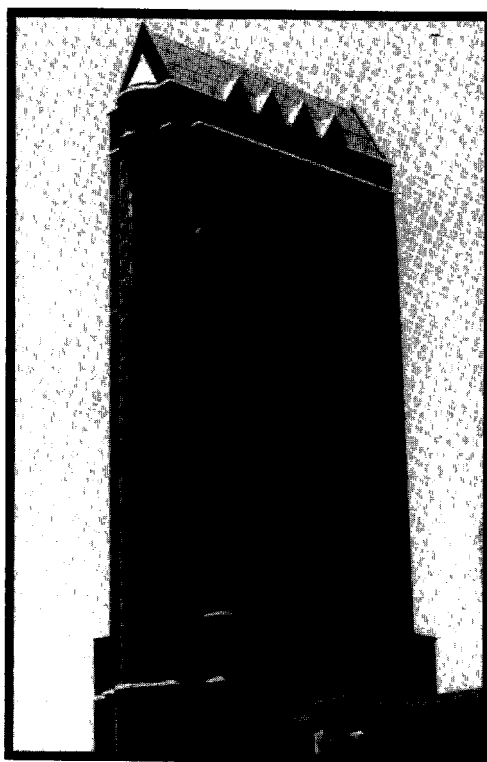


High-Performance Concrete

Proceedings
ACI International Conference
Singapore, 1994



V. M. Malhotra
Editor

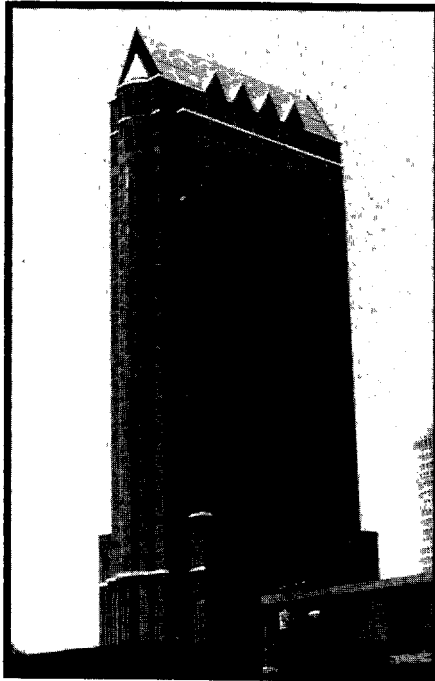
SP-149



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SP-149 

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PREFACE

In December 1991, the American Concrete Institute sponsored an International Conference on Evaluation and Rehabilitation of Concrete Structures and Innovations in Design. This was in keeping with the mission of the Institute, and the specific purpose of the conference was to disseminate technical information on emerging concrete technology in the Pacific rim region, and to provide technical support for a growing number of ACI International Chapters and members. The conference was held in Hong Kong, December 2-6, 1991. More than 80 papers were published in the conference proceedings issued by ACI as SP-128.

As a follow-up of the very successful Hong Kong conference, ACI Board of Direction approved a second international conference for 1994. The theme of the conference was High-Performance concrete and the conference was held in Singapore. More than 80 papers from 20 countries were received and reviewed in accordance with the policies of the American Concrete Institute, and 45 were accepted for publication as SP-149. In addition, a number of papers were selected for presentation, and for publication as supplemental papers. To all those whose submissions could not be included in the conference program, the Institute and the Conference Organizing Committee extend their appreciation for their interest and hard work. Thanks are extended to the members of the review panel who met in Las Vegas, December 13-15 to review the submissions. Without their prompt review and constructive comments, it would not have been possible to publish ACI SP-149 for distribution at the conference. The cooperation of the authors in accepting reviewers' suggestions and revising their manuscripts accordingly is greatly appreciated.

The help and assistance of William R. Tolley and his staff for performing the administration duties associated with this conference are gratefully acknowledged. Particular thanks are extended to Barbara Cheyne for her devotion to the conference work and for performing tasks sometimes well beyond the call of duty.

V. Mohan Malhotra, Chairman
ACI International Conference on High-Performance Concrete
Editor SP-149

November 1994

ACI International Conference on High Performance Concrete

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SP 149-1

The United States Government's Role in High-Performance Materials for Infrastructure

by T.J. Pasko, Jr., and G.J. Frohnsdorff

Synopsis:

Sixteen agencies of the United States Federal Government have developed an interagency proposal for promoting the use of high performance concrete and other materials for use in the Nation's Infrastructure. They are working jointly with the Civil Engineering Research Foundation (CERF) to enlist private sector support for sponsoring a research and development program aimed at getting the materials into use. CERF is drawing upon the technical community, such as that in ACI to define the various research needs and studies which will lead to materials acceptance. Materials other than concrete are addressed in other parts of the total program. Workshops were held in the spring and fall of 1993 to develop schedules and priorities. A tentative cost for the concrete program is approximately \$200 million over 10 years, which includes some technology transfer and which would be expected to be matched by some private sector funding.

Keywords: Civil Engineering Research Foundation; high-performance concretes; high-strength concretes; infrastructure; United States Government

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Thomas J. Pasko, Jr., P.E., is the Director of the Office of Advanced Research in the U.S. Department of Transportation, Federal Highway Administration and is the chairman of an interagency task group on infrastructure and construction under a larger committee on materials. He has been involved in concrete research since 1959 and has served on numerous ACI committees.

Geoffrey J. Frohnsdorff, Ph.D., is the Chief of the Building Materials Division of the Building and Fire Research Laboratory in the National Institute of Standards and Technology. He is the secretary of the interagency task group on these activities and is active in numerous related activities in American Society for Testing and Materials (ASTM) and the American Concrete Institute (ACI).

INTRODUCTION

Background

In January 1991, the Civil Engineering Foundation (CERF), an affiliate of the American Society of Civil Engineers (112,000 members), conducted a workshop for approximately 350 persons in Washington, D.C. The attendants discussed the problems of the Nation and subsequently published "Setting a National Research Agenda for the Civil Engineering Profession" (Ref. 1). One of the resultant thrusts was a need for the "Revitalization of the Public Works Infrastructure." This challenge was further defined as a need to develop a plan for the use of High Performance Concrete and Steel, the materials which form the backbone of the Nation's infrastructure.

While CERF was rallying the profession, there was a relatively unrelated effort taking place within the government to get the various agencies doing similar research to coordinate their work. The Federal Coordinating Council for Science, Engineering and Technology (FCCSET) reports to the Science Advisor to the President and it was successful in developing major interagency programs in global warming, high performance computing, and others. In 1991 one of the subcommittees of the coordinating council, the Committee on Materials (COMAT) developed a new interagency program on Advanced Materials and Processing (AMPP). Ten agencies budgeted to spend \$1.6 billion on advanced materials (superconductivity, fiber optics, etc.) in 1992. They were successful in obtaining an increase of 10 percent (\$162 million) for 1993 (Ref. 2).

In January 1992, a Task Group was established under COMAT to develop a program on infrastructure and construction materials, partially in response to the challenge set forth by CERF and the private sector. This report presents the deliberations of that Task Group. In February 1994 the committees were reorganized and the work continues under a task group of the National Science and Technology Council.

Status

As of April 1994, the following efforts are noted. CERF held a workshop on April 29, 1993, to draw attention to the National Needs and produced a report (Ref. 3). Experts from approximately 12 different materials areas (concrete, steel, aluminum, composites, etc.) and their representative associations met on November 2-3, 1993 in workshops to delineate the research needs of their industries to participate

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in the construction of the infrastructure of the next generation. The total program is to be unveiled in about August 1994 in a final combined report and presented at a special national conference.

The Task Group has produced a draft internal report which identifies who is doing what within the U.S. Government and sets forth some general guidance about how the program might operate and interface with the private sector. The Clinton Administration has reorganized the effort to give greater emphasis to infrastructure renewal. The Task Group continues to gather information and collaborate on research of common interest. Several agencies such as the National Institute of Standards and Technology (NIST) and the Corps of Engineers (COE), have proposed picking up portions of the proposed program in their annual budgets. Also, the Federal Highway Administration (FHWA) has provided significant support to Texas to build a bridge during 1994 with high strength concrete of about 90 Mpa (13,000 psi) (Ref. 4), and has raised pooled funds for high strength bridge research and fatigue testing. The National Science Foundation (NSF) has initiated the establishment of new infrastructure research centers. Additionally, some elements of the proposed needed research are competing for funding under the grant programs of the Technology Reinvestment Program (TRP) of the Department of Defense and the Advanced Technology Program (ATP) of the Department of Commerce.

Definition: Infrastructure

The infrastructure considered in this report is defined as all constructed facilities that form the basis of our society, such as buildings, waterworks and transportation. Some examples of elements of the infrastructure are given in Table 1.

State of the Art

Independent research on high performance materials, such as concrete and steel, has been underway for many years in many different agencies to support their missions. As an example from the highway field, the Strategic Highway Research Program (SHRP) is concluding five years of research and development (R&D) on the overall improvement of portland cement concrete at a cost of \$12 million -- a significant amount by highway standards. Over \$2 million was specifically designated for high performance concrete, as defined in the program. Also, the COE recently completed the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Program, a \$36 million study to develop improved technology for evaluation and repair of civil works structures. Approximately \$1.5 million was devoted to development of high-performance concrete. The results of both programs will be added to the vast knowledge base on concrete

and related materials, such as that resulting from research funded by the NSF in which compressive strengths of over 690 MPa (100,000 psi) have been attained in small laboratory specimens. By itself, and in the short term, this uncoordinated research will not bring about much change in the construction community where only limited amounts of high-strength concrete are presently being used.

Many definitions have been proposed for "high performance concrete." High performance could mean high quality and highly durable concrete with little reference to strength, however, it is difficult to quantify the durability aspects. Hence, this report emphasizes the more easily quantifiable comparisons which can be made based on the high strength aspects of improved concretes. However, if it can be shown that, as is believed to be the case, high-strength concretes can be high-durability concretes, there will be an additional incentive to use them. For example, the REMR Program demonstrated that 95 MPa (13,500 psi) high-strength concrete exhibits significantly improved resistance to erosion, particularly in hydraulic structures where the concrete is subjected to the abrasive action of waterborne debris.

In practice, to date, 160 MPa (23,000 psi) concrete has been used experimentally in Norway to "armor" pavements subjected to studded tires and 130 MPa (19,000 psi) concrete has been used to reduce column sizes in tall buildings in Seattle. In the bridge technology area, the East Huntington Bridge in West Virginia was constructed with 55 MPa (8,000 psi) design strength concrete, the highest strength concrete used in U.S. bridges to date. Some experimentation is presently underway in the U.S. with 70 MPa (10,000 psi) concrete in bridge girders, as reported in this conference and in the *PCI Journal* (Ref. 5).

One reason higher strengths have not been used in bridges is that the present design criteria, which are based on the properties of conventional strength concrete, may limit the economic benefits that can be obtained from using thinner cover over reinforcing steel. Knowledge of the expected durability of efficiently designed high-strength concrete members is needed before full exploitation of high-performance concrete is possible. Also, because high-strength concrete is quite brittle and tends to fail suddenly, research is needed to assure adequate ductility in the structural system.

A major deficiency of high performance materials (especially referring to concrete and steel) has been the limited scope and lack of vision in setting the goals of the R&D programs. In particular, because the R&D activities have been set to match the limited funds available, they have tended to focus on the search for solutions to existing operational problems and, therefore, lack innovation. Few projects have been carried out

with the goal of building and testing prototype structures for demonstrating the inherent economies and the safety of an integrated design/construction package or system. Most research studies compare one structural member to another, often on a one-to-one basis, supplemented by a theoretical study and, sometimes, verification by a small model study. Few studies have been done to analyze a structure from materials selection to final concept testing such as was done for the proposed Three Sisters Island Bridge for Washington, D.C., which was never built.

One of the largest bridge model tests to date was a 0.4 scale model, 34.4 m long x 6.1 m wide (113 ft. x 20 ft.), built in the FHWA laboratories to demonstrate alternative load factor design of a composite structure. Total study costs from 1985 to 1990, including model construction and loading to destruction, were about \$2.5 million. Such research is costly in both time and money.

In 1990-92, the NSF, in collaboration with the FHWA and the Ohio Department of Transportation, supported a progressively destructive field test of a full-size decommissioned bridge to validate modeling and analysis. The project was conducted by the University of Cincinnati and the total cost was \$760,000. Another planned destruction test is underway in New Mexico.

In the future, it is imperative that the research and development be planned on a scale commensurate with the problems faced, if innovation is to be achieved.

THE GOAL

The goal of this effort is to optimize the design of infrastructure systems using high performance materials, demonstrate the construction and testing of prototypes, and provide assistance in implementing the technology. Along the way, appropriate R&D will be done to solve associated materials/construction detailing problems and deficiencies and to make it possible to use high performance materials to extend the limits of design. A coordinated interagency program leveraged with the private sector will produce major breakthroughs and economies of scale that will save dollars for investment in reducing the backlog of needed improvements in the infrastructure.

Impediments to Meeting the Goal

There are a number of problems which must be overcome:

- a. The cost of the needed technical program, from research through demonstration, will be great compared with the costs of earlier, less ambitious efforts.

- b. The available funds are presently divided among many agencies, thus making the efficient management of any program difficult.
- c. The money now being used for studies of high performance materials is, for the most part, distributed among many researchers doing relatively small, uncoordinated studies. These researchers may have to be mollified if the funds are diverted to the few organizations capable of undertaking the larger programs which must include the construction and testing of prototypes.
- d. The existing design codes and standards are usually conservative to protect the public, and tend to restrict the use of new materials until, and unless, a substantial database about them has been established. Related to this is the need to adopt life-cycle costing principles in the bidding process.
- e. The use of designs based on the higher strengths attainable with high performance materials must place greater emphasis on quality control so as to avoid deficiencies that could lead to catastrophes. Is the construction industry ready for this? Is the labor force adequately educated?
- f. When strength is the issue, savings will result only if less of the higher-quality, higher-strength materials is used in place of the volumes of normal materials. Among major challenges that can be foreseen are the proper connection of smaller members, protection of the members from deterioration by the environment, prevention of failures from localized buckling or impact, improvement of ductility and fracture toughness, coping with handling stresses, and overcoming problems associated with increased deformations resulting from higher working stresses and smaller members.
- g. The use of less massive structures may require "smart" technology so that they may monitor themselves to assure public safety. The question of liability exposure must be overcome.
- h. Implementation of the new technologies will take much time because of the need to develop new codes and standards and to disseminate the new knowledge to about 39,000 local governmental entities.

Opportunities

The need for establishing a new construction-oriented R&D effort is apparent from the growing recognition that the United States must:

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- a. Restore its infrastructure.
- b. Become a world leader by being more competitive and productive so as to be able to compete in the European community and with Pacific Rim countries.
- c. Gain a share of the market in developing countries, including those of the former Soviet Union.
- d. Do more to conserve natural resources by using them more efficiently.

These concerns have led to a new interest in infrastructure research, as demonstrated by:

- a. The completion of the \$150 million Strategic Highway Research Program and emphasis placed on implementation.
- b. The completion of the \$36 million REMR Research Program and initiation of the REMR-II Program at a similar funding level.
- c. The passage of the 1991 Intermodal Surface Transportation Efficiency Act which addresses new technologies (such as magnetic-levitation) and encourages research and technology transfer in many new ways.
- d. The proposed shift from a national defense mode to emphasizing the rebuilding the Nation's infrastructure to stimulate economic growth.
- e. The institution of new incentives to encourage private sector involvement in R&D, such as the newly-formed private research foundations for concrete, aggregates, asphalt and specifications. Similarly, initiatives on the government side are the Corps of Engineers' cost-shared R&D Program with the private sector, (the Construction Productivity Advancement Research Program, CPAR), and the Department of Commerce's Advanced Technology Program (ATP).

On the "pull" side of R&D, several organizations now in place can help strengthen Federal technology development. Examples of actions being taken are:

- a. The American Society of Civil Engineers (112,000 members), through its Civil Engineering Research Foundation (CERF), with the support of the private sector, is using a forum of national experts to develop a strategic plan of action for civil engineering R&D.

- b. The CERF, together with the American Concrete Institute (20,000 members), the American Iron and Steel Institute (1,200 members), and others, is planning research to improve the country's ability to exploit high-performance concrete and steel technologies.
- c. The Federal agencies have been encouraged to be active in organizations such as these mentioned in (a) and (b) to promote synergism between the private and public sectors.
- d. The use of Cooperative Research and Development Agreements, CRADA's, such as the Corps of Engineers' CPAR (Construction Productivity Advancement Research) Program are developing partnerships with industry.
- e. The CERF, the COE, AASHTO, and FHWA are launching a center for evaluating new technologies to help promote their implementation in the 39,000 local governmental organizations. This Highway Innovation Technology Evaluation Center (HITEC) started operation in February 1994 and is initially funded for 4 years (Ref. 6). CERF is presently negotiating with government agencies to establish similar centers for environmental technologies and building innovations.

APPROACH

Because about one-third of new construction receives some Federal support, the U.S. Government is in a unique position, by virtue of its property ownership and its influence on new construction, to be a leader in the development and transfer to practice of new infrastructure technology. Similarly, it has the capability, by virtue of its technical resources and expertise, to work with the private sector to improve engineering/ construction technology. It also provides funding to Federal-aid projects.

Ways in which the U.S. Government can lead in the development and demonstration of new construction technology is by building with high performance materials and improved structural systems. This is because the Government can obtain exemptions from codes and standards, particularly in pilot programs; in part, this is because it is self-insuring. Of course, final designs must be shown to be safe for public use before they are adopted by the private sector. Examples of ways in which the Government might lead in the introduction of new construction technology are:

- a. The DOT agencies and the Corps of Engineers might test innovative designs or processes by using them in the building of bridges, and in water supply, flood control and other transportation facilities.

- b. The General Services Administration, the Postal Service, the Bureau of Prisons, and the Department of Veterans Affairs might demonstrate new concepts in structural design and automated construction.
- c. The Environmental Protection Agency (EPA) might build prototype structures for water supply, sewage treatment, and solid waste handling. They might also further the development of nonhazardous protective systems (such as paints).
- d. The NSF, the National Institute for Standards and Technology, the Department of Energy (DOE) and other agencies, might continue to expand the horizons of research into the design and use of new materials, and assist in the improvement of codes and standards, while the Federal Emergency Management Administration might assist in the development of new protective systems for structures and lifelines.
- e. The Department of Housing and Urban Development and the DOE might exert a greater influence on the use of high performance materials in residential housing and urban applications.
- f. The Departments of Education and Labor might help provide training in the proper and safe use of the new technologies.

Presently, in the construction industry, the U.S. Government has the reputation of being a very conservative designer and builder. It is very traditional in its approach to infrastructure projects. This could be changed through the interagency activities of this program. It could be further enhanced through the issuance of an executive order that charges the agencies to design/build on the leading edges of the technology and to promote "show-and-tell" aspects of the prototypical features.

The inherent features which would make it possible for the U.S. Government to influence the design and construction industry in the United States are the vast amounts of government ownership which exists. Some items of government ownership or influence are shown in Table 2.

Interagency Cooperation

Table 3 shows how the various agencies might coordinate their activities on a concrete program which covers basic research through demonstration prototypes and education. More user agencies would be added later. The complexity is more apparent when one considers the U.S. Government has 14 departments (each

with numerous sub-agencies, for instance, DOT has 9 major modal agencies [FAA, FHWA, etc.] with separate research entities) and 135 agencies.

The table shows how the different agencies could complement each other in carrying out the parts of the program. However, the exact subdivision of responsibilities between the agencies would be worked out as the detailed planning proceeded. The concept would be that each program area would be championed by a lead agency which should receive technical support from other agencies that could contribute to that area.

Management

The U.S. Government is in a unique position to lead, assist, and catalyze the development and implementation of more cost-effective materials and construction technologies to enhance the Nation's infrastructure. Of course, nothing will be accomplished if the private sector is not involved in the planning and implementation of a program to improve the infrastructure. Hence, CERF has assembled numerous representatives of contractors, suppliers, other industry, academia, designers, local governments, and associations to define the proposed work to be done and to get industry input into the government process.

The program, such as described herein, needs to be designed such that the following concerns are addressed:

1. Local agencies (States, etc.) will be beneficiaries of the development of more cost-effective technology, even though they lack the resources for funding much of the program. They must be involved if the technology is to trickle down.
2. The construction industry wants to be a partner in the program and is willing to share the cost if Federal funding is made available for cooperative work.
3. The Federal agencies need access to some of the funding because they normally cannot legally compete with the private research firms. The agencies with unique facilities are the only entities that are capable of doing some of the proposed studies.

Two basic management philosophies have been proposed. In one, the various agencies have their budgets enhanced (a cross-cutting process that has been used in other programs, such as Advanced Materials and Processing Program), and each administers its own program with an interagency coordinating council. This is essentially the way it has been happening.

The other philosophy is to set up a special central fund, similar to that used for the SHRP where \$30 million per year for 5 years came from the Highway Trust Fund. The National Academy of Science (a non-government organization) administered the program through an executive committee and a hired staff of approximately 40. It completed its business and ended in 1993 (Ref. 7).

Regardless of the type of management, the process must have private sector input into determining the needs and priorities of the program.

THE PROGRAM

The purpose of this program is to develop a coordinated concrete research effort that will provide benefits that could not be obtained by separate, smaller research efforts. An interagency program carried out in a partnership with industry could lead to considerable dollar savings by implementing high performance materials in infrastructure construction and repairs. In turn, the savings could be used to reduce the backlog in rehabilitating decayed infrastructure and meeting other needs.

Concrete is the most extensively used material in the \$400 billion per year construction industry. In spite of its importance to the economy, there are many gaps in knowledge about factors affecting its performance. Among those gaps which need to be filled if the full potential of high-performance concrete is to be achieved, the most critical relate to:

- a. Control of the production process to ensure concrete of consistently high performance.
- b. Design of members such that local or member buckling does not occur, reinforcing steel is protected, the concrete is durable and sufficiently ductile that greater deformations (deflections, ductility) can be tolerated, and the members are resistant to impact (not fragile).
- c. Procedures for ensuring redundancy of a structure so as to prevent collapse.
- d. Procedures for ensuring that higher temperature gradients caused by hydration of cement in the members can be tolerated without excessive cracking.
- e. Guidelines showing how thinner members can be adequately interconnected (floor to columns, joints in decks, parapets to decks, etc.).

- f. Design procedures indicating where steel and concrete can be used together in a composite structure so as to optimize the structure. For example, large thin-walled box girders might be extruded with internal steel stiffening diaphragms added later.
- g. Guidelines on fire ratings of high-strength concrete members.
- h. Long-term performance and life-cycle economic analyses.

The details of the research needs for implementing high-performance concrete will be presented by Dr. H. S. Lew in his paper, "U.S. National Program on High-Performance Concrete."

Benefits

One example of the problems and potential benefits that can accrue is the bridge situation. There are about 575,000 bridges in the United States and many exhibit distress, deficiencies, or obsolescence. Many are undergoing rehabilitation or replacement and rough estimates of bridge investment requirements given in "The Status of the Nation's Highways and Bridges: Conditions and Performance," a report to Congress in September 1991, (Ref. 8) were:

- The cost of removing the backlog by repairing all the bridge deficiencies that existed on June 30, 1990, is approximately \$91 billion. This figure could increase to as much as \$131 billion if improvements are delayed.
- Between \$6 and \$8.5 billion annually will be required to eliminate all the backlog and accruing bridge deficiencies through year 2009, depending on the treatment of the backlog.
- The cost to maintain current overall bridge conditions is estimated to be \$4.2 billion annually.

Reducing the backlog through the year 2009 would require that about 16,000 bridges (about 300 per State) be rehabilitated/replaced each year.

The possible savings from using higher strength materials are dependent on many factors and assumptions. Some specific examples (figure 1) are:

- a. A bridge was built in Joigny, France, in 1989, using 60 MPa (8,600 psi) concrete in lieu of 35 MPa (5,000 psi) concrete. The volume of concrete needed was reduced 30 percent with a resulting 24 percent decrease in dead load on the bridge foundations (Ref. 9).
- b. An analysis by Zia (Ref. 10) indicated that, for spans of about 29 m (95 feet), using 80 MPa (12,000 psi) concrete in lieu of 40 MPa (6,000 psi) in AASHTO prestressed box beams allowed the span lengths to be increased up to 17 percent, and to 30 percent for special cases.
- c. Another analysis (Ref. 11) indicated that, by increasing the strength of the concrete from 40 MPa to 70 MPa (6,000 psi to 10,000 psi), the number of supporting girders could be reduced from nine to four for an 11 m (36 foot) wide, 45.7 m (150 foot) long, simple span bridge, also reducing the total weight of the structure.

EXTENSIONS

The proposed technical programs for high performance concrete and steel are already documented (Ref. 12). Similar programs are being developed for the other materials that are used in large amounts in infrastructure construction, such as aluminum, plastic composites, and others. A grand total cost for the program is estimated to be \$2-\$4 billion, plus significant matching from industry. The final program should be fully documented in 1994.

SUMMARY

A proposed program for researching and implementing high performance concrete is described. It is part of a larger program that includes about 15 material groups that are extensively used in infrastructure construction. The total program should be presented about August 1994 and is estimated to cost from \$2-\$4 billion to be carried out over 10 years.

The uniqueness of the program is built upon:

- Infrastructure-related interagency cooperation
- Possible cross-cutting of agency budgets
- Government constructing facilities to the state-of-the-art technology
- Demonstration of prototypical U.S. Government structures

- Partnership with Industry

- * Program guidance from industry
- * Co-funding
- * Joint use of research facilities
- * Information exchange
- * Joint executive committee

Execution of the proposed program should provide significant benefits to the government, industry, and most importantly cost savings to the public.

ACKNOWLEDGMENT

It is a privilege to be able to present this paper which is extracted from a draft committee report that is undergoing continual updating and expansion. The committee members are thanked for their help. The authors can be contacted to obtain the latest information on "Needs and Opportunities for Exploiting Improvements in Infrastructure Materials Technology." Mr. Pasko's telefax number is (703) 285-2679. Alternatively, the telefax for the representative industry group in Washington, D.C., the Civil Engineering Research Foundation, is 202-789-2943 or phone 202-842-0555.

ABBREVIATIONS

NSF	National Science Foundation
COE	U.S. Army Corps of Engineers
FHWA	Federal Highway Administration
FAA	Federal Aviation Administration
NIST	National Institute of Standards and Technology
DOE	Department of Energy
NAVY	U.S. Naval Facilities Command
DOI	Department of Interior
USDA	U.S. Department of Agriculture
GSA	General Services Administration
HUD	Department of Housing and Urban Development
DOED	Department of Education
FRA	Federal Rail Administration
FTA	Federal Transit Administration
ASTM	American Society for Testing and Materials
ACI	American Concrete Institute
ASCE	American Society for Civil Engineers
CERF	Civil Engineering Research Foundation
FCCSET	Federal Coordinating Council for Science, Engineering and Technology
COMAT	Committee on Materials (U.S. Government)
CONMAT	Construction Materials (a CERF entity)
NSTC	National Science and Technology Council
SHRP	Strategic Highway Research Program
R&D	Research and Development

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REMR	Repair, Evaluation, Maintenance and Rehabilitation Program
DOT	Department of Transportation
ISTEA	Intermodal Surface Transportation Efficiency Act
ATP	Advanced Technology Program
RTP	Reinvestment Technology Program
AISI	American Iron and Steel Institute
CRADA	Cooperative Research and Development Agreement
HITEC	Highway Innovative Technology Evaluation Center
USPS	U.S. Postal Service
EPA	Environmental Protection Agency
DOL	Department of Labor
DOC	Department of Commerce

REFERENCES

1. Setting a National Research Agenda for the Civil Engineering Profession, 3 vols. available for purchase from Civil Engineering Research Foundation, Washington, D.C., 1991.
2. Advanced Materials and Processing: The Fiscal Year's 1994 Federal Program, COMAT c/o National Institute of Standards and Technology, Room B309, Materials Building, Gaithersburg, Maryland 20899, 1993.
3. High Performance Construction Materials and Systems: An Essential Program for America and Its Infrastructure, Exec. Report 93-5011.E, available for purchase from CERF, Washington, D.C., April 1993.
4. Ralls, Mary Lou, and Carrasquilla, Ramon, Texas High-Strength Concrete Bridge Project, Public Roads, spring 1994, Vol. 57, No. 4, Federal Highway Administration, Washington, D.C., pp. 1 to 7.
5. "High Strength Prestressed Concrete: Special Issue," PCI Journal, May/June 1993, Vol. 38, No. 3, Precast/Prestressed Concrete Institute, Chicago, Illinois.
6. Highway Innovative Technology Evaluation Center Information Booklet, available from CERF, Washington, D.C., November 1993.
7. Strategic Highway Research Program: Research Plans, Transportation Research Board, Washington, D.C., May 1986.
8. The Status of the Nation's Highways and Bridges: Conditions and Performance, a report to Congress by DOT, September 1991.

9. Malier, Y., and Pliskin, L., "Bridge at Joigny: High-Strength Concrete Experimental Bridge," Transportation Research Record (TRR) 1275, Transportation Research Board, Washington, D.C., 1990, pp. 19-22.
10. Schemmel, J. J., and Zia, P., "Use of High-Strength Concrete in Prestressed Concrete Box Beams for Highway Bridges," Transportation Research Record (TRR) 1275, 1990, pp. 12-18.
11. Jobse, H. J., "Application of High Strength Concrete for Highway Bridges: Executive Summary" FHWA/RD-87/09, Federal Highway Administration, Washington, D.C., 1987, p. 29.
12. _____, High-Performance Construction Materials: An Essential Program for America and its Infrastructure, Technical Report 93-5011, available for purchase from CERF, Washington, D.C., April 1993.

TABLE 1 — ELEMENTS OF THE INFRASTRUCTURE

Highways
Railroads
Airports
Transit Systems
Navigation Systems
Port Facilities
Water Supply Systems
Sewerage Systems
Irrigation/Dams
Flood Control Systems
Natural Hazard Protection Systems
Waste Disposal Systems

Nuclear Containment Systems
Power Plants
Power Transmission Lines
Pipelines
Mines and Quarries
Communication Systems
Defense/Security Facilities
Prisons
Manufacturing Facilities
Recreation Facilities
Residential Buildings

TABLE 2 — GOVERNMENT ABILITY TO CREATE A "PULL" FOR TECHNOLOGY

THE UNITED STATES GOVERNMENT:

OWNS:	230,000 MILES OF HIGHWAY (6% of the Nation's total)
PROVIDES FEDERAL AID TO:	600,000 MILES OF HIGHWAY (16% of the Nation's total)
SUPPORTS:	270,000 BRIDGES ON FEDERAL AID (47% of the Nation's total)
MAINTAINS:	2800 MILES OF RAILROAD
OWNS:	417,000 BUILDINGS
LEASES:	68,000 LOCATIONS
ADMINISTERS:	622 MILLION ACRES OF LAND (30% of the Nation's total)
MAINTAINS	300 MILLION SQ. FT. OF LOW SLOPE ROOFS (ARMY)
BUILDS AND CONTROLS:	PRISONS, POST OFFICES, MILITARY AIRFIELDS AND INSTALLATIONS, VETERANS HOSPITALS, COASTAL/ HYDRAULIC INSTALLATIONS, ETC.

TABLE 3 — AGENCY PARTICIPATION IN THE HIGH-PERFORMANCE CONCRETE PROGRAM

COMAT HIGH PERFORMANCE CONCRETE PROGRAM		PARTICIPATING AGENCIES														
TASK	LEAD AGENCY	D O E	C O E	N a y	N S F	M S F	N F H A	F F H A	F A A	N I S I	D O S I	U S S A	G S D A	H U D A	D O E A	F F T A
Basic Cement/Concrete Research	NSF	x	x		x					x						
Applied Concrete Research/QA-QC	COE		x		x		x	x		x	x	x				
Reinforced Concrete Research	FHWA		x		x		x	x		x						
Structural Systems Research	FHWA		x		x		x	x		x			x			
Behavior/Performance Research	FAA	x	x	x	x		x	x		x	x		x			
Codes/Standards/Specifications/Design	NIST		x	x						x	x		x			
Knowledge-Based Systems	NIST				x					x						
Construction/Demonstration	COE	x	x	x							x	x	x	x	x	x
Education	NSF				x		x	x		x	x			x	x	

Reduction in Superstructure Dead Load

The Experimental Bridge built in Joigny, France, in 1989

- 60 MPa (8,600 psi) design strength
- Three-span, continuous, externally prestressed double-T section, 114 m (375 ft) long, 15.8m (52 ft) wide
- Cast in place using concrete made with local materials
- Compared with 35-MPa (5,000 psi) concrete, 30% less concrete was used leading to a 24% reduction in the dead load from the superstructure

Increase in Span Length of Precast Beams

1989 Engineering Study for North Carolina Department of Transportation by Schemmel and Zia

- Investigated the economic benefits of increasing concrete strength from 40 to 80 MPa (6,000 to 12,000 psi)
- Considered modified AASHTO Type A box beams, 0.91 and 1.22 m (3 and 4 ft) wide
- On average, the maximum span length was increased by 17%; for some sections the increase was nearly 30%

Reduction in Number of Supporting Girders

1987 FHWA Study on Application of High-Strength Concrete for Bridges

- Studied the potential benefits of increased concrete strengths up to 70 MPa (10,000 psi)
- Benefits included increased span lengths, wider girder spacings, and reduced section of compression members
- For example (see sketch below), for a 45.7m (150-ft) simply-supported bridge, the number of girders could be reduced from nine to four by increasing the concrete strength from 40 MPa (6,000 psi) to 70 MPa (10,000 psi)

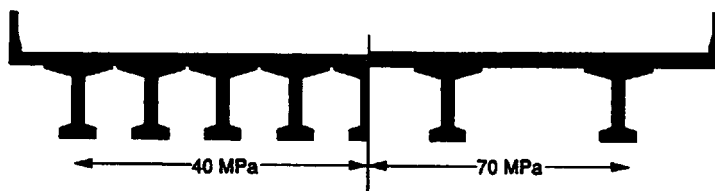


Fig. 1—Benefits of high-strength concrete in highway applications

SP 149-2

Effects of Physical and Chemical Treatments of Silica Fume on the Strength and Microstructures of Mortar

by S. Nagataki, N. Otsuki, and M. Hisada

Synopsis : Recently, there has been a great demand for high quality concrete and concrete structures with high performance. In this background, silica fume is one of the most remarkable mineral admixtures that can give concrete high performance, such as high workability, strength and durability. However, it is unclear as to the types of form silica fume exists in concrete, mortar and cement paste. Some researchers point out that silica fume may be in high agglomeration. Therefore, it is very important to disperse silica fume in concrete effectively to get high performance concrete. Consequently, this paper deals with the effect of physical treatment (ultrasonic homogenizer) and chemical treatment (superplasticizer) of silica fume on the properties of mortar. In this study, different silica fumes were used, 1 Japanese and 5 imported ones. The investigated properties of mortar were workability (flow values), compressive strength, and total pore volume. Through this study, the following conclusions were clarified ;

- 1) Silica fumes in Japanese market were highly agglomerated in the natural state. This agglomeration of silica fume can be broken up by using some treatment methods, such as ultrasonic homogenizer and superplasticizer.
- 2) Physical treatment (ultrasonic homogenizer) before mixing mortar was useful to improve compressive strength and to decrease total pore volume of mortar containing silica fume. The use of superplasticizer could result in highly workable mortar.
- 3) The effectiveness of ultrasonic homogenizer treatment and that of superplasticizer treatment are different.

Keywords: Agglomeration; compressive strength; durability; high-performance concretes; microstructure; mineral admixtures; mortars (material); porosity; silica fume; strength; superplasticizer; workability

Dr. Shigeyoshi Nagataki, FACI, is a professor of Civil Engineering at Tokyo Institute of Technology. He has been associated with concrete technology for about 30 years.

Dr. Nobuaki Otsuki, a member of ACI, is an associate professor of Civil Engineering at Tokyo Institute of Technology, where he received his Ph. D. His primary research interest is the durability of concrete structures.

Mr. Makoto Hisada, is a Lecturer of Civil Engineering at Tokyo Institute of Technology. His research interests include concrete admixtures.

INTRODUCTION

Silica fume is one of the best mineral admixtures to improve concrete with high workable, strength, and durability. It is said that high performance concrete can be produced by using silica fume because of its very small particle size (average diameter is $0.1\mu\text{m}$), its very large surface area, and its high pozzolanic reactivity. However, some researchers[1] point out that there is high degree of agglomeration of silica fume (average diameter is more than $1.0\mu\text{m}$) in concrete. This agglomeration of silica fume can easily change its effectiveness on properties of concrete and mortar, because of the existence of secondary grains of silica fume, which has large diameter, small surface area and small pozzolanic reactivity. Consequently, silica fume should be well dispersed in concrete or mortar. So, in this paper, at first, agglomeration and dispersion properties of silica fume were investigated. Then, effects of physical and chemical treatment, such as ultrasonic homogenizer, ball mill and superplasticizer, on dispersion properties of silica fume are discussed. And finally, the effect of physical (ultrasonic homogenizer) and chemical (superplasticizer) on some properties of fresh and hardened mortar are discussed.

AGGLOMERATION AND DISPERSION PROPERTIES OF SILICA FUME

It is identified that there is following three principle types of interparticle force[2] ;

- 1) Forces due to electrostatic charging
- 2) Van der Waal's forces
- 3) Forces due to moisture

These three forces depend on their electrical conductivity, particle size and particle shape. Van der Waal's forces are generally several orders of magnitude higher than electrostatic forces, and the attractive force due to the adsorbed water layer (by moisture) may be about 50 times higher than the van der Waal's forces. The effect of moisture in the atmosphere forms liquid bridges at higher

humidities. The critical relative humidity is typically in the range 65 – 80%, which is typically in Japanese climate. However, it is unclear that how silica fume acts in circumstances of water mixture of fresh mortar or concrete. So, in this study, properties of agglomeration and dispersion of silica fume in water mixtures that were pretreated by physical and chemical methods were investigated.

Measurement of size distribution

To measure particle size or specific surface area, blaine method and BET adsorption isotherm (Nitrogen Adsorption Method) are typically used in cement material science and concrete technology. Especially, BET adsorption isotherm is determined to measure the specific surface area of silica fume in ASTM Designation Draft #13[3], because this method can measure all the particles' surface, even when they are agglomerated. In this study, to measure size distribution curves of silica fume, laser diffraction particle size analyzer (Shimadzu, SALD-2000) was used. This analyzing method, since diffracting, can measure secondary agglomerated grain itself. So, agglomeration and dispersion properties of silica fume can be measured by using this method.

Test method

Six types of silica fumes were evaluated; their characteristics are shown in Table 1. Each silica fume was carefully kept in dark, air-conditioned environment before measurement. Before measuring them, two kinds of physical treatment and chemical treatment were respectively to water-silica fume mixture (water : 100g, silica fume : 20g) as shown in Table 2. As physical treatment, ultrasonic homogenizer (max. power = 300W) and ball mill were prepared. And naphtharene salphonate type superplasticizer (Kao, Mighty 2000-WH) was used as chemical treatment. Superplasticizer was added before each physical treatment was applicated.

The influence of the form of silica fume

Fig. 1 shows the original size-distribution curves of each silica fume mixture without treatment. Silica fumes, two densified types, S2 and S4, and undensified types, S1 and S3, have more than 100 μ m of their average diameter (50% diameter). Moreover, the other silica fumes of undensified type, S5 and S6, have more than 10 μ m of their average diameter. It is very clear that all silica fumes are highly agglomerated in the natural state, even in the water. However, relationship between average diameter and moisture content of silica fume were not so clear (see Table 1). So, it has to be tested and discussed more to clarify it.

Effect of physical treatment

The size-distribution curves, when silica fumes were treated by using ball mill, are shown in Fig. 2. All silica fumes were well dispersed by ball mill more than natural state (compare to Fig. 1). From these curves, difference in the form of silica fume cannot be seen. Size-distribution curves treated by ultrasonic homogenizer, as shown in Fig. 3, were shifted to the smallest part, nevertheless average diameters of densified silica fumes were yet not less than $0.1\mu\text{m}$. And it is remarkable that undensified silica fumes, except S3, tend to be broken up more than densified ones. It is very clear that ultrasonic homogenizer can disperse silica fume very well, more than ball mill.

Effect of superplasticizer

When two silica fumes, named S1 and S2, were treated with and without ball mill or ultrasonic homogenizer and after added superplasticizer, the size-distribution curves are shown in Fig. 4 and 5. From these figures, it can be said that changes of curves do not depend on the existence of superplasticizer but physical treatment, such as using ball mill or ultrasonic homogenizer. So, it can be considered that superplasticizers do not act directly on dispersion of silica fume in water. Table 3 shows the diameters by two methods, BET (by calculation) and laser diffraction particle size analyzer (by measurement, 50% diameter). Differences of particle sizes of same silica fume were quite significant. This result is more remarkable when observing by SEM, like shown in Photo 1. From these phenomena, it can be considered that silica fume exists partially dispersed in single particle and partially in secondary grains. Some researchers point out that the effect of silica fume on the properties of concrete relates to its very small, round particle, and its high degree of pozzolanic reactivity. These effects may appear when silica fume is well dispersed into single particle in concrete. So, it can be said that dispersion characteristics of silica fume are very important in evaluating silica fume as admixture for high performance concrete and mortar.

EFFECT OF THE DISPERSION OF SILICA FUME ON SOME PROPERTIES OF MORTAR

Test method

In this study, two types of silica fumes, undensified and densified named S1 and S2, were tested. They were produced from same factory in Norway. Using these silica fumes, compressive strength and total pore volume of each hardened mortar was measured at 7, 14, and 28 days, respectively. To make mortar

specimens, ordinary Portland cement (Specific gravity : 3.17, Fineness : 3230 cm^2/g , $\text{Na}_2\text{O}_{\text{eq}}$: 0.65%) and Japanese standard silica sand were prepared. 0.5 of water binder (cement + silica fume) ratio and 2.5 of sand binder ratio were selected for mix proportion of mortar. Before mixing mortar, silica fume was mixed into water and treated by physical and chemical treatment. Under 88 μm paste were screened out by using wire mesh just after mortar was mixed, and they were used to measure size-distribution curves. In addition, mortar flow values were measured by using fresh mortar. Mortar specimens, the size of $\phi 50 \times 100$ mm cylinders, were cured in tapped water at 20°C until measurement. Total pore volume was measured by mercury porosimetry using oven-dried mortar specimen.

Size-distribution curves of particles in screened paste

Fig. 6 and 7 show size-distribution curves of particles in screened pastes by using S1 and S2, respectively. There are remarkable differences under 10 μm diameter in two figures. In Fig. 5, there is a particular peak in curves at about 5 μm diameter that may be due to adding silica fume. However, it is not so clear that whether physical or chemical treatment is really useful to break out agglomerated silica fume. On the other hand, there could be some important results in Fig. 6. In this figure, under 10 μm peak of curve can be seen, and this peak get higher when silica fume was added, and more, physically treated before mixing.

Workability

Flow values of each mortar were shown in Fig. 8. From this figure, densified silica fume was most affected for using chemical treatment. Especially, for densified silica fume, the biggest flow value appeared in the mortar that was treated by using both ultrasonic homogenizer and superplasticizer. On the other hand, in using undensified silica fume (S1), the effect of physical treatment was not so clear. However, the effect of superplasticizer was significant as well as the cases of densified silica fume (S2). Considering workability of fresh mortar, chemical treatment, using superplasticizer, is more effective than physical treatment, by using ultrasonic homogenizer.

Compressive strength

Compressive strength of each mortar with and without superplasticizer is shown in Fig. 9 and 10. In both figures, it is well considered that treatments of silica fume before mixing, either physical or chemical, was very effective to improving the compressive strength of hardened mortar. This tendency was especially more remarkable in using densified silica fume, which has a high rate of agglomeration in the natural state or in water mixture. From these results, silica

fume, even with no treatment, is highly effective in improving compressive strength of hardened mortar. Silica fume can be highly effective when it is treated by using ultrasonic homogenizer or superplasticizer.

Total pore volume

Relation between total pore volume and compressive strength of hardened mortar aged 7 days is shown in Fig. 11. This figure shows that compressive strength improves when total pore volume decreases. Hardened mortar without silica fume has the biggest pore volume and smallest compressive strength. It is very clear that total pore volume of hardened mortar was also decreased by adding silica fume. In addition, hardened mortar with silica fume, which were treated by ultrasonic homogenizer before mixing, had the smallest pore volume and larger compressive strength. There is no relations between this tendency and form of silica fume. From these results, it can be pointed out that hardened mortars, by just adding silica fume, have higher density of their microstructures. And when silica fume is treated by ultrasonic homogenizer, microstructures of hardened mortar can attain higher more high density. Relation between compressive strength and amount of under $10\mu\text{m}$ of screened paste is shown in Fig. 12. From this figure, it can be said that compressive strength improves when amount of under $10\mu\text{m}$ of screened paste increases. Since total pore volume of hardened mortar can be decreased by treated silica fume, this result may be defined to be due to silica fume itself, and more, physical or chemical treatment of silica fume.

CONCLUSION

The following conclusions can be obtained from the present study.

1. Silica fumes in the Japanese market, both densified and undensified, were highly agglomerated in the natural state, even in the water mixture.
2. Agglomeration of silica fume can be well or partially dispersed by using some treatment methods, such as ultrasonic homogenizer and superplasticizer.
3. Ultrasonic homogenizer, as physical treatment method for silica fume in this study, is a useful methods in improving compressive strength and the microstructures of hardened mortar with silica fume. This method is more effective when densified silica fume is used.
4. Superplasticizer, as chemical treatment material for silica fume in this study, can improve the effectiveness of silica fume on workability, compressive strength and microstructures of mortar. Especially, flow index gets remarkably large when superplasticizer is added.

REFERENCES

1. Edited by Martin Rhodes, "Principles of Powder Technology", published by John Wiley & Sons Ltd., pp. 84-85, 1990
2. Edited by Malier Y., "High Reformance Concrete -from Material to Structure-", published by E & FN SPON, pp. 34-47, 1992
3. F. Lopez-Flores, ASTM Designation Draft #13, Standard Specification for Silica Fume for Use in Concrete and Mortar, CANMET/ACI International Workshop on the Use of Silica Fume in Concrete, pp. 67-82, 1991

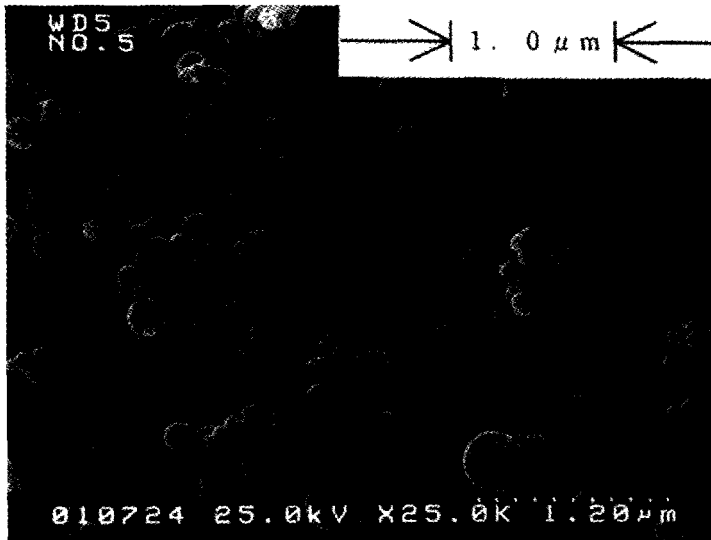


Photo 1—Appearance of undensified silica fume (S1) by SEM

TABLE 1 — PHYSICAL AND CHEMICAL CHARACTERISTICS OF SILICA FUME

No.	Unit	S 1	S 2	S 3	S 4	S 5	S 6
Country	-	Norway	Norway	Norway	Norway	Japan	Canada
Form	-	Undensified	Densified	Undensified	Densified	Undensified	Undensified
Specific Gravity	-	2.56	2.46	2.49	2.43	2.66	2.49
Surface area	m ² /g	19.55	17.73	21.77	17.21	15.95	17.64
(by BET)							
Moisture	%	1.25	1.14	0.96	1.02	1.76	0.75
L.O.I.	%	2.36	2.24	1.60	2.42	2.62	2.84
SiO ₂	%	93.6	92.7	92.7	90.0	85.8	93.6
Al ₂ O ₃	%	0.60	0.51	0.36	0.69	0.79	0.21
Fe ₂ SO ₃	%	0.36	0.26	1.31	1.37	1.03	0.26
CaO	%	0.23	0.21	0.69	0.47	0.61	0.28
MgO	%	0.85	0.71	1.55	1.91	1.97	0.29
SO ₃	%	0.26	0.39	0.35	0.41	0.52	0.29
Na ₂ O	%	0.32	0.48	0.32	0.38	1.29	0.12
K ₂ O	%	1.17	1.56	0.54	1.68	2.73	0.55
C(total)	%	1.47	1.27	0.80	1.31	1.58	3.56

TABLE 2 — TREATMENT FOR DISPERSION OF SILICA FUME IN WATER MIXTURE

Silica Fume No.	S 1	S 2	S 3	S 4	S 5	S 6
1) No Treatment	x	x	x	x	x	x
2) Physical Treatment						
a) Ball Mill	x	x	x	x	x	x
b) Ultrasonic Homogenizer	x	x	x	x	x	x
3) Chemical Treatment						
Superplasticizer (SP)	x	x	-	-	-	-
4) Physical + Chemical						
a) Ball Mill + SP	x	x	-	-	-	-
b) Homogenizer + SP	x	x	-	-	-	-

TABLE 3 — CALCULATED DIAMETER OF SILICA FUME BY BET AND MEASURED ONES BY LASER DIFFRACTION PARTICLE SIZE ANALYZER

Silica Fume	Unit	No.	S 1	S 2	S 3	S 4	S 5	S 6
by BET	μm		0.120	0.138	0.111	0.143	0.141	0.137
by LDPA	μm	A*	140	230	180	140	40	23
		B*	0.62	7	6	3	1.0	0.52

Note: A; No Treatment, B; Treated by Ultrasonic Homogenizer
LPDA; Laser Diffraction Particle size Analyzer

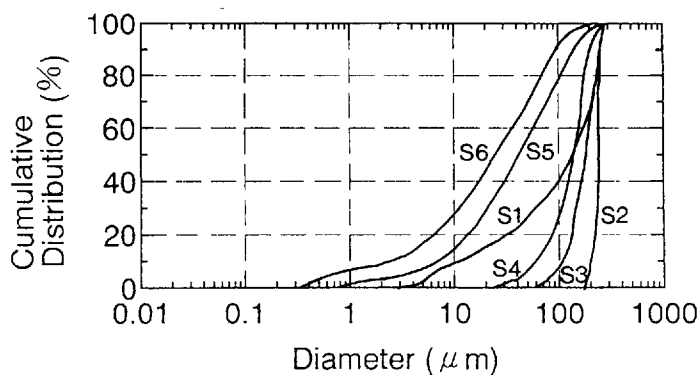


Fig. 1—Cumulated size distribution curves of silica fume in water mixture with no treatment

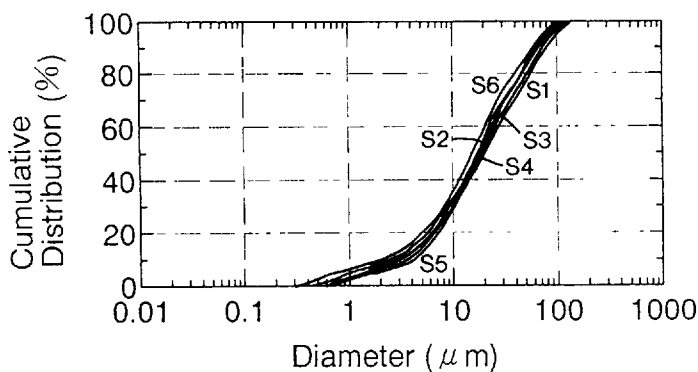


Fig. 2—Cumulated size distribution curves of silica fume in water mixture treated by ball mill

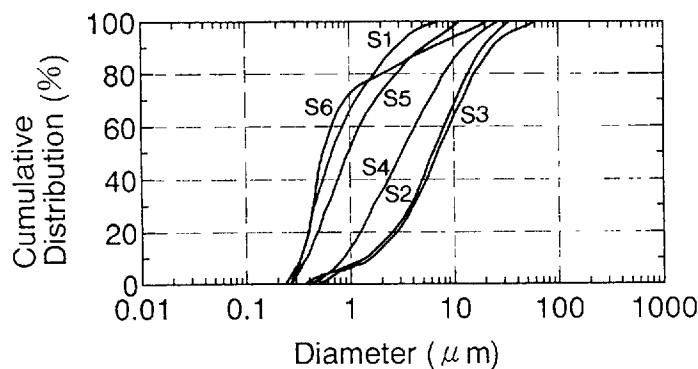


Fig. 3—Cumulated size distribution curves of silica fume in water mixture treated by ultrasonic homogenizer

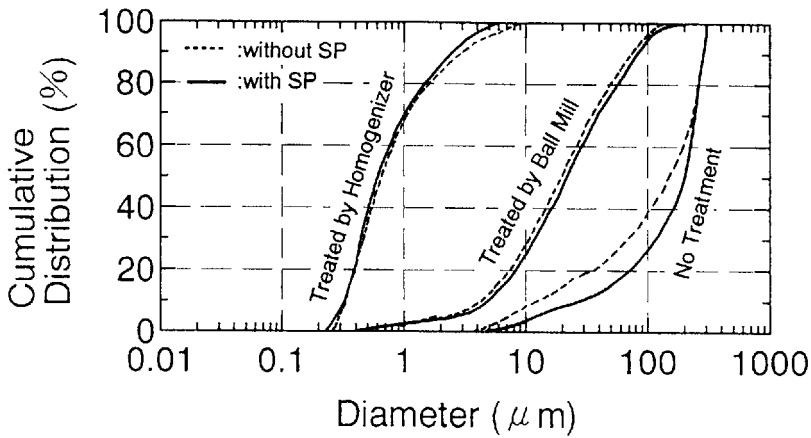


Fig. 4—Cumulated size distribution curves of silica fume in water mixture with and without physical/chemical treatment (S1)

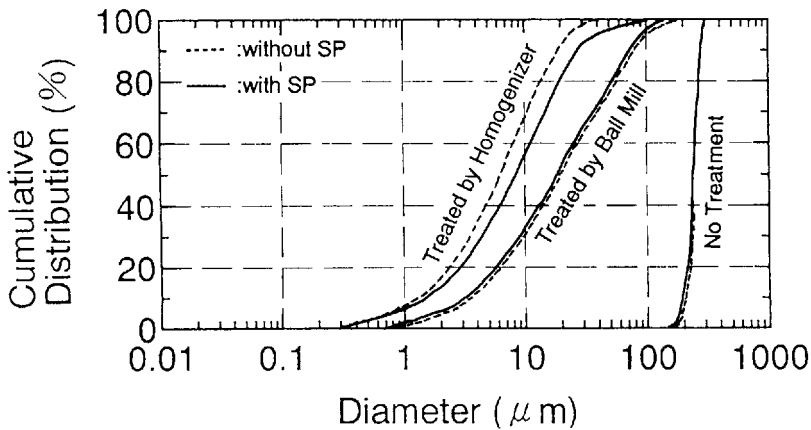


Fig. 5—Cumulated size distribution curves of silica fume in water mixture with and without physical/chemical treatment (S2)

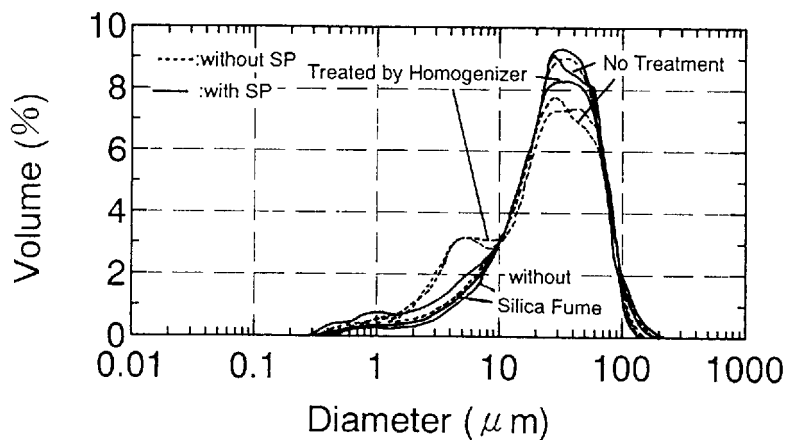


Fig. 6—Size distribution curves of screened paste with and without physical/chemical treatment (S1)

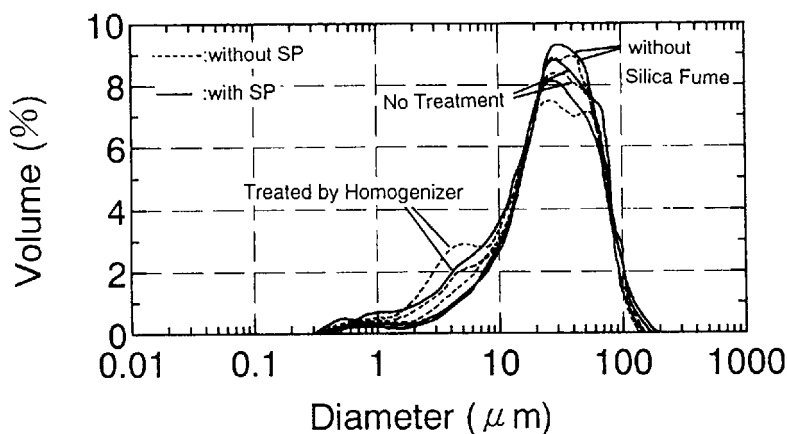


Fig. 7—Size distribution curves of particles in screened paste with and without physical/chemical treatment (S2)

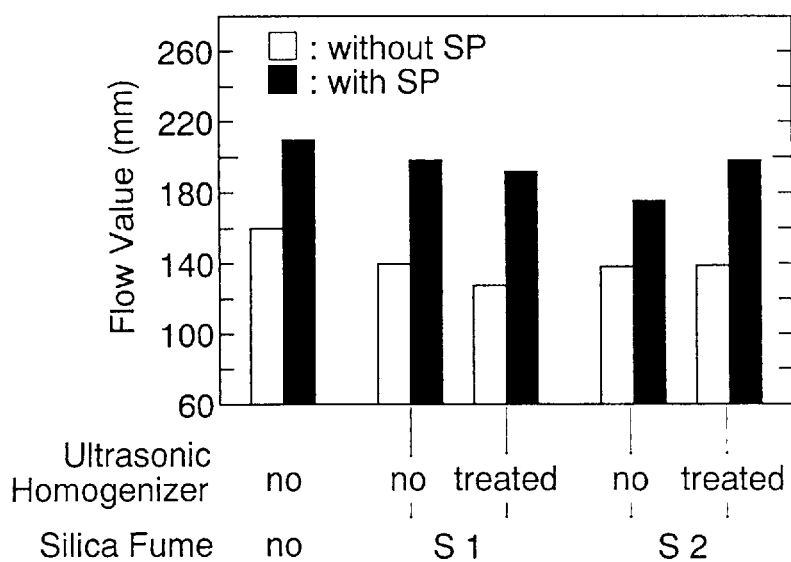


Fig. 8—Flow values of mortar with and without physical/chemical treatment (S1 & S2)

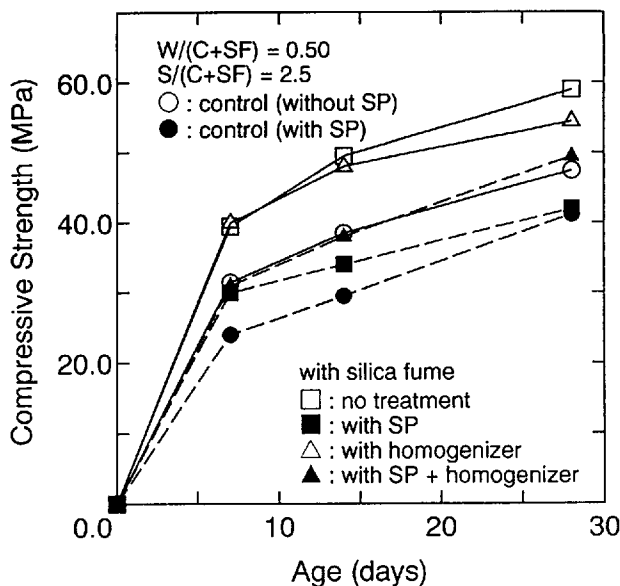


Fig. 9—Compressive strength of hardened mortar with and without physical/chemical treatment (S1)

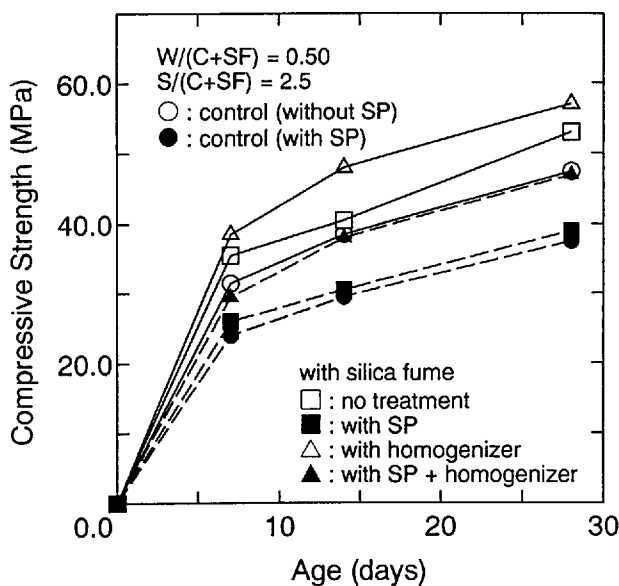


Fig. 10—Compressive strength of hardened mortar with and without physical/chemical treatment (S2)

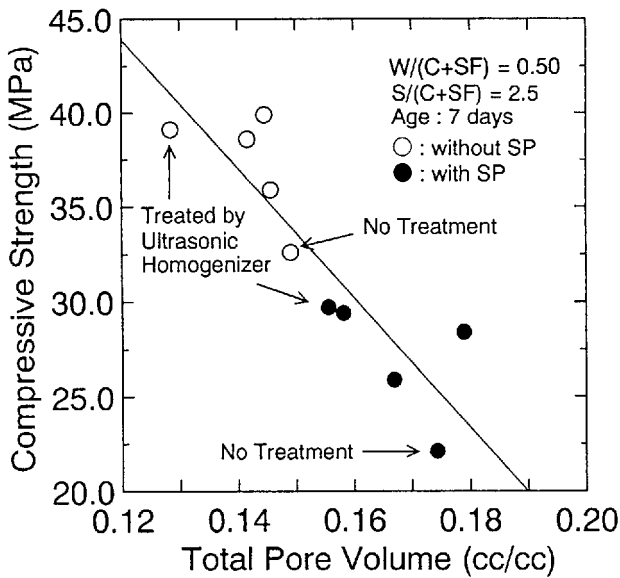


Fig. 11—Relation between total pore volume and compressive strength of hardened mortar

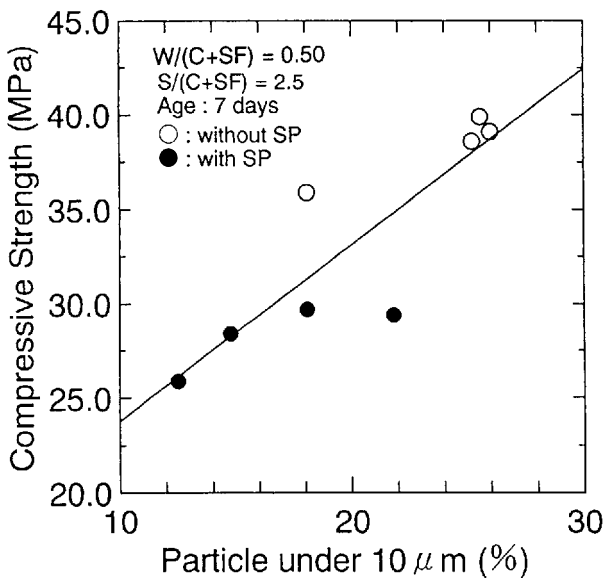


Fig. 12—Relation between amount of particles under 10 μm and compressive strength of hardened mortar

SP 149-3

Production of High-Strength Concrete for the Hibernia Offshore Concrete Platform

by G.C. Hoff, R. Walum,
R. Elimov, and H.R. Woodhead

Synopsis:

The Hibernia offshore concrete platform is being constructed in Newfoundland, Canada, and will be used in hydrocarbon production on the Grand Banks off the east coast of Canada. The 111-m tall concrete structure will contain approximately 165,000 m³ of high-strength concrete. Construction of the concrete platform through 1993 consisted of a 108-m diameter base slab which rested on a series of precast and cast-in-place concrete skirts. Specified 28-day compressive strengths (cylinder) for the skirts and base slab were 49 and 69 MPa, respectively. Actual average compressive strengths achieved were 73.8 and 81.7 MPa, respectively. The remaining construction will be completed by 1996. The use of two different concrete production systems and its results are described.

Keywords: Blended cements; compressive strength; concrete construction; high-strength concretes; mixing plants; mix proportioning; offshore structures; precast concrete; quality control

ACI Fellow George C. Hoff is a Senior Associate Engineer for Mobil Research and Development Corporation, Dallas, Texas. He is a Past-President of ACI and former chairman of ACI Committee 357, Offshore and Marine Concretes.

ACI member Rolf Walum is the QC Coordinator-Concrete for the Hibernia Management and Development Company, St. John's, Newfoundland. Prior to working on the Hibernia platform, he had extensive experience in the construction of offshore concrete platforms in Norway.

ACI member Radoslav Elimov is the QC Supervisor-Concrete for Newfoundland Offshore Development Constructors, St. John's, Newfoundland. Prior to working on the Hibernia platform, he had extensive concrete experience in the Middle East and Europe.

ACI member H. Roger Woodhead is the Construction Design Manager (GBS) for Newfoundland Offshore Development Constructors, St. John's, Newfoundland. Prior to working on the Hibernia platform, he worked for both consulting and construction companies in Vancouver, British Columbia, Canada.

INTRODUCTION

The Hibernia Oil Field is located offshore 315 km southeast of St. John's, Newfoundland, Canada on the Grand Banks. It was discovered in 1979. Recoverable reserves are contained in two reservoirs and are estimated at 615 million barrels. Members of the Consortium in the Hibernia Field are Mobil Canada, Chevron, PetroCanada, Murphy Oil, and the Canadian Government. The project is being developed on behalf of the Consortium by a specially formed operating company, the Hibernia Management and Development Company (HMDC). The platform selected to develop the Hibernia reserves is a concrete gravity base structure (GBS) which will be located on the Grand Banks in 80 m of water. The Hibernia GBS (Fig. 1) is the first large offshore concrete platform to be built for use in North America (1) although many small concrete platforms have been built in the Gulf of Mexico since the early 1950's (2). Construction of the concrete GBS was begun in 1991 and will be completed in 1996. The concrete GBS is the largest

single use of high-strength concrete in North America to date. It will contain approximately 165,000 m³ of concrete, 75,000 Mg of reinforcing steel, 6,500 Mg of prestressing steel and have a mass of over 500,000 Mg. This paper reports on the progress of the concrete construction through 1993.

The platform geometry is shown in Fig. 2. The Hibernia GBS is essentially a cylindrical concrete caisson which rests on the seabed and is 85 m high. Four shafts extend above the caisson for another 26 m to support the Topsides. The water depth is 80 m at the installation site. The GBS is being constructed in a similar manner as North Sea gravity base structures with both a dry-dock and wet-dock construction phase. Details of the GBS construction can be found elsewhere (3).

The Hibernia platform is a first for the offshore industry in that it is designed to resist iceberg impacts. Icebergs, which can weigh more than 5,000,000 Mg, can occur in the waters where the platform will be located. The decision to construct a platform capable of passively resisting iceberg collisions established the basic structural form of the massive GBS. Conditions imposed by the icebergs in the vicinity of, and colliding with, the platform dominated the specific form to be used. When in operation, the GBS will support a collection of equipment and material, commonly called the Topsides, along with personnel necessary to process and export the produced hydro- carbons. The Topsides will have a mass of approximately 60,000 Mg.

CONSTRUCTION SITE

The Hibernia Platform construction site is located approximately 155 km from St. John's, Newfoundland, Canada at Bull Arm at the south end of Trinity Bay. It was developed from a wilderness area for this project. At that site, the GBS will be constructed along with one of the five Topsides "super-modules". The entire assembly of the Topsides will also occur at that location along with the mating operation of the GBS and Topsides. Sheltered water with depths up to 200 m within 500 m of the shore exist there with good deep water access to the open sea.

GRAVITY BASE STRUCTURE

The basic elements of the GBS are shown in Fig. 2. The structure begins with an arrangement of reinforced concrete skirts which are 2.4 m high. These skirts are both precast units that were concreted together along with some cast-in-place units to form the skirt arrangement. On top of the skirts is the base slab which is 108-m diameter and varies in thickness from 900- to 1400-mm. It is heavily reinforced and prestressed in two directions.

The ice wall forms the perimeter of the caisson and has 16 teeth that are designed to dissipate the impact energy of an iceberg. The number and size of the teeth have been engineered to minimize the global iceberg force and distribute local iceberg loads in both the vertical and horizontal direction. The teeth which form the ice wall are supported by an arrangement of X and V walls that transmit the load to an interior tie wall. All of these walls form the "ice belt" which performs in a manner similar to a circular truss. The ice wall is 1400 mm thick. The X and V walls vary from 700- to 950-mm thick with the tie wall being 900-mm thick. The cells provided by the X and V walls are to be filled with solid ballast at the lower elevations and with sea water at the top.

The four cylindrical shafts extend from the base slab to the underside of the Topsides. They are approximately 17-m inside diameter. Two shafts are drilling shafts which will be filled with seawater. The third shaft is a riser shaft which will also be water filled but can be dewatered. The fourth shaft is a utility shaft which will be kept permanently dry. Each shaft is connected to the tie wall of the ice belt by a small connecting wall.

Four connecting walls join the shafts together and two additional connecting walls join these walls together. The connecting wall thickness varies from 600 to 800 mm. These walls, together with the tie wall and its connecting walls, compartmentalize the interior of the caisson for the purpose of oil storage. The total storage capacity is 209,000 m³ or 1.3 million barrels. All of these internal walls and the tie wall are post-tensioned horizontally and vertically. Above the base slab there is an arrangement of 8-m high walls which function as beams to reduce the base slab span to approximately 10 m. These beams are post-tensioned horizontally.

The caisson roof is supported by the ice belt, diaphragm walls and a system of precast beams beneath the roof. The roof is sloped away from the shafts to provide runoff of the waves which will splash on it. It is post-tensioned in two directions.

The four shafts, which begin with a circular cross-section are changed above the roof to include two flat sides that decrease the out-to-out distance between the shafts. The tops of the shafts are thickened to provide a greater bearing area for the Topsides. Steel deflectors are mounted on the shafts to minimize wave run-up to the Topsides.

GBS CONSTRUCTION

The GBS will be constructed in two separate operations. First, the base of the GBS will be constructed in a dry dock. Once the base is completed to a predetermined height, the dry dock is flooded, the dock closure removed, and the base is towed to a deep-water site (DWS). At that location, it is anchored in place and the remainder of the structure is built while it is afloat. When completed, the entire structure will be towed to its final installation site on the Grand Banks. Details of GBS construction can be found elsewhere (3 and 4). At the time of preparation of this paper (December 1993), the construction is proceeding in the dry dock with the completion of the concrete skirts and the base slab. Details of the concrete for those parts of the structure are described later in the paper. In the remaining dry-dock construction, the ice wall will be constructed to an elevation 18.8 m and the remainder of the ice belt and internal walls to elevation 9.2 m. After removal to the DWS which is immediately adjacent to the dry dock location in Bull Arm, the remaining concrete work will be completed using floating batch-plant facilities. Details of the plans for that construction are given elsewhere (3). The completion of the DWS work will take several construction seasons.

CONCRETE MATERIALS

The aggregates are produced from a local glacial deposit of granitic and meta-volcanic rock. The material is screened, and oversize rock is crushed and screened with the gravel to produce a mix of natural shaped and crushed material possessing excellent mechanical and physical properties. A 20-mm

nominal maximum size aggregate was used for the concrete skirts. This was reduced to 14-mm nominal maximum size for the base slab concrete due to the greater density of reinforcing bars in the base slab. The fine aggregate is a manufactured sand from the same crushing operation that produces the coarse aggregate.

The cement is a blended cement produced in Quebec. The cement contains approximately 8.5 ± 1 percent silica fume and has an alkali equivalent (Na_2O equiv.) content of 0.70 percent (average). A typical analysis for actual cement being used is shown in Table 1. The cement was evaluated with the aggregates used, and found to be acceptable with respect to alkali-aggregate reactivity (5).

Three chemical admixtures are being used: a high-range water-reducing admixture (superplasticizer), a water-reducing admixture, and an air-entraining admixture.

CONCRETE SKIRTS

The skirts are a series of reinforced concrete elements which were joined together to form continuous concrete walls under the GBS as shown in Fig. 3. The skirts serve several purposes. During construction in the dry-dock, they support the base slab and the concrete walls above the base slab up to prescribed elevations necessary for the GBS to be floated out of the dry dock. This elevation for the outer walls is 18.8 m. The second function the skirts perform is to provide air-tight cells into which compressed air can be pumped once the dry-dock is flooded. This requires crack-free concrete. The air provides an air-cushion to assist in the buoyancy of the structure as it is floated out. The third function of the skirts is to penetrate the seabed when the platform is installed at its final location on the Grand Banks. The depth of penetration is controlled by ballasting of the GBS. Space between the underside of the GBS and the seabed after penetration is grouted to insure proper contact with the seabed. The compartmentalization of the skirts aids in the grouting operations.

A typical skirt element is shown in Fig. 4. The skirts are connected to the base slab by reinforcing steel and post-tensioning bars that will be stressed after the slab is placed. A total of 122 skirt elements were made using a total of 1100 m³ of