

Seventh International Symposium on Utilization of High-Strength/ High-Performance Concrete

Volume I

Editor

Henry G. Russell



American Concrete Institute®
Advancing concrete knowledge

SP-228

First printing, June 2005

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 December 2005. All discussion approved by the Technical Activities Committee along with closing remarks by the authors will be published in the March/April 2006 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 © 2005
AMERICAN CONCRETE INSTITUTE
P.O. Box 9094
Farmington Hills, Michigan 48333-9094

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: Lindsay K. Kennedy

Library of Congress catalog card number: 2005925875
ISBN: 0-87031-180-8

PREFACE

This special publication contains the papers presented at the Seventh International Symposium on the Utilization of High-Strength/High-Performance Concrete that was held in Washington, D.C., USA, June 20-24, 2005. The symposium continued the success of previous symposia held in Stavanger, Norway, (1987); Berkeley, California (1990); Lillehammer, Norway, (1993); Paris, France, (1996); Sandefjord, Norway, (1999); and Leipzig, Germany, (2002). The symposium brought together engineers and material scientists from around the world to discuss topics ranging from the latest applications to the most recent research on high-strength and high-performance concrete.

In the years since the first symposium was held in Stavanger, there has been worldwide growth in the use of both high-strength and high-performance concrete. In addition to more research and applications of traditional types of high-performance concrete, the use of self-consolidating concrete and ultra-high-performance concrete has moved from the laboratory to practical applications. This publication offers the opportunity to learn the latest about these developments.

Thanks are due to the authors, who contributed papers to the symposium and made it possible to have this publication; to members of the Technical Review Panel, who reviewed the papers in accordance with ACI procedures; to the Symposium Steering Committee, who guided the symposium activities; and to ACI staff for their organization of the symposium and this publication. Particular thanks are due to Thomas H. Adams, Symposium Secretary, and Nicholle Cormier, Symposium Coordinator.

Henry G. Russell
Symposium Chair

Symposium Secretary

Thomas H. Adams
American Concrete Institute
Farmington Hills, Michigan, USA

Symposium Steering Committee

Pierre-Claude Aïtcin
University of Sherbrooke
Sherbrooke, Quebec, Canada

Yuebo Cai
Nanjing Hydraulic Research Institute
Peoples Republic of China

George C. Hoff
Hoff Consulting, LLC
Clinton, Mississippi, USA

Tony C. Liu
U.S. Army Corps of Engineers
Washington, D.C., USA

Shigeyoshi Nagataki
Aichi Institute of Technology
Toyota, Aichi, Japan

Rameshchandra N. Raikar
Structural Designers and Consultants, Pvt. Ltd.
Mumbai, India

Vijay Rangan
Curtin University of Technology
Perth, Australia

Luc Taerwe
Ghent University
Belgium

François Toutlemonde
LCPC
Paris, France

Suneel N. Vanikar
Federal Highway Administration
Washington, D.C., USA

Richard N. White
Cornell University
Ithaca, New York, USA

Paul Zia
North Carolina State University
Raleigh, North Carolina, USA

Technical Review Panel

Pierre-Claude Aïtcin
Robert N. Bruce, Jr.
James T. Dikeou
Kenneth S. Harmon
Eugene D. Hill, Jr.
Kal R. Hindo
Brian B. Hope
Mohammad S. Khan
Dimitrios Konstantinidis
Hani H. Nassif
William C. Panarese
Thomas J. Pasko, Jr.
Bertil Persson
Rameshchandra N. Raikar
Vijay B. Rangan
Luc Taerwe
Richard N. White
Paul Zia

TABLE OF CONTENTS

Preface	iii
SP-228—1: Implementation of High-Performance Concrete Bridge Technology in the USA	1
by S.N. Vanikar and L.N. Triandafilou	
SP-228—2: Performance Based Design for Self-Compacting Structural High-Strength Concrete	13
by H. Okamura, K. Maekawa, and T. Mishima	
SP-228—3: High-Performance Concrete—A Proven Material with Unfulfilled Potential	35
by J. Moksnes	
SP-228—4: Ultra-High-Performance Concrete: Research, Development and Application in Europe	51
by M. Schmidt and E. Fehling	
SP-228—5: High-Strength Concrete (ACI 363R)	79
by ACI Committee 363 - High-Strength Concrete	
SP-228—6: Use of High-Strength Concrete for Seismic Applications	81
by ACI Innovation Task Group 4	
SP-228—7: Very High-Strength Rapid-Hardening Concrete	85
by V.R. Falikman, Y.V. Sorokin, and O.O. Kalashnikov	
SP-228—8: Prediction of Concrete Rheology Based on Analytical Mix Design Model ...	97
by T.T. Roshavelov	
SP-228—9: Fracture Energy of Rice-Husk Ash Concrete	111
by G. Giaccio, G.R. de Sensale, and R. Zerbino	
SP-228—10: Non-Conventional Aggregates and Mineral Admixtures in High-Performance Concrete	123
by R.A. Gayoso Blanco and M.R. Lam	
SP-228—11: The Maturity Approach for Predicting Different Properties of High-Performance Concrete	135
by J. Zhang, D. Cusson, L. Mitchell, T. Hoogeveen, and J. Margeson	

SP-228—12: Effect of Silica Fume and Water to Binder Ratio on the Diffusion of Chloride Ion into Concrete in Persian Gulf Region 155
by M. Chini, M. Hoseini, P. Ghods, R. Alizadeh, M. Ghalibafian, and M. Tadayon

SP-228—13: The Correlation between the Water/Cementitious Material Ratio and HPC Compressive Strength 165
by S.F. Freyne, W. Micah Hale, and B.W. Russell

SP-228—14: Entraining Air in High-Performance Concrete and Its Effect on Compressive Strength 173
by W. Micah Hale, S.F. Freyne, and B.W. Russell

SP-228—15: Strength, Durability and Shrinkage of High-Strength Rice Husk Ash Concrete 189
by H.B. Mahmud, E. Majuar, M.F.M. Zain, and N.B.A.A. Hamid

SP-228—16: The Myth, Reality, and Construction Practicality of High Volume Fly Ash Replacement 203
by R. Szecsy

SP-228—17: Comparision of Two Metakaolins and a Silica Fume Used as Supplementary Cementitious Materials 213
by J.M. Justice, L.H. Kennsion, B.J. Mohr, S.L. Beckwith, L.E. McCormick, B. Wiggins, Z.Z. Zhang, and K.E. Kurtis

SP-228—18: Properties of High-Strength Concrete Using a High Fly Ash Content 237
by K.-Ch. Thienel, A. Kustermann, J. Junggunst, and R.K. Zimebelmann

SP-228—19: Fast Track Construction with High-Strength Concrete Mixes Containing Ground Granulated Blast Furnace Slag 255
by M.N. Soutsos, S.J. Barnett, J.H. Bungey, and S.G. Millard

SP-228—20: Performance of High Volume Fly Ash Concrete Exposed to Acidic Environment 271
by L.V.A. Seshasayi, K. Ramu, and Y. Srinivasarao

SP-228—21: Properties of High-Performance Concrete Containing High Reactivity Metakaolin 287
by A. Bonakdar, M. Bakhshi, and M. Ghalibafian

SP-228—22: Implementation of Self-Consolidating Concrete for Prestressed Concrete Girders 297
by P. Zia, R.A. Nunez, L.A. Mata, and H.M. Dwairi

SP-228—23: Textile Carbon Reinforcement for Base Slabs of Self-Consolidating Concrete	317
by J. Hegger and J. Niewels	
SP-228—24: Stability of Long-Span Pretensioned High-Performance Concrete Girders	333
by A. Saber and L.F. Kahn	
SP-228—25: The Effect of Steel Fibers on the Moment Redistribution and Rotation Capacity of Post-Tensioned High-Strength Concrete Beams	351
by P. De Pauw and L. Taerwe	
SP-228—26: Effect of ρ' on Ductility of HSC Members Under Bending	363
by A.A. Maghsoudi and H. Akbarzadeh Bengar	
SP-228—27: An Evaluation of the Fatigue Behavior of High-Strength/High-Performance Concrete Bulb-Tee Girders	381
by C.B. Tanner and P.H. Ziehl	
SP-228—28: Behavior and Design of HSC Members Subjected to Axial Compression and Flexure	395
by H.C. Mertol, S.J. Kim, A. Mirmiran, S. Rizkalla, and P. Zia	
SP-228—29: Flexural Behavior and Design of High-Strength Concrete Members	421
by Z. Wu, W. Choi, A. Mirmiran, S. Rizkalla, and P. Zia	
SP-228—30: Prestress Losses in Pretensioned Girders	
Part I: Method Development	439
by N. Al-Omaishi and M.K. Tadros	
SP-228—31: Prestress Losses in Pretensioned Girders	
Part II: Experimental Program	461
by N. Al-Omaishi and M.K. Tadros	
SP-228—32: Evaluation of the Behavior of the Bond in High-Strength Concrete	481
by M.T. Barbosa	
SP-228—33: Bond Anchorage Behavior of Pretensioned Tendons in High-Performance Concrete (HPC)	495
by J. Hegger, B. Kommer, S. Bülte, and A. Sherif	
SP-228—34: Bond of Reinforcement in Ultra High-Strength Concrete	513
by K. Holschemacher, D. Weiße, and S. Klotz	

SP-228—35: Lap Splices with High-Strength Concrete under Combined Flexure and Shear Loading	529
by N. Morohashi and T. Sakurada	
SP-228—36: Shortcomings of Current Compression Strength Tests for HSC and a Proposed Solution	545
by I. Luker and S.W. Tabsh	
SP-228—37: Uniaxially Loaded High-Strength Concrete Spiral Columns	557
by E. Canbay, Z.B. Koru, G. Ozcebe, and U. Ersoy	
SP-228—38: Behavior of Geopolymer Concrete Columns under Equal Load Eccentricities	577
by D.M.J. Sumajouw, D. Hardjito, S. Wallah, and B.V. Rangan	
SP-228—39: Seismic Response of High-Rise RC Buildings Made of High-Strength Materials	595
by D. Konstantinidis	
SP-228—40: Development of High Seismic Performance Concrete Frames	615
by Y. Sun and T. Fukuhara	
SP-228—41: Development of Precast High-Performance Fiber Reinforced Cement Composite Coupling Beams for Earthquake-Resistant Wall Systems	633
by G.J. Parra-Montesinos, J.K. Wight, and B.A. Canbolat	
SP-228—42: Shear Design Procedure for Reinforced and Prestressed High- and Normal-Strength Concrete Beams	651
by A. Cladera and A.R. Marí	
SP-228—43: Minimum Flexure and Shear Reinforcement for HSFRC	669
by Z. Savir and A.N. Dancygier	
SP-228—44: Experimental Study on Shear Resistance of Steel Fiber Reinforced High-Strength Concrete Beams	687
by C.-K. Huang, H.-Z. Zhang, and Z.-G. Guan	
SP-228—45: Shear Behavior of HPC Bulb-Tee Girders	705
by K.K. Raymond, R.N. Bruce, and J.J. Roller	
SP-228—46: Shear Capacity of Beams Made of High-Performance Concrete	723
by J. Hegger, A. Sherif, and S. Görtz	
SP-228—47: Torsional Behavior of High-Strength Concrete Beams with Lower Amounts of Torsional Reinforcement	741
by I.-K. Fuang and H.-J. Chiu	

Implementation of High-Performance Concrete Bridge Technology in the USA

by S.N. Vanikar and L.N. Triandafilou

Synopsis: The utilization of high performance concrete (HPC) has increased substantially in the last decade. HPC can provide enhanced mechanical and durability properties and at the same time allow efficient placement and finishing. HPC has been utilized for cost-effective construction of bridges, buildings and pavements in most countries. The Federal Highway Administration (FHWA) has played a key role in the HPC technology transfer from research and development to routine practice for bridge and pavement design and construction. FHWA's HPC implementation activities began in 1991. HPC implementation for highway bridges in the USA has been a success story. The success has been largely due to a long-term continuing partnership between FHWA, State Departments of Transportation, American Association of State Highway and Transportation Officials (AASHTO), local agencies, industry and academia.

This paper provides an historic perspective on the HPC implementation activities since the Strategic Highway Research Program (SHRP) in late 1980's and the subsequent programs and activities. Forty-four State Departments of Transportation have utilized HPC. HPC implementation has contributed significantly to improvements in highway infrastructure. Implementation of the long-term strategic plan developed by the industry will further contribute toward meeting the goals which include reduced congestion and improved safety, trained workforce, reduced life cycle costs and improved quality as well as reliability.

Keywords: bridges; construction; design; durability; high-performance concrete; implementation; mechanical properties; prestressed concrete; self-consolidating concrete; silica fume

2 Vanikar and Trindafilou

ACI member Suneel N. Vanikar is a Professional Engineer and the Concrete Group Leader at the Federal Highway Administration (FHWA), United States Department of Transportation in Washington, D.C. He has been with FHWA for 25 years. He was with the New Hampshire Department of Transportation prior to the career with FHWA. He received a Masters Degree in Civil Engineering from Colorado State University and his area of interest is the design and construction of high performance concrete pavements and bridges.

Professional Engineer Louis N. Trandafilou is the High Performance Structural Materials Specialist in the National Resource Center of FHWA in Baltimore, Maryland. He has been with FHWA for 30 years. He received a Bachelors Degree in Civil Engineering from Rutgers--the State University of New Jersey. He leads FHWA's technology delivery team for high performance concrete for bridges.

INTRODUCTION

Use of high performance concrete (HPC) has mushroomed over the last decade. Rather than being seen as an experimental material, it is now routinely used in industry. Norway, Sweden, Denmark and Germany have utilized HPC technology for several decades. France has built more than 100 HPC bridges in the past 20 years. In Canada, the Ontario Ministry of Transportation started using silica fume HPC in 1992 and HPC implementation began under the Concrete Canada program. In the United States of America (USA), the Federal Highway Administration (FHWA) has played a key role in the HPC technology transfer from research and development to routine practice in bridge and pavement design and construction. This paper is limited to HPC bridges in the USA.

HPC has certain characteristics which are developed for a certain application and environment. These may include ease of placement, consolidation without segregation, early-age strength, long-term strength and other mechanical properties, permeability, density, heat of hydration, toughness, volume stability and longer life in a severe environment. High strength and high durability properties can be utilized in designing cost effective, aesthetically pleasing structures. Because a lower w/c ratio concrete is typically used, HPC usually provides higher strength than conventional concrete. However, high strength is not always the primary requirement. HPC is valuable where any of the following properties are required: high strength, high early strength, low permeability, resistance to freeze-thaw damage, resistance to chemical attack, such as sulphates, abrasion resistance, low absorption, high resistivity, high modulus of elasticity and volume stability.

FHWA's HPC implementation activities began in 1991. HPC implementation for transportation structures in the USA has been a well documented success. The success has been largely due to a continuing partnership between FHWA, State Departments of Transportation (DOT), American Association of State Highway and Transportation Officials (AASHTO), local agencies, industry and academia. This paper provides an overview of implementation activities, accomplishments and anticipated future activities.

BACKGROUND

Strategic Highway Research Program

In 1987, the United States Congress initiated the five-year Strategic Highway Research Program (SHRP) to integrate various products to improve the constructability and reduce the maintenance of the nation's highways and bridges. HPC or "engineered concrete" was one of the products from the SHRP program. To implement these products, Congress authorized additional funding over the following six years. AASHTO, in cooperation with FHWA, created a Task Force for SHRP implementation. The Task Force's approach for technology transfer was through the use of teams consisting of the States that took the lead on various products; hence the AASHTO Lead State Team for HPC Implementation was formed.

AASHTO Lead State Team for Implementation

The Team, along with other Lead State Teams, first met in September 1996 to put together a mission, goals, strategies, and action plans. The team members represented industry, FHWA and the States. The Team's mission was to promote the implementation of HPC technology for use in pavements and bridges and to share knowledge, benefits, and challenges with the States and their customers. In order to spread the word on HPC, the Team made presentations at various AASHTO meetings, to other professional organizations, and to States adjacent to the lead States; wrote papers for various publications; and supported other efforts such as publication of *HPC Bridge Views*. The Team conducted a survey about each State's current use of both conventional concrete and HPC. The team partnered with FHWA and industry to develop a generic HPC bridge implementation workshop. Working together, the Team contributed significantly to make HPC the standard product for use in bridges. The Team completed its activities in 2001.

FHWA Technology Delivery Team

FHWA's HPC Technology Delivery Team (TDT), through funding in the Intermodal Surface Transportation Efficiency Act (ISTEA), produced positive results in helping State DOTs implement HPC in their highway bridges. The TDT created, in 1997, helped 13 States build HPC bridges and host or participate in technology transfer activities such as showcases and workshops. Working with the AASHTO Lead States Team of HPC implementation, the TDT influenced many additional State DOTs and other public agencies to try HPC in their highway bridges.

When the ISTEA ended, about 25 States had used HPC. Though lacking a direct funding mechanism, the TDT continued to promote HPC and encouraged States to build HPC bridges through a new program for constructing bridges utilizing innovative materials – the Innovative Bridge Research and Construction (IBRC) Program. In addition to FHWA engineers, the TDT membership includes representatives from academia, State DOT's and industry. The TDT continues its activities and has formulated a business plan, which includes statements of the team's vision, mission, and goals. The

4 Vanikar and Trindafilou

emphasis of these statements is to provide leadership in advancing HPC technology and in implementing HPC for increased structural efficiency and durability, thereby leading to reduced life-cycle costs for bridges and pavements. The TDT has established an HPC community of practice website.

ACCOMPLISHMENTS

SHRP Implementation Program

In 1993, the FHWA initiated a national program to implement the use of HPC in bridges. The program included the construction of demonstration bridges in each of the FHWA regions and the dissemination of the technology and results at showcase workshops. A total of 18 bridges in 13 States were included in the national program. In addition, other States implemented the use of HPC in various bridge elements.

The bridges were located in different climatic regions of the United States and used different types of superstructures. The bridges demonstrated practical applications of high performance concrete. In addition, construction of these bridges provided opportunities to learn more about the placement and actual behavior of HPC in bridges. Consequently, many of the bridges were instrumented to monitor their short – and long-term performance. Additionally, concrete material properties were measured for most of the bridges.

A project report summarizing results and analysis from HPC bridge projects, recommendations for AASHTO specification revisions and needs for additional research was prepared by Russell, Miller, Ozyildirim and Tadros.¹

Innovative Bridge Research and Construction (IBRC) Program

The 1998 Transportation Equity Act for the 21st Century (TEA-21) provided substantial funding to extend the service life of structures cost-effectively by incorporating high performance materials. Almost all State DOT's and several Federal and local agencies have participated in the IBRC program.²

Forty-one HPC-related projects were funded during the first five years of the IBRC program. Of the \$72 million in project allocations, about one-fifth has gone to projects incorporating HPC bridge components or elements. Nineteen HPC projects were submitted for review and approval under the FY 2003 program.

By far, cast-in-place bridge deck construction has been the most common application of HPC with 40 bridges constructed under the IBRC program. In a few instances, HPC full-depth precast, prestressed concrete deck panels have been used. Virginia is planning to construct a HPC lightweight concrete bridge deck and one with fibers. State DOTs are seeking ways to extend the service life of existing sound concrete bridge decks by using HPC overlays in seven bridges. In addition, HPC has been used in the parapets and railings of three bridges.

Prestressed concrete girder superstructures are the next most common application of HPC with 20 bridges built under the IBRC program. HPC substructures and foundations, including piling, bents, solid piers and precast abutments have been funded on ten additional bridges. In at least two instances, HPC has been used in all components and elements of a bridge.

Silica Fume Program

Under the United States Department of Transportation (USDOT) Appropriations Act provisions, Congress for a number of years made funds available for research and development on the use of silica fume in concrete. Additional usage will decrease waste materials and increase the quality and durability of concrete structures and pavements. The silica fume program will highlight development of the following partial list of products: Website, guide specification, service life prediction model, user manual, and other technology transfer materials. FHWA and the Silica Fume Association are working together to accomplish the program goals.

Other Accomplishments

To establish a clear understanding of HPC, the FHWA proposed a HPC definition in 1996. Goodspeed, Vanikar and Cook proposed the definition for use on the HPC bridge projects.³ The definition generated a healthy discussion in the engineering community. Subsequently, the American Concrete Institute and several State DOTs have defined HPC.

Based on recommendations provided in Reference1, appropriate AASHTO Subcommittees are considering changes in the current specifications for concrete materials, structural design and construction related to HPC.

Implementation Status

Since the initiation of the SHRP implementation program for HPC over 10 years ago, there has been an aggressive effort by the concrete industry, State DOTs and the FHWA to achieve nationwide implementation of HPC on bridge projects. Outstanding progress has been made in response to the FHWA Executive Director's 1997 challenge to construct at least one HPC bridge in every State by 2002. Recently the FHWA's HPC Technology Delivery Team conducted a 14 question national survey to track the progress and other related concrete issues.⁴ Figures 1, 2, 3 and 4 provide some of the details from the survey.⁵ The following are the highlights of the survey results:

- Forty-four States have utilized HPC specifications in last 10 years.
- Thirty-seven respondents selected HPC for low permeability, 30 for high strength, and 26 for both performance criteria.

6 Vanikar and Trindafilou

- As background on why HPC was being used, respondents ranked deck cracking at ages less than 5 years as the most common distress, followed by reinforcing steel corrosion, cracking of girders and substructure elements, and freeze-thaw-damage.
- Over the past 10 years, 77 percent of the respondents have made changes in their bridge deck curing requirements, 72 percent have made changes in their specified concrete strengths, and 64 percent have made changes in testing and acceptance requirements.
- Lightweight concrete has been used by 26 percent of respondents.
- Eighty-one percent of respondents utilize chemical and/or supplementary cementitious materials.
- Thirty-eight percent of respondents specify permeability requirements for bridge decks whereas 19 percent specify permeability requirement for precast, prestressed members.

Thirteen HPC bridges constructed under the FHWA program utilized concrete with design compressive strengths ranging from 55MPa (8,000psi) to 97MPa (14,000psi) for girders and 28MPa (4,000psi) to 55MPa (8000psi) for decks.

As a result of various Federal and State programs and routine Federal-aid funding, some States are using HPC on a regular basis. Virginia has over 100 HPC projects constructed, under construction or in the design phase. Ohio and New York have incorporated HPC specifications for routine bridge deck use for several years. Sixty-four percent of respondents have made changes in testing and acceptance requirements.

FUTURE

Strategic Plan

In 2000, the HPC Lead States Team published a Transition Plan that listed several goals. One of the main goals was to “develop a long-term strategic plan for HPC bridges in partnership with government, industry, and academia.” Under the leadership of the National Concrete Bridge Council (NCBC), a focus group of Federal and State bridge engineers, professors, and industry representative met to identify critical issues in the design and construction of long-life bridges to help solve the deficient bridge problem in the United States.⁶ Discussion at the focus group meeting provided the foundation for a strategic plan prepared by NCBC. The strategic plan focuses on the public’s expectations for the present and future. This outlook translates into the following four goals for HPC bridges:

1. Reduce congestion and improve safety:
 - Replacing bridge decks with minimal interference with traffic..

High-Strength/High-Performance Concrete 7

- Constructing entire short-span bridges within one week.
 - Reducing the average use delay by 20 percent for typical urban bridge reconstruction projects.
2. Train the workforce:
- Transferring HPC technologies to all 50 States by building several HPC bridges in each State.
 - Training 500 bridge engineers per year in HPC technology through seminars.
 - Training 2000 construction personnel per year in HPC bridge technology.
 - Adding HPC technology course to the engineering curricula at ten universities.
3. Reduce life cycle cost:
- Establishing a life cycle cost analysis procedure.
 - Improving service life prediction models
 - Collecting cost data on various conventional bridge systems.
 - Developing tools to perform life cycle cost analysis.
4. Ensure bridges meet expectation:
- Developing reliable materials tests.
 - Developing reliable quality assurance methods for construction.
 - Developing certification programs for products, procedures, and personnel.
 - Training 500 bridge engineers per year in HPC technology through seminars.
 - Training 2000 construction personnel per year in HPC bridge technology.

This ambitious but realistic plan provides a framework for the next decade's HPC program in the public and private sectors.

Self-Consolidating Concrete (SCC)

As the industry has gained confidence with using HPC over the last decade, new generations of the technology have emerged such as self-consolidating or self-compacting concrete. When properly proportioned and controlled, SCC can flow significant distances and consolidate to normal density without the use of vibrations and without segregation. It can fill intricate formwork shapes, especially when casting heavily reinforced elements and sections with restricted access, and still result in high-quality, smooth surfaces that are free of honeycombing and signs of bleed. It reduces labor demand and noise on construction sites and in precasting yards.

8 Vanikar and Trindafilou

SCC has already been used in the high-rise buildings and bridge construction industries, and more transportation agencies are now learning about it and taking advantage of its properties. A recent AASHTO/FHWA European scanning tour of accelerated bridge construction methods noted the extensive use of SCC in drilled shaft foundation construction.

Lightweight HPC

While a relatively new technology in the US, incorporation of lightweight aggregates into HPC mix designs has had an excellent performance record for more than 15 years in Norway. Lightweight HPC translates into lighter superstructures and smaller loads for substructure design. Lightweight concrete improves constructability and hydration due to internal curing. Although the aggregates are more expensive than conventional concrete aggregates, this small percentage materials premium is offset by the reduced size and cost of girders, piers and foundations.

Ultra High Performance Concrete (UHPC)

On the horizon is the development of UHPC for bridges. UHPC usually provides strength levels in excess of 150MPa (22,000psi). The FHWA Turner – Fairbank Highway Research Center's structures laboratory has implemented a testing program to verify the material properties of UHPC. FHWA has also funded an analytical study to determine an efficient highway bridge girder shape for UHPC.

CONCLUSIONS

In conclusion, the State DOTs and the industry have made enormous progress over the past 10 years with implementing some form of HPC into their everyday usage on concrete bridge projects. They have taken advantage of the benefits related to higher strengths for prestressed concrete girder elements and, and improved durability for reinforced concrete bridge decks. The researchers and academia have contributed tremendously in providing solutions to design and construction problems and in the technology transfer efforts. The widespread national use of this technology is consistent with industry, state and FHWA goals of mitigating congestion and improving safety at construction sites. HPC addresses these goals by extending service life, reducing costly maintenance activities, and lowering life cycle costs.

A strategic plan for HPC bridges has been proposed by NCBC. The successful implementation of the strategic plan and subsequent action plan will require management support and resource commitments over several years. The public and private sector partnership in the implementation of HPC technology during the recent past has been highly successful. This partnership needs to be maintained so that the general public continues to benefit from HPC bridges.

REFERENCES

1. Russell, H.G., Miller, R.A., Ozyildirim, H.C. and Tadros, M.K., "Compilation and Evaluation of Results from High Performance Concrete Bridge Projects - Final Report." FHWA, U.S. Department of Transportation, 461 pp. To be published. (Contact FHWA, Turner-Fairbank Highway Research Center, McLean, Virginia, 22101, USA)
2. Triandafilou, L.N., "HPC Accomplishments under TEA-21—What's Next?", *HPC Bridge Views*, Federal Highway Administration, Washington, D.C. pp 1-2 Issue, No. 26, March/April 2003.
3. Goodspeed, C.H., Vanikar, S., Cook, R.A., "High Performance Concrete Defined for Highway Structures", *Concrete International*, ACI, Detroit, MI, pp. 62-67, February 1996.
4. Triandafilou, L.N., "HPC Implementation Status", *HPC Bridge Views*, Federal Highway Administration, Washington, D.C. PP. 1-2, Issue No. 32, March/April 2004.
5. <http://knowledge.fhwa.dot.gov/cops/hpcx.nsf/home>
6. Vanikar, S.N., "Implementation of Strategic Plan for HPC Bridges", *HPC Bridge Views*, Federal Highway Administration, Washington, D.C. Page 1, Issue No. 20, March/April 2002.

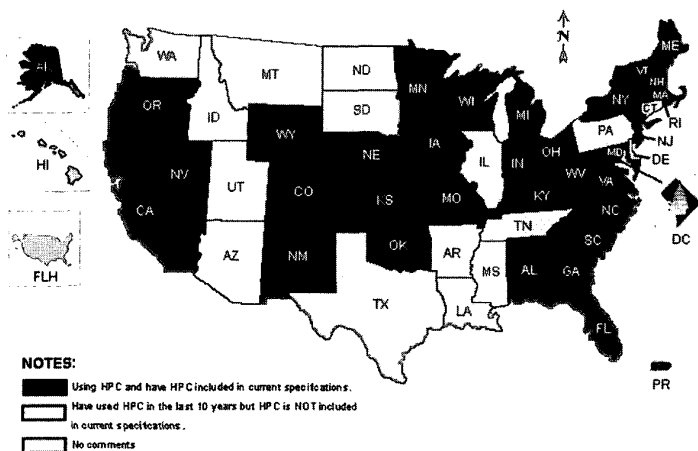


Figure 1 – States implementation of high-performance concrete

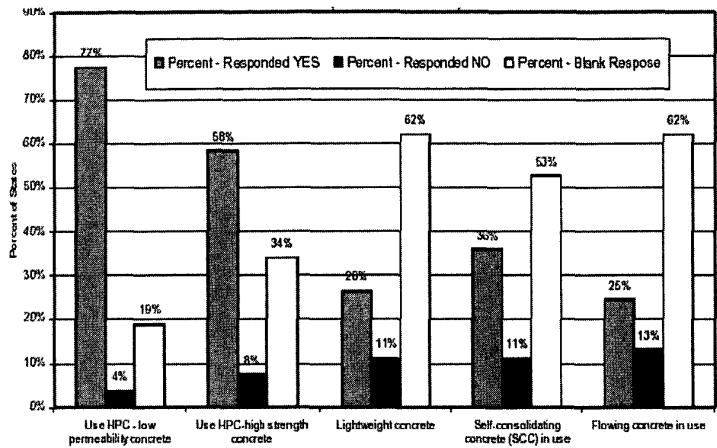


Figure 2 – Changes made in last 10 years

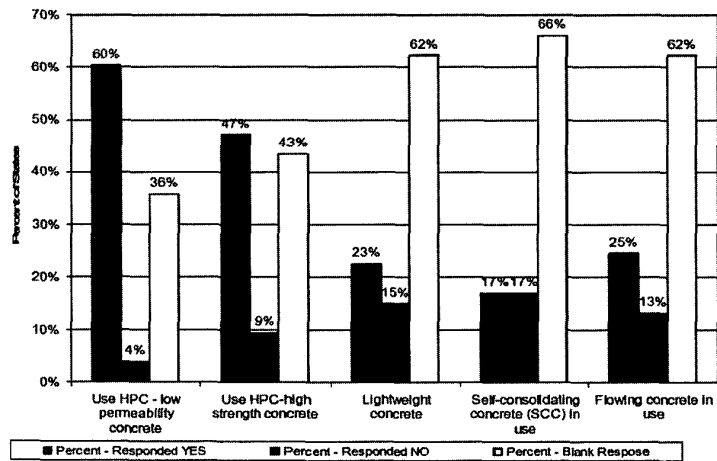


Figure 3 – Concrete characteristics included in current specifications

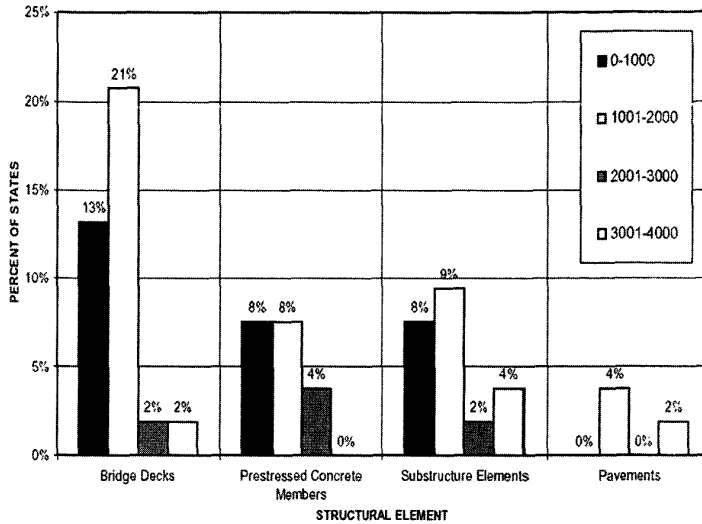


Figure 4 – Specified coulomb values for aggressive environments

Performance Based Design for Self-Compacting Structural High-Strength Concrete

by H. Okamura, K. Maekawa, and T. Mishima

Synopsis: This paper contains an historical review of self-compacting concrete clarifies and the original concept. Further, combinations of self-compacting concrete for high strength and durability are discussed in relation to structural concrete design, construction and maintenance, and recent development of performance-based design codes and manuals for SCC. On the competitiveness in industries, life-cycle cost is estimated for sustainable development of the infrastructure.

Keywords: construction; durability; high-strength; life cycle cost; maintenance; performance assessment; self-compacting concrete; structural concrete

14 Okamura et al.

Hajime OKAMURA is currently the President and a Professor of Kochi University of Technology, Japan. He is a former Dean of Engineering School of The University of Tokyo and the President of Japan Society of Civil Engineers.

Koichi MAEKAWA is a Professor of Department of Civil Engineering at The University of Tokyo, Japan. He received his doctorate degree from The University of Tokyo in 1985.

Tetsuya MISHIMA is currently a manager at the Structural Engineering Section of Technical Research Institute, Maeda Corporation.

INTRODUCTION

Since the breakthrough of self-compacting concrete (SCC) in 1988, its practical application to structural concrete has been driven in world construction industries. Meanwhile, additional higher performances, such as strength, durability and environmental friendliness, have been coupled with the self-compacting feature. Structural and material design methods have been also proposed to rationally extract the potential of SC based concrete. This paper summarizes SCC development in the past decades and introduces the updated performance-based design of high strength structural concrete with self-compacting nature.

SCC development history in the Japanese construction industry is illustrated in **Figure 1**. In early 1980s, shortened structural life of reinforced concrete drew public interest and criticism. Insufficient workmanship and compaction were recognized as primary causes of these defects. This was the background to make the first move towards self-compacting concrete. We accepted it as true that SCC may ensure the inherent capability of concrete composites in practice. Hence, no compaction is the best way to achieve material potential. This was the first message to the industry and was given at the occasion of Japan Cement Association Meeting in 1986. This message presented by the first author was regrettably thought of as just a vision.

Before the first prototype innovation, multi-particle physics was chiefly investigated to clarify the dynamic segregation of the liquid matrix - particle suspension system^{1), 2)}. Here, fresh concrete was firmly understood as a multi-sized particle assembly as clearly figured out by T. C. Powers³⁾. The frictional stress transfer was also studied for segregation-free concrete as an analogy of SCC.

After the 1988 SCC discovery at the University of Tokyo, chemo-physical assessment of super-plasticizer was challenged for the mix design procedure⁴⁾, which was issued in 1991. Next, the production manual and quality control system were developed for ready mixed concrete manufacturing and practical applications⁵⁾. The first terminology for this compaction free concrete was *high performance concrete (HPC)*. In those days, some confusion occurred in academia as HPC was chiefly used for high strength concrete. Then, to elucidate the original concept of development, the terminology SCC was introduced. Main focus was directed to high quality concrete that can be achieved in real structures.

Since Hanshin-Awaji Great Earthquake in 1995, high seismic structural performance has been required in Japan. In concert, life cycle capacity of infrastructures has become the great social demand. In fact, with increases in maintenance costs for existing structures,

self-compacting, high-strength and durable concrete has been drawing attention as an engineering solution. At present, this combination is denoted as super quality concrete (SQC) in Japan. Based on this activity, a performance-based design guideline for structural SQC was issued in 2000 and approved by Concrete Committee of the Japan Society of Civil Engineers (JSCE) (**Figure 1**). With this, the initial cost of structures can be equivalent to that of conventional reinforced concrete (RC) in spite of their increased durability and greater seismic resistance with much less life-cycle cost.

This paper presents an outline of the design and management to rationally realizing SCC as “*high performance structural concrete*.”

SIMILARITY OF SCC AND HIGH STRENGTH CONCRETE in 1940

There is a surprising similarity between the 1988 innovated self-compacting concrete and the high-strength concrete⁶⁾ developed by Dr. T. Yoshida in 1940 at University of Tokyo. After the innovation of SCC in 1988, the volumetric mix proportions of SCC were found to be so close to this old time high-strength concrete (HSC) of more than 110 MPa as shown in **Figure 2**. This HSC was mainly utilized for precast concrete railway tunnel linings in the 1940s. In order to obtain the high strength, compression force was first applied to fresh concrete carefully encased inside the steel forms and the mixed water was squeezed out through the voids of the forms. Then, the water - cement ratio by weight was reported to be 0.22 from the initial 0.31.

For efficiently squeezing water, applied compressive stress shall be directly transferred to the cement paste phase residing inside the voids of fine and coarse aggregates as shown in **Figure 2**. The coarse aggregate phase should not bear the contact compression so that the mortar phase may carry the total stress in between the coarse aggregates. In concert, the sand particle assembly shall be loosely dispersed for conveying total compression to the cement paste phase. Although this multi-scale stress transfer is rather volumetric for long-standing high-strength concrete, the design concept of SCC in terms of shear flow is basically the same.

It can be said that the matching mix proportions are not mere coincidence but they result from the logic no matter how different the deformational modes are. The authors believe that if there were a super-plasticizer about 70 years ago, Dr. T. Yoshida would be the innovator of SCC, because old high strength concrete mix proportion as shown in **Figure 2** was verified to turn into SCC when we use the same properties of sands and gravels with the current super-plasticizer. Nowadays, the old high-strength concrete continues to serve in the undersea railway tunnel facilities since 1940, and there is no problem even without maintenance for more than 60 years. This is evidence of the possibility of SQC with a long service life.

SELF-COMPACTING HIGH-STRENGTH CONCRETE (SQC)

Mix Proportions and Concrete Materials

The highly flowing character of SCC specified by the SQC design guideline is obtained

16 Okamura et al.

by a large dosage of powder and the use of no viscous admixture agent. Typical mix proportions specified in the guideline are listed in **Table 1**. The SQC design guideline specifies the quality requirements of 1) self-compacting feature, 2) water-binder ratio less than 0.40 by weight, 3) autogenous shrinkage less than 200×10^{-6} at 28 days, 4) concrete strength of 60 to 100 N/mm² at 56 days. The major concrete constituent materials are described as follows: cement: belite rich, cement with admixtures or low-heat when the unit cement content becomes high, aggregate: durable hard crushed stone with stability against alkali-aggregate reaction due to the higher unit cement content, admixtures: air entraining water reducing chemicals to have air content around 6% when resistance to freeze-thaw cycles is required.

Mechanical Properties of High-Strength Deformed Steel Bars

Currently, the use of high-strength deformed steel bars is growing, especially for RC tall buildings and high bridge piers. Thus, the SQC design guidelines include high-strength reinforcement in order to combine high performance steel and concrete for structural enhancement against earthquakes. The mechanical properties are shown in **Table 2** and typical stress-strain relationship is shown in **Figure 3**.

Materials and Construction Costs

The main materials used for SQC structures are high-strength steel (USD685 or other type) and SCC. At present, the unit cost of high-strength steel is slightly more than double that of ordinary electric furnace steel. The unit cost of SQC is 1.5 to 2.5 times the ordinary concrete cost and varies greatly from region to region. Material costs are needlessly high in Japan owing to the cartel market structure.

The SQC Association conducted trial structural designs and estimated costs under various conditions. Some estimates exhibited lower construction costs even though the high expense of SQC is inevitable in Japan, because smaller volumes of concrete can be sufficiently placed and less quantities of excavated soil are produced if the cross section of the structure can be reduced. **Figure 4** shows a cost comparison for bridge piers and box culverts. SQ structural concrete is competitive although SQ material costs much more. This is the reason why SQC design codification is demanded on a performance basis.

STRUCTURAL PERFORMANCES

Seismic Resistance

(1) Experimental outline--Kondoh et al. reported the results of reversed cyclic loading to verify the ductility of SQC column members^{7), 8)}. The materials stated in the previous section were applied to specimens subjected to reversed cyclic loading. **Table 3** lists the properties of specimens used in the laboratory experiments. **Figure 5** shows an external view of the specimen with the cross sectional dimensions and loading points.

Major parameters used in the experiment were the longitudinal reinforcement ratio and the shear capacity ratio defined by $V \cdot L / M$, where V denotes the shear capacity, L , the shear

span and M , the flexural capacity. The axial force was set at approximately 10% of the design axial capacity of each specimen. For specimen No. 9 with a reduced cross sectional area, a mean axial stress of 4.69 N/mm^2 was applied to maintain comparison with No. 0 under the same axial force.

(2) Experimental results--**Figure 6** shows flexural moment displacement relations for typical specimens. Specimen No. 1 has a longitudinal reinforcement ratio equivalent to that of No. 0, and was made of high-strength material. The experimental result shows that the yield strength M_y of specimen No. 1 becomes larger than that of No. 0 in proportion to the increase in the yield strength of longitudinal steel, but that the ultimate displacement is almost the same for both cases. It is thus found that an increase in the strength of column members is possible while maintaining their ductility, and that SQC column members may absorb energy and resist seismic forces no less than ordinary reinforced concrete members.

Specimen No. 9, which was designed to have a reduced cross sectional area to provide a flexural capacity equivalent to that of No. 0, possesses a ductility equivalent to or greater than that of No. 0. Thus, SQC members can maintain their strength and ductility even after their cross sectional area is reduced to 60 to 70% of that of ordinary reinforced concrete members. Then, it is possible to reduce the dead weight of the structure and to elevate seismic resistance, simultaneously. All three specimens as shown in **Figure 5** have the same shear capacity ratio of 1.5. For lateral hoops, D10s (SD345s) were placed at intervals of 6 cm, D10s (USD785s) at intervals of 6 cm, and D10s (USE785s) at intervals of 9 cm in specimen Nos. 0, 1 and 9, respectively.

(3) Ductility--**Figure 7** shows the relation of the ultimate rotational capacity (mean drift angle) and the shear capacity ratio. It was reported that specimen No. 9 with a shear span to depth ratio, which slightly differs from the other specimens, has slightly higher ductility but that a certain correlation is observed between shear capacity ratio and the ultimate rotational angle for the other specimens, and could be expressed by equation (1). The equation seems fully applicable as a design formula for simply identifying the ductility of SQC members with a shear span to depth ratio (approximately 3.0) equivalent to that of the specimen shown in this paper.

$$\theta_u = 0.018 \cdot \left(V \cdot \frac{L}{M} \right) + 0.018 \quad (1)$$

The Seismic Design Standards for Railway Structures adopt design methods that take disaster-induced damage levels into consideration. If the Design Standards are applicable to SQC members, practical design using SQC structural characteristics is possible. For example, the yield strength can be set at a high level by using high-strength materials without over-use of steel. Then, it is easy to design structures to control the degree of disaster-induced damage by considering how important the target structure is. The correlation of the damage level and the load-displacement relation is shown in **Figure 8**. **Figure 9** shows a comparison between experimental and calculated results for specimen No. 1. The formula in the Design Standards evaluates ductility of SQC members at respective damage levels fairly well. It may be confirmed that the Design Standards are applicable to SQC members, too.

Shear Strength

The material strength and member shear capacity are not proportional. At present, rational design formulae are being developed for simply evaluating the shear capacity of structural reinforced concrete members using high-strength materials, although the use of nonlinear finite element based assessment is advanced especially for size effect⁹⁾. Recently much research has been performed and data have been accumulated.^{10), 11)} The proposed design formulae in detail is explained in reference 12.

Strength of Lap Splice

Ito et al. studied the basic anchorage length of SQC members using beam specimens with lap splices along the length in a region of constant bending moment.¹³⁾ They compared the experimental bond strength with the calculated one in the Standard Specifications for Design and Construction of Concrete Structures¹⁴⁾, and suggested that the present bond strength should be reduced slightly for SQC members. **Table 4** lists the specimen tests carried out by Ito et al. and **Figure 10** shows the details of the specimens.

Table 5 is a list of experimental results. The experimental values were below the calculated ones by about 10%. Then, equation (2) is proposed for calculating the bond strength of SQC while considering a reduction factor β of 0.89, a mean value among all specimens. It is confirmed that setting the material factor for bond strength γ_c at 1.3 may ensure safety as for lap splice strength as shown in **Figure 11**.

$$f_{bo} = \beta \cdot (0.28 f_c'^{2/3} / \gamma_c) \quad \beta = 0.89 \quad , \quad \gamma_c = 1.3 \quad (2)$$

DURABILITY AND LIFE-CYCLE ASSESSMENT

Durability simulation of structural concrete is one of challenges in concrete science and technology¹⁵⁾ and practical application to life cycle assessment is also expected¹⁶⁾. The major determinant of durability of reinforced concrete structures is the corrosion of reinforcement and embedded steel. Steel corrosion is generally accelerated by concrete cracking, carbonation, chloride ion penetration, erosion by acid rain, freezing and thawing cycles, chemical erosion and alkali-aggregate reaction. In turn, the corrosion may accelerate cracking and cover concrete spalling. Together, and they mutually quicken corrosion itself. Thus, quantitative risk assessment of concrete deterioration due to these factors is necessary for ensuring the long-term service life of durable structural concrete. Outlined below are the results of experiments for the resistance to carbonation, freezing and thawing cycles and acid rain for self-compacting, high-strength and highly durable concrete. The formula for predicting deterioration is also described^{17), 18), 19)} in this section. The SQC Association has been the driving force in establishing SQC guidelines in practice.

Carbonation

As self-compacting, high-strength and highly durable concrete has a water-binder ratio

less than 0.40, the hardened concrete is normally dense and has greater resistance to carbonation than ordinary concrete. **Figure 12** shows the result of an accelerated carbonation test for SQC with a water-binder ratio less than 0.40. The accelerated carbonation was started at 56 days at a carbon dioxide concentration of 5%. The compressive strength at the beginning of the experiment is indicated along the horizontal axis, and the depth of carbonation after 26 weeks of acceleration is shown on the vertical axis. The figure shows that the greater the compressive strength is at the beginning, the more quickly the depth of carbonation decreases.

According to *Recommendations for Design and Construction Practice of High Durable Concrete of the Architectural Institute of Japan*, a carbonation depth of 30 mm in service for 500 years under normal conditions corresponds to 12 mm after 26 weeks of accelerated carbonation.

A carbon dioxide concentration of 5% during the experiment was converted to a value in the air and the coefficient of carbonation rate was obtained for practical use. The relationship of the coefficient to the effective water-binder ratio is shown in **Figure 13**. The coefficient, α , of carbonation rate for self-compacting, high-strength and highly durable concrete α can be estimated by,

$$\alpha = -0.38 + 1.63 W/B' \left(\text{mm} / \sqrt{\text{year}} \right) \quad (3)$$

where, W/B' = effective water-binder ratio = $W/(C_p + k \cdot A_d)$,

W = unit content of water (kg/m^3),

B' = unit content of effective unit binder (kg/m^3),

C_p = unit content of Portland cement (kg/m^3),

A_d = unit content of admixture (kg/m^3),

K = constant determined by the type of admixture,

For fly ash $k=0$, for iron-blast furnace slag powder $k=0.7$, for silica fume $k=0$.

Acid Rain

When acid rain acts on concrete, the hydrogen ion in the acid rain reacts with the hydroxide ion in the pore solution of concrete, the alkalinity of concrete is lost, and hydro-oxide ion concentration by pH is decreased. When acid rain has a great impact on concrete, the calcium silicate hydrate that constitutes the cement paste gets vulnerable to decomposition under much lower pH environment. Then, embrittlement causes erosion of the concrete texture. Other types of ions contained in acid rain may also have adverse effects. For example, the sulfate ion is likely to cause expansion of the concrete and lead to mechanical deterioration.

An accelerated test was conducted to evaluate the resistance of SCC against acid rain under the conditions listed in **Table 6**. The results are shown in **Figure 14**. The figure indicates that the erosion depth is proportional to the duration of acid rain, and that the depth after 50 cycles is about 1 mm regardless of the mix proportions. As a result of the accelerated test, the eroding rate C_0 was estimated at 1/50 mm/day, or 7.30 mm per year, based on the fact that the eroding time per cycle was one day. The value of pH was set 3.0 and it was assumed that the erosion depth is proportional to the acid rain concentration.

Then, the standard eroding rate denoted by C_p based on a pH of 4.6 was estimated at 0.183 mm per year through the calculation of $7.30 \times 10^{(3.0-4.6)}$. Thus, the eroding rate for self-compacting, high-strength and highly durable concrete during acid rain can be obtained by,

$$C_d = C_p \cdot \beta_{ph} \cdot \beta_t \quad (4)$$

where, C_d = concrete eroding rate during acid rain (mm/year),

C_p = standard concrete eroding rate during acid rain (mm/year),

β_{ph} = coefficient for considering the acid rain concentration, $= 10^{(pH_0 - pH)}$

pH = pH value of acid rain, 4.6 is set as the standard for durability design,

pH_0 = standard value for obtaining the standard eroding rate,

β_t = coefficient for considering the impact of acid rain

= total annual rainfall hour/(365x24).

Freeze-thaw Cycles

Some experimental results are shown in **Figure 15** to evaluate the resistance of self-compacting, high-strength and highly durable concrete to freezing and thawing. The experiment was conducted by a JSCE - compliant method. Freezing and thawing were repeated until the relative dynamic Young's modulus decreased to 60% to evaluate long-term durability although JSCE stipulates that the maximum number of freezing and thawing cycles is 300. The figure shows that the relative dynamic Young's modulus exceeded 60% even when the freezing and thawing cycles reached 2500 times at target air contents of freshly placed concrete of 4.0% for the design strength of 60 N/mm², 3.5% for 80 N/mm² and 3.0% for 100 N/mm².

For the same mix proportions, the relationship of the air content obtained by analyzing the air-void configuration in hardened concrete by a linear traverse method and the durability factor obtained by equation (5) based on a specified number of cycles of 2500 is shown in **Figure 16**. The figure enables the number of cycles of freezing and thawing before the relative dynamic Young's modulus drops to 60% to be predicted. Then, determination of the required freeze/thaw cycles according to the regional risk of freezing damage, lowest maximum temperature, number of repetitions of freezing and thawing or saturation level enables us to evaluate resistance to freezing and thawing.

$$DF = \frac{P \cdot N}{M} (\%) = \frac{60 \cdot N}{2500} \quad (5)$$

where, DF= durability factor of the specimen, P= relative dynamic Young's modulus at the N_{th} cycle of freezing and thawing (%) =60%, N= number of cycles before P reaches a designated value or the test ends, M= designated number of cycles where the test is terminated at 2500 times.

Draft Design and Construction Guideline

The SQC Association requested the Concrete Committee of the Japan Society of Civil Engineers to review and develop a new authorized design and construction guideline focused on performance assessment of SQC based upon the voluntary draft for design and construction of structural SQC prepared by the Association in 1996. After two-years of serious discussion and enhancement, the new guideline was published in March 2001 by JSCE. It consists of five volumes: I. Design and construction guideline focused on performance evaluation, II. Design manual, III. Construction manual, IV. Maintenance and V. Appendix -Design guides and examples-. The configuration of the guideline emphasizes performance verification and is on the basis of JSCE Standard Specifications for Design and Construction of Concrete Structures.

Chapter I only describes conceptual design and construction issues, basically independent of specific technical knowledge. The subsequent chapters describe the latest technology, but should be revised step by step whenever new progress is obtained. The second and the following chapters are mutually related. For example, the descriptions on maintenance presuppose that design and construction comply with the contents of Chapters II and III.

Flow of Design and Design Conditions

This section outlines an example of design presented in the appendix to the guideline. The flow of a design example is shown in **Figure 17**. The review process is divided into two major phases: material design and performance evaluation of the structure. In material design, targeted physical properties (characteristic values) are specified and performance for construction work is evaluated. Performance evaluation of the structure consists of the evaluation of performance requirements for safety, serviceability, durability and seismic resistance.

In design focused on performance evaluation, design conditions are defined first, and evaluated to check whether they satisfy the design requirements of the target structure. A fast finding of the design conditions that satisfy performance requirements in all terms is the key to work efficiency. The discussion of the sample design emphasizes the procedure for evaluating the specified design conditions, but does not refer to the method for efficiently establishing the design conditions that pass assessment. The major design conditions demanded for the sample design are listed as (1) design period of performance retention assurance: 100 years, (2) substantially expected period of service: 300 to 500 years: for superstructure, (3) prestressed concrete five-span continuous bridge with hollow slabs, (4) substructure: wall piers and pile foundations (cast-in-place piles), (5) environmental conditions: inland, coastal or cold area, (6) (coastal area is defined within 500 m from the coast line), (7) concrete: LC72 ($f_{ck}=60 \text{ N/mm}^2$), (8) longitudinal reinforcement: USD685, transverse reinforcement: USD785.

22 Okamura et al.

Results of Performance Evaluation

As an example of a structure that satisfies performance requirements for safety and seismic resistance, the dimensions and shape of substructure are shown in **Figure 18**. As for construction work, the second-level self-compaction is required in view of density of reinforcement arrangement. The LC72 mix proportion satisfies all the standard values required for the second level, and thus passes assessment. It is verified that the structure with the concrete cover specified in **Table 7** satisfies performance requirements for serviceability and durability in the inland and cold areas. In a coastal area, however, the structure has insufficient resistance to salt attack even if the LC72 mix proportion be used. In this case, some measures are required such as providing a concrete cover of about 95 mm in the bridge pier or applying surface protection by coating.

Life Cycle Cost – Comparison of SQC and Conventional Structural Concrete -

In order to clarify the competitiveness of self-compacting high strength concrete, life cycle cost was compared with 9 design details of a RC bridge pier located close to the sea. (See **Figure 19**)²⁰⁾. Here, life cycle cost is defined as the sum of initial construction cost and estimated maintenance expense. The recycle cost is not included and no discounting rate is set up. For estimating the maintenance cost, repair and rebuilt expenses by currency are calculated in terms of steel corrosion and probabilistic earthquake induced damage. The corrosion risk assessment was conducted with following equations of the JSCE Standard Specifications²¹⁾ according to the cover depth and the quality of concrete.

$$\frac{\partial u}{\partial t} = D_d \frac{\partial^2 u}{\partial x^2} \quad (\text{equation of diffusion}) \quad (6)$$

$$C_d \geq C_{\text{lim}} = 1.2 \text{ kg/m}^3 \quad (\text{judging standard}) \quad (7)$$

where, u = Density of chloride ion (kg/m^3) at $x=0$, $u=C_0$
 t = time (s)

x = distance from concrete surface (cm)

D_d = Diffusion coefficient of chloride ion (cm^2/s)

C_0 = Density of chloride ion at concrete surface (kg/m^3)

C_d = Density of chloride ion at steel bar (kg/m^3)

C_{lim} = Corrosion limit density of chloride ion (kg/m^3)

The repair cost to recover the function after earthquake can be estimated with the possibility of seismic event of different magnitudes and corresponding damage magnitude of the structure. The damage level can be computed by conducting nonlinear dynamic analysis under the estimated seismic action. If much reinforcement is placed, the recovery cost may be less even under great seismic loads but the initial cost will be increased. If we itemize high quality concrete, larger initial cost will be demanded, but the maintenance cost can be compressed. Then, the material / structural capability, which have much to do with initial cost, are trade-offs of maintenance cost.

High-Strength/High-Performance Concrete 23

Here, nine cases of design details are discussed as listed in **Table 8**, and the corresponding LCC estimation is lined up in **Table 9**. All cases satisfy the requirements of the design code specification for road bridges in Japan. SQC design exhibits a little bit higher initial cost than others as an extremely high unit price of self-compacting concrete is defined. However, the life cycle cost of SQC is the lowest with greater competitiveness. The high strength of constituent materials can bring lightweight and higher seismic resistance, and at the same time, dense cementitious texture is realized and longer life is brought about.

This multiple benefit is the main source of cost competitiveness. **Figure 20** shows the sensitivity of compressive strength of concrete to the cost configuration. Dramatic cost reduction is obtained when the strength of concrete is increased. It is obvious that the reduced maintenance cost relies greatly on the enhanced durability rather than the reduced seismic risk. As a matter of fact, the highly durable character of the high strength concrete enables cost benefits.

CONCLUSIONS

Systematically arranged experiments have been conducted to identify the basic characteristics of super quality concrete structures. This paper also outlines structural experiments for quantifying structural safety and serviceability after the rare extreme loading. For durability, assessment to realize long-life structural concrete, quantitative assessment of resistance to carbonation, acid rain and freezing and thawing cycles was discussed. The design guideline and construction practice for SQC were introduced to rationally utilize self-compacting character in the industry, and the life-cycle cost was compared with conventional and the new SQC performance-based design. Some design examples for a new generation transportation system were explained in order to make sure the competitiveness of structural high-strength and self-compacting concrete. This guideline was completed in April 2001 and paved the way for design by any concrete engineer. This is expected to contribute to wider use of next generation of civil engineering structures with high durability, structural safety, serviceability and restorative capability against rare extreme loadings.

ACKNOWLEDGMENT

The structural performance and durability assessment in the paper were mainly conducted by the SQC Association with 15 regular member firms and 34 associates. The authors deeply appreciate cooperation by Mr. Makoto Kito of Choudai Corporation, Mr. Makoto Kikuchi of Tekken Corporation, Mr. Sakae Ushijima of Aoki Corporation, Mr. Yuji Ito of Fujita Corporation, Mr. Hitoshi Tanaka of Tobishima Corporation and Mr. Tadashi Watanabe of Maeda Corporation.

REFERENCES

1. Nanayakkara, A., Gunatilaka, D., Ozawa, K. and Maekawa, K., Flow and segregation of fresh concrete in tapered pipes - Two-phase computational model, ASME, FED-Vol.75, 1988.12.
2. Ozawa, K., Nanayakkara, A. and Maekawa, K., Flow and segregation of fresh concrete around bifurcation in pipe lines, ASME, FED-Vol.75, 1988.12.
3. Powers, T. C., *Properties of Fresh Concrete*, McGraw-Hill, N. Y., 1968.
4. Okamura, H., Maekawa, K. and Ozawa, K., *High Performance Concrete*, Giho-do Press, Tokyo, 1991.
5. Okamura, H. and Ohuchi, M., Self-Compacting Concrete, *Journal of Advanced Concrete Technology*, 1(1), 5-15, 2003.
6. Yoashida, T., On the highest strength concrete, *Proceedings of JSCE*, Vol.26, No.11, 1940.
7. Kondo, M., Mishima, T., Shimono, K. and Sato, T., A study on ductility evaluation methods for reinforced concrete members using high-strength material, *Proceedings of the Japan Concrete Institute*, No.3, 1999, pp 217-222 (in Japanese).
8. Kondo, M., Mishima, T., Tanimura, Y. and Sato, T., A study on ductility checking Methods for reinforced concrete members using high-strength material, *Proceedings of the 55th Annual Conference of Japan Society of Civil Engineers*, Vol. 478, September 2000, pp 958-959 (in Japanese).
9. Maekawa, K., Okamura, H. and Pimanmas, A., *Nonlinear Mechanics of Reinforced Concrete*, Spon Press, London, 2003.
10. Nitta, K., Tanimura, Y., Kashiwabara, S. and Sato, T., An experimental study on the shear strength of reinforced concrete beams using high-strength material, *Proceedings of the 55th Annual Conference of Japan Society of Civil Engineers*, Vol. 521, September 2000, pp 1044-1045 (in Japanese).
11. Tsuchiya, S., Mishima, T. and Maekawa, K., Shear failure analysis of RC beams using high strength materials, *Proceeding of fib congress, Osaka, fib*, W-150, 2002.
12. Mishima, T., A performance design method of RC structures using high strength self-compacting concrete and high strength steel bars, *Proceeding of fib congress, Osaka, fib*, K-24, 2002.
13. Ito, H., Hara, N. and Mishima, T., A study on the basic anchorage length of a member using self-compacting high-strength concrete and high-strength steel, *Proceedings of the 55th Annual Conference of Japan Society of Civil Engineers*, Vol. 577, September 2000, pp 1156-1157 (in Japanese).
14. Japan Society of Civil Engineers, *Standard Specifications for Concrete Structures -2002, Structural Performance Verification*, March 2002, pp 136-137 (in Japanese).
15. Maekawa, K., Chaube, R. P. and Kishi, T., *Modeling of Concrete Performance*, Spon Press, London, 1999.
16. Maekawa, K., Ishida, T. and Kishi, T., Multi-scale Modeling of Concrete Performance - Integrated Material and Structural Mechanics -, *Journal of Advanced Concrete Technology*, 1(2), 2003.
17. Ushijima, S., Shirokuni, S., Yanagi, H., Inagaki, M. and Kitoh, M., A study on the

High-Strength/High-Performance Concrete 25

resistance of super high quality concrete to freezing and thawing, and neutralization, *Proceedings of the 53rd Annual Conference of Japan Society of Civil Engineers*, Vol. 339, October 1998, pp 678-679 (in Japanese).

18. Makishima, O., Tanaka, K., Kimachi, Y. and Tsuzaki, J., An experimental study on acid resistance of super quality concrete, *Proceedings of the Japan Concrete Institute*, Vol. 21, No.2, 1999, pp 391-396 (in Japanese).
19. Sato, F., Ueda, H., Shutto, K. and Ushijima, S., Long-term resistance of super quality concrete to freezing and thawing, *Proceedings of the Japan Concrete Institute*, Vol. 21, No.2, 1999, pp 385-390 (in Japanese).
20. Obara, T., Kaneko, O., Kanetoh, M., and Mishima T., A study on estimation for life cycle costs of RC bridge piers, *Proceedings of the Japan Concrete Institute*, Vol. 25, No.2, 2003, pp 1957-1962 (in Japanese).
21. Japan Society of Civil Engineers, *Standard Specifications for Concrete Structures –2002, Construction*, March 2002, pp 24-28(in Japanese).

Table 1--Standard SQC mix proportions.

Mix Proportion	Required Strength	Target Slump Flow	Water-Binder Ratio	Target Air Content	Unit Content of Material (kg/m ³)										
					Water	Cement	Admixtures			Fine Aggregate	Coarse Aggregate	Chemical Admixtures		Steel Fiber	
							Fly Ash	Iron-blast Furnace Slag Powder	Silica Fume			AE and High-range Water Reduce Agent	AE Agent		
(N/mm ²)	(mm)	(%)	(%)	W	C	FA	BS	SF1	S	G			SF2		
LC72	72	600	0.386	4.0	165	427				891	827	4.27	8.5		
FA72	72	600	0.349	4.0	165	378	95			809	827	5.81	35.5		
BS72	72	600	0.415	4.0	165	199		199		891	827	4.18	10.0		
BL98	96	650	0.326	3.5	165	506				852	811	6.83	10.1		
SF120	120	650	0.257	3.0	165	578			64	750	795	12.84	51.4		
BS120	120	650	0.220	3.0	165	675		75		681	795	13.13	9.0		
SFRC	72	600	0.289	5.5	165	571				1039	510	11.40	15.4	80	

Maximum Size of Coarse Aggregate Particle = 20mm

Table 2--Mechanical properties of high-strength deformed steel bars.

Mark of Type	f_y (N/mm ²)		f_u (N/mm ²)	Type of Reinforcement
USD685A	685	785	$f_y \times 1.0.85$	Longitudinal Reinforcement
USD685B	685	755	$f_y \times 1.0.80$	
USD980	980		$f_y \times 1.05$	
USD785	785		930	Shear Reinforcement
USD1275	1275		1420	

f_y : yield strength or 0.2% strength, f_u : tensile strength

Table 3--Detail of specimens

Specimen	Dimensions of Cross Section (mm)	f_c (N/mm ²)	Longitudinal			Shear Reinforcement				Axial Stress (N/mm ²)	Shear Capacity		
			Diameter	P_s (%)	Type	Diameter	Pitch (mm)	P_s (%)	Type				
0	B500×500	60	30	D25	1.0	SD295	D10	60	0.478	SD345	3.0	1.5	
1				D25	1.0		D10	60	0.476			1.5	
2				D25	0.5		D10	90	0.317			1.5	
3				D29	1.5	USD685	D13	75	0.676			1.5	
4				D25	1.0		D13	75	0.878	USD785	6.0	2.0	
5				D25	1.0		D13	45	1.126			3.0	
6				D25	0.5	SD345	D10	140	0.204			1.5	
7				D25	1.0	USD685	D10	60	0.476			10.0	1.5
8				D25	1.0		D13	120	0.422	USD1275	6.0	2.0	
9				D25	1.0	USD685	D10	90	0.386	USD785	4.7	1.5	
	B400×400	80											

Table 4--List of specimens.

No.	Longitudinal Reinforcement	Shear Reinforcement	f'_c (N/mm ²)	C_b	α_b	Lap Length l/ ϕ	Parameter
K1	D19	-	88.1	30	0.68	24.4	Area of transverse reinforcement 1.15 times the lap length of K2
K2	$f_y=720$	$f_y=922$	$\phi 50$	88.1	30	0.58	
K3	(N/mm ²)	(N/mm ²)	$\phi 0$	89.5	30	0.50	
K4			$\phi 50$	89.5	30	0.58	

Table 5--Test results.

No.	Lap Length l/ ϕ	α_b	f'_c (N/mm ²)	Bond Strength		$f_{bo\ exp}$ / $f_{bo\ cal}$
				Experiment $f_{bo\ exp}$ (N/mm ²)	Calculate $f_{bo\ cal}$ ^{*1} (N/mm ²)	
K1	24.4	0.68	88.1	4.59	5.54	0.83
K2	21.1	0.58	88.1	4.97	5.54	0.90
K3	18.1	0.50	89.5	5.39	5.60	0.96
K4	24.3	0.58	89.5	4.83	5.60	0.86

Average 0.89

^{*1} Formula of JSCE Code $f_{bo}=0.28f'_c{}^{1/3}$

Table 6--Conditions of accelerated test for chemical resistance to acid rain.

Item		Acceleration condition
Soaking	Density of Solution	pH3.0
	Type of Solution	Sulfate:Nitrate=2:1
	Temperature of Solution	20 degC
Drying	Relative Humidity	R.H.60%
	Environmental Condition	20 degC
Environmental Conditions		Soaking 1day + drying 6days

Table 7--Minimum concrete cover.

Element		Minimum concrete cover c_d (mm)	Concrete cover used for durability evaluation c' (mm)
Substructure	Bridge Pier	70	60
	Footing	Top:70, Bottom:110	Top:60, Bottom:100
	Pile	110	100

 $c = c_d - c_{be}, c_{be}$: Allowable Construction Error(mm). Generally set at -10--+10mm.

Table 8--Design cases for LCC calculation.

No.	Section		C	Type	f _c '	W/C	Main reinf.		Web reinf.		Chloride C ₀	Measure	
	Height	Width					type	P%	type	P%		initial	repair
1	2.2m	5.0m	12cm	Conv.	24 MPa	0.55	SD295	0.48	SD295	0.16	13.0 kg/m ³	NO	rebuild
2			8cm					0.47		0.16			
3			15cm					0.49		0.19			
4			0.61					0.16					
5			0.38					0.16					
6	2.7m	5.5m	12cm	Conv.	24 MPa	0.55	SD295	0.48	SD295	0.16	13.0	coating	
7	2.2m	5.0m	12cm	Conv.	24 MPa	0.55	SD295	0.48	SD295	0.16	4.5		
8											9.0		
9											13.0		

*: surface epoxy resin coating

High-Strength/High-Performance Concrete 27

Table 9—Life cycle cost assessment.

Table 9- Life Cycle Cost assessment.										
No.	Seismic Performance:Pa/Khc W				No. of repair	LCC million ¥	Initial cost mill ¥		Earthquake Recovery Cost mill ¥	Chloride Damage recovery
	longitudinal		transverse				main structure	Chloride prepare		
	Type I	Type II	Type I	Type II						
1	1.43	1.15	2.77	2.07	5	12.60	4.16	0.0	0.76	7.68
2	1.48	1.18	2.80	2.09	12	21.40	4.17		0.67	16.57
3	1.39	1.13	2.74	2.07	3	9.81	4.15		0.85	4.81
4	1.77	1.43	3.16	2.38	5	12.46	4.49		0.29	7.68
5	1.25	1.07	2.60	1.99	5	12.92	3.98		1.27	
6	1.52	1.14	2.84	1.95	2	7.05	4.33		0.39	2.32
7					2	7.43	4.16		0.76	
8	1.43	1.15	2.77	2.07	4	10.74	4.16			5.82
9					3	10.68	4.16	5.76		0.00

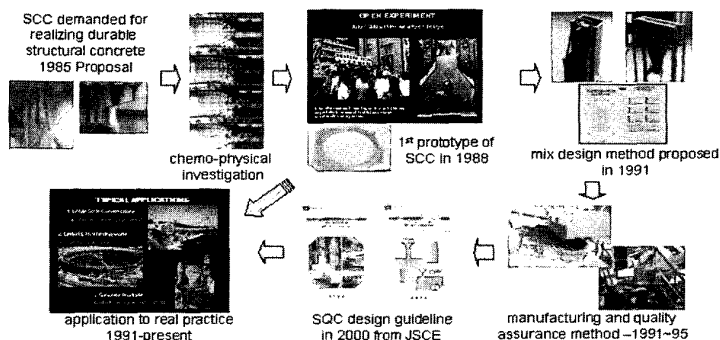


Figure 1—Progress of self-compacting concrete in the past decades.

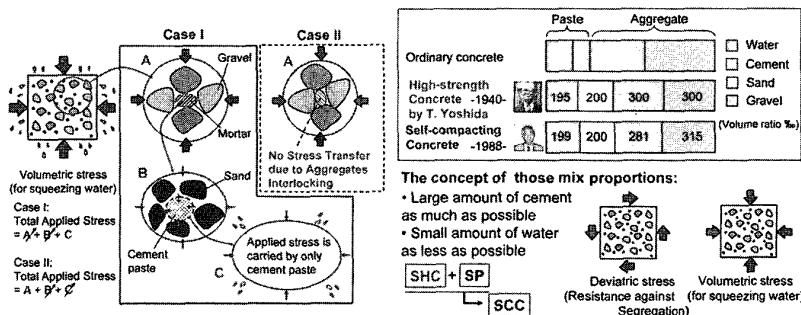


Figure 2—100 MPa high-strength concrete (T. Yoshida) in practice of 1940

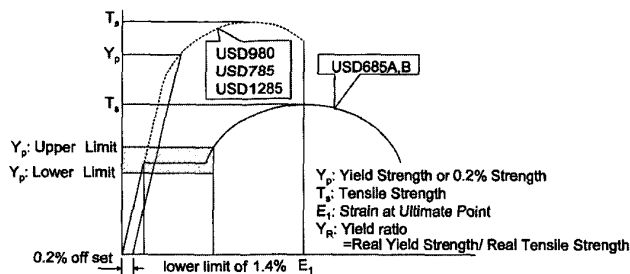


Figure 3—Stress-strain relations of high-strength deformed steel bars.

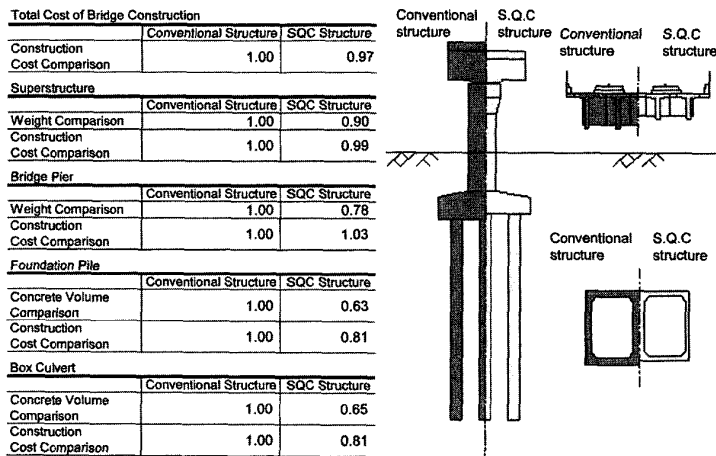


Figure 4—Trial designs and cost comparison.

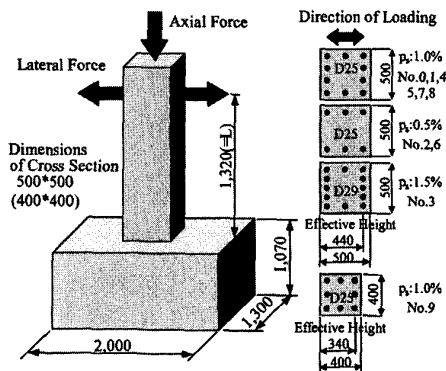


Figure 5—Specimen details.

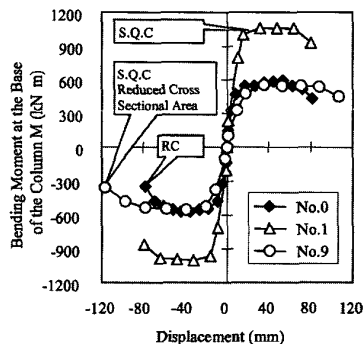


Figure 6—Flexural moment-displacement relations.

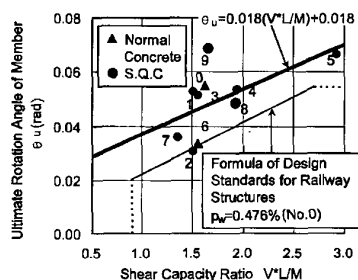


Figure 7—Shear capacity ratio and ultimate rotation angle of member.

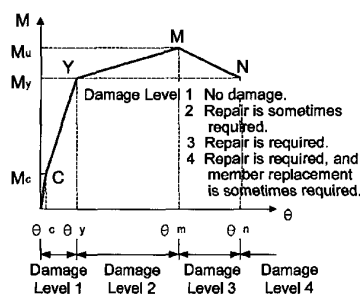


Figure 8—Damage levels and load displacement relationship.

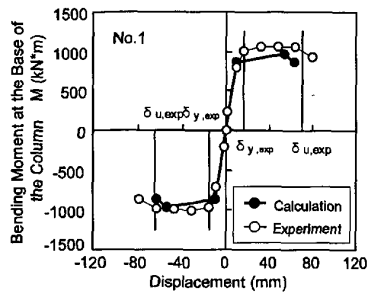


Figure 9—Load displacement relations for SQC specimen.

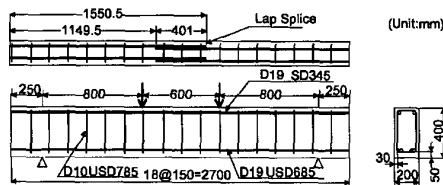


Figure 10—Detail of specimens (K2).

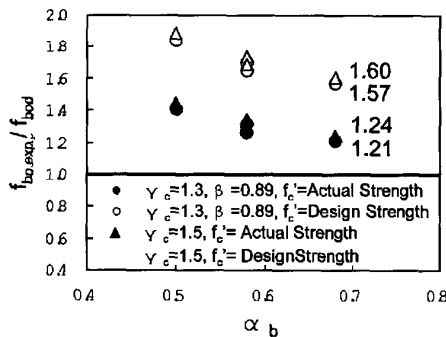


Figure 11—Design bond strength

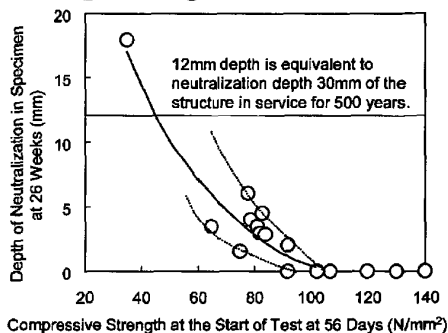


Figure 12—Results of accelerated carbonation test for SQC.

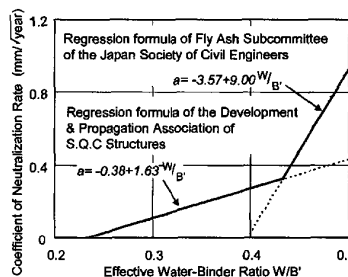


Figure 13—Coefficient of rate of carbonation and effective water-binder ratio.

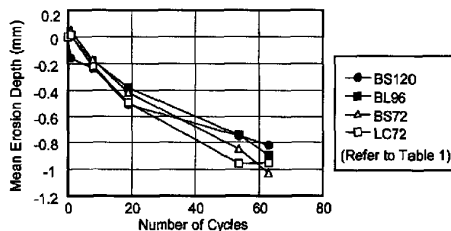


Figure 14—Mean erosion depth in accelerated acid rain resistance test.

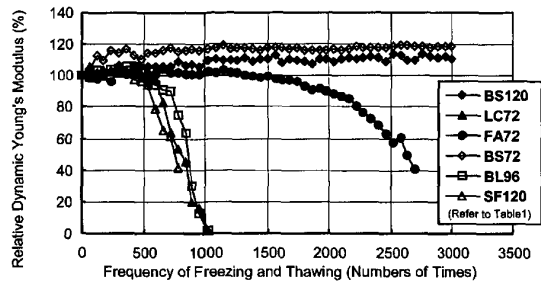


Figure 15—Relative dynamic Young's modulus versus freezing and thawing cycles relation.

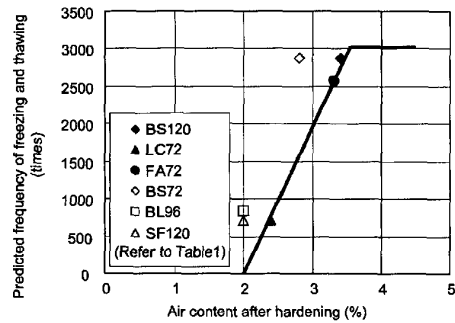


Figure 16—Post-hardening air content and predicted cycles of freezing and thawing.

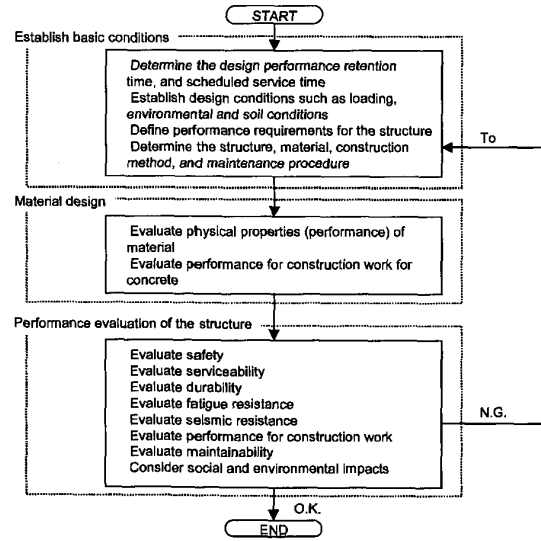


Figure 17—Scheme of performance based design.

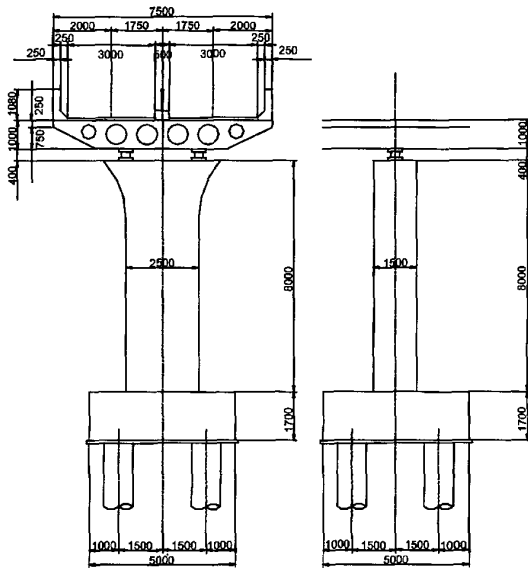


Figure 18—Example of substructure.

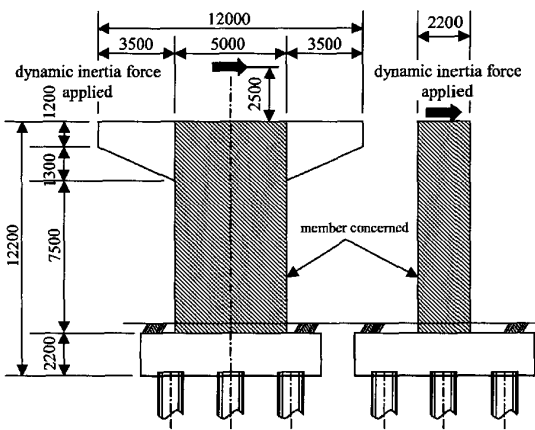


Figure 19—Design example for life cycle cost estimation.

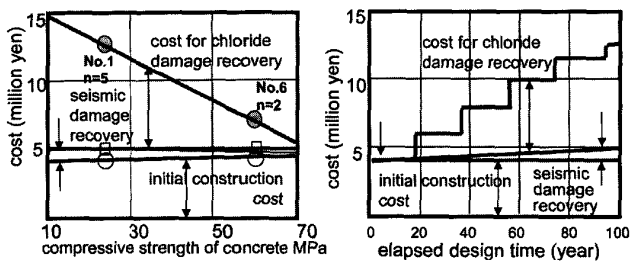


Figure 20—LCC estimation and sensitivity analysis.

High-Performance Concrete – A Proven Material with Unfulfilled Potential

by J. Moksnes

Synopsis: Since the 1970's the concrete industry has seen major developments in high strength/ high-performance concrete (HPC). New materials, design codes and construction methods have enabled us to design and build taller, slimmer, lighter, more attractive and more durable concrete structures. Through research and development and practical applications we have improved our knowledge on strength, ductility, durability, constructability, appearance and other properties to where technology is not the limiting factor, but rather our ability to utilize what we know and to promote our ideas for more sustainable and competitive concrete structures.

HPC is now covered by a number of design codes and high-performance structures can be produced almost anywhere with selected local materials and competent workmanship. The volume of available literature on HPC has increased almost exponentially in recent years. Large research and development programmes have been executed and shown to produce remarkable results and provide very satisfactory returns on the investment.

HPC still constitutes only a small part of the output of the concrete industry and is largely limited to marine structures, large span bridges and prestigious buildings and to some extent precast components. The market of ordinary structures is still dominated by ordinary concretes with ordinary performance.

The paper discusses some aspects related to the evolution of high strength concrete (HSC) and high performance concrete and how the concrete industry, for the benefits of the clients and its own performance and image, needs to more actively utilize the proven HPC technology.

Keywords: high-performance concrete (HPC); high-strength concrete (HSC); research and development (R&D); utilization of knowledge

36 Moksnes

Jan Moksnes has for more than 30 years been involved in the design and construction of large concrete structures for the offshore oil and gas industry and in the management of heavy civil engineering projects. He is a former president of the Norwegian Concrete Association and of FIP and is presently an independent consultant to the construction industry.

INTRODUCTION

During the past 20 to 30 years there has been a considerable progress in the development of high strength/ high-performance concrete. From an initial focus on strength, the attention has subsequently broadened to other properties such as durability, density, constructability and appearance. Thus “high-performance concrete (HPC)” has become a more pertinent term, embracing concretes that meet the requirements with respect to overall performance. This often means concretes in the high strength and low water-binder ratio area.

The 1980's and 90's was a “golden age” for concrete in Norway and a considerable research and development (R&D) programme was executed, fuelled to a large extent by the needs of the offshore oil and gas industry for a new breed of marine production facilities. Similar R&D efforts were made in other countries and national and international associations for concrete took initiatives to develop new codes and guidelines and to organise symposia and conferences on the subject. One such initiative was the FIP sponsored “1. International Symposium on the Utilization of HSC” organised in Stavanger, Norway in 1987 (1). This has been followed by a series of 3 yearly events leading to this 7. International Symposium on HSC/ HPC in Washington in 2005. These symposia have been augmented by other national and international HPC conferences and the numerous proceedings and technical papers constitute a library of information and demonstrate the merits and exciting potential of HPC.

(It is interesting to note that the transition from HSC to HSC/ HPC in the title of the series of FIP symposia first occurred in France in 1996, demonstrating that the two are closely related and sometimes inseparable)

The terms High Strength Concrete (HSC) and High Performance Concrete (HPC) are often used indiscriminately and this may create some confusion. HSC is generally understood to be concretes with compressive strengths in the region of 60 MPa and upwards to 100 MPa or more. HPC is a term which in most peoples mind embraces high durability and suitable constructability in addition to high strength. The high strength/ high durability aspect is generally associated with low water-binder ratio concretes. Most HPC issues are also closely associated with design and constructability, thus making HPC a more all embracing concept.

A joint CEB/FIP Working Group compiled a state-of-the-art report on the ‘Application of High Performance Concrete’ in 1994 (2). The object of this report was to provide information about the potential benefits of changing current design and construction practices in order to utilise higher concrete qualities. The report demonstrates the

High-Strength/High-Performance Concrete 37

application of high performance concrete to high rise buildings, bridges, offshore structures and pavements and provides a summary of relevant Codes and regulations for up to 115 MPa (16 000 psi) concrete.

The research efforts and initiatives described above have not, as one might have expected, had a very profound effect on the advancement, in a more general sense, of concrete as the most important construction material for civil infrastructure applications. On the one hand, the definition of feasible “high strength” is forever moving upwards, from 50 MPa in the 1970’s to 100 MPa in 1990’s and to some recent bold examples in the region of 150 MPa. On the other hand the bulk of everyday structural concrete, which we see on construction sites all around us, is still an ordinary strength, ordinary performance material with limited durability and a negative public image.

Clearly, not all structures can utilize the potential for higher strength properties that is available through the recent high strength R&D programmes. Leivestad and Vik gave us some interesting food for thought at the 1987 Stavanger Symposium (1) and shown in Figure 1. By plotting the increases in permissible design strengths over the years according to the Norwegian design code versus the corresponding required cross sectional area for a centrally loaded concrete column, the dotted extrapolated curve ended up with a cross section of 0 shortly after year 2000!

This example above, although humorous, points to the fact that the present high strength materials technology has left the designers with the challenge of utilizing the higher strength in our modern structures; at the present time it may appear that the materials technologists and the designers are a little bit out of sync.

The high-performance aspects associated with the high strength development, however, ought to have a much wider appeal. We do have the knowledge to achieve much improved durability through attention to important design details, proper mixture proportions and competent execution; similarly, improved consolidation and better surface finish and productivity can be achieved through efficient admixtures. Innovations in aggregate production and selection, tailoring of cement qualities, inclusion of silica fume, the technology of self compacting concrete, availability of high strength lightweight aggregate (LWA) and improved batching and pumping equipment are but some of the innovations that we could utilize to a better advantage.

Available statistics from the Ready Mixed Industry in Norway show that for the total production volume over the past 10 years, only about 4 % falls into the category which could be labelled high strength concrete. Some 20 % is defined as 45 MPa and come close to having a HPC potential (medium to low water-binder ratio), but the remaining 75 % or so is run of the mill medium or low quality concrete. It seems that the recent offshore HPC experience has not rubbed off on the land based market, and HPC has not been fully embraced for the land based market in Norway.

It is argued that the new and more sophisticated concretes are less tolerant and more dependent on predictable conditions and competent workmanship. This is true, but can surely be managed through proper planning, training and supervision and should not be

38 Moksnes

seen as a barrier to progress which can otherwise contribute to improve our structures and enhance our image. Several national and international codes pay attention to importance of workmanship and the competence of the operators and include provisions that are minimum requirements in this respect. The concrete industry needs to recognise that training at all levels is a prerequisite to full utilization of the potential of HSC/ HPC.

THE EVOLUTION OF HIGH PERFORMANCE CONCRETE

The North Sea Experience

Significant contributions to the advances of high performance concrete came from the developments of offshore concrete structures in the North Sea from 1971 to 1995. The oil and gas industry had the need and the resources to sponsor research and developments on a large scale in order to develop materials and structures that would meet the demands of a very hostile marine environment. Nothing drives research and development more effectively than recognised needs and demanding clients. The North Sea experience in turn stimulated developments in other fields, particularly the design of medium and large span bridges, where the Norwegian Public Roads Administration provided the driving force (3).

The history of the more than 20 major offshore concrete structures that were delivered in this period is well documented and well known (4). The era culminated with the delivery in 1995 of the giant Troll A platform, Figure 2, installed in 300 m water depth and consisting of 240 000 m³ of 75/ 80 MPa heavily reinforced and prestressed concrete. The design and construction of this impressive structure was only made possible through an extensive R&D programme evolving through the preceding 15 years.

The basic requirements to design and construction of durable marine concrete structures (read High Performance Concrete Structures) are well known and understood and have been for many years. It is interesting to note that when the oil and gas industry started to pay attention to marine concrete structures in the early 1970's, FIP made a management decision to produce a document defining the state of the art and providing guidelines to the industry and comfort to the clients (5). This is an example of a kind of documents the concrete industry could do well to produce for different applications of concrete, targeting the clients and future users of the structures, rather than the technologists only.

Examples of some prototype concrete mixture proportions and properties from the offshore era are given in Table 1, and serve to demonstrate the apparent simplicity of the mixtures. Some well understood basic rules (5) regarding minimum cement content, aggregate quality, maximum water-cement ratio and efficient admixtures were used as a basis for extensive test programmes tailored to each individual project. The main factors contributing to this development from a demanding 40 MPa concrete in the 1970's to the more comfortable 80 MPa concretes of the 1990's are shown in Figure 3.