

International Workshop on High Performance Concrete

Bangkok, Thailand: November 1994



EDITOR

PAUL ZIA



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International Workshop on High-Performance Concrete

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**November 21-22, 1994
Bangkok, Thailand**

***Editor*
Paul Zia**

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PREFACE

Many recent innovations in advanced concrete materials technology have made it possible to produce concrete with exceptional performance characteristics. High-performance concrete (HPC) is defined as concrete which meets special performance and uniformity requirements that cannot always be achieved by using only the conventional materials and normal mixing, placing, and curing practices. The performance requirements may involve enhancements of: placement and compaction without segregation, long-term mechanical properties, early-age strength, toughness, volume stability, or service life in severe environments.

Recognizing the importance of HPC to the renewal of infrastructure, programs in this strategic research area have been developed in several countries including Canada, France, Japan, Norway, Sweden, and the U.S. This workshop was organized to provide an opportunity for leading researchers and engineers engaged in this important and rapidly advancing technical field to assess the state-of-the-art of the technology in Europe, the Pacific Rim, and North America. Based on the assessment of the current status of the technology, the workshop participants would then identify the research needs to further advance the technology and accelerate its acceptance into practice.

The workshop included a keynote address, presentations of 26 papers in three consecutive sessions, and a session for general discussions and summation. To promote and facilitate free exchange of ideas, the size of the workshop was purposely kept small. A total of 44 delegates from 20 different countries of Europe, North and South America, the Middle East, and the Pacific Rim participated in the workshop. In addition, 125 Thai engineers attended the workshop as observers.

This volume of proceedings, presented in three parts, serves as a record of the workshop. A summary of the workshop and three session reports are presented in Part I. Part II contains 28 papers formally prepared for the workshop and they have been reviewed in accordance with the publication policy of the American Concrete Institute. All the papers were presented at the workshop except the one from Sweden. Included in Part III for reference are the workshop program and a list of the participants.

It would have been impossible to organize this workshop without the substantial financial support of the U.S. National Science Foundation (Dr. Ken Chong, Program Director), the Thai National Science and Technology Development Agency, Thailand Research Fund, the Thailand Chapter of the American Concrete Institute, and the Engineering Institute of Thailand. Special appreciation is extended to the Local Organizing Committee, under the leadership of Professor Arun Chaiseri and Professor Ekasit Limsuwan, for producing the preliminary publication and for arranging the excellent meeting facilities and accommodations in Bangkok. Professor Methi

Wecharatana of the New Jersey Institute of Technology played a critical role as the liaison between the Local Organizing Committee and the Workshop Director. His tireless efforts assured the success of the workshop.

The overall organization of the workshop was guided by the Steering Committee and the workshop program was developed by the Scientific Committee. Their collective efforts deserve special recognition.

The cooperation and support of the American Concrete Institute and its affiliate, the Concrete Research and Education Foundation, the New Jersey Institute of Technology, and the North Carolina State University are also gratefully acknowledged.

Paul Zia, *NCSU*
Workshop Director

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SUMMARY OF THE WORKSHOP

by Shuaib H. Ahmad, Henry G. Russell,
and Paul Zia

INTRODUCTION

High Performance Concrete (HPC) represent a rather new development. Worldwide there is an increasing interest in the development and proper use of HPC in a variety of applications. An International Workshop on High Performance Concrete (HPC) was conducted on November 21-22, 1994, in Bangkok following the ACI International Conference on High Performance Concrete which took place on November 15-18, 1994, in Singapore. The Workshop was co-sponsored by the U.S. National Science Foundation, the National Science and Technology Development Agency of Thailand, Thailand Research Fund, Thailand Chapter of the American Concrete Institute and Engineering Institute of Thailand. The objective of the Workshop was to convene a panel of international experts in the field of HPC to summarize the recent advances and developments in their respective countries and to define the research needed to further advance the technology and accelerate its acceptance into practice.

The two-day workshop included a keynote address and 26 formal presentations followed by a session for general discussion. Representatives from Australia, Canada, England, Denmark, France, Germany, Israel, Japan, Korea, New Zealand, Norway, Singapore, Sweden, Taiwan, Thailand, and the United States participated in the workshop. The workshop was divided into three main sessions:

Session I – HPC in the Pacific Rim
Session II – HPC in Europe
Session III – HPC in North America

In his keynote address, Dean E. Stephan identified three major barriers to technology transfer within the construction industry. They include the fragmented nature of the industry with low levels of capitalization relative to the economic volume of its business activity, the lack of construction industry participation in

research and development, and the societal impediments largely in the form of a dysfunctional legal system. He offered several suggestions that may help overcome the barriers: (1) establishment of a recognized national evaluation system for innovations in concrete construction, (2) widespread dissemination of research results not only by publishing peer reviewed technical papers but also by actively involving the construction industry in the process of developing information, and (3) development of extensive training materials for the designer, constructor, supplier and craftsman.

The first session was chaired by Methi Wecharatana and Hans W. Reinhardt served as the reporter. In this session, eight papers from Australia, Japan, Korea, New Zealand, Singapore, Taiwan, and Thailand. The papers dealt with numerous aspects of the production, characterization and applications of HPC. They clearly demonstrated the high level of interest and activity in development and use of HPC in the Pacific Rim countries. The development of flowable (self-compacting) concrete in Japan seemed to advance rapidly.

The second session was chaired by B. V. Rangan and the reporter was Antoine E. Naaman. Six papers describing applications, experiences and research in Denmark, England, France, Germany, and Norway were presented in this session. Much emphasis was placed on the issue of durability as well as high strength.

The third session was chaired by H. S. Lew with R. N. Swamy serving as the reporter. Twelve papers were presented in this session. Of these twelve, nine papers dealt with the engineering properties or applications of HPC. The remaining three provided supporting and complementary information relative to the U.S. effort in development of high performance materials research and the activities of two of the research programs organized to focus and coordinate research on HPC. Taken together, the twelve papers provided a wealth of information on design and characterization of HPC in the laboratory as well as production and application of HPC in the field.

A more detailed account of each of the three sessions is contained in the respective session following this summary. The technical highlights of the workshop are presented below in seven topical areas: Materials, Resources and Production of HPC, Properties of Fresh Concrete, Early-Age Properties, Mature-Age Properties, Structural Design and Code Limitations, Applications, and Economy. The issues and research needs pertaining to HPC are presented in the final section of this summary.

MATERIALS, RESOURCES AND PRODUCTION OF HPC

While there are no limitations of natural resources in most countries, a few reported shortages of good materials for HPC such as the lack of sand and gravel

in Taiwan, and silica fume in Korea. In some regions, the essential constituent materials have to be imported, which makes the cost of concrete relatively more expensive. In Hong Kong, the cost of concrete increases when silica fume is added. The consequence is that either a lower strength concrete is used (up to 60 MPa) or a much higher strength is used because the cost differential between concrete of 70 and 100 MPa strength is small once silica fume is added. Industrial by-products like slag and fly ash could replace other materials used in HPC production, if reliable quality assurances are available.

Environmental concern in Australia was the primary reason for producing lightweight aggregates from residential waste. If one considers the gross energy requirements, concrete is environmentally a rather friendly material.

PROPERTIES OF FRESH CONCRETE

Mixing, workability, compactability, flowability and self-compaction were the topics addressed with respect to properties of fresh concrete. An example from New Zealand showed the importance of good dispersability of silica fume in densified small particles (DSP) systems. Undispersed agglomerates of silica fume can cause long-term failure due to alkali-aggregate reaction when DSP is exposed to wetting and drying. The homogeneity after mixing is important for all properties. In many applications of HPC, especially below 70 MPa, silica fume is not needed for strength but is used to enhance workability. The experience with HPC in Thailand indicated that workability was the first concern, followed by higher strengths. Today both aspects are combined in the production of HPC in Thailand. Workability of concrete at delivery is crucial and should be guaranteed without compromising its other properties. This is a critical question regarding quality assurance of concrete construction especially for HPC. The answer from Japan where skilled construction workers are in shortage is a shift toward construction automation. In such a system, the use of self-compactable concrete is a critical component. It was reported that the materials cost of self-compactable concrete placed in one of the anchorages (250,000 m³) of Akashi Kaikyo Bridge was 10% higher than that of normal concrete.

EARLY-AGE PROPERTIES

Heat of hydration, strength development and cracking potential are early-age properties of concrete. Curing and early age cracking are important issues for concrete at this stage. Heat of hydration has to be controlled in order to prevent early age thermal cracking and to assure higher strength of concrete in its mature state. Early age cracking due to plastic shrinkage may be a problem in flat surfaces and has to be avoided by immediate curing. However, curing is perhaps the process that is least understood, widely neglected or improperly handled at the job site. It was suggested that producing a binder system for concrete that would need only 24 hours curing would be a significant contribution.

MATURE-AGE PROPERTIES

Mechanical Properties — The fundamental property is compressive strength which is often used as an indirect measure for other mechanical properties and durability through empirical relationships. Nearly all countries represented at the workshop can produce concretes with a compressive strength of 60 MPa quite readily and most have gained field experience with concretes of up to about 100 MPa. Ductility is seen as an essential requirement for safe structures.

Creep and shrinkage are properties which determine long-term serviceability. In general, these long-term properties of HPC are improved when compared with the conventional concrete. It was reported that the long-term properties of the self-compacting concrete developed in Japan were similar to those of normal concretes.

Durability — Physical properties like permeability of liquids and diffusivity of gases and ions are certainly less for HPC than for normal performance concrete (NPC). Durability was discussed in length following the report of failure of some DSP cementitious products in New Zealand. The failure was attributed to a high silica fume content together with high superplasticizer content by necessity. Mix proportions, inadequate mixing (undispersed particles) and exposure to humid environmental worked together in an unfavorable way. Durability remains a major consideration in many HPC applications worldwide.

STRUCTURAL DESIGN AND CODE LIMITATIONS

Limits on concrete strength are imposed by different national codes. In France, concretes with compressive strengths of up to 60 MPa are acceptable in all reinforced and prestressed concrete structures. From 60 to 80 MPa, permission is granted on a case-by-case basis. Beyond 80 MPa, a special investigation of the particular application is required. In Germany, current use is up to 55 MPa, with anything above that limit requiring a special study. In Norway, the current acceptable limit is 100 MPa. It was also revealed that in Europe, standards will soon be established with a compressive strength limit of 105 MPa. In the USA, no concrete strength limit has been established by the building code except that in the design for shear and development length the concrete strength may not exceed 70 MPa. The U. S. code standards are often followed by other non-European countries.

Currently, the use of high performance concrete, with strength between 35 and 60 MPa, is about 5% to 10% of the total amount of concrete used in France, and that seems to be the case in the rest of Europe as well. The usage of HPC in other countries is about on the same scale.

APPLICATIONS

Pacific Rim — Most projects in this region utilized HPC of normal weight and lightweight HPC is still in an experimental stage. Tests in Australia are being carried out to establish the design criteria for structural members subjected to simultaneous normal force with bending and shear. The design of ductile structures utilizing brittle materials is a challenge for further research. It can be achieved by appropriate reinforcement, geometry, and structural redundancy. Toughness of the material is a different issue. It is believed that cementitious materials cannot be made ductile since the bond between matrix and aggregate behaves in a brittle manner and the aggregates are also brittle when they fracture in the case of high strength concrete. However, when continuous or chopped fibers are added in a sufficient quantity, the material becomes quasi-ductile due to well distributed cracking with reduced spacing. Ferrocement is being used successfully in Singapore for sunscreens and secondary roofs. In these HPC applications ductility is accompanied with water tightness but not necessarily high strength.

Europe — Basically, high performance concrete is used in all major structural applications including bridges, buildings, tunnels, and power plants. Some impressive examples are the Normandy bridge in France, the Great Belt Link bridge in Denmark, and the Channel Tunnel between France and England. All new nuclear power plants in France will use high performance concrete. An application of particular interest in Germany is the use of HPC in containers for toxic materials or in impervious barriers to organic hazardous waste.

North America — In North America, the traditional application of HPC has been in columns of high-rise buildings, but more recently the focus has shifted to the use of higher strength concretes for bridge girders. The recent national programs in both Canada and the United States have served to identify the needs and applications of HPC to improve all aspects of the infrastructure. As a result, the definition of HPC now includes a broader range of properties than just higher strength. Increased emphasis is being placed on applications where durability is important. Accordingly, the range of applications of HPC has increased to include highway pavements, especially for repairs with early opening requirements. The current emphasis on high performance materials and life-cycle costing will continue to expand the range of applications in the future.

ECONOMY

The current perception by the user-owner is that high performance concrete is a concrete with high strength and high cost. However, it was strongly suggested that life-cycle cost analysis would indicate a lower overall long-term cost. Thus high performance concrete should be quantified as high quality lower

cost concrete, i.e., with a lower life-cycle and maintenance cost than conventional concrete.

ISSUES AND RESEARCH NEEDS

In addition to the limited discussions which followed the formal presentations in each of the three sessions, the workshop concluded with the final session for general discussions. From these discussions, several issues were raised and a list of research needs identified.

Issues — The issues raised are more general and philosophical in nature. They include the following:

- (1) Which problems can be solved cooperatively worldwide without regard to regional conditions, i.e., which problems apply equally to America, Asia, Europe, etc? An example is the design of ductile structures using brittle materials.
- (2) Which problems are local or regional, i.e., problems dictated by local aggregates, cements, and climatic conditions? It is rather clear that frost attack is not a major factor to many countries in the Pacific Rim.
- (3) Which aspect of concrete technology needs the primary attention? Is it the mix design, properties at the fresh, the young or the mature state? Along with this question the philosophy of achieving quality plays an important role, i.e. by sophisticated quality management system or by a robust mix?
- (4) Where is the economic potential of HPC? In Hong Kong every square meter of office space is at a premium due to the astronomical rental rates. What is the experience elsewhere?
- (5) More attention should be paid to mix proportioning and concrete behavior in its pre-hardening stage, i.e., how can one test early shrinkage? what should be the maximum amount of silica fume used? how can the effect of curing be quantified?
- (6) A great deal of attention is paid to durability and system approach of concrete design and yet a fundamental question remains unresolved, i.e., how can one measure and quantify durability for all exposure conditions? What is lacking is an appropriate methodology to evaluate service life of a concrete construction.
- (7) Concrete strength of 70 – 80 MPa appears to be the current practical limit. What are the technological needs to extend this limit?
- (8) In some laboratories and countries, serious efforts are being made to extend to extra-high strength concrete and yet the current knowledge and technology of high strength concrete are still not being used effectively.

Research Needs — Since the world population may double over the next fifty years, the demand for improved building materials such as HPC is likely to be substantial. This justifies large investments in research on HPC. The following is a random list of research needs. Their order does not reflect any

ranking of urgency or priority.

(1) Research on why some long term strength loss is observed in some cases where silica fume is used? It has been observed that this may occur only for large percentages of silica fume, i.e., more than 10% by weight of cement.

(2) Develop and document test methods for flowability of concrete.

(3) Develop a workability-based design for HPC.

(4) Develop and document test methods for early cracking of HPC.

(5) Study and quantitatively characterize cracking behavior of HPC during hardening (plastic shrinkage cracking).

(6) The Mohr-Coulomb failure criterion does not seem to be valid for HPC and different failure criteria must be developed. There seems to be a change in the failure mode of HPC when its compressive strength increases.

(7) Conduct research and document the interaction of HPC with various fluids and other chemicals, especially for applications in containers for toxic waste and other hazardous fluids.

(8) Conduct research on improved methods to quantify durability.

(9) Develop appropriate methodology for prediction of service life

(10) Conduct research on the use of fiber reinforcement as secondary reinforcement in HPC in order to improve ductility, bond with reinforcing bars and prestressing tendons, and other properties.

(11) Develop proper modelling for high-volume/high-stiffness fibers.

(12) Conduct research on structural use of post-cracking strength of fiber reinforced high performance concrete.

(13) Develop appropriate tensile test for fiber reinforced high performance concrete.

(14) Conduct research on methods to develop ductility at the structural level with high-strength concretes.

(15) Develop methods to improve the tensile strain capacity of concrete.

(16) Conduct research on fire resistance of normal weight and lightweight high performance concretes.

(17) Monitor and evaluate performance records of existing high performance concrete applications.

(18) Develop optimum member shapes for structural applications.

(19) Develop design concepts of hybrid structures making use of HPC.

(20) Develop high capacity prestressing tendons and anchorages for use with high performance concrete.

(21) Develop practical performance evaluation technique and conduct research to develop performance data for HPC subjected to marine and high sulphate environment.

REPORT ON SESSION I— HPC IN THE PACIFIC RIM

by Hans W. Reinhardt

INTRODUCTION

Eight papers from Australia, Japan, Korea, New Zealand, Singapore, Taiwan, and Thailand were presented in this session. In addition, there was an informal presentation from Hong Kong. The papers dealt with numerous aspects of HPC and showed their applications, demonstrating the high standard that has already been achieved.

In order to make a complex material such as HPC more comprehensible, reference will be made to Fig. 1. The four blocks on the left side are the main fields which have to be considered and evaluated with respect to *High Performance*. Since this session of the workshop dealt in large measure with materials, the topic is therefore further split into three blocks on the top line. Following the chart in Fig. 1, *Quality Management* is mainly attached to the fresh and young states of concrete while *Structural Design* considers the mature state of concrete. The *economical* aspects were treated to a lesser extent than the technical ones.

RESOURCES OF HPC CONSTITUENTS

There are no limitations of natural resources in Australia while other regions reported shortages, such as lack of sand and gravel in Taiwan and silica fume in Korea. Some countries import constituents which makes the cost of concrete more expensive. A good example was shown from Hong Kong where the cost of concrete increased when silica fume was added. The consequence is that either a lower strength is used (up to 60 MPa) or a much higher strength is used because the cost differential between 70 MPa and 100 MPa is small once silica fume is added.

Industrial by-products like slag and fly ash could replace a portion of other cementitious materials if a reliable quality assurance were available.

Environmental concern in Australia was the primary reason for producing lightweight aggregates from residential solid waste. With respect to gross energy requirement, concrete is environmentally a rather friendly material.

FRESH STATE OF CONCRETE

In this state, mixing, workability, compactability, flowability and self-compaction were the items addressed. An example from New Zealand showed clearly what can happen when nondispersed silica fume can react with alkali to form cracks and complete deterioration. The homogeneity after mixing is important for all properties. Workability was a first challenge for HPC in Thailand, followed by high strength. Now, both aspects are combined to make up modern HPC. Workability of concrete at delivery is relevant and this should be guaranteed without changing the intended properties. It was revealed that in Taiwan the habit of adding water to fresh concrete by untrained workers still persists.

There is a fundamental question with respect to the realization of the intended quality of concrete. Should it be achieved via a *sophisticated quality management system* or via a *robust mix*? To answer this question several factors have to be kept in mind such as the skill of the site workers, the place of the easiest and most reliable control and the climatic conditions. The answer from Japan was very clear: the use of a self-compactable concrete is the most reliable. This type of concrete appears to be an important high performance aspect which applies to all grades of concrete.

YOUNG STATE OF CONCRETE

This state starts after compacting and finishing the concrete and ends about four days later. Heat of hydration, curing, and early age cracking are important aspects of this stage. Heat of hydration has to be controlled in order to prevent early age thermal cracking and to assure high strength in the mature state. To produce a curing insensitive concrete which needs only 24 hours curing would be a great achievement (Australia). Early age cracking due to plastic shrinkage may be a problem at horizontal surfaces and has to be avoided by immediate curing.

MATURE STATE OF CONCRETE

Most topics addressed in this session deal with concrete in its mature state. The first is strength which is still a principal property of HPC and, as such, it serves often as an indirect measure for physical properties and durability based on empirical relations. The countries of the Pacific Rim represented at the workshop produce concrete with a strength of 60 MPa quite readily and they have gained

site experience for concrete with strength up to about 100 MPa.

Most projects which have been shown are realized with normal density concrete, lightweight HPC is in a more experimental stage. Ductility is seen as a requirement for safe structures. Tests in Australia are carried out in order to establish the behavior of structural members subjected to simultaneous normal force and shear. The design of a ductile structure made of brittle materials is a challenge for further research. Ductility can be achieved by appropriate reinforcement, geometry, and structural redundancy. Toughness of the material is a difference issue. It is believed that cementitious materials cannot be made ductile since the bond between matrix and aggregate behaves in a brittle manner and the aggregates also have brittle behavior when they fracture in the case of high strength concrete. However, when continuous or chopped fibers are added in a sufficient quantity the material becomes quasi ductile due to cracking with small crack spacing. Ferrocement used in Singapore for sunscreens and secondary roofs were good examples. Ductility is accompanied with water tightness.

Creep and shrinkage are properties which determine long-term serviceability. It was stated that self-compacting concrete has the same creep and shrinkage values as the normal concrete.

Physical properties like permeability of liquids and diffusivity of gases and ions are certainly less for HPC than for normal performance concrete. Durability has been discussed in length after the failure of some DSP cementitious products in New Zealand. The failure has been attributed to a too high silica fume content together with necessarily high superplasticizer content. Mix proportion, mixing (dispersion of particles) and exposure to humid environmental condition work together in an unfavorable way.

GENERAL QUESTIONS

After having discussed the achievements of the Pacific Rim countries there are some questions left.

(1) Which problems can be solved cooperatively worldwide, i.e., which aspects apply equally well to America, Asia, Europe, etc? One could think of the design of ductile structures using brittle materials.

(2) Which problems are local or regional, i.e., dictated by local aggregates, cements, and climatic conditions? It became rather clear that freezing and thawing attack does not apply to the countries in the Pacific Rim.

(3) What is the technical area which needs primary attention? Is it the mix design, the fresh, the young or the mature state? Along with these questions, the philosophy of achieving quality plays an important role, i.e., sophisticated

quality management or a rosust mix?

(4) Where is the economic potential of HPC? In Hong Kong every square meter of office space is premium due to the astronomical rates. What is the experience elsewhere?

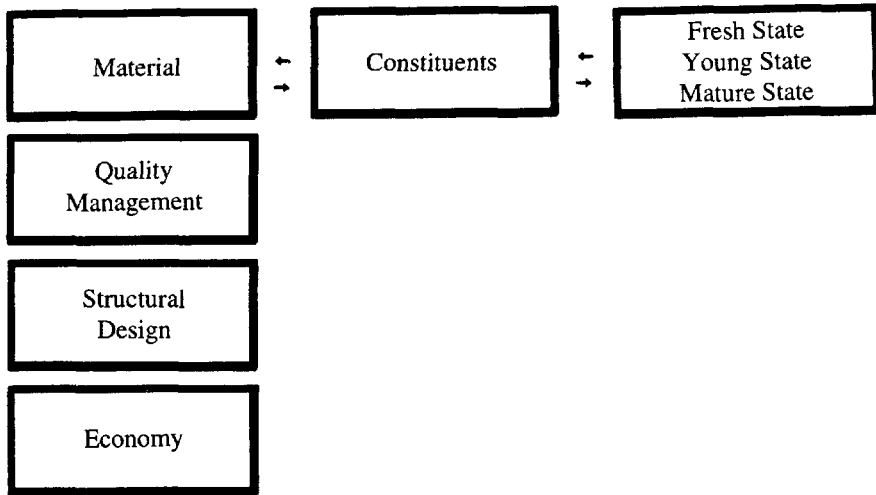


Fig. 1—Fields in which "high performance" has to be considered and defined

REPORT ON SESSION II— HPC IN EUROPE

by Antoine E. Naaman

INTRODUCTION

Six papers were presented in this session describing experiences in Denmark (Christoffersen, Nielsen), England (Swamy), France (Cheyrezy), Germany (Reinhardt), and Norway (Sellevold). A summary of the main issues addressed and related discussion is given below.

CURRENT LIMITATIONS AND CODES

In France, using compressive strengths of up to 60 MPa is acceptable in all structures. From 60 to 80 MPa, permission is granted on a case-by-case basis. Beyond 80 MPa a special investigation of the particular application is required. In Germany, current use of up to 55 MPa is normal and it is expected that the acceptable limit will soon be increased to 95 MPa, with anything above that limit requiring a special study. In Norway, the current acceptable limit is 100 MPa. It was also revealed that common European standards will soon be established with a compressive strength limit of 105 MPa. In many applications of HPC, especially below 70 MPa, silica fume is not needed but is used as an aid to workability.

The usage of high performance concrete, with strength between 35 and 60 MPa, is about 5 to 10% of total concrete currently used in France, and that seems to be the case in the rest of Europe as well.

APPLICATIONS

High performance concrete is used in all major structural applications - bridges, buildings, tunnels, and power plants. Some impressive examples are the Normandy bridge in France, the Great Belt Link bridge in Denmark, and the Channel Tunnel between France and England. All new nuclear power plants in

France will use high performance concrete. An application of particular interest in Germany is the use of HPC for containers of toxic materials or as impervious barriers to organic hazardous waste.

DEFINITION

The issue of definition was addressed by most speakers and was part of the discussion that ensued. While compressive strength seemed to be the parameter most commonly cited to distinguish HPC from normal concrete, there was strong agreement that durability, life-cycle serviceability and cost were the most important characteristics, advantages or derivatives. Durability was described by low porosity, low permeability, improved resistance to chemical attack, low water-to-cementitious materials ratio, and good resistance to freezing and thawing. Several speakers ventured to suggest a service life of more than one hundred years as a possible specification for HPC under normal use conditions. There was also a discussion of the role of the steel reinforcement in durability, to the effect that, while a durable concrete can be produced, corrosion of the steel will remain the main culprit. The use of fiber reinforced plastics (FRP) reinforcements may provide a solution when steel corrosion cannot be controlled or prevented.

DESIGN

The design for high performance concrete should integrate criteria for the fresh state, hardening state and hardened state. Design criteria include: 1) for the fresh state: strength, durability, and workability; 2) for the hardening state: plastic shrinkage and crack nervousness, and 3) for the hardened state: strength, durability and robustness. A global design strategy following an optimum design algorithm for strength, serviceability, performance and reliability, could also be followed. The lack of ductility of HPC can be overcome by addition of fibers. Thus documenting the properties of high performance fiber reinforced concrete and related design criteria should eventually be integrated in the design process.

PROMOTION, MARKETING, ACCEPTANCE

The current perception by the user-owner is that high performance concrete is a concrete with high strength and high cost. However, it was strongly suggested that life-cycle analysis would indicate a lower overall long term cost. Thus for future promotion-marketing purposes high performance concrete should be qualified as high quality low cost concrete, i.e. with a lower life-cycle and maintenance cost than normal concrete.

SILICA FUME, FLY ASH, AND OTHER FILLERS

Some discussion focused on some observed results that the addition of

silica fume may lead to a reduction in strength after several years. This seemed to be associated with the addition of high percentages of silica fume. It was observed that silica fume in proportion of 5 to 8% by weight of cement and fly ash in proportion of 10 to 15% by weight of cement provide excellent long term stability. Research to find and evaluate different types of fillers is also underway in France where Ciment Lafarge is currently marketing a premix of cement and fly ash. From an analysis view point, it was recommended that a packing analysis be routinely undertaken for any HPC mix design.

Concern was raised about the color of the concrete when silica fume is used. It was revealed that a white silica fume exists (as a by-product of the zirconia industry) and that it is being used in the "Bibliotheque de France" HPC project in France.

RESEARCH NEEDS

Since the world population may double over the next fifty years, the demand for improved building materials such as HPC is likely to be phenomenal; this justifies large investments in research in HPC. Various topics for future research are pointed out in the papers presented. Topics that seemed to be of particular interest to the audience are as follows:

- (1) Research on why some long term strength loss is observed in some cases where silica fume is used? It has been observed that this may occur only for large percentages of silica fume, i.e., more than 10% by weight of cement.
- (2) Research to develop a workability based design for HPC.
- (3) The Mohr-Coulomb failure criterion does not seem to be valid for HPC and failure criteria must be developed. There seems to be a change in the failure mode of concrete when its compressive strength increases.
- (4) The interaction of HPC with various fluids and other chemicals needs to be further documented. This is especially useful for applications in containers for toxic waste and other hazardous fluids.
- (5) Cracking behavior during hardening (plastic shrinkage cracking) should be studied and quantitatively characterized, such as by the cracking index suggested by Sellevold from Norway.
- (6) There is a true need to further document and quantify the durability of HPC, especially since durability is suggested as an essential part of the definition.

(7) High strength concrete tends to be increasingly brittle. Research into the use of fiber as secondary reinforcement in HPC in order to improve ductility, bond with reinforcing bars and prestressing tendons, and other properties is strongly recommended.

REPORT ON SESSION III— HPC IN NORTH AMERICA

by R. Narayan Swamy

INTRODUCTION

Twelve papers were altogether presented in this session. Of these twelve, nine papers dealt directly with the engineering properties or applications of HPC. The three other papers provided supporting and complimentary information related to the organization of the HPC research program and the activities of two of the organizations set up to focus and coordinate research on HPC.

COORDINATED PROGRAMS

The U. S. Government's role in developing and organizing research on High Performance Materials for Infrastructure was the subject matter of the paper by Pasko and Frohnsdorff. The overall goals of the total program costing \$2 – \$4 billion over 10 years were to revitalize infrastructure, improve competitiveness, enhance environment and develop innovative technologies. First cost is still considered to be the determining factor in construction, and thermal cracking and durability were identified as two of the major challenges in this effort to optimize the design of infrastructure systems using high performance materials.

In this vast program for researching and implementing the use of high performance concrete, a coordinated research program relating microstructure with engineering properties and structural performance is critical if we are to provide the technical basis and tools for optimization needed to facilitate the design of structures utilizing high performance concretes and other new cementitious systems. The NIST Cementitious Materials Modelling Laboratory (CMML) and the NSF Science and Technology Center for Advanced Cement-Based Materials (ACBM) have played significant roles in this respect, and the activities of these two centers were described in detail in two papers. The work of CMML concentrated on digital-image-based computer models to quantify and clarify microstructure-property relationships and examples of models such as those simulating hydration and capillary porosity vs w/c ratio illustrate the ability

to model at scales ranging from nanometers to centimeters to characterize and optimize concrete performance. The paper by Shah presented an illuminating overview of the cross-disciplinary work of ACBM and showed examples of their work in developing computer models and new experimental tools such as nuclear magnetic resonance, impedance spectroscopy and microwave technology to give a better insight into the microstructure of HPC materials. The work on high performance FRC materials showed how toughness can be enhanced at different scales and the use of extrusion technology to fabricate new composites.

MICROSTRUCTURE AND DURABILITY

The key to high performance and long-term durability lies in the microstructure of the cementitious material and the paper by Della Roy showed how superior products can be engineered by increased packing efficiency. A high packing density with a clear understanding of the thermo-mechanical and chemical processes involved in degradation processes and transport mechanisms can lead to a fine microstructure which can lead to low permeability and a high resistance to the penetration of aggressive elements of the environment. If such a fine microstructure can be obtained by using cementitious/pozzolanic industrial by-products such as fly ash, then the advantages of utilizing cost-effective energy resources can be fully realized. The differences in the properties of dry and wet bottom ashes are not always clearly understood and the paper by Wecharatana and Liskowitz makes a distinct contribution to our knowledge in this area and shows that not only high strength but an enhanced durability, particularly in corrosive environments, can be achieved by the incorporation of these materials in concrete.

PRODUCTION OF HPC

The need for efficient quality control and careful selection of materials cannot and should not be ignored in the production of high performance concrete, and this was ably illustrated in the paper by Aitcin and Baalbaki. For example, not all cementitious materials and not all superplasticizers are compatible or perform well in high performance concrete. Although there is currently some controversy concerning the need for air-entrainment for freeze-thaw durability of HPC, air entrainment has other benefits, and clearly enhances the rheological properties of concrete even if there is a strength loss of 4 – 5% for each 1% air content. The heat of hydration also appears to have an influence on the performance of HPC, and the use of crushed ice and liquid nitrogen to control temperature during construction has been adopted in practice.

MECHANICAL PROPERTIES

There needs to be a well-documented data base on the mechanical properties of HPC and three papers describe in detail the experimental programs which have enabled such data to be accumulated. The paper by Navalurkar and

Ansari has concentrated on developing test methodologies to establish the properties in compression and tension of concretes with 28-day strengths of 45 – 80 MPa. They found explosive failures with higher strengths, and fiber optic sensing systems were used as a feedback signal. Ahmad and Zia report a comprehensive program to characterize the properties of HPC for highway applications. These concretes were designed to give 14 to 18 MPa at 4 – 6 hrs, 35 MPa at 24 hrs and 70 MPa at 28 days. The type of aggregate was found critical for the concretes to reach their target strengths and some reduction in strain capacity was found with increasing strengths. The development of mechanical properties of the wide range of mixes incorporated in their study shows that it is entirely feasible to produce HPC with conventional materials and normal techniques provided adequate quality control is exercised in the selection of materials and at the various stages in the concrete production process.

These tests on plain concrete are complimented by an equally comprehensive study on concretes incorporating steel and polypropylene fibers by Naaman and Al-khairi whose paper gives extensive data on mechanical properties of high early strength fiber reinforced concrete (HESFRC). As in the previous study, these concretes were designed to achieve a minimum compressive strength of 35 MPa in 24 hrs. The data presented in the paper show that FRC possesses better engineering properties than normal concrete in terms of flexural strength, toughness and fatigue life in the cracked state. Potential applications envisaged include construction of transportation structures apart from repair and rehabilitation.

STRUCTURAL APPLICATIONS

The paper by Russell and Fiorato provides that much needed bridge linking material properties of HSC to their use in structures and, in particular, the applicability of current code provisions to HSC in predicting engineering properties such as elastic modulus, creep and shrinkage and structural performance criteria such as bond stress, development length, shear strength, column strength, prestress losses, and transfer length. It was good to know that no in-place strength loss, whether due to heat of hydration or other material characteristics degradation, was detected in actual structures built with high strength concrete after 18 years' service life. The paper stresses the influence of test methodologies developed for normal concrete when they are applied to HSC, and concludes that the provisions of current bridge design standards in the US are conservatively applicable for members with concrete strength up to about 70 MPa.

QUALITY ASSURANCE FOR SEVERE MARINE ENVIRONMENT

Whatever be the material and structural advantages of HSC, without proper production processes of this type of concrete in the field, the benefits of

high performance cannot be achieved in practice. Hoff in his excellent paper has identified the various operational quality control steps needed in the production of HPC, particularly in relation to offshore platforms. Operations such as mixing water, the introduction of admixtures, air-entrainment, mixing, transporting and placement methods, and control tests are all critical in obtaining a uniformly consistent concrete which will be able to develop the properties needed to resist the effects of severe marine environment. Offshore structures pose severe and complex challenges to concrete technology in terms of high cement contents, requirements for workability, effects of pumping on air entrainment, and placement to produce concretes which must be maintenance-free for up to 30 years. This paper shows how these challenges can be met very ably and very satisfactorily.

HISTORICAL PERSPECTIVE

While a great deal of research effort is currently being spent in formulating, characterizing, and producing HSC, Mather in his fascinating paper showed how concretes with specific properties and special performance requirements have been made by the U.S. Army Corps of Engineers even prior to 1962. His paper shows several such applications of HPC, such as wash-out resisting concrete for underwater placement, nuclear waste isolation, and abrasion-resistant stilling basins. While the technical capability to solve the needs of specific applications has always been there, the more recent studies have systematically developed data at both microstructural and engineering levels, giving a better understanding of their relationships and the steps needed to achieve them in the field.

CONCLUDING REMARKS

The twelve papers, taken together, provide a wealth of data of HPC in "the making" and HPC "in service". This reporter has to compliment all the authors for the high quality of their papers, and the planning and thinking that has gone into the detailed conduct of the test programs that they have reported. Many authors have also given suggestions for future research, in addition to the conclusions of their own study, and this is to be certainly welcome. In the various discussions that ensued during the presentation of these papers, several aspects of the material, structural and durability characteristics of HPC were raised and debated. It will be impossible to summarize all of them in a short report such as this, but a few of the global issues that surfaced during the discussions and that relate to the concept and role of HPC as a whole are briefly presented. To some extent they are a personal choice, but hopefully they will identify areas that perhaps need further clarification and thinking.

It is clear that engineers now have the capability to formulate, fabricate

and place high performance concrete that can and will withstand the aggressive environments in which they have to live and carry loads safely, strongly and durably. The issue of durability is still very much in debate, and whether we can quantify it as well as characterize and quantify the local environment – the microclimate – which ultimately decides the serviceability of structures, in a way that can be understood and adopted by practicing engineers, is still uncertain. Stochastic methods and reliability techniques can be very helpful in these tasks. However, it is clear that it will be futile to produce HPC for all situations and applications irrespective of the environments in which they have to survive. HPC, for example, designed to resist aggressive external environments, will not improve performance in seismic regions!

Toughness, or more importantly, ductility at material and structural level is critical, but for long-term serviceability, we also need to think in terms of the ductility of the structural system as a whole. In aggressive environments, durability and ductility have to go hand in hand, and high performance design for durability should be integrated with structural detailing and appropriate construction techniques if we are going to ensure structural integrity in the field in the long term. National codes have an important role to play in this respect, because without a clear understanding of their applicability and limitations to these new material systems, technology transfer cannot be effected very quickly. Perhaps we need also to identify the types of structures that can benefit from the HSC – structures such as offshore platforms, nuclear containers, highways and highway structures and long span bridges.

At the material level, much more needs to be done and understood. How can we improve the tensile strain capacity of concrete, which probably is the most critical factor that characterizes, in a fundamental way, the durability of the material? How effective is curing – in other words, how do we enable concrete placed in an aggressive microclimate to develop its strength and impermeability satisfactorily, and maintain these properties with time? Plastic shrinkage cracking has been a source of deterioration in many constructions, and what is the best approach – mesh or fibers – to contain their damaging effects? The heat of hydration can now be predicted with confidence, but how do we protect concrete from the very high tensile strains developed by large thermal gradients that are induced in practice? We know that thermal cracking is not easily healed, and microcracking can adversely affect stiffness much more drastically than strength.

There is clearly more need for us to understand the mechanics and mechanisms of degradation processes and diffusion characteristics. We now know that there is no rigid boundary between thermo-mechanical and chemical processes, but the fundamentals of transport mechanisms, and the interrelationship between porosity and permeability still seems to elude us. If we can correlate these to the fundamentals of packing, theoretically at least, we should be able to develop the High Performance Concrete that can withstand almost any external

attack. Toughness and ductility still exercise our minds. Coarse and microfibers can enhance these at different levels to varying degrees, but how effective are they in concretes subjected to thermal cracking, and how can we extrapolate these data to real structural behavior?

The discussions seemed to focus on two important ways forward – optimize the material characteristics for a given load and climatic condition; optimize the structural section design to maximize the benefits of the material properties. At the end of the day, however, construction technology has to be cost-effective. So cementitious/pozzolanic materials from industrial by-products have to be an integral constituent of all high performance concretes. Engineers can learn a great deal from information obtained from structures in service and exposed to aggressive environments, and one of our top priorities in research should be to monitor the performance of such structures, built with HPC, over a sufficiently long period of time to enable us to draw valid conclusions.

SP 159-1

Technology Transfer: An Industry Point of View

by D. E. Stephan

Synopsis: Technology transfer within the construction industry is difficult due to (i) organization of the industry, (ii) lack of construction industry participation in research, (iii) societal impediments. These barriers are discussed in relation to transferring innovation to practice.

Differing activities that can mitigate the barriers are discussed and recommendations are offered to enhance the transfer of technology from research results to application in the construction industry.

Keywords: Construction; construction management; evaluation; research

1994-95 American Concrete Institute president, **Dean E. Stephan**, is president of Charles Pankow Builders, Altadena, CA. As chairman of the Corporate Advisory Board, Civil Engineering Research Foundation, Mr. Stephan was involved in formulating the United States research program for high performance concrete.

INTRODUCTION

Technology transfer, the incorporation of innovation into practice, within the construction industry is recognized as a difficult problem. Many of the impediments found within the United States (US) are also common in varying degrees in other countries. The problems are caused by several industry characteristics which can be categorized as follows:

- (i) Organization of the industry.
- (ii) Lack of construction industry participation in research.
- (iii) Structural social impediments.

BARRIERS TO TECHNOLOGY TRANSFER

Organization of the Construction Industry

The organization of the US construction industry is fragmented into many small companies who operate, for the most part, in limited geographical areas. Over 80 percent of the firms are very small with less than 10 employees, two-thirds have less than five employees [1]. Services are bifurcated into design and construction. Design is performed by professional business entities. Construction is performed by specialized business entities organized around a trade (specialty contractors) with a non-trade business unit (general contractor) coordinating and scheduling the specialty contractors' activities. This organizational structure creates a very large and diverse audience with widely varying interests and economic motivations. This significantly impedes the efficient transfer of innovations into practice. Communication with and within such a diverse group is difficult. There is substantial capital and intellectual investment in the status quo by all parties. An innovation which is perceived as advantageous by one group is often viewed as threatening by another.

The fragmented structure also results in low levels of capitalization relative to the economic volume of business activity. This means that any capital required by an innovation will have to compete with other uses for a very scarce resource.

The organization of the construction industry results in diversity of both economic interest and expertise, complicated communication, and low capitalization among all of the economic units involved in construction. This fragmentation creates a difficult maze through which an innovation must move if it is to be incorporated into practice.

Industry Research and Development

If industry is involved in the creation of innovation, the efficiency of transfer of the innovation into practice is greatly enhanced. Unfortunately, the US

construction industry has a dismal investment rate in research and development as indicated by Table 1.

The low level of investment by the US construction industry as compared to other industries is due to the lack of a rational basis for investment [2]. This is primarily due to procurement systems for the constructed project based upon price only selection and the inability to achieve a return on R&D investment due to the bifurcated delivery system and the use of prescriptive specifications.

Simply put, investment in R&D does not improve business performance for designers or constructors. Designers do not have a financial incentive to utilize new technologies. In most cases, utilizing or specifying new technologies increase the designer's cost and risk of doing business without financial reward or benefit. The constructor has marginal ability to introduce new technologies because he is divorced from the design. In the US, construction contracts are prescriptive rather than performance based. The constructor can only execute the work in accordance with the documents he has contracted against; that is to say, "as designed". This greatly reduces the opportunity for innovation. In addition, innovation often entails new procedures and unknowns which can increase the constructor's risk; a strong disincentive under a price only selection system.

If the construction industry invested in research and development, technology transfer would occur automatically because a return on investment can only be achieved when the innovation is employed in practice. Unfortunately, the irrationality of industry investment in R&D is a formidable barrier to technology transfer.

Societal Impediments to Technology Transfer

Societal impediments in the US primarily take the form of a dysfunctional legal system. Construction disputes between users, owners, designers, constructors and suppliers are rapidly escalating. The number of construction lawyers has grown from approximately 2,000 in 1985 to over 4,000 in 1989 [3]. The cost of the US tort system in 1986 was \$108 billion; 2.6% of the 1986 GNP [4]. It is estimated that number now exceeds \$200 billion.

The constructed project often directly impacts public safety; thus participation in the construction industry entails special social responsibilities manifested by professional and contractor licensing requirements. Public safety and a litigious environment demand a universal and responsive evaluation system for innovation to assure safety and efficacy. Unfortunately, such an evaluation system does not exist in the US environment of multiple codes and standards. Some progress has been made in the area of manufactured product evaluation; little progress has been made in the area of process, engineering science and material science evaluation.

Need for Overcoming Barriers to Technology Transfer

The existence of these formidable barriers to the application of innovation begs the question of whether it is proper to challenge them. Perhaps their very existence warns us that construction is an inappropriate industry for innovation; an

industry where the "status quo" should be maintained. I would argue that this is not the case.

Construction and construction-related activities constitute approximately 13 percent of current US Gross Domestic Product (GDP), employing over 6 million people in the US [1]. It is the second largest contributor to GDP. Constructed facilities provide the renewal and expansion of the infrastructure that is essential for a modern industrial society to function effectively and provide an acceptable quality of life for its citizens. Construction impacts all aspects of a national economy. The economic efficiency of that economy is largely governed by cost effectiveness and functionality in its infrastructure system. The cost of any manufactured product or delivery of a service is directly impacted by the cost effectiveness of the constructed physical plant, the constructed distribution systems and constructed support systems such as water, power, communication and waste disposal. Thus, we must overcome the barriers of transferring construction innovations to practice if we are to enhance and advance mankind's standard of living. The efficiency and the quality of the constructed facilities must be of paramount concern as they determine the quality, efficiency and effectiveness of a society's economic activity and relative quality of life.

High performance concrete and the transfer of the enabling technologies for achieving high performance concrete to practice is essential to advancing the efficient delivery and maintenance of infrastructure. The research results, knowledge and innovations yielding high performance concretes must overcome the barriers and move from the laboratory to application as rapidly as prudently possible so the benefits can be realized by both the construction industry and society.

TRANSFERRING TECHNOLOGY

Evaluation

Codes and standards are often considered a barrier to the application of innovation. In fact, they can enhance technology transfer by defining proper application of a technology, documenting the performance and characteristics of a technology and disseminating knowledge that a technology is ready for application. Institutions such as the American Concrete Institute (ACI), which develop and promulgate codes and standards, are the technology gatekeepers for concrete. The institutions currently determine technology acceptance. This acceptance is essential for the widespread use of a technology. Timely and efficient evaluation and acceptance is essential if research is to warrant industry investment. Evaluation and acceptance is crucial to technology transfer from the laboratory and technical paper to practice. The gatekeeper role precedes the market force determination of efficacy. The investment in high performance concrete (HPC) research justifiably requires efficient evaluation and acceptance of the results, as appropriate, so a return on the research investment is possible. Lyle H. Schartz, director of The National Institute of Standards and Technology (NIST) materials science and engineering laboratory is quoted as stating "The codes on which Civil Engineers are operating are out-of-date. We need to ensure that new materials are available that will allow roads and bridges to last twice as long to justify the money spent under any new infrastructure program" [5].

The need for evaluation means that codes and standards responsive to high performance concretes and their use must be developed in a timely fashion. The HPC program currently being pursued in the US promises major investment by both government and industry in developing HPC materials and procedures for their use. The research will be both basic and applied. The applied research will include development. The proposed program entails funding for technology transfer and demonstration projects. This means that those providing research funding and the researchers need to consider and provide for technology transfer. Researchers can and should develop their findings to include design and use procedures to facilitate evaluation of the resulting technologies and the training necessary in their use.

Competent evaluation of innovation removes major societal barriers by providing responsible public protection and life safety considerations in the use of new technologies. In addition, comprehensive technical evaluation provides protection for the users and implementors of new technologies by establishing their prudence within the context of the U.S. legal system.

Training

From industry's perspective, training in new technologies is essential to the transfer of innovation to practice. Training can overcome the inefficiencies and risks associated with new technologies.

Publication of research results is an appropriate end product for basic research. If technology transfer is to be facilitated, publication of research results is not an adequate product for applied research. Practicing engineers have expressed frustration at "another unusable technical paper" on a subject and pleaded for "inclusion of design procedures" to make the research meaningful to them. Where appropriate, effort needs to be made to have research projects and their funding include technology transfer by including in the deliverables, at some stage, draft design procedures and/or draft standards for the use of the technology so industry and technology gatekeepers can efficiently handle the absorption of the new technology. Too often the procedures for the use of an innovation are developed through trial and error experience due to the lack of research guidance. This is a very inefficient process.

Proper use of technology is essential to successful application. Successful use of various high performance concretes will undoubtedly demand special procedures in their manufacture and use and development of unique practices that will require training of both designers, constructors, suppliers and craftsmen.

Information Dissemination

Our fragmented industry makes communication of technical advances very difficult. Expanding general awareness of new technology and technological development enhances its transfer to use. Familiarity facilitates acceptance; unfamiliarity raises unnecessary suspicions and doubts. Widespread knowledge of developing technology also increases the probability of financial support of additional research.

Institutes such as ACI have placed a major emphasis on the publication of peer reviewed technical papers and sessions presenting technical information. These efforts are necessary but reach a limited audience and are, of themselves, an ineffective way of transferring innovation to practice.

Our diverse industry needs easy access data bases on current research underway and associated published research findings. The data bases should separately delineate research findings or research in progress on the developmental aspects of a technology such as use and application procedures.

One of the best ways of disseminating information is to actively involve multiple parties in the process of developing information. Because the construction industry has limited experience in funding and participating in research and because of its fragmented nature, ACI and other technology gatekeepers would provide an invaluable service if they would form multi-company consortiums from industry; including designers, constructors, manufacturers and suppliers, to fund and participate in research projects together. In the United States, HPC research and the transfer of new HPC technology would be greatly enhanced if ACI would form industry consortiums to fund and participate in HPC research, particularly as it reaches the development stages and, through the use of ACI's technical membership, provide oversight of the industry funded HPC research projects.

CONCLUSION

The application of research requires widespread dissemination of results, evaluation of the results and training in the use of the results if some of the more formidable barriers to technology transfer are to be overcome.

From industry's perspective, if we can lower the barriers to technology transfer and move innovation to practice efficiently, we will see industry demand for and support of research that will outstrip our capacity to advance the state-of-the-art. The beneficiaries of the timely and efficient transfer of technology affecting construction will be society, through the efficient delivery of its infrastructure and enhancement of its quality of life.

RECOMMENDATIONS

Industry and the American Concrete Institute cannot, by themselves, overcome all the barriers to transferring concrete technology, but we can address a number of them by instituting and supporting the following:

- A recognized national evaluation system of innovation, including products, material science and engineering science, by expert panels.
- Codes and Standards based upon science as well as experience.

Greater emphasis on development aspects of research and development with applied research deliverables including:

- (i) draft codes and standards or revisions to existing codes and standards, and

- (ii) application procedures for the innovation (i.e., design procedures, recommended practices, etc.).
- Formation of industry consortiums for research funding and participation with oversight provided by ACI technical membership.
- A five (5) year rolling file containing abstracts of current research pertaining to concrete.
- Development of training materials in the use of HPC for the designer, constructor, supplier and craftsman.

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TABLE 1—COMPARATIVE U.S. INDUSTRY INVESTMENT IN RESEARCH AND DEVELOPMENT⁶

Sector	Annual Industry R&D Investment (% of annual sales)
Electrical/Electronics	5.4
Telecommunications	4.7
Aerospace	4.1
Chemicals	3.8
Automotive	3.4
Construction	0.5

SP 159-2

Self-Compactable High-Performance Concrete in Japan

by Hajime Okamura and Kazumasa Ozawa

Synopsis: Self-compactable high performance concrete requiring no consolidation in situ has been recently developed in Japan to improve the reliability of concrete and concrete structures. This concrete is a significant material innovation for a new generation of concrete structures. A review of the concrete and the applications are described.

Keywords: Compacting; consolidation; high-performance concretes

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ACI member **Kazumasa Ozawa** is an Associate Professor in the Department of Civil Engineering, The University of Tokyo, Tokyo, Japan. He developed a successful self-compactable, high performance concrete in 1988, and has conducted several investigations on this type of concrete.

CONCEPT OF SELF-COMPACTABLE HIGH PERFORMANCE CONCRETE

Concrete is one of the essential structural materials for constructing the infrastructure of the society. However, careful placing by skilled workers on site is vital for constructing durable and reliable structures. In other words, reduced durability resulting from improper placement is a serious defect of concrete. To improve the reliability of concrete, it is necessary to develop a concrete, which is not affected by workmanship during placing, or self-compactable concrete requiring no consolidation [1].

The self-compactable concrete can not only produce durable and reliable concrete structures, but also save labor, eliminate the consolidation noise, lead to the innovation of construction systems, and realize the modernization of concrete construction. Many new construction methods and materials that have recently been developed will find wider applications if they are combined with self-compactable concrete.

In the summer of 1988, the prototype of self-compactable concrete was successfully completed by combining materials on the market [2]. This prototype proved to have satisfactory performance with regard to drying and hardening shrinkage, heat of hydration, denseness after hardening, and other properties. Simultaneously, this concrete was named "High Performance Concrete".

The prototype is proportioned to have a slightly lower coarse aggregate content and a higher powder content than conventional air-entrained concrete (**Table 1**). Its slump flow is designed to remain unchanged for 90 minutes after mixing by the use of a low-slump-loss-type superplasticizer, which is a material essential for enhancing the flowability without increasing the unit water content.

In addition to ordinary portland cement, fly ash, granulated blast-furnace slag and an expansive admixture are employed as powders. Fly

ash is used for enhancing the flowability without increasing the water content and the heat of hydration. Fine granulated blast-furnace slag contributes to adjusting the grading of ordinary portland cement. The expansive admixture is for compensating the early-age shrinkage. A small dosage of a viscosity agent is added to impart adequate viscosity. The prototype of High Performance Concrete was realized with limited drying shrinkage, limited heat of hydration and adequate strength, in addition to the self-compactability.

Having succeeded in developing the prototype, the authors conducted an open experiment, inviting more than 100 engineers to the campus of the University of Tokyo in 1989, and the experiment created a sensation among the guests. Since then, a number of experiments to confirm the self-compactability have been conducted by many researchers in major construction companies. The self-compactable concrete has been used in Japan for a number of projects such as bridge girders, bridge towers, bridge piers, LNG tanks, culverts and buildings. Precast concrete plants are producing the products by using the self-compactable concrete on a commercial basis mainly because of the prevention of noise from vibrating machines.

Recently the authors [3] published the system for designing the mix proportions of the standard type of self-compactable high performance concrete, which uses neither powder materials, except the moderate heat portland cement, nor viscosity agents.

METHODS OF ACHIEVING SELF-COMPACTABILITY

Self-compactable concrete requires high deformability without segregation of materials. The increased viscosity of the paste is effective in inhibiting segregation (**Fig.1**). "Antiwashout underwater concrete" is a kind of self-compactable concrete placed underwater, in which segregation is strictly inhibited by the addition of a high content of a viscosity agent, so as to prevent the cement particles from dissolving into the water. It is therefore not suitable for reinforced concrete structures in air, since the viscosity is so high that entrapped air may not easily be released and the concrete may not easily pass through congested reinforcing bars.

Self-compactable concrete with a viscosity agent is an antiwashout concrete with reduced viscosity, so as to be applicable in air. Takeshita et al. produced self-compactable concrete for the first time by this method, and attempted to apply it to actual structures [4]. The balance between the viscosity agent and the superplasticizer is important for increasing self-compactability. However, there is a limit to increasing self-compactability

by this method. This is a method the authors once adopted but abandoned in the process of development.

Another method is to limit the volume of aggregate so as to inhibit the collision of aggregate particles near obstacles, while the water-powder ratio by volume is adjusted to approximately 1.0 to impart an adequate viscosity to the paste, so as to avoid segregation, thereby ensuring self-compactability. This is the method the authors used for the prototype of self-compactable high performance concrete (Fig.2).

In this method the powder content is higher than in conventional concrete, due to the increased paste content. Increases in the cement content may cause problems in certain types of structures. Therefore, part of the powder is substituted with such mineral admixtures as fly ash and ground granulated blast-furnace slag, or limestone powder. This is the type of self-compactable concrete used for the anchorages of *Akashi Straits Bridge* connecting *Honshu* and *Shikoku* Islands. Its powder content is increased by using a large amount of limestone powder [5] (Table 2). This is the first case of a self-compactable concrete in which the maximum aggregate size is 40 mm.

Shindo and *Matsuoka* et al. developed a method of increasing the level of self-compactability easily by adding a segregation-inhibiting agent, which is a polymer insoluble in water, to the prototype of self-compactable high performance concrete [6] (Fig.3). This level of self-compactability has become attainable by suitably designing such proportions as the water-powder ratio, without using any segregation-inhibiting agent.

Whereas a superplasticizer is essential in either method, it is also important to suitably proportion the aggregate content and to impart suitable deformability and viscosity to the paste. The frequency of collision and contact between aggregate particles increases as the relative distance between the particles decreases. Therefore, the internal stress increases when concrete is deformed, particularly near obstacles. It has been revealed that the energy required for flowing is consumed by the increased internal stress, resulting in blockage [7] (Fig.4). Limiting the coarse aggregate content, whose energy consumption is particularly intense, to a level lower than normal proportions is effective in avoiding this blockage.

To increase the deformability of the paste, the water-powder ratio should be increased, or a superplasticizer should be added. In order to impart viscosity, the water-powder ratio should be reduced, or a viscosity agent should be added. Imparting deformability means to reduce the energy to be consumed internally or by friction on the boundary, when the

paste is deformed. Conversely, imparting viscosity means to increase the energy required for deformation. Thus, there is a trade off between deformability and viscosity. If viscosity is to be increased by reducing the water-powder ratio, there is no choice but to use a superplasticizer for a higher deformability. If there is a range where deformability and viscosity are balanced, self-compactability can be achieved without the help of a viscosity agent. Fortunately, a superplasticizer was found to cause little loss of viscosity, while it greatly improves deformability. Thus it was found that there is a range where high viscosity and high deformability coexist in a balanced manner.

The reasons for the necessity of imparting viscosity to the paste are as follows:

- (1) Paste with high viscosity prevents the settlement of coarse aggregate particles, which have a higher specific gravity than the other ingredients, and thereby maintains the uniformity of the concrete.
- (2) When the concrete is deformed, paste with a high viscosity also prevents localized increases in the internal stress due to the approach of coarse aggregate particles with large grain diameters. It is important to regard concrete as having both liquid and solid properties, because it is a composite of particles of various sizes and specific gravities.

MIX DESIGN OF SELF-COMPACTABLE HIGH PERFORMANCE CONCRETE

There are numerous solutions, i.e. mix proportions, for the achievement of self-compactability. By specifying a part of the materials or proportions, the optimum proportions within the range are determined. In other words, a variety of proportions are obtained depending on what is specified first. The proportions currently used may not necessarily be the optimum obtainable from the combination of materials, but rather may simply be one of the many possibilities of achieving self-compactability.

Assuming general supply from ready-mixed concrete plants, a mix design system for self-compactable, general purpose, high performance concrete has been proposed (**Fig.5**). This is a limited system based on the use of moderate heat portland cement or cement with a high belite content. Assuming application to structures in general, it is appropriate at present to use these cements, in consideration of not only the properties of fresh concrete, such as the ratio of retained water, but also the properties of plastic and hardened concrete, such as heat generation, strength development, drying shrinkage, and carbonation.

This is a system whereby the quality of hardened concrete is normally

automatically ensured if the concrete attains self-compactability while fresh. The mix design is simplified and its reliability is increased by limiting the range of cement quality. In addition, the improvement of the superplasticizers to be used in combination with these cements may be accelerated when enough data has been accumulated. Thus limiting the quality of the powder or cement to be used is of great significance.

The target deformability and resistance to segregation are specified at a high level of self-compactability. Self-compactability is therefore ensured for general structures. The self-compactability levels may become discretionary, when the reliability of quality control technology has been increased and the relationship between the self-compactability in real structures and the characteristics of concrete has been quantitatively elucidated.

In the proposed mix design system, the amounts of coarse and fine aggregates are specified on the safe side. A method of determining the coarse aggregate amount in concrete or the fine aggregate amount in mortar with respect to specific material properties is indicated in this system, so as to adapt to various types of coarse aggregate, as well as to fluctuations during production.

Methods of increasing aggregate content may be presented in the future, when the quantitative evaluation of the effects of the interference between fine and coarse aggregate particles has become available and the quality control technology during production has been improved. In this system the water-powder ratio and the dosage of the superplasticizer are not determined until the mortar or concrete is actually mixed. The major reason for this is that the effects of mixing are difficult to deal with quantitatively. If the effects of the superplasticizer and other conditions could be evaluated without conducting actual mixing, there would be a possibility of designing concrete without trial mixing. A future study will be directed to the development of an analytical technology whereby the behavior of fresh concrete can be sequentially predicted from the materials, proportioning, methods of production, and environmental conditions.

Volume of coarse aggregate

When the volume of coarse aggregate in concrete exceeds a certain limit, the opportunities of contact between coarse aggregate particles drastically increase, causing interlocking, and increasing the possibility of blockage on passing through spaces between steel bars. Therefore, the first point to be considered when designing self-compactable concrete is to restrict the volume of coarse aggregate below this limit.

According to the research results obtained by the authors, this limit is

more closely related to the percentage of the solid volume than to the absolute volume of coarse aggregate. It has also been revealed that the possibility of such interlocking is negligible if the volume of coarse aggregate is lower than 50% of the solid volume when proper mortar is used (Fig.6). This implies that the volume of coarse aggregate can be increased, if well-graded and well-shaped aggregate is used. Use of river gravel generally permits a large coarse aggregate volume. The limit seems to vary slightly depending on the properties of mortar, particularly those of powder.

Volume of fine aggregate

If the volume of coarse aggregate is specified, the volume of mortar is determined. The volume of fine aggregate in mortar is important as in the case of coarse aggregate. Conversely, however, the volume of fine aggregate as such is found to be more important than the percentage of the solid volume, though the reason for this has not been elucidated.

If a proper paste is used and the volume of fine aggregate is below a certain limit, self-compactable concrete is obtained with no appreciable direct interlocking of fine aggregate particles. This limit seems to be independent of the type of fine aggregate, but seems to depend on the properties of the paste.

It has been revealed that self-compactable concrete can safely be produced if particles larger than 0.090 mm are assumed to be coarse-grain fine aggregate and those smaller than this are assumed to be powder, and if the volume of coarse-grain fine aggregate is set at 40% of the volume of mortar.

Water-powder ratio by volume and dosage of superplasticizer

When the volume of aggregate has been specified, the water-powder ratio and the dosage of the superplasticizer are then determined. An excessively high water-powder ratio not only causes segregation of water, but also excessively reduces the viscosity of the paste, resulting in segregation of coarse aggregate. Conversely, an excessively low water-powder ratio leads to an excessively high viscosity of the paste, impairing the capability of concrete to pass through spaces. This is also the case when a superplasticizer is used. However, general methods have not been established, whereby the water-powder ratio and the dosage of the superplasticizer are determined so as to impart suitable deformability and viscosity to the paste or mortar.

APPLICATIONS FOR BRIDGES

Kiba Park Bridge is a prestressed concrete cable-stayed bridge, 186 m in length. This beautiful large-scale bridge is a symbol of the park. The tower consists of two columns 60 m in height and a crossbeam connecting these columns. Precast concrete stay-in-place forms impregnated with a polymer were adopted for the column to improve the durability and efficiency of construction, eliminating the form construction and removal. This structure has extremely congested reinforcement and therefore the consolidation was expected to require careful control and be labor intensive. It was also pointed out that it would be difficult to confirm the filling of concrete into all the corners of the form because the forms were not to be removed. In consideration of these factors, self-compactable high performance concrete with strength of 60 MPa [8] was adopted. This concrete was applied to the crossbeam and blocks 7-17 of the tower, where the cables are anchored and the reinforcement is more congested. The total amount of concrete for these portions was 650 m³, and was placed during March to November 1991.

Lightweight self-compactable high performance concrete was used in the main girder of the central span of 45.5 m in *Relent Country Club* (Fig.7) [9]. The design strength of the concrete was 40 MPa, and the unit weight was required to be in the range of 1.85 and 1.95 t/m³. It was also required that the field-cured concrete would have a compressive strength of more than 30 MPa in 3 days for applying prestress. This concrete was placed successfully without using vibrators during April to July 1992, although it was planned in 1990.

Akashi Straits Bridge is a three-span bridge 3,910 m in length, with its central span being 1,990 m. It will be the world's longest suspension bridge when completed in 1998. The amounts of concrete to be placed including the foundations are 520,000 m³ for one anchorage and 250,000 m³ for another. Both are huge mass concrete structures, in which cable anchor frames weighing 4,000 tons are to be embedded. In the anchorages, an amount as large as 1,900 m³ of concrete of assured good quality has to be placed per day. To improve placeability, self-compactable concrete with maximum coarse aggregate size of 40 mm was developed and used. Concrete was pumped by 6 trains of 8 inch pipes to the site. One train is equipped generally with 8 automatic gate valves at intervals of 5 m. A lift was set at 1.5 to 3.5 m, in consideration of the daily output of the plant, 1,900 m³ [5].

CONCLUDING REMARKS

Conventional concrete restricts construction in many ways, such as restriction on the height of a lift, necessity of constructing scaffolding for vibration, and necessity for separate placing of the bottom and walls of box-section members, because of the need for consolidation during placing. If consolidation is not necessary by using the self-compactable concrete, construction systems can be improved remarkably without being disturbed by such restrictions.

Such a construction method, in which concrete is just pumped into built-in forms which are assembled with steel reinforcement fabricated and constructed in a plant, is promising. The development of this construction systems is anticipated, which are to be justified in a variety of aspects, such as the reduction in the number of workers on site, reduction in the number of skilled workers required, constant number of workers required throughout the construction period, shortened construction period, non-interference of the elements, and improved safety. The possibility of new structural systems will become stronger. For instance, a steel-concrete sandwich structure, which has been impractical due to the placeability problem, has been realized.

The self-compactable high performance concrete is a material with a huge potential, and is a technology that can transform concreting sites. By combining this with related technologies, greater innovations may be possible. It is anticipated that a new system utilizing this concrete would be introduced towards the turn of the century, while material manufacturers, ready-mixed concrete manufacturers, contractors, and owners commit themselves consciously reform.

The research, development, and technology transfer of self-compactable high performance concrete will bring about a higher reliability of concrete structures and a higher status for engineers involved in the concrete industry, and that concrete technology will be rated more highly in society.

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TABLE 1—COMPARISON OF MIX PROPORTIONS BETWEEN SELF-COMPACTABLE AND CONVENTIONAL CONCRETES

	W	C	A1	A2	A3	S	G	Admixture
Prototype	154	144	10	154	197	753	963	*
Conventional	150	300				752	1176	**

W: Water; C: Cement; A1: Expansive agent; (Unit: kg/m³)

A2: Granulated blast-furnace slag; A3: Fly ash

* : 4800cc of Superplasticizer + 6g of Cellulose viscous agent

** : 750cc of Water reducing agent

TABLE 2—MIX PROPORTIONS OF SELF-COMPACTABLE CONCRETE USED IN ANCHORAGES OF AKASHI STRAITS BRIDGE

	W	C	LF	S	G	Admixture
Anchorage 1A	145	260	150	769	965	6.335
Anchorage 4A	145	260	150	609	1121	7.8

(Unit: kg/m³)

W: Water; C: Low heat type blended cement with slag and fly ash;

Lf: Limestone powder; Admixture: Superplasticizer

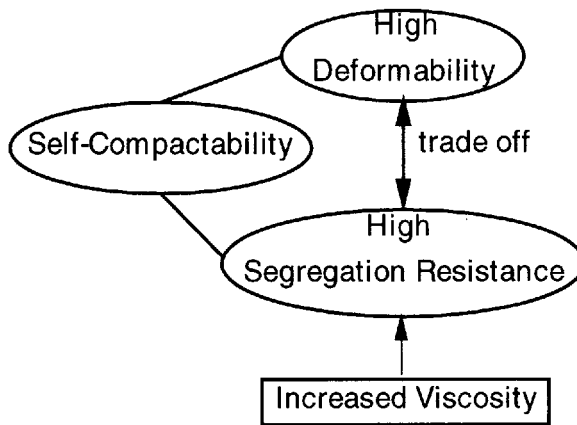


Fig. 1—Effect of increased viscosity of paste on self-compactability

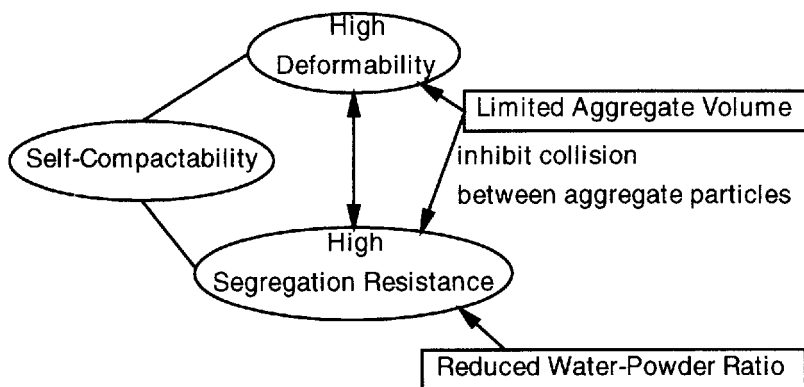


Fig. 2—Achievement of self-compactable concrete by controlling mix proportion

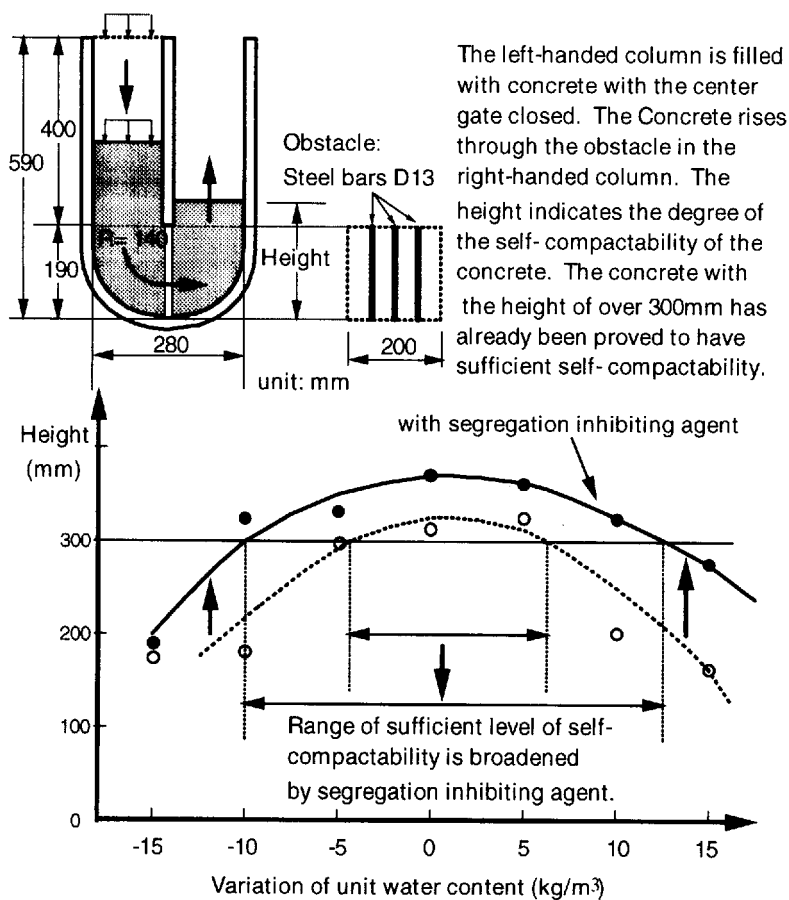


Fig. 3—Example showing effect of segregation-inhibiting agent