Concrete Durability

A Multibillion-Dollar Opportunity

National Materials Advisory Board
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Concrete industry practices today fail to take advantage of the many opportunities for increased durability and service life of concrete structures that could be achieved through better use of currently available knowledge. A number of technical and institutional factors have led to this situation; this report discusses specific issues and barriers that affect increased durability. Those deemed most important are inadequate education opportunities, low level of research funding and coordination, lack of technology transfer mechanisms, and short- rather than long-term economic approach of the industry. The technical sophistication of the managerial, technical, and blue-collar work force is lower than needed, and the necessary close cooperation between industry, government, and universities required to achieve improvements in concrete durability is lacking. Action directed to improving this underlying situation will prove less costly in the long term than very expensive premature rehabilitation of deteriorating structures. Numerous opportunities for improvement are identified. Recommendations are made for steps to be taken by government agencies, industry, and educational institutions to address the many factors that can lead to improvement in the industry's performance.

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CONCRETE DURABILITY:

A MULTIBILLION-DOLLAR OPPORTUNITY

Report of the Committee on

Concrete Durability: Needs and Opportunities

NATIONAL MATERIALS ADVISORY BOARD

COMMISSION ON ENGINEERING AND TECHNICAL SYSTEMS

NATIONAL RESEARCH COUNCIL

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ABSTRACT

Concrete industry practices today fail to take advantage of the many opportunities for increased durability and service life of concrete structures that could be achieved through better use of currently available knowledge. A number of technical and institutional factors have led to this situation; this report discusses specific issues and barriers that affect increased durability. Those deemed most important are inadequate education opportunities, low levels of research funding and coordination, the lack of technology transfer mechanisms, and the short- rather than long-term economic approach of the industry. The technical sophistication of the managerial, technical, and blue-collar work force is lower than needed, and the necessary close cooperation between industry, government, and universities required to achieve improvements in concrete durability is lacking. Action directed to improving this underlying situation will prove less costly in the long term than very expensive premature rehabilitation of deteriorating structures. Numerous opportunities for improvement are identified. Recommendations are made for steps to be taken by government agencies, industry, and educational institutions to address the many factors that can lead to improvement in the industry's performance.

PREFACE

— Concrete is one of the world's most important construction materials, and it has a significant impact on the national economy. When properly produced, concrete structures perform adequately even under very severe conditions of use. However, many instances of deterioration and poor performance can be cited, and concerns have been expressed as to how to improve the quality of concrete produced to give better durability in service. These concerns prompted the Department of Defense and the National Aeronautics and Space Administration to request the National Research Council through its National Materials Advisory Board to convene a committee of experts to assess the current situation and to identify actions that can improve the durability of concrete.

The committee examined present concrete production practices, evaluated available technologies for producing durable concrete, and identified existing and emerging technologies that offer promise of producing concrete with the physical properties and durability to perform satisfactorily under severe environmental conditions. Technical and institutional barriers were discussed by the committee, and recommendations are made regarding opportunities for improving end-use performance of concrete in an economical manner.

J. P. Skalny
Chairman

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Special thanks go to Robert E. Philleo and Della M. Roy, who, as technical advisors, assisted the committee in various areas of its assessment. Gunnar M. Idorn, a consultant on technical and institutional aspects of concrete technology, and Geoffrey Frohnsdorff of the National Bureau of Standards, are thanked for their input and critical review of segments of the committee's draft report.

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The chairman of the committee thanks the members for their dedication and for the patience shown during the numerous iterations and revisions of the report drafts. Particular thanks are given to the committee members who served as the chapter coordinators to assemble pertinent facts for the report, and who presented the data in an open-minded and professional manner. The committee's final meeting was held at the Bechtel Group's headquarters in San Francisco, and the company and staff are thanked for their gracious hospitality.

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CONTENTS

EXECUTIVE SUMMARY

The construction and repair of buildings and other structures constitute a substantial portion of the gross national product. Many of these structures, as well as a considerable segment of the public and private infrastructure, including highways, airport and maritime facilities, and municipal sewage systems, are made of concrete. Contrary to the beliefs of some, concrete is not indestructible, and appropriate maintenance of these structures must be provided for. Concerns about improving concrete durability led to this study conducted by the Committee on Concrete Durability: Needs and Opportunities.

A number of technical and institutional factors directly or indirectly influence concrete durability. Among the institutional factors are (a) the political, economic, and labor-relations environment, (b) educational approaches, (c) the management of technology transfer, and (d) the quality and quantity of research and development. The major technical aspects of concrete durability are well known to the concrete community through first-hand experience, publications, and presentations at technical meetings. It is important to acknowledge the advanced level of U.S. concrete engineering design, construction, and project management. Also, U.S. cement research has been, and in many ways still is, of the highest scientific quality. For all practical purposes, however, the cement and concrete industries perform little advanced durability research. Most concrete research in the United States is government-sponsored work or is conducted by specialty products manufacturers such as admixture companies.

It is often unappreciated how severe the effects are of all the service stresses sustained during the life of a structure. Because concrete structures generally perform well, it is possible to become lulled into a false sense of security. The fact remains, however, that unsatisfactory performance and premature deterioration of structures occur. The reasons for unsatisfactory performance of concrete structures are complex and are usually the result of a combination of technical or institutional factors or both. According to some, all the knowledge needed to design, specify, and construct concrete structures is readily available or referred to in reference works. However, many factors, such as new developments in materials, in processing and construction techniques, in the economic and political situation, and in the educational and legal systems, tend to cause the "durability guidelines" to lag somewhat behind actual construction practices. What is needed is rapid dissemination, acceptance, and intelligent application by the engineering community of available as well as newly developed knowledge.

ECONOMIC FACTORS

The false sense that concrete is an almost indestructible material results in an undue emphasis on construction costs rather than life-cycle costs of structures. Concrete structures rarely cease to be serviceable within 10 years of construction. The fact that concrete structures may continue to be serviceable for long periods does not, however, reduce the significance of durability as an economic issue. Prevention of structural damage is the most cost-effective measure available, and it is far cheaper than repairs or rebuilding. The costs of repairing or replacing damaged structures, or of accepting curtailed performance and service, are large enough to warrant additional expenditures to limit or eliminate economic losses from insufficient durability.

One avenue that may be taken toward solving the problem is life-cycle costing. Under such a system, suppliers and users would take into account the costs of maintaining, repairing, and ultimately replacing a structure along with the costs of the original construction. Despite the widespread acceptance of these principles, they are not always followed in practice. Among governmental agencies, funds for construction typically come out of a different budget from funds for operation and maintenance, and, historically, funding for new construction has been easier to obtain than funding for maintenance of existing structures. In addition to these budgetary practices, low-bid procurement practices put a premium on minimizing first costs.

EDUCATION

There has been a steady decline in the number of student applicants interested in civil engineering. Of those interested, only a few are interested in concrete as a material. Because of the emphasis on more fashionable "high-tech" subjects, some engineering curricula have been sharply curtailed--among them the materials science of concrete. The lack of support for research and development not only has damaged short-term innovation capabilities but, more importantly, has had negative long-term effects on the educational system and thus on the nation's competitiveness in this area.

The development and degradation of concrete properties are complex physicochemical processes. A better understanding of these processes is imperative to improved concrete durability. Not one chemistry or chemical engineering department at a U.S. university can be identified that is interested in the complex problems of concrete chemistry. A few civil engineering departments have interests in concrete technology, but most of them tacitly ignore the chemical aspects of the subject. There is need for a proper background in, or an understanding of, the basic chemical principles governing the development and degradation of mechanical properties of concrete.

A related problem exists in the education of the labor force, which has resulted in a declining quality of workmanship. For financial, legal, and other reasons, training programs have been curtailed, contributing to the decline in quality of the already "low-technology" concrete labor force.

The quality of management also is a problem area, especially that controlling technology development. Managers are needed who possess financial, marketing, and a technical background; only individuals with an appreciation for the complexities of technology can lead in the long-term development of new construction materials and structures.

TECHNOLOGY TRANSFER

Technology transfer is closely related to education in that it is critically dependent on the proper organization and dissemination of knowledge. It depends on the quality of communications between technical and managerial people as well as on a close exchange of knowledge between specialists in different technical fields, such as chemists, physicists, materials scientists, and engineers. Durability issues are so complex as to strain the capacity of individuals to deal with them without guidance. The technology of service-life prediction in concrete is advancing very slowly, even though the tools for generating and organizing knowledge (e.g., smart instruments, data base management systems, expert systems) are advancing rapidly.

SPECIFICATIONS

For years, specifications for concrete durability consisted merely of largely prescriptive limits on the mixture proportions. The past 40 years, however, have seen the development of air entrainment and a large variety of materials to be added to concrete. It is now possible, for example, to place concrete with much less water than was previously possible. The pace of new developments is accelerating; however, there are still no simple rapid tests for many of the important parameters that control durability.

With the variety of ways now possible to achieve a given level of performance, including durability, there is considerable pressure to use performance specifications. Purely prescriptive specifications, it is alleged, in many cases may inhibit innovation. The development of such performance standards has not kept pace with the development of materials, primarily because of the lack of scientific and field data needed for standards development. As a result, some specification writers are reluctant to abandon old approaches. A more direct means is required for linking the properties of the concrete materials and the production practices with the quality and performance of what is actually produced. Introduction of performance specifications will require improved understanding of the relationships between composition, microstructure, and physical performance.

QUALITY ASSURANCE

The effectiveness of quality assurance (QA) is another factor influencing concrete durability. If a QA system fails to provide adequate durability, it is mostly for one of the following reasons: The required tests and inspections were inadequate or not relevant to durability; the system degenerated into a paperwork system operated by accountants rather than knowledgeable technologists; or the testing and inspection by the contractor were used by the owner as a substitute for acceptance testing to avoid the expense of double testing. Inadequate QA systems lead to overspecification or underspecification, to conflict of interest, and to allegations of fraud.

To make QA programs more effective, the relationships between the concrete material, construction practices, and service performance of the structure have to be put on a solid base, and the inspectors doing the work on behalf of the owner and contractor must be schooled in concrete materials as well as QA procedures. Here again, the federal government, which is directly or indirectly the largest customer of the concrete construction industry, can play an important role in requiring the use of state-of-the-art QA methodology in all federally sponsored construction.

In summary, a problem exists with respect to inadequate durability of concrete in service, and its magnitude is great enough to merit national action. Much premature deterioration could be prevented if existing knowledge were properly used, but additional knowledge must be generated to ensure against further degradation.

The committee recommended a two-step approach. The first is recognized as being difficult to implement in a short time, but is preferred; the second does not require a departure from the current allocation of responsibility for durability and could be adopted by the public and private sectors in the short term.

Step 1. Responsibility for durability should be shifted from the design to the construction sector. This sector would assume responsibility for concrete durability performance for a specified time during the service life of the structure as a part of the construction contract.

Step 2. Short-term initiatives should be pursued in the following areas:

- Intensified education of concrete specialists at all levels
- Improved teaching, research, and management skills of academic, government, and industrial personnel
- Development of a favorable business climate, including financial incentives, and improved management techniques for knowledge and technology transfer

- Increased quantity and improved quality of research and development

- Development of knowledge-based systems to disseminate concrete durability guidance

- Development of quality control and quality assurance procedures that would provide penalties for inferior durability as well as rewards for adequate durability

- Creation of an integrated, multidisciplinary cement-concrete research establishment

Needed research involves a state-of-the-art, multidisciplinary approach that uses the best available knowledge and methods from related scientific disciplines. The following specific areas of inquiry are recommended: cement composition versus concrete performance in different environmental conditions; marginal aggregates versus environmental reactivity; mineral admixtures versus the chemical and physical behavior of concrete; chemical admixtures involving the exploration of surface-colloidal phenomena versus concrete performance; concrete rheology; the placing and curing of concrete; environmental stability (degradation mechanisms, permeability phenomena, etc.); and design that includes materials properties versus structural integrity.

PART I

PRINCIPAL ISSUES OF CONCRETE DURABILITY

I-1

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

These conclusions represent a consensus of the opinions and judgments of the committee members, based on individual expertise, literature review, exposure to presentations by invited expert specialists, and extensive committee discussions. The recommended actions based on these conclusions are given in a following section.

The committee finds that

1. A problem exists with respect to inadequate durability of concrete in service. The reasons for the problem are both technical and institutional. The manifestation of the problem is premature distress and degradation of concrete in structures. Many different physical and chemical processes, including corrosion of steel reinforcement, sulfate attack, freezing and thawing, and alkali-aggregate reactions, interact to bring about premature deterioration.

2. The magnitude of the problem is great enough to merit national action. The value of the existing concrete infrastructure is estimated at $6 trillion; current replacement and repair requirements, due in large part to durability problems, are conservatively estimated to be several hundred billion dollars. Highly specialized durability problems exist in the Department of Defense, National Aeronautics and Space Administration, and other government agencies and in the domestic construction industry.

3. The problem needs to be addressed now, since the United States is being forced to contemplate a major rehabilitation of its infrastructure. To ensure against further degradation, such rehabilitation must be carried out using state-of-the-art technology.

4. Much premature deterioration would be prevented on the basis of existing knowledge if this knowledge were properly used. Proper use of knowledge implies both proper design and proper implementation. To this end, better specifications and better quality control (QC) and quality assurance (QA) are needed.

5. Available concrete technology is inadequately used because of the fragmentation of the industry, confused responsibility for the training and skill development of workers, lack of financial or other incentives for the industry, and poor management and dissemination of

available technical information. Negotiated contracts to replace lowest-bidder contracts are an alternative approach.

6. Specific institutional barriers that tend to restrict the adequacy of concrete construction with respect to durability include

• Failure of both public and private owners of concrete structures to properly specify and control construction practices with respect to their effects on durability.

• Undue focus on maximizing short-term financial returns. As a result, many structures are built without adequate regard to long-term durability and life-cycle costing, since the owner, the lender, and the builder have insufficient interest in other than short-term use.

• The separation of design and construction responsibilities, which leads to a lack of financial or other incentives for the contractor to produce concrete of high potential durability and to a lack of any penalty for not doing so.

• Inadequate financial support of R&D on all aspects of construction (estimated to be less than 0.1 percent of sales of materials alone). More knowledge--especially at the materials science-technology interface--is needed to take advantage of the high potential for the advancement of concrete technology.

• Inadequate standards and uninformed development and application of standards.

• Inadequate education of civil engineers in chemistry and materials science.

• Inadequate incentives by the government for the construction industry to employ state-of-the-art technology.

• Lack of interest by and incentives for equipment manufacturers to develop specialized machinery needed for introducing new construction products.

• Specification of required concrete properties solely on uniaxial compressive strength rather than on overall long-term performance, including durability.

• Purchase of concrete is solely on the basis of price rather than on price <u>and</u> quality.

7. Technical barriers to improved durability are related to lack of coordination in R&D activities on industrial, academic, and public levels and to the consequent inadequate amount, quality, and focus of research activities. Some of the technical barriers are

• Inadequate knowledge of the mechanisms of development, and subsequent degradation, of concrete properties.

• Lack of sufficient generally accepted short-term testing methods for assessing the long-term durability of concrete and concrete structures.

• Inadequate understanding of the importance and control of concrete curing conditions.

• Difficulty of assessing the present condition and remaining service life of concrete structures.

• Inadequate methods for making existing knowledge available quickly and in comprehensible form to users at all levels.

RECOMMENDATIONS

The committee recommends two major avenues for action. The preferred approach would entail some shifting of the responsibility for durability from the design to the construction sector of the industry (see item 1 below) and the pursuit of initiatives whose implementation does not require departure from the current allocation of responsibility between the design and construction sectors (see item 2 below).

1. The committee recommends that mechanisms and institutions be developed under which construction contractors would be obliged to assume responsibility for concrete performance by requiring a durability performance guarantee for a specified time during the service life of the structure as a part of the construction contract. This would entail such actions as

• Extending the current concept of construction bonds to provide a bonded guarantee for satisfactory durability; and

• Setting up a mechanism for bonding agencies to use part of the bonding premium revenue to support development of accelerated and nondestructive test methods that would improve the effectiveness of quality control during construction and to conduct other research and development related to concrete durability.

Under this concept the industry sector that can most directly influence durability (e.g., the designer, contractor) would be required to act independently to improve its service to its clients.

2. The committee, recognizing that implementation of these initiatives cannot be accomplished quickly, suggests that a number of initiatives be adopted by the public and private sectors:

- Require that all professionally approved civil engineering curricula include instruction in the science of materials durability, with special emphasis on relevant physics and chemistry.

- Encourage and expand multidisciplinary university-industry-government cooperative programs to help bridge the gap that separates researchers from decision-makers.

- Request and encourage continuing education of engineers and concrete technologists and more extensive training and licensing of concrete artisans.

- Require development of better research and teaching skills.

- Develop management methods for better focusing and use of R&D results by industry.

- Develop in-depth understanding of the manner in which the composition and microstructure of materials affect their performance, with the goal of engineering better durability; the use of proper curing practices is imperative.

- Increase the available funds for construction-related R&D by at least an order of magnitude. Extension of the DOD IR&D (independent R&D) concept to the construction industry is one mechanism for achieving increased funding; another possibility is to place a surcharge on the sales of all building materials (e.g., concrete components) to fund the needed R&D.

- Develop knowledge-based systems to facilitate, at affordable costs, effective use of available knowledge related to concrete durability by persons not expert in concrete durability. Set up a feedback-loop system to encourage the use of past experience in repair and maintenance to minimize future problems.

- Encourage equipment manufacturers to take advantage of the large potential market to develop equipment that would permit effective application of new technological developments in cement-based materials.

- Develop criteria that will predict the durability of concrete structures. This will require that new and improved short-term testing methods (including those to be used in the field) be developed to predict long-term behavior. These criteria can be incorporated in QC and QA systems.

- Develop QC and QA procedures to encourage, through appropriate rewards, the production of structures in which there is greater assurance of durability and to penalize the production of structures in which there is insufficient probability of durability.

- Increase the intelligent use of available knowledge of technology to properly specify and build concrete that is durable. Establish and enforce criteria for training and increasing the competence of specification writers, their supervisors, and others involved in the process.

- Increase direct funding by federal agencies to underwrite the first-application risk of newly developed R&D knowlege.

- Explore ways to provide a more favorable climate for diffusion of R&D knowledge--e.g., aggregation of fragmented R&D, multiyear procurement in DOD, specification standardization, novel contracting procedures.

- Establish as an integral part of preconstruction costs the evaluation, testing, and consideration of alternatives (which may contain uncertainties to the architect, engineer, and contractor) in order to reduce costly design and high bids; a practice of prejob meetings to reach a consensus on durability issues is suggested.

- Explore the use of negotiated contracts for critical structures.

- Create an integrated, multidisciplinary national cement and concrete research center. Such a government-sponsored and industry-supported center would supplement rather than replace existing institutions. Alternatively, develop mechanisms for the better coordination of nationwide research and development activities and dissemination of findings.

INTRODUCTION

In 1980 the National Research Council's National Materials Advisory Board (NMAB) issued a report sponsored by DOD and NASA entitled "The Status of Cement and Concrete R&D in the United States" (NMAB, 1980b). The report critically analyzed the two industries, identified problem areas of national concern, and made recommendations for action, primarily in the area of research funding.

RESPONSE TO THE 1980 REPORT

The 1980 report, widely distributed among academic, industrial, and governmental technical communities, brought attention to the inadequate level in the United States of cement and concrete R&D activities and precipitated a useful discussion on solutions to the challenges. Unfortunately, in this committee's view, the recommended actions have not materialized. On the contrary, today the volume and level of cement and concrete R&D is less than it was 5 years ago. In addition, the U.S. cement industry faces severe foreign competition, and the construction-materials industry as a whole continues to face serious technical, financial, and business problems. This has recently been recognized also by other organizations, resulting in the establishment of R&D-promoting and funding schemes such as the Strategic Transportation Research Study, sponsored by the Federal Highway Administration and conducted by the Transportation Research Board, and the American Concrete Institute's Concrete Materials Research Council.

Aware of these problems, DOD and NASA requested that NMAB conduct this new study aimed at more detailed examination of a specific question: What actions should be taken that would lead to the improved durability of concrete? This topic is of crucial importance to the sponsors, who can assist industry efforts to develop proper technologies and mandate their use. Such efforts can lead to an improved product once they have been identified and adequately assessed. Assistance may be available through economic, legislative, and other support.

AUDIENCE

The audience for this report is not the single category of readers who have a technical involvement with concrete durability. It is important that the conclusions and recommendations of the committee reach others, especially the following:

1. The management, economic, and political communities. This diverse group has a common interest in concrete durability because of safety and environmental implications, cost to the nation, strategic importance, resource protection and recovery, and legal questions. It is particularly critical that the conclusions be presented to federal and state legislators and administrators responsible for operation and maintenance of the public infrastructure, both civilian and military, and to the private-sector groups concerned with concrete in service in that sector.

2. The engineering community, which includes technologists in the cement, concrete, and other construction industries; structural engineers and architects; contractors and concrete producers; and public-service engineers and teachers in engineering schools. This group is the audience at the "receiving end." It is very diversified but is crucial in finding a common language and ways of unifying the important tasks of designers, chemists, and the civil engineering and manufacturing communities to ensure an adequate, economically acceptable service life of structures. International knowledge transfer is imperative.

3. The research community--a rather weak group today because of inadequate recruitment in past years and the generally inadequate quantity and quality of well-focused, long-term research programs. This community is inclined to work on conventional, outdated concepts and methodologies. As a result, an important objective of this report is to inform the young, well-educated scientific community of the great challenges and opportunities in applying chemistry, physics, materials science, engineering, economics, and management to concrete durability problems.

Hence, the language of the report was designed to be comprehensible to a wide audience. The issues covered have important implications for the general public, and it is the committee's hope that the technical nature of the problem will not prevent its being understood by all willing readers.

PURPOSE, FOCUS, AND GOALS

The formal objective of this study was to assess the state of the art of cement and concrete science and technology, with special focus on materials, products, and processes that affect the short- and long-term in-service behavior of concrete structures exposed to a variety of environments. The goal of the committee was to identify and analyze the factors that seem to have the most crucial influence on the industry's capabilities to maintain and further develop the concrete-based parts of the U.S. national infrastructure.

The intent and hope of the committee, however, is that this report, when widely distributed and read, will lead to fruitful discussions among scientists, producers, users, and state and federal officials.

The hope is that it will lead to wide realization of the seriousness of the situation, and eventually to proper and timely actions. Thus, this report strives not only to assess the situation but, much more importantly, to provoke a commitment needed to identify and resolve the challenges that must be faced in the future.

PRIMARY CONCERNS: TECHNICAL AND INSTITUTIONAL

Durability issues are extremely complex because they involve a multitude of technical and institutional challenges. In principle, there are four main avenues to ensuring adequate durability of concrete in service: (a) require compliance during construction with current standards of good practice; (b) require use of new and improved materials and innovative construction systems, especially when they lead to increased durability and lower overall costs as compared to conventional materials and systems; (c) provide improved protection of existing, undamaged structures against adverse environments; and (d) require use of materials and procedures that incorporate the best available standards of good practice in the repair, replacement, and subsequent protection of already-damaged structures.

The successful use of these avenues, when analyzed in detail, depends on a variety of interrelated efforts, the majority of which are complex and depend on close multidisciplinary cooperation between universities, industry, and government at several levels. The technical challenges include better organization and dissemination of available knowledge, more effective use of currently available materials and processing technologies, development of novel materials and building practices, transfer and adoption of scientific and technical knowledge from other related disciplines, and wider introduction of advanced mathematical modeling and quality control and quality assurance systems into the field of building materials and construction. These and other challenges include a variety of subtopics. For example, in the field of novel materials development, very specific questions have to be answered with respect to the possible use of materials such as ferrocement, polymer concrete, sulfur concrete, and industrial wastes and by-products. "High-tech" approaches to technically and economically feasible materials are available, such as low-porosity, ceramic-like composites or new coating systems that can make use of portland cement-based products in novel applications. Can these be used effectively to make concrete durable in situations in which its use is now contraindicated, or can they allow concrete structures having adequate durability in severe environments to be constructed at lower cost or with greater assurance of success?

Many of the institutional factors were briefly discussed in the 1980 report (NMAB, 1980b). Among these were the management and funding of pertinent R&D; overall work morale; level and focus of technical education; the financial situation of the cement and concrete industries; and some antitrust, energy-cost, and environmental issues.

As an example of the complexity of each of these, the issue of proper education may be examined. Specific points here include the following: Does the U.S. educational system produce the specialists needed? Is there a proper balance between the scientific and technological competence of graduates? Do building industry workers, professionals, and managers have the proper background and educational level to enable them to bring the construction industry to the level of technical and financial sophistication required? Unfortunately, the answer to most aspects of these questions is no. According to Idorn (1985), closer cooperation between industries and universities is imperative and "can supply industry and engineering with applicable knowledge for technical services and new developments."

These examples--i.e., the development of new building materials and the need for proper education--suggest that a complex interrelationship exists between the technical and institutional issues. They also demonstrate that there are no simple solutions and that approaches to effective improvement will require proper planning, timing, and execution. Therefore, the only way to face the challenges is to establish close cooperation between industry, government, and universities (David, 1986). Each of these institutions has an important function to perform, and none can succeed in isolation.

CONCRETE DURABILITY AS AN ISSUE OF NATIONAL IMPORTANCE

Building of structures represents a substantial portion of the U.S. gross national product (GNP). It is estimated that the U.S. volume of building materials and construction business is approximately $300 billion per year (Moavenzadeh, 1985). The value of all the buildings and other concrete-based structures on the U.S. territory is believed to be about $6 trillion (Bureau of Census, 1981). In addition, the industry employs 5.5 million workers, or about 17 percent of the total U.S work force.

Thus the fraction of GNP invested in construction is of major importance to the economy. Equally important is that a healthy construction industry is a precondition for extending and maintaining large parts of the U.S. national public and private infrastructure. Such important segments of the infrastructure as the interstate and state highway systems, the civilian and military air and naval port facilities, and the municipal sewage systems are involved. Maintenance of the concrete-based infrastructure is very closely related to the issue of concrete durability. Two examples of the cost to society of maintenance of structures can be cited to illustrate this point:

First, according to a National Materials Advisory Board report (1980a), the total naval facilities have a replacement value of about $62 billion, with increases of nearly $600 million annually for new construction. Although it is well established that preventive maintenance is less costly than "reactive" maintenance, the report states

> It appears that less than 1 percent of the value of the facilities is spent by the Navy in maintaining them. Such a percentage is surprisingly low compared with the percentage spent by the civilian sector on plant maintenance . . . .

The latter amount is believed to be well above 10 percent. A recent report from the Transportation Research Board (1984) states

> Over the years Americans have invested an astronomical $1 trillion in their highway system and are just beginning to realize that, without a massive infusion of funds for rehabilitation and maintenance, the system will deteriorate rapidly.
>
> An epidemic of bridge deck deterioration plagues the United States. Some 253,000 bridges are currently deficient, and 3,500 more become deficient each year.
>
> Overall, the nation currently spends more than $40 billion per year on roads. A 1 percent cost reduction would save $400 million a year compared with the $70 million or so now spent on research in highways.

The above quotations well document not only the value of the infrastructure but also the importance and cost of inadequate durability.

The value of the nation's construction in place and the deterioration in service due to neglect during the past decades, when emphasis was placed primarily on new construction, make the present need to address the durability problem more critical (National Materials Advisory Board, 1980b). Attention must be focused today on the changes taking place in building technology, specifically on new construction methods and materials, and on the environmental factors affecting these. According to Ugianski (1985), the cost to the nation of excessive corrosion of metals in service is about $167 billion per year; the overall cost of concrete bridges in need of repair or replacement alone is estimated to be about $50 billion (Transportation Research Board, 1984). The overall cost of the deterioration of concrete in structures caused by all mechanisms is believed to be a multiple of that for bridge repair and replacement.

In spite of the obvious national importance of concrete, R&D in cement and concrete remains almost completely unfunded (NMAB, 1980b):

- Spending on basic research on cement and concrete is minimal in the United States, and spending on all other types of research in the field is very limited.

- The cement industry's figures show expenditures of less than 0.03 percent of gross sales on research. Greater spending on basic studies--even to the extent of only 0.1 percent of sales--could quickly pay for itself in a better and more controllable product and lower processing costs.

• Similarly, it is estimated that concrete producers spend less than 0.01 percent of sales on research. Here again, greater effort could lead in the long term to better control methods and a more durable, less costly product.

Since publication of the NMAB report (1980b), the situation has deteriorated. Cement research funded by industry is virtually nonexistent, and the limited but important industrial concrete research is fragmented. Only a small part of the concrete R&D funds is spent on materials development, even less on durability issues. Governments tend to regard such research as the responsibility of the private sector. On the other hand, industry regards it as a public-sector problem; hence, neither sector takes action remotely commensurate with the importance and magnitude of the problem.

Deterioration and maintenance of the national infrastructure is a complex problem. It involves not only technical issues but also the need for a variety of managerial decisions at the industrial, educational, and governmental levels. Current cost estimates for repairing the infrastructure are between $1 and $3 trillion over the next 20 years (Moavenzadeh, 1985). Many aspects of such institutional issues are discussed elsewhere in this report.

An example of an institutional issue is the development of a proper knowledge-based expert system for providing the rules for producing durable concrete. Its development for use by engineering practice should be be considered. According to Wright and Frohnsdorff (1985), such a system could contribute importantly to proper decision-making in all aspects of the building cycle (Figure 1). At present, only limited information is available on predicting the long-term behavior of a building material or structure in a specific environment, and even less is normally made use of. A complete system for predicting service life of construction materials should contain a mathematical model to document the observed degradation, to compare the data with past experience and test data, and to permit calculation of the acceleration factor (Sjöström, 1985). No such system currently exists for concrete structures.

Table 1 shows the hierarchy of the types of information that are useful in the building process. Today, only the first five relatively unsophisticated types of information are used to make decisions on the durability of building materials. In the future, use of the more sophisticated approaches must be encouraged (Lide, 1985; Frohnsdorff and Skalny, 1983). However, such endeavors will require improvements in the quality of technical management that, in turn, depend on the quality of engineering education. In addition, an increased knowledge of the components of the information system will have to be developed.

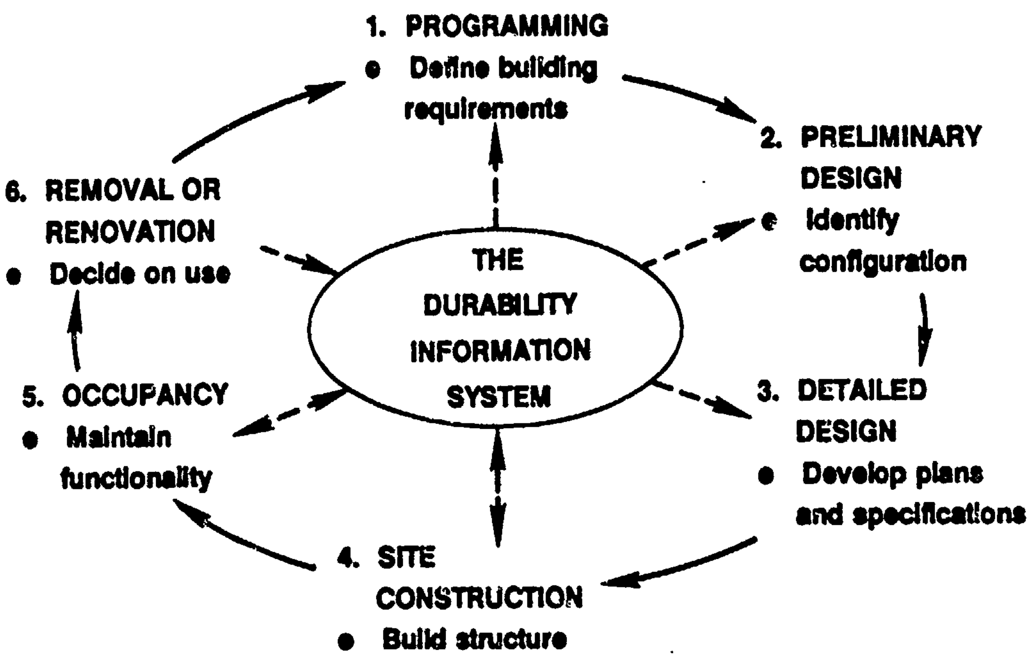

FIGURE 1. The durability information system and the building cycle. As indicated by the radial arrows, all stages of the cycle require information on building materials durability, and several contribute to the durability information system. Improved feedback could make the system more effective. SOURCE: Wright and Frohnsdorff, 1985.

TABLE 1. Hierarchy of Types of Information That Are or Could Be Used in the Building Process

1.	Anecdotal information
2.	Expert opinion
3.	Documented performance
4.	Measured properties and characteristics
5.	Reference data
6.	Predictive models
7.	Expert systems

CONCRETE DEFINED

Concrete, as discussed in this report, is a composite construction material produced only an hour or so before its use in a structure or structural element in which it will remain for years. To be called "concrete," it must be a mixture of hydraulic cement, fine and coarse aggregate, and water. It may, and today usually does, contain added ingredients called admixtures, which are either liquid or solid and which interact to modify the properties of the concrete as solidification develops. Concrete typically develops most of its structural strength within a month of its production.

The most widely used type of hydraulic cement is portland cement, and most aggregates are natural sand, gravel, or crushed stone. Mineral admixtures include materials such as fly ash, the fine incombustible material recovered from power plants using powdered coal. Chemical admixtures include chemical agents that act to entrain air in the concrete so that it can subsist in service when subjected to the freezing and thawing of entrapped saturated water. More information on these products is given elsewhere in this report.

DURABILITY DEFINED

Durability is the capability of a material, product, component, assemblage of components, or complete construction system to maintain its serviceability over a specified period of time under specific chemical, physical, and mechanical environmental conditions.

Serviceability, as defined by ASTM Practice E 632 (ASTM 1985), is the "capability of a building product, component, or construction to perform the functions for which it was designed and constructed." In other words, it is possible, although not probable, to have a building product or system in a state that will not undergo deleterious changes during its lifetime yet will, through inadequate design or construction practices, become unserviceable at the time of production or construction. Serviceability and durability are two complementary aspects of the same challenge: production and maintenance of building systems having the longest useful service life at the lowest cost, without excessive damage by or to the environment into which they are placed.

"Environmental conditions" include all possible chemical, physical, and mechanical external influences (e.g., temperature, humidity, movement of chemical species) that may change the internal properties of a building product or system (Figure 2). Included are not only the usual conditions, such as the effects of extreme temperature changes (during production, construction, and use) and a variety of chemical attacks, but also the degradation of concrete under mechanical stresses, such as those encountered in earthquake zones or in military applications. Service life encompasses both the serviceability, a property primarily acquired by a materials system during its

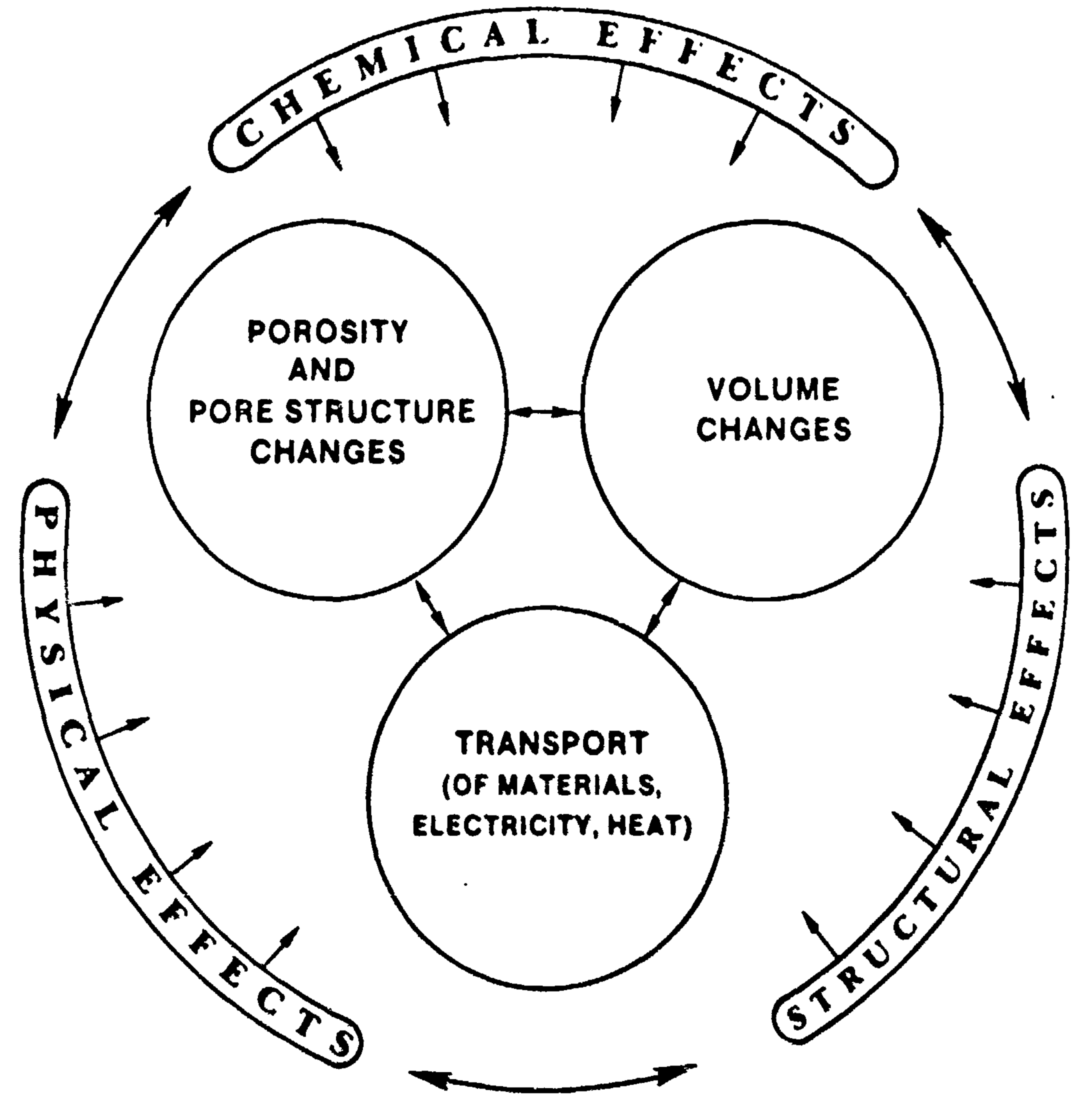

FIGURE 2. A simplified schematic representation of the interrelationships between the environmental effects and internal changes causing degradation.

production, and durability, a kind of performance that depends on the environmental conditions of use--both of which give a measure of success that may be compared with the planned, predicted, or expected life of the system under consideration.

This report obviously cannot discuss all aspects of durability and serviceability. Emphasis is given to topics that, in the view of the committee, are the pivotal issues relative to durability that deserve in-depth coverage. Thus, some well-known technical challenges are mentioned only briefly, whereas some institutional issues are covered in somewhat more detail.

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PART II

TECHNICAL AND INSTITUTIONAL BACKGROUND OF CONCRETE DURABILITY

II-1

TECHNICAL ASPECTS OF CONCRETE DURABILITY

This chapter reviews the fundamental causes of at least the major classes of durability problems that affect concrete in service and discusses methods available for preventing or at least ameliorating their effects.

OVERVIEW

This report is confined primarily to matters concerned with the durability of concrete in service; techniques of repair and replacement of damaged concrete are not included. Considerable information on these latter matters is available in the technical press, in the documentation assembled by the Repair, Evaluation, Maintenance, and Rehabilitation project of the U.S. Army Corps of Engineers (Scanlon et al., 1983), and as part of the Strategic Highway Research Program (SHRP) of the National Research Council on behalf of the nation's highway departments (TRB, 1986).

Some of the special characteristics of ordinary portland cement concrete should be discussed before proceeding to more specific considerations of durability problems. As usually proportioned and placed, fresh concrete is a mixture of rock or synthetic fine and coarse aggregates, portland cement, sometimes mineral and chemical admixtures, and water. It is made at the construction site or at a central plant; it is not an "off-the-shelf" finished product. The flow properties or rheological behavior of the fresh concrete system is strongly influenced by the suspended fines in the liquid phase that constitute the fresh cement paste that, when hardened, acts as the binder material. There must be a sufficient amount of this binder material to coat all of the aggregate and provide a continuous matrix in the hardened concrete. Equally critical is the water content in this binder, expressed either as a water:cement ratio or a water:cementitious solids ratio, which controls the porosity, microstructure, and permeability of the final concrete and, to a large extent, its resistance to environmental attack.

This is well understood, and existing standard methods of proportioning concrete mixtures provide for a maximum water:cement ratio that can be allowed, depending on the anticipated conditions of exposure (ACI, 1984). These restrictions are specifically aimed at preventing durability problems or at least mitigating their effects.

However, the extent to which the local water content and, in consequence, the porosity and permeability of the hardened product may be inhomogeneous in individual concrete members is not generally appreciated. Concrete is ordinarily batched at a sufficiently high water content so that slight sedimentation takes place within the mass before it sets, which brings water to the upper surface of the member--the so-called bleed water. While this is useful in providing water at the upper surface for curing, it also results in the more important but unappreciated fact that the upper portion of the concrete member may have a substantially higher local water content than the bulk of the concrete (Dewar, 1985). Similar, but usually smaller, increases in local water content may also occur at the side surfaces. Even within the "heart" of a concrete member, where the local water content is not higher than expected, local inhomogeneities occur that may have important consequences.

While the strength in these affected zones may be decreased slightly by the higher local water content, these structural consequences are unimportant compared to the influences these inhomogeneities may have on durability. The sedimentation processes described tend to set up local bleeding channels. These are, in effect, vertical pipes of very high water content that provide paths of relatively high permeability throughout the hardened concrete. Where such channels encounter large aggregate pieces, pools of water tend to form immediately under the aggregates, and porous, or even empty, zones may develop in the hardened concrete (Powers, 1939).

As will be explained later, many concrete durability problems arise as a result of the transport of water and dissolved solutes into the concrete. The surface of a concrete member serves as a kind of skin that acts as the barrier to substances entering from the external environment. Unfortunately, the upper surface of a concrete where extensive bleeding has taken place may be a poor barrier because of the permeability caused by the high local water:cement ratio at the time of setting. If, as is often the case, curing is neglected, the excess water evaporates quickly, and the hydration in these surface regions slows down and stops, making the barrier layer even less effective (Neville, 1981). Even worse, once solutions have entered the concrete, the presence of bleeding channels may provide an easy distribution path within the concrete member itself. These effects are probably relatively limited in a concrete having a low water:cement ratio, but, as the water content increases, the effects may become progressively more pronounced. As a consequence, much concrete actually placed in service is ill-equipped to withstand the various processes of deterioration that may result from exposure to the outdoor environment. This lack of in-service reliability is a major problem facing the concrete industry. Industry leaders recognize that, if concrete is to maintain its position as the basic material for building and civil engineering, its reputation as a solid, reliable material must be restored (Newman, 1963).

CAUSES OF PREMATURE CONCRETE DETERIORATION IN SERVICE

Concrete in service is susceptible to a variety of difficulties--usually induced by environmental exposure but occasionally produced by internal effects alone--that lead to premature deterioration. In this section are described the characteristics of various concretes that render them susceptible to the chemical and physical responses that constitute deterioration processes.

Pore Structure of Cement Paste in Concrete

The important characteristic that most nearly governs the behavior of concrete in terms of durability responses is the existence of an at least partly continuous pore structure within the hardened cement paste component, along with a connected set of voids prominent in the regions of the interfaces between individual pieces of aggregate and the cement paste. Like fully dense ceramics, hypothetical fully dense concretes would be very strong; equally important, they would be free of most types of durability problems (Neville, 1981).

The paste pore system arises from several distinct effects. The larger pores--the so-called capillary pores--are remnant spaces that were originally occupied by water in the concrete mix when it hardened and that were not wholly filled in by subsequent deposition of cement hydration products. The finest pores, on the order of nanometers in size, may be at least in part intrinsic internal spaces developed within, rather than between, individual cement hydration product particles. These do not ordinarily influence durability.

The amount and degree of continuity of core pores in concrete are very much reduced by incorporating silica fume or slag in appropriately large proportions and are also somewhat reduced by fly ash and other pozzolans. This is especially true if these mineral admixtures are accompanied by high-range water reducers or high dosages of ordinary water reducers, which deflocculate the fresh cement paste. In all these approaches, proper curing cannot be ignored. It is the combination of these beneficial approaches that gives the desired impermeable pore structure and durability.

The zones within the paste near, and influenced by, adjacent aggregate pieces tend to develop a special system of coarser and more nearly continuous pore spaces. In addition, microcracks tend to develop at the actual interfaces as a result of drying shrinkage or from even comparatively modest loadings that augment local permeability of these zones. On a much grosser scale, the existence and importance of bleeding channels in many concretes has already been mentioned.

The various types of pore or void space tend to be filled with water solutions when concrete is continuously wet, but they dry out progressively if the concrete is subject to external drying or in some cases to internal "self-desiccation" by hydration. Most of the pore spaces will refill readily when the concrete is rewetted, because of the partial continuity of the pore system. Concretes batched at low water contents and properly consolidated tend to develop a much tighter, less impermeable internal pore structure, with smaller pores and less pore continuity.

The existence of these systems of internal pores influences durability in some distinct ways:

- Under wet or partly wet conditions, the water solution present in the pores will freeze if the temperature goes low enough. The freezing action may generate local distress. Repeated cycles of freezing and thawing can result in accumulation of damage and eventual deterioration and cracking of the concrete.

- The pore system provides the means of ingress of dissolved substances from the external environment, some of which may react with specific concrete constituents and result in various forms of chemically induced deterioration processes.

- Certain concrete components are chemically susceptible to in situ alteration involving production of new phases of larger volume, with sometimes detrimental consequences.

The major components of the hardened cement paste in concrete are calcium silicate hydrate gel (C-S-H gel) and calcium hydroxide. Both are susceptible to dissolution by flowing water. Indeed, if the concrete is subject to the action of extremely pure water, such dissolution results in measurable and in some cases severe damage.

Other minor hardened cement paste components may be altered chemically under the influence of dissolved substances that may enter through mass action when partly dry concrete is rewetted or by diffusion through the pore system if the concrete is continuously wet. Dissolved alkali or calcium sulfates may cause conversion, in situ, of existing calcium aluminate sulfate hydrates of low sulfate content to ettringite, which is the equilibrium high-sulfate variety of calcium aluminate sulfate hydrate. In concrete exposed to sea water, the sulfate may cause in situ conversion of calcium hydroxide to gypsum, and also magnesium hydroxide may be produced from MgO. These products have increased volume that causes the development of expansive forces within the concrete and may cause cracking of the concrete; also, the formation of secondary gypsum may result in softening of the concrete, with a significant loss of strength.

Still other effects may result from entry of dissolved substances through the concrete pore system. Salts--specifically, sodium chloride or calcium chloride deicer salts--may enter in sufficient amount to interfere with the usual passivation of steel reinforcement in concrete and cause active steel corrosion (ACI, 1985). Sodium and other dissolved alkali ions introduced from the external environment through the pore system may raise the pH of the water solution held in the pores. This can initiate, or increase, the rate of a reaction with certain aggregate components (alkali-aggregate reaction), and the resulting reaction products can produce internal expansive forces and cause cracking.

It should by now be evident that one of the fundamental causes of concrete deterioration in service is the existence within the concrete of a continuous system of pores and channels within which freezable water solutions may be held and through which dissolved species from the external environment may enter and spread throughout all parts of the concrete. A hypothetical pore-free concrete would be free of these effects and their detrimental consequences. More attention therefore should be paid to concrete microstructure, particularly the actual pore structure developed in actual, field-produced concrete. Proper curing practices are most important in ensuring formation of the required pore structure.

Effects of Pores Within Aggregates

The various kinds of rock or synthetic rock used as aggregates in concrete may contain a degree of porosity and an internal pore structure that could contribute to certain harmful processes affecting concrete in service.

A particular type of problem with severe economic consequences is a characteristic freezing-induced deterioration of certain concrete pavements, called "D-cracking." The problem involves the freezing of water entrapped in the pores that exist within individual pieces of susceptible aggregate particles, especially coarse pieces located in the lower portions of concrete pavements adjacent to joints, where water typically accumulates. The larger sizes of such aggregates are particularly prone to damage in these circumstances (Stark and Klieger, 1973). Relatively nonporous aggregates are immune, and studies have shown that the damage is associated especially with aggregates that have a large amount of pores of a particular intermediate size range (Kaneuji et al., 1980).

Pores in aggregates also may contribute to other kinds of problems. The fine but continuous pore system contained within grains of most opals and some cherts permits rapid distribution of alkalies to all parts of an aggregate piece when any part of it comes in contact with an alkali-rich concrete pore solution, and thus rapid alkali aggregate attack is facilitated. Other alkali-reactive aggregates, lacking such an internal network of pores, react slowly and progressively from the outside inward.

On the other hand, not all effects of pores in aggregates are harmful to durability. For example, aggregates with a large amount of relatively large and free-draining pores are often used in lightweight concrete structures. The pores become water-saturated during the concrete mixing process. They have the beneficial effect of acting as water reservoirs capable of providing extra water for curing and cement hydration without at the same time increasing the effective water:cement ratio of the paste. In this manner, difficulties such as plastic shrinkage cracking and incomplete or spotty hydration can be avoided without also producing a coarse, permeable interconnected pore structure within the hardened cement paste itself.

There is a special class of "shrinking aggregates" that have caused certain difficulties in concrete in California and a few other places. These aggregates apparently contain clay components that may be wetted readily in the concrete mixing process but shrink on subsequent internal dehydration brought about by cement hydration processes. Loss of rigidity, high shrinkage, and sometimes cracking of the concrete may then occur.

Freezing and Thawing Damage in Concrete

Freezing damage has been alluded to earlier as a consequence of the existence of water solution-filled pores in cement paste and in certain aggregates. Because of the widespread nature of the problem and the seriousness of freezing and thawing damage in concrete, additional discussion is given here.

Damage on freezing occurs only if either the paste or the aggregate pore system is critically saturated with freezable water solution (Fagerlund, 1975). The pore water in concrete is ordinarily a fairly concentrated alkali hydroxide solution that requires a somewhat lower temperature than 0°C (32°F) to freeze; indeed, pore solution held in very fine pores may not freeze unless temperatures substantially lower than this are reached.

If the cement paste in concrete is provided with a system of closely spaced air bubbles, the paste will be protected against damage from freezing even if the pores are critically saturated and freeze repeatedly. Air-entraining agents that produce satisfactory bubble systems are almost universally used today in concrete in freezing climates. Nevertheless, considerable damage actually does occur in areas with many freeze-thaw cycles because the specifications regarding the air bubble system or indeed the required total air content in concrete are not always met.

The incidence of damage associated with freezing and thawing appears to be enhanced and magnified if high concentrations of salts, especially sodium chloride, are present at the time of freezing.

Distress from the freezing of water in aggregates is relatively uncommon in building structures but is not uncommon in slabs on grade, such as highways and airfields, where the opportunity exists for the concrete to be almost continuously wet. The presence of an appropriate air bubble system in the paste part of the concrete does not, however, protect the aggregate from freezing.

The susceptibility of particular classes of aggregate to freezing damage is a function of the total porosity, the size distribution of the pores, and the mechanical competence of the aggregate solid--i.e., its ability to resist dilation induced by freezing. Large-sized aggregate pieces are far more susceptible than small-sized pieces of aggregate of the same type and pore structure.

Sulfate Attack

Another mode of deterioration of concrete that stems from the existence and continuity of its pore structure is sulfate attack. This process produces either internal expansion followed by cracking or else softening of the paste in concrete without consequent expansion, both as the result of penetration of dissolved sulfate ions into the concrete.

The expansive response is associated with concrete made from portland cements that have a relatively high content of tricalcium aluminate, a compound nearly always present in portland cement. In the presence of intruded sulfate, usually from ground water, tricalcium aluminate hydration products other than the ettringite already present, and any residual tricalcium aluminate are converted to ettringite (6-calcium aluminate trisulfate-32-hydrate). Ettringite formation under such circumstances involves a volume increase, and the internal expansion may result in cracking and deterioration of the concrete. Use of cements low in tricalcium aluminate is effective in preventing this form of sulfate attack.

The softening response mentioned is characteristic of reactions of certain concretes in sea water. Sea water contains large concentrations of sulfate and magnesium ions as well as sodium and chloride ions. The softening attack appears to involve decomposition of certain cement paste constituents and precipitation of secondary gypsum (calcium sulfate dihydrate) and magnesium hydroxide within the concrete. Sulfate attack in sea water is inhibited to a large extent by the chloride ions present. In general, concretes with high cement content and low water:cement ratio are not susceptible to sulfate attack.

Alkali-Aggregate Reactions

The durability problems stemming from alkali-aggregate reactions have already been noted in terms of the influence of the pore structure of the paste and, to a lesser extent, the pore structure of certain aggregates. The existence of the paste pore structure is a necessary but not a sufficient feature for this type of problem to develop in concrete. For the reaction to occur, the pores must contain a sufficient concentration of dissolved alkali hydroxides, and this reactive-pore solution must come in contact with reaction-susceptible aggregate components. Depending on the particular type of reactive aggregate present, certain other conditions also must be met before the concrete will suffer notable distress.

Two broad classes of alkali-aggregate reactions are commonly recognized: alkali-silica reactions and alkali-carbonate reactions. In alkali-silica reactions, glassy, amorphous, or thermodynamically unstable forms of silica in the aggregate are converted to gels by reaction with sufficiently concentrated alkali-hydroxide pore solutions. If the proportion of reactive aggregate is near the pessimum (or worst case) proportion characteristic of that kind of aggregate, the gels formed tend to swell and produce local and then overall expansion that results in cracking of the affected concrete. In the alkali-carbonate reactions, specific kinds of dolomitic rock, usually containing the clay mineral illite, have been found to be alkali-reactive. The mechanism involves conversion of magnesium from dolomite to magnesium hydroxide, which again results in expansion and cracking.

In alkali-silica reactions with aggregates containing silicate rocks, notably graywackes and phyllites, it has been found that the reactions with the alkaline pore solutions occur slowly and over a period of years, and only limited amounts of gel are produced.

The alkali hydroxide found in concrete pore solutions is usually derived from certain alkaline constituents in the portland cement, but it may also be supplemented by outside sources such as salt intrusion. More recent evidence indicates that another source is alkali liberated internally from certain alkali feldspars and other alkali-bearing rock constituents that may be present in aggregate.

Practical damage to concrete structures almost always depends on the continued presence of a high moisture level in the concrete; if concrete is allowed to dry out permanently, little damage should be expected. Thus, interior concrete in office buildings is usually not at risk whereas exterior concrete in the same structures may be.

Steel Corrosion in Concrete

Concrete in service usually contains reinforcing steel, and many concrete structural members are prestressed or post-tensioned with high-strength bars or cables. Both types of steel are ordinarily immune from corrosion within concrete because of the mechanism of passivation, which arises from the highly alkaline pore solution present around the steel as well as elsewhere in the concrete. Passivation depends on the formation and maintenance of a thin protective layer of oxide formed around the steel.

However, the presence of chloride ions in the pore solution, either from chloride-bearing substances incorporated in the concrete mixture or by entry from the outside, depassivates the steel and renders it subject to corrosion. A similar effect may result in some cases from progressive inward movement to the steel of a surface zone of concrete that has reacted with atmospheric carbon dioxide. The solutions within such carbonated zones have much lower pH levels than uncarbonated concrete, and steel passivity is not maintained when in contact with them. In well-proportioned and consolidated concrete, the rate of inward movement of the carbonated zone is slow enough that carbonation-induced depassivation is usually not a significant factor. Once passivation is lost, electrolytic corrosion of the steel may take place at a rate limited either by the rate of oxygen transport to the steel or by the electrical conductivity of the concrete surrounding the steel.

Important sources of chloride ions that cause depassivation and allow corrosion damage in concrete include deicing salts and chlorides deliberately introduced as accelerators or as ingredients of other admixtures or those inadvertently introduced by the use of brackish water or salt-contaminated aggregate. Penetration of salt water from external sources, including sea water exposure and salt spray, are also of importance.

The effect on concrete durability does not stem from the corrosion process itself but rather from the continued production of the corrosion products (rust), which occupy more volume than the steel from which they form. This generates expansive stresses that eventually cause cracking and spalling of the concrete cover over the steel. Structural collapse that is due to steel corrosion itself is relatively rare but not unknown.

Thermal Cracking

A source of distress in concrete that does not involve the pore structure of concrete but may have serious durability consequences is thermal cracking. This occurs when stresses are set up within different parts of concrete that are subjected to significantly different temperatures. Usually the immediate source of the temperature gradient is the heat developed and to some extent retained in the interior parts of thick concrete members that are undergoing rapid cement hydration, ordinarily during the first day after placing. The problem is particularly severe when the exterior portions of the concrete are exposed to cold weather. The cracks formed permit later entry of water and dissolved substances into the concrete, with all of the problems that ensue from such entry.

Mechanical Distress Induced By Nonconventional Loads

Concrete structures are ordinarily designed to withstand conventional service loads, including wind loads, and in earthquake-prone areas they are designed to resist seismic loads as well. Ordinarily, distress resulting from underdesign of concrete structures for conventional loadings is extremely rare. However, some concrete structures in service may be subjected to unforeseen mechanical loadings, sometimes transient in character, that may produce cracking or other distress sufficient to impair the durability of the structures. Illustrations of sudden transient loading may involve unexpected seismic events, explosions, exposure to tornadoes or other unusually high wind loadings, and sudden foundation movements. Distress caused by dynamic fatigue cracking, especially where the fatigue cycles include a significant tensile component, may sometimes occur.

Concrete is fundamentally a brittle material, although not particularly notch-sensitive. Nevertheless, in large structures, stress intensities locally exceeding the critical stress intensity factor may sometimes occur and may lead to cracking and crack propagation. While the cracking ordinarily produced by such processes does not usually reach a level sufficient to threaten the structural performance of the concrete, the presence of the cracks produced provides easy access to the interior of the structural members by water and outside agents, with severe effects on the durability. Progressive deterioration from such processes as repeated freezing and salt intrusion may follow once the structural members have cracked from any of these causes.

Deterioration as a Result of Fire Exposure

Although not in itself flammable, concrete is susceptible to deterioration when exposed to fire. Some of the fire-induced damage may be associated with the concrete pore system, and some may arise from other causes. In response to rapid heating, pore water and loosely bound structural water are rapidly evolved as water vapor or steam. In impermeable concrete, the rate of evolution exceeds the capacity for mass transport through the pore system, resulting in cracking and spalling.

The problems of concrete in fire situations are not limited to water transport difficulties. Even for dry concrete, the almost inevitable mismatches between the coefficients of thermal expansion of the cement paste and of the aggregate minerals may result in cracking and structural damage. Also, certain materials used as pore fillers or reinforcement in some concretes may not survive fire exposure; such materials include sulfur, polymeric impregnants, and polymer-fiber reinforcing materials.

Finally, there is a specific effect peculiar to concrete that contains certain aggregates. There is a sudden conversion of alpha-quartz to beta-quartz at 573°C (1063°F) that involves a substantial volume increase. Heating above this temperature severely impairs the integrity of quartz-bearing aggregate. If the temperature reaches 900°C (1652°F), damage caused by chemical decomposition of calcium carbonate (limestone) will also occur.

In severe fires, structural damage may require that the entire structure be replaced, but often this is not the case. For structures that remain in service, the cracking and distress experienced in the fire may severely impair the resistance of concrete to subsequent freezing and thawing or other environmentally induced degrading agents.

Abrasion and Scour

Concrete exposed to rapidly flowing water that is carrying suspended particles will suffer abrasion damage to an extent determined largely by the internal structure of the hardened cement paste and also the abrasion resistance of the aggregate. Abrasion in concrete exposed to contact with moving solids, such as ice flows, is also a problem in some circumstances.

When the flow of a fluid past concrete is sufficiently rapid and the surfaces of the exposed concrete contain irregularities, cavitation may occur that generates very strong impact forces that concrete is generally unable to resist. To avoid cavitation, hydraulic channels and conduits need to be designed so that flow does not encounter irregularities that create pockets of greatly reduced pressure, the collapse of which causes cavitation.

Penetration of High-Velocity Projectiles and Protection of Hardened Installations

The resistance of concrete to penetration of high-velocity projectiles, either as a result of military operations or from exposure to tornadoes or other natural disasters, is an area of importance. Unfortunately, comparatively little fundamental information on this problem is available in the open literature. Research into the effects of high-velocity impact loadings on concrete is still in a very early stage. Similarly, comparatively little information is available concerning the protective properties of concrete in installations hardened against access by conventional or unconventional means that do not involve high-velocity penetration.

Other Durability Problems

Salt Action--Concrete, especially in sidewalks, curbs, gutters, and highways, that is exposed to repeated cycles of wetting and drying and of temperature cycling in the presence of salts sometimes undergoes progressive scaling and breakdown of cement paste, even in the absence of freezing and thawing cycles. Details of the mechanisms involved are fairly obscure. The influence of repeated recrystallizations of salts within the concrete is implicated by various authorities but categorically rejected by others. Nevertheless, damage to concrete structures said to be associated with the action of salt and other ionic species is reported from many parts of the world.

<u>Soft-Water Attack</u>--Soft-water attack may occur in those few areas where the ground water or industrially produced desalinized water is extremely pure. Movement of such water through or over concrete dissolves calcium hydroxide and other cement hydration products and results in progressive deterioration of the concrete by leaching.

<u>Acid Attack</u>--Acid attack on concrete is more frequently encountered. Concretes exposed to acids from industrial processes, organic decomposition, sewage, mine waste, or food suffer progressive chemical deterioration, especially when the exposure is continued over long periods.

<u>Miscellaneous Sudden Exposures</u>--Most of the problems previously discussed, with the exception of cavitation damage, fire, and projectile impacts, arise from long-continued exposure of concrete structures to certain more-or-less normal environmental factors. Concrete structures may be damaged by brief and often sudden exposure to special conditions or assaults. In this category, in addition to others previously mentioned, are the effects of exposure to lightning; to sudden high temperatures, as in the case of concrete jet-engine test stands; and to repeated impacts at low velocities, such as might be experienced by concrete marine structures with ice bodies in Arctic or Antarctic waters.

<u>Radiation Damage</u>--Possible effects of ionizing radiation on concrete are not well understood, but experience suggests that low-level exposure to most forms of radiation does not induce severe deterioration in concrete. However, damage may be sustained under high levels of exposure to some forms of radiation. The subject is of obvious importance in view of the widespread use of concrete containment structures at nuclear power plant facilities in the United States, and especially so in view of the Chernobyl accident.

PREVENTIVE AND AMELIORATIVE MEASURES

Successful application of measures to prevent or ameliorate premature degradation of concrete in service requires an understanding of the problems to be expected and of existing knowledge concerning the effectiveness of various preventive methods. The current situation is difficult to summarize, and generalizations can be dangerous. Some durability problems are reasonably well understood as to occurrence, mechanism, and preventive measures. Other problems are well understood by experts but generally not by designers, specifiers, or concrete producers. Still others need more long-term research on both causes and preventive measures for successful implementation.

Being able to make workable concrete mixtures having a low water:cement ratio produces a modified pore structure that results in decreased permeability and thus increased overall durability.

A development of importance in recent concrete practice is the growing use in concrete of ground granulated iron blast-furnace slag, silica fume, and fly ash. To different degrees, depending on the specific material incorporated, use of these materials tends to promote concrete durability; a finer, tighter cement paste pore structure is ordinarily developed, and permeability is reduced, sometimes very significantly. Also, the amount of calcium hydroxide produced and retained in the concrete is reduced, sometimes substantially, with beneficial consequences for most durability responses.

However, the effects of the use of such materials on durability may not always be as favorable as hoped. Problems may arise from the replacement of too much of the portland cement that would otherwise have been used in the absence of these materials, the use of excessive amounts of these materials, poor selection of the specific material, and poor quality control of the material. In addition, special problems may arise from interactions of these materials with chemical admixtures widely used in current concrete practice.

In general, widespread use of these materials is viewed as a positive development with respect to potential concrete durability, but their effective use will require a higher degree of technical sophistication on the part of many concrete producers than they have traditionally exhibited in the past.

The following comments relate to prevention or amelioration of some specific concrete durability problems.

Prevention of Freezing and Thawing Damage

Air entrainment is considered a reliable method of preventing freezing damage in paste, provided that a proper spacing of air bubbles can be assured. Information on such use is widespread in the industry, and actual use when specified is almost universal. Unfortunately, structures continue to suffer damage from this cause. Actual control over the dosage of air-entraining admixture is ordinarily maintained by a simple procedure of measuring the total volume of air in a sample of fresh concrete taken from the mixer at intervals. This test has been found to correlate well with bubble-spacing factor when specified air-entraining agents are used with normal concrete. However, when fly ash is used, the possibility exists that at least some of the time the expected bubble size distribution and spacing factor are not attained at the specified air content. A similar problem may arise when certain high-range water-reducing admixtures are used along with the air-entraining admixture.

The related problem of freezing damage within aggregates, especially in the form of D-cracking, is not widely understood except by specialists. The only method of prevention is to avoid the use of susceptible aggregates. Laboratory procedures are available both for empirical testing of resistance of aggregates to freezing and thawing and for determining the total porosity and the pore size distribution of rocks so that the use of susceptible aggregates can be avoided. Unfortunately, local political considerations often appear to preclude adoption of the needed specifications.

Damage caused by freezing in aggregates can also be limited by specifying aggregates of small nominal maximum size, even though such practice ordinarily leads to greater cement content and thus more expensive concrete.

Prevention of Sulfate Attack

Sulfate-resistant portland cements with limited tricalcium aluminate content are widely available in areas subject to sulfate attack problems and are ordinarily specified and used with good results. Use of certain high-calcium fly ashes with active calcium aluminate compounds or alumina-rich glass has been shown to increase damage of concrete exposed to sulfate attack. Mather (1982), for example, found that several such fly ashes, when used at 30 percent replacement levels in concrete with cements having high tricalcium aluminate content, made the resulting concrete less sulfate-resistant.

There has been some question of the validity of the standard test methods for sulfate resistance on which these and other results have been based, and, indeed, general uncertainty exists as to the influence of different fly ashes on resistance to sulfate attack. However, current research (Mehta, 1986, personal communication) indicates that, if the incorporation of a fly ash into cement results in an increased amount of calcium aluminate monosulfate hydrate being produced in the paste, such pastes will suffer damage when immersed in sulfate-bearing solutions. Conversely, if only ettringite is produced, the pastes were shown to be immune to sulfate-induced damage. Thus, it appears that a more unequivocal procedure can be developed to test fly ashes for their contribution to sulfate attack susceptibility.

The susceptibility of concrete to damage in sea water is a related topic of much practical concern. The most important characteristic determining the durability of concrete under such exposure appears to be its permeability (Mehta, 1980), but the attack is restricted by the deposition of insoluble coatings of magnesium hydroxide and calcium carbonate. It appears that limiting the tricalcium aluminate content in cement to less than 10 percent and at the same time limiting the water:cement ratio to 0.40, or perhaps 0.45, will confer satisfactory resistance in most cases.

Prevention of Deterioration From Alkali-Aggregate Reactions

Conventional tests for determining the susceptibility of specific aggregates to alkali-aggregate reactions, other than the "quick chemical test," ASTM C 289 (ASTM, 1986), are time-consuming and often are not attempted, and the results of the quick chemical test often are considered unreliable. Reliance, therefore, is often placed on previous history of successful use of a particular aggregate or else on the incorporation of fly ash, natural pozzolan, or silica fume as a preventive measure. Accelerated test procedures for the recognition of susceptible aggregates have been developed in several countries (Oberholster and Davies, 1986) although not yet adopted by standardizing bodies.

Alkali-aggregate reaction may be avoided if a nonsusceptible aggregate is used, if the alkali-hydroxide concentration of the pore solution in the concrete is maintained at a sufficiently low level by use of low-alkali cement and avoidance of any other source of alkali, or if structures are continuously maintained in a dry condition. Use of silica fume in adequate dosage appears to reliably prevent damage. Use of fly ash, natural pozzolan, and slag may prevent damage, but testing of the specific material is usually necessary to assure favorable results in practice, since some materials of this type are relatively ineffective or indeed hazardous. Damage, once started, may be progressive, although sometimes at a very slow rate, continuing until either all the available alkali is in the reaction products or all the available reactive constituent is reacted. Treatments aimed at isolating the concrete from sources of water in certain cases may be effective in arresting the progress of the distress, but they are not universally effective. Certain silane coatings when properly applied appear to be particularly effective.

The practical importance of sources of alkali other than that contained in the portland cement is controversial. Some authorities maintain that cases of alkali-aggregate attack damage caused by such non-cement alkali sources are uncommon and that the use of low-alkali cement will practically always confer immunity.

Expanded research on alkali-aggregate reactions and preventive measures has recently been undertaken in a number of countries, notably the United Kingdom, Japan, Canada, and Denmark, and new insight into testing and preventive measures may be forthcoming.

Prevention of Damage Due to Steel Corrosion

An effective measure for preventing steel corrosion appears to exist in the use of an epoxy coating on reinforcing steel. Chemical admixtures for the prevention of corrosion, notably calcium nitrite, are another possibility. The mechanism of their action and their effectiveness is being explored. Strict enforcement of minimum depth of concrete cover of the reinforcement would be the best type of protection, but it is often not obtained. The importance of providing tight, impermeable, well-consolidated concrete as the cover over steel is not generally appreciated.

The use of specially modified concrete compositions for achieving a dense and impermeable cover over steel has been recommended. Latex-modified concrete or special concrete prepared with heavy dosages of high-range water reducers and incorporating large amounts of silica fume have been suggested. The purpose of these actions is to modify the internal structure to minimize both the electrical conductivity of the cover concrete and the rate of oxygen transport through it. Thus, corrosion would be prevented from occurring at any but negligibly slow rates. The use of special gypsum-free "low-porosity" concrete incorporating lignosulfonates and alkali bicarbonates would have the same effect and would provide the added benefit of an extra degree of alkalinity in the pore solution to help maintain steel passivation.

The continued use of admixtures containing at least small amounts of chloride is a subject of much current controversy within the concrete field. Some authorities propose a complete ban on such inclusion, while others feel that the economic benefit associated with the acceleration attained by the use of chlorides outweighs the enhanced corrosion risk associated with this practice.

Possibly the single most expensive and widespread specific form of concrete deterioration is the corrosion of steel in concrete bridge decks, bridge structural members, and parking garages induced by deicing salt. Possible replacement of salt for this purpose by less aggressive (but far more expensive) chemicals--notably calcium magnesium acetate--is under serious study. Active cathodic protection for both new and existing concrete bridges is becoming accepted, and an unconventional experimental procedure for electrochemically induced removal of chloride from existing salt-contaminated structures is under study.

Some General Preventive Measures

Use of Impermeable Coatings--As mentioned previously, many durability problems arise as a result of the penetration of water and of dissolved substances, such as salt, sulfates, and alkalies, into the concrete. The recent development of new and more effective concrete coating formulations, principally based on silanes, may help prevent such problems. These coatings typically retard penetration of water into concrete but permit outward vapor transport so that the concrete may dry out. Use of such coatings in applicable circumstances may prevent or mitigate some forms of sulfate attack, alkali-aggregate attack, and steel-corrosion problems.

Development and Prospective Durability of "High-Performance" Concretes--"High-performance" concretes, usually made with high cement content and containing high dosages of both silica fume and high-range water reducers, are being developed and used by a number of agencies. Such concretes are batched at extremely low water contents and develop very impermeable pore structures that have completely eliminated most coarse, connected porosity. Selected aggregates, sometimes entirely synthetic, may be used to avoid the strength limitations ordinarily imposed by the usual types of crushed rock or gravel aggregate materials. Extremely high strengths, several times higher than those of conventional concretes, can readily be obtained.

Tests indicate that, in addition to the high strengths obtained with such concrete, nearly all of the conventional durability problems can be avoided. The interior of concrete made this way is ordinarily self-desiccated and almost completely isolated from the external environment as a result of the impermeability developed. Thus, it is generally free from any effects of ingress of dissolved substances. While corrosion of steel may start to take place because of the relatively low pH levels produced in such concrete, the rate of corrosion that can be supported is negligible. The lack of freezable water or pore solution may prevent freezing damage, even in the absence of a deliberately introduced air-bubble system.

While such concretes are more expensive than ordinary concrete, their availability for use in situations where assurance of concrete durability is essential is a significant development.

Avoidance of Minimum-Cement-Content Concrete--One of the ultimate causes of the tendency of much present concrete to lack durability is the extreme focus of the concrete design and current specification procedures on strength, specifically f'_c, the design compressive strength at 28 days. In response to market demand based on this criterion, the strength-producing properties of many cements have been increased progressively over the years by a combination of finer and more uniform grinding and altered composition, especially resulting in increased ratios of tricalcium silicate to dicalcium silicate. The result is that a given strength can be attained at 28 days with a lower amount of cement than was formerly necessary. Unfortunately, low-cement concrete, while adequate to meet structural requirements, may be in a poor position to withstand the durability problems that concrete must if it is to perform adequately in long-term service.

Specific requirements for concrete components and the proportioning of concrete to promote durability are available and are generally imposed by larger and more technically sophisticated agencies. However, such agencies are distinctly in the minority, and most concrete is specified and produced with only cursory attention paid to durability considerations. It is this state of affairs that must be modified in the future.

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STATUS OF THE CONCRETE CONSTRUCTION INDUSTRY

The concrete construction industry is diverse and multifaceted, and this affects durability considerations. Concrete is used in almost every conceivable type of construction, from sidewalks and driveways to huge dams for flood control, irrigation, and waterpower needs. Because of the wide range of construction activities, the industry is highly fragmented. This fragmentation affects durability, since the large number of construction companies and the number of people employed make it difficult to ensure uniform construction quality.

Table 2, adapted from the Bureau of the Census' 1982 Census of Construction Industries, shows that over 95,000 contractors engaged in concrete work during 1982 and nearly $150 billion in annual receipts resulted from these activities. The obviously diverse nature of the industry and of the types of construction creates significant demands on the materials used to formulate the variety of concretes required.

Performance requirements for concrete durability have imposed a range of necessary characteristics for the components that make up concrete--hydraulic cement, aggregates, water, mineral admixtures, and chemical admixtures. Different cements are made to provide properties for different uses, including adequate resistance to aggressive environments. Aggregates may also be selected for performance in specific environments, but more often they are selected from locally available sources because of high transportation costs.

THE CEMENT AND CEMENTITIOUS MATERIALS INDUSTRY

Cementitious materials include hydraulic cements and pozzolans such as fly ash and silica fume. Portland cement is by far the most common type of hydraulic cement used in the production of concrete. The second most widely used hydraulic cement is ground granulated iron blast-furnace slag. A number of special hydraulic cements designed to achieve specific types of performance are also available. Materials such as fly ash, silica fume, and ground granulated iron blast-furnace slag are playing an increasingly important role in improving the durability of concrete in specific environments.

Portland Cements

The concrete construction industry in the United States in 1985 consumed about 87.6 million tons of portland cement, of which domestic

TABLE 2. Contractors Engaged in Concrete Work and Their Economic Significance

Standard Industry Classification (SIC)	Number of Companies	Number of Employees	Total Annual Receipts, billion $	Annual Payroll, billion $
Concrete Work Special Trade Contractors (1771)	19,986	157,241	8.21	2.31
General Contractors--Residential Buildings Other Than Single Family (1522)	7,464	62,702	7.85	1.08
General Contractors--Industrial Buildings and Warehouses (1541)	7,435	153,821	17.83	3.23
General Contractors--Nonresidential Buildings Other Than Industrial Buildings and Warehouses (1542)	22,112	359,856	52.30	7.26
Highway and Street Construction Contractors (1611)	10,111	212,610	18.16	3.99
Bridge, Tunnel, and Elevated Highway Construction Contractors (1622)	999	37,581	3.50	0.82
Heavy Construction Contractors (1629)	7,662	415,199	33.66	11.06
Excavating and Foundation Work Special Trade Contractors (1794)	19,646	135,968	8.18	2.15
Totals	95,415	1,534,978	149.69	31.90

Source: Bureau of the Census, 1982

production provided about 73.4 million tons and imports about 14.2 million tons (PCA, 1985). Consumption is expected to grow slowly, despite cyclical ups and downs, to about 80 million tons of domestic production and 12.5 million tons of imports for a total consumption of about 92.5 million tons in 1992 (PCA, 1986).

Manufacture of Portland Cement--Portland cement is produced by pulverizing clinker, which consists essentially of hydraulic calcium silicates and about 5 percent calcium sulfate as an interground, set-regulating addition. Materials used in the manufacture of portland cement also contain appropriate proportions of ingredients calculated as lime, iron oxide, silica, and alumina. The selected raw materials are crushed, milled, and proportioned in such a way that the resulting mixture has the desired overall chemical composition, generally dictated by strength and durability requirements.

Types of Portland Cement--Different types of portland cement are manufactured to meet different physical and chemical requirements for specific purposes, such as durability considerations. ASTM Designation C 150 (ASTM, 1985) provides for eight types of portland cement. A brief description of their uses is given in Table 3.

Blended Hydraulic Cement

Blended cements, which are made by a blending portland cement with pozzolan or slag, can provide increased durability by (a) helping avoid the detrimental effects of alkali-aggregate reaction, (b) providing potentially greater resistance to sulfate attack, and (c) providing for lessened heat evolution during hydration, thus moderating the chances for thermal cracking on cooling. American blended cements, covered by ASTM C 595 (ASTM, 1985), are of two major types: portland blast-furnace slag cement and portland-pozzolan cements.

Other Cements

Other types of cement are not covered by ASTM specifications. These include certain portland cements such as oil-well cements, waterproofed portland cement, plastic cement, expansive cement, and regulated-set cement. In addition, soluble silicate cement, hydrothermal cement, phosphate cement, and high-alumina cement are produced for various special purposes.

Availability of Cements

Some types of cement may not be readily available in all sections of the United States.

Type I, normal or "ordinary," portland cement is generally carried in stock and is furnished when no other type of cement is specified.

TABLE 3. Types of Portland Cement and Their Uses

ASTM Cement Type	Use
I, IA*	General-purpose where special properties not required.
II, IIA	Aids in providing moderate resistance to sulfate attack. Can be made to provide moderate heat of hydration for massive elements where control of thermal cracking may be required.
III, IIIA	Provides for the development of high early strength. Permits forms to be removed sooner and less curing time in cold weather. At later ages (more than 28 days) performance similar to Types I and IA.
IV	Provides for low heat of hydration where rate and amount of heat generated must be minimized (in massive structures) to avoid thermal cracking.
V	Aids in providing for sulfate resistance where soils or groundwaters have a high sulfate content.

Note: All of these cements can optionally be furnished as low-alkali cements having a maximum of 0.60 percent (calculated as Na_2O) for use with reactive aggregates.

* "A" denotes air-entraining capability to provide resistance to freezing and thawing.

If a given type is not available, comparable results frequently can be obtained using an available type. For example, high-early-strength concrete can be made by using higher cement content of Type I portland cement when Type III cement is not available. Also, the effects of heat of hydration can be minimized by using lower cement content, lower lifts, or artificial cooling when Type IV (low heat) cement is not available. Indeed, Type IV cement is only available under special order, and Type V portland cement may also sometimes be difficult to obtain.

Table 4 gives Bureau of Mines (1985) information on cement shipments from U.S. plants. It is obvious that portland cements are used far more extensively than blended cements and total well over

TABLE 4. Cement Shipped From U.S. Plants by Type of Product, 1985[a]

Cement Type	Quantity of 1,000 short tons	Percent of Consumption
General-use and moderate-heat (Types I and II)	73,700	91.3
High-early-strength (Type III)	2,772	3.4
Oil well	1,942	2.4
White	311	0.4
Sulfate-resisting (Type V)	372	0.5
Portland slag and pozzolan blended cements	802	1.0
Miscellaneous[b]	845	1.1
Masonry cement[c]	3,187	-

[a]Includes Puerto Rico. [b]Includes waterproof, low-heat (Type IV), expansive, and regulated fast-setting cements. [c]Special use not included in totals.

Source: U.S. Bureau of Mines, 1986, Cement in 1985, Annual Advance Summary

90 percent of shipments. This is in contrast with most European countries and Japan, where the use of blended cements is much more extensive.

Portland cement shipments to specific customers provide a good market index. Table 5 shows information compiled by the U.S. Bureau ofMines for 1985. In addition, the apparent use of portland cement by markets is shown in Table 6 as a 5-year average for the 1981-1985 period (PCA, 1986).

Other Cementitious and Pozzolanic Materials

Some pozzolanic materials are used to reduce or eliminate potential expansion from alkali-reactive aggregates. Where reactive aggregates are used in concrete for lack of nonreactive aggregates, a low-alkali cement or a proved pozzolan--i.e., tested according to ASTM C 441 (ASTM, 1986)--can be used to prevent expansion. Some pozzolanic materials also may improve the sulfate resistance of concrete. Other cementitious and pozzolanic materials, such as fly ash, ground granulated blast-furnace slag, and silica fume, play an increasingly important role in the production of concrete for a variety of uses.

TABLE 5. Percent of Portland Cement Shipments by Type of Customer, 1985

Customer	Percent
Building materials dealers	5.5
Concrete product manufacturers	12.2
Ready-mixed concrete plants	70.1
Highway contractors	4.6
Other contractors (including oil well)	5.8
Federal, state, and other government agencies	0.3
Miscellaneous and own use	1.5
	100.0

Source: U.S. Bureau of Mines, 1986, Cement in 1985, Annual Advance Summary

TABLE 6. Apparent Use of Portland Cement by Market, 1981-1985

Market	Percent Distribution (5-year average)
Building construction	
Residential building	29.5
Public building	7.1
Commercial building	24.3
Farm construction	3.9
Total building	64.8
Public works construction	
Streets and highways	19.4
Water and waste	6.7
Utilities	1.3
Other public works	2.0
Total public works	29.4
Nonconstruction (oil wells, mining, miscellaneous)	5.8
Total all uses	100.0

Source: Portland Cement Association, 1986

Materials of this type are extensively used as supplements or partial replacements of portland cement by concrete producers, in a manner similar to their use in blended cements.

Fly ash--A by-product of burning powdered coal at electric power plants, fly ash is a fine material collected from the combustion airstream by electrostatic precipitators. Although many fly ashes do not act as cements in themselves, when combined with portland cement in concrete they produce additional amounts of hydration products by reacting with the calcium hydroxide present, thereby reducing the amount of calcium hydroxide formed, and beneficially modify the microstructure of the cement paste formed. Some fly ashes contain a relatively high percentage of lime, which confers a greater degree of reactivity in the concrete.

ASTM C 618-85, "Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete" (ASTM, 1986), at present contains specifications for two classes of fly ash, Class F and Class C. Approximately 10 to 20 million tons of fly ash that meet ASTM C 618 specifications are available annually in the United States. However, a 1984 survey of ready-mixed concrete producers conducted by the National Ready-Mixed Concrete Association (NRMCA) indicated that fly ash use in 1983 (NRMCA, 1984) was only about 2.5 million tons. This amount is low for an industry that consumes approximately two-thirds of the portland cement consumed in the United States.

Pozzolanic materials are sometimes used in concrete to help reduce internal temperatures during the period of active hydration. In massive structures such as dams, high internal temperatures can develop because of the slow dissipation of heat generated by the cement hydration processes. The generation of these temperatures can be minimized by using Types II, IV, V, IS, or IP cement (defined and specified in ASTM C 595, 1985); by lowering the temperature of the mixing water and aggregate; or by using pozzolanic admixtures. Frequently a combination of all three methods is used.

Ground Granulated Iron Blast-Furnace Slag--In the smelting of iron ore in a blast furnace, a slag is formed that is compositionally imilar in some aspects to the chemical composition of portland cement. Slag that is quickly cooled, as by quenching by high-pressure cold-water jets, remains in the glassy state, and when finely ground it is suitable for use in the manufacture of blended portland cement or as a separate material possessing cementitious properties. Slowly cooled slag crystallizes into unreactive minerals and is unsuitable for this purpose.

Since the late 1950s or early 1960s, the use of granulated slag as a separate cementitious material, added at the concrete mixer, has gained acceptance in several countries. Identified benefits to concrete are moderate heat evolution and increased durability, especially resistance to sulfate attack and alkali-aggregate reaction.

Silica Fume--A very fine, spherical particulate of amorphous silica collected by bag-house collection systems in the manufacture of silicon metal and ferrosilicon alloys, silica fume is a very effective reactive mineral admixture in concrete. Because of its fineness, its amorphous structure, and its high silica content, it is used in concrete in smaller amounts than fly ash, either as an admixture that supplements the hydraulic cement or as a substitute for some of the cement. It usually is used in combination with regular or high-range water-reducing admixtures. Interest in silica fume is currently increasing, but its total availability is relatively low and its current cost is significantly higher than fly ash or slag. Other similar fine silica sources may become available in the future.

Outlook for the Future

Portland cement probably will continue to be the most widely used cement in the construction market in the foreseeable future. There will no doubt be significant increases in the use of fly ash and ground granulated iron blast-furnace slag, and other similar materials added at the concrete mixer or used in blended cements are expected. These increased uses are now stimulated by Environmental Protection Agency guidelines (EPA, 1983) for federally financed construction. An increasing use of silica fume in specialty concretes, particularly for specific durability situations, also is expected. The emphasis currently being given to performance-oriented specifications also should accelerate such actions.

Because of very limited investments into research and development, few if any new developments are expected to be generated by the U.S. cement industry. Rather, adoption of foreign-developed technology and contributions is anticipated by specialty chemicals producers who are active in supplying the construction industry.

THE AGGREGATE INDUSTRY

By far the greatest volume of material used in concrete is the aggregate, which may be natural sand and gravel, crushed stone, crushed slag, or occasionally other synthetic materials. Concretes contain both coarse aggregate and fine aggregate. Because of the large volume and diversity of materials used, their variety provides significant opportunities to influence the durability of concrete. Aggregates are generally, but incorrectly, assumed to be inert fillers that reduce the cost of concrete with no effect on durability. Poor concrete durability is occasionally caused by the inclusion in some aggregates of materials, usually organic, that interfere with the hydration of cement. Another problem stems from the inclusion of an excessive quantity of fine material generated in aggregate processing or of friable material in the aggregate that disintegrates to fines in the concrete mixer. Such fines increase the water requirement of the concrete, and the resulting increase in its water-cement ratio can have an adverse effect on the durability. Specifications usually protect against these contingencies.

Perhaps the most widely publicized aggregate-derived concrete durability problem is the "alkali-aggregate" reaction. Susceptible aggregate constituents are principally certain glassy or crystalline forms of silica, although there is a class of carbonate aggregates consisting of a calcite-dolomite mixture with included clay that also may be subject to attack. Inclusion of such components in the aggregate and their use with a high-alkali cement provide a concrete that is subject to expansion and cracking, especially in a moist environment.

Other pertinent aggregate characteristics include modulus of elasticity and thermal properties. Aggregate having a low modulus of elasticity will produce concrete with correspondingly low elastic modulus and also with high creep potential, resulting in excessive deflection in slender structural members. Excessive deflection is not usually associated with lack of durability, but it can be very undesirable. On the other hand, low-modulus concrete of high creep potential is highly appropriate for massive concrete, since its increased strain capacity reduces cracking on cooling. In addition, aggregates with thermal properties that accelerate the dissipation of heat produced during the hydration of cement are favorable for reducing thermal stresses in mass concrete. Generally, the producer of concrete has a limited choice of aggregates because of high transportation costs. The producer thus faces the challenge of making use of locally available materials in such a manner that will not impair concrete durability.

Over 5,000 companies in the United States operate nearly 9,000 facilities for producing aggregates (PCA, 1985; Bureau of Mines, 1985a, 1985b). The bulk of the productive capacity, however, is managed by a small proportion of the operators; 63 percent of the total tonnage is produced by 15 percent of the companies. Most of the aggregate being produced is either natural sand and gravel or crushed stone, with the tonnage about equally divided between the two types. Other sources of aggregate include air-cooled blast furnace slag, steel-industry by-product, and artificial lightweight materials produced by expanding shale, clay, slate, or slag. Another recently developed potential source is crushed recycled concrete from the demolition of existing structures or pavements. While this source may become significant in the future, at present it is not a quantitatively significant part of the total aggregate production. There also is need to assess the potential harmful effects of using crushed recycled concrete if it has been afflicted with alkali-aggregate reaction or has harmful materials in it, such as chlorides, that will affect new construction.

Industry Structure

Since most of the aggregate industry produces natural sand and gravel or crushed stone, most of this discussion is devoted to those two types of aggregates.

The lightweight aggregate industry is not insignificant. There are 39 rotary-kiln plants producing lightweight aggregates from expanded shale or clay, 4 sintering plants producing lightweight aggregates, and 11 plants producing expanded blast-furnace slag aggregates (ACI, 1984). In some parts of the world lightweight aggregates are produced by processing fly ash, but there is at this time no such U.S. commercial operation. More than half of the lightweight aggregate produced is for concrete blocks. However, it is commonplace to use lightweight aggregate in cast-in-place concrete floors of high-rise buildings to reduce dead weight. In some applications, lightweight aggregate is the aggregate of choice for durability. It has a long history of successful use for bridge decks, and recent developments in offshore structures in the Arctic have demonstrated the superiority of lightweight concrete in resisting abrasion by floating ice because of its energy-absorbing capacity. The lightweight aggregate industry recently has been particularly hard hit by rising energy costs; although some improvements have been made in energy-efficient processing technology, more is needed if this industry is to remain viable. Here, too, research and development efforts are minimal.

Normal-weight aggregates are produced for a variety of end uses besides concrete. Only about half of the normal-weight aggregates produced are used in concrete. Other uses include asphaltic paving mixtures, road bases, fill, and industrial sand. Because of their low unit value, aggregates are produced only near the point of use. Since hauling aggregates long distances is expensive, there is great pressure on concrete producers to use locally available materials. The economics of the industry would be improved if it were possible to define applications in which aggregates of marginal quality could be used safely and, indeed, if "marginal quality" itself could be adequately defined. The industry is concentrated in large urban areas and, on a transitory scale, in areas where highways, dams, and other large-scale public and private works are under construction. Aggregates are produced in every state, and the total reserves are virtually inexhaustible. However, the geographic distribution often does not match market patterns or requirements, and the quality of available materials differs from one deposit to another.

Sand and Gravel--About 4,300 producers of sand and gravel operate over 5,900 plants with current annual production of about 800 million tons, which represents about 70 percent of total capacity (Bureau of Mines, 1985a). The leading producing states are California, Texas, Michigan, Arizona, Ohio, Alaska, New York, Colorado, Illionis, and Minnesota. Reserves owned or controlled by domestic producers total 15 billion tons, and an additional reserve of 50 billion tons is thought to be available. Sand and gravel are usually found together in areas where they have been transported years ago by flowing water.

Crushed Stone--About 1,800 companies operate 3,600 plants with an annual crushed stone production of about 1 billion tons, representing about 70 percent of total production capacity (Bureau of Mines, 1985b). Crushed stone is produced in every state except Delaware. The leading states, in order of production, are Texas, Florida, Pennsylvania, Georgia, and Virginia.

Specifications

By far the most commonly cited specification for concrete aggregates is ASTM C 33 (ASTM, 1986), which provides limits for both grading and quality. State highway departments have their individual specifications, as do many federal government construction agencies. Although most specifications are adequate, improved analytical characterization methods could lead to better selection and more proper use of available aggregate for concrete exposed to severe environments. Incorporation of newly generated knowledge into appropriate standards is slow and should be accelerated.

Outlook for the Future

Because of the extensive aggregate reserves available, it may be anticipated that the materials now used will continue to be produced and used. In urban areas where higher quality materials are being depleted locally and expansion of working areas is impossible because of zoning or environmental restrictions or because land value dictates some other use, the price of aggregate will undoubtedly increase. There will probably be an increase in underground mining of stone for environmental as well as technological reasons. A more widespread use of recycled concrete as aggregate may develop if needed information on the effects of possibly harmful constituents in the old concrete can be developed. Better energy-efficient processing technology in the lightweight aggregate industry and a closer and more realistic definition of what constitutes marginal aggregates are needed.

CHEMICAL ADMIXTURES

Chemical admixtures are soluble components other than portland cement, aggregates, water, and minerals. They can be classified by function as follows:

1. Air-entraining admixtures
2. Water-reducing admixtures, conventional and high-range
3. Retarding admixtures
4. Accelerating admixtures
5. Miscellaneous agents, such as bonding, damp-proofing, permeability-reducing, grouting, and gas-forming agents and corrosion-inhibiting admixtures

Chemical admixtures are used when special properties are required that cannot be practically attained by selection of the appropriate type of portland cement. Such properties include extended time of setting, accelerated rate of early strength development, and intentional air entrainment. The effectiveness of chemical admixtures may be influenced by such factors as type, brand, and amount of cement; water content; aggregate shape, grading, and mixture proportions; mixing time; slump; and temperatures of the concrete and ambient air.

Admixtures being considered for use in concrete for the purpose of water reduction or set regulation should meet ASTM C 494, "Chemical Admixtures for Concrete" (ASTM, 1986). Trial mixtures are generally made with the admixture and the job materials at temperatures and humidities anticipated on the job. This gives an evaluation of the compatibility of the admixture with other admixtures and job materials, as well as the effects on the properties of the fresh and hardened concrete. The dosage recommended by the manufacturer or the amount determined to be optimum by laboratory tests should be used. Admixtures used in prestressed concrete should not contain chlorides or other constituents that can contribute to corrosion of the reinforcement.

Air-Entraining Admixtures

Air entrainers are used to purposely entrain microscopic air bubbles in concrete. A properly entrained air-bubble system dramatically improves the durability of concrete exposed to cyles of freezing and thawing when wet, and it also provides resistance to surface scaling caused by the use of chemical deicers. The workability of fresh concrete will also be improved, and segregation and bleeding may be reduced or eliminated. Possible interactions with other chemical admixtures may influence the air void system produced; this needs to be examined before combining such admixtures.

An entrained air-bubble system can be produced in concrete by use of an air-entraining cement, in which the air-entraining addition has already been incorporated during manufacture. Active ingredients used in air-entraining additions and admixtures include alkylbenzene sulfonate, polyethylene oxide, detergents, and salts of fatty acids. Specifications and methods of testing air-entraining admixtures are given in ASTM C 260 (ASTM, 1986). Air-entraining additions also must meet the requirements of ASTM C 226 (ASTM, 1986), and applicable requirements for air-entraining cements are given in ASTM C 150 (ASTM, 1986).

Water-Reducing Admixtures

Water reducers are materials used to reduce the quantity of mixing water required to produce concrete of a given consistency or to increase the flow or slump of the concrete for a given water content.

High-range water-reducing admixtures (also called "super-plasticizers") are particularly effective and assist in producing a concrete with low water:cement ratio and low permeability and having significantly improved durability. Chemically, these materials usually are sulfonated melamine formaldehyde condensates and sulfonated naphthalene formaldehyde condensates. The use of water-reducing admixtures is increasing rapidly. Specifications are contained in ASTM C 494 (ASTM, 1986). Specifications for high-range water-reducers for producing flowing concrete are given in ASTM C 1017 (ASTM, 1986).

Many, but not all, water-reducing admixtures also retard the setting time of concrete, and some are specifically modified to give varying degrees of retardation. Some water-reducing admixtures also entrain air in concrete. An increase in strength is generally obtained with water-reducing admixtures as water content is reduced for a given concrete, if the cement content and slump are kept the same. Despite reduction in water content, concretes made with some water-reducing admixtures have been reported to show significant increases in drying shrinkage.

Retarding Admixtures

Retarders are used to delay the time to setting and slow the rate of early strength gain of concretes. High temperatures during production of fresh concrete, of the order of 85°F to 90°F (30°C to 32°C) and higher, often cause an increased rate of hardening that makes placing and finishing difficult. Practical methods of counteracting this effect also include reducing the temperature of the concrete by cooling the mixing water or the aggregates or both. Retarders do not decrease the initial temperature of concrete.

Retarders also are sometimes used in concrete to delay the initial set of concrete (or grout) when difficult or unusual conditions of placement occur, such as placing concrete in large piers and foundations, cementing oil wells, or pumping grout or concrete over considerable distances. Because most retarders also act as water reducers, they are frequently called water-reducing retarders. In addition, retarders may also entrain some air in concrete.

In general, some reduction in strength at early ages (1 to 3 days) accompanies the use of retarders, and the effects of these materials on the other properties of concrete, such as shrinkage, may not always be predictable. Therefore, acceptance tests for retarders should be made with normal job materials under anticipated job conditions.

Accelerating Admixtures

Accelerators are used to speed up the strength development of concrete at an early age. Under most conditions, the common accelerators cause an increase in the drying shrinkage of concrete. Early strength development of concrete can also be accelerated by (a) using Type III high-early-strength portland cement, (b) lowering the water:cement ratio by increasing the cement content, or (c) curing at higher temperatures.

Calcium chloride is a common active material in many accelerating admixtures. Its use is not recommended in prestressed concrete because of the increased likehood of corrosion, and the dosage level acceptable in conventional reinforced concrete is limited. Chlorides should not be used in concrete containing embedded aluminum (for example, conduit) since serious corrosion of the aluminum can result if the aluminum is in contact with embedded steel and the concrete is in a humid environment.

Accelerators that do not contain chlorides are available for use where corrosion is a potential problem, but they are less effective as accelerators.

Miscellaneous Agents

Damp-proofing and permeability-reducing agents, bonding and corrosion-inhibiting admixtures, grouting agents, and gas-forming agents are used only occasionally. There are no ASTM specifications for these materials.

THE CONSTRUCTION INDUSTRY

General Contracting

Competitive bidding in concrete construction today involves an increased amount of risk-taking if the contractor is to use innovative methods to reduce construction time and to minimize labor and equipment costs. These economic factors are not necessarily compatible with the production of durable structures. Construction materials and processes that require specialized training and experience and involve an increase in project completion time are likely to be ignored or abused, even though proper use of such materials and processes might improve the durability of the structure. The designer may provide for durable concrete in design and job specifications, and the contractor may be knowledgeable about the application of those specifications, but, unfortunately, the cost of construction will most often take precedence if a choice is to be made.

Advances in concrete materials technology in the past decade or two allow contractors to place concrete at lower water content and also give enhanced resistance to aggressive substances. There is great need to develop construction practices that permit and encourage the use of present knowledge while still retaining the competitive edge of concrete in life-cycle cost comparisons. The number of skilled concrete constructors will continue to diminish if they continue to lose money when applying costly techniques and materials in order to provide durable concrete. In their place is the unskilled or unknowing contractor, who is permitted to build the structure in disregard of known good practice standards. The use of available QC and QA practices therefore should be encouraged, and a reward or penalty system should be developed to ensure a high probability of durability.

General Construction Practices--Fragmentation of responsibilities for construction has led to the contractor's resources being applied to things other than ensuring durability. The widespread use of subcontractors in all phases of construction has led to control problems, particularly when fulfillment of an overwhelming number of disparate supervisory and accounting procedures often takes priority over field supervision. Contractors claim that the owner and designer have removed the incentive to ensure durability by overspecifying the procedures and materials to be used. These factors sometimes lead to a reliance on outside agencies to perform testing and inspection rather than on the designer or the contractor, who most often have a better understanding of the exposure conditions and need for durability (Isaak, 1982; Ledbetter and Ledbetter, 1985).

Risk Assessment--It is apparent that, as the owner's risk increases from the loss of serviceability or the loss of ability to maintain a structure because of a lack of durable concrete, the likelihood of good practices for durable construction will also increase. This interplay can be seen in the successful record of offshore concrete structures for the oil industry. Few if any serviceability problems have occurred in the large volume of concrete used in North Sea, Arctic, or warm-water structures (Moksnes, 1982; Kunze, 1986; Special Report, 1984). The high cost to the owner of downtime due to loss or damage to these structures is known from the beginning by all parties to the construction. This has resulted in intensive efforts to reduce the potential of defective concrete, including the following actions:

- R&D programs sponsored by owners and contractors to develop materials, designs, and procedures for durable concrete
- Close cooperation by all parties during the construction phase
- Extensive pretesting of materials and procedures prior to construction
- Provisions for monitoring the performance of the concrete while in service

If the success of the application of concrete to offshore structures is due, at least in part, to the knowledge of the risks of nondurable concrete, perhaps it is time to assess these risks for other types of construction as well.

Ready-Mixed Concrete Industry

Ready-mixed concrete producers supply approximately 60 percent of all concrete produced in the United States. Ready-mixed concrete production is a highly competitive, capital-intensive industry. The industry represents a series of vivid contrasts in structure and capabilities:

- Large, metropolitan operations versus small, rural firms

- Companies with a well-developed and staffed technical base versus organizations with no technical backup

- Firms with total reliance on commercial and industrial construction versus companies mostly dependent on residential construction

These capabilities often determine the ability of the concrete producer to influence the quality of the final product and the planning that must precede the manufacturing process. Contractors often choose a supplier solely on the basis of price, and there are few standard methods by which a buyer can judge the ability of a ready-mixed concrete producer to provide durable, high-quality concrete.

Influence on Durability--Concrete manufacturers generally know the characteristics and capabilities of their materials and concrete, but they are seldom consulted prior to construction. The ACI Building Code requires a concrete plant to provide a history of strength data or, in the absence of the data, to pay a penalty by supplying more expensive concrete (ACI, 1983). No such requirement exists, however, for documenting the other factors that influence durability, except perhaps the quality of the aggregate.

The concrete supplier can have a profound impact on the long-term performance of his product if he knows in advance the performance criteria, the planned method of placing the concrete, and the environment in which it will be used. Perhaps the biggest source of problems leading to abuse of fresh concrete is the lack of coordination in delivering the concrete at a time and rate that allows it to be placed at the required water-cement ratio and density.

Materials and Equipment--In some areas, the sources of sound, durable aggregates are controlled by a limited number of producers, and therefore the choice of supplier and the impact on quality may be influenced. Rapidly changing sources of cement and the other constituents of concrete, such as slag, fly ash, silica fume, or natural pozzolan from distant places, may lead to a revelation that a long-used aggregate has detrimental properties that were never evident before. The economics of construction is leading to the use of marginal aggregates that have suspect or undocumented performance records. Such circumstances show the need for developing more reliable testing methods that can predict the durability of concrete containing a particular aggregate.

The capability of some ready-mixed concrete plants to use new technologies such as high-range water reducers, silica fume, and high-energy mixing varies considerably. The owner or contractor is sometimes required to provide the expertise and meet the expense of installing this capability. It may involve the erection of a new storage silo to allow the use of a special cement or other material, or it may require an educational program to permit truck drivers to properly introduce a liquid admixture into the concrete transport truck. The designer or contractor must have sufficient knowledge of the concrete supplier to evaluate these capabilities.

Precast and Prestressed Concrete Industry

There are a limited number of precast concrete producers in the United States today, and their location usually controls the use of the product. The rather advanced technology required to produce prestressed and precast products usually yields a more durable concrete than that from other sources. This results from the fact that the cement content and water:cement ratio required to obtain the high early compressive strength for rapid form turnover is conducive to good durability. Ultimate strengths in the range of 6,000 to 12,000 psi (41.5 to 83 MPa) are commonplace in the industry today, and the capability exists for producing a 20,000-psi (138-MPa) concrete.

The prestressed concrete industry has in operation a self-imposed plant certification program that has permitted a certain amount of standardization of quality surveillance (Prestressed Concrete Institute, 1986). This program may provide a model for introducing other concrete industry performance certification processes.

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INSTITUTIONAL FACTORS

The interaction of a variety of complex institutional factors has resulted in concrete structures that are less durable than is technically feasible and economically efficient. Because of social changes and weak economic incentives, there is both an inadequate dissemination and use of existing knowledge relating to concrete durability and an underinvestment in the research and development necessary to increase this knowledge. This chapter discusses some of the principal institutional factors that have contributed to this situation.

The institutions that shape the concrete industry and influence the durability of structures are diverse; they include the government structure, the economy, the educational system, and the way in which the society as a whole is organized. The role and performance of institutions may be the central issue in the effort to improve the durability of structures. Specifically, the evolution of U.S. legal practices and the growing importance of international institutions are beginning to force changes in how concrete and structural durability are defined and managed.

In the United States, designers increasingly are held strictly liable by the courts and the public at large for the performance of structures they design and specify. Public owners and private designers are held negligent if the structure does not perform well in service, and as a consequence designers are much less flexible in their approaches to design and construction. This overbearing emphasis on legal responsiblity for performance can stifle creativity in new design development. In some cases outside the United States, however, the overriding emphasis seems to be on improving durability and less on the precise legal obligations for every aspect of the work. The U.S. focus on specifying and controlling concrete in a structure seems to be counterproductive and, unless changed, the structures built in the future may be even less durable than those built in the past.

ECONOMIC FACTORS AFFECTING CONCRETE DURABILITY

For a variety of reasons, owners of buildings and other concrete structures have historically paid little attention to the durability. This myopia is found among commercial as well as public owners and is rooted in several causes. Foremost among these is the false sense that concrete is almost indestructible, and this results in an undue emphasis on the first costs of the structure, as opposed to its life-cycle costs. In addition, at least for commercial owners and buyers, the generous depreciation provisions of the Internal Revenue Code, especially those in effect after 1981, lead not only to rapid turnover in the ownership of structures but also to the new buyer's giving inadequate consideration to the long-term productive life of the structure. This short-term view is reflected also in the level and type of R&D activity related to concrete: There is little R&D done, and what little is undertaken is oriented toward large, quick, and relatively sure payoffs.

Life-Cycle Costing

Rarely will a concrete structure cease to be serviceable within the first 5 to 10 years after construction, and many concrete structures show little or no deterioration after 20 or more years of service. The fact that concrete structures may continue to be serviceable for long periods does not, however, reduce the significance of durability as an economic issue. The costs of repairing or replacing these structures, or of accepting curtailed performance and service, are large enough to warrant additional initial expenditures to limit or eliminate economic losses from insufficient durability.

Under life-cycle costing, suppliers and users take account of the costs of maintaining, repairing, and ultimately replacing a structure along with the costs of the original construction. Costs incurred in the future must, of course, be discounted to the present at the appropriate rate, but they should not be ignored. In practice, because many practicing engineers have little working knowledge of how to assess durability in the field and its consequent effects, the issue is tacitly ignored. If the present value of increased costs of maintenance and repair or of the costs of premature replacement attributable to insufficient durability in the concrete exceeds the costs of increasing the durability, then it pays to invest more up front to enhance the durability of the concrete and avoid larger costs later.

Despite the widespread acceptance of the principles of life-cycle costing, however, these principles often are not followed in practice. Among governmental agencies, funds for construction typically are in a different budget from funds for operation and maintenance of the structure. In addition to these budgetary practices, low-bid procurement practices put a premium on minimizing first costs. On the other side of the bidding table, contractors seek to meet the concerns of the funding agencies. For example, the Transportation Research Board report, "America's Highways: Accelerating the Search for Innovation" (TRB, 1984), noted that contractors' products whose first costs exceed those of competitors tend to be avoided, regardless of their life-cycle costs. As a result, products of superior quality do not necessarily fare better in procurement systems that are characterized by rigid standards and an overriding emphasis on low bids. The TRB report also quotes the president of the Portland Cement

Association, who has argued that "the low first-costs concept is a serious deterrent to new product development, quality improvement, and innovative technology."

Depreciation

Normally, the value of a commercial building or other commercial structure is a function of the amount and duration of earnings that the building is expected to generate over its remaining economic life. The owner of the building or structure should then be concerned about its durability, because the more durable the building, the longer it will be generating revenues and the lower will be the total cost of maintaining it. Even if the owner were planning to sell the building, durability should still be an important factor to him because the price he might get for the building should also be related to its expected remaining economic life. However, in the real world, where buyers and the experts they hire find it difficult to assess durability and its consequent effects, durability becomes at best a secondary consideration, particularly if there are depreciation benefits in purchasing the structure. Buildings and other structures then become more valued for the depreciation benefits than for their remaining productive life.

The change to the Accelerated Cost Recovery System (ACRS) of depreciation in 1981 significantly increased the depreciation benefits of investing in buildings and other concrete structures. An owner planning to sell a building in a few years to a buyer who is purchasing it primarily for the tax advantages will pay less attention to the durability of the structure than he would if the return on his investment depended solely on the productive life of the structure.

Although the depreciation benefits of structures are not a primary cause of the insufficient attention paid to durability, they exacerbate a tendency toward the myopia that already exists because of other factors.

QUALITY CONTROL AND QUALITY ASSURANCE

In all construction, the intent is to maximize proper performance, minimize improper performance, and do this at the lowest practicable cost (Mather, 1986). This can be achieved by, among other things, proper quality control (QC) and quality assurance (QA).

The term quality assurance refers to all activities carried out by or for the owner to ensure that a structure conforms to its design requirements. A successful QA system can ensure a durable structure only if the specifications are adequate. Quality control (QC) activities consist of those activities performed by the contractor to ensure that the construction presented to the owner for acceptance complies with the plans and specifications. Acceptance testing, which is the operation that ultimately determines whether portions of a structure should be accepted, is part of the latter activity. Some contracts require very explicit QC activities on the part of the contractor, but some do not. Where none are required, some contractors voluntarily execute a QC program. Most often, however, they merely rely on the owners' testing and inspection to assess the adequacy of their work. When the system works properly, there is adequate documentation to establish which parts of a structure are in compliance with the specifications and which are not. Where nonconforming work exists, the owner must make a decision to remove it or to accept it, with or without qualifications.

Ordinarily the QC and QA processes cease at the completion of construction. There is some current interest, however, in extending it into the service-life phase of the structure. This interest derives both from a desire to provide feedback to designers of future structures and the need for documentation to defend against lawsuits, which increasingly are establishing that owners and their engineers have a responsibility for what occurs in a structure during its service life as well as during construction.

Barriers to Effective QC and QA

Most systems have failed to provide durable concrete for three principal reasons:

1. The required tests and inspections are not relevant to durability. The owner wants a structure that will withstand the environment to which it is subjected for its design life, with no harmful deterioration in its load-carrying capacity or physical appearance and with no need for abnormal maintenance. Such requirements are not included in the specifications since, under the present system, the acceptability of the structure must be determined at the end of construction. In that way, a judgment may be rendered on whether the contractor should be paid for the work, and in the end the contractor assumes no long-term responsiblity for its performance. The contractor must satisfy requirements that, in the opinion of the specification writer, will provide a high probability of good durability performance but are not expected to ensure durability per se.

In the general absence of performance requirements, these are usually prescriptive requirements. Most specifications do not permit the contractor to propose another method for accomplishing the objective. Also, it is impractical to wait until durability has been established or discredited before evaluating the contractor's work. This system produces both overspecifying and underspecifying what is needed, and it eliminates any incentive for the contractor to conduct any research to find a more effective or more efficient method for achieving durability.

2. <u>There is a tendency for the system to degenerate into a paperwork project handled by accountants rather than by knowledgeable technical people</u>. People implementing the program lose sight of the objective when they are preoccupied with the completeness of the documentation and not with performance of the structure. It is widely held that this type of paralysis has seriously crippled the nuclear power industry.

3. <u>Testing and inspection by the contractor are used by the owner as a substitute for acceptance testing, thereby avoiding the expense of double testing</u>. This item is especially pernicious. An intolerable conflict of interest is created when the organization doing the work also performs the tests and inspections that evaluate the adequacy of the work. While some contractors have performed very well under these circumstances, the system by its very nature invites allegations of fraud and produces test results that cannot be verified except by the company that has the most to gain from acceptable results.

In principle, QA programs represent the best of good contract administration and construction practice. With an effective QA program, knowing the service performance desired in the structure, the owner prescribes the proper materials and construction methods, monitors the actual construction and service performance, and exercises informed judgment about any changes that may affect the service performance.

Optimally, the owner and contractor can anticipate the effect of each construction material and method on the service performance of a structure. To do this, there is need not only to have sound contract administration practices but also a thorough understanding of concrete as a material and of the environmental factors affecting its durability. In practice, however, it is sometimes difficult to establish a link between the original construction and later service performance of the structure. Therefore, to make QA programs work effectively, more effort must be made to identify the links between concrete materials, mixture proportion, construction methods, and service performance of the structures and the persons doing the field work on behalf of the owner and contractor, who must be well schooled in this technology. The federal government, which is directly or indirectly the largest customer of the concrete construction industry, can play an important role by requiring the use of state-of-the-art QA techniques.

EDUCATION

Education and training in the United States have always been considered the key to better individual career opportunities and to a more skilled and productive work force for the country. Vocational training programs are available for virtually every major industry in the United States, and students interested in the engineering professions can choose from many different colleges and universities. The committee's concern, then, is less with the availability of opportunities for an individual to receive vocational or advanced professional training than with the direction these educational programs are taking. According to the Committee on Education and Utilization of the Engineer (National Research Council, 1985), the challenges facing the educational system include excessive specialization at the undergraduate level; declining support by industry of valuable co-op programs; expected decline in the number of qualified students entering engineering colleges; erosion of content and standards in the secondary school system, which is the base of the qualified engineering personnel pool; unattractiveness to U.S. citizens of careers in certain engineering disciplines; inadequacy of continuing engineering education; and steady decline in quantity and quality of laboratory equipment available to educational institutions.

The educational system is being disabled by both internal and external developments. Externally, the financial support and cooperation previously offered by government and business are declining, and educational institutions have difficulty making up the shortfall. Internally, in response to changing student interests and the necessity to cover more material in the same academic program, fewer laboratory courses are offered, and students receive more specialized rather than broad fundamental training with less emphasis placed on basic science. The net effect is that graduates of vocational and professional programs are becoming more narrowly trained. This training itself also is being hampered by inadequate resources and a shrinking pool of qualified researchers and teachers.

University Education

The emphasis in higher education has turned increasingly to high technology. In particular, both to attract new students and to strengthen existing programs, universities are placing more emphasis on computer science, mathematics, and electrical and electronic engineering. For example, the number of applicants to the electrical and civil engineering curricula at the University of California at Berkeley is summarized in Table 7. It shows a progressive increase in the one and a relative steady-state condition in the other. A similar situation is found in most engineering schools across the country. For example, at the Johns Hopkins University in Baltimore, for each 1985 applicant for civil engineering there were about 15 applicants for electrical engineering and computer sciences. The ratio in the actual 1985-86 freshman class is 1 to 17 (private communication from Johns Hopkins University Admissions Office, 1986).

This rapid growth in high-technology areas has other aspects. Clearly, today's society demands more from technology in medicine, in computer science, and in other areas, and universities have moved to address this demand. It must be recognized that, as selected parts of the engineering and science curricula expand, other programs are being sharply curtailed. In practice, at least for the engineering

Table 7. Freshman Applicants to College of Engineering

Year	Civil Engineering	Electrical Engineering
1980	196	639
1981	160	650
1982	122	775
1983	184	969
1984	185	1481
1985	206	1349

Source: College of Engineering, University of California, Berkeley--personal communication to the committee.

curricula, this means that chemistry classes are being reduced from 1 year to 1/2 year and physics from 2 years to 1 year, while laboratory classes are being phased out. Where faculty positions are available, many are being transferred away from civil and other more traditional branches of engineering to electrical and other more fashionable areas. It is possible now to obtain a Ph.D. degree in civil engineering from most major U.S. universities without significant background in, or any understanding of, the basic chemical principles that govern the development and degradation of mechanical properties of concrete. These developments are in sharp opposition to the need for durable structures. Universities are increasingly emphasizing analytical modeling and more abstract technologies, and not those aspects related to tangible materials. Durability includes an essential materials aspect, and it cannot be achieved unless there is adequate understanding of relevant materials technology.

The importance of chemistry to the understanding of cementitious systems has recently been recognized in a report by the National Research Council's Panel on Surface and Interfacial Engineering (1986):

> In general, it appears that the injection of modern physicochemical, surface-science-oriented research into the field of cement and concrete would harness as-yet untapped technological potential in this area.

Today fewer than 10 universities in the United States offer advanced coursework on concrete materials and construction practices, and this number is expected to decline further. Universities seeking faculty with an interest in concrete materials have reported a near-complete absence of qualified candidates and a progressively declining student interest in the area.

Over the short and long term, little improvement in the education of U.S. engineers in topics relevant to concrete durability can be anticipated. As a first step, concrete and materials technology must receive a higher priority within the universities, if only to provide sound professional training. Secondly, the funding agencies--e.g., the National Science Foundation--should provide more funding for both basic and multidisciplinary engineering research. This funding should not only encourage new faculty to work in the area but also contribute to real technological advancements.

Concrete as a material and durability as an issue will receive less emphasis in universities if the present trend of declining educational interest continues. Confronted by static or reduced funding, universities are deliberately reducing available courses and shifting materials-oriented faculty to accommodate greater student interest in more fashionable fields. It can be expected over time that very few universities will be able to offer even the most basic courses in concrete technology.

Vocational Training and Workmanship

More than in any other material, the durability of concrete is linked to the workmanship with which it is placed in the field. Although it is usually produced in a central plant, water and chemical admixtures are frequently added as the concrete is placed, and the craftsmen who finish it virtually dictate the quality and uniformity of the wearing surfaces.

In principle, proper training is the key to good workmanship. Increasingly, workmanship and the training of the site work force are being buffeted by a number of other external forces. Demographically, the construction work force is becoming more diverse, the sources of site labor are changing, and the types of training available are becoming less consistent.

In part as a result of the deliberate effort to increase minority participation in the construction industry, and in part as a reflection of the changing population base in the United States, the construction work site is increasingly multilingual. Although English is the national language and certainly the medium of communication in construction contract documents, increasing proportions of the work force speak English only as a second language and often have limited experience and English vocabulary in construction. In the multilingual job site, the basic skills of the individual workman notwithstanding, communication among workers on the job site is becoming more difficult. It is concomitantly more difficult to communicate standards of construction and the effects of certain work practices on long-term durability.

Traditionally, labor unions have been the source of skilled labor for the concrete industry. Through union training programs, the workers were instructed in the use of the tools and techniques associated with good construction practice and the ill effects of improper practices. Today, nonunion contractors, who may or may not have organized training programs, are performing an increasing proportion of the concrete construction. With fundamental geographic shifts in population from the North to the South and West, there is further intermingling of workers. These collective changes have a dramatic impact on the quality of work performed. An encouraging development is ACI's ongoing effort to train and certify field technicians and finishers.

Changes are taking place in the availability and training of workers associated with the production, placement, and finishing of concrete. With an increasingly multilingual job site situation and diverse labor pool, the level of training and workmanship practiced in the field is much more variable.

Management Education

As implied earlier, there is an inadequate appreciation by the technical professionals of the economic and trade issues facing the construction industry. Because their understanding of the business complexities is limited, their impact on important decision-making is compromised.

Such a situation seems equally pronounced when assessing the scientific and technological education of construction industry management. With a few exceptions, low-technology areas such as cement and concrete production are managed by individuals having financial and marketing rather than technical expertise. This experience and the severe economic pressures of past years have caused management to restrict support of new technologies and of long-term exploratory R&D. This is often accentuated by the norms for compensating managers, in which short-term financial gains are overvalued whereas investments in long-term technological advances are de-emphasized and unappreciated. This clearly affects the quality and durability of structures.

This situation not only affects the quality of materials, structures, and production but also has negative effects on the educational process, on the development of standards, on quality assurance practices, and ultimately on the durability of materials and serviceability of structures. It is imperative that the overall level of technology management be improved by selecting as managers in important positions, persons who are well educated in economics, marketing, human relations, and, most important, in the technical aspects of the particular industry. Development of state-of-the-art educational texts, introduction of postgraduate workshop programs, and proper adjustment of financial compensation systems are only a few avenues available for shifting top management's attention toward technology developments.

It has been well documented (National Materials Advisory Board, 1980) that past intellectual investments in cement and concrete technology made the U.S. concrete industry economically sound and a technological leader. Today's investments in high-technology materials (e.g., National Materials Advisory Board, 1984; Westwood and Skalny, 1985) are examples of business success through support of developing technologies. It is hoped that the cement and concrete industry management will follow the example of some of the specialty chemical companies in supporting, implementing, and publicizing economically viable construction technology developments.

Technology Transfer

A potentially important result of increased educational levels is improved technology transfer. Such transfer is extremely important in the fields of cement and concrete because it is not only the communication among the worker, technologist, and business manager that is of concern but also the technology transfer among various technical fields such as physical chemistry, materials science, mineralogy, civil and chemical engineering, and physics as pertinent, for example, to nondestructive evaluation. Each of these disciplines has developed its own terminology, and this often detracts from mutual understanding.

In addition, technical communication between various research establishments and among government, academia, and industry is often inadequate. Proper organization and dissemination of knowledge is critical to technology transfer. Durability issues are so complex as to strain the capacity of individuals to deal with them without guidance. If the present fragmentation that separates researchers from decision-makers continues, it is likely to doom the industry to continued slow progress in advancing the important technology of service-life prediction. The tools (e.g., smart instruments, data base management systems, and expert systems) for generating and organizing knowledge are becoming available today and are advancing rapidly, offering great opportunities for the future.

If the industry desires to expand its technology base, and if universities are expected to produce future generations of first-class technical and managerial specialists for the construction industry, then cooperative industry-university R&D ventures are of greatest importance. The federal funding agencies could and should play an important role in facilitating such cooperation, as, for example, the Ministry of International Trade and Industry (MITI) functions in Japan, by support of multidisciplinary rather than only science-oriented work. The areas of building diagnostics (NDE and other methods of structural condition assessment) and the relationship of structure properties to service life are examples of such multidisciplinary work. A more important role could and should be played by the National Bureau of Standards.

RESEARCH AND DEVELOPMENT

In pure or fundamental research, the goal is an understanding of a basic mechanism or principle without regard to its commercial application. In practice, however, even the basic research performed by most industrial companies and government agencies is at least indirectly linked to a particular mission or application--hence the term research and development. Very few people would argue that all research should be truly basic and performed without regard to its application, but substantial controversy has arisen regarding the extent to which basic research should be linked with its possible application to current needs and practices.

The cement and concrete industries, in relation to their size, have traditionally undertaken very little R&D activity, and what has been spent on R&D has been devoted predominantly to applied research directed toward quick payoffs rather than to basic research (National Materials Advisory Board, 1980). Although the public sector also sponsors research related to concrete, short-term budget cycles inhibit development of new approaches to durability in two ways. First, multiyear research studies are seldom funded because they require the sponsor to commit scarce funds well into the future, and it is a practice that may even be prohibited by formal regulations. The scarce funds are usually subdivided into small, insignificant contracts, so that no research group has the critical mass to perform, conclude, and transfer to practice the results of these efforts. In any event, such funding is at variance with the usual near-term objectives of the funding agency. A second factor is that short-term budget cycles, which interact with traditional aversion to risk and the transient nature of the professional work force, tend to inhibit, both implicitly and explicitly, risk-taking and the exploration of innovative alternatives. The budgeting process generally puts a premium on big payoffs realized over a short time, in contrast with innovative approaches that often require substantially longer time and usually have more uncertain outcomes. With a few exceptions, before deciding to fund new research, particularly if it involves changing directions in the principal technology used or making substantial personnel commitments, sponsoring agencies will look instead for the prospect of a big and relatively quick payoff.

A proper balance has to be found between the basic research that is needed as a foundation for future technology developments and engineering research that applies substantial available knowledge to engineering practice. With respect to concrete durability and extension of the service life of structures, funding for both types of research needs to be markedly increased. In addition, it can be noted that the lack of funding for basic research has a long-term effect on education. Because little research is being conducted on concrete durability, universities in turn devote limited attention to this issue, and as a result the pool of scientists, engineers, and educators knowledgeable about durability issues is shrinking.

For many years the United States was the world leader in basic research in cement and concrete, and it has contributed significantly to engineering applications. Today, as in the past, exciting opportunities exist for applying new knowledge concerning the chemistry and physics of cement hydration to extending the performance, and specifically the durability, of concrete structures. There seems to be a failure in the widespread application of available knowledge to solving engineering challenges. This is due in part to the institutional factors discussed earlier, but it is also due to the industry's conservatism and conventionalism in thought and action. What is needed is infusion of new blood, capable of applying modern chemistry and physics (e.g., kinetics, thermodynamics, electrochemistry, surface and colloid chemistry, and fracture mechanics) to solving practical problems. There is a need to create an adequate technical interface between the research and engineering communities, because sole reliance on changes in institutional perceptions and structures would be inadequate.

The committee believes that most concrete durability problems can be eliminated, thus re-establishing concrete's role as an economical, reliable, and durable construction material. Multidisciplinary research (and subsequent application of research data) should be done in at least the following areas of relevance to durability:

- Cement composition and performance--the relationship to concrete performance in different environmental conditions of use (e.g., structure of hydrates, alkali distribution, importance of pore liquid phase, materials science aspects)

- Aggregates--effective use of marginal aggregates and development of improved test methods

- Slag and pozzolan--establishment of the relationships between fracture properties and each of the following: composition, reactivity, heat evolution, fresh concrete workability, alkali content, curing conditions, and environmental resistance

- Chemical admixtures--proper application of surface physics and colloid chemistry to the development of cost-effective specialty chemicals, tailored to reduce or eliminate deterioration of concrete

- Fresh concrete--development of relationships between surface-chemical phenomena and rheological behavior of concrete, including improved test methods and standards

- Placing and curing--improved understanding of the effects on concrete durability of materials and the heat transport during initial curing, development of monitoring techniques (including nondestructive evaluation), and influences of heat and materials inhomogeneities

• Structure-properties relationship--application of advanced materials science to permit microstructural engineering of properties, understanding of phenomena governing the behavior of interfaces in cement-based composites, and micromechanics of fracture behavior under load (which can yield opportunities for tensile strength improvement)

• Environmental stability--permeability and diffusivity phenomena, microstructure-porosity relationships as related to materials transport and structural deterioration, and the simultaneous action of physical and chemical degradation mechanisms

• Design--consideration of the best materials science and chemical principles in the design of structures to ensure that durability of materials is not compromised by design or architectural preferences.

All these as well as other areas of applied research need to be conducted in full appreciation of the possibilities of appropriate use of computer-managed durability data bases, simulation models, and expert systems. Such computer-based technologies do not eliminate the need for laboratory and field research, but they can vastly improve the knowledge and technology transfer capabilities, improve decision-making related to durability of concrete and structures, and upgrade educational approaches. These technologies are not panaceas but should be introduced where they can improve cost-effectiveness, productivity, and information feedback.

SPECIFICATIONS AND TEST METHODS

Early in the historical development of portland-cement concrete, concrete consisted only of cement, water, and aggregate. The important scientific developments during those early years were the discovery of the significance of the water:cement ratio and the effect of portland cement composition under various environmental exposures. Specifications for concrete durability consisted merely of the largely prescriptive limits on the mixture proportions--i.e., the requirements for the proper type of cement, minimum cement content, and an adequately low water:cement ratio.

The past 40 years, however, have seen the development of the use of air entrainment and of a large variety of materials that are added to concrete. These materials include pozzolans, the most popular of which is fly ash, many types of chemical admixtures, and metallic and nonmetallic fibers. It is now possible, for example, to place concrete with much less water than was previously possible. Indeed, the pace of new developments is accelerating. However, few simple rapid tests are yet available for many important parameters relating to durability of concrete systems. Some of the available methods are extremely time-consuming, many are imprecise, and others are simply not appropriate for use under field conditions.

With the variety of possible ways available now to achieve a given level of performance, including durability, there is considerable pressure to use performance specifications. Purely prescriptive specifications may inhibit innovation and stifle competition. This trend toward performance specifications and the introduction of new materials and processes have produced the need both to establish performance criteria that correlate with long-time durability and to provide tests for detecting harmful side effects, if any, of the many new materials that might be proposed for use by a contractor. The development of such standards has not kept pace with the development of new materials, primarily because of the lack of scientific and field data. Hence, some specification writers are reluctant to abandon old approaches.

Today the concrete producer and the contractor have a greater choice of materials and production practices, and thus a much more sophisticated approach is needed to assess, control, and specify durability-related parameters. Specifically, what is required is a more direct means of linking the properties of the concrete materials and the production practices with the quality and expected future performance of what is actually produced. One avenue to improved durability is the development of and adherence to sound specifications. Introduction of performance specifications will in turn require improved understanding of the relationships between the composition, microstructure, and physical performance of cement-based composites.

POSSIBLE IMPROVEMENTS

Almost by definition, institutional influences are larger than those of any one public or private owner. The effects of institutions are pervasive, but the directions that institutions take can be changed. With respect to improving durability, several basic changes in the existing approaches would be helpful, including the following:

1. Place greater emphasis on and give financial support to long-term research programs. Well-managed research programs on durability problems should be exempt from a necessity to demonstrate a payout in less than 3 years. By its very nature, the evaluation of alternative approaches to improve durability may take many years to complete.

2. Recognize that the entire field of concrete technology is becoming more complex, both technically and in the way institutions relate to it. On this basis, greater attention should be given to alternative contracting practices for concrete construction, to academic and on-the-job training of workers and of design and

construction professionals, and to techniques for evaluating long-term durability performance.

3. Develop analytical means for estimating the return on investment generated by improved durability and for disseminating these data. The cost of R&D and changes in educational approaches can and should be shown to be minimal when compared with the financial and societal benefits derived (e.g., savings on depreciation of public buildings; elimination of costs of premature repair of infrastructure; and legal costs related to litigation).

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II-4

SPECIALTY MATERIALS: RECENT DEVELOPMENTS

This chapter highlights developments in materials and technologies that could offer alternative or additional measures to ensure durability of concrete under adverse conditions and provide supplements, substitutes, and complements to conventional portland cement-based concretes for special applications. Unless otherwise noted, most of the data given are based on recent publications (Hirsch, et al, 1983; Young, 1985; presentation by J. F. Young to the committee, October 31, 1985). It is not the intention of this summary to encompass all novel materials and approaches but only to identify some important ones.

Among the recent developments in portland cement and concrete technologies are high-strength materials such as the silica-fume mortars and concretes. This chapter reviews some of the characteristics of these materials and briefly summarizes the qualities of other alternative materials such as sulfur cements and fiber-reinforced concrete. Table 8 summarizes some of the classes of materials considered. Table 9, based on a compilation by Diamond (1985), summarizes some of the physical and mechanical properties of relevant materials.

SILICA-FUME-CONTAINING PRODUCTS

Finely divided amorphous silica--e.g., silica fume, a by-product of silicon metal and ferrosilicon alloys production (in principle, use of other similar products is possible)--undergoes a pozzolanic reaction that starts as soon as water is added to the cement-silica system. In silica fume (SF) concretes, the usual range of silica-fume addition is 5 to 15 percent by weight of cement, and usually it is used in combination with a high-range water reducer. This amount of silica fume usually is not quite enough to completely eliminate the calcium hydroxide formed during cement hydration. However, highly beneficial changes are usually produced in the microstructure of the cement paste in the concrete.

DSP (densified with small particles) products can be perceived as highly modified cement paste that incorporates a large amount of SF (i.e., much higher than SF concretes), an effective high-range water-reducing admixture (HRWRA), which ensures physicochemical deflocculation of the portland cement and the SF, and usually a very-high-strength aggregate. The HRWRA-SF system acts as an effective mixing and mechanical processing agent to produce a well-consolidated paste

TABLE 8. Examples of High-Performance Cement-Based Materials

Class*	Commercial Trade Name	Company	Compressive Strength (psi)	Compressive Strength (MPa)	Flexural Strength (psi)	Flexural Strength (MPa)	Approximate Young's Modulus (10^6psi)	Approximate Young's Modulus (10^3MPa)
SF concrete	EMSAC	Elkem	14,000	96.5	1,800	12.4	5	34.5
	Corrocem	Norcem	12,000	83	-	-	-	-
	Force 10,000	Grace	>10,000	>69	-	-	-	-
DSP concrete	Densit	Densit	30,000	207	2,000	13.8	7	48.4
	Ceramite	Elkem	28,000	193	2,000	13.8	7	48.4
	Dash 47	Cemcom	50,000	345	3,500	24.1	7	48.4
MDF concrete	NIMS	ICI	42,000	290	21,000	145	7	48.4
Steel fiber-reinforced concrete	MS-Mortar[a]	-	14,000	96.5	5,000	34.5	5	34.5
	SIFCON[b]	Lankard Matls. Lab.	21,000	145	6,000	41.4	4	27.6

*SF = silica fume; DSP = densified with small particles; MDF = macro-defect-free.

[a]4 volume percent of fibers; [b]10 volume percent of fibers.

TABLE 9. Properties of Various Materials

Material	S[a] (MPa)	E[b] (GPa)	R[c] (J/m^2)	K_{Ic}[d] (MPa√m)
Cement paste	6.5	18	15	0.2
Concrete	8	25	80	1.2
DSP materials	-	80	1	-
MDF materials	150	50	200	3
Polycarbonate	65	2.5	4,000	3
"Typical" ceramic	280	300	100	5
"Mild" steel	280	210	140,000	170
High-strength steel (4340)	1,400	210	140,000	170

[a]Tensile strength; [b]Young's modulus; [c]Fracture energy; [d] Critical stress intensity factor

Source: Diamond, 1985.

with minimum water. The basic idea is to ensure that the space between the cement grains is filled to the maximum possible extent by the much finer silica-fume particles. In effect, the idea is the same as that for the production of SF concrete but on a more sophisticated level that is useful for specialized, low-volume products. No clear break exists between these two classes because there is a continuous spectrum of SF content and water:cement values possible. DSP materials usually have a much lower water:cement ratio (around 0.20) and the silica-fume content is higher; very strong, dense, impermeable matrices result.

SF Concrete

The composition of C-S-H formed in the presence of reactive pozzolans is slightly different from that formed during normal cement hydration. In particular, the $CaO:SiO_2$ (C:S) ratio is reduced from about 1.7 to about 1.5, but the silicate structure is not significantly different. When calcium hydroxide is entirely eliminated, the C:S ratio drops to around 1.0, and the silicate structure is more highly polymerized. It is likely that both types, normal (C:S = 1.7) and pozzolanic (C:S approximately 1.0), coexist, giving rise to a mean value of around 1.5.

The presence of silica fume causes marked changes in pore structure and size distribution. Addition of silica fume, even at relatively high water-to-powder ratios, virtually eliminates the macroporosity (greater than 100 nm in diameter), which controls permeability, after only 7 days of moist curing. Thus, the production of very-low-permeability concretes with extended durability seems feasible. Accumulated evidence indicates that the microstructure of the interfacial zone between cement paste and aggregates in normal concrete is not typical of that observed in the bulk paste. The typical paste is characterized by a more porous structure and oriented calcium hydroxide crystals and, as a result, is more prone to cracking, particularly under the stress concentration that may occur at the interface (Struble et al., 1980). In the presence of SF, the interfacial zone has a more dense, uniform structure that does not appear to differ significantly from the bulk paste. The small particle size of the microstructure inhibits the development of segregated water films, which probably are the cause of the porous zone, and also inhibits the growth of oriented calcium hydroxide crystals. As a consequence, the bond between paste and embedded materials, such as fibers, can be improved.

Predictions made from considerations of pore size distributions seem to be correct. The effectiveness of SF in reducing the permeability of concrete was demonstrated (Mindess et al., 1985; Rosenberg and Gaidis, 1986; Regourd, 1986). Data show that even with low cement content and high water:cement ratios, low permeability coefficients are attained. Replacement of 1 part of cement for 1 part of SF is equivalent to adding 10 parts of cement with respect to permeability reduction; i.e., for well-cured concrete the reduction in permeability with 10 percent of silica fume is approximately equivalent to doubling the cement content. Inadequate curing, however, will have a greater detrimental effect on SF concrete than on conventional concrete, because the pozzolanic reaction will be inhibited.

The fine pore structure in SF concrete increases the chemical resistance of concrete and reduces the access to oxygen. Lowered alkalinity caused by the pozzolanic reaction is not sufficient to destroy the passive layer needed to protect the steel reinforcement. Diamond (1985) has measured a pH greater than 12 after 145 days of hydration in the presence of 30 percent SF. Carbonation could destroy the passive layer but, if properly cured, SF concrete is no more susceptible to carbonation than conventional concrete of similar water:cement ratio.

When chlorides are introduced into SF concrete, the chloride ion does not appear to be bound by the hydration products to the same extent as in conventional concretes. Thus, depassivation can occur at lower dosages of added chlorides. However, ingress of external chloride ions is significantly reduced--by at least a factor of 10. SF concrete exposed to salt spray for over 10 years shows no apparent signs of corrosion.

It is known that calcium-silicate cements that have lower C:S ratios are capable of taking up greater quantities of alkali ions. This might be a major reason for the success of pozzolans in controlling alkali-aggregate attack. The effectiveness of silica fume in controlling alkali-aggregate reactions is now well established by several independent studies. In Iceland, 7.5 percent SF is routinely added to all cement for this purpose. It also has been documented that the addition of SF does indeed reduce the concentration of alkali in the pore solution (Diamond, 1983). It should be noted that many of these effects can be achieved by the use of other materials--for example, fly ash, slag, and natural pozzolans.

The low permeability and reduction in calcium hydroxide content should also improve resistance to attack by sulfates. Laboratory studies and field trials have shown that SF additions provide excellent sulfate resistance, comparable to the performance of concrete made of sulfate-resistant cement. Field trials under severe conditions in Norway have shown good performance over a 30-year period (Bernhardt, 1952; Aitcin, 1983). Concretes containing 15 percent SF performed as well as concretes made with sulfate-resistant cements even at a water:cement ratio of 0.62.

A general recommendation is made that concrete containing SF should be air-entrained for frost resistance. It appears that SF concretes of equal or higher strengths will be more frost-resistant than conventional concretes because the finer pore structure results in less freezable water. Theoretically, below a certain water:cement ratio (about 0.38) there is no freezable water in mature paste, but it would be unwise not to provide some air entrainment in such cases. Factors such as inadequate curing and wetting and drying cycles can coarsen the pore structure. Inadequate curing is particularly critical since it will inhibit the pozzolanic reaction. Furthermore, the volume of fine pores (mesopores, fine capillary pores) and micropores (associated with C-S-H) will increase and thus lead to a higher potential drying shrinkage. Shrinkage cracks could provide zones of freezable water; cracking caused by excessive plastic shrinkage could cause similar problems.

Tests by the Corps of Engineers have shown that SF concrete has improved resistance to abrasion-erosion conditions (Holland et al., 1986). The high resistance to wear may be due to the improved cement-aggregate bond. In addition, it could be advantageous to use it in overlays and other protective coatings. For this reason it was chosen for the repairs to the stilling basin of the Kinzua dam and has been used subsequently for repairs on other hydraulic structures in Southern California.

The apparent enhanced strength and durability of SF concrete make it suitable for designs involving thin cross sections (e.g., shell structures), precast structures, and structural elements of reduced mass and thickness. The combined high strength-to-mass ratio and low permeability suggest applications in the marine environment, including ship construction, offshore drilling platforms, marine pilings, and surfaces subjected to high degrees of cavitation and erosion. Also, numerous critical military and space applications exist for such high-strength, low-permeability, and enhanced environmentally-resistant concretes, such as runways, VTOL pads, magazine doors, fire-resistant structures and structural supports, and weapon silos. However, further understanding of the relevant chemical processes is desirable, and control of curing conditions is crucial if durable SF concrete structures are to be built.

DSP Materials

The microstructure of the paste in DSP materials is generally similar to that of SF concrete. The very low water:cement values are attained by the particle-packing attributes of the fine silica. Actually, so little water is provided and so little space is available that much of the cement never hydrates. The hydration product that develops is primarily C-S-H gel, which is found to have a lower C:S ratio than usual. Few distinct calcium hydroxide crystals can be detected.

No significant volume of air voids remains in properly processed products, and few and only very fine capillary pores exist. Drying shrinkage due to cement hydration is limited by the small amount of hydration product, although some shrinkage may occur. The tendency toward shrinkage cracking is resisted by the homogeneity of the structure and by its inherent strength. Residual cement grain cores act as strong internal fillers or microaggregates.

Strength development is very rapid after an initial delayed setting time of 15 to 20 hours, and after 2 days strengths of the order of 100 MPa (14,000 psi) are possible. Strength continues to increase with extended moist curing, approximately doubling after 28 days. The rate of strength gain can be increased by heat curing, particularly if water loss is suppressed.

Unfortunately, DSP materials are extremely brittle. Thus, reinforcement will be needed to provide appreciable ductility. This high degree of brittleness raises concerns regarding the possibility of microcracking arising from internal stresses.

The permeability of DSP materials has not received the same attention as that of SF concrete. One would expect extremely low permeabilities because of the low water:cement ratio and the high SF content. Hansson and Hansson (1983) found some DSP formulations to have good corrosion resistance. Not only is chloride diffusion reduced about 30 times compared to a dense conventional cement paste, but also low oxygen and water permeabilities limit corrosion rates even after it has been initiated by chloride-induced depassivation. The electrical resistance is also significantly higher.

A key to the successful performance of Dash 47, a commercially available DSP product (Table 8), as a molding (injection and blow molding) and tooling material is its ability to withstand temperature cycling without impaired properties. The hot cure cycle is critical for these applications because it provides a more stable microstructure, suggesting that specialized curing regimes will be necessary for optimum performance. However, 200 to 250°C (392 to 482°F) represents the upper limit for such systems since, at higher temperatures, incipient decomposition leads to a deterioration in properties. Polymer impregnation with high-temperature polymers is one approach to the problem. Vacuum impregnation not only improves the vacuum leak rate but also improves significantly the flexural strength.

DSP products exhibit properties closely related to SF concrete materials, and many applications would be interchangeable. The major virtues offered by the DSP are the somewhat higher service temperature and the reported greater resistance to chloride diffusion. In addition, the amount of SF used in DSP is sufficient potentially to eliminate calcium hydroxide. The low degree of clinker hydration is compensated by a high degree of reaction by the amorphous silica with the lime. The resulting amorphous matrix is a ceramic-like body whose chemical and heat resistance warrant its employment in agressive environments unsuitable to unmodified portland cement concretes. High strength is not achieved in its early cure, and for this reason DSP concretes are not favored in construction practices requiring early and immediate structural qualities. Such uses include slip casting, general cast-in-place construction, and as topping for bridge deck surfaces. Where ample time is allowed for optimization of strength and integrity, DSP might markedly extend bridge deck service life. Careful consideration of this requirement must be given to minimize crack formation.

MDF MATERIALS

In a broader sense, the macro-defect-free (MDF) materials belong to the category of cement-polymer composites. They are described here to demonstrate an attempt at a multidisciplinary approach to solve technical challenges.

An essential feature of the MDF materials is the incorporation of a fairly significant amount of one or more of several water-soluble polymers in the cement (best results were achieved with high-alumina cement) and a limited amount of water. The presence of the polymer is said to be instrumental in preventing cavitation under the very high shear action of the mixer, and it also serves to reduce interparticle friction so that adjacent cement grains can slide past each other and promote a dense packing arrangement (Birchall, 1983). The dough so produced is described as having a substantial air content after mixing, but the air is said to be removable by application of modest pressure. It can then be processed by conventional plastics technologies such as calendering, extrusion, and pressure molding.

Optimization of the mixture by the use of a specially graded portland cement packing and the selection of an appropriate polymer system permits the attainment of a compressive strength above 40,000 psi; to reach even higher strengths, a calcium aluminate cement must be used. A flexural strength of about 21,000 psi and a total porosity of about 1.5 percent is the best yet reported. However, the compressive strength is only about 42,000 psi, and the low ratio of compressive to flexural strengths (2:1) suggests that it is the polymer that is playing the active role. The water-soluble polymers used in MDF materials noticeably retard hydration, and thus flexural strength develops relatively slowly. Special curing and drying conditions are required to obtain the desired properties.

If during the drying step dehydration and stiffening of the polymer phase occurs, then at least partial rehydration might be expected, with a concomitant reduction in strength and in modulus. Although no actual data have been published, it is acknowledged that such moisture sensitivity has indeed been observed. This presents a serious potential limitation to the use of the present MDF materials by the conventional construction industry.

FIBER-REINFORCED MATERIALS

Fibers derived from glass, carbon, asbestos, cellulose, polymers, and metals are currently being used or tested as cement reinforcement.

They are needed for specialty applications where tensile strength and fracture toughness are of importance. In common with other brittle solids, cement-based materials are toughened much more by the incorporation of fibers than by inclusions of other shapes.

Classical concrete itself is a composite material which, in simple terms, is a two-phase system of coarse and fine aggregate particles embedded in hardened cement paste. In reality, however, concrete products are multiphase systems consisting of a variety of cements, fine and coarse aggregate particles, blending materials, and physical and chemical admixtures that have different sizes and shapes and different chemical and mineralogical compositions. Because of this complexity, development and exploitation of new cement composites is challenging and opens new opportunities.

The addition of any type of fiber to a concrete matrix produces important changes in concrete properties, both in the fresh and hardened states. In the wet slurry, a substantial reduction in workability is observed and, in instances where air voids are entrained by the fibers, there is a noticeable increase in porosity that may lead to a reduction in strength. Assuming that no adverse effects are encountered, the addition of fibers to a concrete matrix should improve all its mechanical properties. The most notable benefit of judicious addition of fiber is the noticeable increase in the peak strain (strain at peak stress) and a commensurate significant increase in ductility. This enhanced toughness is critical to the design of low-mass (small cross section) columns of high-strength concrete for earthquake and other dynamic stress loads (Hannant, 1978).

The use of fibers in concrete for structural applications has made great progress in the past decade, but more research is needed, especially in fiber-augmented, high-strength concretes. The use of a combination of fibers, reinforcing bars, and established high-strength concretes should provide the optimum choice to the designer. Research to date indicates that the use of fiber-containing reinforced concrete in the structural arena may soon be a widespread reality. When this technology is coupled with SF, water-reducing admixtures, and other evolving technologies and materials, portland-based concrete should enjoy greater breadth of use and greatly extended, low-maintenance service life.

Present applications of steel-fiber-reinforced concrete include refractories, pavements, overlays, patching, hydraulic structures, thin shells, armor for jetties, rock slope stabilization, mine tunnel linings, and precast products. Specific structural applications include hemispherical domes, ductile concrete joints for seismic applications, both military and nonmilitary blast-resistant structures, and lightweight structures. Combinations of fibers are also used to give more workable fiber-concrete mixtures, high-strength concrete, and polymer concrete.

Use of fibers in structures could lead to elimination of hoops and stirrups in construction, which can help alleviate congestion of joint areas. In addition, the use of HRWRA in preparing fibrous concrete should help improve workability. Engineering construction practices must be improved to ensure that the fibrous concrete is properly specified, designed, placed, cured, and finished.

Slurry-Infiltrated Concrete

In steel-fiber-reinforced concrete (SFRC) prepared using conventional premixing techniques, a maximum practical limit of fiber loading is about 2 volume percent. Higher steel-fiber loadings (up to 20 volume percent) have now been achieved using a technique that involves infiltration of a packed fiber bed with a hydraulic cement-based paste or mortar (Lankard, 1985).

Slurry-infiltrated fiber-concrete (SIFCON) composites prepared with portland cement or calcium aluminate cement-based pastes or mortars exhibit strength and ductility behavior that is dramatically superior to conventional SFRC materials. SIFCON has now progressed beyond the laboratory stage with the successful experimentation in pavement and bridge deck overlay repair, security concrete, refractory concrete, precast concrete products, and explosive-resistant structure applications. Although the technology is still in its infancy, the constructability of SIFCON has been demonstrated, most dramatically with the recent construction of a 1/8-scale model hardened missile silo structure by the New Mexico Engineering Research Institute of Albuquerque. The material is viewed as having potential application in severe service situations where conventional concretes are not performing satisfactorily. In view of its outstanding strength properties, ductility, and crack and spall resistance and its ability to be formed as complex shapes, it may also be suitable for use in applications and products currently served by materials other than concrete--e.g., wood, cast iron, steel, and fiber-reinforced plastics.

Continued research and development efforts are needed to provide a better understanding of the engineering properties of such materials. Specifically, these efforts include a better understanding of the effects of fiber and matrix variables on engineering properties and improvements in construction methodology, and a detailed evaluation is needed of new application areas, such as seismic-resistant structures, precast railroad crossties, and thin plate construction.

MODIFIED-SULFUR CONCRETES

Molten sulfur-sand grouts have been used for many years in the construction of acid vats because of their excellent acid resistance. In the mid-1960s, an extensive characterization of sulfur concretes employing fine and coarse aggregates was undertaken for the U.S. Air Force by Southwest Research Institute (Dale and Ludwig, 1966, 1967, 1968). Typical compressive strengths of 5,000 to 7,000 psi (33 to 47 MPa) were attained in 6 to 12 hours after solidification with limestone aggregate.

The major problem with grouts or concretes employing pure sulfur as the binder was poor resistance to thermal cycling and subsequent loss of strength. Small amounts of plasticizers readily overcame this problem, as reported by the U.S. Bureau of Mines (Crow and Bates, 1970; Sullivan and McBee, 1976); combinations of oligomers and polymers of dicyclopentadiene were used.

The sulfur concretes developed by the Bureau of Mines combine high early strengths, good durability, low permeability (virtually zero moisture permeation), acid and alkali resistance, good thermal shock, and resistance to freezing and thawing. Costs vary with the international sulfur supply and various political and environmental policies. Generally they are very attractive in cost, especially in contrast to the polymer concretes that compete with sulfur in the specialty concrete market. Sulfur concrete has been used in a number of industrial environments for 5 years with no sign of deterioration compared to portland cement concretes. Compressive strengths of 8,000 to 10,000 psi have been attained. The high strength potential of this material has yet to be fully explored (McBee et al., 1985).

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Appendix

BIOGRAPHICAL SKETCHES OF COMMITTEE MEMBERS

JAN P. SKALNY received a chemical engineering degree in 1958 from the University for Chemical Technology, Prague, Czechoslovakia, and a Ph.D. degree in technology of silicates in 1965 from the Academy of Mining and Metallurgy, Cracow. He was a visiting research worker in cement chemistry for the Cement and Concrete Association Research Station, Slough, England, in 1967, and a research fellow in cement and surface chemistry at Clarkson University from 1968 to 1969. He worked for the American Cement Corporation from 1969 to 1972, when he joined the Martin Marietta Laboratories. In 1985, he joined the W. R. Grace and Company Washington Research Center as director of construction materials research. He is a fellow of the American Ceramic Society and a member of the International Union of Testing and Research Laboratories for Materials and Structures, the American Concrete Institute, the American Society for Testing and Materials, and the Materials Research Society. He has served on numerous National Research Council panels and committees. He is a visiting professor at Johns Hopkins University and an editor of Cement and Concrete Research. His areas of specialization include building materials and research administration.

RAYMOND F. DECKER received a Ph.D. degree in metallurgical engineering from the University of Michigan in 1958. He joined INCO in 1958 to perform research on superalloys and co-invented maraging steels in 1960. In 1982 he was named vice president of research and corporate relations at Michigan Technological University. In 1986 he joined University Partners, Inc., as president and chief executive officer. He is president of the American Society for Metals and a member of the National Materials Advisory Board and the National Science Foundation's Materials Research Advisory Committee. He has served as adjunct professor at the Polytechnic Institute of New York and New York University and on numerous government panels and boards. In 1980 he was elected to the National Academy of Engineering. His areas of specialization include high-temperature alloys; alloy design of maraging and stainless steels; nonferrous alloys; electrochemistry; corrosion; and biotechnology materials.

SIDNEY DIAMOND received a B.S. degree in forestry from Syracuse University in 1950, an M.F. degree in forest soils from Duke University in 1951, and a Ph.D. degree in soil chemistry from Purdue University in 1963. He worked for the Federal Highway Administration from 1953 to 1965, when he joined the Purdue University faculty. He is a fellow of the American Ceramic Society and a member of the American Concrete Institute, the American Society for Testing and Materials, the

International Union of Testing and Research Laboratories for Materials and Structures, and the Materials Research Society. He served on the National Materials Advisory Board's Committee on the Status of Cement and Concrete Research and Development in the United States. His areas of specialization include cement chemistry and hydration products, alkali-aggregate reactions, admixture effects, fly ash utilization, and various areas of concrete technology.

WESTON T. HESTER received a B.S. degree in 1969, an M.S. degree in 1970, and a D. Eng. degree in 1974, all in civil engineering, from the University of California, Berkeley. He worked as an engineer for Stanley Structures from 1973 to 1976. In 1976 he was appointed assistant professor of civil engineering at the University of California, Berkeley, and in 1982 he was promoted to associate professor. He is a member of the American Society for Testing and Materials, the American Society of Civil Engineers, the American Concrete Institute, and the Prestressed Concrete Institute. He served as chairman of the ACI educational activities committee and the PCI high-strength concrete committee. His area of specialization is in concrete as a material in applications demanding high performance.

PAUL KLIEGER received a B.S. degree in civil engineering from the University of Wisconsin in 1939. He joined the Portland Cement Association Research Laboratories in 1941, working on the Long-Time Study of Cement Performance in Concrete. In 1971 he was appointed director of the Concrete Materials Research Department, a position he held until 1985, and he is at present consultant to the Concrete Technology Laboratories and Research and Development Division of the Portland Cement Association. He is a member and fellow of the American Society for Testing and Materials, an honorary member and fellow of the American Concrete Institute, and a member of the Prestressed Concrete Institute. He served on the U.S. Committee on Large Dams and is active in the Transportation Research Board of the National Research Council. He currently specializes in the supervision and administration of concrete technology research projects, particularly in the field of concrete durability.

ROBERT W. LaFRAUGH received a B.S. degree in civil engineering in 1958 and an M.S. degree in structural engineering in 1960 from Michigan State University. He worked at the Portland Cement Association from 1960 to 1965, at Dundee Cement Company from 1966 to 1970, and at Concrete Technology Corporation from 1970 to 1982. From 1983 to 1986 he was with ABAM Engineers, and in 1986 he was made West Coast branch manager for Wiss, Janney, Elstner Associates. He is a fellow of the American Concrete Institute and a senior member of the American Society for Quality Control, the American Society for Testing and Materials, the Prestressed Concrete Institute, and the Structural Engineering Association of Washington and has contributed to meetings of the National Research Council's Transportation Research Board. His areas of specialization include research and development, testing, and quality assurance of concretes; construction planning, design, and assurance; Arctic structural concrete; constuction troubleshooting and repair methods and maintenance; and prestressed hull construction quality assurance.

ROBERT J. LARNER received a B.A. degree from Georgetown University in 1964 and M.A. (1967) and Ph.D. (1968) degrees from the University of Wisconsin, all in economics. Between 1968 and 1976 he was an assistant professor of economics at Brandeis University, concurrently serving as staff economist at the Federal Trade Commission from 1971 to 1973. In 1976 he joined Charles River Associates, where he is now vice president. He is a member of the American Economics Association. He received a NSF Graduate Dissertation Fellowship from 1966 to 1968 and serves as an associate editor of the Journal of Industrial Economics. His areas of expertise include industrial organization, price theory, the economics of antitrust and regulation, innovation, and science and technology policy.

WILLIAM A. MALLOW received a B.S. degree from the University of Akron in 1952 and an M.S. degree from St. Mary's University in 1968, both in chemistry. He was a technician at the B. F. Goodrich Research Laboratories from 1948 to 1950; an academic instructor at the Naval School of Radiation Technology and Decontamination from 1950 to 1954; and a senior research technician at Southwest Research Institute from 1954 to 1957 and at Pittsburgh Plate Glass Company from 1957 to 1961. He rejoined Southwest Research Institute in 1961. He is a member of the American Chemical Society and holds 18 patents. His areas of expertise include synthesis of new polymers, micro-encapsulation, development of vitreous ceramic foam insulation, high-pressure synthesis, and development and production of new building products and novel cements, concretes, and refractory materials.

ROBERT E. PHILLEO received a B.S. degree in civil engineering from Carnegie Institute of Technology in 1946. He worked as research engineer at the Portland Cement Association from 1946 to 1958, then joined the U.S. Corps of Engineers, moving to chief of the structures branch in the Office of the Chief of Engineers. He retired in 1983 and now provides consulting services to the construction industry. He is a member of the American Concrete Institute, the American Society for Testing and Materials, the National Research Council's Transportation Research Board, and the Concrete Society of London. His areas of specialization include the rheological properties of concrete, the response of concrete to high temperatures, the development of nondestructive test methods, and mass concrete technology.

DELLA M. ROY received a B.S. degree in chemistry from the University of Oregon in 1947 and M.S. (1949) and Ph.D. (1952) degrees from Pennsylvania State University, both in mineralogy. She worked at Pennsylvania State University in various research capacities from 1949 to 1963, when she joined the Materials Research Laboratory of the university. She was appointed professor of materials sciences in 1979. She serves on committees of the National Research Council's Transportation Research Board, was chairman of the NMAB Committee on the Status of Cement and Concrete Research and Development in the

United States, and is the editor-in-chief of the journal Cement and Concrete Research. She is a recipient of the American Ceramic Society's Jeppson Medal and is a fellow of the American Association for the Advancement of Science, the Mineralogical Society of America, the American Ceramic Society, and the American Concrete Institute. Her areas of specialization include phase equilibria; crystal chemistry, phase transitions, and crystal growth; cement and concrete chemistry and microstructure; special glasses; biomaterials; and nuclear waste management.

M. JACK SNYDER received a B.S. degree in chemistry from Ohio State University in 1943. He joined Battelle Memorial Institute in 1943 and has moved through various staff appointments to his present position as program manager. He received the Wason Medal from the American Concrete Institute and is a member of the Society of Sigma Xi. He is a fellow of the American Ceramic Society and a member of the American Concrete Institute, the American Chemical Society, and the National Institute of Ceramic Engineers. He has extensive research and development experience in the fields of cement and concrete technology, glass technology, structural ceramics, surface chemistry and physics, and chemical engineering.

GEORGE S.-C. WANG received a B.S. degree from the University of Michigan in 1958 and an M.S. in 1960 and a Ph.D. in 1970 from the University of California, Los Angeles, all in civil engineering. He was assistant research engineer at the University of Michigan Research Institute from 1961 to 1962. He worked for the Bechtel Power Corporation and the Bechtel Group, Inc., in various capacities from 1962 to 1985. He is now vice president of Fluor Corporation. He is a member of the American Nuclear Society and the American Society of Chemical Engineers Chi Epsilon Club. His areas of specialization include various aspects of civil and environmental engineering, engineering management, biotechnology, fission, fusion, and metals.