NISTIR 4465

Outline of a National Plan on High-Performance Concrete: Report on the NIST/ACI Workshop, May 16–18, 1990

ent of Commerce
itute of Standards and Technology
ilding Technology
, MD 20899

NISTIR 4465

Outline of a National Plan on High-Performance Concrete: Report on the NIST/ACI Workshop, May 16–18, 1990

Nicholas J. Carino
James R. Clifton

December 1990

U.S. Department of Commerce
Robert A. Mosbacher, *Secretary*
National Institute of Standards and Technology
John W. Lyons, *Director*
Center for Building Technology
Gaithersburg, MD 20899

ABSTRACT

A workshop on high-performance concrete (HPC) was held in Gaithersburg, MD on May 16, 17, and 18, 1990. The workshop was co-sponsored by the American Concrete Institute. High-performance concrete was defined as concrete having desired properties and uniformity which cannot be obtained routinely using only conventional constituents and normal mixing, placing, and curing practices. The workshop objectives were to:

- Identify current and planned research programs on HPC;
- Identify potential applications where HPC could be used on a routine basis;
- Identify the technical barriers to widespread use of HPC;
- Identify institutional barriers and deficiencies in standards which hinder the use of HPC;
- Develop a listing of critical research to overcome the technical barriers and provide a sound basis for the needed standards.

To achieve these objectives, noted international experts in concrete technology were invited to participate in the workshop. Eight working groups were organized to address different topics. This report summarizes the discussions and conclusions of the working groups. Each chapter begins with a brief introduction providing background on the nature of the problems addressed by the working group. Specific research topics are identified, and discussions are provided to explain the rationale for the needed research. The recommended research is proposed as the basis for a national program to exploit the potential of high-performance concrete and ensure U.S. competitiveness in concrete technology. Recommendations for implementing the plan are provided.

Keywords: Concrete; durability; high-performance concrete; high-strength concrete; institutional barriers; low-permeability concrete; mechanical properties; mixture proportioning; research; specifications; standard test methods; structural design; workshop.

EXECUTIVE SUMMARY

Good concrete is essential to the Nation's wellbeing. Two-thirds of the Nation's fixed wealth is in buildings and other structures.[1] During the 20th century, concrete has become an essential element of construction and its importance is likely to grow even more in the 21st century.

Historically, the development of concrete technology has been a slow evolutionary process. Some notable exceptions include the discoveries of the water-cement ratio law in 1919 and air entrainment in 1938. Today we are at another revolutionary stage in the development of concrete technology. The introduction of new admixtures and cementitious materials has allowed the production of highly workable concrete with superior mechanical properties and durability. This new class of concrete is being called "high-performance concrete" (HPC). The definition for high-performance concrete adopted in this report is:

> **Concrete having desired properties and uniformity which cannot be obtained routinely using only conventional constituents and normal mixing, placing, and curing practices. As examples, these properties may include:**
> - **Ease of placement and compaction without segregation**
> - **Enhanced long-term mechanical properties**
> - **High early-age strength**
> - **High toughness**
> - **Volume stability**
> - **Long life in severe environments**

National programs on high-performance concrete have been implemented in several countries, including Japan, Canada, Norway, and France. In the U.S., some important research programs are in place, but there is no overall program to coordinate the Nation's efforts to develop high-performance concrete and the design criteria for its safe use. To fill the gap and to ensure that the U.S. remains a leader in concrete technology, the National Institute of Standards and Technology (NIST) and the American Concrete Institute co-sponsored a workshop to identify the major elements of a national research plan for the development and exploitation of high-performance concrete.

The workshop was held in Gaithersburg, MD on May 16-18, 1990. The goals of the workshop were to:

- Identify current and planned research programs on HPC.
- Identify potential applications where HPC could be used on a routine basis.
- Identify the technical barriers to widespread use of HPC.
- Identify institutional barriers and deficiencies in standards which could hinder the use of HPC.

---

[1] Statistical Abstract of the United States: 1990, 110th Edition, U.S. Department of Commerce, Bureau of the Census, Washington, D.C., pg. 463.

- Develop a listing of critical research to overcome the technical barriers and provide a sound basis for the needed standards.

To achieve these goals, eight working groups were organized to address different aspects of the problem. This report summarizes the discussions and recommendations of the working groups.

The working group on Potential Applications identified a variety of applications which could benefit from the enhanced qualities of HPC and identified some of the critical research needed for the widespread use of HPC. Most of these research needs were discussed in greater detail by other working groups which addressed specific areas related to the production and use of HPC.

A substantial amount of research was identified as being of primary importance, i.e., essential to establish the needed technical basis for widespread use of HPC. Much of this work will do more than solely enhance our understanding of HPC; it will bring about a general enhancement of the state of technology of the U.S. concrete construction industry. The aim is to transform concrete technology from empiricism to a technology firmly rooted in materials science and structural mechanics. This change will make concrete a more predictable, better performing material, and reduce the risk of unexpected results.

The following outline of research needs encompasses five major technical areas (I through V). Three levels of research needs were recommended by the working groups: primary (P), secondary (S), and other recommendations addressing less urgent needs. In addition, needs for standards and acceptance criteria are given in VI, and needs for overcoming institutional barriers are given in VII. The order in which these needs are listed is not intended to indicate priority ranking.

* * * * *

I. MATERIALS AND PROPORTIONING

1(P). Improved Proportioning Methodology
Develop a proportioning process using available materials which will provide the optimum performance for the particular application, not just adequate strength.

2(P). Evaluation Methods
(a) Develop methods for evaluating the placement characteristics of fresh concrete.
(b) Develop standard early-age testing procedures and evaluation criteria to allow accept/reject decisions to be made at the earliest possible age.

3(P). Statistical Methods for Optimization of Mixtures
Develop statistical procedures that can be used by industry to obtain optimum mixtures from a limited number of trials.

4(P). Basic Understanding of Material Effects
Develop relationships, based on a sound understanding, between the properties of HPC and the properties of the ingredients (cement, additions, admixtures, aggregates).

5(S). Procedure for Evaluation of New Materials
Develop a recommended procedure to assess the potential contributions of new materials to the performance of HPC.

II. PROCESSING AND CURING

1(P). Understanding of Rheology and Workability
(a) Develop test methods to characterize the essential rheological properties of HPC needed to optimize mixture proportioning.
(b) Develop relationships between workability and mechanical properties, durability, and ease of placement.

2(P). Effect of Mixing on Properties
Develop guidelines for selecting the type of mixer and the resulting shear action so as to optimize the properties of HPC.

3(P). Effect of Curing Conditions
(a) Evaluate effectiveness of moist curing considering the completeness of hydration as a function of time.
(b) Seek an understanding of interactions between ambient exposure conditions, mix rheology, and needed evaporation control measures.
(c) Develop a more comprehensive understanding of the effect of internal curing temperatures on HPC.
(d) Develop guidelines for curing HPC based on sound technical knowledge.

4(P). Effect of Setting Time
Develop guidelines to deal with the effect of extended setting time, sometimes encountered with HPC, on its interaction with reinforcement.

5(P). Field Studies
Field studies on mixing and placing HPC should be undertaken to develop guidelines for field procedures.

6. Other Recommendation
Develop methods to determine degree of curing of HPC.

III. MECHANICAL PROPERTIES AND TEST METHODS

1(P). Compressive Strength Testing
Examine applicability of current standards for curing, specimen preparation, and testing machine requirements related to the compressive strength test for high-strength concrete, and develop the basis for improved testing procedures, if necessary.

2(P). In-Place Strength Tests
Establish reliable methods for estimating in-place strength of high-strength concrete.

3(P). Core Testing
Establish the inherent difference between the strength of a core and a cylinder made from identical concrete.

4(P). Understanding of Elastic Modulus
(a) Develop a reliable model for predicting the modulus of elasticity of concrete based on properties of the constituents.
(b) Examine the applicability of the current ASTM standard for measurement of elastic modulus, and develop an improved method, if necessary.
(c) Investigate the applicability of a standard method for measuring dynamic elastic modulus in the laboratory and in structures.

5(P). Relationships Among Mechanical Properties
Examine applicability of current empirical relationships for estimating other mechanical properties based on compressive strength, and develop improved relationships, if necessary.

6(P). Thermal Effects on HPC
(a) Obtain a fundamental understanding of the effects of early-age temperature on the long-term properties.
(b) Establish allowable differential temperature profiles for HPC.
(c) Develop guidelines to minimize the detrimental effects of high early-age temperature and temperature differentials.

7(S). Methods for Measuring Strain Capacity
Develop standard test methods to determine complete stress-strain curves and strain capacity.

8(S). Establish Mechanical Properties Data for Local Materials
Projects should be undertaken, at the local level, to establish the expected mechanical properties of concrete made from local materials.

9. Other Recommendation
Abandon obsolete standard test methods.

IV. DURABILITY AND TEST METHODS

1(P). Durability Design Code
Carry out a comprehensive research program to provide the basis for a Durability Design Code.

2(P). Applicability of Present Test Methods
Determine the appropriateness of using existing test methods developed for conventional concrete to evaluate the durability of HPC, and develop improved methods, if necessary.

3(P). Permeability Test for Concrete
Develop a reliable test method for measuring the permeability of HPC in the field and laboratory.

4(P). Service Life Predictions
Develop a methodology to predict the service life of HPC under any pre-defined set of service conditions.

5(P). Degradation Mechanisms
Develop an improved understanding of degradation mechanisms of HPC.

6(P). Freezing and Thawing Resistance
Develop the ability to predict the freezing and thawing resistance of HPC.

7(S). Performance Criteria Based on Type of Structure
Develop performance criteria for HPC for different types of structures and elements.

8(S). Effect of High Cement Content
Investigate the effect of high cement contents on alkali-aggregate reactions.

9. Other Recommendation
Determine the effects of low w/c ratio and other compositional factors on D-cracking.

V. STRUCTURAL PERFORMANCE AND DESIGN

1(P). Monitoring of HPC Structures
Monitor structures made with HPC to compare expected with actual performance so that deficiencies in current design methods can be discovered and corrected.

2(P). Seismic Performance
Establish how high-strength HPC should be used for seismic-resistant design and identify those topics requiring detailed investigation.

3(P). High-Strength Lightweight Concrete
Establish the significant differences in the behavior of high-strength HPC made with lightweight aggregates compared with normal weight, high-strength HPC.

4(P). Axial Load plus Bending
Verify current design practice for estimating the strength of high-strength HPC members under the combined action of axial load plus bending, and develop improved provisions, if necessary.

5(P). Development Length and Details of Reinforcement
(a) Evaluate the applicability of current design provisions for anchorage, development length, splices, and other reinforcement details, and develop improved provisions, if necessary.

(b) Establish rational models to deal with the interaction of steel and concrete which will be applicable over a wide range of variables.

6(P). Shear and Torsion

(a) Investigate the shear behavior of reinforced and prestressed concrete elements made with high-strength HPC, examine the applicability of current design criteria for shear and torsion, and develop improved provisions, if necessary.

(b) Develop rational models for shear strength.

7(S). Effects of Increased Tensile Strength

Establish the influence of increased concrete tensile strength on the design of high-strength HPC members, and, if appropriate, develop guidelines for taking advantage of this property.

8(S). Use of Higher-Strength Reinforcing Steels

Investigate the implications of using higher-strength reinforcing steels, and, where appropriate, develop guidelines for their use.

9(S). Reliability Aspects

Study the implications of current practices in the use of HPC in relation to the target reliabilities of design codes, and modify design practices, if necessary.

10(S). Constructability Issues

(a) Develop guidelines for construction schemes to handle the problems of interfacing high-strength HPC with conventional concrete.

(b) Develop guidelines for effective control of cracking.

(c) Develop guidelines on shoring/reshoring procedures for multi-story construction where high-strength HPC is used.

VI. STANDARDS AND ACCEPTANCE CRITERIA

Showing compliance with standards and acceptance criteria is the major means of ensuring that new concrete will perform as specified. The working group on this subject identified the following needs to facilitate the growth of confidence in the use of HPC.

- Develop performance standards for HPC.
- Establish appropriate acceptance criteria and uniformity requirements for HPC.
- Identify and implement ways to ensure that specifications are appropriate.
- Establish in-place tests for acceptance to determine if the specifications for HPC are being met.

VII. INSTITUTIONAL BARRIERS

In addition to the need for improved standards, other institutional barriers must be surmounted to ensure continued development of concrete technology and greater use of HPC. In general, institutional barriers fall into two categories: (1) barriers to wider implementation of demonstrated technology; and (2) barriers to the development of new technology. The working group on Institutional Barriers identified the following needs:

1. **Information Transfer**
(a) An improved system for information transfer both nationally and internationally.
(b) Programs to give civil engineering students industrial experience.

2. **Product Approval System**
A product approval system, such as the Agrément Board system used in Europe, to facilitate acceptance of new construction materials and products.

3. **Life-Cycle Costing**
An acceptable, practicable, and standardized method to evaluate life-cycle costs of construction materials.

4. **Contract Bid System**
An analysis of the current contract bid system in the U.S. to determine if a more efficient system could be developed which would reduce overall costs.

5. **Marketing System**
A marketing system to promote innovative concrete technology and to overcome institutional barriers.

* * * * *

The above outline addresses essential elements to develop a national program to make high-performance concrete a viable material. It is the first of several necessary steps towards the exploitation of the potential of high-performance concrete and to enhance the quality of the Nation's construction and its competitiveness in concrete technology.

Implementation of a national HPC program will require the collaborative efforts of Federal agencies, the academic sector, and the concrete industry. It will require the establishment of a central group to coordinate the program and develop detailed plans for carrying out the indicated research and transferring the results expeditiously to the U.S. concrete and construction industries. Since the most significant use of HPC is likely to be in the rebuilding of the nation's infrastructure, funding for HPC research should be linked to national infrastructure programs. Dissemination of the results will require the development of new standards, guidelines, mathematical models, and databases, in addition to the use of the more traditional mechanisms.

Table of Contents

1. INTRODUCTION

1.1 High-Performance Concrete

Concrete is one of the most versatile construction materials. By adjusting the mixture proportions and/or constituents, the properties of the concrete can be tailored for particular applications. When suitable materials are used and the quality of production is properly controlled, concrete is produced having reasonably predictable and satisfactory performance.

Historically, the development of concrete technology has been a slow evolutionary process. A notable exception was the formulation of the water-cement ratio law in 1919 which established that the potential strength of concrete was inversely related to the water-cement ratio. Another example was the revolutionary discovery in 1938 that the resistance of concrete to cycles of freezing and thawing could be greatly enhanced by using an air-entraining admixture to incorporate microscopic bubbles in the fresh concrete. In the past, the production of quality concrete had to strike a balance between two competing factors. On one hand, the construction industry desired highly fluid mixtures which could be placed with a minimum of effort. On the other hand, to attain desired mechanical and durability properties, it is desirable to have a mixture with a low water-cement ratio, which results in low workability. Today, we are at another revolutionary stage in the development of concrete technology. The introduction of water-reducing admixtures and new cementitious materials, such as condensed silica fume, has allowed the production of highly workable concrete with superior mechanical and durability properties. This new class of concretes is being called "high-performance concrete" (HPC).

The first widespread use of HPC was as high-strength concrete[1] (HSC) for columns of very tall reinforced concrete buildings. In some minds, high-performance concrete is synonymous with high-strength concrete. However, others believe that HPC should also have high durability. For example, researchers on Project C-205 of the Strategic Highway Research Program have defined HPC as concrete that meets the following criteria:

- It shall have one of the following characteristics:
    - 28-day compressive strength ≥ 10000 psi (70 MPa), or
    - 4-hour[2] compressive strength ≥ 3000 psi (20 MPa), or
    - 24-hour[2] compressive strength ≥ 5000 psi (35 MPa).
- It shall have a durability factor >80% after 300 cycles of freezing and thawing.
- It shall have a water-cementitious materials ratio ≤ 0.35.

---

[1]The meaning of high-strength concrete is quite arbitrary, but presently the generally-accepted definition is concrete having a compressive strength above 6000 psi (42 MPa).

[2]Time after placement.

Researchers at the University of Tokyo have taken another approach in defining HPC and have characterized HPC as a "forgiving concrete" which compensates for poor construction practices and structural detailing. Some of the essential characteristics of HPC according to their definition are:

- Ability to fill forms with little or no external compactive effort
- Cohesive mixture with low segregation
- Minimum of cracking at early ages due to shrinkage and thermal strains
- Sufficient long-term strength and low permeability

The general definition for high-performance concrete used in this report is:

> **Concrete having desired properties and uniformity which cannot be obtained routinely using only traditional constituents and normal mixing, placing, and curing practices. As examples, these properties may include:**
>
> - **Ease of placement and compaction without segregation**
> - **Enhanced long-term mechanical properties**
> - **High early-age strength**
> - **High toughness**
> - **Volume stability**
> - **Long life in severe environments**

1.2 Ongoing Research Programs

Along with the U.S., many countries are faced with the problem of a decaying infrastructure, many components of which are made of concrete. The potential long-term savings that may be realized by replacing old concrete structures with HPC structures have been recognized world wide. As a result, several national-scale research programs have been established to study various aspects of HPC. The following summaries of notable research programs indicate the range of activities being pursued. For readers interested in obtaining additional information about these projects, the Appendix lists addresses of the responsible organizations.

1.2.1 Center for Science and Technology of Advanced Cement-Based Materials (ACBM)

The Center is a research consortium of five organizations with its headquarters at Northwestern University. The University of Illinois, the University of Michigan, Purdue University, and the National Institute of Standards and Technology are the other members. The Center was established in Spring 1989 and will receive support from the National Science Foundation for a minimum of five years. The goals of the Center are to: (1) carry out research advancing the fundamental science required for the design of new cement-based materials with enhanced properties; (2) improve the understanding of the science underlying cement-based materials processes and methodologies; (3) develop mathematical and computer-based models to simulate the structure and performance of cementitious materials; and (4) enhance the basic knowledge necessary to improve the competitiveness of the U.S. construction industry. These activities are also intended to develop the scientific knowledge for designing the next generation of cement-based materials with improved properties.

1.2.2 Strategic Highway Research Program (SHRP)

The five-year Strategic Highway Research Program is a highly-focused program[3,4] managed by the National Academy of Science. It addresses four critical areas of pavement and bridge performance: asphalt, long-term pavement performance, concrete and structures, and highway operations. The mission of the concrete research is to increase the durability of portland cement concrete in highway applications. The following projects comprise the concrete subprogram.

1.2.2.1 Project C-201: Concrete Microstructure

This project addresses the materials science aspects of concrete. The project is being led by researchers in the Materials Research Laboratory at Pennsylvania State University. Relationships are being developed between the hydration reactions and the structure-property characteristics of concrete. Based on these relationships, recommendations are being developed for optimizing concrete microstructure to obtain desired performances. Optimization may necessitate adjustments in mixture proportions, development of improved test methods, and improvements in specifications for concrete and concrete-making materials. The project is planned to be completed in December 1990.

1.2.2.2 Project C-202: Eliminating or Minimizing Alkali-Silica Reactivity

The objectives of this project are to develop: (1) practical test methods for predicting the alkali-silica reactivity susceptibility of aggregates; (2) specifications for concrete-making materials that are resistant to alkali-silica reactivity in new construction; and (3) techniques for mitigating the harmful effects of alkali-silica reactivity in existing concrete pavements and structures. The key product of the project is to be a quick and reliable method for identifying potentially-reactive aggregates. Criteria are being developed for avoidance of alkali-silica reactivity based on quantitative definition of the environmental conditions, combination of materials, and mixture proportions specifications. The project is being led by Construction Technology Laboratories and the planned completion date is March 1993.

---

[3]"Strategic Highway Research Program: Research Plans," Transportation Research Board, National Research Council, Washington, DC, May 1986.

[4]"Concrete and Structures: Progress and Products Update," Strategic Highway Research Program, National Research Council, November 1989.

1.2.2.3 Project C-203: Resistance of Concrete to Freezing and Thawing

This project is intended to develop methods for avoidance of freezing and thawing durability problems. The mechanisms by which entrained air protects concrete from freezing and thawing damage are being examined. Also, the effects of various cementitious materials on the requirements for entrained air are being investigated. Rapid and relatively inexpensive methods for identifying and screening of non-durable aggregates are also being developed. The project is being led by the University of Washington and is scheduled to be completed by December 1992.

1.2.2.4 Project C-204: Nondestructive Testing for Quality Control/Condition Analysis of Concrete

Improved quality control/quality assurance systems for concrete are being developed in this project. These systems are being based on rapid, reliable nondestructive methods which can be used in the field. This project also includes the development of a condition-evaluation system based on nondestructive techniques for determining the condition of concrete and for estimating its remaining service life. It is being led by Trow, Inc., and is planned for completion by March 1993.

1.2.2.5 Project C-205: High-performance Concrete

The objective of this project is to obtain information on the mechanical properties and durability characteristics of different high-performance concrete mixtures intended for highway applications. The project is headed by researchers at North Carolina State University, and includes others from the University of Michigan and the University of Arkansas. Specimens from concrete mixtures made with different paste systems, aggregate types and, in some cases, fiber reinforcement will be evaluated in terms of the development of strength and elastic properties, strain capacity, and time-dependent deformations. Durability characteristics will be evaluated in terms of freezing and thawing resistance and chloride ion permeability. In addition to experimental work, a comprehensive literature review and state-of-the-art report on high-performance concrete will be completed. Also, a database structure will be developed that will permit the incorporation of new research findings and allow query by users. The project is expected to be completed in 1992.

1.2.2.6 Project C-206: Optimization of Highway Concrete Technology

This project is intended to use the knowledge gained in the SHRP-sponsored research on concrete and apply it to the development of new concretes and methodologies for increasing the service life of highways. The project will include the evaluation of new materials and processes in concrete technology and establish plans for using them in highway applications. Specifications for environment-specific superior concrete will be developed. An expert system will be developed for use in diagnosis of concrete durability problems and to increase the service life of highway concrete. This project, which is lead by Construction Technology Laboratories, is scheduled to start in fall 1990 and to be completed in 30 months.

1.2.3 Chicago Joint-Industry Project

The Chicago area has been a leader in the development and use of high-strength concrete (HSC) in the United States. Various joint-industry projects have been performed on the properties of high-strength concrete and the behavior of structural elements. One of the current projects addresses the strength development of high-strength concrete in two drilled caissons. Two concrete mixtures are being investigated: a low elastic modulus mixture with compressive strength of about 10,000 psi (69 MPa) and a high elastic modulus mixture with a compressive strength of about 16,000 psi (110 MPa). The study is aimed at comparing the strength development in the caissons with that of standard-cured specimens. Cores taken from the caissons will be tested for strength at different ages and will be subjected to petrographic analysis to evaluate the extent of microcracking that is expected to occur because of the high in-place temperatures. In another project, the development of the engineering properties of five HSC-mixtures will be determined. In addition, comparisons will be made of the compressive strengths obtained by different specimen preparation procedures.

1.2.4 Norwegian Project

The Royal Norwegian Council for Scientific and Industrial Research and the Norwegian concrete industry initiated a joint research program on high-strength concrete in 1986. Phase 1 of the program was completed in 1988 and Phase 2 is scheduled to be completed in 1991. Its main objectives are to: (1) broaden the knowledge of HSC in the range of 65 to 105 MPa, and to consider extension to higher strengths; (2) determine the influence of variations in the major concrete constituents on the properties of fresh and hardened HSC; (3) determine the appropriateness and reproducibility of standard test methods when applied to HSC; and (4) transfer the technology on HSC to the Norwegian building industry. Investigations are being carried out on the structural performance, durability, and design criteria for HSC.

1.2.5 Canada NCE Program on High-Performance Concrete

In 1988, the Canadian government initiated a competition for the creation of Networks of Centers of Excellence (NCE) to perform multi-disciplinary research on a wide range of subjects. In 1989, 14 such "Networks" were created, one of which was in the area of high-performance concrete. The HPC-Network is headed by researchers at the University of Sherbrooke and includes six other universities and two industrial partners. The research plan involves three projects. Project 1 — Development of New Building Materials — will investigate topics such as fresh concrete, interfacial characteristics, durability, materials selection criteria, influence of fiber types on strength, and economic/technological optimization for HPC. Project 2 — Design of High-Strength Concrete Structures — will investigate constitutive models, shear strength, column behavior, bond and anchorage, high-strength reinforcement, and the development of new design criteria. Project 3 — Development of New Products and Techniques — will investigate the use of HPC as a substitute for stone and ceramic materials, fiber reinforced shotcrete, destructive and nondestructive laboratory tests, monitoring of structures, and standard test procedures. The program will have a 4-year duration.

1.2.6 Japanese New Concrete Program

In 1988, the Japanese Ministry of Construction initiated the five-year project "Development of Advanced Concrete Buildings using High-Strength Concrete and Reinforcement" (termed "new RC"). The major objectives of the project are to: (1) survey and analyze existing research and development related to high-strength concrete to establish a technology system for "new RC" buildings; and (2) develop an understanding of the mechanical behavior of buildings using high-strength concrete and high-strength reinforcing steel and to develop design systems for "new RC" buildings. Major research areas are shown in Figure 1 where the vertical axis is yield strength of reinforcement and the horizontal axis is concrete strength. This figure illustrates the potential advancements which can be made by considering new combinations of material strengths for "new RC" buildings. It has been found that one of the most important technology elements in high-strength, reinforced concrete buildings is the quality control of the concrete.

1.2.7 French National Program

In France, a national project called "New Ways for Concrete" has been undertaken to demonstrate the feasibility of producing HPC for major construction works. The demonstration project involved the construction of a 114-m, three-span, cast-in-place, post-tensioned bridge. The "experimental bridge" at Joigny was built with HPC having a 28-day design compressive strength of 60 MPa (8700 psi). The high strength was achieved with existing construction equipment, using local materials, and without using condensed silica fume. It is anticipated that the concrete will have a superior service life. Therefore, an external prestressing system was used so that tendons could be replaced in the event of their deterioration. The structure was instrumented to monitor thermal performance during construction and deformation response during service. Data from the bridge were used to validate computational models. The project successfully demonstrated that HPC can be produced on a routine basis using existing equipment and materials. The success of the project has convinced French officials that HPC should be specified for all works where superior durability is desired, even if the high strength of HPC is not structurally necessary.

1.3 NIST Workshop

Recognizing the potential of high-performance concrete, in 1989 the National Institute of Standards and Technology (NIST) proposed the initiation of a national research program on HPC. NIST (formerly the National Bureau of Standards) has had a long tradition of concrete materials research, development of standard test methods, and assisting the construction industry. Thus it was felt to be important that NIST should work with the cement and concrete community to develop the outline for a plan which would provide a framework for NIST and other organizations who wish to make resources available to advance the knowledge of HPC for the benefit of the U.S. construction industry and protection of future investments in the infrastructure.

The objective of the first year's effort was to identify the state-of-the-art related to HPC so that the critical research areas could be identified and incorporated into a national plan. It was decided that an important step toward meeting the objective would be to sponsor a workshop. Thus an organizing committee composed of experts in different phases of concrete technology was assembled to plan the workshop. The organizing committee was composed of the following individuals:

Nicholas Carino, Structures Division, National Institute of Standards & Technology
James Clifton, Building Materials Division, National Institute of Standards & Technology
Richard Gaynor, National Ready Mixed Concrete Association
Inam Jawed, Strategic Highway Research Program
Robert E. Philleo, Consultant
Jan Skalny, W.R. Grace Company

The workshop was held in Gaithersburg, MD on May 16-18, 1990. It was co-sponsored by the American Concrete Institute (ACI). A list of the participants and the workshop schedule are included in the Appendix. The goals of the workshop were to:

- Identify current and planned research programs on HPC.
- Identify potential applications where HPC could be used on a routine basis.
- Identify technical barriers to the widespread use of HPC.
- Identify institutional barriers and deficiencies in standards which hinder the use of HPC.
- Develop a listing of critical research to overcome the technical barriers and provide a sound basis for the needed standards.

To achieve these goals, eight working groups were organized to address different aspects of the problem. Each working group had a chairman and a secretary as indicated in the Appendix. Prior to the workshop, participants were asked to submit topics for discussion during the sessions. Individuals were invited to make short informal presentations on ongoing research or projects related to HPC. The conclusions of each working group were presented at the plenary session. All written materials submitted to the workshop and developed during the group discussions have been filed for future reference. In addition, the group discussions and the plenary session were tape-recorded.

The remainder of this report is based upon the discussions and conclusions of the eight working groups. The recommendations of the working groups form the basis for an outline of a plan to enhance the development and exploitation of high-performance concrete in the U.S.

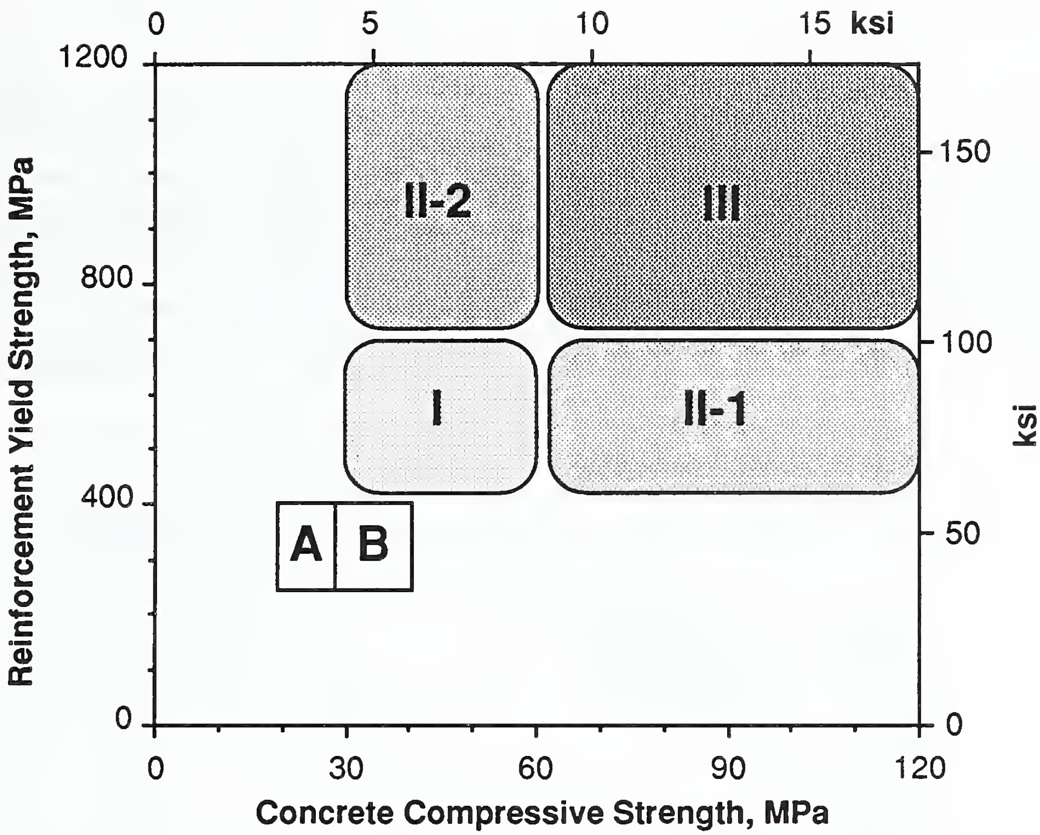
1.4 Scope of Report

The following eight chapters summarize the findings of the working groups. Each chapter begins with a brief introduction providing background on the nature of the problems addressed by each working group. Specific research topics are identified, and a discussion is provided to explain the rationale for the needed research. The original intent was to list the research topics in order of decreasing priority, but it was found that this could not be accomplished in the time available and, in any case, was not realistic. As a result, the research topics were identified as "primary" or "secondary". The final chapter presents recommendations for implementing this ambitious research program.

It will be seen that a substantial amount of research has been identified as being of primary importance. It should be noted that much of the proposed research is intended to do more than solely enhance our understanding of HPC. The research results will bring about a general enhancement of the state of technology of the U.S. concrete construction industry, which is often viewed as being "low tech." The need is to transform concrete technology from empiricism to a technology firmly rooted in materials science and structural mechanics. This change will make concrete a more predictable, better performing material and reduce the risks of failure in the increasingly costly structures which will be built to take advantage of the opportunities provided by HPC. The potential savings to the nation which can be realized by using HPC are well documented.[5]

---

[5]"Concrete Durability: A Multibillion-Dollar Opportunity," National Materials Advisory Board Report, NMAB-437, National Research Council, 1987, 105 p.



LEGEND

A: Common low-rise buildings
B: High-rise buildings constructed in last decade
I : High-strength concrete and reinforcement
II-1: Ultra high-strength concrete and high-strength reinforcement
II-2: High-strength concrete and ultra high-strength reinforcement
III: Ultra high-strength concrete and reinforcement

Adapted from: Aoyama, H. et al., *Outline of the Japanese National Project on Advanced Reinforced Concrete Buildings with High-Strength and High-Quality Materials*, Proc. 2nd Int. Symp. on Utilization of High-strength Concrete, Berkeley, May 1990.

Figure 1. Research areas being addressed in the Japanese "new RC" program.

2. POTENTIAL APPLICATIONS

2.1 Attributes of HPC

In Section 1.1, high-performance concrete was defined as concrete having desired properties and uniformily not readily obtainable using conventional materials and procedures, and examples of such properties were given as part of the definition. Table 2.1 provides a comprehensive listing of the properties or attributes that are achievable using HPC. These attributes can be grouped into three general categories: (1) properties which benefit the construction process; (2) enhanced mechanical properties; and (3) enhanced durability properties. These are the key qualities which can be exploited by the selection of HPC for a project.

Table 2.1 Exploitable attributes of high-performance concretes

Attribute	Abbreviation
Adhesion to hardened concrete	AD
Abrasion resistance	AR
Corrosion protection	CP
Chemical resistance	CR
Ductility*	DUC
Durability	DUR
Energy absorption (toughness)*	EA
Early strength	ES
High elastic modulus	EM
High compressive strength	CS
High modulus of rupture	MOR
High tensile strength	TS
High strength/density ratio**	S/D
High workability and cohesiveness	WRK
Low permeability	IMP
Resistance to washout	WSH
Volume stability	VS

*Fiber-reinforced concrete
**Especially with high-strength, lightweight concrete

2.2 Applications

There are many applications which can benefit from the enhanced qualities of HPC. Some of those identified during the workshop session are listed in Table 2.2. The categories "primary" and "secondary" are intended to reflect the potential volume of HPC that would be used for these applications. In those cases where HPC is already being used, the applications have been listed as "existing." Efforts should be made to promote more widespread use of HPC for these existing applications. Other examples in Table 2.2 are "new" applications which can benefit from the use of HPC. The attributes of HPC that satisfy the needs of these applications are given in the last column (abbreviations are as in Table 2.1).

Also given in Table 2.2 are two "speculative" applications: lunar concrete and concrete for automated construction. While lunar concrete is not expected to be a "big volume" item, it is anticipated that significant advances in concrete technology will occur as a result of ongoing and future research. It is anticipated that in the future concrete will be placed, consolidated, and finished using robotic machinery. This will require high-performance concrete with excellent placement characteristics and uniformity.

2.3 Research Needs to Enhance Applications

A reason for not selecting HPC for a project is the greater expense per unit volume of concrete. This is likely, however, to be a false reason for excluding HPC if consideration is given to the following factors:

- The enhanced workability of HPC, or the high early-age strength, can reduce construction costs.
- The enhanced mechanical properties can reduce the sizes of structural elements.
- The enhanced durability will increase the service life.

Other reasons for not specifying HPC are questions concerning its use or performance under certain situations. The workshop session on Potential Applications identified some of the critical research needed to remove the unknowns which may hinder the widespread application of HPC. These are listed in Table 2.3; the order is not indicative of priority. Subsequent chapters will expand on these and other research needs.

In addition to technical factors, the workshop session also identified an institutional barrier to widespread use of HPC, namely, the need for independent verification of commercially-produced data. A significant amount of data related to the performance of HPC are produced by manufacturers of materials for HPC. Potential users often view such data with skepticism. There is a need to establish a system for verifying these data so that beneficial materials can be accepted more readily by potential users.

At the Second International Symposium on Utilization of High Strength Concrete held at the University of California, Berkeley on May 21-23, 1990, an informal survey was conducted by the symposium chairman. The participants were asked to list those areas related to high-strength concrete for which additional research is needed and those areas where there is a general consensus and further research is not critical. The results of the survey are listed in Table 2.4. The survey findings are generally consistent with the recommendations of the NIST workshop sessions presented in subsequent chapters. Some interesting results are the conflicting opinions about the need for additional research on "ductility" and "durability."

Table 2.2 Opportunities for exploitation of high-performance concretes

Application	Existing/New	Needed Attributes*
	PRIMARY IMPORTANCE	
Buildings		
- Columns	E	WRK, CS, EM, Predictable time-dep. deformations
- Post-tensioned Slabs	N	CS, EM
- Foundations	N	CS
Bridges		
- Decks	E	CP, DUR, AR, S/D
- Long spans	E	EM, S/D
Cold weather construction	N	ES
Chemical & food processing plants	N	IMP, CR, AR
Fast-track construction		
- Tilt-up, recycling of formwork, automation, safety	N	WRK, ES, MOR
Hazardous waste containment	N	IMP, DUR
Parking garages	E	CP, DUR
Pavements		
- Fast track construction	E	ES, MOR
- Repair	E	WRK, ES
- Heavy traffic zones	E	AR
Precast/prestressed concrete	N	WRK, CS, MOR, ES, CP, S/D
Repair		
- Emergency	E	WRK, ES, AD
- Underwater	N	WSH
- Long-term	N	DUR, CS, AD
- Use of fiber concrete	N	EA, AD
Sanitary structures	N	IMP, CR, DUR
Seismic applications	N	EA, WRK
	SECONDARY IMPORTANCE	
Military structures	N	EA, TS, CS
New transportation systems		
- High-speed rail, mag-lev	N	VS, CP, CS, EM
Offshore structures		
- Gravity structures	N	CS, TS, EM, DUR
- floating structures	E	CS, TS, EM, DUR, S/D
Security structures	N	EA, TS, CS
Tunnel linings	N	IMP, ES, CS, TS, DUR
	SPECULATIVE APPLICATIONS	
Lunar concrete		
Automated construction		WRK

*See Table 2.1 for attributes

Table 2.3 Areas requiring research* for wider use of HPC

- Curing of low w/c HPC (and development of recommended practices)
- Explore approaches for enhanced volume stability -- control of plastic & drying shrinkage
- Understand fracture processes in HPC (strain capacity, brittleness, crack characteristics)
- Understand needs for minimum reinforcement in high-strength HPC
- Consequences of using higher yield strength steel (f_y > 75 ksi (520 MPa))
- Establish applicability of high-strength HPC in seismic design, explore feasibility of fiber-reinforced concrete in beam-column joints
- Develop techniques to facilitate finishing HPC flatwork
- Characterize chemical resistance of HPC
- Develop methods to repair HPC for (inevitable) construction defects
- Develop protective coatings for rebars to which concrete bonds well
- Understand the compatibility of HPC with conventional concrete (in new construction at slab-column joints and in repairs)
- Understand consequences of high compressive strength in applications of HPC for durability -- take advantage of it when possible

* In addition to these research areas, the verification of commercially-produced data by an independent agency was identified as a need for removing an institutional barrier to the wider use of HPC.

Table 2.4 Summary of responses to informal survey at Second International Symposium on Utilization of High Strength Concrete

	Number of Responses
I. Topics for additional research	
Ductility	14
Testing methods	14
Shear behavior (bond)	13
In situ properties	13
Shrinkage	9
Durability	8
Test methods for resistance against frost and fire	7
Fatigue	6
Setting temperature (heat of hydration)	6
Tensile behavior	4
Fracture energy	4
Modulus of elasticity-strength relationship	3
Repairs	3
Relationship between different test samples	2
Effects of curing conditions	2
Effects of coarse aggregate on properties	2
Lightweight concretes	1
New types of composite members	1
Performance of concretes with fly ash	1
High strength concrete in structures	1
Relative compressive and tensile stresses	1
New workability measurement system	1
Curing compounds	1
Physical chemistry	1
II. Topics on which you believe we have consensus	
Durability	7
Use of additives (admixtures and additions)	7
Ductility	7
Feasibility to commercially produce HSC	7
Flexural behavior	5
Shortening	4
Mix design	4
Economic advantages	1
Heat of hydration control	1
Long-term behavior	1
Self-curing propensity of HSC	1
Freezing and thawing resistance	1
E-modulus	1
Fire behavior	1
Mechanical properties except creep and shrinkage	1
Real existing market for HSC	1

3. MATERIALS AND PROPORTIONING

3.1 Introduction

The first step in the production of HPC is to select and proportion the ingredients. This will establish the potential quality of the concrete mixture.

The process for proportioning a trial mixture of conventional concrete is relatively simple. First, a water-cement ratio is selected based on the desired compressive strength or the expected exposure conditions. The water content is selected based on the desired slump range, and the aggregate proportions are selected to provide for a cohesive mixture with good finishing characteristics. Different types of portland cement may be used to allow some tailoring of the strength-gain characteristics or for additional resistance to chemical (e.g., sulfate) attack. An air-entraining agent would be used for resistance to freezing and thawing. The primary requirements for suitable aggregates are that they be clean and hard, properly graded, and not susceptible to excessive volume changes during wetting and drying or freezing and thawing.

Proportioning HPC is more complex. The cementitious system is usually composed of portland cement in combination with other materials, such as fly ash, blast-furnace slag, and silica fume. In contrast with conventional concrete, there is no longer a simple relationship between water-cement ratio and potential strength. The aggregate may have to be carefully selected when trying to achieve concrete with high strength or high elastic modulus. Chemical admixtures are needed to achieve the required levels of workability, to enhance durability, or to control the setting process. Because there are so many factors to consider, the selection of the ingredients and determination of optimum mixture proportions is a difficult task. The traditional empirical approach of making alternative trial mixtures is an ineffective method for choosing acceptable materials and for arriving at the optimum proportions.

To evaluate alternative mixtures requires test methods and predictive tools. Traditionally, test methods have included the measurement of fresh concrete properties, such as slump, air content, and unit weight, and the measurement of strength after a specified period of standard curing. The suitability of this traditional approach for the evaluation of HPC mixtures is questioned.

3.2 Primary Needs

3.2.1 Improved Proportioning Methodology

Develop a proportioning process using available materials which will provide the optimum performance for the particular application, not just adequate strength.

Discussion -- The key feature of HPC is that it can be tailored to perform as needed to suit a particular application. The performance requirements may include one or more of the following: economical construction, ability to carry large forces, and long-term durability.

The proportioning process should be capable of producing a trial mixture which satisfies the requirements of the particular project. This includes satisfying the contractor's placement and finishing requirements (ease of placement and compaction, segregation resistance, low bleeding, good finishability, and low plastic shrinkage). In addition, the proportioning process should be able to satisfy early-age requirements, such as:

- control of heat of hydration
- minimum amount of cracking
- high early strength

Finally, the process should produce a mixture having the potential to attain the required hardened properties, such as:

- mechanical properties (strength, stiffness, toughness)
- low permeability
- durability for specific exposure conditions
- abrasion resistance

The usual practice has been to evaluate the performance of a trial mixture under standard temperature conditions. This approach will not provide a true indication of how the mixture will behave under field conditions. High-performance concretes are complex chemical systems, and it is common knowledge that the rates of all chemical reactions are temperature dependent. In addition, there can be interactions among admixtures, or between cement and admixtures, which are temperature dependent. Thus it is important that the performance of a trial mixture be evaluated not only at standard temperature but also at the expected extreme application temperatures.

3.2.2 Evaluation Methods

(a) Develop methods for evaluating the placement characteristics of fresh concrete, and (b) develop standard early-age testing procedures and evaluation criteria to allow accept/reject decisions to be made at the earliest possible age.

Discussion -- The slump test is the present standard for evaluating the workability characteristics of fresh concrete. However, it has long been recognized that this test defines the behavior of concrete under the action of gravity and provides little direct information on the behavior of concrete during consolidation by vibration. There is a need for a test that will accurately indicate performance of concrete during placement and consolidation. The test must be practicable for use in the field as well as in the laboratory. The work on rheology being performed at the Center for Advanced Cement-Based Materials may contribute to the basis for an improved test method.

Often HPC is proportioned with a high cement factor compared with conventional concrete. As a result, HPC mixtures may have high "stickiness" which presents problems in finishing. There is a need for a method to characterize this attribute of rich HPC mixtures so that the influence of various materials on reducing this problem can be evaluated.

The usual practice has been to evaluate the potential strength of a concrete mixture by testing at later ages (usually 28 days, but sometimes 56 or 91 days in high-strength concrete projects). As a result, acceptance testing is also performed at these later ages. It would be of value to develop correlations between early-age and later-age tests during the mixture evaluation process. This would permit using tests for acceptance at early ages, before the concrete has hardened to such an extent, or construction has proceeded to such a level, that the cost to remove deficient concrete becomes excessive. In such early-age testing, it is likely that the maturity method may be used to properly account for the temperature history during the curing period up to the time to testing.

3.2.3 Statistical Methods for Optimization of Mixtures

Develop statistical procedures that can be used by industry to obtain optimum mixtures from a limited number of trials.

Discussion -- To obtain an optimum concrete mixture, one needs to consider a range of different ingredients (cementitious materials, aggregates, and admixtures) and their proportions. It is not economically feasible to test all possible combinations to arrive at the optimum mixtures. There are statistical methods for planning experiments so that the effects of the main factors (ingredients and their addition rates) and their interactions can be determined without testing all combinations. Unfortunately, such methods are unknown to the majority of concrete producers. It would be beneficial to develop a recommended practice to assist concrete producers in using statistically-based testing plans for optimization of mixture proportions[6].

3.2.4 Basic Understanding of Material Effects

Develop relationships, based on a sound understanding, between the properties of HPC and the properties of the ingredients (cement, additions, admixtures, aggregates).

Discussion -- Empirical testing during the mixture optimization process could be reduced if there were a clear understanding of how the properties of the ingredients affect the properties of the resultant concrete.

Some of this understanding could be derived from other research programs if there were a standard format for reporting the basic properties of the

---

[6]An example, of how statistical tools can be used is discussed in "The Use of Statistical Methods to Optimize the Performance of High-Strength Concrete," by J. Luciano and G. Bobrowski, presentation at 1990 meeting of the Transportation Research Board, Washington, DC.

ingredients and of the concrete used in research. Technical committees of professional organizations, such as the new ACI Committee 126 on Concrete Materials Property Database, should seek to develop such a standard format. To assist in developing this understanding requires new, more meaningful tests to characterize the ingredients.

An improved understanding of the relationship between the properties of the ingredients and those of concrete will allow determination of allowable tolerances in the characteristics of the ingredients such that there will not be serious effects on the concrete properties. The Norwegian study on the effects of aggregate characteristics will provide important information that could serve as a foundation for additional investigations.

Some of the important properties of the concrete that need improved understanding are volume changes and strain capacity, because non-structural cracking is the most widespread problem in concrete. Another key area is the improvement of the understanding of the paste-aggregate interface and how its characteristics are affected by the materials used. The paste-aggregate interface has a major role in defining the mechanical and durability properties of concrete. There is a need for practical methods to evaluate the characteristics of the paste-aggregate interface. The fundamental work on microstructural development being performed under SHRP C-201 may provide some of the needed insight into this important area.

3.3 Secondary Needs

3.3.1 Procedure for Evaluation of New Materials

Develop a recommended procedure to assess the potential contributions of new materials to the performance of HPC.

Discussion -- Two approaches have been suggested for evaluating the performance of new concrete materials. In one case, a reference mixture is used and the properties of the concrete made with the new material(s) are compared with the properties of the reference mixture. This is a "go"-"no go" approach, and it will identify the positive or negative qualities of the new materials. Another approach is to carry out a series of "screening" tests, using mortar cubes, to discern the main effects of the new materials or the interactions among materials. The mortar tests are more economical than testing concrete. The mortar tests would be followed by tests on concrete specimens for verification of the performance of those combinations believed to be adequate based on the screening tests.

4. PROCESSING AND CURING

4.1 Introduction

The quality of high-performance concrete is largely controlled by the mixing, placing, and curing conditions. Improved understanding of the relationships between these factors and the quality of high-performance concrete is needed to ensure that HPC will have the desired properties.

4.2 Primary Needs

4.2.1 Understanding of Rheology and Workability.

(1) Develop test methods to characterize the essential rheological properties of HPC needed to optimize mixture proportioning.

Discussion: The rheology of fresh HPC will affect both the processing and the ultimate properties of the cured HPC. For example, the equipment and practices for mixing, transporting, and placing fresh HPC may depend on the rheology of fresh HPC. The rheology will affect the uniformity of the cured HPC and thus its performance. Test methods, based on fundamental principles of rheology, are needed. The methods should: (1) be field usable; (2) give usable results over a wide range of mixture properties; and (3) provide a means for characterizing HPC with respect to pumpability.

(2) Develop relationships between workability and mechanical properties, durability, and ease of placement.

Discussion -- Demands imposed by labor attitudes and cost considerations will require that HPC have high workability.

4.2.2 Effect of Mixing on Properties.

Develop guidelines for selecting the type of mixer and the resulting shear action on the properties of HPC.

Discussion -- For HPC to achieve its optimum properties, its ingredients must be thoroughly dispersed to produce a homogeneous mixture. Because of the dense packing of particles and the use of rheology modifiers, the mixing of HPC may place more severe demands on the mixer than conventional concrete. Comparisons among different types of mixing equipment and procedures should be obtained. Also differences in central mixers should be evaluated. The effects of mixer type and action on rheology, microstructure of hardened HPC, mechanical property development of HPC, and uniformity need to be evaluated.

4.2.3 Effect of Curing Conditions

(1) Evaluate effectiveness of moist curing considering the completeness of hydration as a function of time.

Discussion -- HPC will typically have very low permeability which may restrict the inward movement of moisture, thereby, impeding the hydration of the inner core of concrete elements made with low water-cement ratios. Information is needed on the effectiveness of moist curing to determine if new curing practices should be developed.

(2) **Seek an understanding of interactions between ambient exposure conditions, mix rheology, and needed evaporation control measures.**

Discussion -- HPC usually does not exhibit bleeding and thus surface drying cracking can develop if the evaporation of moisture is not curtailed. Information is needed on the effectiveness of methods for controlling evaporation, such as fogging and evaporation retardants. The effects of the methods on the quality of the near-surface hardened cement paste should be investigated by considering the resulting surface w/c ratio, durability (e.g., abrasion resistance), and permeability.

(3) **Develop a more comprehensive understanding of the effects of internal curing temperatures on HPC, and develop guidelines for curing HPC based on sound technical knowledge.**

Discussion -- HPC will usually have higher cement contents than normal concrete, and thus higher internal temperatures. The effects of higher internal temperatures on microstructure (e.g., microcracks) and strength need to be determined.

4.2.4 Effect of Setting Time

Develop guidelines to deal with the effect of extended setting time sometimes encountered with HPC on its interaction with reinforcement.

Discussion -- The use of chemical admixtures, such as high-range water reducers, can lengthen the setting time of concrete. Information is needed on the effects of increased setting times on the bond strength development between reinforcement and HPC, including the effects of vibration prior to setting. Also, information is needed on the influence of temperature and admixtures on the setting time of HPC.

4.2.5 Field Studies

Field studies on mixing and placing HPC should be undertaken to develop guidelines for field procedures.

Discussion -- The guidelines on mixing and placing of HPC will significantly contribute to the optimization of its performance.

4.3 Other Recommendation

Develop methods to determine degree of curing of HPC.

Discussion -- The cement in HPC will not hydrate to the same extent as that in conventional concrete. The properties of HPC may be more sensitive to degree of curing than conventional concrete. Therefore, methods are needed to reliably determine the degree of curing of HPC.

5. MECHANICAL PROPERTIES AND TEST METHODS

5.1 Introduction

Measurement of mechanical properties provides the basic information needed to use concrete in the design of a structure and for acceptance of concrete during construction. In many applications, HPC is proportioned with a low water-to-cementitious materials ratio. As a result, HPC is often high-strength concrete. The procedures and equipment used in existing standard test methods are based on experience and data obtained from testing lower-strength concrete (generally less than 6000 psi or 40 MPa). Divergent test results have been reported by different agencies testing the same high-strength concrete. Examination of the underlying factors causing the differences often revealed differences in testing equipment or procedures. There is an urgent need for critical review of current standard test methods. Where deficiencies are noted, it will be necessary to develop the technical basis for modifying existing methods so that reliable measurements can be made on high-strength concrete.

The compressive strength of concrete is by far the most widely-specified property on construction projects, but there are cases where other mechanical properties, such as flexural strength and elastic modulus, are equally important. In lieu of obtaining these other properties from tests, it may be acceptable to estimate their values using the compressive strength and accepted empirical relationships. However, the existing relationships are based on data from conventional, lower-strength concretes. There is a need to establish the validity of existing relationships over the full range of available high-performance concretes, and to develop improved relationships where necessary.

The testing of the standard-cured compression specimen is viewed by many as the only valid and necessary test for concrete. However, it is recognized that testing standard-cured cylinders does not necessarily provide information which is relevant to the properties attained in the structure. The main function of the standard-cured specimen is to provide assurance that the concrete delivered to a project satisfies contract requirements. However, once concrete is delivered to the site there are many factors that will affect its actual in-place performance. There is a need for reliable methods to assess the in-place strength of concrete to verify that the required properties are achieved.

5.2 Primary Needs

5.2.1 <u>Compressive Strength Testing</u>

Examine applicability of current standards for curing, specimen preparation, and testing machine requirements related to the compressive strength test for high-strength concrete, and develop the basis for improved testing procedures, if necessary.

Discussion -- Current standards for testing concrete are based on experience with lower-strength concrete. There is a need for systematic analysis of the testing variables to identify those which have significant effects on the measured compressive strength. For example, one of the issues raised during the workshop is the effect of the range of initial curing temperatures currently permitted by ASTM C 31. For the first 16 to 32 hours, the ambient temperature is permitted to be between 16 and 27 C.

Another important issue that must be resolved concerns the use of 100 by 200-mm cylinders in place of the standard 150 by 300-mm cylinders. The smaller specimens are needed for testing high-strength concrete, otherwise testing laboratories are not able to test with existing machines. Research to compare strengths resulting from these two specimen sizes have been performed by several organizations. There is a need for a critical review of the available data to determine whether there is consensus on the difference in strength and repeatability. If there is no consensus, it will be necessary to explain the differences, or perform independent studies to confirm or refute previous findings.

There also needs to be a consensus on methods for preparing the ends of high-strength cylinders prior to testing. Some recommend grinding as the most appropriate method, but others argue that grinding is not economically feasible for commercial testing laboratories. It would be desirable to develop a high-strength capping material that is as convenient to use as sulfur, but does not lower the measured strength or increase the variability of test results. It would also be of value to conduct fundamental analytical studies of the interactions between test cylinder, capping material, and testing machine.

Finally, there is a question of testing machine requirements. The current ASTM C 39 has no requirements for minimum axial or lateral stiffness of the testing machine. Limited research has been done on this subject. There is a need for data to determine whether machine stiffness affects strength measurements. If machine stiffness is found to be important, it will be necessary to develop appropriate stiffness criteria.

5.2.2 In-Place Strength Tests

Establish reliable methods for estimating in-place strength of high-strength concrete.

Discussion -- It is recognized that, because of a variety of factors, the in-place compressive strength can differ significantly from the standard-cured cylinder strength. Among the most important factors are consolidation and curing conditions. To assure that the required strength is attained in the structure, in-place strength tests are needed. Several reliable in-place test methods have been developed for conventional concrete. These rely on the use of an empirical relationship to estimate compressive strength from the in-place test results. As was the case for compressive strength testing discussed in 5.2.1, most of the in-place testing experience has been limited to lower-strength concrete. There is a need to verify the reliability of existing methods when applied to high-strength concrete. In some cases it may be necessary to modify test equipment in order to be able to test at the higher strength levels.

While much work has been done in the study of the correlations between in-place tests and compressive strength, there has been limited work on the applicable statistical methods for using such relationships to estimate in-place compressive strength. There is a need to develop a consensus procedure for statistical analysis of in-place test results. The validity of such a procedure should be verified by field trials. This procedure would be applicable to HPC as well as conventional concrete.

The maturity concept has proven to be a convenient tool for monitoring strength gain during the curing of conventional concrete. The applicability of the maturity concept to HPC mixtures needs to be investigated. Questions exist regarding whether the maturity concept will work for HPC mixtures having low water-cement ratios and employing complex mixtures of cementitious materials and admixtures.

5.2.3 Core Testing

Establish the inherent difference between the strength of a core and a cylinder made from identical concrete.

Discussion -- Drilled cores are often used to verify the attainment of in-place compressive strength. In some high-strength concrete applications, it has been reported that the measured core strengths were substantially lower than the standard-cured strengths. It has been argued that core strengths are expected to be lower than cylinder strengths because of damage during the drilling process and because of the lack of confining mortar around the exposed peripheral coarse aggregate particles. Others argue that the differences represent actual strength differences because of unfavorable curing conditions in the structure. Systematic studies are needed to establish what portion of the observed differences between strengths of core and cylinders is due to the inherent differences between testing a core and testing a cylinder and what portion is due to real differences in strength of the concrete represented by the core and the cylinder.

An equally important question, but one that is more difficult to answer, is: What is the relationship between core strength and member strength? In current practice, the concrete is judged to be adequate if average core strengths exceed 85% of the design strength. The rationale for this criterion is often questioned. Thus there is a need for rational criteria for the acceptable difference between core strength and design strength. The acceptance criteria probably should include consideration of the type of structural member, because the importance of concrete strength on member resistance is not the same for all members.

5.2.4 Understanding of Elastic Modulus

(1) Develop a reliable model for predicting the modulus of elasticity of concrete based on properties of the constituents.

(2) **Examine the applicability of the current ASTM standard for measurement of elastic modulus, and develop an improved method, if necessary.**
(3) **Investigate the applicability of a standard method for measuring dynamic elastic modulus in the laboratory and in structures.**

Discussion -- High-performance concrete is often used because of the need for a high elastic modulus to control deflections. Designers typically use the current ACI-formula to estimate elastic modulus based on the design strength of the concrete. However, it is known that this empirical formula is highly uncertain and can lead to estimates that are grossly in error. There is a need to develop a more reliable, empirical relationship for estimating elastic modulus which is based on other characteristics of the mixture besides compressive strength and density. It would also be useful to have a model for estimating the elastic modulus as a function of the compressive stress level.

There are concerns about the relevance of elastic modulus and Poisson's ratio values obtained from the current ASTM procedure in relation to actual values in a structure. For example, there are reports that the measured elastic modulus is affected by loading rate and moisture condition of the specimen. In the standard method, there is an implicit assumption that the deformation (or strains) are associated with a uniaxial state of stress. However, it is known that the standard cylinder is subjected to a complex state of stress because of end friction. There is a need for a critical review of the standard method for measuring static modulus of elasticity and Poisson's ratio.

An alternative technique for measuring modulus of elasticity is to use stress wave propagation methods, such as resonant frequency or ultrasonic pulse velocity. Because these dynamic tests subject the specimens to very small elastic strains, the computed dynamic elastic modulus is closer in value to the initial tangent modulus than the secant modulus. Thus a reduction factor is needed to estimate the secant modulus at the working stress level. This reduction factor is expected to be dependent on the compressive strength, since it is known that, with increasing strength, the compressive stress-strain curve of concrete is more nearly linear-elastic. The measurement of dynamic modulus of elasticity offers the potential for simplification of the testing procedure and allows for in-place measurement of elastic modulus.

5.2.5 Relationships Among Mechanical Properties

Examine applicability of current empirical relationships for estimating other mechanical properties based on compressive strength, and develop improved relationships, if necessary.

Discussion -- Properties such as flexural and splitting tensile strength have been correlated with compressive strength. For high-strength concrete, especially mixtures with silica fume, there are questions about the applicability of existing empirical relationships, which are based on data from conventional concrete. The applicability of these empirical relationships should be investigated for representative HPC mixtures. It is important that these relationships be studied as a function of maturity and as a function of curing conditions expected in HPC members. The statistical properties of these relationships should be considered in addition to mean values.

5.2.6 Thermal Effects on HPC

(1) Obtain a fundamental understanding of the effects of early-age temperature on the long-term properties.
(2) Establish allowable differential temperature profiles for HPC.
(3) Develop guidelines to minimize the detrimental effects of high early-age temperature and temperature differentials.

Discussion -- HPC mixtures typically have higher cement contents than conventional concrete. As a result, temperature rise in structures due to heat of hydration is greater than in conventional mixtures. For conventional concrete, high early-age temperature is known to reduce the long-term properties. Some data show that the same reduction may not occur in certain HPC mixtures. There is a need to gain a fundamental understanding of the relationship between early-age temperature history and long-term properties.

In addition to the higher temperatures attained in elements cast with HPC, there will also be higher thermal gradients. Existing allowable temperature differentials are based on experience with conventional concrete. There are questions about whether these allowable differentials are applicable to HPC mixtures, especially high-strength concretes which may able to tolerate higher differential strains.

In regard to temperature rise in structural elements, there should be more widespread use of computer simulation of the expected thermal history in structures, so that appropriate curing and protection schemes can be planned to minimize the likelihood of thermal cracking.

5.3 Secondary Needs

5.3.1 Methods for Measuring Strain Capacity

Develop standard test methods to determine complete stress-strain curves and strain capacity.

Discussion -- Strain capacity of concrete is of fundamental importance in regard to cracking potential. However, there are no standard methods for measuring this characteristic. There is a need to develop a standard procedure for determining the stress-strain response of concrete. Such a method should be relatively simple to perform and provide information that can be used in predicting in-place structural response.

5.3.2 Establish Mechanical Properties Data for Local Materials

Projects should be undertaken, at the local level, to establish the expected mechanical properties of concrete made from local materials.

Discussion -- The mechanical properties of a given HPC mixture are dependent on the properties of the component materials. To assist designers who intend to use HPC, it would be advantageous if the expected properties of typical HPC mixtures in a given locale were known. This would lead to the use of more realistic values in design compared with the use of empirical relationships to estimate various mechanical properties. This would give the designer more confidence in specifying HPC for local projects.

5.4 Other Recommendation

Abandon obsolete test methods.

Discussion -- Many ASTM test methods were established 40 to 50 years ago and may no longer serve a useful function due to changes in concrete technology. For example, the testing of field-cured specimens as an indicator of in-place strength should be replaced with the use of modern in-place test methods. It is generally acknowledged that field-cured cylinders rarely experience the same curing conditions as the structures they are supposed to represent. Another example is the use of flexural strength tests to accept concrete for pavement applications. It is argued that this is the correct approach because flexural strength is the key design parameter. However, it has been shown that the measured flexural strengths of field-prepared specimens have high variability because of the sensitivity of flexural strength to environmental conditions. A better approach might be to develop the correlation relationship between flexural and compressive strength in the laboratory, and use compressive strength tests to accept the concrete.

6. DURABILITY AND TEST METHODS

6.1 Introduction

From a materials standpoint, HPC is not fundamentally different from conventional concrete and thus it is expected that both will exhibit the same type of durability problems. One of the major benefits anticipated with HPC is improved durability. However, there are conflicting opinions on the requirements to assure durable concrete. In addition, far more information than presently available is needed on the relationships among the composition, microstructure, and properties and the durability of HPC. This information will contribute to the formation of a technical basis for designing HPC with the desired durability.

6.2 Primary Needs

6.2.1 Durability Design Code

Carry out a comprehensive research program to provide the basis for a Durability Design Code.

Discussion -- Concrete is at present mainly designed for strength with durability being given inadequate consideration. HPC has the potential of being significantly more durable than conventional concrete. To exploit the potential increased durability of HPC, research is needed on the mechanisms of concrete degradation, relationships among composition and microstructure and durability of concrete, and the effects of the environment on durability. This knowledge should be used to develop a Durability Design Code which is applicable to the range of environmental conditions encountered in the U.S.

6.2.2 Applicability of Present Test Methods

Determine the appropriateness of using existing test methods developed for conventional concrete to evaluate the durability of HPC, and develop improved methods, if necessary.

Discussion -- Accelerated durability tests developed for conventional concrete are currently being used to predict the durability of HPC. However, there is considerable controversy regarding the applicability and reliability of some of the tests. Such tests include the rapid freezing and thawing test for concrete (ASTM C 666) and the rapid chloride permeability test (AASHTO T 259). The applicability of other existing durability tests to HPC should be evaluated and, if necessary, new test methods developed. The variability of results from the test methods also should be determined.

6.2.3 Permeability Test for Concrete

Develop reliable test methods for measuring the permeability of concrete in the field and laboratory.

Discussion -- Permeability is one of the key properties of concrete controlling its durability. For some exposures, the in-place, near-surface permeability is critical in terms of long-term performance. Because a relatively-easy-to-use and reliable standard permeability test method does not exist, there is a need to develop test methods for laboratory and field use. Relationships between permeability and durability of HPC should be developed. Similar tests are needed for the diffusivity of concrete.

6.2.4 Service Life Predictions

Develop a methodology to predict the service life of HPC under any pre-defined set of service conditions.

Discussion -- HPC will often be designed to have a longer service life than conventional concrete. Also, HPC will be likely used when aggressive environments are encountered because of potential longer service life.

Methodologies for predicting the service lives of concrete are at an embryonic development stage. They need to be developed so that they can be used to aid the design of concrete for specific applications where durability is essential.

6.2.5 Degradation Mechanisms

Develop an improved understanding of degradation mechanisms of HPC.

Discussion -- Understanding of the degradation mechanisms of HPC and factors affecting their kinetics is needed to: (1) determine the adequacy of present durability tests, (2) develop accelerated tests which realistically simulate actual degradation processes, and (3) develop models for making service life predictions.

6.2.6 Freezing and Thawing Resistance

Develop the ability to predict the freezing and thawing resistance of HPC.

Discussion -- The freezing and thawing resistance of HPC has been a controversial topic, especially the need for entrained air. Investigations are still required on the need for air-entrainment for HPC. Relationships between air content, air void spacing, and freezing and thawing resistance should be developed based on an improved understanding of freezing and thawing damage mechanisms. The effect of chemical and mineral admixtures on freezing and thawing resistance should be further investigated.

6.3 Secondary Needs

6.3.1 Performance Criteria Based on Type of Structure

Develop performance criteria for HPC for different types of structures and elements.

Discussion -- The durability requirements for HPC will vary depending on the specific structure or element. For example, the freezing and thawing requirements could be different for bridge decks than for foundations.

6.3.2 Effect of High Cement Content

Investigate the effect of high cement contents on alkali-aggregate reactions.

Discussion -- HPC will usually have a higher cement content than conventional concrete which could result in an increase in the alkali contents of the concrete and, possibly, an increase in alkali-aggregate reactions. There is a need for design guidelines to avoid problems due to alkali-aggregate reactions.

6.4 Other Recommendations

Determine the effects of low w/c ratio and other compositional factors on D-cracking.

Discussion -- D-cracking takes place when porous aggregates are saturated with water and are subjected to freezing temperatures. Low w/c HPC concrete may adequately protect such aggregates from critical saturation and thus permit their use.

7. STRUCTURAL PERFORMANCE AND DESIGN

7.1 Introduction

From a structural viewpoint, high-strength concrete (HSC) is the form of HPC which has gained the most widespread interest. Modern design methods for concrete structures are based on the ultimate strength of members. There are significant differences between the failure process of HSC and that of conventional concrete. For example, HSC is known to fail in a more brittle fashion and to have smoother fracture surfaces than conventional concrete. Such differences have caused concern about the applicability of existing design criteria for reinforced and prestressed concrete.

Current design methods for concrete structures are based on a combination of mechanistic and empirical models. The conservative nature of the design equations has been documented by many tests. However, the bulk of this validation has been limited to specimens made of conventional concrete. There are concerns about extrapolating the design equations to the HSC range. As a result, there are restrictions on the maximum concrete strength that can be used in certain design equations. For example, in the ACI Code there are empirical design provisions that incorporate the square root of compressive strength as a factor. Chapters 11 and 12 of the 1989 version of the ACI Code place a limit of 100 psi (0.7 MPa) on this factor, which impedes the use of concrete in excess of 10,000 psi (70 MPa).

A deficiency of empirical design criteria is that their applicability is limited to the strength range over which test data were obtained. It would be desirable to replace empirical models with rational models that would be applicable for all values of concrete strength and steel yield strength.

Current design criteria have evolved over many years and after a tremendous amount of experimental and analytical research. It would be unrealistic to suggest that all previous research has to be repeated using HSC. Thus the first objectives of new research programs should be to establish which of the current criteria are not applicable to HSC.

7.2 Primary Needs

7.2.1 Monitoring of HPC Structures

Monitor structures made with HPC to compare expected with actual performance so that deficiencies in current design methods can be discovered and corrected.

Discussion -- The mechanical properties (strength and stiffness) of HPC are used to design a structure. However, the design assumptions are rarely verified by in-place tests on the completed structure. As a result, it is not known whether the construction methods were adequate to achieve the required results. The availability of such feed-back would allow us to discern which construction methods work and which do not.

As has been previously mentioned, HPC is often used in building construction because of the higher stiffness that can be obtained to control structural deformation. Typically, the design value of elastic modulus is obtained from laboratory tests of standard specimens. It would be of value to know whether the design values are actually achieved in the structure. This would provide some assurance that the structure will perform as intended.

One of the most difficult design tasks is to predict reliably the service-load deformations of structural components and the structure as whole. In order to be able to refine design methods, it is necessary to obtain feed-back from the performance of the completed structures. In addition to monitoring deformations, it would also be of value to monitor the nature of service-load cracking. It is important to know whether the use of HPC leads to cracking problems not found in conventional concrete structures.

A potential drawback to HSC is its "less forgiving nature" because of its reduced creep (or stress relaxation) properties. There should be an examination of HSC structures to determine whether unforeseen distress arises because of this characteristic. In a similar manner, there should be investigations of the performance of "nonstructural" HPC, i.e., concrete that is required to have high durability but does not need high strength for structural purpose. For example, bridge decks may be built of low water-cement ratio concrete to achieve low porosity for corrosion protection.

In summary, all structures offer the opportunity to perform full-scale tests that can provide invaluable information for assessing the success of design and construction methods.

7.2.2 Pilot/Screening Studies

(a) Seismic Performance

Establish how high-strength HPC should be used for seismic-resistant design and identify those topics requiring detailed investigation.

Discussion -- The brittle nature of HSC compared with conventional concrete has raised concern about its applicability in seismic- resistant construction, where energy absorption is of major importance. Studies are needed to demonstrate whether such concerns are well-founded. Potential benefits of HSC, if they exist, should be investigated. This is an area where high-strength, fiber-reinforced concrete may play an important role.

(b) High Strength Lightweight Concrete

Establish the significant differences in the behavior of high-strength HPC made with lightweight aggregates compared with normal weight, high-strength HPC.

Discussion -- High-strength, lightweight HPC was identified at the workshop as being of significant importance in the future. It is believed that, because of the low aggregate strength, high-strength, lightweight concrete has more brittle characteristics than normal weight, HSC. There is need to establish whether design with this material can be approached in the same way as normal weight, HSC.

7.2.3 Comprehensive Research Program

(a) Axial Load plus Bending

Verify current design practice for estimating the strength of high-strength HPC members under the combined action of axial load plus bending, and develop improved provisions, if necessary.

Discussion -- Current design methodology is based largely on concrete strength less than about 6000 psi (40 MPa). Tests of structural components have usually been performed using reduced scale models because of testing machine limitations. In addition, the compressive strengths of companion cylinders have been used to represent concrete strengths in the structural elements. New research should include the measurement of the in-place compressive strength along with the standard cylinder strength so that the relationship between member strength and actual concrete strength can be understood. Concrete strengths from 8000 psi (55 MPa) to the maximum attainable value should be used.

Structural mechanics approaches for predicting member strength based on idealized stress-strain behavior of the materials need to be verified. If necessary, new analytical models should be developed which are applicable over the complete range of concrete strength.

Tests need to be performed on full-scale specimens so that there will be proper modeling of thermal history. As an alternative, special curing procedures should be used to simulate the temperature rise in actual full-scale members. In addition, attention should be paid to structural performance as a function of maturity. Tests should establish minimum reinforcement requirements. Complete load deformation responses should be monitored to establish ductility of HSC elements.

(b) Development Length and Details of Reinforcement

(1) Evaluate the applicability of current design provisions for anchorage, development length, splices, and other reinforcement details, and develop improved provisions, if necessary.
(2) Establish rational models to deal with the interaction of steel and concrete which will be applicable over a wide range of variables.

Discussion -- Due to insufficient data using HSC, Chapter 12 of the 1989 ACI Code limits the value of the concrete strength that can be used in equations related to development length. There is an urgent need for research to establish applicable development length design provisions for HSC.

Rational models are needed to replace the current empirical models for development length. Otherwise, questions about applicability will arise whenever new materials are introduced. Studies should include deformed bars, plain bars, and bars with epoxy coating. Response under reversed loading should be included for seismic considerations.

(c) Shear and Torsion

(1) Investigate the shear behavior of reinforced and prestressed concrete elements made with high-strength HPC, examine the applicability of current design criteria for shear and torsion, and develop improved provisions, if necessary.
(2) Develop rational models for shear strength.

Discussion -- The 1989 ACI Code places the same limit on the design compressive of concrete for use in shear strength equations as in the development length equations. Thus there is an urgent need to define the range of applicability of the current design provisions related to shear strength.

The smoother crack surface associated with the failure of HSC may have important consequences in regard to the load transfer mechanism for shear. In addition, the question of size effect in relation to shear strength should be considered. There is evidence that shear strengths of large-scale members are significantly lower than ordinary members. There are concerns about punching shear strength, shear strength of deep beams, and the behavior of beams with small amounts of shear reinforcement. Models for shear strength which are more rational than the current models should be developed.

7.3 Secondary Needs

7.3.1 Effects of Increased Tensile Strength

Establish the influence of increased concrete tensile strength on the design of high-strength concrete members, and, if appropriate, develop guidelines for taking advantage of this property.

Discussion -- The enhanced tensile strength of HSC may affect the requirements for minimum reinforcement. It may also be significant in reducing the deflection of members under service loads. If high-strength concrete has enhanced tensile properties, this could be exploited in prestressed concrete design.

7.3.2 Use of Higher-Strength Reinforcing Steels

Investigate the implications of using higher-strength reinforcing steels and, where appropriate, develop guidelines for their use.

Discussion -- Higher-strength reinforcing steel is being introduced into foreign markets. The use of higher-strength steels in flexural members will allow greater utilization of the capabilities of high-strength concrete. In compression and flexural members, there could be a reduction in reinforcement congestion. The implications of using higher-strength steels (nonprestressing and prestressing) need to be investigated in terms of construction economies and serviceability issues.

7.3.3 Reliability Aspects

Study the implications of current practices in the use of HPC in relation to the target reliabilities of design codes, and modify design practices, if necessary.

Discussion -- High-performance concrete is characterized by increased quality control during its production and placement. Thus the in-place variability of HPC is expected to be lower than that of conventional concrete. It should be examined whether it is feasible to incorporate the higher level of quality control and construction quality into the assignment of strength reduction factors for HPC members.

In applications of high-strength concrete, design strengths at ages later than 28 days have been used, for example, 56 and 91 days. The current safety provisions in the ACI Code are based largely on 28-day strengths. Thus there is an implicit assumption that further strength gain above the 28-day value is likely to occur during the life of the structure. When later-age strengths are used in design, the potential additional strength gain over the structure's lifetime will be lower. The consequence of specifying other than 28-day design strengths needs to be studied in relation to the influence on member reserve strength.

7.3.4 Constructability Issues

(1) Develop guidelines for construction schemes to handle the problems of interfacing high-strength HPC with conventional concrete.

Discussion -- One of the problems in using high-strength concrete in building construction occurs at the interface between the HSC used in columns and the conventional-strength concrete used in slabs. The "sandwiching" of the slab-concrete between the lower and upper column segments is undesirable from a strength point of view. The "mushrooming" of the high-strength column concrete into the slab is undesirable from a construction point of view. There is a need to develop economical schemes for assuring the compatibility of the structural system when using HSC and conventional-strength concrete.

(2) Develop guidelines for effective control of cracking.

Discussion -- Cracking is recognized as the most persistent problem in concrete construction. To promote the application of HPC, it is necessary to develop techniques that will control cracking due to such factors as temperature and shrinkage. The use of shrinkage-compensating materials in HPC should be investigated.

(3) Develop guidelines on shoring/reshoring procedures for multi-story construction where high-strength HPC is used.

Discussion -- The use of high-strength concrete in multi-story construction can allow dramatic increases in the construction rate, because of the possibility of rapidly attaining the required concrete strength for construction loading. The consequences of such accelerated construction schemes should be examined, to assure that the long-term performance of the structure is not sacrificed.

8. STANDARDS AND ACCEPTANCE CRITERIA

8.1 Introduction

The use of codes, standards, and acceptance criteria is the major means of ensuring that new concrete will perform as specified. They are based largely on the body of knowledge resulting from research and experiences with conventional concrete. Development of standards and acceptance criteria, based on improved understanding of the factors controlling the performance of HPC, and the meeting of them, will facilitate the growth of confidence in the use of HPC.

8.2 Primary Needs

8.2.1 Performance Standards

Develop performance standards for HPC.

Discussion -- Development of performance standards should stimulate innovation which will result in improved quality. In cases where inadequate information is available on performance, performance specifications should be combined with prescriptive specifications. Test methods to measure the in-place performance of HPC (e.g., in-place early strength, permeability, long-term performance and durability) do not exist and need to be developed.

8.2.2 Effectiveness of Specifications.

Identify and implement ways to ensure that specifications are appropriate.

Discussion -- If specifications for HPC are to work, they must contain realistic requirements (e.g., slump is not a realistic requirement for HPC with high-range water reducers) and have well-defined responsibilities for the parties involved in the project. Lines of responsibility will make it possible to determine legal liability when performance specifications are used.

8.2.3 In-Place Testing

Establish in-place tests for acceptance to determine if the specifications for HPC are being met.

Discussion -- Confidence in the performance of HPC in structures is necessary if it is to be accepted widely. In-place testing will help to determine if the hardened HPC will have the desired properties. Data are needed to establish the reliability of in-place tests, such as pullout and maturity, in estimating early-age strength properties. Field testing techniques are needed to evaluate the long-term durability of HPC.

8.3 Secondary Needs

8.3.1 Acceptance Criteria

Establish appropriate acceptance criteria and uniformity requirements for HPC.

Discussion -- There is a need to identify the properties of HPC, in addition to compressive strength, for which acceptance criteria should be established. Test methods are needed to determine these properties, preferably at early ages. There is a need to establish acceptable levels of variation in the properties of HPC which are realistic and achievable. Also, the frequency of testing needs to be established.

9. INSTITUTIONAL BARRIERS

9.1 Types of Institutional Barriers

In general, institutional barriers fall into one of two categories: (1) barriers to wider implementation of demonstrated technology; and (2) barriers to the development of new technology. The barriers themselves can be classified based on their causes, which, in broad terms, can be related to communicational and societal differences. Examples of communication-induced barriers are the use of different physical units (e.g., metric and inch-pound), differences in educational backgrounds, and historical differences (including different languages). Societal barriers may be political, legal, and financial, and are manifested in many ways, e.g., local, national, and international standards and building codes. Also, the use of indigenous materials and traditional practices may give rise to local societal barriers.

Technical barriers to the use of HPC can be reduced by: (1) developing information on how to obtain the potential properties of HPC using current technology; (2) stimulating innovation to further improve the technology of HPC; and (3) stimulating the dissemination of information on the benefits of using HPC and ensuring that the proper information on HPC technology is transferred.

9.2 Needs

9.2.1 Information Transfer

(1) There is a need for an improved system for information transfer, both nationally and internationally.

Discussion -- Several approaches can be used for information transfer including development of expert systems, databases, models, and standards for HPC.

(2) Develop programs to give civil engineering students industrial experience.

Discussion -- At present, civil engineering students entering the workplace have insufficient knowledge of concrete technology. The use of HPC will undoubtedly require a higher-level of knowledge of concrete technology than the use of conventional concrete. It is recommended that the proposed program include the awarding of university educational credits.

9.2.2 Product Approval System

Establish a product approval system, such as the Agrément Board system used in Europe, to facilitate acceptance of new construction materials and products.

Discussion -- Materials and products would be tested and certified to show that they meet manufacturers' claims. This would encourage the selection of innovative materials, such as HPC, by designers and engineers. This concept would need to be evaluated, and the best way for implementing it determined.

9.2.3 Life-Cycle Costing

Develop an acceptable, practicable and standardized method to evaluate life-cycle costs of construction materials.

Discussion -- Life-cycle costing estimates would provide a means for determining the benefits of using HPC by facilitating comparisons with other materials. Actions needed to implement the system need to be identified, including ways to obtain service life data for concrete.

Also, the actions required for having service life design concepts incorporated into building codes should be identified.

9.2.4 Contract Bid System

Analyze the current contract bid system in the U.S. to determine if a more efficient system could be developed which would reduce overall costs.

Discussion -- The current contract bid system probably could be replaced with a more cost-effective system. Alternative systems would need to be identified and the consequence of their use investigated. An award system should be included for higher performance during construction and also based on lower maintenance cost of the concrete.

9.2.5 Marketing System

Develop a marketing system to promote innovative concrete technology and to overcome institutional barriers.

Discussion -- The market-place will ultimately control the use of HPC. A marketing system which includes cost considerations of life-cycle cost, improved performance and durability, reliability of performance, ease of use or application of construction materials, should stimulate the development and use of HPC.

10. IMPLEMENTATION

Implementation of a national program on HPC, as outlined in this report, will require developing detailed plans for each work area and obtaining the necessary funding. Detailed plans must provide for carrying out the indicated research and addressing issues which affect the use of HPC (such as institutional barriers). In addition, the results of the work must be transferred to the U.S. concrete industry, if it is to remain competitive in the market-place. The implementation of a national program on HPC should be given top priority.

10.1 Approach

Implementation of the research plan outlined in this report will require the collaborative efforts of the Federal laboratories, the academic sector, and the concrete industry. The national effort should be well-organized and focused as the work needs to be expedited for the U.S. to ensure its leadership in HPC technology. An approach for implementing the plan would include the establishment of a national consortium or foundation which could be guided by, for example, the American Concrete Institute (ACI) or by an interagency council. Such an interagency council should have representatives of both federal and state organizations with significant interest in HPC; such organizations are the Federal Highway Administration, Department of Energy, U.S. Army Corps of Engineers, Nuclear Regulatory Commission, Bureau of Reclamation, NIST, and the American Association of State Highway and Transportation Officials (AASHTO). As far as ACI is concerned, it should be noted that its technical committees have representatives of many of the organizations which would logically carry out the work specified in the outlined plan. Also, the ACI's Concrete Materials Research Council's mission is to stimulate funding of research on concrete materials.

Since, the most significant use of HPC is likely to be in the rebuilding of the nation's infrastructure, funding for HPC research should be linked to infrastructure programs.

10.2 Technology Transfer

The results of the proposed research and development might be disseminated in several ways such as the development of new standards, guidelines, predictive models, and databases. New standards are urgently needed in several areas, e.g., for measuring the compressive strength of high-strength concrete. It is anticipated that the work on mechanical properties will form the bases for new ASTM standards on testing of HPC. ACI committee guides and future revisions of the ACI Building Code Requirements for Reinforced Concrete (ACI 318) would be expected to reflect advances made by implementing the HPC plan and thus disseminate the results to concrete practitioners.

The use of computer-based models to disseminate knowledge is being demonstrated by the prototype Cementitious Materials Modeling Laboratory at NIST. The Laboratory is supported, in part, by the NSF Center for Advanced Cement-Based Materials. Mathematical models for predicting different aspects of concrete performance can be electronically accessed remotely through the laboratory. As new models for predicting the performance of HPC are developed they could be made available to users through a Modeling Laboratory whether at NIST of elsewhere.

Few databases on concrete have been developed and thus much of the data from studies of concrete are difficult to retrieve, or are not widely known to exist. To encourage the development of such databases, the ACI recently formed Committee 126, Concrete Materials Property Database, to develop standard formats for computerization of concrete materials property data. Development of databases for HPC will serve to disseminate what is known about its properties and performance, and to identify gaps in our knowledge.

An attractive means for technology transfer would be the development of an integrated knowledge system[7] for HPC. Integrated knowledge systems might consist of text bases, databases, models, expert systems, and images which could be interfaced through computer networks. Integrated knowledge systems have the potential of becoming the authoritative source of knowledge on the science and technology of HPC.

---

[7] G. Frohnsdorff, "Integrated Knowledge Systems for Concrete Science and Technology," in Materials Sciences of Concrete I, ed. J.P. Skalny, pp. 315-332 (American Ceramic Society, 1989).

11. ACKNOWLEDGEMENTS

The authors express their sincere appreciation to the workshop participants whose contributions were vital to the success of the workshop. Special thanks are extended to Henry Russell and Weston Hester[8] for their keynote presentations. The group chairmen, John Bickley, Ellis Gartner, Geoff Frohnsdorff, Ken Hover, Tony Liu, Rick Meininger, Larry Roberts, and Mike Russell, are commended for their efforts in organizing their group discussions and presenting succinct summaries at the plenary session. The group secretaries, Ed Garboczi, Larry Knab, Joe Lamond, Jim Pielert, and Paul Stutzman, are commended for their conscientious efforts in documenting the contents of the group discussions. We thank all those individuals who reviewed the report and submitted constructive suggestions. We thank the American Concrete Institute for acting as co-sponsor of the workshop.

Finally, we thank Ms. Denise Herbert for her diligence in planning for the workshop and for processing this report.

[8]We are saddened to learn that Dr. Hester passed away a short time prior to publication of this report. We will miss the vitality with which he promoted the use of high performance concrete.

APPENDIX

HIGH PERFORMANCE CONCRETE WORKSHOP
National Institute of Standards and Technology
Gaithersburg, MD
May 16-18, 1990

SCHEDULE
HIGH PERFORMANCE CONCRETE WORKSHOP
National Institute of Standards and Technology
Co-Sponsor: American Concrete Institute

Wednesday, May 16, 1990

8:00 am - 9:00 am *Opening Presentations*

Welcome	Dr. Richard N. Wright, Director, Center for Building Technology, NIST
Goal of Workshop	Dr. Nicholas J. Carino, Structures Division, NIST
Presentations	"High-Strength Concrete: Yesterday, Today and Tomorrow"
	Dr. Henry Russell, President, Construction Technology Laboratories, Inc.
	"Two Perspectives on High Performance Concrete"
	Prof. Weston T. Hester, University of California, Berkeley

9:00 am - 12:30 pm		*Session 1*	*Session 2*
		Materials and Proportioning	*Processing and Curing*
	Chairman:	Rick Meininger	Larry Roberts
	Secretary:	Paul Stutzman	Jim Clifton
1:30 pm - 5:00 pm		*Session 3*	*Session 4*
		Mechanical Properties and Test Methods	*Durability and Test Methods*
	Chairman:	Mike Russell	Tony Liu
	Secretary:	Nick Carino	Joe Lamond

Thursday, May 17, 1990

9:00 am - 12:30 pm		*Session 5*	*Session 6*
		Structural Performance and Design	*Standards and Acceptance Criteria*
	Chairman:	Ken Hover	John Bickley
	Secretary:	Larry Knab	Jim Pielert
1:30 pm - 5:00 pm		*Session 7*	*Session 8*
		Potential Applications	*Institutional Barriers*
	Chairman:	Geoff Frohnsdorff	Ellis Gartner
	Secretary:	Ed Garboczi	Jim Clifton

5:00 pm Video Presentation on Tokyo University HPC

Friday, May 18, 1990

9:00 am - 12:00 pm *Plenary Session*
Summary of Working Group Recommendations
Concluding Remarks

NIST WORKSHOP ON HIGH PERFORMANCE CONCRETE
List of Participants

Prof. Shuaib H. Ahmad
North Carolina State Univ.

Prof. P.C. Aitcin
University of Sherbrooke, Canada

Mr. John A. Bickley
Consultant, Canada

Dr. Reid H. Brown
Vulcan Materials Company

Dr. Nicholas J. Carino
NIST

Dr. James R. Clifton
NIST

Prof. Michael Collins
University of Toronto, Canada

Dr. Stephen W. Forster
Federal Highway Administration

Dr. Geoff Frohnsdorff
NIST

Dr. Ellis Gartner
W.R. Grace & Company

Prof. Weston T. Hester
University of California

Mr. John H. Hoge
Professional Engineer

Prof. Kenneth Hover
Cornell University

Dr. Inam Jawed
Strategic Highway Research
Program

Mr. Art King
Materials Service Corp.

Mr. W. D. Kirkpatrick
Lone Star Industries Inc.

Prof. Masahiko Kunishima
University of Tokyo, Japan

Mr. Joseph F. Lamond
Consulting Engineer

Dr. Gerard Litvan
National Research Council,
Canada

Dr. Tony Liu
Corps of Engineers

Prof. James G. MacGregor
University of Alberta, Canada

Mr. Gary R. Mass
Concrete Technology Corp.

Mr. Richard C. Meininger
National Aggregates Association -
National Ready Mixed Concrete
Association

Dr. Paulo Monteiro
University of California

Mr. Jaime Moreno
Materials Service Corp.

Mr. Charles Nmai
Master Builders

Dr. Celik Ozyildirim
Virginia Highway Research
Council

Mr. Toy Poole
Waterways Experiment Station

Mr. Lawrence R. Roberts
W.R. Grace & Company

Prof. Della Roy
Pennsylvania State University

Dr. Karl H. Runge
Exxon Production Research

Dr. Henry Russell
Construction Technology
Laboratories

Mr. Michael T. Russell
STS Consultants LTD

Ms. Hannah C. Schell
Ontario Ministry of
Transportation, Canada

Prof. Erik Sellevold
Norwegian Institute of
Technology, Norway

Mr. Bryce Simons
Simons Engineering Services

Prof. Erik Thorenfeldt
Norwegian Institute of
Technology, Norway

INFORMATION SOURCES ON HIGH-PERFORMANCE CONCRETE

<u>Research Programs</u>

NSF Center for Advanced
Cement-Based Materials
Northwestern University
Technological Institute
Evanston, IL 60201

Strategic Highway Research Program
818 Connecticut Ave., NW
Washington, DC 20006

Chicago Area Joint-Industry Projects
c/o Construction Technology Laboratories
5420 Old Orchard Road
Skokie, IL 60077

Norwegian High-Strength Concrete Project
Foundation for Scientific and Industrial Research
Norwegian Institute of Technology
N-7034 Trondheim, NORWAY

Network of Centres of Excellence
on High-Performance Concrete
University of Sherbrooke
Sherbrooke, Quebec
CANADA J1K 2R1

Japan's New Concrete Program
Building Research Institute
Azuma 1-407-302
Tsukuba, Ibaraki 305
Japan

French National Project on
High-Performance Concrete (PN VNB)
ENS 94235
Cachan, Cedex
France

Selected Bibliography

"State-of-the-Art Report on High-Strength Concrete," ACI 363R-84, Report on Committee 363, 1990 ACI Manual of Concrete Practice, Part 1, American Concrete Institute, Detroit, MI.

Leming, M., et al., "High Performance Concrete -- An Annotated Bibliography 1974 - 1989," SHRP-C/WP-90-001, Strategic Highway Research Program, National Research Council, Washington, DC.

"High Strength Concrete -- State-of-the-Art," Report by FIP-CEB Working Group on High-Strength Concrete, 1990.

"Research Needs for High-Strength Concrete," ACI 363.1R-87, Report by ACI Committee 363, ACI Materials Journal, Vol. 84, No. 6, Nov./Dec. 1987, pp. 559-561.

NIST-114A
(REV. 3-90)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION OR REPORT NUMBER
NISTIR 4465

2. PERFORMING ORGANIZATION REPORT NUMBER

3. PUBLICATION DATE
DECEMBER 1990

4. TITLE AND SUBTITLE

Outline of a National Plan on High-Performance Concrete: Report on the NIST/ACI Workshop, May 16-18, 1990

5. AUTHOR(S)

Nicholas J. Carino and James R. Clifton

6. PERFORMING ORGANIZATION (IF JOINT OR OTHER THAN NIST, SEE INSTRUCTIONS)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
GAITHERSBURG, MD 20899

7. CONTRACT/GRANT NUMBER

8. TYPE OF REPORT AND PERIOD COVERED

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (STREET, CITY, STATE, ZIP)

U.S. Department of Commerce
National Institute of Standards and Technology
Gaithersburg, MD 20899

10. SUPPLEMENTARY NOTES

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

A workshop on high-performance concrete (HPC) was held in Gaithersburg, MD on May 16, 17, and 18, 1990. The workshop was co-sponsored by the American Concrete Institut. High-performance concrete was defined as concrete having desired properties and uniformity which cannot be obtained routinely using only conventional constituents and normal mixing, placing, and curing practices. The workshop objectives were to:

- Identify current and planned research programs on HPC;
- Identify potential applications where HPC could be used on a routine basis;
- Identify the technical barriers to widespread use of HPC;
- Identify institutional barriers and deficiencies in standards which hinder the use of HPC;
- Develop a listing of critical research to overcome the technical barriers and provide a sound basis for the needed standards.

To achieve these objectives, noted international experts in concrete technology were invited to participate in the workshop. Eight working groups were organized to address different topics. This report summarizes the discussions and conclusions of the working groups. Each chapter begins with a brief introduction providing background on the nature of the problems addressed by the working group. Specific research topics are identified, and discussions are provided to explain the rationale for the needed research. The recommended research is proposed as the basis for a national program to exploit the potential of high-performance concrete and ensure U.S. competitiveness in concrete technology. Recommendations for implementing the plan are provided.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

Concrete; durability; high-performance concrete; high-strength concrete; institutional barriers; mechanical properties; mixture proportioning; research; specifications; standard test methods; structural design; workshop.

13. AVAILABILITY

X	UNLIMITED
	FOR OFFICIAL DISTRIBUTION. DO NOT RELEASE TO NATIONAL TECHNICAL INFORMATION SERVICE (NTIS).
	ORDER FROM SUPERINTENDENT OF DOCUMENTS, U.S. GOVERNMENT PRINTING OFFICE, WASHINGTON, DC 20402.
X	ORDER FROM NATIONAL TECHNICAL INFORMATION SERVICE (NTIS), SPRINGFIELD, VA 22161.

14. NUMBER OF PRINTED PAGES
62

15. PRICE
A04

ELECTRONIC FORM