash Content, %	Visual Rating**																
					1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
D01	I	0.40	0	0	0	0	0	0	0	0	0	0	1	1	2	2	2	2	3	3	3
D02	I	0.40	0	0	0	0	0	0	0	0	0	0	1	1	2	2	2	2	2	2	2
D03	I	0.40	0	0	0	0	0	0	0	0	0	0	1	1	2	2	2	2	2	2	2
D04	I	0.40	0	0	0	0	0	0	0	0	0	0	1	1	2	2	2	2	2	2	2
D05	I	0.40	0	0	0	0	0	0	0	0	0	0	1	1	2	2	2	2	2	2	2
D06	I	0.40	40	20	0	0	0	0	1	2	2	3	3	4	4	4	4	4	4	4	4
D07	I	0.40	40	20	0	0	0	0	1	2	2	3	3	4	4	4	4	4	4	4	4
D08	I	0.40	40	20	0	0	0	0	1	2	2	3	3	4	4	4	4	4	4	4	4
D09	I	0.40	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
D10	I	0.40	60	20	0	0	0	0	1	3	4	4	4	5	6	6	6	6	6	6	6
D11	I	0.40	60	20	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
D12	I	0.40	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
D13	V	0.40	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
D14	V	0.40	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
D15	II	0.40	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
D16	II	0.40	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
E01	I	0.50	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
E02	I	0.50	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
E03	I	0.50	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
E04	I	0.50	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
E05	I	0.50	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
E06	I	0.50	40	20	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
E07	I	0.50	40	20	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
E08	I	0.50	40	20	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
E09	I	0.50	40	20	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
E10	I	0.50	60	20	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
E11	I	0.50	60	20	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
E12	V	0.50	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
E13	V	0.50	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
E14	V	0.50	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
E15	V	0.50	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
E16	II	0.50	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
F01	I	0.60	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
F02	I	0.60	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
F03	I	0.60	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
F04	I	0.60	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
F05	I	0.60	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
F06	I	0.60	40	20	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
F07	I	0.60	40	20	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
F08	I	0.60	40	20	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
F09	I	0.60	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
F10	I	0.60	60	20	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
F11	I	0.60	60	20	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
F12	I	0.60	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
F13	I	0.60	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
F14	I	0.60	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
F15	I	0.60	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
F16	II	0.60	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1

* Water-to-(cement + slag + fly ash) ratio.

** See rating scale on page 7.

TABLE 19—VISUAL RATING OF TEST SPECIMENS, PHASE III

Prism	ASTM Cement Type	(C+BFS)* kg/m ³	Slag Content, %	Visual Rating **															
				1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
G01	I	240	0	0	0	0	0	1	2	2	2	2	3	3	4	4	4	4	4
G03	I	240	25	0	0	0	0	2	3	3	3	3	3	3	4	4	6	6	6
G04	I	240	25	0	0	0	0	1	3	3	3	3	3	3	4	4	6	6	6
G06	I	240	0	0	0	0	0	1	2	2	2	2	2	2	3	3	3	3	3
G07	I	240	45	0	0	0	0	2	3	3	3	3	3	3	4	4	6	6	6
G08	I	240	45	0	0	0	0	2	3	3	3	3	3	3	4	4	6	6	6
G10	I	240	0	0	0	0	0	1	2	3	3	3	3	3	3	3	3	3	3
G11	I	240	65	0	0	0	0	3	4	4	4	4	6	6	6	6	7	7	7
G12	I	240	65	0	0	0	0	2	3	4	4	4	5	5	6	6	7	7	7
G14	V	240	0	0	0	0	0	2	2	3	3	3	4	4	4	4	4	4	4
H01	I	360	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	2	2
H03	I	360	25	0	0	0	0	0	0	1	2	2	2	2	2	2	2	2	2
H04	I	360	25	0	0	0	0	1	1	1	2	2	2	2	2	2	2	2	2
H06	I	360	0	0	0	0	0	0	0	1	1	1	1	1	1	1	2	2	2
H07	I	360	45	0	0	0	0	1	1	1	1	1	2	2	2	2	2	2	2
H08	I	360	45	0	0	0	0	1	1	1	1	1	2	2	2	2	2	2	2
H10	I	360	0	0	0	0	0	1	1	1	1	1	1	1	1	1	2	2	2
H11	I	360	65	0	0	0	0	1	1	2	2	2	2	2	2	2	3	3	3
H12	I	360	65	0	0	0	0	1	1	2	2	2	2	2	2	2	3	3	3
H14	V	360	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	2	2
I01	I	480	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	2	2
I03	I	480	25	0	0	0	0	1	0	1	1	1	1	1	1	1	2	2	2
I04	I	480	25	0	0	0	0	0	0	1	1	1	1	1	1	1	2	2	2
I06	I	480	0	0	0	0	0	0	0	1	1	1	1	1	1	1	2	2	2
I07	I	480	45	0	0	0	0	1	1	1	1	1	1	1	1	2	3	3	3
I08	I	480	45	0	0	0	0	0	1	2	2	2	2	2	2	2	2	3	3
I10	I	480	0	0	0	0	0	0	0	1	1	1	1	1	1	2	2	2	2
I11	I	480	65	0	0	0	0	0	0	1	1	1	1	1	1	2	2	3	3
I12	I	480	65	0	0	0	0	0	0	2	2	2	2	2	2	2	2	3	3
I14	V	480	0	0	0	0	0	0	0	1	1	1	1	1	1	1	2	2	2

* Nominal content of (cement + slag).

** See rating scale on page 7.

TABLE 20—VISUAL RATING OF TEST SPECIMENS, PHASE IV

Prism	ASTM Cement Type	W/(C+FA)*	Fly ash Content %	Visual Rating**													
				1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
J01	I	0.40	0	0	0	0	0	0	1	1	1	1	1	1	2	2	2
J02	I	0.40	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
J04	I	0.40	25	0	0	0	0	0	0	0	1	1	1	1	3	3	3
J05	I	0.40	25	0	0	0	0	1	2	2	2	2	2	2	3	3	3
J07	V	0.40	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
K01	I	0.50	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
K02	I	0.50	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
K04	I	0.50	25	0	0	0	1	1	2	2	2	2	2	2	3	3	3
K05	I	0.50	25	0	0	0	1	1	2	2	2	2	2	2	4	4	4
K07	V	0.50	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
L01	I	0.60	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
L02	I	0.60	0	0	0	0	0	0	1	1	1	1	1	1	2	2	2
L04	I	0.60	25	0	0	0	1	2	3	3	4	4	4	4	6	6	6
L05	I	0.60	25	0	0	0	1	1	3	3	3	3	3	4	6	6	6
L07	V	0.60	0	0	0	0	0	0	1	1	1	1	1	2	2	6	6

* Water-to-(cement + fly ash) ratio.

** See rating scale on page 7.

TABLE 21—VISUAL RATING OF TEST SPECIMENS, PHASE V

Prism	ASTM Cement Type	W/(C+BFS) or W/(C+SF)	Slag Content, %	Silica Fume Content, %	Visual Rating**														
					1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	
M01	I	0.40	0	-	0	0	0	0	0	0	1	1	1	1	1	1	2	2	2
M02	I	0.40	0	-	0	0	0	0	0	0	0	0	0	0	1	1	2	2	2
M03	I	0.40	80	-	0	0	0	0	1	1	1	1	1	1	1	1	2	2	2
M04	I	0.40	80	-	0	0	0	0	0	0	0	0	0	0	1	1	2	2	2
N01	I	0.50	0	-	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
N02	I	0.50	0	-	0	0	0	0	0	0	0	0	0	0	1	1	2	2	2
N03	I	0.50	80	-	0	0	0	0	1	1	1	1	1	1	1	1	2	2	2
N04	I	0.50	80	-	0	0	0	0	1	1	1	1	1	1	1	1	2	2	2
O01	I	0.60	0	-	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
O02	I	0.60	0	-	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
O03	I	0.60	80	-	0	0	1	1	3	3	3	3	3	3	3	3	3	3	6
O04	I	0.60	80	-	0	0	0	0	0	2	2	2	3	3	3	3	3	3	3
P01	I	0.60	-	0	0	0	0	1	2	2	2	2	2	2	2	2	2	2	2
P02	I	0.60	-	10+	0	0	0	1	2	2	2	2	2	3	3	3	3	3	3
P03	I	0.60	-	15+	0	0	0	1	3	3	3	4	4	4	4	4	4	4	4
P04	I	0.60	-	20+	0	0	0	1	3	3	3	4	4	4	4	4	4	4	4
Q01	I	0.60	-	0	0	0	1	1	2	2	2	2	2	2	2	2	2	2	3
Q02	I	0.60	-	10	0	0	0	1	2	2	2	2	2	2	2	2	3	3	4
Q03	I	0.60	-	15	0	0	1	1	3	3	3	3	3	3	3	3	3	3	4
Q04	I	0.60	-	20	0	0	1	1	3	4	4	4	4	4	4	4	4	4	4
R01	I	0.60	-	0	0	0	0	0	1	1	1	6	6	6	7	7	7	7	8
R02	I	0.60	-	10	0	0	0	1	2	2	2	7	7	7	7	7	7	7	8
R03	I	0.60	-	15	0	0	1	2	2	2	3	6	6	6	7	7	7	7	8
R04	I	0.60	-	20	0	0	4	4	4	4	5	6	6	6	7	7	7	7	7

* Water-to-(cement + slag) ratio or water-to-(cement + silica fume) ratio.
Note: '+' indicates an addition rather than a replacement of cement with silica fume.