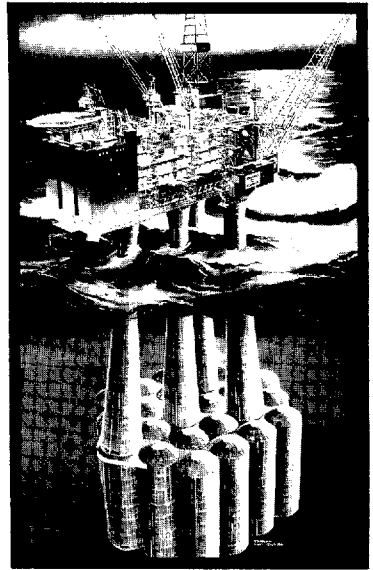


CONCRETE TECHNOLOGY PAST, PRESENT, AND FUTURE

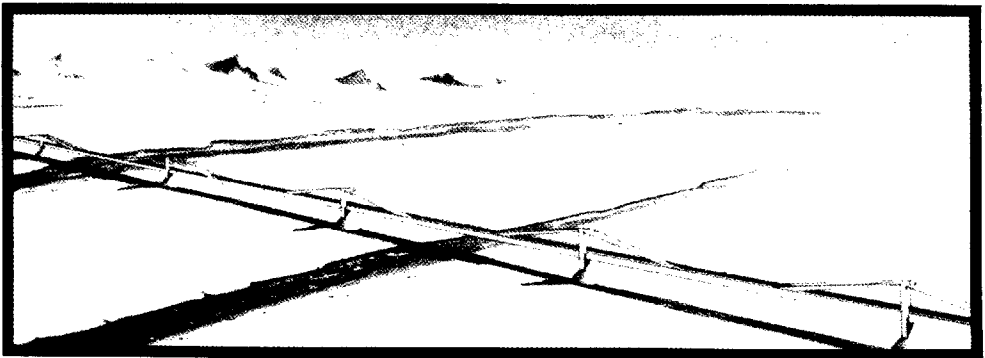
Proceedings of
V. Mohan Malhotra Symposium



**Eddystone Lighthouse
1756**



**World's Largest Offshore Platform
Gulfaks C — 1989**



Concept of Inter-Continental Peace Bridge Linking Alaska and Siberia

P. Kumar Mehta
Editor

AA Documents
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CONCRETE TECHNOLOGY PAST, PRESENT, AND FUTURE

Proceedings of
V. Mohan Malhotra Symposium

American Concrete Institute, Detroit
SP-144

COVER CREDITS

Eddystone Lighthouse, built in 1756 by the British engineer, John Smeaton (reproduction of a painting made by the Danish artist, Anton Melbye).

* * * * *

Gullfaks C, the world's largest offshore concrete platform, was installed in 1989. It contains 240,000 cubic meters of high-strength concrete (70 MPa) and 70,000 tons of reinforcing steel. Being the largest man-made structure ever towed, the displacement during tow was 1,500,000 tons (photograph, courtesy of J. Moksnes, Norwegian Contractors).

* * * * *

The idea to build a bridge across the Bering Strait, linking Alaska with Siberia, was originally presented by Professor T.Y. Lin to President Ronald Reagan. The bridge, with 220 spans of 1,200 feet length each, is expected to require over three million cubic yards of lightweight concrete and five million cubic yards of normal-weight concrete (concept illustrated by Peter Fu).

DISCUSSION of individual papers in this symposium may be submitted in accordance with general requirements of the ACI Publication Policy to ACI headquarters at the address given below. Closing date for submission of discussion is January 1, 1995. All discussion approved by the Technical Activities Committee along with closing remarks by the authors will be published in the May/June 1995 issue of either ACI Structural Journal or ACI Materials Journal depending on the subject emphasis of the individual paper.

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PREFACE

Eighteen review papers and twelve research papers are included in the Proceedings of the Mohan Malhotra Symposium on Concrete Technology: Past, Present, and Future. The purpose of the Symposium was to serve as a forum for discussion on the current state of the concrete industry and technology, and to identify important issues that need to be addressed in the future. A quick look at the table of contents will show that a wide range of topics is covered by contributions from well-known authors in the field of concrete technology.

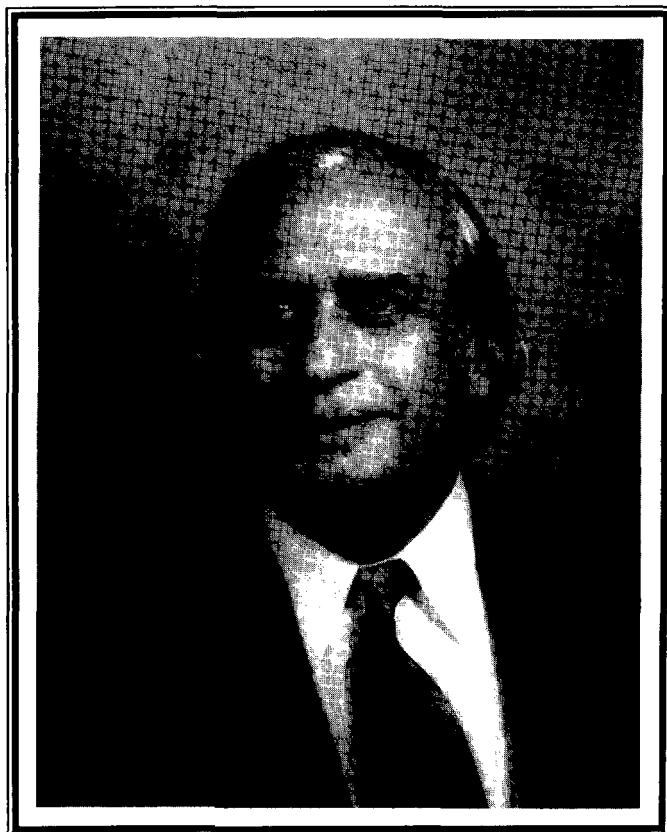
The first four papers of the Proceedings contain an overview of the concrete technology today, and the forces that are shaping tomorrow's world. Since many concrete structures are being exposed to severe environmental conditions, premature deterioration of concrete has emerged to be a matter of major concern. Three state-of-the-art papers and seven research papers address some of the critical issues in durability. Noteworthy for their originality are the research papers on interactive modeling of the causes of concrete deterioration, and mathematical modeling of concrete durability.

There are two comprehensive papers on trends in construction technology: one concerning off-shore and marine structures, and the other on roller compacted concrete for dams. Eight papers highlight the concrete materials and products for the future, including new cements, superplasticizers, mineral admixtures, reinforcing fibers and polymers. Of special note is a highly ductile and very high strength product (up to 800 MPa) based on an innovative, although expensive, technology. Among the remaining six papers of the proceedings, one deals with the history and trends in the methods of proportioning concrete mixtures, and five discuss testing methods and quality assurance. The last paper, "Nondestructive Testing of Concrete: History and Challenges," has the distinction of being the most comprehensive document on the subject in recently published literature.

The proceedings of the Mohan Malhotra Symposium, which excel for the variety and richness of information contained in the 30 papers, reflect the respect and admiration of the authors for the honoree. As a researcher, scholar, and technology-transfer crusader, Mohan has undoubtedly made unique contributions to the concrete technology. It would indeed be a fitting tribute to him if the deliberations of the Mohan Malhotra Symposium are able to make a significant impact in preparing the concrete industry for the 21st century.

University of California, Berkeley
3 November, 1993

P. Kumar Mehta
Symposium Co-Chair, and Editor



V. Mohan Malhotra

BIOGRAPHICAL SKETCH OF V. MOHAN MALHOTRA

V. Mohan Malhotra received his B.Sc. degree from the University of Delhi, India, and B.S. in Civil Engineering from the University of Western Australia, Perth. Since 1962 he has been with his present employer, Canada Center for Mineral and Energy Technology (CANMET), where he is at present the Principal of the Advanced Concrete Technology Program.

Dr. Malhotra has made outstanding contributions to many areas in concrete technology, such as testing, materials, and education. He is particularly known for his original research in accelerated strength testing, nondestructive testing, and development of the ring-tension apparatus for determining the tensile strength of concrete. He has made original contributions to utilization of industrial by-products by the concrete industry, for example by-product sulfur, fly ash, metallurgical slags, and silica fume. His latest work, leading to the discovery of high strength and durable concrete products containing large volumes of fly ash, is of considerable global significance because of its economic, energy, and environmental implications. Besides numerous technical papers authored or co-authored by him, he has edited 12 special publications for the ACI. In recognition of his valuable contributions, the University of Dundee, Scotland, honored him by awarding the Honorary Degree of Doctor of Laws in 1984.

Dr. Malhotra's record of professional service is equally impressive. A member of the ACI since 1960, he has actively participated in the Institute's affairs in various capacities, which is evident from the many awards and honors received by him. In 1977 he received the Chapter Activities Award; in 1978 the Kennedy Award for promotion of ACI activities, and the Wason Award for materials research; in 1983 the Turner Medals and the Bloem Distinguished Service Award for outstanding service to the concrete industry. In 1986, he was elected as an Honorary Member of the Institute, the youngest member to be so honored. In addition to his service to the ACI, Dr. Malhotra is also active with the technical committees of ASTM, Canadian Standards Association, RILEM, and International Standards Organization.

As the Chairman of the Organizing Committee of CANMET/ACI International Conferences on Concrete Technology, Dr. Malhotra has become world renowned for the role these conferences have played in technology transfer. His unique organizational skills and his ability to select hot topics for the concrete industry are universally admired. Since 1978, he has organized three conferences on superplasticizers, four on mineral admixtures, and four on concrete durability aspects. Consequently, in the world of concrete technology, Dr. Malhotra is not only respected as a sound researcher and a prolific author, but also as an expert in technology transfer.

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Concrete Technology at the Crossroads—Problems and Opportunities

by P.K. Mehta

Synopsis: The future of the concrete industry appears to be bright from projections based on current trends in population growth, and increasing industrialization and urbanization. However, this optimism must be tempered with changing attitudes in the society on ecological issues such as conservation of natural resources, durability of engineering materials, and environmental pollution. Due to the increasing public concern with durability of concrete as a construction material, this subject is discussed in detail with reference to deficiencies in the science of concrete durability, methods of testing for quality assurance and service-life prediction, and education in concrete technology.

Keywords: Air pollution; concrete technology; conservation; deterioration; durability; education; models; quality assurance; research; service life; urban development; waste management.

2 Mehta

P. Kumar Mehta is Professor Emeritus in the Civil Engineering Department at the University of California at Berkeley. He is the author or coauthor of numerous papers on cementitious materials and properties of concrete including a textbook on the subject. A Fellow of the American Ceramic Society and the American Concrete Institute, he has received several awards including the ACI's Wason Medal for materials research, CANMET/ACI award for outstanding contributions to research on performance of concrete in the marine environment, and Mohan Malhotra Award for research on supplementary cementing materials. He holds the Roy Carlson Distinguished Professorship in Civil Engineering at Berkeley, and has recently received the highest campus honor, the Berkeley Citation, for exceptional contributions to his field and to the university.

1. INTRODUCTION

We are at the crossroads. In a few years, a new century will begin and the twentieth century will become a part of history, leaving behind many accomplishments as well as disappointments. This is an appropriate juncture in time to look into the future because, due to a heightened public awareness of energy, resources, and ecological issues, unhindered industrial growth cannot be taken for granted.

Predicting the future is never easy; however, we can always speculate about the future prospects of any industry if we have a clear understanding of current trends in both opportunities and problems before our society. In other words, we can assure a bright future for the concrete industry by bringing its goals into line with the changing needs and aspirations of the society. Accordingly, in this paper, first, some of the changes taking place that are shaping the future world, are described. Next, an overview of the state of the concrete industry and technology today is presented. This is followed by a discussion of the deficiencies in modern concrete technology that must be resolved before the concrete industry can respond effectively to the needs of tomorrow's world.

This subject is not being addressed for the first time. The earliest report "Concrete - Year 2000," was published 23 years ago.¹ Among the recent are a paper by Neville,² and the proceedings of an international symposium held last year at University of Dundee, Scotland.³ It would indeed be a fitting tribute to Mohan Malhotra if the deliberations of this symposium in his honor were to make a significant contribution in setting the agenda of the concrete industry and technology for the 21st century.

2. TOMORROW'S WORLD

Compared to the world we inherited at the beginning of the twentieth century, the world at its end is much different. Among the powerful forces that are shaping tomorrow's world and are expected to have a great influence on human attitudes in the future are population growth and urbanization, pollution and waste management, technological innovations and globalization, and a paradigm shift in scientific research. They are briefly discussed below.

2.1 Population Growth and Urbanization

The twentieth century has seen an unprecedented population explosion, mainly as a result of sharp decline in infant mortality due to immunization and availability of antibiotics. For example, during the 50-year period, 1925-1975, the world population rose from 2 to 4 billion. Although the rate of population growth has slowed down significantly in some countries, the overall rate is still so high that the current world population, which is nearly 6 billion, is projected to increase to 9 billion by the year 2025. The search for more food, energy, and other resources to support the additional population means a continuation of pressure for further industrialization. As oceans cover twice as much surface as the combined surface area of the seven continents of the earth, the world is already becoming increasingly ocean-oriented for the recovery of energy and mineral resources. More than 25% of the world's hydrocarbons are being extracted from coastal and offshore deposits. During the last two decades many marine construction projects involving sophisticated structures, such as offshore oil platforms, undersea tunnels, and superspan bridges have been successfully executed. Many more are underway, as discussed by Gerwick and by Hoff at this symposium.

As a result of population growth and industrialization, by the end of this century, for the first time in history, more people will live in and around cities than in rural areas. According to a projection by the United Nations, shown in Table 1,⁴ there will be at least 20 **megacities** with 11 million or more inhabitants in addition to numerous big cities of more than 1,000,000 people. The infrastructure, both new construction and rehabilitated old structures, to support these megacities and big cities, such as buildings for housing and industry, mass transit for moving people and goods, and facilities for handling water and sewage will require large amounts of construction materials.

2.2 Pollution and Waste Management

During the last quarter of this century, many individuals and organizations have contributed to public education on the state of our environment. The U.N. sponsored Earth Summit at Rio de Janeiro in 1992 was a milestone in this regard. Industries causing excessive pollution of air, land, or water are being scrutinized and controlled in many countries of the world. Considerable research is ongoing to develop methods for safe disposal of nuclear and hazardous chemical wastes. In the future, engineers responsible for the

selection of materials will be expected to exercise social responsibility by considering not only the engineering properties and cost but also the ecological friendliness of a material.

That increasing environmental pollution can really become a **serious threat to all industrial growth** is a prospect which is being advanced by many observers from a variety of disciplines. The problem is that, driven by demographic pressure and helped by technology, recently the earth's ecosystem has come under great stress. To support more and more people and to provide better living conditions for most, the engines of the industry for converting raw materials into consumer products must be run faster and faster. Even if the technology is able to find sufficient raw materials or fuel for running the engines of industry, a cost-effective technology neither exists today nor is expected to become available in the near future to remove one bottleneck, namely **the ecologically friendly disposal of all the waste produced by the industrial activity**. For instance, CO₂ emissions from the combustion of hydrocarbons are projected to double by the middle of the 21st century and thus, through the "greenhouse effect," will result in raising the temperature of the environment to a potentially disastrous level. As the United States consumes more than 25% of the world's hydrocarbons, according to the U.S. Environmental Protection Agency, the CO₂ emissions must be rolled back to the 1950s level; otherwise there is little prospect of avoiding global warming.

Environmental pollution from industrial activity is not a new problem. However, according to Kennedy,⁵ the environmental crisis we now confront is quantitatively and qualitatively different from anything before, simply because so many people have been inflicting damage to the world's ecosystem during the present century that the system as a whole - not simply its various parts - may be in danger. The author comments:

The earth, unlike its neighboring planets, is covered with a film of matter called life... Within that film, co-existing alongside plants, animals, insects, crops, and other organisms, is the human race. It assumed the form of *Homo sapiens* some half a million years ago, well after the emergence of many of the other members of the earth's film of life. But because of the human race's growth and its economic activities, it now risks endangering the delicate envelope of matter that makes this planet unique.

2.3 Technological Innovations and Globalization

The recent **revolution in communications and information technologies** is transforming our world into a global village. As a result, the pace of technology transfer has accelerated to an unprecedented rate across both geographical and industrial boundaries. For example, developments in concrete technology in Norway are almost immediately available for use to the concrete industry throughout the world. Similarly, developments in polymer technology are quickly picked up by the concrete industry everywhere. This growing web of

interconnections within and between multinational companies is the cause of rapid globalization of industry, technology, and trade. In general, our socio-economic world is increasingly governed by multinational corporations and international institutions, such as the International Monetary Fund and the World Bank. In recent times, the negative implications of this have been manifested by numerous incidents to show that the global reach of the multinational and international companies is not always matched by their global responsibility.

Two other technological revolutions, **robotics and biotechnology**, with potentially far more serious global consequences than the information technology, are discussed by Kennedy⁵ in his provocative book. The use of robotics in the Japanese industry is spreading. Kennedy cites the example of a radio-cassette recorder factory where 850 industrial robots were installed to reach full production with only 16 employees compared with 340 before the automation. If the robotics revolution spreads worldwide, it would eliminate millions of jobs in factory assembly, manufacturing, and construction industries. Similarly, for the production of basic food products if we replace the currently used farming methods in the agricultural technology with the biotechnological methods under developments in many laboratories, we would cause a serious unemployment problem in the agriculture sector throughout the world.

Kennedy⁵ points out that the robotics technology and biotechnology are driven by the same profit motive in the world market that has propelled technological innovations since the industrial revolution. We now seem to have arrived at a stage in the journey when further advance in the same direction may lead to disastrous results. In the past, the population increase was sustained by corresponding industrial growth because we had seemingly unlimited natural resources to feed the industry and unlimited space on earth to absorb the industrial waste products. Now that the earth apparently has reached the limit of sustainability of industrial development, we will endanger the human civilization if we do not take immediate steps to drastically reduce the rates of population increase and industrial growth, and also strictly control the use of technological innovations that have the potential of causing massive economic and social upheavals. In the remaining sections of this paper, it is assumed that collective human wisdom will somehow intervene and this "worst-case scenario," which has the potential of destroying the human civilization, will not occur.

2.4 Paradigm Shift in Scientific Research

There is no question that society today is enjoying many benefits from the scientific and industrial revolutions. The analytical method of reasoning has become an essential characteristic of modern scientific thinking, and has proved very useful in the development of scientific theories and realization of many spectacular technological achievements. However, an overemphasis on **reductionism in science** -- the belief that all aspects of a complex structure or phenomenon can be fully understood by reducing them to parts -- has led to fragmentation and limitation of knowledge. Professionals in many disciplines are increasingly recognizing this problem.

Commenting on the disadvantages of the reductionist approach, Capra⁶ commented:

"The rational and the intuitive are complementary modes of functioning of the human mind. Rational thinking is linear, focused, and analytical. It belongs to the realm of intellect whose function it is to discriminate, measure, and categorize. Thus rational knowledge tends to be fundamental. Intuitive knowledge, on the other hand, is based on a *direct, non-intellectual experience of the reality arising in an expanded state of awareness. It tends to be synthesizing, holistic, and nonlinear.*"

The term **holistic** from the Greek word "holos," refers to an understanding of a phenomenon or a structure in terms of an integrated whole whose properties cannot be deduced from the sum of the properties of the constituent parts. Capra predicts that this paradigm shift in science will greatly influence the directions of future research in all scientific disciplines.

3. AN OVERVIEW OF THE CONCRETE INDUSTRY AND TECHNOLOGY

In the context of the changing world, as described above, let us take a look at the present state of the concrete industry and technology. This should help us identify the problems and the opportunities lying ahead.

3.1 Demand, Supply, and Materials

Due to well known reasons, such as a low relative cost, easy availability, versatility, adaptability, and adequate engineering properties for many structural applications, portland-cement concrete has already become the most commonly used material of construction throughout the world. The estimated annual cement and concrete production rates are 1.2 and 7 billion tons, respectively. As the component materials for making concrete, namely cement, sand, gravel or crushed stone, water, and admixtures are available in abundance almost everywhere, according to current trends the concrete industry should continue to grow at a steady rate in response to growing population and urbanization in the world.

Portland cement is the principal hydraulic cement used for making concrete today. Raw materials for the manufacture of portland cement are plentiful, however the need for conservation of energy and resources has already pushed the production and use of blended portland cements containing up to 70 percent blast-furnace slag or up to 30 percent fly ash or another pozzolan. In this regard, pioneering studies by Malhotra⁷ on the use of high volumes of fly ash as a mineral admixture in concrete, are noteworthy. According to these studies, 50 to 60% cement replacement with fly ash can be made in concrete mixtures containing high-range water reducers, popularly known as superplasticizers, to obtain products that are not only high in strength but also

excellent in impermeability. This work takes on an added significance if the production of portland cement in the future is frozen at the current level in efforts to prevent a rise in CO₂ emissions.

In regard to concrete aggregates, as they are being consumed at an annual rate of about 5 billion tons, high quality aggregate sources close to urban and industrial areas are either already depleted or becoming rapidly depleted. Economic and environmental considerations require that in the future we learn how to live with marginal aggregates. For instance, aggregates known to cause high drying shrinkage in concrete may be used in combination with expansive cements, and those known to cause alkali-silica related expansion may be used in combination with active pozzolans. Also, there is a considerable interest in recycling demolished concrete as an aggregate, and using fly ash and metallurgical slags for making aggregate. Finally, almost all concrete made today contains one or more chemical and mineral admixtures, which are readily available and are used to achieve a variety of objectives. Several state-of-the-art reports on trends in chemical and mineral admixtures for concrete are being presented at this symposium.

3.2 Durability of Concrete

Normal concrete, typically, has 20 to 40 MPa (3,000 to 6,000 psi) compressive strength, which is adequate for most structural applications. The tensile and flexural strengths are relatively low; therefore, the material tends to crack easily under tensile stress. A concrete structure with a few visible cracks usually continues to perform satisfactorily under compressive loading; however, if the cracks are interlinked with the microcracks, the susceptibility of concrete to water penetration is greatly increased, and therefore, durability may be adversely affected depending on the environmental conditions. Consequently, concrete structures exposed to severe environments such as temperature or humidity extremes and aggressive chemicals tend to deteriorate earlier than their intended service life. For instance, in 1987 the National Materials Advisory Board⁸ made a reference to the epidemic of deterioration of concrete bridge decks in the U.S. It was estimated that 253,000 concrete bridge decks, some of them less than 20 years old, were in varying states of deterioration, and about 35,000 were being added to this list every year. Premature deterioration of concrete in tunnels,⁹ parking garages,¹⁰ marine structures,¹¹ and railway sleepers¹² has been reported by several investigators. This offers a unique opportunity to determine what is lacking in the current state of our scientific knowledge on concrete durability and in the field practice of what is already known.

3.3 New Technologies for Improved Performance

Some technologies developed during the last two decades have led to improved performance of the concrete construction industry; others were aimed at improving the performance of concrete as an engineering material. Roller-compacted concrete technology, which is the subject of two comprehensive reports at this symposium, offers considerable savings in construction time and cost for building concrete dams. Since 1982, when the first roller-compacted

concrete dam was built at Willow Creek in Oregon, over 100 dams worldwide have been completed or under construction using this technology.

To improve the performance of concrete, numerous new technologies and products have been developed. Notable among them are high-strength concrete containing superplasticizers, fiber-reinforced concrete with steel, glass, polymer, or carbon fibers, latex-modified concrete, chemically bonded ceramics, macro-defect free cement products, and epoxy-coated reinforcing steel. These technologies are discussed in detail by other authors at this symposium. Due to high cost and special problems, many researchers including Neville² believe that the total volume of concrete made by the application of these technologies is not likely to be large. Due to their relevance to durability, the high-strength and the high-performance concrete technologies will be briefly discussed here.

High-strength concrete, with water/cement 0.35 to 0.45 and compressive strength in the 40 to 60 MPa range, is usually made using a superplasticizer and with or without mineral admixtures. It can generally be produced from locally available materials, using conventional mixing, handling, and curing methods. Depending on the physico-chemical characteristics of cement, admixtures, and aggregate, highly workable concrete mixtures with water-cementitious ratios in the range of 0.25 to 0.35 have also been commercially produced. The products show not only very high strength (60-130 MPa compressive strength) but also very high impermeability, which is the key to long-term durability in aggressive environments. From a worldwide survey of about one hundred structures made with high-performance concrete, Malier¹³ estimates that compressive strength was the sole criterion for 25% of the structures; for the rest durability was the primary consideration.

It should be noted that high-strength and very-high-strength concrete in particular (> 60 MPa) is a special material requiring special aggregate (strong and closely graded), special admixtures (viz. superplasticizers), and meticulous care in mixing and handling. In a personal communication, Jan Moksnes of the Norwegian Contractors made the following observations, based on 20 years of experience of his company with the construction of high-strength concrete offshore oil platforms in the North Sea:

High-strength concrete upgrades the unglamorous product of our youth to a more respectable, sophisticated, and high-tech. product for the future. We have acquired a fashionable material which enables us to design and build stronger, taller, longer, slimmer, and lighter structures. At the same time we are under considerable pressure to perform the work in less time; to stricter tolerances and to increasingly ambitious specification requirements. What used to be a robust and tolerant site-produced material designed with adequate redundancies is, in extreme cases, becoming a schizophrenic product balancing on a knife's edge of feasibility in terms of site performance.

High-performance concrete is the term used by some researchers for concrete mixtures which possess high workability, high strength, high dimensional stability, and high durability. This type of concrete finds application in heavily reinforced, sophisticated structural elements in high-rise buildings, offshore platforms, superspan bridges, and heavy-duty pavements. The microstructural principles underlying the composition and properties of high-performance concrete are described in several papers including those by Mehta and Aitcin,^{14,15} Regourd,¹⁶ Larrard,¹⁷ and Gjorv.¹⁸ It is well known that many characteristics of ordinary concrete, viz. relatively low strength and elastic modulus are related to the highly heterogeneous microstructure of the material, particularly the porous and weak transition zone which exists at the cement paste-aggregate interface. By densification and strengthening of the transition zone the properties of concrete can be improved and the risk for easy microcracking in service (and consequential increase in the coefficient of permeability) can be reduced. To achieve this end, firstly, a substantial reduction must be made in the quantity of mixing water. This is accomplished mainly by the use of a powerful cement dispersant (superplasticizer). For additional densification, strengthening, and homogeneity of the hydrated cement paste and mortar in concrete, a number of mineral admixtures possessing very fine particle size and high specific surface have been used, such as condensed silica fume, rice husk ash, fly ash, ground blast-furnace slag, metakaolin, limestone powder, and carbon black. The selection of the type and amount of mineral admixture is guided by cost, reactivity, and contribution to the packing density and workability of fresh concrete. Highly reactive pozzolans tend to reduce the curing time needed to obtain a desired level of strength and watertightness; less reactive or non-reactive powders will improve the resistance to thermal cracking by lowering the heat of temperature rise.

It should be pointed out here that some concrete technologists question the use of the term, high-performance concrete, to describe many recently developed high-strength products such as those with more than 100 MPa compressive strength. It is argued that in addition to strength and durability the cost of materials and processing must be taken into consideration. According to a personal communication from Idorn, in the context of the cost of making durable ordinary-concrete, it seems that many researchers have neither interest in, nor knowledge, of the exorbitant cost of production of the "high-tech." type concretes they have chosen to designate as high-performance concrete.

3.4 Ecological Profile of Concrete

Kreijger¹⁹ predicts that materials selection in the future will be governed by their ecological profile. For a given engineering property such as strength, elastic modulus, or durability, the material with the best ecological profile is that which requires least deforestation and desoiling of the earth, consumes least energy and water for its production, and yields the least amount of harmful by-products. Using Kreijger's criteria, compared to metals, polymers, and glass, concrete has an excellent ecological profile. Also, it is generally accepted that from economic and engineering considerations there seems to be no better home than the concrete industry for the disposal of millions of tons of siliceous

by-products, such as fly ash, blast-furnace slag, condensed silica fume, and rice husk ash. The use of these by-products in concrete is generally accompanied by a significant reduction in permeability and improvement in workability. Depending on the particle size, reactivity, and the quantity used, mineral admixtures can also improve the resistance of concrete to thermal cracking.

Storage of enormous quantities of these siliceous by-products, which generally contain some heavy metals, causes air and water pollution. Even low-value applications, such as landfill and sub-bases for pavements, can be hazardous because toxic metals will eventually find their way into groundwater. Incorporation into concrete either in the form of mineral admixtures or as components of blended portland cement presents a relatively safe and inexpensive method of disposal. Recent work by McCarthy et al.²⁰ shows that selenium and chromium can be permanently bound in the crystal structure of ettringite, which is one of the products formed during cement hydration. Also, because up to 50-60% granulated blast-furnace slag or fly ash can replace portland cement in concrete without causing any deleterious effects on the ultimate strength and with considerable potential for enhancement of concrete durability, the use of these by-products is not only energy-saving but also resource-conserving. From the above-described ecological profile, the author²¹ has called concrete Lord Siva (one of the gods in Hindu mythology) of the construction materials world. Once the gods decided to drain an ocean to recover a pot of nectar lying on the ocean floor. In the process, a stream of poison was released and it started destroying the world. Whereas the other gods ran away from the poison, Siva handled the problem by drinking the whole stream of poison, which left only a blue mark on his throat.

4. PROBLEMS WITH CONCRETE SCIENCE AND TECHNOLOGY

From predictions about the nature of tomorrow's world and its needs, and an overview of the state of the concrete industry and technology today, it is possible to identify critical issues which must be addressed expeditiously if concrete is to continue occupying the position of the most favored material for general construction. It seems that **the most important issue that needs urgent attention is the durability of ordinary concrete and the growing lack of public confidence in long-term service life of the material.**

In a recent report on performance of concrete in transportation, presented at the Annual Meeting of the Transportation Research Board, Mather²² stated, "If concrete in a transportation use fails to perform as desired, it is either due to specifications having been wrong or not being followed." Specifications can be wrong in one of the two ways; either a specifier has erred in the choice of right specifications or **the available specifications are based on a faulty science.** The author would like to address the latter issue with the purpose of destroying the myth that there would not be any durability problems if the currently available specifications and codes of recommended

practice are correctly prescribed and faithfully followed. In this report, in addition to a state-of-the-art review on the science of concrete durability, the following topics are discussed: a holistic model of the concrete durability science, new approaches to the making of ordinary concrete, current specifications and codes, prediction of service life of structures, and needed intervention in education and research in concrete technology.

4.1 The Science of Concrete Durability

All scientific research proceeds by simplification. When dealing with a complex structure or phenomenon, the researcher arbitrarily simplifies the system and usually studies one aspect at a time in order to make the task manageable. Scientifically, this is a valid procedure but the results will have a limited value unless all other related aspects of the structure or the phenomenon are studied and an effort is made to integrate the available information. Furthermore, to deal with complex systems in accordance with the holistic approach, we must also integrate **the experiential knowledge with the totality of available scientific knowledge**. Instead, in our studies on one part of a complex system, too often we treat the data as if they pertain to the whole. Again, in modeling the results, seldom do we take into consideration the knowledge derived from experience. This, in short, is the sum and substance of what is wrong with most of the sciences today including the science of concrete durability.

A knowledge base that is solely derived from the reductionist approach in science is a serious deficiency which must be corrected because science provides the foundation upon which technology stands. For example, how can we expect concrete structures to be durable if, in the development of test methods and specifications, we have relied on inadequate scientific theories and models? To illustrate this point, let us consider the currently accepted theories behind the four principal causes of deterioration of concrete, namely sulfate attack, alkali-silica reaction, corrosion of reinforcing steel, and freezing and thawing.

Sulfate Attack

Recently the author²³ reviewed case histories of several structures that were exposed to sulfate environments and came to the following conclusions. First, there is no universally accepted hypothesis on ettringite-related expansion of cement paste. Crystal growth pressure from ettringite formation and the swelling pressure from water adsorption by poorly crystalline ettringite are two of the several hypotheses that have been proposed. Verification of these hypotheses from deteriorated field structures has been difficult because this involves the observation of processes that leave behind only the effect but not the cause which produced the effect. It has been suggested that damage to concrete from sodium sulfate crystallization is an example of the crystal growth pressure phenomenon. This is not proven. On the contrary, the phase change between thenardite (Na_2SO_4) and mirabalite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) is an expansive phenomenon. In any case, this has nothing to do with ettringite formation and sulfate attack on the cement paste itself. The water adsorption tendency of ettringite which is often responsible for rapid slump loss in fresh concrete, is

well known in concrete technology. In hardened concrete, ettringite formation and subsequent water adsorption by ettringite may cause pressures large enough for expansion and cracking especially when, at the same time, the cement paste has lost some of its strength and stiffness due to sulfate attack on the principal products of cement hydration, namely C-S-H and CH. Field observations have confirmed that concrete exposed to long-time sulfate attack suffers a loss in adhesion and strength.²³

Another noteworthy observation from deterioration of concrete as a result of chemical attack is that only **permeable concretes in moist environment** are vulnerable. If concrete in a structure is not permeable to begin with, it can become so during service due to microcracking from any number of causes. It seems that expansive chemical phenomena do not occur until concrete has acquired a high degree of saturation through water penetration. It has also been observed that sulfate attack is seldom the sole cause of concrete damage. Evidence of carbonation (associated with CaCO_3 and thaumasite formation) and/or alkali-silica reaction can often be found in concretes deteriorated from sulfate attack. It should be noted that both the carbonation of the cement paste and alkali-silica reaction tend to accelerate the sulfate attack because they reduce the alkalinity of the cement paste and, therefore, its adhesion and strength.

Alkali-Silica Reaction

Chemical reaction between certain reactive forms of silica present in aggregate particles and a highly alkaline solution resulting from the hydration of a high-alkali portland cement can produce a swelling-type alkali-silica gel which can cause considerable expansion on water adsorption. Like the sulfate attack when alkali-silica reaction is involved in a damaged concrete structure, it is usually found that other causes of deterioration are also present. For instance, according to Shayan and Quick¹² the alkali-silica reaction is implicated in damage to precast concrete railway sleepers in several countries such as Canada, U.S.A, South Africa, Finland, and Australia. In South Africa and Finland, it was reported that microcracking due to freezing and thawing cycles contributed to the expansion associated with the alkali-silica reaction. In Australia, according to Shayan and Quick's investigation,¹² the affected sleepers showed a partial loss of stiffness, fatigue cracking, and expansion.

Idorn,²⁴ who has a long experience with durability problems in concrete structures around the world, has recently made the following observations in regard to sulfate attack and alkali-silica reaction:

Studies of deterioration of concrete due to sulfate attack inevitably show degradation, carbonation, and loss of strength by the cement paste while aggregates are unaffected. The mechanical effects of such attacks are therefore crumbling of the concrete inward from the surface, spalling, and eventually volumetric reduction of the concrete mass. In field cases of deleterious alkali-silica reaction, the cement paste is chemically unaffected

while the reacting aggregate particles are internally fractured and/or partially dissolved. **This mechanism brings about internal expansivity, which may also cause the concrete member to expand if there are no constraints, such as steel reinforcement.** Nevertheless, for both forms of chemical attacks, the conventional laboratory testing methods use linear expansions of (unrestrained) mortar bars. This is a deceptive misconception of modeling.

Reports in the published literature by many investigators, including a paper by Swamy at this symposium, confirm that, as a result of alkali-silica reaction, adequately reinforced concrete structures do not suffer any significant deterioration in mechanical strength. Idorn's comment questioning the practical value of laboratory test results to predict the behavior of field structures is also highly pertinent. As will be discussed later, the expansion data from unrestrained mortar bars may have little or no relevance to actual service conditions and, therefore, should not be used for service-life predictions.

Corrosion of Reinforcing Steel

Fig. 1(a) shows the mechanism of electrochemical corrosion of steel, and Fig. 1(b) a typical model based on the pioneering studies of Tuutti²⁵ for predicting expansion and cracking of concrete due to corrosion of embedded steel. Note that the model considers the effect of penetration of water, oxygen, carbon dioxide, and chloride ions **on depassivation of steel only**; it does not take into consideration the effect of these penetrating ions on the strength and stability of cement hydration products, such as C-S-H. Fig. 2, which is being proposed by this author, illustrates **the physico-chemical changes occurring simultaneously in the steel and concrete** in response to attack by the penetrating ions.

The mechanisms shown in Fig. 2 are holistic in the sense that no part of the system is overlooked. For instance, since C-S-H is the primary source of strength in the cement paste and since the stability of C-S-H is dependent on the surrounding OH^- ions in the pore fluid, the effect of replacement of $(\text{OH})^-$ by acidic ions such as carbonate, sulfate, and chloride on the strength and elastic modulus of concrete is taken into consideration. The mechanism of expansion and cracking shown here also takes into consideration the effect of formation of expansive products, such as a colloidal rust, on the hydraulic pressure in the pores of a water-saturated system. Thus Fig. 2 demonstrates what the author means by integration of total scientific knowledge that is available about the effects of a particular process on all components of the system. The model in Fig. 3(a) on cracking-corrosion-cracking of reinforced concrete structures exposed to seawater, proposed by Mehta and Gerwick,²⁶ is a simpler version of the model in Fig. 2. Note that in these models an attempt is made to integrate the experiential knowledge with the available scientific knowledge. For instance, during their investigation of the steel corrosion-related damage to concrete in the spandrel beams of the San Mateo bridge, the authors observed that the

damage was limited to the side which was more vulnerable to microcracking from exposure to daily cycles of heating-cooling and wetting-drying. With concrete structures damaged by the reinforcement corrosion, many other investigators have also observed that microcracking of concrete from causes other than corrosion plays a great role in increasing the penetration of water, oxygen, and CO_2 which are instrumental in the initiation and progress of corrosion-related damage. Thus, for the purpose of predicting the service-life of concrete, the models in Fig. 2 and 3(a) are holistic and, therefore, more realistic than the model in Fig. 1(b).

Freezing and Thawing Cycles

It is generally accepted that a saturated concrete without proper air-entrainment, when subjected to freezing and thawing cycles, can undergo deleterious expansion as a result of internal hydraulic pressure that is generated from freezing of water in the capillary pores, and migration of water from gel pores to capillary pores. The magnitude of the hydraulic pressure depends on permeability of the cement paste, degree of saturation, amount of freezable water, the rate at which ice is forming, and the air-void spacing factor or the distance through which water under pressure must travel to seek pressure relief. There is some controversy whether or not high-strength concrete mixtures with less than 0.3 water-cement ratio and high cementitious material content, which readily become impermeable on curing, require air entrainment for protection against freezing and thawing. If they have little freezable water and low degree of saturation it is argued that such concretes would not expand on exposure to cycles of freezing and thawing, even when no entrained air is present. Thus microcracking due to one or more of the numerous causes and subsequent increase in the permeability of concrete and degree of saturation appear to be the steps that are necessary for damage to concrete by freezing and thawing. This is illustrated by the model in Fig. 3(b) proposed by Moukwa,²⁷ which has a striking similarity to Mehta and Gerwick's model on cracking-corrosion-cracking cycle in reinforced concrete, Fig. 3(a).

4.2 A Holistic Model of Concrete Deterioration

From the comprehensive review of the concrete deterioration processes described above, the author has constructed a holistic model, which is shown in Fig. 4. Again, the model is holistic in the sense that it takes into consideration the effect of both the known scientific facts and the experiential knowledge about environmental factors on each component of concrete including water in the pores. It is assumed that the permeability* of a well-cured, moderate-

*In scientific literature a distinction is made between permeability and diffusion - the two phenomena primarily responsible for the transport mechanism of harmful substances from the outside into the interior of concrete. In the concrete-industry literature the term, "permeability," is commonly used in a broad sense covering the **penetration** of fluids into a porous solid by diffusion as well as permeation.

strength (e.g. 30 MPa) concrete remains negligible until the existing microcracks (i.e. cracks invisible to the naked eye) propagate and become interlinked with the wider cracks originating from the concrete surface. Due to a variety of well-known causes, discontinuous microcracks are always present in concrete. For instance, reinforcement of concrete with steel tends to distribute the potential cracks from drying shrinkage or thermal contraction into a network of very fine cracks which may be beneficial from the standpoint of structural loading but are harmful from the point of view of permeation of aggressive substances from the surface into the interior of concrete.

The model in Fig. 4 considers the influence of environmental factors in two stages. During the first stage, loading and weathering effects (cycles of wetting and drying as well as heating and cooling) facilitate the propagation of microcracks until they become continuous. Once this happens the penetrability of concrete increases greatly and we have the beginning of the second stage during which water, oxygen, CO_2 , and acidic ions are able to penetrate easily into concrete. The presence of these elements facilitates various physico-chemical interactions as a result of which, on the one hand, the hydraulic pressure in the pore fluid increases and, on the other hand, a partial loss of concrete strength and stiffness takes place. Under the influence of these two simultaneously occurring processes the material eventually undergoes cracking, spalling, and loss of mass. This, in turn accelerates deterioration of concrete by causing a dramatic increase in the penetrability.

Note that the holistic model in Fig. 4 also provides a clear justification why impermeability of concrete should be the first line of defense against any of the physico-chemical deterioration processes described earlier. If adequate attention in concrete making and processing is paid to hold the first line of defense, why would one need epoxy-coated reinforcing steel for protection against corrosion, ASTM Type V cement for protection against sulfate attack, and low-alkali cement or non-reactive aggregates for protection against expansion associated with the alkali-silica reaction? From the standpoint of life-cycle costs and conservation of resources, the ecological implications of the foregoing proposition cannot be ignored for too long.

4.3 New Approaches to Making of Ordinary Concrete

In general, the future of the concrete industry will not be determined by the technologies that require special materials and processes; instead, it will be determined by our efforts to solve the problems that confront the conventional concrete technology. Of course, as suggested below, some lessons from the practice of new technologies, such as the high-performance concrete technology, can be usefully incorporated into making and processing of ordinary concrete.

The field practice in the selection of materials, mixture proportioning, and concrete manufacture and construction is strength-oriented. It is obvious that the focus in the current practice must now shift from strength to durability. As cracking of concrete has a great influence on the permeability and, therefore, on durability to a variety of physical and chemical attacks, we must do everything

possible in selecting materials, mix proportions, and concrete construction practice to prevent cracking of structures in service. It is evident that this point is not being sufficiently emphasized at present. For instance, the current codes of recommended practice do not pay adequate attention to the role played by aggregate in controlling the cracking of concrete due to thermal contraction and drying shrinkage.

Experience shows that compatibility between cement mortar and coarse aggregate with respect to the linear coefficient of thermal expansion and elastic modulus is important to insure freedom from cracking due to cooling and drying. Also, to reduce the magnitude of shrinkage, a maximum limit on the cement content by requiring a minimum total aggregate content is highly desirable. Whenever economically viable, more stringent controls on the aggregate shape, size, and grading than provided by current standard specifications, should be imposed to achieve improvements in packing density and workability of concrete which, in turn, determine the water requirement and homogeneity of the mixture.

There is little that is profound or new in these recommendations. However, due to an overemphasis on strength rather than durability in specifications and an overdependence on w/c-strength relationship in mixture proportioning procedures, many fundamental principles of concrete technology that are relevant to durability are being ignored and it is necessary to bring them back into everyday construction practice. This can be achieved by developing durability-oriented recommended procedures for selection of materials and mix proportions. As it is the free water content in fresh concrete, not necessarily the water-cement ratio, that is the key player in determining homogeneity, permeability, and durability, even low and moderate-strength concrete can benefit from the use of water-reducing admixtures. Relatively inexpensive high-range plasticizers should be extensively used when they become available in the future. Furthermore, to achieve satisfactory performance, strict adherence must be observed to proper mixing, handling, consolidation, finishing, curing, and quality assurance procedures. Idorn²⁴ predicts that during the next decade on-site monitoring technology of fresh concrete processing and early curing developed in Denmark will completely replace conventional quality control by sample testing. With regard to the slump test for workability and the compressive strength test with standard-cured cylinders, the author suggests that the use of such procedures is a survival not of the most suitable but of the easiest method of testing.

4.4 Test Methods, Specifications, and Service-Life Prediction

Most of the tests and related specifications that are relevant to durability issues seem to serve a limited purpose, namely the quality control of component materials used for making concrete. Twenty three years ago, the ACI Committee Report on Concrete - Year 2000 drew attention to the problem of, "inadequate, intolerant, and over-demanding test methods and specifications in use today." The problem has yet to be solved, as concluded by the author²⁸ from an earlier review of the subject. As the economic and ecological costs

would be too high if we continue using prescriptive and irrelevant standards, a brief review of typical laboratory tests currently in use is presented here.

With regard to **alkali-silica reaction**, ASTM C 289 test provides a quick method for testing the potentially reactive aggregate. This test neither reflects the mechanisms of alkali-silica expansion in concrete nor simulates the mechanical effects that lead to distress in a real structure. Consequently, worldwide many aggregate sources are being rejected on the basis of this test, in spite of the fact that concrete structures containing these aggregates have shown a good field performance. Similarly, ASTM Method C 227 is commonly used for detecting a deleterious alkali-aggregate combination from measurement of expansion of standard mortar bars, stored for 6 months or more under given conditions. As with C 289, it has been often observed that there is a poor correlation between the mortar bar expansions and structurally significant distress in concrete.

ASTM Method C 452 and C 1012 are used for evaluation of **sulfate resistance of cements**. By ignoring a common manifestation of sulfate attack in field concrete, namely the loss of adhesion and strength, these expansion-based procedures help to differentiate between the high and the low C_3A cements which, incidently, can be accomplished by relatively simple and quick test methods. Furthermore, C 452 does not take into consideration the differences in concrete permeability and neither method takes into account the effect of environmental variables on sulfate attack (the degree of constraint, temperature, pressure, pH of the solution, and the presence of other ions). Therefore, both tests have a limited value in predicting the field performance of concrete. For instance, seawater has a deleteriously high sulfate content, yet high- C_3A cement concretes continue to perform well in marine structures.

Resistance of concrete to freezing and thawing cycles is usually evaluated by using ASTM Method C 666, Procedure A. Specimens are tested in a saturated condition and at freezing rates ranging from 4 to 16 C/h. Some 40 years ago, Powers had cautioned that the test was too severe (i.e. too accelerated to simulate the field conditions) to be of practical value. By comparing the test results from ASTM C 666, Procedure A, with long-time field performance of non-air-entrained concrete mixtures, Ontario Hydro researchers concluded that poor results in the test did not necessarily mean poor field performance. Incidently, ASTM C 666 may also be cited as an example of how a test method can become an obstacle in the development of new products. Researchers seem to agree that, with 60 MPa or higher compressive strength (0.25 to 0.3 w/c), concrete specimens do not contain enough freezable water to be at risk in freezing and thawing. Yet, unless the concrete is adequately air-entrained, it often fails in the ASTM C 666 test. However, incorporation of air into a high-strength concrete mixture, just to comply with the ASTM C 666 test and related specification, may be counterproductive because air entrainment affects strength adversely.

Unsoundness of cements due to free CaO and MgO is tested by means of an autoclave test (ASTM C 151) which requires that cement paste specimens be exposed to a steam pressure of 2 MPa for 3 hours. If the expansion exceeds 0.8%, the cement is considered unsound. This test is a classical example of accelerating a phenomena to the point when the test loses its meaning and purpose. Exaggerated expansion values are obtained in the test with high free lime and MgO cements because the main strength-producing hydration product present in normally-cured cement, namely C-S-H, is destroyed by autoclaving. Also, no correlation has ever been shown between the autoclave expansion specification limit (0.8%) and the soundness of concrete in service. To comply with the ASTM C 151 test and the related specification, the cement industry is, at times, compelled to reject dolomitic deposits in their limestone quarries which has a negative impact on resource conservation and ecology.

In conclusion, the current test methods and specifications are in need of a critical examination and a thorough review. Like the compressive strength data on laboratory-cured cylinders, some of the test methods may still be useful for the purpose of quality control but none of them appear to be usable for the prediction of service-life of concrete, which is greatly influenced by concrete processing and by actual environmental conditions as discussed below.

Concrete processing, i.e. consolidation and curing has a great influence on the properties of in-situ concrete. Yet most quality assurance programs rely solely on laboratory-made specimens.²⁴ Thus deficiencies in placement, compaction and curing including early-age microcracking due to settlement or thermal shrinkage effects, remain undetected. Obviously, a holistic quality assurance program will rely more on the tests for the microstructure and properties of in-situ concrete than on data from laboratory-cast specimens. To this end, relevant test methods for durability are described in a paper by Gjorv at this symposium.

Concrete is being used increasingly for building structures exposed to hostile environments, such as deicing chemicals and seawater. It is also being used or is under active consideration for use in containment structures for toxic as well as radioactive wastes. In response to the need for quantitative data on projected service-life, **computer-generated expert systems based on mathematical models** have been developed. If the assumptions underlying mathematical models used in expert systems happen to be incorrect, the credibility of the quantitative data on service life predictions would be questionable. The three key elements of a reliable method for mathematical prediction of service life are: **a precise definition of the material (concrete), a precise definition of the environment, and a dependable database from accelerated test methods on durability.** As shown above, the currently available laboratory methods are inadequate for the purpose of predicting the field performance of concrete in a structure. The problems of modeling the material and the environment are discussed in the following paragraphs.

To model the microstructure of concrete that is being subjected simultaneously to a variety of environmental influences, as shown in Fig. 4, is like attempting to shoot at a constantly moving target. A static model will not be realistic since the microstructure of the material, including the pore structure and permeability, is continuously changing in response to penetration of water, CO_2 , oxygen, and aggressive ions at a rate which is influenced by local conditions of temperature, humidity, and pressure. Ongoing physico-chemical processes, such as hydration of any unhydrated cementitious and pozzolanic particles, dissolution of the hydration products already formed and subsequent precipitation of new products (a phenomenon often responsible for autogenous healing of microcracks) will be simultaneously creating and destroying the forces of adhesion in the cement paste. **How can we model a kaleidoscopically changing system, when we know little about many of its components, their characteristics, and the rates at which they are appearing or disappearing? In short, the mathematical modeling of a deteriorating concrete is, at best, based on the current science of concrete durability which, as discussed above, is inadequate.**

In modeling the environment, we face similar difficulties. There is no question that cycles of wetting and drying, heating and cooling, freezing and thawing, and loading and unloading can have a profound effect on the physico-chemical processes of deterioration. For instance, corrosion of steel and alkali-silica reaction are considerably accelerated with temperature whereas sulfate attack, reportedly, decreases with high temperature but increases with high pressure. Also, it is reported by Chandra²⁹ that carbonation attack is increased in the presence of even small amounts of SO_2 and NO_x , which are found in acid rain and urban fog. As we generally know about the effects of one environmental variable at a time, and little about the **synergistic effects** of two or more variables present simultaneously, the actual combinations of environmental factors to which a concrete structure might be exposed during its service life, are often ignored in modeling the environment. Furthermore, Rostam³⁰ considers the ability to define the **micro-environment** from the macro-environmental observations as a major challenge for future research in concrete technology.

In conclusion, an observation frequently made by experienced designers of structures is also applicable to computer-aided durability predictions. In his Ferguson lecture at the Fall 1992 ACI Convention in Puerto Rico, Tedesco³¹ said, "It is a misconception that sophisticated computer analysis through greater accuracy will lead to better designs. The quality of a design is not a function of the exactness of calculations and **it is not necessary to strive for great accuracy in a numerical analysis when the accuracy of assumptions of the analysis is not known.**" Given the types of problems described above, obviously it would be difficult to make **exacting quantitative predictions** of service-life; however, it should not be difficult to **design qualitatively for durability**. This concept is illustrated by Fig. 5 which is based on the work of CEB, the Euro-International Committee for Concrete. According to Rostam,³⁰ during the "damage initiation phase" no noticeable weakening of the material occurs but some protective barrier is being broken down, such as the depassivation of the reinforcing steel by CO_2 or chloride penetration. However, according to the holistic model

presented in Fig. 4 by the author, fundamentally speaking, the first protective barrier is the water-tightness of concrete as both the damage initiation and propagation have to wait until this barrier is overcome. Therefore, a modified version of Fig. 5 is presented by the author in Fig. 6 which shows that: (a) the longevity of Stage 1 can be manipulated through proper attention to the selection of materials, mixture proportions and concrete processing; (b) the loss of water-tightness, the initiation of damage, and its propagation are not distinct points on the curve but are overlapping stages which can best be represented by a smooth bend (like the bend in a river); (c) the service life of a concrete structure with a predetermined damage limit "D" would vary with the type of structure and the microclimatic conditions to which the given component of the structure is exposed.

4.5 Education and Research in Concrete Technology

That "fewer and fewer civil engineering schools are requiring their students to complete courses in quality control and behavior of concrete," was another problem to which attention was drawn 23 years ago by the ACI Committee Report on Concrete - Year 2000.¹ Today, judging from the problems that need to be addressed by the concrete industry, the situation is worse than it was in 1971. The undergraduate and graduate curricula in civil engineering at well known institutions in the U.S., such as M.I.T. and Stanford, do not seem to contain any courses in concrete technology. Others, such as the University of California at Berkeley and the University of Illinois at Urbana, are not as strong today in teaching and research in concrete technology as they were in 1960s. Neville² has also asserted that the best universities teach next-to-nothing about concrete technology. He suspects that **not teaching about something so ordinary as concrete actually adds to the status of the teaching institution. And this all is happening when we cannot depend on the available specifications and codes or on computer-generated models for long service-life of structures made with normal concrete.**

Technological solutions that claim to solve a problem, such as the use of epoxy-coated reinforcing steel or cathodic protection against corrosion of steel in concrete, are not only expensive but also tend to create other problems. The simplest and the most cost-effective solution is **to go back to the basics** or the root cause for lack of durability, namely the permeability of concrete and the factors responsible for increase in the permeability during service. And to address this issue effectively in field practice we must provide sufficient relevant educational opportunities to those who would be responsible for the design and construction of concrete structures. Clearly, a sound academic preparation together with adequate laboratory and field experience in modern concrete processing technology are necessary prerequisites to prepare tomorrow's materials scientists and engineers if we want them to respond imaginatively to the challenges described in this paper. In their presentation at this symposium, Shilstone and Shilstone advocate a special degree course in concrete engineering. Lack of a **holistic education in concrete technology**, integrating research and practice, is responsible for costly delays in the execution of several major projects recently. Private communications from Gerwick and from Idorn,

who are well connected with the concrete industry, show that unrealistic specifications from inexperienced designers have often been a cause of the problem.

With reference to concrete research, 23 years ago the ACI Committee on Concrete - Year 2000¹ made the statement that a lot of ongoing research was narrow and therefore of limited value. The position of research today is no better. For instance, Idorn* made the following observations on the current research in alkali-aggregate reactions. Since 1974, seven international congresses on alkali-silica reaction have been held. At the last congress, although 134 research studies were presented, they represented a frightfully trivial amount of new knowledge towards prevention of the problem, testing methods and cost-effective evaluation of acceptance criteria for specifications. According to Idorn, this was the state of affairs after 50 years of worldwide research. A similar situation prevails in other areas as described by the author in a review of past 50 years of research on concrete durability.²⁸

Education rests on the foundation of research. To provide relevant education for meeting the needs of the society as described above, we must support relevant research. **Research that has only a marginal relevance to the mainstream concrete technology is a luxury that should be discouraged during hard economic times.**

5. CONCLUDING REMARKS

In this paper, the author has attempted to present his personal view of tomorrow's world and the state of the concrete technology today. With increasing population, industrialization, and urbanization in the future it is expected that the concrete industry should experience a high rate of growth provided uncontrolled population and certain technological developments discussed in this paper do not bring all industrial activity to a halt.

The most serious problem in concrete technology today is the premature deterioration of concrete structures that are subjected to harsh environments. There is overwhelming evidence from field experience that many of the durability problems, such as sulfate attack, carbonation, alkali-silica reaction, and corrosion of reinforcing steel in concrete would not have occurred had the concrete been impermeable at the time of exposure to the environment and remained impermeable during the intended service life. Therefore, to address the durability-related issues in selecting materials, mix proportions and construction practice for concrete, we must develop new, comprehensive models on concrete deterioration showing the effect of environmental influences on the permeability of concrete.

*Idorn, G. M., "Concrete Forever," R & H Bulletin No. 17, Denmark, 1990.

A paradigm shift in the science of concrete durability--from a reductionist to a holistic approach--is also necessary before we can test methods and specifications or codes that are truly applicable to durability of concrete in structures. The science behind many of our current test methods is rather narrow. It focuses on one, visible symptom of the disease rather than both visible and invisible symptoms as well as all the possible causes behind them. For instance, in sulfate attack the emphasis is on ettringite formation and C_3A content of cement. The test methods and the specifications ignore the effect of sulfate ions on calcium hydroxide and C-S-H phase of the hydrated cement paste. The following observation by Goode,³² which is from the field of mental health science, is also applicable generally to the science of concrete durability:

"Some mental-health professionals wonder if the present system of psychiatric diagnosis at times does more to obscure patients' problems than it does to clarify them. The danger, they say, is that taking the diagnostic categories too literally may lead clinicians to focus more on symptoms than on the person behind them. What takes place inside the person and how it appears externally--though related--are not identical."

A holistic model showing the effect of weathering and loading on the permeability of concrete, followed by the effect of aggressive ions on all the component phases of concrete, is proposed in this report. While such holistic models are being incorporated into the codes for recommended practice, it is necessary that education and research in concrete technology is suitably strengthened to meet the needs of the society.

Twenty-three years ago, when the ACI report on **Concrete - Year 2000** raised the issues of irrelevant specifications and codes, wasteful and repetitive research, and inadequate education in concrete technology at engineering schools, we had almost thirty years to attend to these problems before the beginning of the 21st century. We have only six years left now and, so far, have done very little to resolve these issues. To reiterate, it would indeed be a fitting tribute to Mohan Malhotra, who has been in the forefront of education in concrete technology through his own research and through well-organized ACI/CANMET conferences on mineral admixtures and durability, if this report and the other reports presented in his honor at this symposium provide the needed stimulus to provoke the concrete industry into action.

6. ACKNOWLEDGEMENT

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TABLE 1 — ESTIMATED POPULATION OF MEGACITIES IN THE YEAR 2000

Metropolitan Area	Population (millions)	Metropolitan Area	Population (millions)
Tokyo	28.0	Seoul	13.0
Mexico City	24.0	Rio de Janeiro	12.2
Sao Paulo	22.6	Buenos Aires	12.8
Bombay	18.1	Calcutta	12.7
Shanghai	17.4	Manila	12.6
New York City	16.6	Tianjin	12.5
Beijing	14.4	Karachi	11.9
Jakarta	13.4	New Delhi	11.7
Lagos	13.5	Dacca	11.5
Los Angeles	13.2	Cairo	11.0

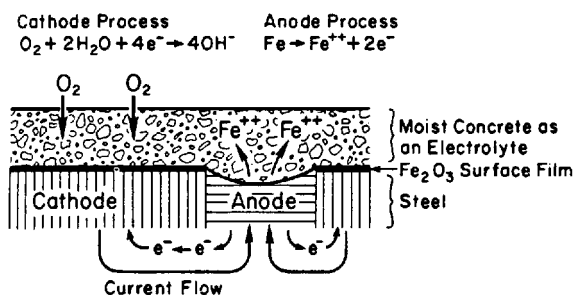


Fig. 1(a)—Mechanism of corrosion of steel in concrete

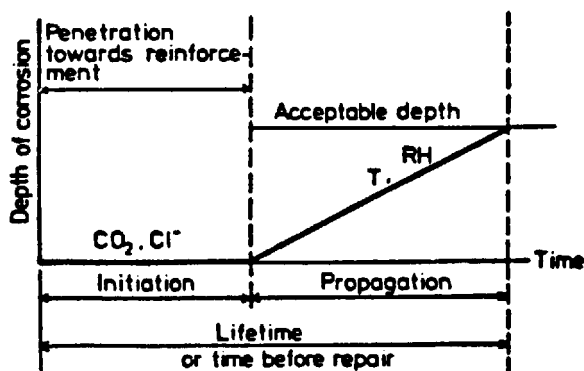


Fig. 1(b)—Schematic sketch of steel corrosion sequence in concrete (Ref. 25)

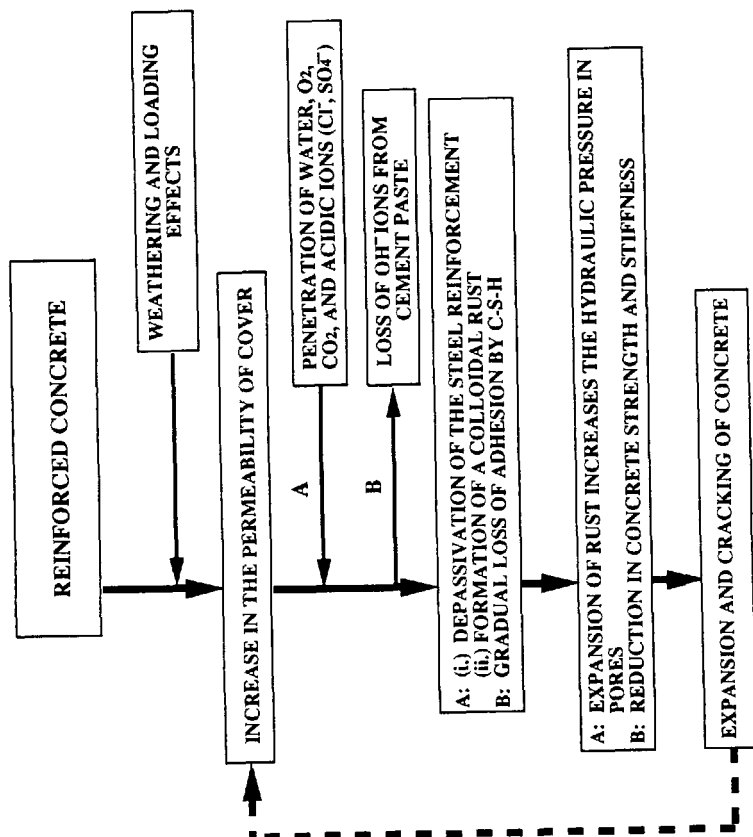


Fig. 2—A model of reinforced concrete damage from exposure to seawater or deicing salts

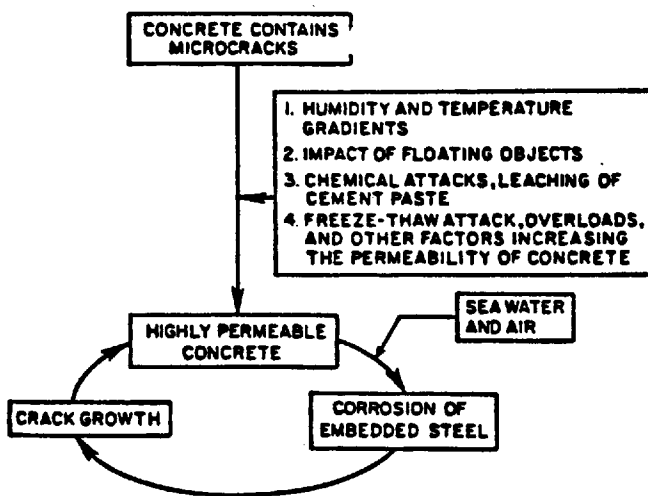


Fig. 3(a) Diagrammatic representation of the cracking-corrosion-cracking cycles in reinforced concrete (Ref. 26)

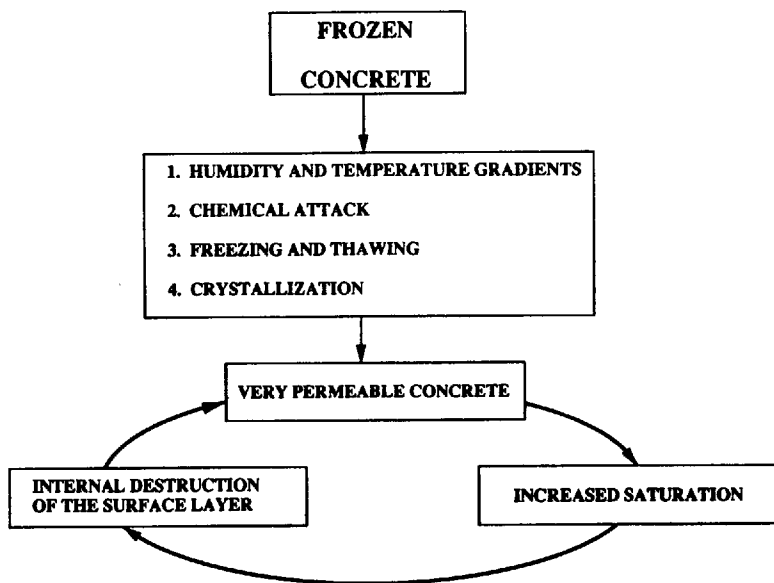


Fig. 3(b)—Diagrammatic representation of concrete deterioration due to freezing and thawing cycles (Ref. 27)

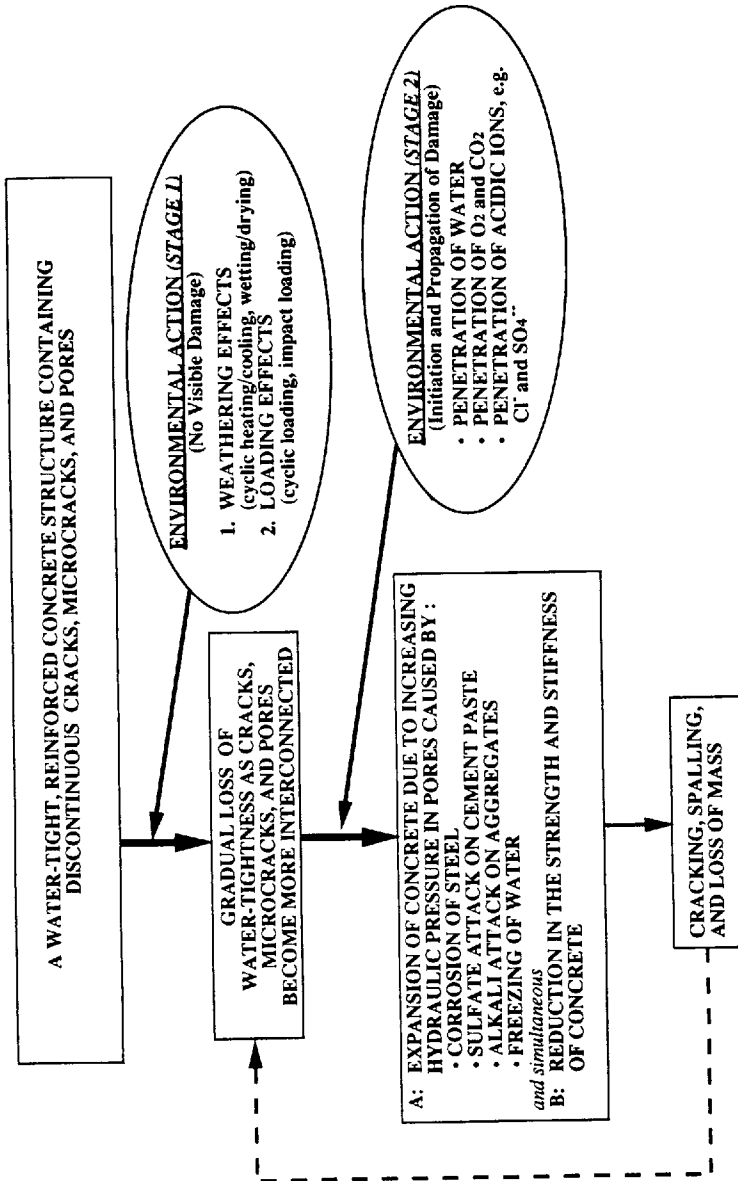


Fig. 4—A holistic model of deterioration of concrete from environmental effects

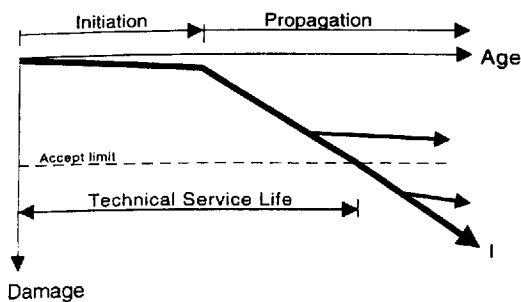


Fig. 5—Determining the technical service life of a concrete structure (Ref. 30)

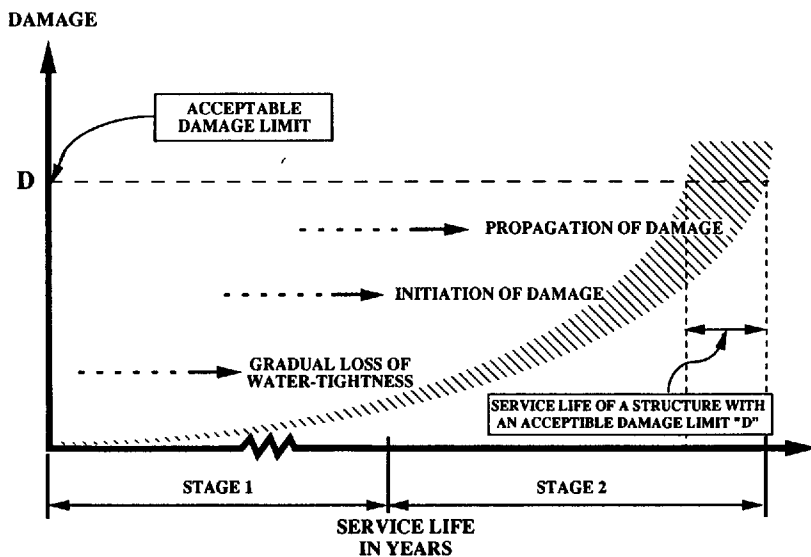


Fig. 6—Designing for service life of concrete structures

SP 144-2**Concrete—Year 2000, Revisited**

by B. Mather

Synopsis: In the August 1971 issue of the ACI Journal the report of the ACI Board Committee on "Concrete - Year 2000" was published. That committee, under the chairmanship of Clyde Kesler, concluded that looking ahead 30 years in 1971 was as difficult as it was in 1900 to look ahead 70 years to 1970 because of the accelerating rate of change. The accelerating rate of change hasn't changed.

I suspect we have made the least amount of progress in the area of cooperation under what the committee called, in 1971, "advancements in attitude." It seems to me there is more rather than less conflict and litigation among participants in concrete technology. I suspect that one of the greatest improvements we can make is in the area that some of us, including the Corps of Engineers, are working in, that is called "conflict resolution." What I am sure of is that, in the 21st Century, concrete technology will be alive and well and continuing to make progress in ways, some of which, cannot now be predicted.

Keywords: Admixtures; aggregates; cements; compressive strength; concrete construction; concrete dams, concrete durability; concrete products; concretes; floating bridges; high performance concretes; high rise buildings; highways; lightweight concretes; precast concrete; reinforced concrete; reinforcing steels; research; runways; specifications; standards; structural design; tensile strength.

Bryant Mather has been with the U.S. Army Corps of Engineers since 1941 and is Director, Structures Laboratory, Waterways Experiment Station, in Vicksburg, Miss. He is an Honorary Member and a past president of ACI. Recent awards include the ACI Delmar L. Bloem Award in 1991 and the Robert E. Philleo Award for Concrete Research in 1992.

INTRODUCTION

Since the intent of this paper is to review the 1971 ACI report "Concrete - Year 2000" from the standpoint of how it might be revised in the light of what we have learned since it was published, I believe we should start by acknowledging the contributors to that report. The ACI Board Committee on Concrete - Year 2000 had as its members the following: Clyde E. Kesler (Chairman), William A. Maples (Secretary), Arthur R. Anderson, A. Allan Bates, G. E. Burnett, Eivind Hognestad, W. R. Hudson, Fazlur Khan, Bryant Mather, Richard Muenow, Emil Schmid, and R. C. Valore, Jr. I expect that none of the others is likely to be present at the meeting at which this paper is given.

The intent of the Symposium of which this paper is a part is to honor Mohan Malhotra for his contributions to concrete technology and to ACI. It is therefore appropriate to note that publications in a majority of the areas in which concrete technology in the 21st Century can confidently be predicted to be significantly advanced over that of 1971 have Mohan's fingerprints on them. He has participated in this progress as author, coauthor, sponsor, or editor of the documentation without which a development does not become transferred technology. Indeed, in my view, one of the significant advances in concrete technology since 1971 has been the improved infrastructure of conferences, symposia, symposium volumes, periodicals, and journals that has markedly shortened the gap between when work is done in the field or laboratory and when the resulting technology is transferred to those who can evaluate it and, if relevant, use it. Mohan has been the major player in this progress in the period since 1971.

Indeed, Mohan, to a significant extent, anticipated the activity in which I am at the moment engaged, when he included, as the first item in the compilation he commissioned and edited in 1992 called Advances in Concrete Technology, a paper by Adam Neville called "Concrete in the Year 2000" (Neville, 1992). I shall compare some of the comments Neville made then with those of the ACI Committee in 1971.

In February 1993, the Civil Engineering Research Foundation (CERF), affiliated with American Society of Civil Engineers (ASCE),

was urging the U.S. Government to sponsor a major research effort on high-performance construction materials at a cost of \$2 to \$4 billion over ten years as "necessary for America's economic well being in the 21st century." In the discussion of this proposal, it was said that 500 million tons (450 Tg) of concrete (two tons (1,800 kg) per person) are produced annually in the USA. This is up from the 1-1/2 tons (1,400 kg) mentioned in the 1971 ACI report. CERF described concrete as "the most widely used man-made product."

The need for airports and airfield pavement is suggested by the statement that the number of commercial aircraft in operation increased 75 percent from 1970-1990 and the number of passengers and passenger miles has doubled.

CERF wrote "today's typical concrete" has 5,000-6,000 psi (34-41 MPa) compressive strength and said "improving this by a factor of 2 or 3" (to about 15,000 psi (103 MPa)) would "afford new design possibilities."

The sorts of things CERF has in mind to have done include better information management, use of technology developed elsewhere, better technical education, better evaluation of new products, use of life-cycle costing with modification of the bid system, and "removal of barriers to use of new technology."

Their concept of "high-performance concrete" is concrete with "enhanced" ease of placement and compaction without segregation, early age strength, toughness, volume stability, and life in severe environments. Their "Vision of Tomorrow's Concrete" is that:

"a) Concretes will be 'high-tech' engineered materials with the composition and structure, on the microscopic level, being designed to give the desired properties.

"b) Intelligent systems will aid the selection of a concrete with the desired combination of performance characteristics for each intended application.

"c) It will be possible to predict the performance, including the service life, of a concrete to be used in a given application.

"d) Concrete construction will be specified on a life-cycle cost basis with guaranteed performance.

"e) Ability to optimize concrete for each application will facilitate decisions concerning the use of recycled, marginal, or other non-traditional materials.

"f) Concrete will be able to be adapted to market place demand taking into account constructibility, automation, and the availability and qualifications of labor.

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"g) New concepts for composite construction using concrete and steel in combination will provide new opportunities for designers to optimize their structures.

"h) Contracting and procurement procedures will facilitate innovation (e.g. implementation of the results of concrete research).

"i) A streamlined standards development process will facilitate technical innovation and concrete will have to meet global standards.

"j) The U.S. will be recognized as a world leader in high-performance concrete technology and construction."

In 1971, the ACI report noted that concrete possessed the advantages of "low relative cost, general availability, use of local materials, versatility, and adaptability. Further, concrete is the one construction material the engineer can personally formulate, within limits, to meet specific individual job requirements of durability, strength, etc. Concrete's versatility makes it exceptionally desirable for industrialized mass production applications. Since it can be produced in almost any shape and finish, it is the ideal material for many uses."

PROGRESS IN CONCRETE TECHNOLOGY

In 1980, Mohan edited a book called "Progress in Concrete Technology" in which Clyde Kesler updated the ACI 1971 "Concrete - Year 2000." This was the springboard for Neville's 1992 update.

In 1980, Kesler predicted, confidently—and correctly, that "the kinds and amounts of wastes from other industries that will be used in making concrete will increase, further assuring that concrete will be an environmentally preferred construction material." He predicted, more optimistically, that "the currently fragmented concrete industry will recognize the necessity of cooperating to plan research, development, training, education, and uses, or simply stated, to plan the future of concrete." He spoke of 60-MPa concrete having been used in a number of structures and 75-MPa concrete in two columns of one building. This is still not very close to the predictions of 138 MPa, routinely, and 414 for special purposes mentioned by the committee in 1971. He gave an excellent list of 17 references.

ADVANCES IN CONCRETE TECHNOLOGY

Neville, 1992, predicted a continuation of the development of "special concretes" and mentioned, as examples: high-performance concrete, roller-compacted concrete, high-volume fly-ash concrete,

special shotcrete, fiber-reinforced concrete, and polymer concrete. He suggested that the major change needed was already within our capability since the knowledge upon which it is based is already available. Elements of the change he believed needed include: Better trained "concretors" and better trained engineers who understand how to select among concrete-making materials in ways appropriate to the work to be done. He suggested we need people who are knowledgeable both about materials and structural behavior. He noted that there have been such people, for example, Raymond E. Davis and Hubert Rusch.

He spoke of a need for a commitment to consistent production of concrete of appropriate quality.

He wrote: "Today 100 MPa can be consistently and regularly achieved and 120 MPa is well within the capability of continuous production." He remarked that these values were up from those of 60 and 75 MPa cited by Kesler (1980). I would point out that had Kesler been talking of cube strengths his numbers would have been at least 65 and 80, while had Neville been talking of cylinder strength his numbers would probably have been 95 and 115—but there's still a real difference.

Neville addressed the "continuing problems" and wrote specifically of protection of reinforcement, curing strength testing, moisture content of aggregate, and sources of aggregate. His final recommendation was that we should "'jazz up' the image of concrete and the people who make it."

DUNDEE, 1993

On 7-9 September 1993, Professor Ravindra Dhir, with numerous co-sponsors, arranged an International Conference called "Concrete 2000, Economic and Durable Construction Through Excellence," held at Dundee, Scotland. Included were sessions on "New Trends in Specification and Design" (18 papers); "Efficient Concrete Production and New Materials" (25 papers); "Construction Techniques" (26 papers); "Infrastructure" (25 papers); "Research, Development, and Education" (22 papers); "New Applications - The Future" (18 papers); and the program listed 27 other papers not scheduled for presentation; a total of 136 papers. My review of these 136 titles reveals that nearly all the current questions are examined, corrosion, alkali-aggregate reaction, sulfate attack, freezing and thawing, abrasion resistance, cracking, fly ash, silica fume, ground slag, pozzolans other than fly ash and silica fume, chemical admixtures, polymers, fibers, precast, shotcrete, high strength, repair methods, statistical quality control, curing, cathodic protection, release agents, etc., etc. The only subject that was relatively new, to me, was use of ground rubber tires ("tyres") in concrete which was addressed in two papers, one by four authors from the University of Pennsylvania, the other by three Canadian

authors, two from the Technical University of Nova Scotia, the third from the Federal Department of Public Works.

CEMENT, 1993

In June 1993, Peter Byland of Holderbank addressed the question of "How might the world of cement look toward the year 2000?" He noted that, at present, Europe has too much of most everything including cement producers. But he predicted that by 2000: (1) the U.S., Canada, and northern Europe will be experiencing flat or declining cement consumption, (2) the European cement industry will be invigorated and profitable—but with no additional capacity, (3) the largest rise in cement consumption will come from the developing economies outside Europe, especially in Latin America and Africa. At present, 15 percent of U.S. cement capacity is technologically obsolete and the profitability of the industry is inadequate to yield or attract investment funds for new production facilities. He suggested that previous U.S. demand peaks at about 90×10^6 tons/yr are likely to be repeated; but U.S. capacity, now about 85×10^6 tons/yr, is declining. New expansion or new plants take 4 to 7 or more years to commission.

SCORECARD

So where does this leave the predictions of the 1971 ACI report? My scorecard comes out as follows:

1. The ACI Committee discussed how concrete could be improved: greater resistance to cracking, greater tensile strength, more rapid strength gain, better volume stability, lower density, greater resistance to wear and deterioration, lower heat evolution, lower permeability, decreased perishability of fresh concrete, increased use in cold weather, reduced labor costs, and reduced cost of demolition. The report discussed advancements in materials, in planning and design, in construction, and in attitude. In the latter case, they discussed cooperation among owners, designers, and contractors; in accreditation; and in pride of technology. Finally they discussed examples of outstanding uses of concrete by the year 2000 in dams, taller structures, longer structures, floating cities, and highways. Many of the anticipated improvements have been made or are being made. Others will probably be made sometime, but not necessarily soon. One comment that was included, for which I was responsible, was the prediction that by the year 2000, SI units of measurement would be universally adopted. I am afraid it is likely that, in 2000, this will read "universally, except in the United States." I hope not, but I am not as optimistic as I was in 1970.

2. In the 21st Century, I believe that the typical concrete production operation will have available supplies of probably up

to several dozen different ingredients that can be included in a batch of concrete and that it will be a simple matter to dispense any desired combination of these into an appropriate conveyance, which takes a finite quantity of concrete to its place of use or to a pipeline system which will deliver any desired quantity to a point that may be quite distant, in which the ingredients are selected for quite specific considerations of use. I see no reason why successive quantities of concrete, intended for successive customers or successive portions of a given project, being carried out by a given customer, could not be distributed from the same concrete-making facility in succession. All that will be necessary is that at the user end, the user be able to identify that the particular concrete that is just reaching him is a particular mixture intended for a particular use in his particular operation. Whether we have very many floating airports in oceans and larger lakes, as was predicted in 1971, and whether the experience of such floating airports will result in floating cities by the year 2000, as was predicted, I cannot guess. However, we know a lot more today about floating bridges and we know a great deal about concrete in off-shore structures, relatively few of which are floating.

3. For the purposes of making unusually tall structures, it was predicted in 1971 that, by the year 2000, one could make 10,000-psi (70 MPa) concrete using relatively lightweight concrete. Shideler, in 1957, reported strengths of over 9,200 psi (6,314 MPa) for expanded-clay lightweight-aggregate concrete having a freshly mixed unit mass of 114 lb/ft³. It was predicted that strengths of over 60,000 psi (415 MPa) could be obtained for special purposes and strengths of 20,000 psi (138 MPa) will be routinely obtainable. I expect 60,000 psi (415 MPa) may be possible and I am confident that 20,000 psi (1,138 MPa) will be routinely available.

4. Concrete will continue to be "the indispensable material of construction" and will be "used in greater quantities than any other man-made construction material."

5. The concrete that the world will need will be available. The degree to which the making of cement and concrete will also be an important means of disposal of wastes from other activities of society has grown and will continue to grow.

6. The well established versatility of concrete will become even greater as more ingredients become recognized as permitting production of concrete with levels of properties not previously available.

7. Research and development will become more needed as the complexity of concrete-making increases, the requirements become more specific and more restrictive, and the variety of ingredients becomes larger and larger.

8. In order for technology that is developed to be efficiently used, we need efficient technology transfer, but, even more, we need increased realization by industry and government that technology should be transferred and procedures changed. Also we need better education and training of the concrete and concrete materials production work force so the improved technology will be accepted and used effectively.

9. We will continue to improve test methods and specifications. We will have more performance specifications and fewer based on composition or design. Test methods will become integral parts of the quality control/quality assurance systems of materials production and concrete production. The goal will no longer be to detect and reject non-compliant lots of material or products but to ensure that no such lots are produced. The tools to do this are becoming available.

10. Producers of cementitious materials, aggregates, and chemical admixtures will take advantage of performance-based specifications to produce concrete-making ingredients from a wider range of raw materials and obtain both economies of production and the ability to produce concrete of a wider range of levels of many relevant properties, some not now considered relevant for concrete.

11. Concrete need not deteriorate. Specifically, concrete can economically be produced to resist all the normal levels of deteriorating influences. When this fails to happen and deterioration takes place prematurely and not due to the unpredictable intervention of catastrophe, it is either due to failure to specify what was required or failure to produce what was specified; in short, ignorance, stupidity, negligence, or fraud.

12. In 1971 it was predicted that making concrete in batches would be obsolete by 2000. I doubt it; but I expect we will have more continuously mixed concrete.

13. The improvements in "attitude," cooperation among owners, designers, and contractors that the committee said in 1971 "must come" are coming but not as quickly as would be hoped. There are still too many, too large litigations that cost lots of money that should better be used, for example, to build more efficient cement-making capacity or educating the concrete work force. We need to follow up on Adam Neville's words of 1992 that we should "'jazz up' the image of concrete and the people who make it."

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SP 144-3

A Holistic Approach to Concrete Technology for Major Bridges

by B.C. Gerwick, Jr.

Synopsis:

The durability criteria for major bridges differs from that of most other structures in that currently, major bridges are designed to serve for 100 to 125 years. Challenging this longevity are not only the normal physical and chemical attacks on the concrete itself and on the reinforcement, but the intentional application of salts to the decks of highway bridges and, in the case of railroad and floating bridges, the accumulation of internal damage (fatigue) due to cyclic dynamic loading.

Great progress has been made recently in identifying causes and finding preventive and mitigating measures aimed at specific phenomena. Advanced laboratory technology and equipment have been combined with field observations to describe the processes, prescribe tests for early diagnosis, and develop appropriate countermeasures.

A number of tests of specific parameters have recently been developed and are now being implemented as mandatory criteria for concrete in major bridges designed for lives in excess of 100 years. Ever more refined linear elastic finite element analyses are being employed to reveal areas of probable cracking due to structural response. Rigid enforcement of specified quantitative criteria, focussed on specific parameters, ignores the interactive complex processes involved. Excessive reliance on such criteria impedes rather than helps the construction progress and may on occasion be counterproductive to durability.

What is required instead is a holistic, systems approach, looking not only at the individual processes and phenomena, but at their interaction.

Keywords: Bridge decks; bridges (structures); corrosion; cracking (fracturing); cyclic loads; durability; fatigue (materials); finite element analysis; freeze thaw durability; microcracking; reinforcing steels; salts; tunnels.

Ben C. Gerwick, Jr. spent 30 years in marine construction, with emphasis on the development and use of prestressed concrete. He then served for 20 years in teaching and research on concrete and now serves as a consultant on major bridges worldwide. He is an Honorary Member of ACI as well as ASCE and PCI, and is a Past President of Fédération Internationale de la Précontrainte.

INTRODUCTION

Dr. Mohan Malhotra, in whose honor this symposium is being given, has served as an inspiration to all of us who are dedicated to enhancing the durability of concrete structures. He has not only conducted some of the most meaningful research on specific aspects of durability but has led the profession in addressing durability in a broad context through his pioneering work in the fields of non-destructive testing methods and of superplasticizing and pozzolanic admixtures.

Durability can be defined as the continued ability of the structure to satisfactorily serve under normal operating conditions with minimum maintenance. Applicable Design Codes address durability by limiting the water-cement ratio and specifying minimum cover of concrete over the reinforcement. Other clauses specify air entrainment and air-void parameters, and the properties of the component materials. The codes also address the structural performance in terms of cracking, and crack width as being significant measures of durability.

Major bridges differ from most other structures in that they are designed for a service life of 100 to 125 years, sometimes even longer. This is three to five times longer than an offshore platform and twice that of most harbor structures or buildings. Even after such a long life, we don't expect to remove and replace them. The San Francisco-Oakland Bay Bridge and the Golden Gate Bridge are approaching 60 years of age and our current plan is to retrofit them for new seismic criteria and to keep them in operation another 50 to 100 years. The Firth of Forth Bridge and the Brooklyn Bridge are both over 100 years of age and carrying even heavier loads than those for which they were originally designed. A few years ago, I had the honor of participating in the dedication of the 1300 year-old Chao-chow Bridge in China as an International Historic Monument (Fig. 1): it is still in service.

A second consideration, relatively unique to bridges, is the intentional