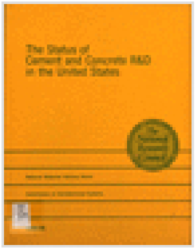

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Data presented show that the level of research and development (R&D) in the cement and concrete industry in the United States is inadequate to meet current needs and future challenges. Specific areas of concern are identified, and various incentives for and barriers to R&D are discussed. Emphasis is placed on the need for a vigorous, coordinated basic research and development establishment (civilian, academic, and governmental) coupled with an efficient mechanism for technology transfer to commercial practice. This mature industry is moving slowly to enlarge and improve its physical plant and increase its production efficiency but is doing little to learn more about its products. Foreign developments are used as examples of what can be done with proper planning and adequate capital outlays.

Recommendations are made where specific efforts are required for economic, institutional, and technological improvement. These include some nontechnical suggestions, such as increasing governmental and industrial support for R&D and reexamining some of the barriers to R&D caused by legislative restraints on vertical integration and lack of tax incentives. Technical issues identified are the need for an interdisciplinary approach to experimental, theoretical, and modeling studies; an increase in studies of basic mechanisms of cement hydration and development of strength in concrete and in studies of long-term durability under extreme environments; and the efficient utilization of energy and resources by the industry. An independent research and development facility is suggested as one way to get the proper nucleus of people together to examine critically various industry-wide problems of immediate and long-range concern.

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Cement Durability
Cement Hydration
Cement Modifiers
Clinkering Process
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Concrete
Construction
Ferrocement
Fiber-Reinforced Concrete
Fly Ash
Gypsum
Highway
Pavement
Polymer Concretes
Portland Cement
Pozzolan
Precast Concrete
Prestressed Concrete
Reinforced Concrete
Rotary Kiln
Slag
Superplasticizers
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THE STATUS OF CEMENT AND CONCRETE R&D IN THE UNITED STATES

Report of

The Committee on the Status of Cement and Concrete R&D in the United States

NATIONAL MATERIALS ADVISORY BOARD
Commission on Sociotechnical Systems
National Research Council

Publication NMAB-361
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NOTICE

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competence and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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ABSTRACT

Data presented show that the level of research and development (R&D) in the cement and concrete industry in the United States is inadequate to meet current needs and future challenges. Specific areas of concern are identified, and various incentives for and barriers to R&D are discussed. Emphasis is placed on the need for a vigorous, coordinated basic research and development establishment (civilian, academic, and governmental) coupled with an efficient mechanism for technology transfer to commercial practice. This mature industry is moving slowly to enlarge and improve its physical plant and increase its production efficiency but is doing little to learn more about its products. Foreign developments are used as examples of what can be done with proper planning and adequate capital outlays.

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PREFACE

The Committee on the Status of Cement and Concrete R&D in the United States was empaneled by the National Materials Advisory Board to assess the present level of research and development activity and to ascertain the factors that affect decisions on investments in R&D. The committee also was asked to explore various opportunities in this area and to identify key problems and delineate alternative approaches to their solution. The committee addressed primarily the problems in the private sector, which would in turn directly reflect the concerns and needs of the military and the government. The committee members and liaison representatives intended this document to be of value to various people involved in the cement and concrete industry as well as to special governmental and academic interests. To meet this objective, both the technical and economic aspects of the problem were considered.

This study is based on information collected through January 1979.

ACKNOWLEDGEMENTS

The committee thanks Dr. Jerome Collins of the Department of Energy for his interest in this study. The special efforts and significant contributions of Dr. Gunnar Idorn are also acknowledged. Dr. Idorn was technical adviser to the committee and came from Denmark several times for its deliberations.

A questionnaire designed to gather information on current research and development was sent to almost 200 people in the U.S. cement and concrete industries. The American Cement Directory, donated by P.B. Bradley (Bradley Pulverizing Company of Allentown, Pennsylvania) for committee use, was most helpful in selecting people to receive the questionnaire. The cooperation of the many respondents to the questionnaire is greatly appreciated by the committee.

Arthur R. Anderson, ABAM Engineers, Inc., and Ben C. Gerwick, Professor of Civil Engineering, the University of California at Berkeley, contributed their thoughts on various issues and offered editorial comment on parts of the committee's report, although they were unable to participate directly in the committee's activities. Discussions with and data from Mr. J. Conners of the Portland Cement Association and Mr. W.G. Gunderman of the NAS Transportation Research Board were helpful in gaining a broad perspective on current problem areas. Dr. H.J. Helm, Executive Director of the American Concrete Paving Association, provided funding data on his organization.

Guest speakers were invited to two special meetings to make presentations and submit written comments for the committee's use. We are grateful to these authorities for their generous participation in this phase of the study. These speakers, some special contributors, and their topics are listed in Appendix D.

Special thanks go to Virginia Gordon of the Department of Energy for her efforts in compiling the statistical data resulting from responses to the questionnaire. Maria Kneas, secretary to George Economos, NMAB staff officer to the committee, compiled the final arrangement of the questionnaire data in Appendix B.

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CONTENTS

TABLES

Chapter One

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

The committee finds in general that research and development in cement and concrete in the United States is inadequate in the light of the needs and opportunities. The health of the industry 20 years from now will reflect strongly the quality and scope of the effort exerted today, but there is little evidence that this relationship is widely recognized. The committee's specific conclusions and recommendations are given in Chapters 7 and 8 and are summarized here.

1.1 CONCLUSIONS

1. Research and development in cement and concrete can yield great rewards. Achievements of the past five years include special applications of concrete, such as in earthquake-resistant structures; the development of polymer concretes; computer-aided design of concrete structures; progress in analytical nondestructive testing of concrete; and significant advances in instrumental methods of quality control in the cement-kiln process.

2. Greater effort in the foregoing areas could yield even greater rewards, and there are other areas that merit intensive investigation. For example, cement-kiln systems designed in recent years in Germany and Japan are capable of reducing the energy consumed by the process to 50 percent of the average requirement in the United States. However, the new systems entail changes in operating parameters, and considerable research will be needed to adapt them to U.S. practice. A second example of the potential rewards of research and development is the deterioration of concrete. The Federal Highway Administration estimates that restoration of bridge decks in the federal highway system in 1978 cost $6.3 billion; even small improvements in durability could yield significant savings.

3. Collaboration and the flow of scientific and technological information among cement producers and users and the related industrial, governmental, academic, and independent establishments is inadequate to advance the state of the art.

   - No college or university in this country offers adequate undergraduate training in cement science and technology, and very few have faculty members who are authorities in the field. The United States has no counterparts of the institutes in Czechoslovakia, West Germany, Poland, and the Soviet Union that offer special courses for cement scientists and technologists.

- Much cement literature is published in foreign-language journals; very little such literature is used in this country because of difficulties in reading foreign languages and the costs of subscriptions and translation.

- Concrete science and technology receive somewhat more attention than cement in American schools, largely in departments of civil engineering. The results of domestic research on concrete are well publicized, but foreign developments are reported less well.

4. 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, concrete producers are estimated to 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.

   - University research continues to rely primarily on limited funds from government agencies. More general support would permit the scope of such research to be broadened to the benefit of the entire industry.

   - Governmental and nonprofit institutional research and development in cement and concrete is very limited. No research and development institute in the field in this country enjoys the guaranteed longevity required to generate basic knowledge in support of future developments. The Portland Cement Association, an ad hoc industry establishment, spent some $3.9 million on research and development in 1978, about 59 percent of it for engineering development. The purchasing power of these funds was only 74 percent of that of the funds expended in 1960, the association's peak year. The cement industry provided only 25 percent of the association's funds in 1978; the remainder came from contracts, mostly in engineering.

5. The present unsatisfactory level of research and development in cement and concrete is a result of several factors:

- The industry is highly fragmented. Legal restrictions on vertical integration appear to hinder scientific and technological cooperation between producers and users.

- The federal tax structure does not encourage industrial investment in research and development.

- The generally low return on investment in recent years deters any increase in nonmanufacturing expenditures. For example, the cement industry's return on net worth during the past 15 years averaged about 7.5 percent, as opposed to the 15 percent often considered necessary for a viable industry.

- The absence of centers for scientific and technological education of people in the industries that produce and use concrete inhibits the generation of new ideas and changes in the status quo.

1.2 RECOMMENDATIONS

The committee makes the following recommendations:

1. That government agencies with responsibilities for energy, materials, the environment, and construction increase their support of long-range fundamental research on the manufacture and use of cement and concrete. Intermediate- and near-term research and development should be supported by cement manufacturers and users, which include builders, contractors, and their associations. Industrially supported research programs should focus on current problem areas, such as raw materials and structural inadequacies, and provide for prompt dissemination of findings. Specific problems that warrent immediate examination include highway de-icing and pothole damage; freeze-thaw disintegration of bridge decks; corrosion of reinforcing bars; deterioration of seawalls and other structures exposed to the sea; and thermal effects on airport runways and jet-blast barriers.

2. That special attention be devoted to the following types of investigations:

   - Studies of basic mechanisms such as hydration and crystal-phase development in cement and hardening and strength development in concrete. The resulting knowledge would help to improve quality control and assurance.

   - Studies of long-term behavior and durability in extreme environments. Such studies are needed to improve the performance and durability of cement and concrete in newly developing engineering applications where very hot or very cold conditions, seawater, and high turbulence or stress are encountered. Such applications include geothermal wells, artic structures, deep-sea oil wells, and transport and storage of liquefied petroleum gas. The results of these studies also would help to reduce overall costs by creating ways to make the available materials go further (less needed with proper design) or to make the same materials do a better job (stronger, more durable, less repair work).

- Studies aimed at more efficient overall use of energy and resources in producing cement and utilizing concrete products. Improvements in production methods and in conservation of both energy and materials probably could increase overall efficiency by as much as 30 percent, to the benefit of the industry and the nation generally.

- Interdisciplinary studies involving the interaction of experiment, theory, and modeling. Important roles in advancing cement and concrete technology are played by chemistry and physics; chemical, ceramic, mechanical, civil, and metallurgical engineering; and computer science. Increased participation and contribution by people in these disciplines would broaden the knowledge base and increase the number of investigators generating new knowledge.

3. That research and development efforts be aimed at a number of specific goals, of which the following are particularly vital examples:

   - To understand reactions taking place in cement kilns -- the basics of the cement-clinkering processes.

   - To determine the effects of changes in the composition of cements and modifiers on the cement hydration processes.

   - To utilize wastes such as fly ash, slag, and incinerator residues effectively as raw materials for clinker and cement.

   - To optimize the use of energy in various stages of cement manufacture, such as crushing and batching raw materials and producing and grinding clinker.

   - To determine the effects of new or changed cements and other components on the properties of concretes and the safety of their use in structures.

   - To identify new uses where concrete can be substituted effectively for less abundant or more costly materials or systems, such as insulating concrete in non-load-bearing structural members, ferrocement, composits, and fiber-reinforced concrete.

   - To develop and use computer methods for on-line modeling of the development of the characteristics of concrete throughout processing and strength development, as in the setting and curing stages.

4. That leaders in government and industry attack the deficiencies of the research and development establishment in cement and concrete

by actions such as establishing an independent Cement and Concrete Research and Development Center. Such a center could pursue an integrated program ranging from fundamental and exploratory studies through intermediate, mission-oriented process development for improving existing technology. Program priorities would be set by rational scientific processes. Alternatives to establishing a center of this kind include the strengthening of other institutional structures, and research and development units are presented in Chapter 8.

5. That particular efforts be made to devise an improved mechanism for transfering the results of fundamental research to development and current practice. Opportunities should be provided for academic investigators to work closely with industry and participate more in standards-setting activities. Included in this academic-industrial collaboration would be studies designed to improve the planning and management of research and development to reduce fragmentation and duplication of effort. Such collaboration also would highlight the results produced by research and development funding and improve the academic and industrial participants' understanding of each others' interests and problems, an essential ingredient in the development of mutual trust and cooperation.

6. That an appropriate body be convened to investigate further those nontechnical areas where change would encourage more effective research and development in cement and concrete. Such change might include legislative actions such as:

   - Allowing vertical integration in the cement and concrete in-industry.

   - Providing tax incentives to encourage response to environmental needs, including conservation. Tax incentives could encourage investment in innovative, capital-intensive equipment and processes that extend the uses of cement and concrete products as alternative materials and could also encourage the use of waste materials in cement and concrete.

7. That a separate additional study be made specifically of the energy aspects of research and development in cement and concrete. The topic was excluded from this study to permit the committee to examine in suitable depth the benefits possibly available from research and development on current or emerging advanced technologies.

Chapter Two

STATEMENT OF THE PROBLEM

The objective of this committee was to assess whether or not the opportunities for research and development in cement and concrete are being properly exploited, particularly in view of anticipated trends and national needs, both military and nonmilitary. This effort involves pinpointing particular successes and difficulties in exploiting R&D opportunities, identifying key problems, and delineating alternative approaches to their solutions. No major segment of the industry can be examined specifically in terms of governmental applications, both military and nonmilitary, without encountering problems and needs similar to those in the private sector. The committee's discussions and evaluations cover aspects of the current situation that have an impact on all segments of the economy: industry, consumers, and the military and other governmental interests.

The cement and concrete industry in the United States is a large but fragmented enterprise of considerable national importance. Because of its size and dispersion, it is unresponsive to rapid change. Research and development have been neglected partly because of the industry's fragmentation and partly because of the perception that cement and concrete, being cheap bulk materials, are "good enough" and do not require further improvement. Recently, however, the National Academy of Engineering jointly with the National Academy of Sciences, in the symposium Materials and the Development of Nations: The Role of Technology, recognized the global need for the development of cement and concrete technology (Idorn, 1977).

The committee finds that the concensus of those familiar with cement and concrete is that the potential for research and development on these materials is by no means being fully exploited. The cement industry is being challenged to increase its efficiency because currently it cannot meet the demand. In view of the sheer magnitude of current usage, the total potential savings that could be realized by improving cement and thus the properties of concrete (GAO, 1979) are enormous. Improvements are possible that would facilitate the design of concrete structures, save material, yield superior performance, and increase the life of structures. New uses involving exposure to extreme environments are currently arising in both the defense and civilian sectors; they bring new performance requirements for concrete materials and structures that must be met by research and development. There appear to be major opportunities for savings through waste utilization in concrete. There also appear to be many opportunities to upgrade the properties of cementitious composites and concrete so that they can be used as substitutes for more costly or less abundant materials.

The committee finds that the present level of research and development on cement and concrete is extremely low. The R&D establishment in cement and concrete is inadequate for such an essential industry that uses so many of our resources and contributes so much to the quality of life.

2.1 HISTORICAL PERSPECTIVE ON U.S. CEMENT AND CONCRETE RESEARCH AND DEVELOPMENT

The history of research and development on cement and concrete worldwide reveals the significant impact of U.S. achievements. While an anthology of these achievements is beyond the scope of this report, it it is useful to mention a few milestones.

In the early 1920s, Abrams formulated the relationship between the water/cement ratio and the strength of hardened concrete. His formula was simple, yet it proved reliable in practice for improving the quality of concrete. This work has provided the basis of concrete-mix design ever since.

Phase equilibria studies by the Geophysical Laboratory of the Carnegie Institution and by the Portland Cement Association (PCA) Research Associateship at the National Bureau of Standards (NBS)*, made a major contribution to knowledge of the chemical reactions occurring in a cement kiln. This work allowed portland cement clinkers to be improved. The comprehensive research at NBS in the 1930s reached important landmarks such as the Bogue formulas for calculating the potential mineral phase composition of portland cement (based on chemical analyses) and the Blaine air permeability method for measuring cement fineness. These accomplishments are still pillars of most cement specifications throughout the world.

At about the same time, McMillan of PCA initiated the association's long-term basic studies of cement paste hydration. These studies, headed by Powers and Brownyard (1948), culminated in the first scientifically based model of the structure and characteristics of cement paste (Powers, 1960). This work has served as a basis for developments and modifications of the properties of concrete ever since. Theoretical research was applied concurrently in achieving significant improvement of the durability of concrete exposed to alternate freezing and thawing. This effort earned manifold returns on the modest research expenditure through extensive postwar construction programs for state and interestate highways, hydroelectric power systems, defense works, etc.

During the 1940s, the identification of deleterious reactions between constituents of cement and susceptible aggregates (the alkali-aggregate reactions) resulted in major research efforts to ensure the safety of large concrete structures. Research institutes belonging to several state highway departments, the U.S. Bureau of Reclamation, and the Army Corps of Engineers played dominant roles. The value of these

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*According to the U.S. National Bureau of Standards Yearbook, 1931: "Eight research associates are stationed at the National Bureau of Standards investigating the constitution and hardening of Portland cement."

efforts has been proved worldwide, and the work started a previously unknown association between research scientists and practical technologists in cement and concrete. This association was enhanced by research-oriented bodies such as the Highway Research Board (now Transportation Research Board [TRB]) of the National Academy of Sciences, the American Society for Testing and Materials (ASTM), and the American Concrete Institute (ACI).

New views and methods having lasting effects were subsequently introduced. The use of precise petrographic methods was initiated (Insley, et al., 1938; Insley and Frechette, 1955; and Brown, 1948, 1959). These methods proved to be the forerunners of the possibilities generated by the physical and chemical instrumentation developed during the explosive growth of electronic equipment in the 1960s. The use of advanced instrumentation, in cement and concrete R&D is now only in its infancy, but has great potential.

Early U.S. leadership is also apparent in concrete construction. Engineering and construction development, backed by research and education on cement and concrete, permitted the construction of bridges, dams, dedefense works, maritime works, and highways that literally mark the foundation of the rise of modern America. The overall availability of primary materials, the versatility of concrete in production and use, and the availability of inexpensive energy were the driving forces behind the economy. Educationally, civil engineering attracted its share of bright students of the professions. However, the impressive postwar mechanization and large-scale development in concrete construction peaked in the United States about 1960. Trends in building and construction change slowly, but the extent to which this country has neglected to pursue development opportunities over the last 15 to 20 years is now evident.

In concrete development, prestressed concrete and the associated design theory were pioneered in Europe and was subsequently refined in the United States. European and Russian developments in precast concrete housing have not yet penetrated this country. In the general field of manufactured cement products, the technology abroad has far surpassed that in the United States. The recent development of concrete offshore oil platforms is a British and Norwegian achievement, despite the fact that American companies have been longtime leaders in offshore oil drilling.

Particularly important for the future is the recognition of the interdependence of basic research and the development and application of the results in response to particular needs. With the growing specialization and complexity in technical knowledge, in contrast to the relative simplicity of earlier developments, it is important that both strands continue. To that end end, it is necessary that major fundamental research efforts be regenerated and coupled to development and practice by skillful R&D management.

2.2 IMPORTANCE OF STATUS OF CEMENT AND CONCRETE DEVELOPMENT: RELATION TO NEEDS

Cement and concrete today comprise a mature and gigantic industry whose needs in research and development are not always obvious but nonetheless are important. World production of concrete amounts to an estimated 7 billion metric tons or 3 billion cubic meters a year and entails \$150 billion to \$200 billion annually in material costs. These totals amount to 1.6 metric tons and \$40 in material costs per person per year worldwide. The binder in essentially all of this concrete is portland cement.

World production of cement (Hall and Ela, 1978) is about 850 million short tons or 200 Kg (450 lb) per capita annually. Switzerland is the leader in per capita output at 580 Kg (1,270 lb) annually, while India, for instance, produces only 24 Kg (50 lb) per capita per year. The United States consumed 345 Kg (760 lb) per capita of cement with a total sales value of more than $3 billion (Hall and Ela, 1978). In 1973, this country produced 87.6 million tons of cement, 11 percent of total world production; today it produces 85 million tons, only 9.5 percent of world output and ranks second or third among world producers of hydraulic cement.* While world production has grown 7.9 percent per year since 1973, U.S. production dropped and then about regained its earlier level (Skovronek, 1976; Hall and Ela, 1978; Hoover, 1979).

The American cement industry, responsible for the invention of the rotary kiln for cement manufacture in the late 19th century, currently lags behind many industrialized nations in the design of efficient cement plants. In 1972 five countries were ahead of the United States in both plant and kiln capacity, the keys to cost efficiency (Table 1). (Plants may have more than one kiln.) Although improvements have been made recently, U.S. plants are still significantly older than in Europe and Japan (Skovronek, 1976; CEMBUREAU, 1977). The cement industry is the sixth most energy-intensive industry in this country, consuming about 3.5 percent of all the energy used in manufacturing (L.U. Spellman, presentation to the committee, 1978). The PCA (1974) told Congress that investments of $5.73 billion were needed to make the U.S. cement industry technically competitive and energy efficient, and that the capital was neither available nor being accumulated by the industry under existing conditions. A more recent estimate (PCA, 1978) placed this investment at $6.44 billion, an 11.4 percent increase.

TABLE 1 1972 Average Plant and Kiln Capacities by Country (1,000 tons)

Country	Plant Capacity	Kiln Capacity
Japan	1,765	480
France	690	275
United Kingdom	555	204
Federal Republic of Germany	510	265
Spain	510	220
United States	490	186
Italy	465	210

SOURCE: Energy Conservation Potential in the Cement Industry. Conservation Paper No. 26. Washington, DC: Federal Energy Administration, 1975. (Cited references: CEMBUREAU, World Cement Directory; Cement Industry Statistics 1972; U.S. Bureau of Mines; PCA Economics and Market Research Department), p. 11.

NOTE: Plants can have more than one kiln; numbers here give average kiln size.

*The United States was slightly behind Japan, ranking third according to 1977 production figures. Total comparisons for 1978 are not yet finalized; although this country may be slightly ahead in total production, it is still behind in per capita production.

Recently, the public's attention has been called to serious and spectacular failures of concrete structures under construction. Such failures raise concern about the reliability of large-scale construction and the availability of trained personnel to execute the best practice. Further, the issues of responsibility may become a major concern in various applications where structural performance is critical, including applications in the energy sector.

Because the ingredients of concrete abound in the earth's crust and can be processed into finished structures using less energy than is required for alternative materials, it is logical to assume that the use of concrete will expand, particularly in the face of materials and energy shortages. The evidence points to the accuracy of this assumption. In 1969, before the recognition of an energy crisis in the United States, this nation ranked only 30th (Daugherty, 1973) among the nations of the world in the per capita production of portland cement. This statistic suggests the ready availability at that time of steel, lumber, aluminum, asphalt, and plastics as well as concrete materials. Other nations, having foreseen a narrowing of their choices, had elected not to divert energy-intensive or energy-producing materials to construction. The United States currently is following the rest of the world in this trend. For example, the skyscraper was once considered the exclusive domain of the steel frame. Since 1969, however, with one exception, all new buildings in the world more than 200 meters high, of which more than half have been erected in this country, have been built of steel-reinforced concrete rather than steel frames. In addition, the world's two tallest free-standing structures, the 540-meter television towers in Toronto and Moscow are steel-reinforced concrete structures. Thus, the growing importance of concrete as the primary construction material is manifest.

2.3 COMPARISONS WITH RESEARCH AND DEVELOPMENT IN OTHER PARTS OF THE WORLD

The downward trend in research and development on cement and concrete is a worldwide problem. However, despite the difficulties of making absolute comparisons with other countries, the evidence suggests that the problem is relatively greater in the United States than in some other industrialized areas. A few indicators show some positive trends in R&D abroad and some negative trends in this country.

The concrete construction industry is notably absent from lists such as "What 600 Companies Spend for Research" [in the U.S.] (Business Week, 1977). Since 1976 the Securities and Exchange Commission has not required companies that spend less than one percent of revenues on R&D to report these expenses. It is assumed that the absence of construction contracting firms, particularly the large ones,* from these lists suggests that their R&D expenditures are below one percent. A recent team survey of cement and concrete R&D in the United States reached a similar conclusion, with the following sole exception:

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*Ten such firms were listed in Energy News Record, April 14, 1977, as having contracts exceeding a total of $1 billion during 1976; another ten exceeded a total of $500 million.

> "A concrete industry (unnamed)...considered a special case with regard to research interest...stated that they spend about 2% of the total sales on their own research. The interest in research through branch organizations was very little." (Bergstrom, et al., 1977)

There was no indication of this particular industry.

While the research and development among American contracting firms apparently is not strong, eight major Japanese contractors reported a total of $43.5 million spent on R&D in 1976. In addition, the central coordinating organization, Japan Building Contractors Society (BCS), in 1977 had an R&D budget of $250,000 (funded by 47 contractors) to supplement work by the individual contractors. The Japanese government provided some additional subsidy to industrial firms to promote their R&D (BCS, 1977). The latter report did not say what fraction of the above R&D was devoted to cement and concrete, but presumably it is substantial. Dr. Gunnar Idorn, who has studied worldwide R&D activities in cement and concrete extensively, states that:

> "although the volume of R&D effort in Japan is far greater than that in the United States, the quality of R&D in the United States has no peers anywhere." (personal communication to the committee, 1978)

The comparisons of spending on research and development correlate with the number of publications. The publications output from the United States is not very favorable. A substantially greater effort on cements in the Soviet Union was noted from comparing papers given at the 6th International Congress on the Chemistry of Cement in Moscow in 1974 (Chemistry of Cement, 1976). This was not a one-time occurrence, dependent on the site of the Congress. Comparisons were made among numbers of publications on two topics from the United States, Japan, and the Soviet Union using data from a 1977 annual review (Young, 1977). On the first topic (special portland cements) 6 of 69 publications were from the United States, 27 from Japan, and 12 from the Soviet Union. On the second topic (durability of hardened cements and concretes), 16 of 185 publications were from the United States, 32 were from Japan, and 36 were from the Soviet Union.

2.4 SUMMARY STATEMENT OF THE PROBLEM AND APPROACH USED

The future of the cement and concrete industry about 20 years distant depends strongly on decisions and research and development being carried out today. The committee's consensus was that substantial improvements and innovations are possible, and that research and development could generate profits through product improvements. Also, new research and development is needed to meet the more stringent performance requirements of concrete structures under extreme conditions.

The committee's basic problem was to examine the current status of research and development on cement and concrete and to determine the adequacy of the R&D establishment to meet current and future requirements. We took as our primary objectives the identification of the important areas of need and the key problems as well as the suggestion of alternative mechanisms for solving of the problems and fulfilling future needs.

The committee was composed of seven members from the cement and concrete research and development community, a technical adviser, ten liaison representatives from governmental institutions and agencies, and the NMAB staff officer. In addition to a preliminary organizational meeting, seven working meetings were held to elaborate the task, formulate a detailed approach, design a questionnaire, receive tutorial input from invited authorities and discuss the various inputs received.

The questionnaire was designed to elicit both objective quantitative information and opinion. It was sent to a cross section of academic, industrial, governmental, and nonprofit R&D establishments. The choice of recipients was intentionally biased toward those believed to be currently conducting R&D on cement and/or concrete and their components. It is recognized that the replies overall reflected the additional bias of absence of data from nonrespondents.

The present report is the considered synthesis carried out by the committee members based on all information received orally and in writing, including consultations and questionnaire answers.

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Chapter Three

CEMENTS AND THEIR COMPONENTS

Inorganic cements are the basic components of the binders of the vast amounts of concrete and related construction materials produced in the world. More than 75 million tons of portland cement were produced in 1978 in the United States alone (U.S. Bureau of Mines, 1979). Most of the following discussion relates to portland cement and portland cement-based products (e.g., blended cements). However, non-portland cements (e.g., calcium aluminates) are also of considerable importance to the national economy, and many of the comments and conclusions apply to them too.

The portland cement clinker, which is ground to make portland cement, is a complex conglomerate of phases varying in their chemical composition, crystal forms, purity, and reactivity with water (Taylor, 1964; Lea, 1971). The four main clinker phases are β-C_2S, belite; C_3S, alite; C_3A; and FSS,* depending on the quality and preparation of raw materials and on the conditions of burning (heating) and cooling. These phases may form a variety of solid solutions with minor components which, to a substantial degree, may change the performance of the cement. Thus, an understanding of the factors governing the composition and activity of cements is a precondition for the rational development of new or improved cements and for the realization of their full potential. It should be noted that, partly because of the lack of confidence in the uniformity of cement, concrete structures are designed with stringent safety factors to reduce the risk of failure. This results in a larger consumption of materials and energy than would be needed if the properties of cement and concrete were more predictable. Although no numbers are available, the cost to the national economy of this under-utilization must be large.

Cement and concrete production necessarily involve economic, energy, and environmental factors in addition to the technical factors related to the quality of the products. The technical aspects of cement and concrete production require inputs from specialists in engineering, physics, chemistry, and geology. Specialists in these fields need to supplement their basic knowledge with experience in one or more of the following: plant operation, product development, basic and applied research, technical service, and management.

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*Cement chemists' nomenclature: C = CaO, A = Al_2O_3, S = SiO_2; Fss = ferrite solid solution; β = a specific form of the compound.

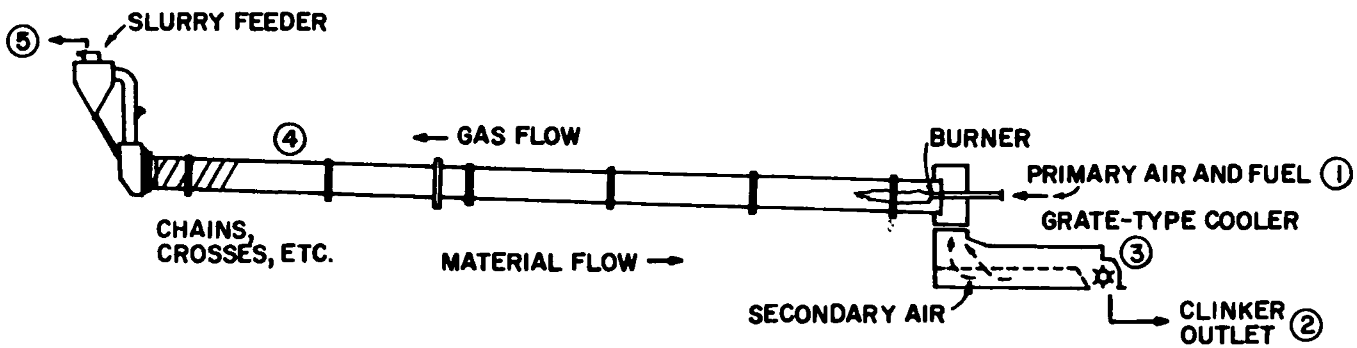
Needs in cement research and development are:

- Optimization of cement manufacture with special emphasis on product quality and efficient use of natural resources, i.e., fuels and raw materials.
- Establishment of relationships between clinker manufacturing parameters (e.g., burning temperature, rates of heating and cooling, composition of kiln atmosphere) and performance characteristics of the cement (e.g., strength development, durability).
- Understanding of the relationships among the various properties of cement and its performance in use (e.g., effects of particle size distribution and composition on shrinkage and rate of strength development).
- Optimization of the performance of cement in concrete, including adjustments required in different environmental conditions, parameters affected by different mix designs and blending materials, effects of the presence in clinker of minor phases, and admixture optimization.
- Development of new cement compositions that perform better or can be produced more economically.
- Development and improvement of technologies involving the use of waste products (e.g., fly ash, blast furnace slag, coal scrubber waste) as cementing materials.

3.1 STATUS OF RESEARCH AND DEVELOPMENT CEMENT MANUFACTURE

The fundamental processes involved in the manufacture of portland cement have changed little since the invention of the rotary kiln (Figure 1) before the turn of the century. Improvements in equipment and quality control have improved manufacturing efficiencies and the uniformity and performance of cement. A new plant today costs about $120 per yearly ton of product capacity; thus, a new plant with today's average capacity of half a million tons per year will cost about $60 million. The need for more capacity and for modernization of old plants (the average age of U.S. kilns today is about 23 years) means that the capital requirements of the industry have priority over research in the use of funds.

In recent years new types of kiln systems (Figure 2) have been designed in Germany and Japan. These new systems have large preheaters (precalciners) which utilize the heat from the exhaust gases for both heating and drying the raw materials. They are capable of decreasing the energy requirements of the kiln system by 50 percent of the average U.S. consumption (now at about 6 million Btu/ton) and of producing cement using 50 percent of the energy theoretically needed in the clinkering process. Because of this already high efficiency, dramatic changes in the energy requirements of the clinker burning process are not expected in the near future, although they cannot be completely ruled out. The preheater/precalciner systems were designed primarily to use oil as a fuel. Operating problems may arise when coal is used or when the raw materials vary significantly from those used in Germany and Japan.



1. MAY ADD DUST BY INSUFFLATION
2. SECONDARY COOLING OF CLINKER IF NECESSARY
3. COOLING AIR NOT USED FOR SECONDARY AIR IS EXHAUSTED THROUGH POLLUTION CONTROL DEVICE TO ATMOSPHERE
4. MAY INTRODUCE DUST THROUGH SCOOP FEEDER HERE
5. EXHAUST GASES PASS THROUGH POLLUTION CONTROL DEVICE TO ATMOSPHERE

FIGURE 1 Wet Process Kiln System (Federal Energy Administration, 1975)

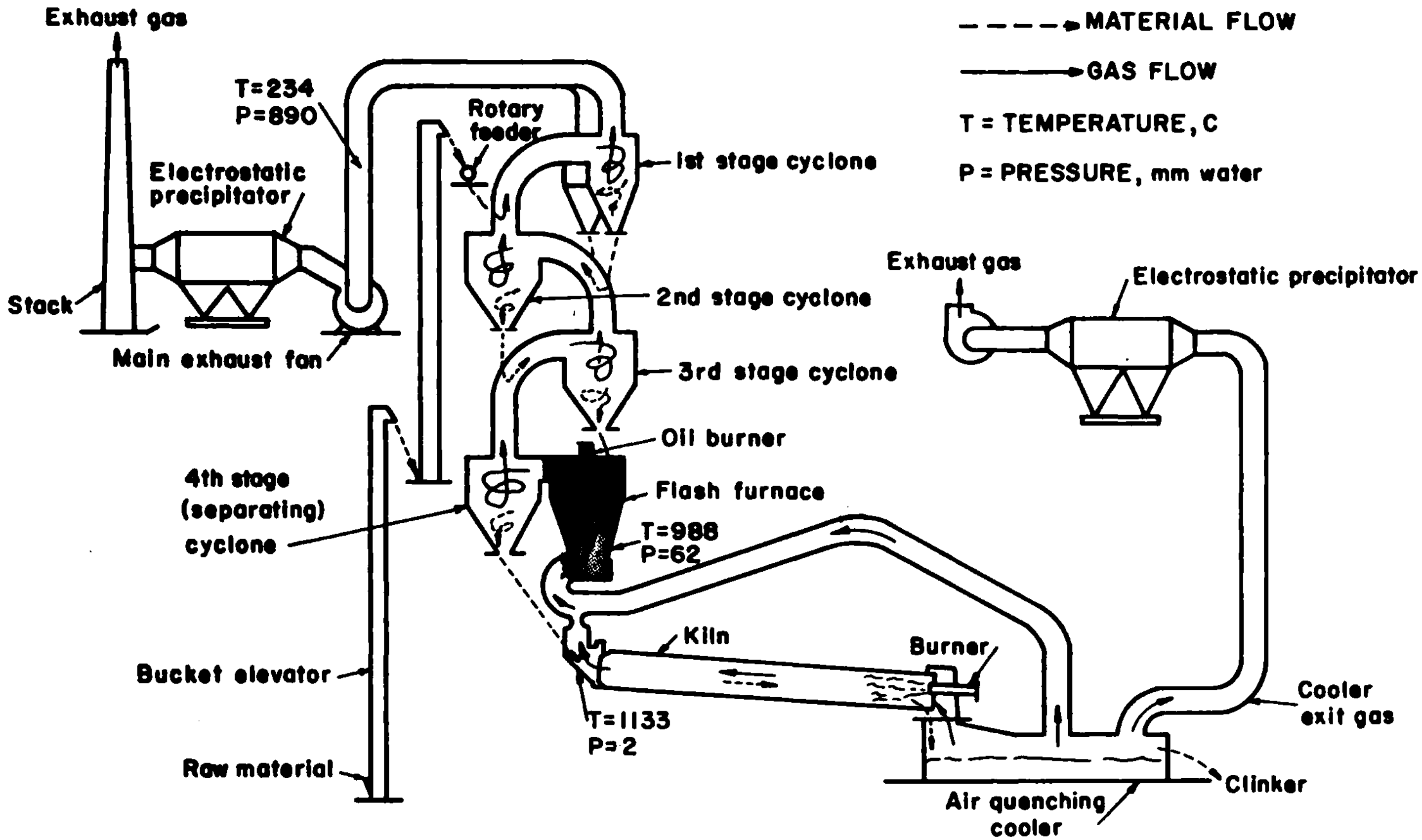


FIGURE 2 Rotary Kiln and Suspension Preheater with Flash Furnace (SF) (Federal Energy Administration, 1975)

Excellent summaries of these new kiln systems and other proposed systems, along with research needs for the cement industry, are given by PCA (1975) and Duda (1977). These references also provide up-to-date data on the other parts of the cement manufacturing process including grinding, raw feed homogenization, and pollution control.

The new kiln systems incur changes in operating parameters for pollution control, fuel costs, and changes of fuel from oil or gas to coal and have led to some undesirable changes in cement compositions. In particular, the alkali and sulfur contents of the clinker have generally increased, and considerable research is needed if the industry is to avoid costly processes for removing these alkali and sulfur compounds. Otherwise, alkali-aggregate problems and the decreases in strength caused by higher alkali/sulfate concentrations in the cement can be expected to occur more frequently.

Grinding is the least efficient process in cement manufacturing. Only a small fraction of the energy input is used in the actual fracturing process. Research on new grinding systems, grinding aids, and the effect of grinding method on particle size, shape, composition, distribution, and the subsequent hydration properties of the cement seems to be warranted (N.R. Greening, presentation to the committee, 1978).*

Little long-term and fundamental research on kiln and cement manufacturing systems is done in the United States. The equipment manufacturers do short-term investigations directed mainly at problems stemming from adaptation of the new energy-conserving preheaters and precalciner systems to different fuels and raw materials. Research on kiln and manufacturing systems seems to be much more intensive already than in this country (Duda, 1977; Richartz and Locher, 1978; Horst Ritzmann, presentation to the committee, 1978). U.S. patents for new systems are held mainly by foreign firms.

3.2 STATUS OF CEMENT MATERIALS RESEARCH

Cement materials research is conducted by a technical community consisting mostly of chemists, physicists, geologists, crystallographers, and chemical, civil, and ceramic engineers. This is understandable because production and use of cement involves inorganic and physical chemistry, high-temperature reactions, surface and colloid phenomena, rheology, mineralogy, and engineering. Additionally, the final product, concrete, must have certain engineering properties that depend on the physicochemical phenomena mentioned in the proceding sentence. This complexity of subject matter and the range of technical backgrounds required hinders cement materials research and the exchange of information among specialists in the various fields.

Cement research is generally encouraged by nonprofit organizations (e.g., American Society for Testing and Materials, Transportation Research Board of the National Academy of Sciences) and technical societies (e.g.,

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*An NMAB Committee on Comminution and Energy Consumption has been organized under the joint sponsorship of the Department of Energy and the U.S. Bureau of Mines to examine this problem.

The American Concrete Institute, The American Ceramic Society). It is funded by governmental agencies (e.g., National Science Foundation, Department of Energy, Department of Transportation, Department of Defense) and private industry.

3.2.1 Research and Development on the Nature and Characterization of Cements

The basic nature of the phases in cement clinker is known, but the range of variations that occurs in practice has not been studied systematically. With the development in the past 20 years of new analytical tools and techniques, new advances should be possible. It should now be feasible to explore relationships between cement performance and crystal structures, including modification, concentration of lattice, defects, and presence and location of impurities of the main clinker phases. This work should lead to an understanding of previously unexplained variations in the performance of cement and concrete. It should also lead to opportunities to improve cement and concrete performance by adjusting the crystallinity, reactivity, and composition of clinker components by changes in processing parameters and, possibly, use of additives. The results of such research might be the production of new cements for special purposes, improved uniformity of cements, easier introduction and acceptance of performance standards, and elimination of some processing and utilization difficulties.

At present, most of the technical work on the nature and characterization of cements and their components is routine and can be characterized as troubleshooting or simple quality control. Academic research on the relationships between the composition and structure of clinker phases and the reactions and performance of cement is practically nonexistent. Most cement producers determine the quality of their product solely to meet the required specifications. That have little economic incentive to invest in improvements in clinker and cement. Limited effort is being made to develop an understanding of the influence of the surface area, particle size, and particle-size distribution of ground cement on its performance in concrete. Limited work is also being done on the question of the optimum form and content of sulfate for different cements. Research and development on the use of waste materials (e.g., byproduct gypsum) to control setting of cement, on the modification of physical properties of cement (admixtures, additives), and on the development of new portland or nonportland cementing systems is scarce.

New analytical techniques are still being introduced into the field. Some of them, such as the Ono technique for characterizing clinker by optical microscopy (Ono and Soda, 1965; PCA, 1977) or methods of selective dissolution (Tabikh and Weht, 1971; Klemm and Skalny, 1977a) are gaining general acceptance. Sophisticated instrumentation, such as x-ray fluorescence, is being introduced for routine quality control. However, economic constraints, lack of interest in new product development, and the industry's relatively low level of personnel education in the specialty areas hinder introduction of other potentially beneficial tools, such as x-ray diffractometers, particle size analyzers, electron microscopes, etc.

3.2.2 Chemical Research and Development

What is generally characterized as cement chemistry is in fact two entirely different fields of chemistry having cement as the common denominator. The two fields are cement production or kiln chemistry and cement use or hydration chemistry. In kiln chemistry, the high-temperature, solid-solid and solid-melt reactions of anhydrous inorganic materials are of concern; in hydration chemistry, surface and colloid reactions in a hydrous system, often containing minor amounts of organic matter, must be explored. No cement chemists are produced by the chemistry departments of U.S. universities, and only limited specialized knowledge can be acquired by studying ceramics or materials engineering. Also, little chemistry is taught in the civil engineering departments which at present are the main source of specialists in cement and fresh concrete. Cement chemistry does not have a prestigious image among chemistry graduates, and it attracts limited numbers of the best people in chemistry and chemical engineering. Even they must obtain much of the needed background through apprenticeship in the few existing cement laboratories.

3.2.2.1 Chemistry of Clinker Production

Cement specifications adopted recently by the American Society for Testing and Materials (ASTM) and the U.S. government cover several specific types of cement, each with broad compositional limits and certain mininum strength-gain requirements in standard tests. The specifications are so broad that, for example, two cements or cement clinkers may vary substantially in their chemical and mineralogical composition yet still qualify as Type I portland cement. This state of affairs exists because large variations are traditionally acceptable in local markets in view of the low cost and large volume of cement used and the traditional overdesign of concrete structures. Thus, the limited application of technology and science to clinker chemistry and control is understandable.

Generally, the only production parameter controlled with great accuracy during clinker burning is the proportioning and chemical composition of the raw materials. We are not capable of accurately measuring temperature in the burning zone of the kiln (reflected, for example, in overburning of clinker because of fear of too high free residual lime content); we do not know all the factors governing the very complex heat and materials exchanges taking place in various kiln systems; and we lack full knowledge of the mechanisms of the chemical reactions leading to formation of a clinker and of how to produce a clinker with predictable quality. The use of Bogue calculations to predict phase composition and thus the approximate performance qualities of clinker (Bogue, 1955) is insufficient for many purposes (the equations assume equilibrium conditions); their use would not be sufficient in other industries producing structural building materials (e.g., steel and aluminum) because of more rigorous requirements for the quality of the final product.

<u>Chemistry of Clinker Formation</u>. A definite need exists to reevaluate the data on high-temperature phase relationships, especially when taking into consideration the nonequilibrium conditions prevailing in a typical rotary kiln. Better understanding of these relationships and of the effect of the composition of the kiln atmosphere could lead to a more

uniform product, new types of clinker, and energy savings. It is necessary to establish the effects of the liquid phase, formed during clinkering, on the reaction kinetics and product performance. It is also necessary to explore the possibility of decreasing the temperature (but increasing the rate) of formation of tricalcium silicate by use of mineralizers or addition of minor components. Knowledge of the relationship between clinker processing parameters and the properties of the clinker produced is adequate. For example, it would be beneficial to establish the effect, if any, of alite (an impure C_3S) and belite (an impure β-C_2S) grain size and interstitial mass composition on the grindability of clinker and the reactivity of ground product with water.

Effect of Processing Parameters. Changes in pyroprocessing technology introduced in the recent decades, primarily in Germany and Japan, have led to substantial improvement of production efficiency and brought new technological challenges to the U.S. cement industry. Simultaneously, the recent return to coal as the primary energy source has introduced new factors into the chemistry of clinker formation. Additionally, environmental restrictions have forced the industry to deal with previously unconsidered issues such as disposal of solid wastes and control of SO_x and NO_x emissions (Duda, 1977; Locher, 1978; FEA, 1977; DOE, 1978; H. Ritzman, presentation to the committee, 1978).

The use of new or modified processes, fuels, and raw materials may lead to serious problems. A situation may develop where the clinker is oversulfated to such a degree that adequate set control by gypsum additions is not possible within the ASTM cement specification limits on total SO_3 content. The presence of sulfates in the form of alkali rather than calcium salts may lead to setting problems, changes in the rate and level of strength development, decrease in volume stability and durability, and variability of response with admixtures (Jawed and Skalny, 1978; Hogan, 1978). Accommodation of alkalies in clinker components and disposal of alkali-containing wastes is a technical challenge and an economic necessity for the industry.

Basic Research. There are a large variety of challenges to basic research in cement clinker chemistry. For example, the chemical and crystallographic reasons for the differences in the reactivity of pure and impure clinker phases need to be explored with the aim of understanding factors affecting the mechanisms and rates of hydration. This is especially true for dicalcium silicate which can be formed at a lower temperature with less energy and at lower cost. This compound does contribute substantially to ultimate strength, but through modification, it might contribute much more to the early strength development (Lea, 1971; Frohnsdorff, et al., 1979). Application of modern experimental techniques and basic studies on the mechanisms and kinetics of clinker mineral formation are two additional areas where fundamental research is badly needed (Klemm, et al., 1977b).

New Product Development. A challenge for both industrial and academic research is the development, testing, and production of new nonportland or portland clinker-based cements, especially in view of the need to conserve natural resources and dispose of by-product materials. Examples of such possibilities include the development of fly ash and slag-containing cements having faster rates of strength development (FEA, 1977; DOE 1978). The production of cements using by-product sulfates, the production of low Al_2O_3/Fe_2O_3 ratio cements (Al_2O_3 is the most expensive of the oxide components in portland cement raw materials), and the development of new or improved cementitious materials based on lime, phosphate, magnesium oxide (Sorel-type), and other chemical by-products (Frohnsorff, et al., 1979).

Further investigations may be warranted on methods of cement manufacture involving the simultaneous production of other products, including sulfuric acid or alumina. The possibility of utilizing the NO_x/SO_x emissions from cement plants for useful purposes also bears looking into. These tasks would benefit from more basic chemical research and collaboration between several industries and the government.

3.2.2.2 Chemistry of Cement Hydration

Research on cement hydration chemistry is the part of cement chemistry that has been given the most support in the United States. Many internationally acknowledged accomplishments were made in a period extending into the 1960s, primarily by the Portland Cement Association and by university research teams supported by grants from the federal government. The areas of success included hydration chemistry at ordinary temperatures and pressures and the hydration chemistry of high-temperature cured and autoclaved materials (Powers, 1960; Brunauer and Greenberg, 1960; Copeland and Kantro, 1968; Copeland and Verbeck, 1976). Although most of the hydration research is basic, some of it is performed on behalf of private industry, e.g., companies producing chemical admixtures, oil-well cements, and chemicals in general. Comparatively little hydration research is supported by the portland cement and concrete industries per se.

One of the possible reasons for the success of the efforts in hydration research is the international character of the field, which is much less restricted than clinker formation research. Generally, hydration research is much less costly to perform and is closer to the needs of the end user than clinker formation research. The greatest progress has been achieved in the mechanisms of interaction with water of the individual clinker phases and in the structure and morphology of the hydration products formed. This knowledge is most important for understanding the principles of cement paste structure development, which in turn is used in improving the properties of the final product -- concrete.

Fundamental Relationships. In spite of the achievements cited above, there are major areas where more intense research and development is needed. For example, we are unable to characterize adequately the anhydrous materials present at the start of hydration. We still do not know the exact mechanisms of the setting and strength development of cement. The relationship between the composition and microstructure of the hydration products and their cementing action, including cement paste-to-aggregate bond, is virtually unknown. Is the type of microstructure related to engineering performance? The available knowledge of the interaction of cements with a variety of admixtures is limited and, for some admixtures, is completely lacking (R.C. Mielenz, presentation to the committee, 1978). The reactions in the cement admixture water system are extremely complex, and the colloid and surface processes leading to development of different microstructures are unexplored. This lack of knowledge hinders the development of new, more economical cementing systems and the utilization of the full potential of portland cement.

Instrumentation. Compared with other areas of chemistry, cement research has been limited in application of modern instrumentation (Klemm, et al., 1977b). Not only do we not benefit substantially from the use of techniques such as electron spectroscopy for chemical analysis (ESCA), Auger spectroscopy, low angle x-ray scattering, and Moessbauer spectroscopy, but because of the complexity and hydrous nature of the hydrating cement system, we still have problems in characterizing the ionic species in the liquid phase of the system and in determining the chemical composition and structure of the major hydration product, the calcium silicate hydrates (C-S-H). Modern instrumentation is costly, and much of it is only availably in a few well funded research organizations. Establishment of a central cement or building research institute (see Chapter 8) could make such instrumentation more accessible to all who need it.

Changing Cement Properties. Changes in raw materials composition and processing technology affect to an unknown degree the composition of such cements (L.V. Spellman, presentation to the committee, 1978). Cement producers and users, as well as industries producing other concrete components (e.g., admixtures, aggregate, fly ash, slag), should have a serious interest in exploring the consequences of changes on the performance of these materials in the composite concrete. Better understanding of the relationships between the chemical processes during hydration and the material's properties could lead to improved ability to predict performance and the development of new cements.

Basic Research on Durability. Improved knowledge of the chemical reactions and forces leading to cement paste-to-aggregate bonds and their deterioration in aggressive environments is badly needed. An understanding of this bonding mechanism, the weakest link in concrete strength, would lead to improved products and thus to saving of national resources. Research on problems of durability warrants increased support by government agencies because of the importance of such problems to all federal and state construction agencies and the DOD. The aim of these research programs should be first to understand the reactions that lead to degradation of concrete (Purdue University, 1978) and then to attempt to eliminate their occurrence or propagation. Important types of structures that suffer severe durability problems include bridge decks, highways, military installations, and naval shore structures.

Nonportland Cements. Currently, only very limited R&D is performed on nonportland cements (e.g., high-alumina cements, magnesium oxychloride cement), and comparatively small investments are being made to develop new, special cementing materials (e.g., for use at low temperatures and in other severe environments). This is not surprising in view of the small volumes of these materials used. Nevertheless, it seems desirable that fundamental research should be done on cementing mechanisms to give insights applicable to both portland and nonportland cements.

3.2.3 Research and Development on Cement Paste Properties

Concrete is bound by and owes many of its useful properties to the hardened cement paste that is produced by the reaction of water with portland cement. The characteristics of this paste are not independent of details of the concrete production process. However, it is current practice in the United States that much concrete is produced on the job site under relatively poorly controlled conditions and placed within forms that are not usually open to inspection. Thus, there is no check to assure that the hardened cement paste structure is developing normally within the forms. Indeed, there are no agreed-on methods in the United States for evaluating the development of the structure. Control is exercised by strength tests of separately cast specimens of job concrete, which may differ to an unknown degree in microstructure and performance from the concrete within the forms. Investigation of the microstructure is only carried out after the fact in response to the development of some serious problem

Research aimed at understanding the details of the development of structure in hardened cement paste in concrete under conditions relevant to field practice is almost absent in this country. The influences of variations in the composition of the portland cement used, particle size distribution, presence of chemical admixtures and additives, and other factors have received almost no attention. What microstructural studies have been made have commonly concentrated on simplified systems -- simple cement pastes or pastes of one component of cement (C_3S, C_2S, etc.) -- mixed and cured under conditions quite foreign to concrete practice. These studies afford useful background information but skirt the real complexity of the system used in practice.

Improved methods of mixing, compacting, and placing concrete are evolving continuously to meet special needs. However, the influence of changes in manufacturing conditions on the development of structure in the hardened cement paste is not currently addressed in U.S. research.

The beneficial effects of extended curing (prolonging the period of active cement hydration) on the characteristics of the cement paste in concrete are well known. Current practice in this country pays lip service to the concept, but in actuality, the curing techniques are often inadequate and the curing operation badly controlled. Research on the effects of curing on cement paste structure is not currently being done to any great extent, although superior curing methods could certainly be developed, and their benefits documented.

It is likely that concrete in the future will contain increased quantities of inorganic additives such as slags, fly ash, or pozzolans, and perhaps other waste or by-product materials. The development of the structure of hardened cement pastes incorporating these components is not well understood, although it is clear that both the character and the rate of development of the structure of the hardened cement paste may be profoundly affected. While some research on this major problem is being pursued, most of it is focused on measurements of the changes in externally measurable properties (e.g., strength, creep, shrinkage) and very little on the internal differences in the hydration products and microstructure responsible for these properties.

Related sources of potential problems are the poorly understood interactions between the organic admixtures used routinely to control such properties as concrete set, rate of strength gain, and air content and the fly ash or other waste products which increasingly are being incorporated in concrete. Such interactions are leading to many field difficulties, in which the characteristics and rate of development of the paste may be profoundly affected. However, little systematic research is being done, and available reports indicate consideration of the problem only on a case-by-case basis. There is considerable need for systematic research in compositions and processing; such work can be expected to yield benefits in the shape of more energy-efficient and resource-conserving materials.

The general conclusion to be drawn from the above discussion is that research and development on cement paste characteristics is meager and not particularly well attuned to providing the information needed to solve the microstructure or paste-related problems confronting the concrete industry. Lack of such information not only precludes improvements, but makes it difficult to maintain the current level of technological effectiveness as conditions change.

3.3 SUMMARY

After World War II, the volume of cement produced worldwide increased dramatically. Research and development for the cement industry was performed primarily by the Portland Cement Association which, during the 1950s and 1960s, gained an international reputation for advancing cement science and technolgoy. During the past 10 to 15 years, however, support for research and development provided by the cement and concrete industries has decreased substantially, and the losses have not been fully replaced by government funds.

On the basis of this chapter, the following conclusions were reached:

1. R&D for cements and concrete (including cement-based composites) is primarily defensive in nature because of the present political and economic environment.

2. In manufacturing, available funds are not invested in R&D but in capital equipment needed to comply with strict environmental requirements and in process improvements that lead to fuel savings (e.g., use of coal to replace gas and oil) and to a decrease in the total energy input.

   In view of the above, and considering the capital cost per annual ton of production for a typical new plant, the cement manufacturing industry has little economic strength to devote to new technologies or products.

3. Financial support from the cement industry for R&D in general and particularly for the Portland Cement Association (the ad hoc industry-supported R&D center) is small.

4. There is a communications barrier between the academic and industrial technical communities for a number of reasons:

   - Academic investigators' inadequate knowledge of the industry's needs

   - Sparse distribution of cement scientists in the industry so that there are no critical masses of researchers

- Conflict between the complex chemical and physical problems in cement production and use and the sometimes relatively simple, unsophisticated processing employed by the industry.

5. The research and development effort in cement and concrete in this country suffers from a lack of intellectual and coherent economic support. This finding is true of the areas of new processing equipment; chemistry and physics of cement formation; and the relationship between processing parameters, clinker properties, and the development of cement properties. Also, investment is needed in basic R&D on the durability of cement and concrete with special emphasis on understanding and preventing deterioration of concrete resulting from environmental effects (e.g., freezing and thawing, de-icing compounds, marine environments), and from changes in composition and character of cement and concrete components (e.g., cement composition changes and use of blending materials, admixtures, and potentially reactive aggregates).

6. Inadequate knowledge of the basic properties of cements and of their interactions with water result in the under utilization of concrete as a material. Inadequate homogeneity testing procedures, performance specifications, placing and finishing methods, curing techniques -- all require concrete structures and products to be designed with larger safety factors than would be necessary if the knowledge base were improved and consistently utilized.

7. The accumulated basic knowledge is not well used to develop new cement-based composite materials (e.g., using urban and industrial wastes and by-products). Such development would benefit the general economy by increasing the profit margins of the cement and concrete industries and by leading to more cost-effective structures and, at the same time, would reduce environmental and energy problems.

In summary, a review of the status quo of the U.S. research and development on the manufacture and use of both portland and nonportland cements points to inadequate intellectual and financial investment by the pertinent industries and governmental agencies. In modernizing the existing obsolete manufacturing facilities, the United States has to rely on new technologies developed primarily in Europe and Japan. Research needed to exploit the unused potential of cement is inadequate, thus hindering solution of such problems of national concern as concrete durability and replacement by concrete or other cement-based composites of more scarce and/or energy-intensive materials (e.g., aluminum, steel, plastics). Improved knowledge of the basic chemical and physical processes involved in the production and use of cement could lead to energy savings (FEA, 1975), better utilization of natural resources, improved methods of concrete manufacture, expanding use of structural concrete, and development of new or improved composite materials based on cement.

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Chapter Four

CONCRETE PRODUCTS AND THEIR COMPONENTS

Research and development on concrete in the United States is carried on by a more diversified community than is the case with cement, partly reflecting the great size of the concrete industry. More university and government laboratories are active, as are a number of private-sector organizations. Significant concerns in concrete include the technology of concrete production (with attention to concrete components, processing, and quality control); the design of concrete to meet specific performance requirements; the determination and understanding of the materials properties of concrete; the design of concrete structures and their mathematical analysis; and the durability of concrete in service (Mielenz, 1975).

In this chapter, the status of previous developments in the various subfields covered will be given as background to a discussion of current research and development needs. Most of the latter are currently unfunded and not under investigation; they are likely to remain so unless major changes occur in the present climate for R&D.

4.1 CONCRETE PRODUCTION AND CONSTRUCTION METHODS

4.1.1 Status of Previous Developments

Methods for producing concrete and incorporating it into concrete structures have undergone major improvements since the early part of the 20th century. Early advances included the concepts of proper aggregate gradation; the development of deformed reinforcing bars; the development of admixtures to regulate setting and improve workability; and the development of methods of providing reliable, centrally mixed concrete for delivery to the job site.

These developments were followed by such improvements as pump placement and shotcreting; methods of routinely producing precast concrete units; slip-forming and jump-forming cast-in-place structures; effective means of vibratory consolidation; the development of welded-wire fabric reinforcement; the introduction of seven-wire strands for prestressing concrete; lightweight concretes incorporating special lightweight aggregates or produced by special foaming techniques; and effective membranes for curing concrete. More recent improvements in concrete production methods include the development of computer-controlled construction equipment; self-contained units for continuous volumetric mixing of concrete; modification of mixing and batching procedures to permit successful incorporation of glass or steel fibers, or of superplasticizers; methods of production of polymer-impregnated concrete to meet special needs for chemical resistance;

production of extruded hollow-core panels for floor and wall systems; construction methods for segmental cantilevered box-girder bridges; and special methods for the construction of massive fixed and floating marine storage units.

4.1.2 Research and Development Needs

Much of the impressive list of advances mentioned above derive from the field and from entrepreneural ingenuity, rather than from formal research. Concrete construction activities lend themselves to informal approaches. It appears that many additional changes in concrete production and construction methods will be required. Research and development is needed to accommodate changes in the character of concrete expected to result from widespread incorporation of pozzolans, fly ash, waste gypsum, recycled concrete, and other energy-sparing components (Frohnsdorff, et al., 1979). Particularly needed are new methods of assessing and ensuring the uniformity of the concrete produced, including new test methods and equipment that would permit closer monitoring and control of relevant processing variables.

Aggregate production is a considerable component of concrete production, aggregates constituting the bulk of mass and volume of most concrete. High quality aggregates are in increasingly short supply in most metropolitan areas, where construction is concentrated. A methodology is needed whereby they can be properly identified, inventoried, and reserved for use in concretes in which their desirable attributes are essential (Kesler, 1979). Conversely, production methods that can accommodate inferior aggregates without excessive degradation of the product would be beneficial.

In this context, the use of recycled crushed concrete as an aggregate is being explored (Frohnsdorff, et al., 1979). Limitations on this practice associated with inadvertent incorporation of gypsum or other associated substances that may have harmful effects on the behavior of the new concrete should be thoroughly investigated.

Methods of mixing and placing high-strength (more than 10,000 psi or 70 kPa) concrete on a consistent basis constitute an important R&D need (W.G. Corley, presentation to the committee, 1978). Such high strength concretes are now produced for special needs, especially in high-rise concrete buildings. There is some concern about potential brittleness of such materials that may limit their use in practice.

Equipment modification and development in the light of changed economic and social conditions must be explored. The equipment used in batching and mixing and, particularly, in delivering concrete to the job site would benefit from redesign to reduce energy consumption and increase service life (Frohnsdorff, et al., 1979).

Methods of producing concrete for special applications offer fruitful areas for research. For example, "dry" concrete, placed and compacted by highway construction equipment, has been suggested for use in dams, pavements, and runways. Such procedures might eliminate the costs of forms and of construction joints. Means of eliminating the need for temporary tunnel supports by placing concrete liners with useful strength immediately behind the tunnel boring machines have been suggested. Research aimed at improving shotcreting methods, especially in reducing the wasteful rebound loss of aggregate, would be highly productive.

The design of joints for precast concrete structures needs considerable development. Energy-absorbing joints can and should be developed for earthquate-prone areas. Attention should also be given to construction procedures that would permit easier dismantling of obsolete or unneeded structures so that sound, precast, concrete structural elements would have salvage value.

A new approach to the present chaotic system of dimensioning and locating precast concrete units, which may arrive at a particular site from several sources, is badly needed. A system based on the aircraft industry's method of "true position and tolerance" might well be developed for this purpose.

Finally, vastly improved means of efficiently fabricating and transporting large concrete tanks and oil-drilling platforms are urgently needed.

4.2 CONCRETE PROPERTIES AND TESTING METHODS

4.2.1 Previous Developments

Concrete constitutes a family of materials whose properties vary significantly with the specific components (types and proportions of cement, aggregate, pozzolan, admixtures); with the details of the methods used for mixing, placing, consolidating, and curing; with early temperature history; with exposure to moisture, freezing, temperature, and humidity cycles; and with age.

Many of the properties of concrete are understood quantitatively and have been reasonably well analyzed and controlled for many years. They include such important properties as elastic behavior, strength in simple loading situations, and elementary creep and shrinkage characteristics. Standardized, if somewhat unrealistic test methods have provided sufficient information for quality control and prediction of behavior under most conditions. The results of recent attempts to apply fracture mechanics studies to concrete indicate that while the concepts of linear-elastic fracture mechanics apply to cement paste, the effects of inhomogeneities introduced by aggregates prevent direct application to structures that are not sufficiently massive (Gjørv, et al., 1977). Thus, such analyses are applicable to dams; approximately applicable to large reactor vessels; and inapplicable to smaller concrete structures and to individual concrete test specimens. Proper criteria for crack propagation in most concrete structures remain to be developed.

In recent years, the widespread development of computer techniques has influenced the concrete area, and the development of mathematical models to describe nonlinear triaxial deformation, failure envelopes, creep, and certain moisture and thermal effects has been pursued with some success (Bazant, 1975). Strength concepts have been placed on a statistical basis, and statistical quality control methods have been applied in monitoring concrete production (American Concrete Institute, 1978). All of these developments have resulted in significant reductions in the safety factors used in designing concrete structures.

During the past few years, a start has been made toward producing "manufactured" concrete in semi-industrial environments with high production rates and relatively close dimensional tolerances. Intensive vibration and relatively short mixing cycles are frequently used. Better methods of monitoring the concrete during the processing and early post-placement stages are being applied. Traditional quality control procedures, comprising after-the-fact testing of small specimens cast separately for testing purposes, are probably inadequate for such concretes.

4.2.2 Research and Development Needs

A variety of needs exist for research and development on concrete properties and test methods. One obvious need is new means of producing concrete of superior properties for general or special applications. A second need relates to the development of adequate methods for monitoring the development of concrete properties during processing. This need is particularly important in the light of recent failures involving "green" concrete that did not develop proper strength on the expected schedule. A third need involves the development of mathematical models to describe the behavior and performance characteristics of concrete. All of these problems require better understanding of the physical and chemical processes controlling the development of strength and structure in concrete.

Test methods for characterizing the properties and performance of concrete require extensive updating, and parameters not usually measured need careful attention. One such parameter is the rate of heat evolution and consequent development of thermal stresses in nonmassive concrete members. The possibilities for damage have been mostly ignored as inconsequential in the absence of visible cracking. However, recent European research suggests that weakening and degradation of new concrete through microcracking caused by early thermal stresses may be important (Freiesleben-Hansen, 1978) and that preventive measures are available.

The traditional and exceedingly crude "slump cone" test method for monitoring and controlling the properties of fresh concrete is inadequate, especially with new developments such as fiber concrete and superplasticized concretes. The development of better means of monitoring the rheological properties of fresh concrete in laboratories and on the job site is an urgent need, but investigations into such methods are almost nonexistent in the United States.

Another area that requires fundamental investigation and test development is concrete fracture parameters. As previously mentioned, although linear fracture mechanics is not applicable to most concrete structures, fracture toughness certainly varies among concretes, which may have good or poor quality aggregates, may or may not have fiber reinforcement, or may have various other distinguishing attributes. Some means of measuring fracture toughness with reliability of methods used routinely to measure strength and durability is required. Such measurement is needed to determine the ability of particular concretes to resist abrasion, to withstand impact, blast, and cyclic or other repeated loading conditions, and for directly determining failure loads for dams and large reactor.

In the general area of test methods, another major R&D need is more effective means of nondestructive testing of existing concrete structures, especially mass concrete. Internal friction, acoustic emission, and other nondestructive instrumental methods need to be pursued and adapted to such measurements.

Much additional effort would seem to be required on models that describe triaxial behavior, which is essentially nonlinear. Such models need to incorporate mathematical descriptions of strength development, creep, dilatancy, ductility, cracking from thermal stresses and fatigue, interaction with reinforcing steel, and changes in these responses with changing moisture contents and temperature (Bazant, 1975). In fact, it is possible to develop models incorporating functional descriptions of the internal structure of cement paste in concrete so that the effects of chemical parameters, pore pressures, and microstructural changes can be taken into account. Such models are necessarily complex, but modern computing power makes their development feasible and their solution practical.

However, to achieve good mathematical modeling of the complex responses of concrete typical of many structural situations, much more detailed experimental information must be acquired and systematized. In this context, better test information is needed with respect to nonlinear triaxial responses to nonlinear and cyclic loadings and to hysteresis, strain-softening, and other effects. Ideal test conditions can rarely be attained, and finite element methods may have to be used with test specimens to identify the patterns of material behavior by fitting a model to the test results (the so-called material identification problem in mechanics).

Development of mathematical models can help solve a number of important but intractable problems in the design and analysis of concrete structures. These include the tensile and shear ductility of concrete plates, shells, and reinforced panels; strain-softening behavior of reinforced concrete elements; and inelastic volume dilatancy effects that normally induce hydrostatic pressure. Other areas needing attention include nonlinear and triaxial creep and their dependence on humidity and temperature; phenomena important in rational analysis of corrosion of steel in concrete such as oxygen and chloride ion diffusion characteristics and electrochemical effects near steel-concrete interfaces; and various others.

4.3 NEW CONCRETES, CONCRETE CONSTITUENTS, AND CEMENT-BASED COMPOSITIES

4.3.1 Previous Developments

Improved varieties of concrete and concrete constituents and new varieties of composites based on cement have been developed in recent years at least partly in the United States. Some of these materials have been brought into limited commercial practice, but applications are not widespread.

A variety of cements, based loosely on portland cement but modified to achieve specific characteristics, have been developed. These materials include regulated-set cements, shrinkage-compensating and expansive cements, some very high, early-strength cements, and others.

New admixtures, particularly superplasticizers or high range water reducers, have also been developed in recent years (Malhotra, et al., 1978). Most of these products were developed in Europe and Japan and are still being imported from there to the United States. High range water reducers are organic admixtures that disperse cement and drastically reduce the water content needed for mixing and placing concrete. Their use permits stronger and more durable concrete to be made or ordinary concrete to be made with less trouble and expense in placing and consolidation.

Development of so-called low porosity cement concrete has proceeded slowly. Low porosity concrete is made from ground clinker without gypsum addition, but incorporating special admixtures that permit placement at exceedingly low water contents. Such concretes seem to have significantly superior strength, dimensional stability, impermeability, and durability (Gomez-Toledo, 1977).

The development and widespread use of synthetic lightweight aggregates had proceeded briskly before 1974, but thereafter the energy and antipollution requirements for producing such aggregates caused most of the development work to be suspended indefinitely. Waste products could be used for this purpose, and often there is an inherent energy contribution from them (Frohnsdorff, et al., 1979).

Research and development on alkali-resistant glass fibers for use with cement has been undertaken by glass manufacturers in several countries including the United States. A number of glasses intended for the purpose have been patented and are being commercially exploited. Alkali-resistant glass fibers have been applied to a variety of thin-panel composites, typically incorporating cement and some sand but not coarse aggregate. These composites have found various architectural uses, but are not yet recommended for load-bearing applications because of the uncertainty of the retention of strength under weathering conditions that possibly may prevail (Majumdar, et al., 1977). Another application of alkali-resistant glass fibers has been to "mortarless" block wall construction (Lankard, 1975). Here, masonry walls are produced by stacking the blocks without mortaring the joints between them; instead, a thin layer of mortar incorporating the glass fibers is troweled or otherwise applied to one or both vertical faces of the entire wall.

Steel fibers have been used in concretes in a variety of ways (Lankard, 1975). Novel and much more efficient forms of steel fiber have been developed, including fibers with deformations along their entire lengths and fibers with special end anchorages. The latter have been produced in parallel assemblages held together with a water-soluble glue. Use of such assemblages has almost elminated previous mechanical problems of incorporating the fibers into the concrete mix.

Concretes and other composites having various unusual features for special applications have been developed in recent years. A good illustration is special high-strength concrete for high-rise buildings, based on selected but conventional portland cements, selected aggregates, incorporation of fly ash, and use of a superplasticizer (W.G. Corley, presentation to the committee, 1978). Another example is shrinkage-compensated concrete used in water impoundment structures, parking garages, and a few large building complexes where crack avoidance was recognized as a primary objective by the designer (American Concrete Institute, 1976). Applications have been developed for ferrocement -- mortars heavily reinforced with wire mesh sheets, especially in small ships and boats.

Other developments that might be noted include a variety of special concretes produced for specific nuclear shielding applications. These materials include extra-dense concretes and, at the other extreme, concretes placed with unusually high water contents for effectiveness in shielding against neutron fluxes (American Concrete Institute, 1972).

4.3.2 Research and Development Needs

Opportunities, indeed requirements, for research and development on new concrete and concrete constituents exist in profusion. Only a few such requirements can be mentioned here.

One area in which research activitv could well be mandated is the general field of incorporating fly ash into concrete. The problem stems from the extreme variation in characteristics and in responses among fly ashes.

Some are exceedingly slow reactors and develop strength; others, including many of the so-called Class C fly ashes (according to ASTM Designation C-618) react quickly in terms of contributing strength gain, but confer great sensitivity to set retardation problems, especially in the presence of many normal concrete admixtures (Purdue University, 1978). Questions relating to durability need to be answered for concrete incorporating fly ashes of different kinds (B.L. Meyers, presentation to the committee, 1978). For example, it has usually been assumed that most fly ash bearing concrete is generally alkali and sulfate resistant, but the former may not be true for alkali-bearing fly ashes, and evidence exists that high alumina, low iron fly ashes may render concrete unduly susceptible rather than resistant to sulfate attack (Dunstan, 1976). Unless a relatively large and well coordinated research effort is mounted shortly to provide more nearly adequate insight into the behavior of various types of fly ash in concrete, we can expect major problems to develop in this area in the foreseeable future.

The shortage of good aggregates is discussed in Appendix A. A related area where additional research is necessary is that of alkali-aggregate re-reactions. Distress here is caused by reaction of alkali components of cement with certain potentially susceptible forms of silica in aggregates. While the outlines of the problem are understood reasonably well, new variants are appearing, perhaps owing to the greater potential for attack built into the newer cements with higher alkali contents that currently are being produced (Diamond, 1975). A further complication is the exhaustion of high quality aggregate in some areas, leading to use of aggregates from inadequately tested new sources.

Organic admixtures of several kinds were discussed previously. Published research on the fundamentals of admixture actions is scarce, and admixture manufacturers seem to pursue little basic work in the field, at least according to information presented informally to this panel. Judging from successful results with conventional admixtures and with the newer superplasticizers, benefits from understanding the details of admixture action should be potentially great -- both in suggesting new admixtures and in understanding problems as they arise in practical systems (R.C. Mielenz, presentation to the committee, 1978).

The physical durability of plain and reinforced concrete in service, particularly in environments marked by repeated freezing and thawing, saltwater exposure, wide temperature cycles, or exposure to chloride, sulfate, or acid solutions, has been the subject of much study in recent years, but probably requires a much more concentrated effort. Far more concrete must be replaced because of inadequate durability than for mechanical reasons. While aspects of the several durability problems are well understood, even such seemingly uncomplicated problems as distress caused by simple freezing and thawing is the subject of continuing controversy as to machanism. Much field concrete deteriorates from a combination of durability-related problems, rather than a single cause. A prime illustration is deterioration of bridge-deck concrete, which arises from a combination of corrosion of embedded reinforcing steel (as promoted by the use of de-icing salt), freezing and thawing damage, bridge vibrations, traffic impacts, and perhaps other causes as well.

4.4 DESIGN AND ANALYSIS OF CONCRETE STRUCTURES

4.4.1 Previous Developments

The major development in structural concrete in recent years has been prestressed concrete. The initial impetus was the postwar shortage and high cost of construction steel in Europe in the 1940s, and European investigators were early leaders.

The U.S. concrete industry kept pace in prestressed concrete in some areas, notably prefabricated prestressed units, and pioneered in others. The record-length Lake Ponchartrain Bridge and the early development of prestressed circular tanks might be cited. Nevertheless, this country lagged in important areas, particularly in the use of post-tensioned concrete for large structures, and specifically in the cantilevered segmental box-girder bridge. In the early 1970s changed economic factors led to further rapid progress in the United States, even in areas that previously had been neglected. An additional example is the floating liquified petroleum gas (LPG) facilities made from prestressed concrete (Anderson, 1977).

Another development that started in Europe and was later applied and refined in this country is the design and construction of prestressed concrete nuclear reactor vessels (Bazant, 1976). Other recent achievements in this area include very tall concrete buildings (more than 70 stories) using high-strength concrete for columns and ocean oil-storage tanks made of concrete, the latter developed largely in Europe (Moksnes, 1978). Considerable development has occurred in hyperbolic paraboloid cooling towers, and in lightweight concrete large span bridges, but unanswered questions remain in both areas.

The use of prestressed concrete for piles in ocean ports has now become widespread. Prestressed concrete piling is now used for substantially all structures on the West and Gulf Coasts of the United States, and its use is spreading to Asia and the Middle East (B.C. Gerwick, personal communication, 1979).

Despite general advances in the design of precast concrete structures, joints in such structures continue to be costly and to perform poorly (J. Janney, presentation to the committee, 1978).

Analysis of concrete structures has been revolutionized by computer methods which have today permitted the development of a much more realistic design (especially for earthquake or other dynamic loads) and allow for inelastic effects (Bazant, 1978). Great improvements have been made in building codes, including the adoption of limit-state design and the consideration of previously neglected effects such as torsional loading on beams, cracking calculations, etc. Linear elastic analysis of concrete structures, the sole approach until about 1965, is now generally regarded as insufficient. Consideration of the behavior of simple structural members, such as beams, columns, etc., has given way to analyses of more complex structural systems, including the joints. Codes are being revised on a much more frequent basis to take advantage of the new developments.

Relatively poor dissemination and application of research results has been a weakness in structural design and analysis, but to a lesser degree than in concrete materials research. In some areas, new and sophisticated computer codes, not without cost, were quickly utilized, and as a result, the designer may be deprived of intuitive insight into the behavior of the structure.

4.4.2 Research and Development Needs

The current trend toward computer analysis and computer code development is strong, and further advances should facilitate the application of the results for the properties of concrete to the design and analysis of concrete structures.

Energy-related concrete structures raise important issues in structural design and analysis, and new advances in connection with such structures will inevitably be required. If the nuclear program remains strong, nuclear concrete structures will be of major importance. Progress is needed in seismic analysis of such structures, especially in the areas of inelastic response and ductility; and further work on the effects of shock loading, heat loading, and impact behavior on nuclear accident analysis must be undertaken. The proposed hardened missle sites for the MX system will require similar concretes of high strength and high fracture resistance.

The economic outlook for ocean oil storage tanks and platforms is also uncertain, but if they are to be used, significant design and analysis problems need to be solved. These include problems with cyclic loading as applied by wave action thermal loading, corrosion, and effects of artic conditions on such structures. Goal gasification and liquefaction will likely require new designs of concrete vessels with many attendant problems.

Research needed for mobile marine structures includes work on methods of reinforcing and prestressing concrete slabs and shells to resist impacts from other ships, ice, etc. (B.C. Gerwick, personal communication, 1979). The properties of prestressed concrete in fatigue, especially at cryogenic temperatures, need to be investigated to qualify this material for service as a secondary barrier for liquefied natural gas vessels. The cyclic behavior of prestressed concrete under the large number of cycles of low intensity typical of marine use also needs to be investigated. Finally, the mechanics of the adhesion of ice to concrete in arctic conditions needs investigation (B. Gerwick, personal communication, 1979).

Continuation of present R&D will be needed for conventional transportation facilities. The design of bridge decks and other reinforced concrete structural elements for salt resistance and durability and of concrete pavement systems against various cracking problems needs to be improved (J. Janney and W.G. Corley, presentations to the committee, 1978). The design of large-span box girder bridges, very tall high-strength concrete structures, and cooling towers, all will require deeper investigation of reserve capacity and safety margin. Design of better joint systems for concrete structures will necessitate greater emphasis on studies of ductility and energy absorption. Much research is required on seismic resistance, fire resistance, and safety of anchorage systems. Creep deflections and inherent cracking continue to plague many structures, requiring costly repairs. Research must be done to take into account triaxial stresses, nonlinear responses, and temperature and humidity effects.

Investigations are needed on progressive failure of complete structures, rather than just structural elements, especially in conjunction with the analysis of spatial action, e.g., torsion of box girders. For assessment of structural reliability, these researchers necessarily will involve elements of stochastic modeling. Studies aimed at evaluation of structural collapses that have occurred, and calibration of finite element programs by modeling well-documented collapse cases, need to be carried out.

Development of better structural building codes needs to be continued; the need for various presently used simplistic semi-empirical formulas should diminish as computer analysis becomes more effective. This development may lead to more concise and simpler codes, put increasingly on a statistical basis.

Finally, one must expect development of completely new and novel structural approaches and systems to meet needs that cannot be predicted at present.

4.5 SUMMARY AND CONCLUSIONS

Significant and continual improvement has occurred in concrete and in its use in this country during the past 200 years. The use of concrete in taller and longer structures, in more severe environments, and in new uses requires continued research and development. These efforts must be planned and directed to be timely and effective. At the same time, resources for research must be directed to those with inventive and creative ideas that may result in major advances.

Energy has now become a major consideration in the production and use of concrete. Also, in recent years, restrictions on land use near metropolitan areas have reduced the amount of aggregates conveniently available and have increased transportation costs of both aggregates and the finished concrete. Studies with objectives ranging from programmed land use to less expensive transportation are needed.

The average strengths of concretes have increased slowly over the years, and continuing progress in this area can be expected. However, for very high-strength concretes to be used safely, much additional information is needed on their fundamental behavior -- creep, shrinkage, ductility, and toughness. High-strength concretes, when properly used, can save materials, energy, and space. The uses of these concretes can be extended to replace materials more limited in supply and more energy intensive.

Because high quality aggregates never were or no longer are available in some areas, studies should be initiated that will result in the use of the minimum quality aggregate required for a particular job. The search for new additives that improve concrete or ease other requirements should continue. Jointing of concrete elements, whether cast in place or precast has been an important problem for many years. The problem has many aspects, ranging from resistance to earthquakes to quick assembly or disassembly. Development of improved methods would increase efficiency and possibly facilitate reuse. Since the development of concrete, its durability has been a major concern. Continued research is needed in all aspects of durability including freezing, chemical attack, and incompatibility of constituent materials.

The improvement of nonlinear design techniques and the increased availability and capability of computers on which to do the analyses increases the need for realistic mathematical models of concrete. Such models must represent the time, temperature, and moisture-dependent properties of the various concretes, as well as their nonlinear triaxial behavior and failure modes. Developers of these models increasingly must seek the assistance of specialists in materials, mechanics, and structures if the models are to be valid and useful.

Standards and codes that dictate details tend to delay innovation and efficiency. Therefore, the trend toward performance type specifications and codes should be supported.

The suggestions in this chapter of areas in which additional research and development would be useful cannot be considered complete, but they indicate the scope of the improvements needed. Because concrete is a relatively energy efficient product whose raw materials are comparatively abundant in this country and need not be imported, and because it is more versatile than any other construction material, it will continue to be the major indigenous material of construction for the foreseeable future. The beneficial results of research and development on concrete in the United States should yield more dividends for many years than reliance upon purchase of most new technology from investors abroad.

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Chapter Five

THE U.S. CEMENT AND CONCRETE INFORMATIONAL SYSTEM AND MECHANISMS FOR TRANSFER OF TECHNICAL INFORMATION

To be effective, research and development must draw heavily from the pool of accumulated knowledge so that consideration of the status of R&D must include consideration of the system for the transfer of technical information. For cement and concrete, as for all technical subjects, this system has many parts. It includes universities and colleges; technical literature such as journals, books, standards, and patents; libraries and other data bases; professional and technical societies and conferences; and private companies and governmental organizations. All but private companies and governmental organizations are discussed below.

5.1 UNIVERSITIES AND COLLEGES

The education of scientists and technologists normally begins with formal training in an institute of higher education. Training in cement science and technology should include elements of materials science, ceramic engineering, chemical engineering, geology, and physical and inorganic chemistry. No college or university in the United States has a special undergraduate program for such training, and very few universities have faculty members who are authorities on cement chemistry and technology. Brief introductions to the science and technology of cement manufacture and use are given in a few university courses, but the training does not impart a thorough understanding of the scientific aspects of the industry's manufacturing processes and the reactions governing the performance of its products. The United States has no counterparts of the institutes offering special courses for cement scientists and technologists in Czechoslovakia, West Germany, Poland, and the Soviet Union.

American universities give somewhat more attention to concrete than to cement. Most civil engineering curricula include a materials course, part of which is devoted to concrete materials and to concrete mixture proportioning. A majority of civil engineering departments give courses that include laboratory work in the subject. Concrete design projects are commonly selected for graduate student research, partly because of the ease of fabricating a structural member of any shape and partly because the empirical nature of reinforced concrete design theory makes it easy to devise original research projects in untested areas.

5.2 THE TECHNICAL LITERATURE

The primary U.S. research journals publishing papers on cement manufacture and use are the international journal, Cement and Concrete Research, and the Journal of the American Ceramic Society. Less frequently, papers on cement research are published in the Journal of Testing and Evaluation published by ASTM and the Research Record published by the Transportation Research Board. Reviews discussing the engineering and operational aspects of cement manufacture are published by the Rock Products and Pit and Quarry magazines. Cement manufacturing literature is regularly abstracted in Chemical Abstracts, published by the American Chemical Society and in Ceramic Abstracts, published by the American Ceramic Society. Noncritical reviews of the world's cement research literature are provided each year in Cements Research Progress, also published by the American Ceramic Society. Reference to these shows that, in terms of number of papers, most of the world's literature on cement technology is published in foreign languages, Russian and Japanese being prominent. Nevertheless, the range and editorial policies of these journals provide an adequate mechanism for publication of the results of U.S. cement R&D.

Very few texts on the scientific aspects of the manufacture and use of cement have been published in English in the last 15 years (Taylor 1964; Lea 1971; and Duda 1977). The books available are essential reading for cement technologists. They do not, however, provide the depth of insight into the reactions in the cement kiln and in the use of cement necessary for the coupling of existing knowledge of materials science with cement technology to provide the greatest benefit to the industry. There is a need for new texts on cement manufacture and use. The richest sources of information on cement chemistry are the proceedings of the six international symposia on the chemistry of cement which have taken place since 1918. The volumes of proceedings from the Washington Symposium in 1960 and the Tokyo Sumposium in 1968 (Chemistry of Cement, 1960; 1969) are particularly valuable in reflecting recent advances and because they are published in English, whereas, unfortunately, the Moscow Sumposium in 1974 (Chemistry of Cement, 1976) was published only in Russian.

Papers on concrete research and practice appear in two publications of the American Concrete Institute (the Journal of the American Concrete Institute and Concrete International) and in the Journal of the Structural Division of the American Society of Civil Engineers. Such papers also appear in technical publications of trade associations such as the Portland Cement Association, the National Ready-Mixed Concrete Association, the Prestressed Concrete Institute, National Sand and Gravel Association, the National Crushed Stone Association, and the National Slag Association. In addition, a new journal, Cement, Concrete, and Aggregates, published by ASTM, was started in 1979. Results of domestic research on concrete are well publicized, but foreign developments are not so well reported in the United States.

Of the available commercial information retrieval systems, those using Chemical Abstracts as a data base are most useful to the cement researcher. The National Technical Information Service (NTIS) is not a major source since it is confined almost solely to governmental publications, and very little work that can be considered cement research seems to be carried out in federal laboratories. Much of the world's cement literature is published in foreign language journals, as noted earlier. Very little of it is used in the United States because of difficulties in reading it and in justifying the costs of subscriptions and translations. Therefore, means of providing regular translations of major foreign cement publications at a moderate cost would benefit U.S. cement research.

Standard tests and specifications for cements and concrete play an important part in technology transfer. The most widely used specifications are those published by ASTM. While the specifications currently available serve the purposes of the industry well, they tend to preserve the status quo because they are not easy to change. Part of the reason is lack of research to provide the technical basis upon which either new or modified specifications can be confidently based. The difficulty of developing new specifications could hinder national efforts to conserve materials and energy and reduce the costs of construction.

5.3 PROFESSIONAL AND TECHNICAL SOCIETIES AND CONFERENCES.

Four technical organizations have regular meetings and promote interactions among cement technologists. These are the American Ceramic Society through its Cements Division; the ASTM through its Committee C-1 on Cements; the NAS Transportation Research Board through its committees such as A2E06 on Basic Research Pertaining to Cement and Concrete; and the American Concrete Institute through its newly formed Committee 225 on Cements. In addition, the Institute for Electrical and Electronics Engineers (IEEE), Rock Products magazine and the Portland Cement Association hold regular conferences on engineering aspects of cement manufacturing processes.

Concrete technologists participate actively in the American Concrete Institute, ASTM Committee C-9 on Concrete and Concrete Aggregates, the Structural Division of the American Society of Civil Engineers, and various committees of the Transportation Research Board. In addition, each year the "World of Concrete," sponsored by several organizations in the concrete community, brings together several thousand practitioners for a series of educational seminars. This activity is probably the most effective in the country for transferring technology of a highly developed, construction-oriented nature. There is no corresponding mechanism for transfer of new scientific information on concrete.

Because of a need for promoting exchange of ideas and research findings between leading cement scientists, a Gordon Conference on Cement Hydraation was held at Plymouth, New Hampshire in 1976. The conference was attended by scientists from the United States and many foreign countries. From the point of view of the participants, it was a substantial success, but the organizers of the Gordon Conferences did not encourage its continuation. To help fill the communications gap, an alternative forum for discussion of advances in cement science and technology was initiated in June 1979 with the convening of an Engineering Foundation Conference on Cement Production and Use at Rindge, New Hampshire.

5.4 REPORTS RELATING TO NATIONAL MATERIALS POLICY

In discussing technology transfer, it is relevant to mention that a number of reports on national materials policy have recently been prepared by groups such as the Committee on the Survey of Materials Science and Engineering (COSMAT) of the National Academy of Sciences (1974; 1975), the

National Commission on Materials Policy (1973), and the Engineering Foundation's Henniker Conference, Requirements for Fulfilling a National Materials Policy (1974). Each of these reports addresses questions related to materials needs, but in no case was research on cements considered of high priority. This may have been because the committees preparing the reports included almost no persons familiar enough with cement and concrete technology to present pertinent views and tended to reflect the specific knowledge and interests of the bulk of their members. The COSMAT committee (National Academy of Sciences, 1974; 1975) did identify R&D on cement and concrete as a vital need of the building industry.

5.5 MATHEMATICAL MODELS AND PERFORMANCE STANDARDS

Because description of the complex relationships between the manufacture, nature, and use of cement poses many problems, it is likely that comprehensive conceptual models will have to be formulated and expressed in mathematical terms to provide a new tool for the efficient transfer of information in cement and concrete. Use of mathematical models in many branches of human endeavor is growing, and steps already have been taken to develop mathematical models for parts of the cement manufacturing process and of some aspects of the behavior of concrete. These activities should be supported because of their implications for improving the technical education of cement and concrete technologists and their potentially beneficial impact on all other aspects of technology transfer in cement and concrete.

Lastly, attention must be given to moving the specifications for cement and concrete toward a more performance-oriented basis. Performance specifications require a higher level of technical information for their application than do prescriptive ones. The development of performance specifications to supplement prescriptive ones will play a part in improving the informational system because it promotes interaction between the affected parties in the specifications committees. The application of the resultant specifications will transfer the knowledge used in their development. A technically strong specifications development activity requires more involvement of researchers from the academic community than is now common. Mechanisms should be established for encouraging participation of academic researchers in this area.

5.6 SUMMARY AND RECOMMENDATIONS

There are many elements in the system for transfer of information and technology. There are similities in, and overlap between, the elements for cement and concrete. However, the cement information system in the United States is weaker than desirable in part because of the much smaller number of people in cement research and technology. Several options for strengthening the information system to the benefit of research and development in cement and concrete are listed below:

1. Establish one or more university-level training programs for cement researchers and technologists.

2. Provide forums for promoting interaction among cement manufacturing personnel and researchers in the universities.

3. Provide for regular, moderately priced translations of major foreign journals publishing research on cement and concrete.

4. Provide support for continued movement toward more performance-oriented specifications for cement and concrete.

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Chapter Six

INCENTIVES FOR AND BARRIERS TO RESEARCH AND DEVELOPMENT

In this chapter, an attempt is made to isolate for analysis a number of factors that appear to act either as potential incentives or as barriers to effective research and development in cement and concrete. To do this, the level of R&D effort and the nature of the cement and concrete R&D establishment in the United States are reviewed using information from a survey by this committee and from other sources. Economic factors are then considered albeit not in great detail because the committee realizes its limitations in this discipline. Factors relating to the performance of concrete and to resource management are considered specifically and, finally, institutional and other factors are discussed in detail as background for recommendations.

6.1 STRUCTURE AND LEVEL OF EFFORT IN CEMENT AND CONCRETE RESEARCH AND DEVELOPMENT

6.1.1 Current Funding

A quantitative picture of the cement research and development establishment is difficult to obtain because of the dispersed nature of these activities. Only a small number of companies have budgets for cement or concrete research of a nature and size as to be listed in the usual R&D compilations (Business Week, 1977).* The source of information finally adopted as the major indicator was the responses to the committee's research and development questionnaire, which is detailed in Appendix B. The questionnaire solicited data from organizations perceived to be doing R&D on cement and concrete. These organizations were in the academic, governmental, nonprofit, and industrial sectors, including related segments of the chemical industry (response rate was 37 percent). The data tabulated revealed some interesting points in budgeting R&D (Table 2).

The data are biased toward high values since the respondents solicited included mostly those perceived by the committee to be conducting substantial research and since certain activities undoubtedly were counted twice. Despite this bias, it is apparent that most of the institutions tallied devote far too little effort in dollars or person-years to be expected to achieve significant advances in the field.

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*This was also true for 1978.

TABLE 2 Questionnaire Results on Cement and Concrete R&D

Percent of Institutions Responding	Money Spent on Cement and Concrete R&D, Average Annual Rate 1973-1977 ($1,000)[1]	Estimated Level of Effort (Person-Years Per Year)[2]
40	< 50	< 1
17	50 - 100	1 - 2
26	101 - 400	3 - 6
9	401 - 1,000	7 - 14
5	> 1,000	> 14
3	unknown amount	--

[1] These figures are biased in the high direction since part of the funds were reported as being spent by agencies which funded work done by other institutions, which may have also reported the expenditures.

[2] Assuming $75,000 per person-year

Data from the Portland Cement Association (PCA), a major institution of the industry and a respondent to the questionnaire, illustrates specifically the downward trend in R&D funding (Table 3). In 1978 the purchasing power of PCA's R&D spending was only 74 percent of that of 1970; indeed, only 25 percent of the 1978 total was supported by the industry, while the rest came from contracts (mostly in engineering).

TABLE 3 Total PCA Research and Development Expenditures (excluding career education and other fringe costs)

Year	Expenditure ($)	$ Value*	1967 $	% of 1960
1955	1,147,000	1.139	1,306,000	52
1960	2,381,000	1.054	2,510,000	100
1965	2,182,000	1.035	2,258,000	90
1970	2,199,000	.906	1,992,000	79
1975	2,377,000	.572	1,360,000	54
1977	3,014,000	.515	1,552,000	62
1978**	3,892,000	.475	1,849,000	74

*Purchasing power of the dollar, producer prices as published by U.S. Department of Commerce, 1967 = $1.000.

**Engineering development was 59 percent of total in 1978.

6.1.2 Cement Research Establishment

The fact that the cement research establishment is not very large is apparent also in the following analysis (G. Frohnsdorff, presentation to the committee, 1978):

> "It is worthwhile to estimate how many persons are involved in cement R&D in support of the $3.0 billion cement industry and the $12 billion concrete industry. For this purpose, I have assumed that most of the scientists and engineers involved in cement (but not concrete) R&D are members of the Cements Division of the American Ceramic Society, a major forum for the discussion of cements research. (The Division membership also includes persons not involved in R&D.) From the Division membership address list for 1976, it appeared that its 77 U.S. members were distributed as shown." [Table 4]

TABLE 4 Distribution of the U.S. Members for 1976 of the American Ceramic Society Cements Division of Type of Organization (based on data from Levine, 1977)

Type of Organization	Number of Members
Universities and National Laboratories	10
Cement and Lime Companies	31
Admixture Companies	7
Trade Associations	5
Nonprofit Research Institutes	1
Government (Federal and State)	3
Other (Affiliations Not Given)	20
TOTAL	77

The lack of depth of the cement R&D effort is suggested by the fact that few organizations had more than one participating member and only four organizations had more than two. If it is assumed that a critical mass of cement researchers is five or six (plus twice that number of permanent technicians and administrators), it appears that in 1976 no institutions in the United States had such a critical mass. Some underlying factors relating to this situation are discussed by Frohnsdorff (presentation to the committee, 1978):

> "Clearly, the level of the U.S. cement research effort was low in 1976. If we assume the R&D expenditures to have averaged $75,000/year for each of the 77 persons mentioned, the total in 1976 would have been about $6 million. The effort remains low today and, in my opinion, inadequately

> low....Among the probable reasons for the low level of investment in cement R&D is the chemical complexity of the cement system; this makes it necessary to form relatively large interdisciplinary teams to bring about progress. Neither individual companies in the fragmented cement industry nor the PCA, the trade association of the manufacturers, can be expected to have much incentive to mount a large effort because of the commodity nature of the product. As a result, the developments which take place are usually evolutionary and not as substantial as those which would be expected from a coordinated R&D program coupled to the needs of the end user."

Cement research is performed by universities, one trade association (PCA), independent research organizations (e.g., Battelle, Illinois Institute of Technology Research Institute, etc.), federal and state agencies (e.g., highway administrations, National Bureau of Standards, U.S. Army), and private industry.

Until recently, most of the research supported by government agencies was related to the users' aspects of cement materials science. However, during the past few years, under the pressures of environmental and energy considerations, some greater emphasis and more money have been given to support research on the production aspects of cement chemistry.

Most academic research on cement materials is being done within the civil engineering departments of Purdue University, the University of Illinois at Urbana, and the University of California at Berkeley and at the Materials Research Laboratory at the Pennsylvania State University. As mentioned earlier, most of this work is related to cement hydration and is funded by governmental agencies rather than by the cement or concrete industries. This is largely true also of the work at independent research laboratories such as Battelle and Southwest Research Institute.

Industrial research, in addition to the under-funded studies performed by PCA, is carried out by a very few cement companies. During the past decade, several well established cement company research establishments were liquidated or converted to customer technical service and quality control groups. Thus, very few industrial laboratories in the United States are capable of doing cement research. The situation appears to be better in some of the related industries, such as those producing and using gypsum and chemical admixtures, despite their relatively small amount of published research. This is probably due in part to the greater concentration of these industries, but in larger part to the fact that the respective industries are parts of chemical or other industries where R&D historically has been an important part of the business venture. On the other hand, little research is done by industries marketing waste materials that can be used in conjunction with cement. Typical examples of such neglected materials are fly ash, slag, and pozzolans. Little R&D is being done on concrete aggregates and on their interactions with hydrating cementitious systems, even though the sales of such aggregates reach about a billion dollars per year.

6.1.3 Concrete Research

Most of the research on concrete is done in academic and governmental laboratories; private institutions concentrate mainly on development or engineering analysis, with perhaps very limited research activity. However, a number of private organizations carry out R&D projects commissioned and paid for by outside agencies. An overall lack of coordination between university and government laboratories on the one hand and the more practically oriented private-sector groups on the other seems endemic. This is an obvious weakness of concrete R&D in the United States especially in comparison with the close coordination evident in some other advanced industrial countries.

Concrete technology generally is regarded as a branch of civil engineering, and so in contrast to cement technology, it has a natural academic base in the civil engineering departments of many universities. Civil engineering students receive adequate training in the elements of the subject at most technically oriented universities, and a number of academic centers carry on graduate training. PCA and several governmental agencies responsible for major construction undertakings also conduct training activities.

Funding for the limited amount of basic research on concrete is provided almost entirely by the government, primarily the National Science Foundation. Applied research and development is supported by various agencies, including mission-oriented subdivisions of the Departments of Defense, Energy, and Transportation, some state agencies, primarily transportation or highway departments; and by industry. The level of industrial funding is unimpressive and compares unfavorably with that supplied by industrial sources in other major industrial countries. The situation in funding of concrete research is not quite as alarming as it is in cement research funding. However, the edge that U.S. firms once held in various areas of concrete technology -- for example, computer-aided structural analysis and design -- seems to be dissipating, and in other areas this country lags significantly.

6.1.4 Unrealized Potential

Most of the cement and concrete is used by construction firms such as those listed in Engineering News Record (1977a, 1977b). Although some $59.9 billion in contracts was realized in 1976 by the top 400 U.S. construction companies (of which $21.8 billion in contracts went to the top ten), research and development by such companies is confined almost completely to on-the-job activities. Relatively little record of such activities exists in the technical literature.

That this state of affairs is far from the ideal and that the construction industry faces major problems in designing for advanced structural applications in concrete is apparent from a number of sources. Myers (presentation to the committee, 1978) speaking as a designer of advanced nuclear installations for one of the largest and most advanced U.S. firms, indicated the scope of the difficulties encountered and concluded with the sobering statement:

> "The above notes do not discuss specific research programs that should be carried out but rather indicate the tip of the iceberg in the area of problems encountered by a project manager for a large complex design and construction effort. These problems are not academic. They are being dealt with every day and the health and safety of the American public depend on how effectively the practicing engineer is answering these questions."

6.2 SPECIAL CHARACTERISTICS OF CEMENT AND CONCRETE RESEARCH AND DEVELOPMENT

The approach to research and development in most industry sectors differs fundamentally from that prevailing in the engineering and construction fields. The usual system is characterized by integrated management of R&D, process development, and product development as part of a total technological and marketing effort. Universities and governmental research establishments provide basic knowledge and supplement the goal-oriented R&D performed by the industrial laboratories with more long-range and less product-oriented efforts.

The industrial R&D carried out in behalf of engineering and construction enterprises is fragmented among materials manufacturers, designers, and contractors. The public sector exerts significant influence as a primary purchaser of the end product (constructions or services) offered for sale. The results of longer range research by universities and government are not generally fed back to the private firms, except indirectly and after much time. Only minor competitive influences are involved, and potential users of the research results generally do not have the knowledge to apply the findings directly. The gap between research and practice traditionally is bridged through slow adaptation of new methods and improvements, with elaborate testing and slow modification of existing specifications and acceptance criteria.

In this framework, most of the limited R&D that does take place is devoted to problem solving, case studies of failures, and analyses of the state of the art. Fundamental research is almost completely lacking, as might be expected from the inadequacies mentioned earlier.

In the current climate, there are implicit dangers that even academic research will lose its major role of generating and disseminating knowledge for general technical progress, and that universities instead will do mostly mission-oriented research.

Despite the general decline of basic research in cement and concrete in the United States (and elsewhere), there is great untapped potential for intelligent application of basic scientific knowledge from the disciplines of chemistry, physics, and materials science. There is a need for infusion of new talent into the field to generate continuity in organization and guarantee funding for basic studies. The potential payoff to society in terms of improvements in the building and construction sector is enormous. Unfortunately, the present system appears not to provide sufficient prospect of short-term reward to induce individual firms to make the necessary investments.

The rather long time lag that must be expected between the development of a concept and its full industrial utilization can be illustrated by the basic-oxygen steelmaking process. About 20 years elapsed between the initial innovation and the full development of the basic oxygen process, now the most important of the several available processes for making steel (Terlecky, 1975).

Yet, despite the slow rate of development characteristic of bulk materials industries, the cement and concrete sector should move toward industrial research and development that utilizes a systems approach. The present R&D approach is inadequate to solve such basic problems as optimum usage of byproducts and shortcomings in performance and reliability, so there is a special urgency in taking the first steps. Blumenthal (1979) puts this in proper perspective:

"It is seldom appreciated that the invention, the R&D, usually costs far less than the process of first commercializing it. Where large capital-intensive projects are concerned, the R&D portion may be as little as 10 percent of the total cost; the remainder needed to convert the invention to an innovation may consume 90 percent of the total cost. Professor Mansfield and his colleagues at the University of Pennsylvania have been studying this kind of relationship and, as might be expected, found in 17 chemical innovations that R&D costs ranged from 7 percent to 71 percent of total project cost (Mansfield, et al., 1977). Though for new products the percentage is higher than for new processes, the important conclusion is that the invention itself (the R&D expenditure) usually costs less than half of the amount spent on the innovation. This relationship has been slow in coming to the majority of economists, who pay little attention to the economics of technology, and it has been even more tardily perceived by politicians who listen to the economists, although their advice has been mixed. Although R&D expenditures, as a percent of gross national product, have been falling, it is only recently, as we in the United States start to probe into the reasons for our apparent decline in innovation, that it is being discovered that it is the risk-taking entrepreneurial side of the innovation process, costing the greater part of the innovation, which has been faltering (Blumenthal, 1978)."

The lack of a more substantial industrial R&D effort may reflect management's awareness of the foregoing situation. A decision-maker would assume there is no value in initiating the relatively low-cost R&D, unless there is a commitment to follow through with the capital required to complete the process of innovation. The long-term consequence of such an evaluation is a state of industrial stagnation.

6.3 ECONOMICS OF CEMENT AND CONCRETE RESEARCH AND DEVELOPMENT

The cement and concrete industry is clearly of major importance to the economy of the United States. Concrete construction is essential to heavy industry, public and defense works, and commercial and residential construction.

6.3.1 Economic Incentives for R&D

In 1976 new construction put in place in the United States reached a record \$142.3 billion (Levine, 1977); it projected to reach \$157.5 billion in 1977 and about \$200 billion in 1978. The pervasiveness of the use of cement and concrete is seen in the estimates given in Table 5 for the use distribution of cement in many public- and private-sector constructions.

TABLE 5 Apportionment of Cement and Concrete Used in Various Types of Construction (1976)

Cement Usage	Apportionment (%)
Residential	31
Industrial and Commercial	24
Non-Building	17
Highways	16
Public Buildings	7
Miscellaneous	5

Ready-mixed concrete shipments within this country were valued at an estimated $6.1 billion in 1977; concrete brick and block were valued at about $1.1 billion; and concrete pipe and precast and prestressed products at about $2.7 billion.

A few of the most obvious illustrations of the potential for return on research and development are sketched here. Recent examples of advances, such as the River Plaza concrete high-rise buildings (W.G. Corley, presentation to the committee, 1978), were made possible using high strength [75 MPa (11,000 psi)] concrete to replace what normally would be a steel structure. Expenditures for R&D to make such developments possible would much more than pay for themselves by achieving advances that make it possible to substitute concrete structural components or more costly structural materials.

Additional savings may be realized through avoiding repairs. U.S. Navy shore facilities, for example, generally are situated in marine environments and subjected to the severe deteriorative influences that characterize marine climates. Reliable estimates indicate that about $10.7 million was spent during fiscal year 1978 in maintaining and repairing naval concrete waterfront structures, while the estimated total cost of newly constructed U.S. Navy concrete waterfront facilities was about $115 million (Naval Facilities Engineering Command, 1978).

Pavements of Air Force bases require some $4 million annually in maintenance costs to correct defects due to alkali aggregate reactivity, shrinkage and weathering, cracking, and other types of concrete deterioration (F. Dall, personal communication to the committee, 1978). Civilian airport pavements require some $125 million per year for structural repair and rehabilitation.

The serviceability of bridge decks is of vital importance for military as well as civilian use. The economic losses from deterioration of concrete bridge decks are enormous. The Federal Highway Administration estimates that $6.3 billion was needed in 1978 to restore bridge decks in the federal highway system (General Accounting Office, 1979). The costs of damages to vehicles caused by potholes in the pavement have been conservatively calculated at $800 to $900 million per year. These costs will inevitably increase over the next decade as construction works age, often under severe environmental conditions and increasing service demands. A fraction of the 1978 budget for pothole and bridge deck repairs (and the appropriate car repair costs) etc. should suffice to develop pavement technology adequate to eliminate or drastically reduce the damage. In some areas we already have much more of the basic scientific knowledge needed to produce relatively repair-free bridge decks or other end-use concrete structures. However, the mechanism and the commercial incentives for integrating such knowledge into the development stage seem to be absent.

6.3.2 Economic Barriers to Effective R&D

The ubiquity of the products of the cement and concrete industry emphasizes its vital importance to the country and at the same time reflects one of its largest problems: the industry is highly dispersed, being composed of many small producers and users, and is not able to organize to do research and development effectively. Grancher (1977) discussed the dispersion of the cement industry in terms of concentration ratio and compared the situation with the automobile industry in which only four firms account for 87 percent of sales and, the eight largest firms have 94 percent. By contrast, in the cement industry the largest four companies have less than 30 percent of sales, and the eight largest have less than 45 percent.

A small company is able to benefit from only a small part of the total profit realized from its inventions, and therefore the research cost/benefit ratio is relatively high. Thus, the incentives for such firms to conduct R&D are weaker than is optimal from the viewpoint of society as a whole. In more concentrated industries, firms will enjoy a larger share of the total benefits from their R&D and thus will have greater incentive to do the optimum amount of R&D. Even then, organizations conducting basic research seldom realize a significant share of the benefits because basic research rarely leads directly to commercially exploitable innovations. Therefore, government must be prepared to support basic research substantially, if a socially optimal amount of basic research is to be done.

During the past 15 years the cement industry's return on net worth averaged about 7.5 percent, which is substantially less than the 15 percent often considered justifiable and necessary for a viable industry (Frondiston-Yannas, 1979). The low profitability of the cement industry over the past 10 to 15 years may have been another factor inhibiting investment in long-range research and development. Table 6 illustrates the low average profits realized.

TABLE 6 1976 Sales and Income of Cement and Related Companies ($ millions) (based on data from Levine, 1977)

Company	Revenue	Net Income
Coplay	26.619	(10.087) less
General Portland	162.7	0.1
Giant Portland	18.193	1.005
Ideal Basic	296.776	31.204
Kaiser Cem. Gyps.	211.774	10.268
Lehigh Portland	104.248	6.137
Medusa	205.461	11.545
National Gypsum	613.4	27.42
Warner Co.	53.538	2.677
Whitehall Cement	14.235	(0.338) less

NOTE: Grancher (1977) indicated that the U.S. cement industry's return on owner's equity for 1976 was about 7.5 percent.

While shortages of cement affected the relative balance of profits for 1978 (Engineering News Record, 1978; Grancher, 1978*), the long-range response and prospects are not known. However, possibilities for generating more funding for research and development are not obvious because of the fragmented structure and the frequently low profits of this industry. A possibility advanced by Weinschel (1978) for other industry was:

> "A committee of the U.S. Congress should explore methods of allowing rapid write-off for capital investments that are required for environmental protection or occupational safety; this would effectively increase the amount of venture capital available for industrial research."

Consideration might also be given to tax incentives tied more specifically to R&D investment.

The record of the concrete industry on research and development investment is even less impressive than that of the cement industry. Bates in the 1968 Stanton Walker lecture (quoted by B. Mather in his presentation to the committee, 1978), indicated (of concrete) that

> "no other industry consequence spends so little...probably less than one-hundredth of one percent of the concrete sales dollar is spent on research to provide fundamental information."

Mather implied that the description probably was basically true of the present situation.

6.4 PERFORMANCE ASPECTS OF CEMENT AND CONCRETE RESEARCH AND DEVELOPMENT

This section discusses certain incentives and requirements for research and development of cement and concrete stemming from increased or expanded performance requirements for the materials and examines certain existing barriers to such activities.

6.4.1 Needs and Incentives

The performance incentives to research and development on cement and concrete are intertwined with a number of factors which have been discussed in previous chapters, especially Chapters 3 and 4. Some additional examples given below illustrate areas where tremendous payoffs could be realized through R&D that could generate materials having superior performance under extreme conditions.

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*A 19 percent net worth financial return was reported for 1978.

The performance of cements in deep wells (oil, gas, and geothermal) presents problems associated with high temperatures and corrosion that are believed to be of serious dimensions. An industrial spokesman has estimated that approximately 37 percent of the oil, gas, geothermal, and injection wells in the United States have had problems with cement during completion of the well or because of deterioration with time (Department of Energy, 1978). These and other extreme environments, such as in coal gasification systems, tertiary recovery of oil, and marine environments, etc., create further need for materials development and the standardization of tests (including nondestructive tests) that relate meaningfully to the lifetimes of materials in use. Performance requirements of floating LPG-storage structures are highly stringent (Anderson, 1977). Although the current trend favors steel structures for offshore oil drilling platforms (Ocean Industry, 1978), problems with stress corrosion in steel platforms (P.L. Pratt, personal communication to the committee) present an invitation for concrete R&D. A number of studies, including those of concrete spherical structures for deep sea submergence (Haynes, 1974) reveal performance that was impressive after nearly eight years' exposure, suggesting the potential of concrete in a variety of ocean structures.

Some of the challenges of the behavior of concrete under high stress, at elevated temperatures, and under static, dynamic, and impactive loads are those faced by nuclear power plant designers (B.L. Meyers, presentation to the committee, 1978). These stresses are common to other structures including defense works, missile silos, and civilian structures that also must withstand tornados and seismic loads.

6.4.2 Performance Barriers

Most of the current specifications for use of cement and concrete are based on prescriptions rather than performance and so do not use the latest knowledge from research. While a basic level of prescriptive procedures for guidance in practice should be maintained, tests and methods must be updated continuously to reflect, where possible, the understanding behind the procedures. Optional procedures based on performance standards would be less stifling to innovative practice and more encouraging to R&D. Thus, these optional procedures should be allowed where possible.

6.5 RESOURCE-RELATED ASPECTS OF CEMENT AND CONCRETE RESEARCH AND DEVELOPMENT

Cement and concrete are favored construction materials in terms of resource demand and utilization; they are derived from earth's most abundant materials, and they are relatively nonpolluting when used. Thus, the incentives are obvious for research and development to find new uses and guarantee adequate performance of cement composites and concrete, which would allow their substitution for less abundant advanced materials or for materials that cause significant environmental pollution.

Barriers to such R&D, however, include the fact that raw materials, including coal and waste byproducts, are subject to significant local or regional variations. This condition serves to inhibit the general applicability of R&D results that would lead to more effective use of these resources. Furthermore, a continuing conflict exists in the cement manufacturing industry among the three dominant resources and environmentally associated factors: energy conservation (Skovronek, 1976; Federal Energy Administration, 1975); environmental pollution control; and effective use of raw materials. All three must be considered; while fuel availability dominates in the short range, economics is the overriding factor.

6.6 INSTITUTIONAL FACTORS IN CEMENT AND CONCRETE RESEARCH AND DEVELOPMENT

The current status of the R&D establishment, described in Section 6.2, indicates clearly that R&D of the type required to address effectively the needs of the next 10 to 20 years cannot be achieved without developing new R&D institutions or renovating existing ones.

6.6.1 Needs for Modification in Research and Development Institutions

In the United States, there is no cement and concrete R&D institution that is guaranteed the longevity necessary to generate basic knowledge as a source of future developments. There are two essential requirements: longevity (continuity) of the basic research component; and a system for feeding research results into product development and use. The same is true of the basic knowledge (of cement) that must be used in research on concrete; a fundamental knowledge of materials must be an integral component of R&D related to structures. Appendix C outlines one example of a research and development center that could be established and in which the intent is to bridge some of the gaps described above.

Critical nuclei of skilled investigators also should be generated at several centers, infusing new talents from related fields of science and engineering and incorporating the interdisciplinary approach. Existing research and development facilities, including academic facilities, are likely sites for such strengthening and for long-range research funding.

6.6.2 Institutional Barriers

The inadequacy of the research and development structure, including the absence of physical plants with a full complement of personnel and of appropriate institutions for training R&D personnel has been mentioned. The suggestion of the IEEE committee for another industry (Weinschel, 1978) seems appropriate here:

> "The U.S. Government should support graduate engineering and science students in their initial attempts to adapt to, and be employed by, industry. A program could be established to fund a portion of the salaries of graduate students willing to work, during summer vacations, in both small and large R&D-oriented corporations throughout the U.S."

The possibility of providing tax incentives for R&D* has already been posed. The possibility of initiating legislation to allow increased vertical integration in the industry deserves serious consideration. This could help overcome economic barriers to the changes needed immediately by the industry and could also help improve prospects for enhanced productivity in the long range based on the consequent R&D.

6.7 OTHER FACTORS RELATING TO CEMENT AND CONCRETE RESEARCH AND DEVELOPMENT

Certain additional factors affect significantly the amount and effectiveness of R&D on cement and concrete, as detailed in the following section.

6.7.1 Miscellaneous Factors Affecting Cement and Concrete Research and Development

The U.S. patent system, which is intended to stimulate the application of scientific knowledge, seems to provide little incentive to the development of U.S. cement technology. One reason may be that the complexity of cement chemistry makes it too risky for private companies to do research at the frontiers of knowledge relating to the manufacture and use of cements when there is no history of successful introduction of proprietary products into this commodity-oriented industry. A patent search made in January 1978 in connection with the preparation of this report (Editec, 1978) found only 918 references in the broad fields of portland cement, concrete, mortar, and gypsum over a 15-year period. The number seems surprisingly low for such an important industry; it appears to reflect a negative attitude toward patents, a low level of R&D, or both. It would be worthwhile to investigate whether the patent system is serving its intended purpose adequately in relation to the cement and concrete industries.

Earlier parts of this report indicated that future performance requirements of concrete demand that structures erected contain a larger fraction of high-quality concrete. It would appear that where joint ventures are allowed, and industry is permitted to integrate vertically, progress has been made toward producing a greater proportion of high-quality concrete. Idorn (presentation to the committee, 1978) described four levels of concrete quality:

Category	Designation
A	Durable concrete, guaranteed
B	High-quality concrete and cementitious products
C	Ordinary concrete
D	"Do it yourself" concrete and cementitious products

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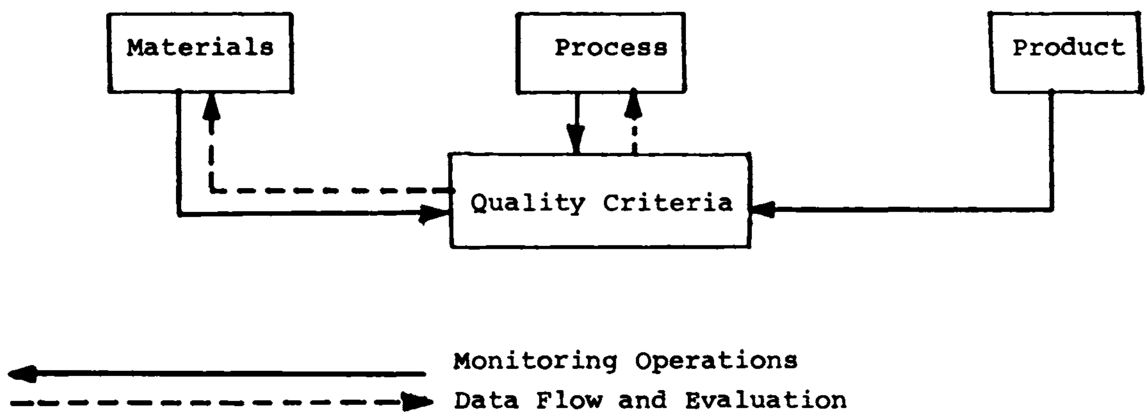
*Both of these measures were mentioned by a significant number of the respondents to the committee's R&D questionnaire (see Appendix B).

Idorn discussed the need to increase the amounts of concrete in categories A and B for use in the future; he suggested that the added value would more than pay for increased R&D necessary to make the change possible. Mather (presentation to the committee, 1978) expressed similar sentiments, with the analysis that there would be an economic payoff.

Monitoring of cement and concrete processing, particularly in the precast industry, is possible (G. Idorn, personal communication to the committee, 1978) so that the rate of hydration can be controlled to generate products of optimum quality. The relationship between these elements and the effect of such monitoring operations are indicated in Figure 3. This is only one of several areas in which R&D can result in the development of technologies leading to superior products.

FIGURE 3 Industrial Monitored Processing (G. Idorn, personal communication to the committee)



6.8 SUMMARY

This chapter discusses a number of factors that appear to act as potential incentives for or barriers to effective research and development in cement and concrete. The existing cement and concrete research and development establishment has been described (individually for cement and concrete), and its limitations in size and activity have been related to the extent and type of R&D financing. The dispersed nature of the cement and concrete industry and the small size of its many components were identified as inhibiting factors. The tremendous untapped potential of the concrete industry, containing both giants and very small units, and having about 100 times the number of companies as the cement industry, was discussed in particular.

Economic and institutional factors were described because they are dominant influences on potential funding for R&D, particularly from industrial sources. Possible new sources for R&D funding were suggested. It is believed that funding and the related economic factors, plus the predominantly nontechnical areas related to institutional structures and possible legislative changes, require urgent attention. There are major benefits to be realized from the results of R&D that can result in enhancement of materials and structures to guarantee performance under the more extreme conditions of many potential applications. The realization of such potential will require adequate functioning of the overall R&D system: management must be able to assure an adequate level, quality, and continuity of fundamental research, and its culmination in innovative practice employing the results of R&D.

The future will see increasing demands on both the quality of materials and structural performance. In addition, there probably will be a substantially greater percentage of industrialized concrete production which will generate a greater need for technology transfer, beginning with establishing mechanisms for properly educating those responsible for the quality of products at all levels. For example, we might look to the training courses and certification for concrete technologists available in the United Kingdom or to Denmark (Danish Concrete Institute, 1978) where such an educational institute was established by private industry to serve at the interface between knowledge and practice.

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Chapter Seven

CONCLUSIONS

This chapter summarizes the major conclusions of the committee's analysis of its findings. The conclusions are based on both oral and written contributions, consultations, and the questionnaire data summarized in Appendix B.

7.1 CURRENT STATUS

The level of research and development in cement and concrete in the United States seems inadequate in comparison with the importance of cement and concrete to the building and construction industries and to dependent technologies. The R&D establishment is weak and is in serious need of revitalization; the means of generating financial support are ineffective. A major question is how cement and concrete R&D can be rejuvenated to do more than serve its industry at a survival level (Chapter 2).

Despite the relative inactivity, R&D on cement and concrete faces critical challenges and opportunities. New applications of concrete and cement composites under extreme conditions place demands on these materials and the structures made from them far beyond those previously experienced. Concerted R&D will be needed to provide guarantees that concrete structures will perform safely in both civilian and defense applications (Chapters 3 and 4).

The durability of concrete and the relationship of changes in the composition and properties of cement to the performance of concrete under extreme conditions have been identified as areas of great importance. There are important new opportunities for these materials, both for the immediate and more distant future, that should not be missed. Efficient processing and superior product performance are required to ensure reliability, make optimum use of resources, and preserve environmental quality. Limited availability of raw materials will require the use of increasingly large amounts of cement composites or concrete relative to less abundant structural materials. Economic factors also demand optimum use of resources. Advances that enhance the performance of concrete will achieve savings by requiring less of it per structure. Significant rejuvenation of the R&D structure and more efficient technology transfer are required to meet present demands and, more importantly, to prepare for future probabilities (Chapters 4 and 6).

There are a number of explanations for the relative downward trend in cement and concrete research and development during the past 15 years. Much apparently is related to the maturity of the industries, a general downward trend in the economy, and lower levels of R&D spending in general. However, certain factors are specific to cement and concrete (Chapter 6). The forces that normally operate in the marketplace to stimulate R&D appear to not operate efficiently with cement and concrete (as discussed in Appendix A). The ability of the cement and concrete industry to generate R&D funding and to preserve functioning research groups at an adequate level thus appears to be in even more danger of critical malfunctioning than in most chemical process industries. This is especially true of the cement component, which has been burdened recently with the high costs of environmental adjustments and attempts to increase energy efficiency (Chapter 3).

Fragmentation of the industry makes it difficult for firms conducting R&D to realize a large share of the benefits produced by this activity. In good seasons, the concrete industry generates large profits for its construction firms, but often, at least in recent years, profits have been low. This, too, has made it difficult for firms to establish or even maintain R&D programs. Yet, it is this vast industry that is called upon to find the means of projecting and meeting future needs that will involve much greater demands on the performance of concrete materials and structures (Chapter 6).

Most of the current research on cement and concrete appears to be funded by government, and it is primarily mission-oriented. Our analyses show that the element particularly missing from cement and concrete R&D in the United States is well planned, long-range programs. As might be expected, most of industry's self-funded R&D involves problem-solving, product-development activities. The same seems true of the related chemical industry (Chapter 6 and Appendix B).

Significant research and development in concrete appear to be in progress in a few topical areas such as earthquake-resistant structures; work continues to improve the durability of concrete on bridges and pavements. Some significant recent accomplishments are listed in Section 7.2 The need for energy conservation and waste utilization has stimulated research, but these efforts are small in comparison with the problems and potential. Use of superplasticizers in concrete was identified as a significant recent development, but recent reports indicate that much research is needed even in this area to acquire the basic understanding needed for optimal and reliable use of these additives (Chapter 4 and Appendix B).

The knowledge required to achieve advances related to current product uses and also to permit future developments includes an understanding of fundamental mechanisms, whether the problem is materials durability or the most advanced structural design. Clarification of mechanisms will necessitate both experimental and theoretical studies. The needs for mission-oriented research and efforts to improve existing technology are nonetheless important, but the results of the latter are expected to be severely limited without continued stimulus by the results of fundamental research (Chapters 3 and 4).

For a full cycle of interaction, means must be found to maximize interaction between R&D and its applications and to use knowledge acquired from basic research in intermediate- to long-range problem solving. Finally, investigators and R&D centers must be available to generate the knowledge and the necessary financing must also be made available (Chapters 5 and 6).

7.2 RECENT ACCOMPLISHMENTS

Significant recent advances resulting from research and development in cement and concrete have been relatively few in comparison with the potential (Chapters 3 and 4 and Appendix B). R&D in this country during the past five years has been responsible for major accomplishments in the following areas:

- Special concrete applications, including earthquake resistance.
- Computer applications to modeling and design.
- Analytical nondestructive testing and adaptation to quality control.
- Polymers in concrete.

Foreign developments primarily have led to major improvements in:

- Cement kiln technology.
- Superplasticizer utilization

7.3 SUMMARY OF NEEDED IMPROVEMENTS: TECHNICAL AND NONTECHNICAL

There are a number of areas, both technical and nontechnical, that require attention in order to correct existing deficiencies and prevent gross neglect of this major building block of our industrial society. Table 7 provides a general survey of improvements needed in specific properties of cement-based materials without giving priorities. R&D is necessary to generate the needed improvements in the performance of concrete and other cement composites in the indicated applications (Chapters 3, 4, and 6).

A more thorough review of some of the nontechnical factors is required. These factors are not exclusive to the cement and concrete industry; many are held in common at least with other materials industries (Chapters 5 and 6). Some of these are:

1. Inadequate technology transfer; communications barriers.
2. Regulations.
3. Antitrust and vertical divergence.
4. Lack of comprehensive national materials policy.
5. Lack of economic incentives for capital-intensive industries to change manufacturing methods and equipment.
6. No coordinated across-the-board industry/government/university cooperative programs to breed innovations in supplier, service, and industries that produce base materials.

TABLE 7   Areas for Needed Improvement in Specific Properties of Concrete

Factory Fabricated Units	Compressive strength	Flexural or tensile strength	Bond strength	Volume stability	Controlled expansion	Uniform appearance	Color	Low density	Flow properties	Young's modulus	Impact resistance	Ductility	Energy absorption	Fracture toughness	Early strength	Quick setting	Low heat liberation	Low permeability	Freeze-thaw resistance	Sulfate and salt resistance	Low thermal expansion	Abrasion resistance	Stain resistance	Low thermal conductivity	High temperature resistance	Low cost	Estimate of fraction of total quantity of cement u:	Alternative Materials
1. Block	x			x		x	x	x			x				x			x						x			4	clay brick, adobe
2. Brick	x			x		x					x													x			0.2	clay brick
3. Pipe	x	x		x							x			x	x	x		x		x		x					2	steel, asbestos/cement, plastic, Techite, clay
4. Panels		x		x		x	x	x			x			x	x						x		x				2	clay brick
5. Beams	x	x		x						x		x		x	x	x					x						2	steel, lumber
6. Tile		x				x		x	x		x				x	x		x	x				x				0.5	clay, tiles, slate, asbestos/cement, wood shingles
7. Extruded products		x		x		x			x		x		x	x	x	x		x									0.2	aluminum, steel, wood, plastic
8. Fiber-reinforced products		x		x		x			x		x	x	x	x	x	x		x		x	x						2	aluminum, steel, wood, plastic, glass, fired clay
9. Boats		x		x				x			x							x	x	x	x						0.1	steel, wood
10. Railroad ties		x									x	x	x	x	x	x			x	x		x				x	0.5	wood
FIELD USE																												
1. Foundations	x	x															x			x						x	40	
2. Missile silos	x	x		x							x		x	x			x	x	x	x					x		0.2	
3. Columns	x	x				x				x																	8	steel
4. Slabs		x		x				x										x	x	x							15	
5. Highways		x		x					x									x	x	x	x	x				x	15	asphalt
6. Canal linings		x		x					x					x				x	x	x	x	x				x	2.5	
7. Tunnel linings	x	x		x					x		x	x			x	x		x		x	x	x				x	2.0	
8. Bridge decks		x		x															x	x	x	x		x			1.5	asphalt
9. Desalinization plants				x														x		x	x	x		x			0.1	metal, plastic, glass
10. Dams	x			x													x		x	x	x					x	0.7	earth fill
11. Marine construction	x	x		x														x	x	x	x	x					1.1	steel
12. Nuclear press. vessels	x	x		x					x								x				x				x		0.1	steel
13. Terazzo		x	x	x		x									x	x		x			x	x	x				0.1	resins
14. Stucco		x	x	x		x			x		x							x					x				0.5	
15. Masonry mortar	x		x	x					x										x		x						4.5	resin formulations
16. Oil well grouts			x	x					x											x					x		1.4	
17. Concrete patching			x	x											x	x			x	x	x	x					0.1	resin formulations, asphalt
18. Refractory linings			x	x				x	x					x	x	x	x				x	x		x	x		0.1	high alumina cement
19. Roofing		x	x	x		x		x	x		x								x		x						0.1	asphalt, metal
20. Elevated railroad structures	x	x	x			x					x	x		x					x	x							0.5	steel
21. Hardened MX missile sites	x	x	x								x	x	x	x				x	x							x	large	steel

7. The tendency of government agencies to fund primarily complete systems (i.e., complex engineering efforts) that are design-oriented rather than materials producer- and supplier-oriented.

8. The need for a focal point for specialized R&D funding and technical training, such as at a small specialized institute. Other approaches have been tried but have not been effective in the long run.

9. The lack of comprehensive across-the-board consensus-building industry/university review processes for government R&D and demonstration projects. This should be built in at the working level and include a significant representation from those parties with minimal vested interest in the specific work being carried out.

10. The lack of suitable materials whose cost, availability, and properties do not limit their use in extreme service applications. Large projects involving advanced technology designs should have peer reviews of critical materials needs and reasonable estimates of life cycle costs before large funding starts on larger scale engineering subsystems and demonstrations.

Chapter Eight

RECOMMENDATIONS

Correcting the critically low level of research and development in cement and concrete, the diminished status of the R&D establishment, and the low level of funding will require significant steps.

The committee recommends that government agencies having discretionary funds devote substantial support to fundamental research, particularly in cement, the area that appears to be most lacking in support (Chapters 3, 4, and 6 and Appendix B).

Nontechnical factors inhibiting funding of research and development in concrete should be reviewed more thoroughly by a primarily nontechnical committee of the National Academy of Sciences. The committee should address the nontechnical factors listed in Section 7.3 and explore ways to make more permanent changes in the entire system of approval for R&D funding and stimulation for private innovation. New sources of funding must be sought for the wider range of cement and concrete R&D. The committee also encourages industrial participation in examining the possibility of legislative initiative in this area.

Means should be examined for increasing R&D incentives, which could increase the possibilities for effective long-range planning and, perhaps, generate capital for investment in R&D. Other possibilities include providing tax incentives for environmental improvement and use of waste materials, thus contributing to resource conservation. An additional possibility is to establish a surcharge per unit of salable product and use the proceeds to fund R&D in cement and concrete. In place of buying foreign technology, as is currently occurring, it appears necessary to invest in R&D to reverse this trend and assist in attaining a positive balance of trade (Chapter 6 and Appendix A).

Studies along the following four major lines (Chapters 3 and 4) are recommended to existing agencies and R&D establishments:

- Studies of basic mechanisms of reactions in manufacturing and use of cement and concrete, such as those related to long-term durability and performance in either new or extreme environments. These studies will extend the potential capabilities of materials and structural entities and will ensure effective use of materials and other resources through the use of cement and concrete composities as alternative materials.

- Studies relating to effective utilization of materials and other resources, including waste products and fuels.

- Studies that involve systems analysis and modeling of cement and concrete systems. Interdisciplinary studies, both experimental and theoretical, should have high priority.

- Studies of the status of R&D related to effective energy utilization in the cement and concrete industries. Since energy considerations underlie cement and concrete production and use, there is great potential for savings.

The establishment of a National Cement and Concrete Research and Development Center should be considered. This center would emphasize integration of investigations of cement and concrete, fundamental studies, mission-oriented research or process development, and improvement of existing technology. The center would carry out and administer R&D and would have substantial coordinating and technology transfer roles. While governmental funds would normally be required for its establishment, there could be opportunity for industrial participation through special shorter term projects. Industrial support might be financed through a surcharge on product sales in the industry (Chapters 5 and 6; a preliminary outline of such an R&D center is given in Appendix C.).

Materials Research Laboratories (DOD-originated and currently NSF-financed) are among other possible sites for research and development in cement and concrete. Special attention should be given to encouraging the optimal functioning of the Portland Cement Association Research and Development Laboratories. This organization suffers from inadequacies in the type of financial support that ensures effective long-range planning and fuller potential output of the R&D effort. R&D on cement and concrete at the National Bureau of Standards also should be strengthened (Chapters 3, 4, and 6).

Critical nuclei of skilled researchers should be generated at several centers with rather specific missions. For these it is important to facilitate the infusion of new talent from relevant basic science and engineering fields and to guarantee interdisciplinarity; this is not feasible at a single establishment. Close relations could be established among several establishments. Existing cement and concrete R&D establishments and academic R&D units are the most feasible sites to be strengthened for such focus groups (Chapters 3, 5, and 6).

Steps should be taken to enhance the utilization of existing research results. Studies and education should transfer experience in R&D management and planning from high-technology industry. Also, evaluation should be made of the factors that have led to the present uncoupling of R&D in academia from that in the cement and concrete industries, and (in most places) of R&D in the cement industry from that in the concrete industry. Incentives should be provided for academic researchers to interact more closely with industry and to engage in specifications activities with industry (Chapters 5 and 6).

Specific topical areas in cement and concrete R&D and needed technological improvements requiring increased attention are below. (A longer list of applications was given in Table 7; also see Chapters 3 and 4 and Appendix B.)

CEMENT

- Reactions in cement kilns
- Utilization of wastes (including flue gases, fly ash) as raw materials for clinker and cement production
- Quality control methods for manufacture of clinker and cement
- Understanding of basic mechanisms (Clinker and hydration)
- Effect of changes in raw materials on recent properties modifiers
- Effects of changes in composition of cements and modifers on the hydration process and resultant properties
- Optimizing use of energy in cement manufacturing

CONCRETE

- Durability of concrete and corrosion resistance of reinforcement
- Performance in extreme environments (seismic, thermal, brines, high stresses, combinations)
- Learning to use new or changed cements and related materials safely
- Development of fiber-reinforced products
- Conserving materials and energy through use of waste by-products
- Preventing disaster in new designs and applications
- Developing performance standards to supplement prescription standards
- Developing new uses substituting concrete for less abundant materials or systems
- Methods for routinely producing concrete of higher strength and improved durability
- Methods for on-line modeling of the development of concrete characteristics throughout the processing phase

TECHNOLOGICAL IMPROVEMENTS

- Concrete design techniques, including theory and modeling
- Testing and quality assurance

Finally, because the implications are so encompassing, an additional study should be carried out on cement and concrete R&D by a committee focusing on problems specific to energy considerations (Chapters 3 and 4, and Appendix B).

Appendix A

FACTORS IN THE MARKETPLACE THAT INFLUENCE R&D IN CEMENT AND CONCRETE*

The factors affecting R&D in portland cement and concrete are largely dictated by economic and social pressures in the society as a whole. Three requirements generally exist before either research or development is undertaken: need, scientific curiosity, and availability of money. Other influences in the society will diminish or augment the importance of these requirements, and research activity varies accordingly. The increase in use of cementitious products for buildings, bridges, highway and airport pavements, dams, and containment vessels has also exposed technical problems that can be solved only by research.

Since the end of World War I (and particularly since the 1960s), the United States has been experiencing the effects of growing monetary inflation. This inflationary cycle has been driven by the increase in the number of middlemen and managers, the diversion of productive labor into jobs related to the interpretation of controls and red tape, the continual agitation of labor for increased wages because its real income has been diminishing, the absorption into the labor force of unproductive labor, the steady rise of service industries, and the recurring unfavorable balance of trade. The monetary conditions in the United States today are very reminiscent of those experienced in Germany between 1914 and 1923. The overhead and administrative burden of research projects have grown in instances to over $35,000 per man-year. In other instances. administrative costs and overhead amount to as much as 50 percent of the project costs. This condition requires the budgeting of large sums of money (for support staff) which have only tangential usefulness to the anticipated end product.

The justification for funding problem-solving research currently is based on the dollar loss that the problem creates in the process or procedure and the savings or profits that could be realized if the results of successful research were implemented. This kind of research is not conducted for the pursuit of knowledge for its own sake but is intended to improve the marketability, areas of application, and service-life of the commodity. It also tends to improve the competitive position of the producer. Funding here is a budget item that can compete successfully with, for example, social programs that exert intense moral and political pressures. While problem-oriented research may be justifiable in terms of the saving in material, processing time, and cost, basic research can seldom be justified using these criteria. Basic research into the interaction of cement components and the rheology of concrete, for instance, could result in the understanding of related problems, could open new frontiers of science, but may require several years to accomplish. Useful results are by no means a certainty. Funding of basic research must be based on the view that it is a necessary and desirable endeavor and should therefore be exempted from competition in the money market.

Universities, which should be the main instrument for basic research, in recent years have been faced with higher operating and payroll costs coupled with decreasing enrollment. Under these conditions the emphasis has been diverted from a research role to a teaching role with

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* This contribution was written by a liaison representative to the committee. This appendix treats a number of factors dealt with elsewhere in the report, with similar findings. Its major thrust supports one of the committee's strong recommendations, that government (in particular) funding agencies must be strongly committed to support basic research. Since its approach to economic factors differs somewhat from that taken in other parts of the report, it was considered valuable to preserve the entirety for reference.

frantic efforts to increase enrollment. Because of the lack of organized effort, economic and political leverage, and convincing arguments universities generally have failed to draw from public funds the means of performing research for its own sake. As a result, many concrete laboratories have been without sponsored projects, gifted researchers have lost interest, and new researchers cannot be attracted. The offices of university research in various federal agencies can make a stronger commitment to preserve the means for the advancement of knowledge. This can be done by a policy of funding, deemed to be necessary, and without any qualification, in the same way defense requirements are deemed necessary in the national interest.

The emphasis of some current research is centered on the realization that our natural resources in raw materials are being depleted. While the demand for longevity and performance are increasing, the sources of good materials are diminishing. As a result, concrete aggregates have had to be transported many miles to batching plants and construction sites (Air Force Civil Engineering Center, 1976; Figure 4). The assertion that high-quality concrete for airport and highway pavement projects justifies the high costs of transportation has been challenged many times. Basic research in the behavior of concrete plates could reduce thickness and strength requirements so that marginally acceptable aggregates could meet minimum standards on a performance basis.

Cement and concrete production requires materials from mining operations that leave large tracts of land denuded. Constructing either a highway or an airport also removes vegetation from wilderness areas, and many environmentalists believe that a point has been reached where these operations should be suspended. The strength of the environmentalist movement has grown in recent years largely because of the lack of concern, demonstrated in the 1950s and 1960s regarding ecological imbalances resulting from manufacturing processes and disposal of wastes. R&D aimed

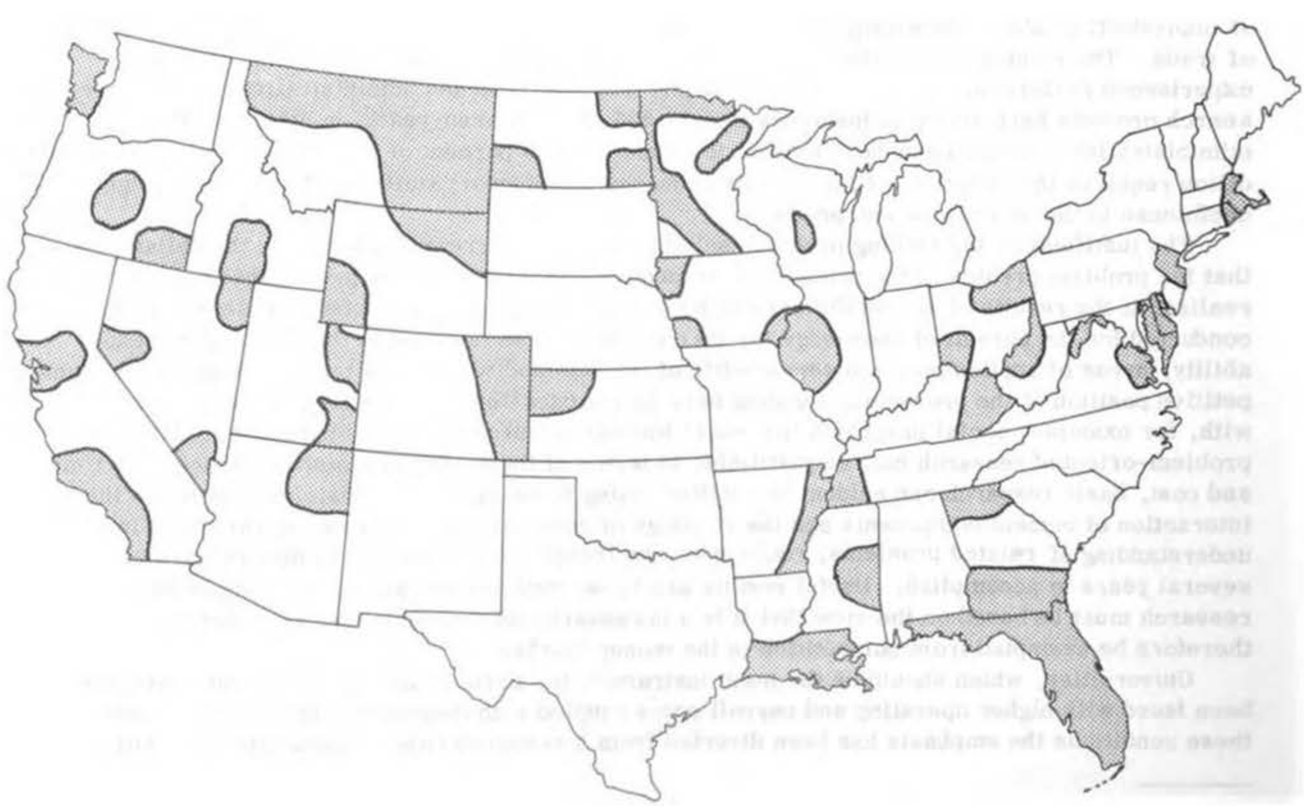

FIGURE 4 State Highway Departments Reported Aggregate Shortage Areas (Air Force Civil Engineering Center, 1976)

at increasing mining activity will be viewed as undesirable, especially if public funds are involved. It has been suggested that recycled-concrete technology and synthetic materials be developed and utilized as substitutes for natural aggregates, but research in this area has not been sufficient to develop standards and induce confidence on the part of engineers.

The belief in many parts of the concrete industry is that a move away from restrictive specifications to performance specifications would foster innovative techniques and permit the use of cheaper and more readily available components. Procurement policy in government has for several years required the writing of performance specifications in order to encourage greater competition among bidders (Code of Federal Regulations). These specifications are easily written when the end item can be defined; definite tests exist to verify that the product will give the required performance. There are instances, however -- in cement and concrete processing -- when the number of variables in the process are so numerous that guidance must be offered. Also, while the end performance may be specifiable, it is very often not met in the end product. Means of reducing contractual fees may have to be based upon how closely various parts of the process satisfy variously located landmarks, i.e. restrictive specifications. Thus, performance specifications are desirable for innovation, but some restrictive ones must be provided as guidelines toward the accomplishment of the end product.

Over the past several years, research has been based on cement and concrete consisting of a certain class of easily available materials. Standards for design have been written on the assumption that these materials meet minimum specifications. With new aggregate sources, cement and concrete cannot be expected to behave in a conventional manner and thus strength, durability, shock resistance, thermal insulation, and other physical factors may all have to be determined anew. Since there may be a variety of substances that could serve as substitutes, it appears important that instead of determining characteristics of various types of concrete on a case-by-case basis, more research work should be done on a general, basic, mathematical modeling technique so that the behavior of concrete with any new ingredient can be immediately determined.

The extent of government participation in research on concrete has mostly been to secure longevity of concrete structures in adverse environments. This has been partially due to efforts to extend the life of products purchased by tax dollars. It is clear that research will be limited to this mission as pressure to spend money elsewhere increases and as taxing authorities find it more and more difficult to increase taxes. Public resistance to raise taxes, or even to maintain them at present levels, seems to be increasing. As projects are cut back, few new public civil projects are on the horizon. It would seem that this period of quiescence should be used to improve and develop new methodology that would increase product efficiency and reduce costs.

The ever-increasing cost of producing cement in the United States is bound to have an influence on the amount that overseas countries can import from this nation. The inflation in the economy is most severely felt in Third World countries and, while increased costs can probably be absorbed domestically, those nations may have to turn to concrete substitutes. Some research must be aimed toward finding some suitable substitutes and also toward reducing cement and concrete production costs.

The fact that prices of all fuel sources have escalated in recent years, alone, would justify research for other fuel sources in cement and concrete manufacture. Although research here would be worthwhile, it does not guarantee that new sources and economies will lead to any ultimate reduction in product costs. There has been a tendency in some areas of industry to adjust rates on replacement products to match previously existing ones. Thus, even if a cheap, safe, and revolutionary energy source could be found, the prices of hardware and labor would likely be raised so that the final cost to the user would be near existing costs. This is the rule of "anti-economic dislocation." It must be conceded, however, that successful research in this area would tend to conserve fossil fuel reserves and make the nation less dependent on foreign imports.

More and more questions are being asked about the need for more dams, more highways, more office buildings, more nuclear plants, etc. In this climate of growing skepticism, greater participation in cement and concrete research is being challenged. With the existing levels of personal income taxes and other levies, some relief is being sought by most wage earners. It is therefore likely that more tax incentives to corporations for research programs will not be realized because the public is not educated to appreciate the usefulness of such programs.

This skepticism is no doubt shared by many corporate shareholders and will shape management policy in the private sector against further R&D investment unless, of course, some improvements in profits are in prospect. Also, more incentives might increase activity in research, but it would be problem-related and the results would be proprietary. The area that needs more activity is basic research, the results of which would be in the public domain; governmental encouragement of this area by greater tax relief could be defended. This same reasoning is true in the context of cooperative research between manufacturers. Any breakthroughs resulting from joint effort, must by custom, be used to improve the competitive posture vis-à-vis other companies and could be used in a price-fixing arrangement. The present tax structure seems satisfactory. Companies either fund their own research and adjust their own prices accordingly or contribute to research institutions with other companies and allow the results to be published for general use.

An R&D area that will be most promising in the short term is that which will improve patching and repair techniques. This aspect will become more important as new projects are canceled and existing structures must be rehabilitated (Collum, 1978). Techniques must include development of new compounds for bonding new concrete to old concrete. In many cases rapid repair is important, especially at military airfields. This area of research will have to be pursued before the eventuality of insufficient funds raised by either local governments or private industry to erect new structures. Several programs are underway in this area of research.

It may be concluded that R&D activity on any industrial product will vary according to the needs generated from time to time for improvements in marketability, competitive posture of the producers, safety in applications, conservation of resources, and preservation of the environment. Whether this type of R&D in any particular area of interest is funded may easily be determined on the basis of cost-effectiveness. On the contrary, as an example, basic research to develop an understanding of the nature and behavior of cement and concrete cannot survive when weighed by these criteria. Such research needs support from a policy of funding that justifies it because it is essential: for the general advancement of science, to preserve the existing facilities for this kind of research, or to maintain the interest of gifted scholars.

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Code of Federal Regulations. 41 CFR1-1-307-1, 2. U.S. Government Printing Office, Washington, DC.

Collum, C. E. (1978). Repair and Restoration of Paved Surfaces -- Report #1, Bomb Damage Repair Field Trials June 1975-November 1976. Technical Report C-78-2. U.S. Army Engineers, March.

Appendix B

QUESTIONNAIRE DATA ANALYSIS

The committee sought, as part of its mission, to obtain quantitative data on current cement and concrete research expenditures in the United States. A number of difficulties were encountered, relating primarily to the fact that there was no comprehensive source of information available, and that submission of information to data collecting agencies is for the most part voluntary. The NAS Transportation Research Board periodically solicits information on cement and concrete research from those who choose to respond; and the American Concrete Institute has again begun to collect such data on a voluntary basis. Also, some limited information is available from business-oriented compilations (Business Week, 1977).

The committee thus chose to generate its own questionnaire to obtain a picture of current R&D activity, recognizing that this would inevitably be incomplete. The recipients of the questionnaire were selected by the committee from a longer list of universities, industries (cement, concrete and component materials), not-for-profit organizations, and some state agencies. Essentially all U.S. government agencies believed to be either doing or funding such R&D were included or otherwise contacted separately. The questionnaire (included in this appendix) was distributed to 195 institutions and received a response rate of 37 percent. The requested data pertained to the nature of the institution, its relative level of cement and concrete R&D activity, financial support (Part I); relevant data and topics of individual projects in progress (Part II); and an opinion survey regarding R&D needs (Part III). The more readily quantifiable data from Part I are summarized in Table 8 and are discussed briefly. Also tabulated and discussed in this appendix are the opinions of the respondents concerning R&D needs.

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Page 1 NMAB Privileged Data

QUESTIONNAIRE ON CEMENT AND CONCRETE R&D EFFORT -- Part I (of 3)

1. Date ____________

2. Name of Institution/Company ____________
   (or relevant subdivision) ____________
   Address ____________

General Interest Section

3. Type of Institution: Industry ☐
   Academic ☐
   Non-Profit ☐
   Government ☐ (U.S. ☐ State ☐)
   Other ☐ ____________
   (specify)

4. Major Interests/Products/Activities (List 3 in order of priority, using number codes from back of cover letter, where applicable.)

   ____________ ____________ ____________

5. Contact Person: Name ____________ Tel. ( ) ____________ ext. ____
   Title (R&D Director ☐ Other ☐ ____________)
   Address ____________

Personnel Section

6. Total Number of Employees of Organization/Institution ____________

7. Number of Technical Employees in Cement and Concrete Related R&D:
   < 10 ☐ 10-19 ☐ 20-49 ☐ 50-100 ☐ 101-200 ☐ > 200 ☐

8. Personnel in Cement and Concrete Related R&D

Number of Technical Staff	Highest Degree Held			
	None	B.S.	M.S.	PhD
1-3				
4-6				
7-10				
11-50				
> 50				

Number of Technicians, Lab. Assistants, Other	Highest Degree Held			
	None	B.S.	M.S.	PhD
1-3				
4-6				
7-10				
11-50				
> 50				

Financial Section

(Give answers applicable to cement and concrete only)

9. Total Gross Sales (million $) [if applicable]

	< 10	10-25	26-50	51-100	101-200	> 200
1975						
1976						
1977						

10. Total R&D Expenditures (million $)

	< 0.05	0.05-0.10	0.11-0.5	0.6-1.0	1.1-10	> 10
1975						
1976						
1977						

11. Average Annual $ on R&D in Last 5 Years: $______________

12. Average % of Item #10 Devoted to the Following (should total 100%):

	1975	1976	1977
Fundamental, Exploratory, Non-Mission-Oriented Research			
Mission-Oriented Research, Innovative Process/Product Dev.			
Improvement of Existing Technology			

13. Source of R&D Funding (1977):

	< 35%	35-70%	> 70%
Internal	☐	☐	☐
External			
(a) Industrial	☐	☐	☐
(b) U.S. Govt.	☐	☐	☐
(c) State Govt. (____)	☐	☐	☐
(d) Non-Profit Org.	☐	☐	☐
(e) Foreign Govt.	☐	☐	☐
(f) Foreign Industry	☐	☐	☐

14. Comments

Inquiry for
NMAB Committee Study
6 January 1978

NATIONAL RESEARCH COUNCIL

COMMISSION ON SOCIOTECHNICAL SYSTEMS

NATIONAL MATERIALS ADVISORY BOARD

Page 3 NMAB Privileged Data

QUESTIONNAIRE ON CEMENT AND CONCRETE R&D PROJECTS -- Part II (of 3)

Name of Institution/Company ____________________
(or relevant subdivision) ____________________
Address ____________________

Contact Person: Name ____________ Tel. ( ) ________ ext. ____
Title ____________ Date ____________

NOTE: If desired, reproduce copies of this form and fill out Section A for each activity for which the annual level of effort meets one of the following conditions:

a. One man-year or more annual level of effort;

b. Less than one man-year annual level of effort, but the cumulative efforts are at least one man-year for all activities.

ALTERNATIVE: If neither of the above can be fulfilled, group the activities (categories) together as a unit and report in Section B.

- -

SECTION A

Individual Project Data

NOTE: Please answer as many of these questions as you can, giving the best data available. Reproduce copies of Section A and fill them out for each individual project.

1. Title of Project: ____________________

2. Person in Charge: Name ____________ Tel. ( ) ________ ext. ____
Title ____________________
Address ____________________
____
____

3. Number of Other Personnel (full-time equivalent): ________

4. Type of Project: ☐ Fundamental, Exploratory, Non-Mission-Oriented Research
☐ Mission-Oriented Research, Innovative Process/Product Development
☐ Improvement of Existing Technology

5. Discipline or Topic which Most Closely Fits Project (use number codes from back of cover letter): ________

6. Research Methodology:
   - ☐ Primarily Theoretical or Mathematical Investigation
   - ☐ Laboratory Investigation, Experimental
   - ☐ Pilot Plant Study
   - ☐ Full-Scale Plant or Site Investigation
   - ☐ Review, Literature
   - ☐ Other (please explain) ______________________

7. Annual Level of Funding for Project: $__________

8. Years Duration of Project: ________ Expected Completion Date: ______________

9. Results of the R&D are to be Used as Follows: [check appropriate box(es)]:
   - ☐ Establishing New Product
   - ☐ Improving Existing Product
   - ☐ Production Control
   - ☐ Standards
   - ☐ Patents
   - ☐ Reports to Sponsor
   - ☐ Publications

   For the last three items, list patents, reports, and publications (issued or pending) for the last five years; use additional sheets if necessary.

SECTION B

NOTE: If it is not feasible to break down into individual projects, please use this section.

For the three major categories of R&D effort occupying the major proportion of your company's effort, indicate in order of decreasing emphasis the percentage and funding involved:

(1) > 70% ☐ 40-70% ☐ 25-39% ☐ $ Effort $__________

____
Name of Category or Project (Use number codes from back of cover letter, where applicable.)

(2) > 40% ☐ 25-40% ☐ 10-24% ☐ < 10% ☐ $ Effort $__________

____
Name of Category or Project (Use number codes from back of cover letter, where applicable.)

(3) > 25% ☐ 10-25% ☐ < 10% ☐ $ Effort $__________

____
Name of Category or Project (Use number codes from back of cover letter, where applicable.)

(4) If category(s) is for company-confidential projects, please give funding level of these projects: $______________

Inquiry for
NMAB Committee Study
6 January 1978

NATIONAL RESEARCH COUNCIL

COMMISSION ON SOCIOTECHNICAL SYSTEMS

NATIONAL MATERIALS ADVISORY BOARD

NMAB Privileged Data

QUESTIONNAIRE ON CEMENT AND CONCRETE R&D NEEDS -- Part III (of 3)

Name of Institution/Company ______________________________
(or relevant subdivision) ______________________________
Address ______________________________

Contact Person: Name ____________________ Tel. ( ) ________ ext. ______
Title ____________________ Date ______________

I. List up to 5 areas of knowledge (A), opportunities (B), and problems (C) which you think will be most important to this field within the next 10 to 20 years for the field as a whole (not necessarily your own or your company's needs).

A. Fundamental, Exploratory, Non-Mission-Oriented Research
1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________
5. ______________________________

B. Mission-Oriented Research, Innovative Process/Product Development
1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________
5. ______________________________

C. Improvement of Existing Technology
1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________
5. ______________________________

II. Where are major innovations needed?

____
____
____
____
____
____

II. (continued)

A. In your opinion, where has R&D made major accomplishments in the last five years?

B. In your opinion, where has sufficient R&D already been accomplished?

C. What government laws, rules, regulations, etc., might be eliminated, added, or changed to encourage research, development and innovation (other than providing direct financial support of R&D projects)?

III. Other Comments (use additional sheets if necessary)

Thank you for taking the time from your schedule to supply the requested date on these three forms. The committee's endeavor will be made most worthwhile by having these details with which to work.

Inquiry for
NMAB Committee Study
6 January 1978

The response rate to the questionnaire is listed below:

	Replies with Data	Replies N/A*	
Universities			Sent to universities = 66 (4)
Cement	1 (1)**	2	Replies with data = 21 (1)
Concrete	16	6	Response Rate = $\frac{21}{66}$ = 31.8%
Both	4	2	
	21	10	
Government			Sent to government agencies = 28 (10)
Cement	1	0	Replies with data = 17 (4)
Concrete	11 (1)	1	Response Rate = $\frac{17}{28}$ = 60.7%
Both	5 (3)	0	
	17	1	
Nonprofit			Sent to nonprofit organizations = 25 (1)
Cement	0	0	Replies with data = 9 (0)
Concrete	6	3	Response Rate = $\frac{9}{25}$ = 36.0%
Both	3	0	
	9	3	
Industry			Sent to industry = 76 (2)
Cement	15	10	Replies with data = 22 (1)
Concrete	6 (1)	4	Response Rate = $\frac{22}{76}$ = 28.9%
Both	1	3	
	22	17	
TOTAL	69	31	Total questionnaires sent = 195 (17)
			Total replies with data = 69 (6)
			Total Response Rate = $\frac{69}{195}$ = 37.1%

NOTE: 198 questionnaires were mailed; 3 were returned by the post office.

* Responded saying questionnaire was not applicable to their organization.

** Numbers in parentheses indicate how many of these involved the committee.
Committee Response Rate = $\frac{6}{17}$ = 35.3%.

SUMMARY OF DATA, PART I OF QUESTIONNAIRE

Table 8 presents a summary of the data obtained from Part I of the questionnaire.

TABLE 8 Summary of Data, Part I of Questionnaire

PERSONNEL DATA -- CATEGORIES OF PRODUCTS, ACTIVITIES, AND INTERESTS

Key to Topical Area Summary

The tables on personnel data for industry, universities, government, and nonprofit organizations use the following numbering to indicate cetegories of products, activities, and interests.

1. CEMENT
   - a. Raw Materials
   - b. Waste Materials
   - c. Processing
   - d. Kiln Chemistry
   - e. Finish Grinding
   - f. Gypsum
   - g. Environment
   - h. Cement Composition
   - i. Hydration Processes
   - j. Additives
   - k. Paste
   - l. Expansive Cements
   - m. Quick-Setting Cements
   - n. Oil Well Cements
   - o. Blended Cements
   - p. Special Cements
   - q. Energy or Efficiency
   - r. Strength
   - s. Chemical Reactions
   - t. Other

2. MORTARS AND GROUTS
   - a. Mortar
   - b. Grout
   - c. Other

3. CONCRETE, FRESH
   - a. Aggregates
   - b. Water
   - c. Admixtures
   - d. Pozzolans
   - e. Polymers
   - f. Waste Materials
   - g. Proportioning
   - h. Mixing
   - i. Transportation
   - j. Placing
   - k. Consolidation
   - l. Finishing
   - m. Curing
   - n. Environment
   - o. Formwork
   - p. Temperature
   - q. Expansive
   - r. Quick Setting
   - s. Special Concretes
   - t. Refractory
   - u. Production
   - v. Other

4. CONCRETE, HARDENED
   - a. Acoustical
   - b. Electrical
   - c. Thermal
   - d. Strength
   - e. Fatigue Strength
   - f. Fracture
   - g. Toughness
   - h. Impact
   - i. Temperature
   - j. Elastic Properties
   - k. Creep and Relaxation
   - l. Durability (corrosion, etc.; state what kind)
   - m. Refractory
   - n. Radiation
   - o. Repairs
   - p. Energy
   - q. Polymers
   - r. Other

5. CONCRETE STRUCTURES
   - a. Bridges
   - b. Buildings
   - c. Cast-in-Place Concrete
   - d. Composite
   - e. Dams
   - f. Elements
   - g. Floating
   - h. Foundations
   - i. Joints
   - j. Mines
   - k. Offshore Structures
   - l. Pavements
   - m. Precast Concrete
   - n. Prestressed Concrete
   - o. Reactors (Nuclear)
   - p. Reinforced Concrete
   - q. Ships
   - r. Tanks
   - s. Tunnels
   - t. Underwater
   - u. Earthquake Resistance
   - v. Blast Resistance
   - w. Durability
   - x. Fire Resistance
   - y. Construction
   - z. Energy
   - aa. Efficiency
   - bb. Other

6. CONCRETE REINFORCEMENT
   - a. Ferrocement
   - b. Fibers
   - c. Reinforcing Steel
   - d. Prestressing Steel
   - e. Other

7. EVALUATION
   - a. Testing, Routing
   - b. Quality Assurance
   - c. Causes of Failure
   - d. Other

8. RESEARCH METHODOLOGY
   - a. Instrumentation
   - b. Experimental
   - c. Theoretical, Physical
   - d. Mathematical
   - e. Review, Literature

TABLE 8 (continued)

PERSONNEL DATA — INDUSTRY

Number	Products, Activities, Interests (in descending order of priority)	Title of Contact Person	Total Employees	Total Technical R&D Employees	Number of Technical Staff and University Degrees				Number of Technicians, Lab Assistants, Other			
					None	B.S.	M.S.	Ph.D.	None	B.S.	M.S.	Ph.D.
Concrete												
1	Oil and Gas	Mgr., External Activities	1,900	< 10	--	--	--	1-3	--	1-3	--	--
2	5c; 3u	Mgr., Technical Marketing	N.A.	< 10	--	--	1-3	--	7-10	--	--	--
3	6b; 3c; 7a; 8c	Senior Research Chemist	750	<10	--	1-3	--	--	1-3	--	--	--
4	5m; 5n; 3a; 3e; 3g; 3h; 3i; 3k; 3m; 3u	Assistant Director	11	<10	--	1	1	3	1-3	--	--	--
5	5; 4k; 8d	Mgr., Structural Engineering	2,000	10-19	--	4-6	4-6	4-6	1-3	1-3	--	--
6	1c; 1e; 1g	Director, Commercial Dev.	350	<10	--	4-6	--	--	--	--	--	--
Cement												
7	Steel	None Given	90,000	<10	--	--	--	1-3	--	--	--	--
8	1n; 1l; 1j	Group Leader	N.A.	N.A.	--	--	--	--	--	--	--	--
9	1q	Vice President	20	<10	--	1-3	1-3	--	--	--	--	--
10	1n; 1o; 3c; 3d; 3e; 2b	Cementing Coordinator	5,000	20-49	2	2	1	1	20	10	3	3
11	1q; 1h; 1t	Director, Tech. Operations	3,500	10-19	--	4-6	1-3	1-3	4-6	--	--	--
12	1c; 1a; 1d	V.P. Engineering & Research	2,700	<10	--	1-3	1-3	--	1-3	1-3	--	--
13	1n; 1t	Supervisor, Product Mechanics	550	<10	--	1-3	--	--	1-3	--	--	--
14	Nuclear & Industrial Waste; Solidification	Consulting Nuclear Engineer	800	10-19	--	4-6	1-3	1-3	4-6	1-3	--	--
15	1a-1k; 1n-1s; 3a-3d; 4d; 7a; 7b; 8a-8c; shrinkage	Technical Director	>1,000	10-19	--	4-6	1-3	--	4-6	--	--	--
16	1; 3; 7	R&D Director	5,000	10-19	--	1-3	1-3	1-3	5	2	--	--
17	1t; insulation; bldg. syst.	Vice President	200+	<10	--	1-3	--	--	1-3	--	--	--
18	1q; 1o; 1g	Vice President	531	<10	--	1-3	1-3	--	4-6	--	--	--
19	General Interest	President	2	<10	--	--	1-3	1-3	1-3	--	--	--
20	1; 3; 7	Group Dir., Mfg. Services	4,760	20-49	--	11-50	1-3	--	4-6	--	--	--
21	1c; 1d; 1e	Mgr., Process Res. & Test Ctr.	--	20-49	--	11-50	11-50	1-3	11-50	1-3	--	--
Both												
22	1c; 1q; 1a	Director, Business Development	100	<10	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.

TABLE 8 (continued)

PERSONNEL DATA -- UNIVERSITIES

Number	Products, Activities, Interests (in descending order of priority)	Title of Contact Person	Total Employees	Total Technical R&D Employees	Number of Technical Staff and University Degrees				Number of Technicians, Lab Assistants, Other			
					None	B.S.	M.S.	Ph.D.	None	B.S.	M.S.	Ph.D.
Concrete												
23	5a-5c; 5i; 5m; 5n; 5p; 5w; 7c	Director, R&D	30	20-49	--	10	5	5	9	1	--	--
24	8c; 8b; 8d	Professor, Civil Engineering	50+	<10	--	--	--	4-6	1-3	--	4-6	--
25	Education; 8c; 8d	Professor, Engineering	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
26	Education Research	Professor, Engineering	26	<10	--	--	--	3	--	--	--	--
27	4f; 5o; 7c	Professor, Engineering	2,000	<10	--	--	--	1-3	1-3	1-3	1-3	--
28	6a; 6b; 4f; 4d; 4e; 5p; 4q; 5b; 8b; 8c; 4l; 4d	Professor, Civil Engineering	N.A.	<10	--	--	--	1-3	1-3	--	--	--
29	5d; 4j; 5p	Professor, Civil Engineering & Director, Concrete Laboratory	2,900	<10	--	--	--	1	3	2	3	--
30	--	Director, R&D	--	<10	--	--	1	4	1	--	--	--
31	5l; 5a; 5d	Professor, Civil Engineering	24	<10	--	--	--	4-6	1-3	4-6	1-3	--
32	4; 5	Professor, Civil Engineering	200	<10	--	--	--	1-3	1-3	1-3	4-6	--
33	3d; 3l; 4l	Professor, Research Engrg.	--	<10	--	1	--	2	4	1	--	--
34	5b; 5u; 5m	Professor, Civil Engineering	50	<10	--	--	--	1-3	--	4-6	4-6	--
35	4f; 6b; 4l; freeze-thaw	Director, R&D	--	<10	--	--	--	1-3	1-3	--	--	--
36	3; 5a; 5b; 4	Chmn. & Prof. Civil Engineering	18	<10	--	3	2	3	1	--	--	--
37	4o; 5u; 5t	Asst. Prof., Civil Engineering	--	<10	--	--	--	3	2	--	--	--
38	3a; 3c-3e; 5b; 5z; 5u; 5l-5n; 5p; 8b; 8c	Professor	26	<10	--	--	--	4	1	3	--	--
Cement												
39	1l; 1i; 1k	Professor, Civil Engineering	--	<10	N.A.		--	--	--	--	2	1
Both												
40	8a-8e; 5q-5bb; 4a-4r	Head, School of Civil Engrg.	100	20-49	--	--	7-10	4-6	--	11-50	7-10	--
41	1i; 1p; 1d; 3s; 3a; 5a	Professor	900	10-19	--	4-6	4-6	7-10	4-6	1-3	1-3	--
42	*	Dept. Chairman, Civil Engrg.	120	10-19	--	1-3	7-10	4-6	--	11-50	--	--
43	3; 1; 4	Professor, Civil Engineering	N.A.	<10	--	--	--	1-3	1-3	--	--	--

* Properties of cementitious materials and concrete; response of concrete structures to external loading; structural response of concrete structures.

TABLE 8 (continued)

PERSONNEL DATA — NONPROFIT ORGANIZATIONS

Number	Products, Activities, Interests (in descending order of priority)	Title of Contact Person	Total Employees	Total Technical R&D Employees	Number of Technical Staff and University Degrees				Number of Technicians, Lab Assistants, Other			
					None	B.S.	M.S.	Ph.D.	None	B.S.	M.S.	Ph.D.
Concrete												
44	5; 4; 7	Technical Director	19	<10	--	--	4-6	--	--	--	--	--
45	3a; 3u; 5z	Managing Director	2	<10	--	1-3	--	--	--	--	--	--
46	3; 4; 5	V.P., Engineering & Research	25	<10	--	--	1-3	--	4-6	--	--	--
47	5b; 5d; 5m; 5n; 5u; 5v; 5x; 5z; 5aa; 4a; 4c; 4h; 4j; 4p; 4q; 3d; 3e; 3f; 3k; 3m; 3s; 3u	V.P., R&D and Engineering	19	<10	--	--	4-6	--	--	1-3	--	--
48	Concrete Pipe; Soil Structural Systems; 5w	Vice President	19	<10	--	1-3	--	--	--	--	--	--
49	3a; 3q; 4d	V.P., Engineering	19	<10	1-3	1-3	1-3 C.E.	--	1-3	--	--	--
Both												
50	1a; 1b; 1h; 1j; 1l; 1m; 1o; 1p-1r; 4a-4h; 4l-4q; 7a-7c	Director, Dept. of Materials Sciences	1,486	<10	--	4	--	1	4	--	--	--
51	5; 1; 4	Group V.P., R&D	425	101-200	1-3	11-50	7-10	11-50	>50	4-6	--	--
52	5a-5c; 5h; 5j; 5l-5n; 5s; 5u-5y; 4a-4m; 4o; 6b; 6c	Director, R&D	900	20-49	1-3	7-10	4-6	4-6	1-3	--	--	--

TABLE 8 (continued)

PERSONNEL DATA — GOVERNMENT

Number	Products, Activities, Interests (in descending order of priority)	Title of Contact Person	Total Employees	Total Technical R&D Employees	Number of Technical Staff and University Degrees				Number of Technicians, Lab Assistants, Other			
					None	B.S.	M.S.	Ph.D.	None	B.S.	M.S.	Ph.D.
Concrete												
53	Contact Control Testing; Research	Chief, Roadbed and Concrete Branch	265	10-19	--	2	--	--	8	--	--	--
54	5; 7; 3	Director, R&D	74	10-19	1	5	2	--	2	1	--	--
55	5l; 7c; 8b	Research Engineer	17,000	< 10	--	1	--	--	3	--	--	--
56	5l; 5a; 5u	Chief, Bureau of Structures	23	< 10	--	--	1-3	--	--	1-3	--	--
57	4d-4g; 4j; 4l; 4o; 4q; 3a; 3d; 3k-3m; 5a; 5l	Research Engineer	13,400	< 10	--	3	--	--	4	--	--	--
58	4l	Research Manager	7,500	10-19**	--	1-3	--	--	7-10	1-3	--	--
59	5c; 3a; 2b	Chief	66	50-100	1-3	11-50	7-10	1-3	11-50	--	--	--
60	5t; 2q; 11	Research Materials Engineer	300	< 10	--	--	1-3	--	1-3	--	--	--
61	5c; 3d; 4q	Research Coordinator	1,270	10-19	--	8	2	--	5	--	--	--
62	Highways & Transport.	Chief, R&D Bureau	7,700	< 10	--	--	7-10	--	--	7-10	--	--
63	3d; 2b; 3i (pumping)	Laboratory Manager	50,000	10-19	--	2	2	--	9	--	--	--
Cement												
64	5z; 4d; 5n	Manager, R&D	5,000	< 10	--	--	1-3	1-3	1-3	--	--	--
Both												
65	5j; 4m; 3s (sulfur)	Cement Commodity Specialist	3,000	< 10	--	1-3	1-3	4-6	1-3	--	--	--
66	7a; 8b; 8c	Assistant Head	75	< 10	--	--	--	4-6	1-3	--	--	--
67	*	Chief, Bldg. Composites Prog.	3,500	10-19	--	1	--	8	5	--	--	--
68	1; 4; 8	Assoc. Dir., Met. & Mat. Sci.	100	< 10	--	--	--	1-3	--	--	--	--
69-1	5l; 5w; 7c	Program Manager	11	< 10	--	7-10	1-3	1-3	N.A.	N.A.	N.A.	N.A.
69-2	5n; 7c; 8b	Division Chief	25	< 10	--	--	--	1-3	--	--	--	--
69-3	5l; 5n; 5c	Group Chief	10	< 10	--	--	2	2	--	1	--	--
69-4	4e; 4f; 5a; 5c; 6b; 6c; 5n; 5r; 8a-8c	Division Chief	37	< 10	--	1-3	1-3	1-3	1-3	--	--	--
69-5	4l; 7a; 1q	Division Chief	38	20-49	--	7-10	7-10	6	7-10	1	--	--

* Provide capability for physical measurement; technological response to the Nation's social and economic needs; services to improve use of materials.
** Number not accurate.

TABLE 8 (continued)

FINANCIAL DATA -- INDUSTRY

Number	Total Gross Sales (million $) 1975	1976	1977	Total R&D Expenditures (million $) 1975	1976	1977	Avg. Annual Expenditure 1973-1977 ($)	R&D Expenditures on Various Types of Research (%) 1975 F*	M*	I*	1976 F*	M*	I*	1977 F*	M*	I*	Sources of 1977 R&D Funding** < 35%	35-70%	> 70%
Concrete																			
1	--	--	--	< 0.05	< 0.05	< 0.05	40,000	--	25	75	--	25	75	--	25	75	--	--	Int
2	< 10	< 10	< 10	< 0.05	< 0.05	< 0.05	30,000	--	80	20	--	80	20	--	80	20	--	--	Int
3	> 200	--	--	> 10	--	--	20,000	--	--	--	--	--	--	--	--	--	--	--	Int
4	< 10	< 10	< 10	0.11-0.5	0.11-0.5	0.11-0.5	200,000	15	45	40	15	45	40	15	45	40	Int, Fi	--	Id
5	--	--	--	0.6-1.0	0.6-1.0	0.6-1.0	500,000	--	50	50	--	50	50	--	50	50	Id, Fg	Int, Ug	--
6	--	--	--	0.11-0.5	0.11-0.5	0.05-0.10	(80,000)‡	--	100	--	--	100	--	--	100	--	--	--	Int
Cement																			
7	--	--	--	0.11-0.5	0.11-0.5	0.11-0.5	30,000	--	100	--	--	100	--	--	100	--	--	--	Int
8	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	Ug	--	Int
9	--	--	--	0.05-0.10	0.11-0.5	0.11-0.5	50,000	--	100	--	--	100	--	--	100	--	Int	--	Ug
10	> 200	> 200	> 200	1.1-10	1.1-10	1.1-10	2,000,000	10	55	35	15	50	35	15	50	35	--	--	Int
11	> 200	> 200	> 200	0.11-0.5	0.11-0.5	0.11-0.5	350,000	2	49	49	2	49	49	2	49	49	--	--	Int
12	101-200	101-200	101-200	0.05-0.10	0.05-0.10	0.11-0.5	60,000	--	30	70	--	30	70	--	30	70	--	--	Int
13	--	--	--	< 0.05	< 0.05	0.05-0.10	50,000	--	100	--	--	100	--	--	100	--	--	--	Int
14	< 10	< 10	< 10	< 0.05	< 0.05	< 0.05	50,000	--	100	--	--	100	--	--	100	--	--	--	Int
15	51-100	51-100	101-200	0.11-0.5	0.11-0.5	0.11-0.5	150,000	--	5	95	--	15	85	--	50	50	--	--	Int
16	> 200	> 200	> 200	< 0.05	< 0.05	< 0.05	25,000	--	90	10	--	90	10	--	90	10	--	--	Int
17	> 200	> 200	> 200	0.6-1.0	0.6-1.0	0.6-1.0	800,000	5	80	15	6	74	20	7	73	20	--	--	Int
18	26-50	26-50	26-50	0.11-0.5	0.11-0.5	0.11-0.5	330,000	--	25	75	--	25	75	--	25	75	--	--	Int, Id †
19	--	--	--	0.05-0.10	0.05-0.10	0.05-0.10	60,000	--	50	50	--	50	50	--	50	50	--	--	Int
20	> 200	> 200	> 200	0.11-0.5	0.11-0.5	0.11-0.5	500,000	10	70	20	10	80	10	10	80	10	--	--	Int
21	10-25	26-50	26-50	0.11-0.5	0.11-0.5	0.11-0.5	200,000	10	10	80	10	20	70	10	20	70	--	--	Int
Both																			
22	< 10	< 10	< 10	< 0.05	< 0.05	< 0.05	20,000	--	100	--	--	100	--	--	100	--	--	--	Int

† Totals over 100%; reason unknown.

‡ Value in parentheses estimated from previous column.

* F - Fundamental, exploratory, non-mission-oriented.
M - Mission-oriented; innovative process/product development.
I - Improvement of existing technology.

** Fg - Foreign govt.
Fi - Foreign industry
Id - Industrial
Int - Internal
Np - Nonprofit org.
Sg - State govt.
Ug - U.S. govt.

Table 8 (continued)

FINANCIAL DATA -- UNIVERSITIES

Number	Total Gross Sales (million $) 1975	1976	1977	Total R&D Expenditures (million $) 1975	1976	1977	Avg. Annual Expenditure 1973-1977 ($)	R&D Expenditures on Various Types of Research (%) 1975 F*	M*	I*	1976 F*	M*	I*	1977 F*	M*	I*	Sources of 1977 R&D Funding** < 35%	35-70%	> 70%
Concrete																			
23	N.A.	N.A.	N.A.	0.11-0.5	0.11-0.5	0.11-0.5	175,000	20	40	40	20	40	40	15	40	45	Int, Id, Np, Fg, Fi	Ug, Sg	--
24	N.A.	N.A.	N.A.	1.1-10	1.1-10	1.1-10	2,000,000‡‡	80	15	5	80	15	5	80	15	5	Ig, Fg	Sg	Ug †
25	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.			N.A.			N.A.			N.A.	N.A.	N.A.
26	N.A.	N.A.	N.A.	< 0.05	< 0.05	< 0.05	(20,000)‡	100	--	--	100	--	--	100	--	--	--	--	Ug
27	N.A.	N.A.	N.A.	0.05-0.10	0.05-0.10	0.05-0.10	100,000	100	--	--	100	--	--	100	--	--	Int	Ug	--
28	N.A.	N.A.	N.A.	< 0.05	< 0.05	< 0.05	30,000	N.A.			N.A.			N.A.			Int, Id, Sg	Ug	--
29	N.A.	N.A.	N.A.	0.003	0.011	0.020	6,900	100	--	--	100	--	--	70	30	--	Int	--	Ug
30	N.A.	N.A.	N.A.	< 0.05	< 0.05	0.11-0.5	34,000	25	--	75	25	--	75	25	--	75	Sg	--	Ug
31	N.A.	N.A.	N.A.	< 0.05	< 0.05	< 0.05	(25,000)‡	--	--	100	--	--	100	--	--	100	--	--	Int, Sg †
32	N.A.	N.A.	N.A.	0.11-0.5	0.11-0.5	0.11-0.5	180,000	50	50	--	50	50	--	90	10	--	--	Id, Ug	--
33	N.A.	N.A.	N.A.	0.05-0.10	0.05-0.10	< 0.05	(50,000)‡	--	25	75	--	50	50	--	100	--	Ug	--	Id
34	N.A.	N.A.	N.A.	0.11-0.5	0.11-0.5	0.11-0.5	150,000	--	50	50	--	50	50	--	50	50	Int	Ug	--
35	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	3,000	N.A.			N.A.			N.A.			--	Int, Id	--
36	N.A.	N.A.	N.A.	< 0.05	< 0.05	< 0.05	(25,000)‡	75	--	25	75	--	25	75	--	25	Int	Id, Sg	--
37	N.A.	N.A.	N.A.	N.A.	< 0.05	< 0.05	5,000	N.A.			N.A.			25	50	25	--	--	Ug
38	N.A.	N.A.	N.A.	< 0.05	< 0.05	0.05-0.10	(65,000)‡	N.A.			50	50	--	50	50	100†	--	--	Sg
Cement																			
39	N.A.	N.A.	N.A.	< 0.05	< 0.05	< 0.05	27,000	100	--	--	100	--	--	100	--	--	Int	--	Ug
Both																			
40	N.A.	N.A.	N.A.	0.11-0.5	0.11-0.5	0.11-0.5	400,000	30	35	35	35	35	30	35	35	30	Id	Ug	Sg †
41	N.A.	N.A.	N.A.	0.11-0.5	0.11-0.5	0.11-0.5	212,500	35	50	15	55	15	30	55	35	10	Sg	Id, Ug	Np
42	N.A.	N.A.	N.A.	0.11-0.5	0.11-0.5	0.11-0.5	445,000	10	80	10	10	80	10	10	80	10	Int, Id, Sg, Np	Ug	--
43	N.A.	N.A.	N.A.	In-house research is done mostly for instructional purposes.															

† Totals over 100%; reason unknown.

* F - Fundamental, exploratory, non-mission-oriented.
M - Mission-oriented; innovative process/product development.
I - Improvement of existing technology.

N.A. - Not applicable

** Fg - Foreign govt.
Fi - Foreign industry
Id - Industrial
Ug - U.S. govt.
Int - Internal
Np - Nonprofit org.
Sg - State govt.

‡ Values in parentheses estimated from previous column

‡‡ Not accurate: exceeds cement/concrete R&D total.

TABLE 8 (continued)

FINANCIAL DATA -- NONPROFIT ORGANIZATIONS

Number	Total Gross Sales (million $)			Total R&D Expenditures (million $)			Avg. Annual Expenditure	R&D Expenditures on Various Types of Research (%)									Sources of 1977 R&D Funding**		
								1975			1976			1977					
	1975	1976	1977	1975	1976	1977	1973-1977 ($)	F*	M*	I*	F*	M*	I*	F*	M*	I*	< 35%	35-70%	> 70%
Concrete																			
44	N. A.	N. A.	N. A.	1.1-1.2	0.9-1.0	1.1-1.2	100,000	5	60	35	5	60	35	5	60	35	Sg	Int, Ug	--
45	N. A.	N. A.	N. A.	< 0.05	< 0.05	< 0.05	4,000	--	--	100	--	--	100	--	--	100	Int	--	--
46	N. A.	N. A.	N. A.	< 0.05	--	--	100,000	--	70	30	--	70	30	--	70	30	--	--	Int
47	N. A.	N. A.	N. A.	0.05-0.10	0.05-0.10	0.05-0.10	80,000	--	50	50	--	55	45	--	60	40	--	--	Int
48	N. A.	N. A.	N. A.	0.05-0.10	0.05-0.10	0.05-0.10	80,000	50	50	--	20	80	--	10	90	--	--	--	Int
49	N. A.	N. A.	N. A.	< 0.05	< 0.05	< 0.05	20,000	80	--	20	80	--	20	80	--	20	--	--	Int
Both																			
50	N. A.	N. A.	N. A.	--	--	--	--	10	80	10	10	70	20	10	60	30	Int	Id, Ug	--
51	N. A.	N. A.	N. A.	2.5	2.8	3.3	2,500,000	21	61	18	20	64	16	23	62	15	Id	Int, Ug	--
52	N. A.	N. A.	N. A.	0.11-0.5	0.05-0.10	0.05-0.10	114,000	--	100	--	--	100	--	--	100	--	--	--	Ug

* F - Fundamental, exploratory, non-mission-oriented.
M - Mission-oriented; innovative process/product development.
I - Improvement of existing technology.

** Fg - Foreign govt.
Fi - Foreign industry
Id - Industrial

Int - Internal
Np - Nonprofit org.
Sg - State govt.

Ug - U. S. govt.

N. A. - Not applicable

TABLE 8 (continued)

FINANCIAL DATA -- GOVERNMENT

Number	Total Gross Sales (million $)			Total R&D Expenditures (million $)			Avg. Annual Expenditure 1973-1977 ($)	R&D Expenditures on Various Types of Research (%) 1975			1976			1977			Sources of 1977 R&D Funding**		
	1975	1976	1977	1975	1976	1977		F*	M*	I*	F*	M*	I*	F*	M*	I*	< 35%	35-70%	> 70
Concrete																			
53	N.A.	N.A.	N.A.	0.09	0.09	0.09	85,000	--	50	50	--	50	50	--	50	50	Int	Ug	--
54	N.A.	N.A.	N.A.	0.18	0.13	0.13	170,000	--	95	5	--	95	5	--	95	5	--	--	Ug
55	N.A.	N.A.	N.A.	1.1-10	1.1-10	1.1-10	1,000,000	--	50	50	--	50	50	--	50	50	Sg	--	Ug
56	N.A.	N.A.	N.A.	< 0.05	< 0.05	< 0.05	18,600	--	75	25	--	50	50	--	55	45	--	Ug, Sg	--
57	N.A.	N.A.	N.A.	1.1-10	1.1-10	1.1-10	2,400,000	--	50	50	--	50	50	--	50	50	Sg	--	Ug
58	N.A.	N.A.	N.A.	< 0.05	< 0.05	< 0.05	10,000	15	75	10	15	5	80	15	5	80	Int	--	Ug
59	N.A.	N.A.	N.A.	1.1-10	1.1-10	1.1-10	2,000,000	10	40	40†	10	40	40†	10	40	40†	Sg	--	Ug
60	N.A.	N.A.	N.A.	0.11-0.5	0.11-0.5	0.11-0.5	200,000	--	65	35	--	65	35	--	50	50	--	--	Ug
61	N.A.	N.A.	N.A.	0.11-0.5	0.11-0.5	0.11-0.5	400,000	--	75	25	--	75	25	--	75	25	--	Int, Ug	--
62	N.A.	N.A.	N.A.	< 0.05	< 0.05	< 0.05	16,000	--	100	--	--	100	--	--	100	--	Sg	--	Ug
63	N.A.	N.A.	N.A.	< 0.05	0.05-0.10	0.05-0.10	75,000	--	60	40	--	70	30	--	60	40	--	--	Int, Ug‡
Cement																			
64	N.A.	N.A.	N.A.	0.6-1.0	0.6-1.0	1.1-10	500,000	--	50	50	--	50	50	--	50	50	--	--	Ug
Both																			
65	N.A.	N.A.	N.A.	0.5-1.0	0.5-1.0	0.5-1.0	550,000	--	100	--	--	100	--	--	100	--	--	Int, Ug	--
66	N.A.	N.A.	N.A.	0.05-0.10	0.05-0.10	0.05-0.10	200,000	10	10	80	10	10	80	10	10	80	--	Ug, Sg	--
67	N.A.	N.A.	N.A.	0.11-0.5	0.11-0.5	0.6-1.0	400,000	--	100	--	--	100	--	5	95	--	Int	--	Ug
68	N.A.	N.A.	N.A.	< 0.05	0.05-0.10	0.05-0.10	75,000	100	--	--	100	--	--	100	--	--	--	--	Int
69-1	N.A.	N.A.	N.A.	0.11-0.5	< 0.05	< 0.05	36,000	--	50	50	--	50	50	--	50	50	--	--	Int
69-2	N.A.	N.A.	N.A.	0.11-0.5	0.11-0.5	0.11-0.5	200,000	--	50	50	--	50	50	--	50	50	--	--	Ug
69-3	N.A.	N.A.	N.A.	0.05-0.10	0.05-0.10	0.05-0.10	100,000	--	50	50	--	50	50	--	50	50	--	--	Ug
69-4	N.A.	N.A.	N.A.	1.1-10	1.1-10	1.1-10	2,750,000	--	50	50	--	50	50	--	50	50	--	Ug, Sg	--
69-5	N.A.	N.A.	N.A.	1.1-10	1.1-10	1.1-10	5,000,000	10	50	40	10	50	40	10	50	40	Sg	--	Ug

† Totals less than 100%; reason unknown.

‡ Totals over 100%; reason unknown.

N.A. - Not applicable

* F - Fundamental, exploratory, non-mission-oriented.
M - Mission-oriented; innovative process/product development.
I - Improvement of existing technology.

** Fg - Foreign govt.
Fi - Foreign industry
Id - Industrial
Int - Internal
Np - Nonprofit org.
Sg - State govt.
Ug - U.S. govt.

INSTITUTIONAL AREAS OF CONCERN WITH CEMENT AND CONCRETE

The variety of institutional "products," topics, or other activities reported by the respondents was broad, and a comprehensive categorization would be unwieldy; the questionnaire summary itself presents the details. However, it may be useful to point out some of the subjects most frequently cited as the areas receiving most attention of the particular institution (Table 9).

TABLE 9 Subjects Most Frequently Cited in Questionnaire Responses

Code	Subject	Times Cited
1a	Cement Processing	4
3a	Concrete Aggregates	4
1a	Cement Raw Materials	3
1n	Oil Well Cements	3
1q	Special Cements	3
5a	Concrete Bridges	3
5b	Concrete Buildings	3
5c	Cast-in-Place Concrete	3
5l	Concrete Pavements	3
4e	Concrete Strength (Fatigue)	2
4l	Concrete Durability	2
6b	Fibers, Concrete Reinforced	2

Other major areas were cited also; however, many were not specific, merely serving to distinguish the major activity as "cement" or "concrete." No individual topic was cited a large number of times, and this broad range of topics reflects the diversity and complexity of the cement and concrete research fields.

FINANCIAL STATUS OF R&D

The questionnaire was designed to solicit information reflecting the extent of activity and capability of the cement and concrete R&D establishment. The following analysis (Table 10) summarizes briefly the financial data reported by about 70 institutions or agencies (returned in response to 195 questionnaires sent out).

A number of governmental establishments included in the data base, such as the Federal Highway Administration (FHWA), contract a major portion of their R&D funds to state agencies, universities, private industry, and not-for-profit agencies, further increasing the duplications in the listing. According to one tabulation, only 5.5 percent of total cement- and concrete-related R&D funds administered through FHWA were spent in-house; the rest were contracted, so added only a small portion to the totals in Table 10.

In addition to the above questionnaire-generated information, the committee received the following information from the National Science Foundation (NSF) on its research sponsorship. An annual average funding for cement and concrete research (emphasizing fundamental research, predominantly on concrete) for a five-year period (FY74-FY78) was $1.7 million* with an average

* NSF financial support data supplied through the courtesy of C. A. Babendrier.

TABLE 10 Annual Cement and Concrete R&D Expenditures Averaged Over Five Years (1973-1977)

	Number of Institutions	% of Institutions	Average Expenditure ($1,000)
	3	4.6	> 1,000
	6	9.2	401-1,000
	17	26.1	101-400
	11	16.9	51-100
	26	40.0	1-50
	2	3.0	unknown
Total	65	99.8*	$15,266,000 (avg./institution $235,000)
Dual Listings**	5		> 1,000 (total expenditure $13,150,000) (avg./institution $2,630,000)

* Does not total 100 percent due to rounding.
** Number of institutions or agencies having dual listing of entries (not included above).

grant of $89,000. A large portion of the funding was provided to institutions that responded to the questionnaire, and hence are included in the data of Tables 8 and 10.

Similar data were supplied for 10 different divisions of the Department of Energy (DoE).* This R&D was identified almost entirely as problem-oriented research, amounting to $5.4 million for FY78 Most would be similarly included in the data of Table 10. The projects include a number of large-scale operations, pilot-plant size, or process developments. The average size of the individual grant or contract, about $206,000, thus was larger than from NSF.

It is difficult to discern precisely, from the total R&D expenditures in all the listings above, those portions that are properly identified as fundamental research from those that are intermediate-range mission-oriented R&D and from those that truly are devoted to technological development. This occurred despite the fact that such a break-down was requested from the questionnaire respondents. For example, from the answers given in response to "Areas of Needed Research" solicited in Part III, it is obvious that a number of respondents designated items of needed research to be "fundamental" which would in the opinion of the committee members be placed in the "problem-oriented" category. It is clear that fundamental research in all estimates constitutes a relatively small portion, perhaps 10 percent of the total. The actual estimated figures denote $1.78 million out of $15.3 million (11.6 percent) which would be further diminished by the inflating factors discussed above. A number of the projects funded through agencies such as the Federal Highway Administration include costly large-scale engineering projects and are properly categorized as technological development activities.

Further evident is the fact that the vast majority of R&D for cement and concrete is supported by governmental funds, primarily derived from U.S. government agencies. This includes all the research listed in the "government" portion of financial data, the major portion of university R&D, a significant portion of not-for-profit agencies, and even a part of the industrial support.

The list of questionnaire recipients was biased toward those expected to be carrying out significant research, but this was by no means comprehensive. To the knowledge of the committee, several major universities believed to be carrying out significant research (probably in amounts of

* DoE financial support data supplied through the courtesy of R. R. Reeber.

more than $100,000) failed to reply. There were notable absences of responses from among the cement manufacturing companies. Essentially all the chemical admixture companies were included as well as oil well cementing* companies, plus aggregate and reinforcement industries; a number of which did not respond. Thus the results can by no means be construed to be accurate for total dollar figures. However, the inflating factors and duplications probably more than offset omissions from lack of response when projecting a total dollar figure spent for R&D.

One additional conclusion is that by far the largest number of the institutions reporting R&D activity (40 percent) were funded in amounts of less than $50,000 per annum; many far less. This is believed by the committee to be far too small to form the "critical mass" necessary to carry out appropriate fundamental research. While it may be possible for an establishment that is devoted principally to mission-oriented research and technological development to accomplish worthy fundamental research by setting aside a relatively small portion of its effort for fundamental research, it is doubtful that breakthroughs or even effective problem solving can take place in grossly underfunded institutions that have inadequate continuity of funding for personnel and equipment.

GENERAL OBSERVATIONS FROM THE QUESTIONNAIRE

The relatively small questionnaire return (69), despite several reminders, limited the type of conclusions that could be drawn from the responses. Nevertheless, it was possible to demonstrate internal consistency, e.g., correlation of number of R&D employees with the annual expenditure level.

As would be expected, the universities show a larger proportion of fundamental research effort, while industry, government, and not-for-profit organizations show a predominance of effort devoted to either mission-oriented R&D or to the improvement of existing technology. Similarly, the educational level of university researchers was generally higher than in the other institutions, but there are enough exceptions that even this correlation is not overwhelming.

SUMMARY OF DATA, PART III OF QUESTIONNAIRE

Tables 11 through 17 represent compilations of replies from cognizant staff in private corporations, professional groups, universities, and government. The compilation for each table is arranged in descending order of frequency of interest. Where there were more than 100 suggestions, the frequency of a particular type of suggestion is in terms of percentages; otherwise, the actual number is given. While these tables do not necessarily indicate where immediate R&D action in cement and concrete is needed, they do indicate common areas of thinking among people in the industry.

The areas where knowledge was perceived to be needed, or where opportunities or problems in cement and concrete were anticipated in the next 10 to 20 years, are represented in Tables 11, 12 and 13. A combined 38 percent of the answers indicated that knowledge will be needed to understand the mechanism of hydration, the rheology of concrete, and the chemistry of interaction between cements and admixtures. Opportunities in the use of uncommon aggregate sources, or the use of blenders, or the development of special application concretes are shown to be the thinking reflected in a combined figure of over 50 percent of the answers in the second category. Nearly 40 percent of the answers indicated that greater energy conservation, better waste disposal methods, or tighter quality controls will present problems in the near future.

Table 14 indicates where major innovations are thought to be needed. About 50 percent of the latter answers are concerned with innovations that would result in economies in the processing and use of cement and concrete.

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* The response rate was highest from government agencies, while an approximately equal response rate, but lower than the government rate, was received from university, nonprofit, and industrial organizations.

TABLE 11 Summary of Responses, Part III of Questionnaire -- Areas of Knowledge

Areas of Knowledge in Cement and Concrete Which Will Be Most Important within the Next 10 to 20 Years	% of Total Comments
Concrete rheology and influencing factors such as rate of hydration, admixtures, air voids, and composition	22
Chemistry and mechanism of interaction between cements and admixtures	11
Development of high strength and high early strength concrete	11
Partial substitution of other components for portland cement	6
Usage of concrete aggregates from unconventional sources including recycled and marginal material	5
Nondestructive and rapid testing techniques for quality control and performance predictions	5
Mechanism of crack propagation and failure modes	4
Load carrying (dynamic, cyclic) mechanism of concrete members	4
Utilization of waste materials in cement production	2
Reduction of energy requirements in cement and concrete production	2
Improved thermal insulation characteristics and impermeability of concrete	2
Structural behavior of prestressed concrete members	2
New types of pozzolans as binders in concrete	2
New fibers for reinforcement of concrete and mortars	2
Environmentally acceptable methods for waste disposal	1
Mechanism of deterioration of concrete in harsh environments	1
Utilization of fly ash and alkali-aggregate reactivity	1
Development of super-lightweight concrete members	1
Behavior of concrete in hydrostatic applications	1
Impact and earthquake resistant concrete	1
Other areas each less than 1 percent of total number of comments	14
	100

NOTE: Total number of comments = 175 (some respondents submitted more than one comment).

TABLE 12 Summary of Responses, Part III of Questionnaire -- Areas of Opportunities

Areas of Opportunities in Cement and Concrete Which Will Be Most Important within the Next 10 to 20 Years	% of Total Comments
Utilization of industrial wastes and synthetic and marginally acceptable aggregates, in cement and concrete production	9
Production of higher strength and high early strength concrete	7
Development of earthquake resistant, fire resistant, impact resistant concretes	7
Combined blenders in cements and increased use of industrial wastes and pozzolans	6
Improved techniques in clinker burning efficiency	6
Production of lighter weight and higher density impermeable concretes	6
Improvements in material properties, crack resistance, and ductility of concrete	6
Increased usage of fiber reinforcement in concrete	5
Development of more low-shrinkage and expansive cements and low- or high-creep concretes for special applications	4
Wider usage of concrete polymers and polymer impregnation techniques	4
Better nondestructive testing and quality control techniques for cement and concrete	4
Improvements in concrete placement methods and properties of materials for field and offshore work	3
Development of high temperature resistant and low temperature resistant concretes for special applications	2
Relaxation of restraints in usage of high-alkali content cements with reactive aggregates	2
Further developments in high-slump low-water content concrete and low slump workable concrete for special applications	2
Simplification of the cement manufacturing process	2
Improvements in rapid patching and repair techniques for concrete structures	2
Advances in the technology of precasting and prefabrication	2
Application of masonry walls as solar panels and the design of energy efficient building envelopes	1
Increased understanding and simulation of the hydration mechanism	1
Other areas each of less than 1 percent of the total number of comments	19
	100

NOTE: Total number of comments = 224 (some respondents submitted more than one comment).

TABLE 13 Summary of Responses, Part III of Questionnaire -- Areas of Problems

Areas of Problems in Cement and Concrete Which Will Be Most Important within the Next 10 or 20 Years	% of Total Comments
Greater pressures to reduce energy or to find new sources of energy in cement and concrete production	11
Inadequate quality control and quality assurance for cement and concrete products	11
Waste disposal problems and the need to utilize industrial wastes for cement manufacture, solidify wastes for placement in disposable containers, restore the land and control pollution	7
Definitive jointing techniques for precast and prestressed concrete units	7
Need for efficient procedures in mixing, placing, finishing, and curing concrete	5
Advanced methodology for predicting alkali-aggregate reactivity and the properties of concrete with admixtures and fly ash	5
More durable concrete that can withstand corrosive environments	4
More efficient design methodology and ratings for containment vessels subjected to thermal shock and thermal expansion	4
Need to optimize blending of cements to reduce cement and concrete variability	4
Quicker, dependable tests for organic material, cement content, wear resistance, and sulfate content in concrete products	3
Increasing need for better shrinkage compensating and expansive cements	2
Greater development of waterproof, fireproof, thermally nonconductive, and lightweight concretes	2
Problems related to the need for better technology in polymer impregnation of concrete	2
More applications for fiber concrete and the need for more sophisticated technology	2
Not enough performance specifications, thereby inhibiting flexibility for innovative techniques	2
Lack of sufficient understanding of concrete failure mechanisms	2
Insufficient understanding of concrete creep behavior in space frames, pavements, and in other structural applications	2
Need for better dissemination of technology and for liaison between research groups and industry	2
Wider application of superplasticizers in concrete production	2
Needed improvements in the bonding characteristics of grouts and grouting techniques	2
Faster and more effective repair and patching methods for concrete	1
Insufficient understanding of the effects of particle size and distribution on concrete properties and performance	1
Other areas each of less than 1 percent of the total number of comments	16
	99*

NOTE: Total number of comments = 167 (some respondents submitted more than one comment).

* Does not total 100 percent due to rounding.

TABLE 14 Survey of Responses, Part III of Questionnaire -- Major Innovations Needed

Areas in Which Major Innovations Are Needed	% of Total Comments
Economical development and design application of new higher strength concretes	9
Nondestructive and accelerated strength testing of concrete together with reliable quality control techniques	8
Fuel efficiency and alternative fuel sources for cement processing along with energy reductions in producing concrete products	8
Cost effective techniques in mixing, handling, placing, finishing, and grinding concrete	6
Natural aggregate substitutes such as marginal, synthetic, and waste materials	5
Use of blending materials such as slag and fly ash to effect economies in the use of cement	4
Chemical and corrosion resistance of concrete and coatings at high temperatures	4
Methods to increase the durability of concrete such as in bridge-deck applications	4
Fast and effective repair and patching of concrete	4
Performance prediction methodology for 20- to 30-year periods	3
Modeling of concrete constitutive behavior and of massive structures from laboratory specimens	3
Development of shrink-free, crack-free and creep-free concretes	2
Light-weight concretes with high elastic limits and greater earthquake resistance	2
Cement-pricing policy	2
Quick-curing concrete and innovations in the curing procedure	2
Control of the hydration process	2
Increases in the bond strength for aggregate and concrete overlay applications	2
Organic fibers for concrete reinforcement	1
Polymer concrete	1
Cooperation between government and industry	1
Development of moisture content tests and a coefficient of moisture expansion	1
Other areas each of less than 1 percent of total number of comments	24
	98*

NOTE: Total number of comments = 141 (some respondents submitted more than one comment).

* Does not total 100 percent due to rounding.

TABLE 15 Survey of Responses, Part III of Questionnaire -- Major Accomplishments

Major Accomplishments in Cement and Concrete within the Last Five Years	% of Total Comments
Polymer concrete	10
Super-water-reducers and super-plasticizers	10
Earthquake-resistant concrete structures	6
Usage of concrete for nuclear reactor vessels, offshore drilling platforms, and geothermal steam wells	6
Increase in knowledge of role of mineral composition, pozzolans, and admixture combinations to effect reductions in concrete cost and increase in strength potential	6
Complex precast and prestressed concrete technology along with jointing techniques	5
High strength concrete	4
Expansive cements	4
Quality control methods including X-ray techniques and rapid strength tests	4
Computer usage in concrete structural design along with computerized cement and concrete production facilities	4
Advances in understanding fatigue failure mechanism, crack growth, D-cracking phenomenon, and concrete creep	4
Concrete sealing including the use of membranes and wax beads	4
Fiber concrete	3
Development of preheater and precalciner kilns	3
Advances in modeling the inelastic behavior of concrete	3
Energy reductions by increased operating efficiency of kiln systems	3
Development of concrete railroad ties	2
Set controlled and quick set cements	2
Concrete-forming, especially slip-forming, techniques	2
Design methodology for sound absorption and fire protection	2
Other areas each of less than 1 percent of total number of comments	13
	100

NOTE: Total number of comments = 108 (some respondents submitted more than one comment).

TABLE 16 Survey of Responses, Part III of Questionnaire -- Areas of Sufficient R&D

Areas in which Sufficient R&D Has Already Been Accomplished	Number of Comments
Not sufficient R&D in any areas	13
Basic creep properties and elastic properties	5
Conventional materials in plain masonry and mass concrete	4
Work on additives without basic information on the chemistry of cement	2
Freeze-thaw durability in de-icing chemicals	1
Kinetics of crystallization of calcium silicates	1
Conventional erosion resistance in non-aggressive environments	1
Cementitious potential of slag and fly ash without implementation	1
Cement dispersant technology	1
Arctic cementing materials	1
Highway-related research	1
Conventional fiber concrete	1
Water/cement ratio	1
Radiation effects on concrete	1
Sound transmission by concrete	1
Reinforcement by prestressed tendons or conventional steel	1
Polymer concrete expect refinements	1
Empirical testing	1
Equilibrium phase relationships (lime, alumina, silicate system)	1
Clinker crystal structure except for innovative ends	1
Concrete curing	1
	41

TABLE 17 Survey of Responses, Part III of Questionnaire -- Government Laws, Rules and Regulations

Government Laws, Rules, Regulations Which Should Be Eliminated, Added to, or Changed to Encourage Research, Development or Innovation	Number of Comments
Increase tax incentives	14
Changes in standards:	6
Use of performance specifications rather than restrictive ones in order to encourage innovations (3)	
Other changes (3)	
Specify the utilization of innovative products and techniques or the recycling of waste products in procurement policy	6
Promote corporate collaboration in research, including by liberalizing antitrust legislation	4
Emphasize importance of basic research rather than strictly specific problem solving research	3
Clarify regulations and remove red tape	3
Foster research program continuity by long-term budgeting policy	2
Other comments	11
	49

The development of special-purpose concretes and additives (noted in nearly 50 percent of the answers summarized in Table 15) was cited as the major accomplishment in the past five years. This development is connected with increases in concrete durability and workability.

Many respondents did not comment on whether sufficient R&D has been performed in any area. As indicated in Table 16, of 41 relevant comments, 13 express belief that sufficient work has not been done in _any_ area. Thirty percent of the remainder think that sufficient work has been done in basic stress-strain behavior and on conventional concrete products.

Only about 25 percent of the respondents commented on what the government should do to encourage R&D activity. Table 17 shows that the largest set of responses reflects a belief that tax laws should be changed to provide greater tax incentives for R&D. Others believe that government procurement policy should be changed toward greater use of performance specifications and toward providing specific requirements for innovative approaches.

REFERENCE

Business Week (1977). "What 600 Companies Spend for Research," June 27, pp. 62-84.

Appendix C

CEMENT AND CONCRETE RESEARCH AND DEVELOPMENT CENTER

Among the possible options available for remedying some of the inadequacies of the current level of cement and concrete research in the United States is the formation of an independent cement and concrete R&D center. Such a center, supported by long-term government and industrial grants and not dependent on short-term project funding might make a major contribution to solutions of many of the problems uncovered in this report.

While detailed planning for such a center was considered by the committee to be beyond its scope, concepts developed by interested members and especially by government liaison representatives to the committee include the following:

- A basic research institute, housed in its own space, perhaps on or adjacent to a university campus, employing a small permanent professional and support staff and a rotating staff of postdoctoral fellows. Provision for a few senior visiting fellows serving short-term (six months or a year) appointments might also be made.

- As part of the overall institute, a small contract management center with a few permanent staff members supplemented by rotating industrial staff people from the cement and concrete industries, primarily to do applied research on contract.

- An applications center, oriented more toward engineering rather than basic research, devoted to furthering application of new developments and advanced technology in the cement and concrete industries.

- A small training institute for cement and concrete technicians.

As envisaged, the overall center would be run by a permanent director reporting to a board of directors representing industry, government, and academic interests. An advisory council to the board might be organized, the members being prominent persons broadly representative of the public interest.

Such a center could be funded from long-term government grants supplemented by industrial funds; eventually some supplemental funding might come from contract research activities and patent sales and licensing fees.

It is hoped that such an institution could eventually develop into a major international center for research and applications of technology in the cement and concrete areas. The provision for rotating and visiting staffs (some of whom might come from abroad) and for training facilities should be instrumental in assisting transfer of new technological developments to American practice, while the basic research center should stimulate necessary re-emergence of U.S. involvement in fundamental research in this area.

Appendix D

GUEST CONTRIBUTORS TO THE STUDY

Guest participants contributing to this report were:

Tutorial Session of February 13, 1978

Geoffrey Frohnsdorff, National Bureau of Standards, "Status of R&D in Cement and Blended Cements: A Government Viewpoint"

Roy A. Grancher, Rock Products magazine, "Economics of the Cement Industry: Current Status Relative to Problems and Needs"

Jack Janney, Wiss, Janney, Elstner & Associates, "Current Status of R&D in Concrete: A Construction Industry Viewpoint"

Bryant Mather, U.S. Army Engineers Waterways Experiment Station, "Current Status of R&D in Concrete: A Government-User Viewpoint"

Louis U. Spellman, Atlantic Cement Co., Inc., "Current State of the Cement Industry: Commercial Problems and R&D Needs"

Tutorial Session of March 28, 1978

Gunnar M. Idorn, Consultant, formerly of Aalborg Portland, Copenhagen, Denmark, "Worldwide Activity of R&D in Cement and Concrete: A Survey of the Economics and Philosophy"

Nathan R. Greening, Portland Cement Association, "R&D Needs from the Viewpoint of Cement Composition Considerations"

Bernard L. Meyers, Bechtel Power Corporation, "R&D Needs from the Concrete Structures Viewpoint"

Richard C. Mielenz, Master Builders Division, Martin Marietta Corporation, "R&D Needs in Concrete from the Perspective of the American Concrete Institute and the Admixtures Manufacturer"

Horst Ritzmann, Polysius Corporation, "Recent Developments in Cement Kiln Processing Systems: Implications of R&D Needed in the U.S."

W. E. (Gene) Corley, Portland Cement Association, "Status of R&D in Concrete: New Challenges"

Arthur R. Anderson, ABAM Engineers, Inc. and Ben C. Gerwick, Professor of Civil Engineering, the University of California at Berkeley, contributed their thoughts on various issues and offered editorial comment on segments of the committee report, although unable to participate directly in the committee activities.