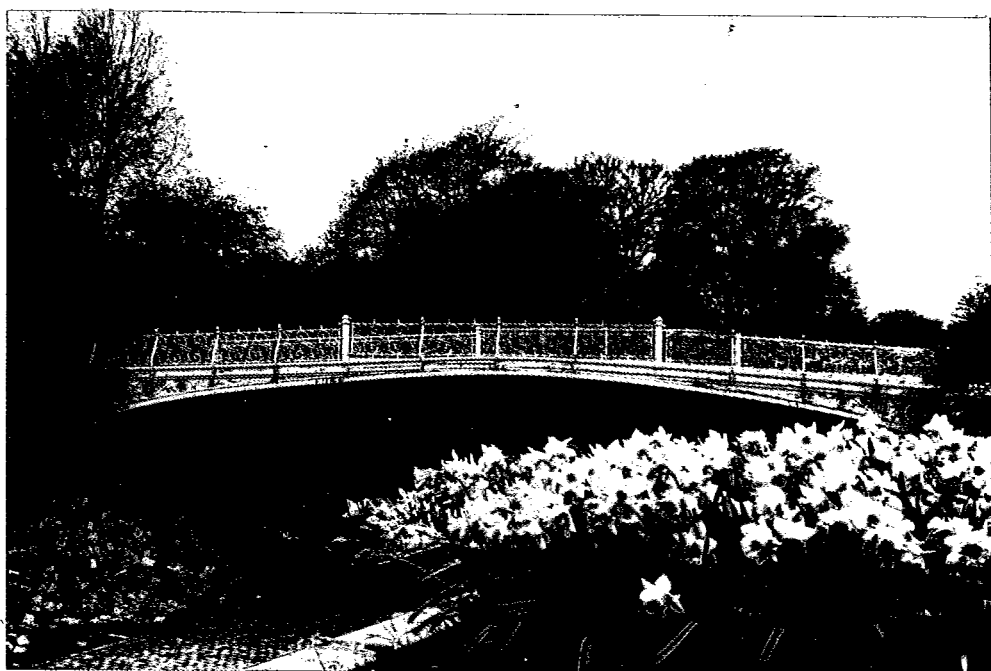


DURABILITY OF CONCRETE

G.M. IDORN INTERNATIONAL SYMPOSIUM



Jens Holm
Mette Geiker
Editors



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PREFACE

The G.M. Idorn International Symposium on Durability of Concrete, sponsored by Committee 201 on Durability, was held at the 1990 Annual ACI Convention in Toronto, Ontario, Canada. This symposium was dedicated to Dr. G.M. Idorn in view of his many decades of relentless dedication to the subject of improving concrete durability. Dr. Idorn, "Gunnar," or known to many of us as "Room Temperature Syndrome Gunnar," enjoys worldwide recognition for his professional attitude, however, to highlight some of the key elements of Dr. Idorn's work in relation to ACI, a brief biography is included in the beginning of this symposium volume.

A total of 32 papers were presented during the four sessions of the symposium. An average of more than 100 attendees representing countries on six continents were attracted to the symposium, making it truly international. The speakers addressed topics ranging from laboratory studies of cementing systems over recent developments regarding improvements in new structures, case histories and recent theories about deteriorating mechanism in concrete.

This volume has been divided into four parts, which all deal with the durability of concrete. Part 1 covers durability aspects in relation to effects of environment and placement. Part 2 covers effects of composition. Part 3 deals with the assessment of durability, and in Part 4 various case stories are given.

I would like to thank Mr. Paul Klieger, Mr. Bernie Erlin, and Mr. Emery Farkas for their very valuable assistance in making the symposium a reality. Also, I would like to express my appreciation of the very substantial effort which my co-editor, Dr. Mette R. Geiker, has devoted to the compiling of the papers and the preparation of this symposium volume.

Jens Holm
Member, ACI Committee 201
Durability

GUNNAR M. IDORN

Gunnar Morten Idorn, born in 1920, grew up in the North Zealand coastal village of Gilleleje. He graduated as civil engineer (M.Sc.) from the Technical University of Denmark in 1943, specializing in port and coastal engineering. After national service in 1943 and 1945 he served with the Board of Maritime Works on the west coast of Jutland from 1945 to 1953.

The requirements for quality management with the introduction of new technology in construction works, combined with observations on a large scale of old marine concrete structures of lasting durability along with cases of severe deterioration became leading highlights for G.M. Idorn's future life in the world of concrete.

From 1953 to 1960 he served with the Danish Building Research Institute. His work included major contributions to guidelines for winter concreting in which the maturity concept was introduced as a means of controlling low temperature hardening of concrete. He managed the field and laboratory investigations of some 600 concrete structures in a ten year program with focus on alkali silica reactions. He introduced thin section petrography as a means of studying chemical and physical reactions in concrete. His D.Sc. was awarded in 1967 for a pioneering study and guidance in diagnosing deterioration of field concrete.

As lecturer at the Academy of Engineers, Dr. Idorn wrote the first Danish textbook on cement for civil engineers. From its opening in 1960 to its closure in 1976 he was head of the Concrete Research Laboratory, Karlstrup, which became renown for its development of a new curing monitoring system, compaction innovations, durability studies and international activities. The series of international conferences on alkali aggregate reactions was launched in Denmark in 1974.

From 1978 G.M. Idorn Consult operated in international markets, after 1986 as an affiliate of the Danish consulting company, Ramboll & Hannemann A/S, with Dr. Idorn as counselor to the management of this company since 1989.

Since the 1950's he has been continuously engaged in international and Danish cooperative activities regarding concrete research and professional research planning and management. He is a member of the Danish Academy of Technical Sciences and a recipient of the Ostenfeldt Gold Medal.

Gunnar has been an ACI member since 1953 and was elected honorary member in 1981. He presented the Raymond E. Davis lecture in 1983, and has been active in several committees, notably in C201 for many years and in CMRC since its creation in 1984.



ON THE COVER -- The pedestrian bridge near Langelinie, Copenhagen is a 19-meter long shallow arc bridge. It was built in 1894 and still serves its purpose, proving that concrete can be made durable.

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CONTENTS

PREFACE	
by Jens Holm	iii
GUNNAR M. IDORN	iv
COMMITTEE MEMBERSHIP	vi
ROOM TEMPERATURE SYNDROME: THE LIFE AND TIMES OF GUNNAR IDORN	
by R.E. Philleo	1
NOTE ON INTERNATIONAL CONCRETE RESEARCH	
by J. Skalny	11

PART I -- DURABILITY OF REINFORCED CONCRETE -- EFFECT OF ENVIRONMENT AND PLACEMENT

CONCRETE STRUCTURE AND PROTECTION OF STEEL REINFORCEMENT	
by V. Ukrainčik and D. Bjegović	21
AN HOLISTIC APPROACH TO THE CORROSION OF CONCRETE IN AQUEOUS ENVIRONMENTS USING INDICES OF AGGRESSIVENESS	
by J.J. Basson and B.J. Addis	33
DURABILITY OF REBARS IN CONCRETE	
by R.N. Swamy	67
THE INFLUENCE OF IMMERSION VIBRATION ON THE VOID SYSTEM OF AIR ENTRAINED CONCRETE	
by M.J. Simon, R.B. Jenkins, and K.C. Hover	99

INFLUENCE OF CURING CONDITIONS ON THE DURABILITY RELATED PROPERTIES OF NEAR SURFACE CONCRETE AND CEMENT MORTARS by F.R. Montgomery, P.A.M. Basheer, and A.E. Long	127
---	-----

PART II -- DURABILITY OF REINFORCED CONCRETE -- EFFECT OF COMPOSITION

CONCRETE MICROSTRUCTURE AND ITS RELATIONSHIPS TO PORE STRUCTURE, PERMEABILITY, AND GENERAL DURABILITY by D.M. Roy, D. Shi, B. Scheetz, and P.W. Brown	139
--	-----

ALKALI SILICA REACTION PROCESSES: THE CONVERSION OF CEMENT ALKALIES TO ALKALI HYDROXIDE by S. Diamond and M. Penko	153
---	-----

CALCIUM CHLORIDE IN TYPE V-CEMENT CONCRETE by B. Mather	169
---	-----

CONTROLLED CEMENT HYDRATION: ITS EFFECT ON DURABILITY OF CONCRETE by E. Senbetta and M.A. Bury	179
--	-----

THE EFFECT OF BLAST FURNACE SLAG AND RELATED MATERIALS ON THE HYDRATION AND DURABILITY OF CONCRETE by D.M. Roy	195
---	-----

DURABILITY OF MORTARS AND CONCRETES MADE WITH A NATURAL POZZOLANA by A.A. Ramezaniapour	209
---	-----

ROLE AND EFFECTIVENESS OF MINERAL ADMIXTURES IN RELATION TO ALKALI SILICA REACTION by R.N. Swamy	219
---	-----

SULFATE RESISTANCE OF CONCRETE CONTAINING FLY ASH by P.J. Tikalsky, R.L. Carrasquillo, and P.G. Snow	255
---	-----

PART III -- DURABILITY OF REINFORCED CONCRETE ASSESSMENT

QUANTIFYING MICROSCOPICAL EXAMINATIONS OF CONCRETE FOR ALKALI AGGREGATE REACTIONS (AAR) AND OTHER DURABILITY ASPECTS by I. Sims, B. Hunt, and B. Miglio	267
--	-----

EARLY AGE PERMEABILITY MEASUREMENTS FOR PREDICTION OF CONCRETE DURABILITY by J. Figg	289
--	-----

IN SITU ASSESSMENT OF DURABILITY OF CONCRETE MOTORWAY BRIDGES by P.A.M. Basheer, F.R. Montgomery, and A.E. Long	305
--	-----

REFLECTIONS ON STEEL CORROSION IN CONCRETE by D.G. Manning	321
---	-----

A NEW METHOD FOR ASSESSING FROST DAMAGE IN NON-AIR ENTRAINED HYDRAULIC STRUCTURES by R.D. Hooton, J.A. Sato, and P.K. Mukherjee	339
--	-----

PART IV -- DURABILITY OF REINFORCED CONCRETE CASE HISTORIES

REHABILITATION AND IMPREGNATION OF A CONCRETE ARCH BRIDGE TO INHIBIT THE FURTHER EFFECTS OF ALKALI AGGREGATE REACTION AND THE MONITORING OF THE EFFECTIVENESS OF THE COATING SYSTEM by G.E. Hoppe	357
--	-----

DURABILITY OF CONCRETE IN ICELAND by R. Kristjánsson and H. Ólafsson	381
OLD CONCRETE ROADS IN DENMARK by A.D. Jensen	393
DETERIORATION OF PRECAST CONCRETE PANELS WITH CRUSHED QUARTZ COARSE AGGREGATE DUE TO ALKALI SILICA REACTION by M.A. Ozol and D.O. Dusenberry	407
CONCLUDING WORDS OF THANKS AT THE ACI BANQUET, 22 MARCH 1990, TORONTO by G.M. Idorn	417
SI (metric) TABLES	421
INDEX	423

Room Temperature Syndrome: The Life and Times of Gunnar Idorn

by R.E. Philleo

Synopsis: Gunnar Idorn attained international fame while doing research in Denmark on rheology of fresh concrete, interfaces between cement paste and aggregate, homogeneity of cement paste, energy considerations, use of pozzolans and slags in concrete, alkali-aggregate reactivity, and curing technology. He has long been a student of American research and has actively cooperated with it. He was, in fact, technical advisor to the National Materials Advisory Board in its study of Cement and Concrete R&D in the United States. In addition to his technical contributions, he has contributed to the organization of research, the integration of industrial and university research, and the internationalization of research. He has been an avid supporter of the young researcher. Probably his greatest contributions are those which defined the effects of the early temperature history of concrete on longterm properties.

Keywords: Alkali aggregate reactions; blast furnace slag; curing; durability; microstructure; pozzolans; research; rheological properties; temperature

2 Philleo

Robert E. Philleo, past president and Honorary Member of ACI, is currently in private consulting practice in Annandale, Va. He retired as Chief, Structures Branch, Office of the Chief of Engineers, U.S. Army Corps of Engineers, in 1983. He chairs ACI's Concrete Materials Research Council.

INTRODUCTION

"To improve the service to modern practice, high priority ought to be given to exile the prevailing 'room temperature syndrome' in research and testing to its beneficial historic service in a past era of concrete practice."

So spake Gunnar Idorn in the 1983 Raymond E. Davis Lecture(1) of the American Concrete Institute. He was not, I believe, joining the legions of those who decry any concrete made in the laboratory as "labcrete," a material completely irrelevant to the real world. Rather, he was punctuating what has been, perhaps, his greatest contribution out of many to concrete technology that, although room temperature research has enabled us to understand the chemical and physical mechanisms which produce the microstructure of concrete, the longterm properties of concrete are critically affected by its temperature history during its very early life. Indeed, these effects can only be understood by carrying out well-controlled laboratory research.

How did this modest Danish high school student (Fig. 1) develop into a figure of international stature (Fig. 2)? Along the way he scaled the heights (Fig. 3) and plumbed the depths (Fig. 4). He overcame any animosity he had ever harbored toward a cluttered desk (Fig. 5). I believe a turning point came in 1956 at the RILEM Symposium on Winter Concreting, held in Copenhagen in February of that year. Gunnar had long been an admirer of American basic research. At this meeting he had the opportunity to meet the man he considered the leader of that effort, Treval C. Powers (Fig. 6). He found the American researcher to be approachable as well as competent, and he became his tour guide around Denmark. This happened to be, also, the first overseas trip by Powers, and I know from personal experience the impact it had on him. While the RILEM symposium had some good papers, I think its most significant accomplishment was the forging of a friendship between two of the giants of the field and in internationalizing the outlook of each. Soon Gunnar became a fixture on the American research scene. In fact, his first widely-read paper in an American publication appeared in the proceedings of the Powers Symposium, properly called the Symposium on Structure of Portland Cement



Durability of Concrete 3

Paste and Concrete, held in Washington, January, 1965(2). I have always been gratified by the fact that the paper appeared in Highway Research Board Special Report 90 immediately adjacent to my own contribution. I was also gratified when his Raymond E. Davis Lecture was published in the same issue of Concrete International as one of my papers. I have been a spear-carrier for Gunnar for twenty-five years. The Powers Symposium paper was on the apparently limited subject of the morphology of calcium hydroxide in cement paste. But by establishing that calcium hydroxide forms preferentially along the surfaces of aggregate particles, it laid the foundation for later work which explained some aspects of the strength-enhancing effect of the pozzolanic reaction in that it reduces planes of weakness along aggregate boundaries as the pozzolans react with the calcium hydroxide.

Gunnar first came to America to present a paper at the Fourth International Symposium on the Chemistry of Cement in 1960(3). That he was accepted into the company of western hemisphere researchers is evident from the photograph taken at the symposium banquet (Fig. 7). That he was accepted in the worldwide arena is evident from the fact that he was invited to give a principal paper at the 5th International Symposium on the Chemistry of Cement in Tokyo(4), and he has been a regular contributor to subsequent symposia. The title of the Tokyo paper was "Hydration of Portland Cement Paste at High Temperature under Atmospheric Pressure," one of the initial assaults on the room temperature syndrome.

BACKGROUND

Gunnar sometimes refers to himself as a simple coastal engineer. True, after he received his Master of Science degree from the Technical University of Denmark in 1943 he went to work for the Danish Board of Maritime Works to design and manage major coastal and harbour construction works. However, this is no small job in a country that consists mostly of coast line. While this experience may have whetted his interest in concrete, it was his move to the Danish Institute of Building Research in 1953 that enabled him to pursue active research on the material. He headed a group which did research on concrete durability, and it was here that he acquired his interest and expertise in petrography. Here he first acquired an international reputation.

Most of us associate him with his work as Director of the Concrete Research Laboratory of the Aalborg Portland Cement Company in Karlstrup, Denmark, a post in which he served from 1960 to 1976. I visited the laboratory during this period and was amazed at the breadth of activities and the expertise of the investigators. Here he added concrete compaction, curing technology, and special admixtures to his bag of tricks.

4 Philleo

this period he obtained a Doctor of Science degree from the Technical University of Denmark. Not surprisingly, the subject of his thesis was "Durability of Concrete Structures in Denmark."

After the company closed the laboratory in 1976, he remained with the company as manager of international development projects until he left in 1979 to form his own firm, G.M. Idorn Consult. The firm's list of clients is a Who's Who of the designers and builders of major construction projects throughout the world today. I have also visited this firm and have worked cooperatively with it, and I can report that it takes a back seat to no one in its ability to analyze a cement or concrete problem and in its ability to mobilize quickly to do the job. In 1986 Gunnar shed his administrative duties by passing on the presidency to another, but he remains the principal investigator for the firm.

Along the way he has garnered many honors, including three from the American Concrete Institute. He is the recipient of the A.S. Ostenfeld Gold Medal of the Technical University of Denmark for outstanding contributions to the research on concrete technology and especially regarding concrete durability and for corresponding contributions to the creation of international contacts regarding the research. His biography appears in the most prestigious compilations of people of achievement.

RESEARCH LEGACY

During the active lifetime of a researcher it is difficult to predict what portion of the research may comprise his chief legacy. Gunnar was among the first in Europe to recognize that an alkali-silica reaction problem existed on that continent, and he has been a tireless researcher of that phenomenon. He was the principal organizer of and keynote speaker(5) at the Sixth International Conference on Alkalies in Concrete in Copenhagen in 1983. Among his more than 200 publications are papers on rheology of fresh concrete, interfaces between cement paste and aggregate, cement polymer materials, homogeneity of cement paste, packing of aggregate particles, energy considerations in concrete technology, and, of course, mechanisms of deterioration of concrete. If I may make a prediction, however, I suggest that the greater part of his legacy will be in those areas where he has made advances by rejecting the room-temperature syndrome. He is a recognized authority on the use of fly ash, slag, and silica fume in concrete. A particular contribution to this field has been his recognition of the role of thermal activation in these processes, a point missed completely in room-temperature research. The slag reaction has long been known to be activated by alkalis or by calcium hydroxide formed during the hydration of portland cement, but he demonstrated that

thermal activation is equally important and is synergistic with the chemical activation. All those who have studied the maturity concept in concrete have discovered the critical importance of concrete temperature during the very early life of the concrete. Gunnar has quantified how these temperatures and temperature changes determine the quality of the cement paste. In addition, temperature increases resulting from early cement hydration, combined with cooling of concrete near surfaces, can produce non-linear temperature gradients which cause cracking that permanently damages the concrete. These effects in large mass concrete structures are routinely monitored, but the effects in smaller structures have traditionally been ignored. There are two kinds of researchers: those who produce research findings and publish them, and those who use the research findings to improve the technology. Gunnar clearly belongs to the latter group. In addition to identifying the importance of early temperature effects, he demonstrated that to a large extent temperature and temperature gradients could be controlled in the field by concrete technologists to maximize the quality of the cement paste. Thus was born the new subsistence of "curing technology." He has contributed two papers to the American literature(6,7) of a technique making headway in Europe.

While we honor Gunnar primarily for his technical contributions, he has had much to say on the organization of research, on the integration of industrial and university research, and on the internationalization of research. Of particular note has been his lifelong fascination with American research. He has at times interpreted American research to Americans. It is significant that in the late 1970's when the National Materials Advisory Board of the National Research Council convened a committee to report on The Status of Cement and Concrete R&D in the United States, it chose as its technical adviser a Dane rather than an American. His grasp of American technology is unique for one who has never been a resident of the United States. Throughout his career he has been guided by an insistence on technical excellence and the encouragement of the young researcher. His technical staff today is an effective blend of experience and youth.

It is altogether fitting that Gunnar Idorn be honored by a symposium on concrete durability and that it be sponsored by the American Concrete Institute. His contributions to and understanding of American technology are legendary; but, in spite of its name, the American Concrete institute, like Gunnar, is international in its outlook and its composition. The subject area of durability may seem unnecessarily restrictive for one of such a breadth of contributions, but in the long run everything he has done has been directed toward more durability. Even his work on cement paste homogeneity, particle packing, and rheology make possible a concrete with a reduced water content. And surely concrete with less water is a more durable concrete.

6 Philleo

Gunnar, we salute you for scientific flexibility, your dedication to improved concrete, your encouragement of youth, your efforts to unify concrete research on a world-wide basis, and your fascination with all things American.

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Fig. 1--Gunnar Idorn as a high school student



Fig. 2--With Bryant Mather at the Fifth International Symposium on the Chemistry of Cement in Tokyo

8 Philleo



Fig. 3--Atop a mountain in Norway



Fig. 4--Photographing concrete in a marine structure





Fig. 5--As Director of Concrete Laboratory,
Aalborg Portland Cement Company



Fig. 6--Sightseeing in Denmark with Treval Powers



Fig. 7--At Fourth International Symposium on the Chemistry of Cement in Washington. Clockwise from lower left: Alexander Klein, Katharine Mather, Richard Mielenz, Bryant Mather, E.G. Swenson, George Verbeck, Gunnar Idorn, and Jessie Mielenz

Note on International Concrete Research

by J. Skalny

Synopsis: In the past two decades, much progress has been made worldwide in the better understanding and utilization of concrete as a composite material; as a consequence, new design approaches have been introduced. However, challenges remain, including inadequate utilization of existing knowledge, poor workmanship, and conservatism in introduction of new technologies. Examples are given and potential approaches are suggested.

Keywords: Concrete technology; education; research; technology

12 Skalny

Jan P. Skalny has been associated with the construction materials industry for more than 25 years. At present he is the Director of Construction Materials Research at the Research Division of W. R. Grace & Co.-Conn., Columbia, Maryland. A member of ACI, ASTM, RILEM, and other organizations, he serves on ACI committees 201 and 544.

INTRODUCTION

It was about a year ago when Paul Klieger and Jens Holm, co-chairmen of this Symposium, asked me to prepare a short presentation on the successes and problems of the international concrete research. The invitation to present such a talk is not only an honor, but also a challenge. It is a challenge, for as a Czechoslovak-born American, I am speaking at a Symposium held in Canada, honoring Dr. Gunnar Idorn of Denmark and attended by numerous internationally-acclaimed concrete specialists. It is even more challenging, because Gunnar is one of the pioneers of international cooperation in concrete research.

It is not my intention to recite all the contributions of Gunnar Idorn to concrete technology and international cooperation. That information is known; it circumnavigated the globe several times. It is not even my intention to agree with everything he said and fought hard for in the past. I do not! But let me say it here, at the onset of my presentation: Gunnar is an exceptional human being, a real gentleman, a dedicated specialist. He is sometimes controversial ... and he loves it. This we have in common. He always was, and still is, very supportive of the young. He has the capability to motivate, to organize, to lead. He is a great friend, a talented colleague, a forgiving opponent. Gunnar, I am sure that I speak also for the other participants of this meeting, when I say: Many thanks for the years of friendship, for the compliments, and for the deserved criticism.

Allow me now to highlight some of the concrete technology issues that I consider important. What I would like to do is to give you a very personal, but pragmatic, view of selected successes and failures, and to solicit your help in increasing international



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cooperation. Do we need such cooperation? Certainly ... we always needed it, but the pressures are greater now. We need it because some of the challenges became global, primarily due to internationalization of the markets, the international nature of technology, and ecological reasons. We need it because we share the same resources and have to learn how to use them for the benefit of all. We need it because the cost of new technologies is too high to afford duplication.

An example demonstrating the international character of technology is the increase in foreign ownership of the U.S. cement industry. As of the end of 1989, about 65% is foreign owned; this compares with less than 10% only fifteen years ago. Similar internationalization is happening in the area of concrete production and concrete admixtures. The trend is global, and this fact contributes to the international information transfer, including dissemination of knowledge.

In her October 1988 presentation at the Industrial Research Institute meeting in Washington, D.C., Carolyn Hannson summarized the obstacles to international cooperation in descending order of importance as seen from the viewpoint of the researcher:

- Funding A Fact: Cooperative research is always more expensive than single-institution research.
- Bureaucracy Solution: Cut reporting to minimum, increase personal interactions to maximum.
- Language Suggestion: Become more sensitive when speaking to each other but, more important, listen better. Avoid slang.
- Culture A Must: Learn to appreciate the partners' customs and cultural biases.
- Distance Should be a minor problem in the Century of Communications.

All true. I fully agree. However, I would like to add to this list of obstacles a few items important from the national rather than the researcher's point of view. These are related to education, our publishing culture, university/industry cooperation methods, etc. Is it possible, for example, that we do not like to cooperate due to the often-desirable individualism that our culture promotes? Is this a barrier in international cooperation? Many of these

14 Skalny

issues are widely discussed also in other technical fields, and in industrial and governmental circles. An example of this is a recent report by the Committee on International Cooperation in Engineering, published by the National Academy of Engineering. Other institutions interested in international cooperation include Industrial Research Institute, National Science Foundation, National Institute of Standards & Technology, and many others.

INTERNATIONAL CONCRETE RESEARCH

I believe we should be generally pleased with the level of international cooperation in concrete materials science. International contacts go back many decades, to the times when activities at the Bureau of Reclamation, Portland Cement Association and a few other institutions were at the cutting edge of cement/concrete science. Personal contacts of the North American researchers with their foreign colleagues are very close, this being also reflected in the very high proportion of foreign members of the relevant professional societies (e.g., the American Concrete Institute, the Materials Research Society, the American Ceramic Society) and their very active participation in scientific meetings, joint publications, and contract work. It is to the credit of G. M. Idorn that he recognized the need and promoted such cooperation throughout his rich professional career.

A recent, more formal example of international cooperation is the Strategic Highway Research Program (SHRP). Numerous foreign specialists are stationed in the U.S. at present to participate in SHRP activities, and several of the awarded contracts are partially performed by foreign universities or private scientific institutions. Again, G. M. Idorn and co-workers are very intimately involved.

How good is our scientific work? The U.S. academic culture requires publishing, publishing, and publishing. In that order! At the same time, organization of conferences and production of technical journals became a business rather than a scientific issue. For these and other reasons, a substantial proportion of published papers does not produce novel information, experiments are at best repeated using newly available equipment (often resulting in more accurate but needless data), and the same data are used by the authors in several

publications. Many otherwise excellent scientific papers avoid discussion of the next logical steps: What is the meaning of these results? What are the results good for? This problem is international in nature, as pointed out by Dr. Calleja at the last International Congress on the Chemistry of Cement in Rio de Janeiro.

As seen from my industrial vantage point, the U.S. cement and concrete research remains one of the best. However, we have to develop a better appreciation of our best students and researchers for the "real-world" challenges and opportunities; some of them are placed in an international setting, and that makes them even more interesting.

Is research needed? Of course it is! Some of the most advanced developments in concrete technology are based on solid scientific principles. To develop such principles, we need to expand and deepen our basic understanding. Use of air-entrainment, high-range water reducers, and condensed silica fume to produce high-performance concrete are only a few examples of products resulting from scientific understanding of basic phenomena. New developments in materials often lead to improved processing techniques and new design approaches which, consequently, result in new technologies and markets.

The most recent example of the importance of R & D is the introduction into modern concrete of microsilica (condensed silica fume). The use of microsilica in concrete was patented in 1944 by J. W. Sharp, but it took years of research, primarily in Norway and other Scandinavian countries, until an adequate data base has been developed enabling its industrial use. Today, microsilica is used routinely in production of high-performance concrete, a well-known example being the Two Union Square building in Seattle.

So is research needed? Yes. We need both academic and industrial research of the highest quality. Most important, we also need vision. It is the combination of materials and engineering research, proper quality assurance, vision, and human dedication that enables first-class innovations. And many more such innovations are possible.

DIFFUSION OF KNOWLEDGE & TECHNOLOGY TRANSFER

Diffusion of international scientific knowledge is happening and, in a global market, it is beneficial to everybody. We should not assume anymore that we can live within our narrow geographic and cultural boundaries ignoring everybody else's technologies. Such attitude is arrogant and self-defeating. We should use others' technologies to benefit our own business desires, to satisfy our own personal and professional needs.

To be able to cope with foreign knowledge, we should learn foreign cultures and languages. Although it is true that "almost everybody speaks (broken) English", we should not count on it! It is equally difficult for a Chinese or a Russian to learn English as the other way around. Unfortunately, we do not see the need for it... and that is a mistake!

Compared to scientific interactions, our international cooperation is much less competent in the area of engineering, in international transfer of technology in both directions. According to the 1989 U.S. Industrial Outlook (Department of Commerce), U.S. construction business in overseas markets declined by 60% from 1982 to 1987, whereas foreign construction firms during the same period doubled their business in the U.S. The 1981 \$744 million trade surplus in construction materials became a \$2.3 billion deficit in 1987. Admittedly, international marketing and use of technology are much more complex than scientific work. But we have to find ways to do it, for, as I said at the beginning, science and technology are global, and so are markets.

Technology transfer, a widely discussed topic these days in the U.S., happens independently of our activities; knowledge diffuses whether we like it or not. The rate of its transfer, however, is a function of our active involvement. The U.S. still is in the forefront of scientific life, but we are failing in using our scientific "know-how" for commercial purposes. The body of knowledge is there, but we did not develop appropriate mechanisms of sharing it. This negatively influences our international competitiveness.

A case in point, to give one example, is the culture of knowledge exchange. Whereas, in the U.S., publications and intensive conferences are by far the most popular means of technology transfer, in Japan,



for example, the key factor in rapid diffusion of technology is close collaboration among and between academic and industrial research organizations, often actively energized (meaning: funded) by the governmental agencies. This approach enables them to learn from their mistakes faster because they genuinely share their experiences for the common good.

Some of the best concrete materials research is done by industrial research organizations; most of the best information is considered to be proprietary. The issue of proprietariness in competition is an obstacle to be reckoned with in international business. International cooperation is likely to be different if it addresses proprietary knowledge, rather than knowledge of non-proprietary technologies, including the technical infrastructure of technology (e.g., knowledge about codes, standards and measurement methods). We will have to develop appropriate approaches to handle the cases individually.

There are many reasons for the just described situation; some of the reasons are technical, some are institutional, others are cultural. We are fully capable of coping with this situation, once we recognize and accept the challenges.

The above, generally valid situation, is equally or more valid for the concrete industry. We have little history, and even less experience, of managing concrete technology commerce on the global scene. Transfer of foreign knowledge to the U.S., particularly in concrete engineering, is slow; this is not to say it is absent ... examples of excellent international businesses do exist. More important, we have difficulties expanding our businesses abroad, although we do have advanced technologies available for marketing.

ACI itself is one of the mechanisms of concrete technology transfer. The Institute represents a great body of knowledge and does its best to disseminate it. But today's best may not be adequate tomorrow ... the next Century is at hand.

MEANS OF IMPROVING INTERNATIONAL COOPERATION

What are some of the steps to be taken to improve the situation?

- We have to improve the quality of our civil engineering education; to produce more first-class engineers with deep knowledge of chemistry and materials science, and having appreciation for foreign cultures and technologies. Such education is a must if we want to continue living in a technologically-literate society. Motivation of the technical staff is crucial and, in an industrial environment, it involves establishment of a solid and stable science base (first-class researchers usually develop into first-class industrial scientists), identification of the correct problem, maximizing communications (technology transfer) by personal involvement rather than by written word, and the need for patience and persistence.

- We have to improve the quality of our technical and business management; it is very often provincial in thinking, not having the willingness to accept new ideas. Management has to be fully committed to meet the challenges in an international setting, accepting and using the relevant differences in business cultures, and to be flexible with respect to asset management (people versus facilities), manufacturing technology, and orientation of R&D (new products and applications versus new processes).

- We have to recognize and exploit characteristics that promote or inhibit transfer of technologies, and adapt the known mechanisms of transfer (e.g., institutionalized interactions and regular communications between developers/producers and clients/customers, personnel transfers, granting patent rights, use of champions, etc.). Among others, we will have to develop international automated information processing systems for accurate and economical exchange of state-of-the-art information.

- For the United States, metrication is crucial: it is a challenge, but also an opportunity. The U.S. is the only non-metric industrialized nation and this puts us at a competitive disadvantage when dealing in international markets. Metrication should be accelerated.

- And, we have to better understand and get more actively involved in the development of international

standards and in establishment of a coherent system for acceptance of innovative building products, particularly in the geographical areas of our business interests. Our standards have to be of first-class quality, to be acceptable in foreign markets.

Not all of the above suggestions are directly related to the international aspects of research. But, as we all know, research and marketing and standards and education cannot be viewed separately from each other. We all have to work in tandem. And this is the message I hear so clearly from Gunnar Idorn's lifetime work. Thank you, Gunnar.

SP 131-1

Concrete Structure and Protection of Steel Reinforcement

by V. Ukrainčik and D. Bjegović

Synopsis: The greatest threat to the durability of reinforced concrete structures is the reinforcement corrosion. The paper presents the importance of the concrete protective cover and the conditions causing the reinforcement corrosion under the action of chlorides and carbonic acid. Processes of absorption, diffusion and flow, i.e. of transport of media through concrete depend on the pore system and the amount of water in the pores. Physical laws describing the penetration of aggressive agents into concrete can serve as a basis for engineering calculations of reinforcement durability in the concrete as well as for the designing of the concrete cover. Physical laws and corresponding material parameters are briefly reviewed in the paper. For engineering purposes, in calculating the durability, four typical tasks can be solved. The processes of degradation depend on the pore system in the concrete structure, and the paper indicates some possible technological measures of structure modifications.

Keywords: Absorption; corrosion; cover; diffusion; durability; physical properties; porosity; reinforced concrete; structural design

22 Ukrainčik and Bjegović

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INTRODUCTION

The greatest threat to the durability of reinforced concrete structures often is the reinforcement corrosion. Conditions for the beginning of electrochemical process of corrosion appear, if concrete carbonatization causes the drop of pH value to below 9.5 i.e. if high alkalinity of pore water no longer presents a passive protection of the reinforcement. Reinforcement corrosion can also start if the amount of free chlorides in the concrete exceeds a critical value. There is no fixed critical value of the amount of chlor ions in the concrete to start reinforcement corrosion. It cannot be fixed because the total amount of chlorides determined by usual chemical analysis is not relevant. Corrosion is caused only by chemically free chlorides in the pore water, and they are difficult to determine. The risk to reinforcement corrosion at the same time also depends on the cement type and amount, concrete moisture, amount of alkalis and free lime and the kind and mechanical treatment of the steel reinforcement/1/. The whole problem of critical amount of chlorides in concrete is therefore an issue of risk-taking readiness, i.e. a probabilistic problem. For safety reasons the regulations usually determine the limit as 0.4 to 0.6 % chlor ions per cement mass.

It would be more suitable to use Page's classification /2/ for the reinforcement danger degree as:

slight risk	$Cl^- < 0.4\%$ weight per cement mass
considerable risk	$0.4 < Cl^- < 1.0\%$ weight per cement mass
great risk	$Cl^- > 1.0\%$ weight per cement mass

Some papers /1/, however, report on reinforced concrete structures where many times greater chloride concentration was found, without reinforcement corrosion.

Microclimatic conditions, heterogeneity of the micro structure and concrete quality essentially influence the corrosiveness of steel in concrete.

Penetration of aggressive media into concrete depends on the pore structure and can be described by three processes: absorption (capillary suction), diffusion, and head flow. This paper describes the influences of pore system on the penetration processes of aggressive media into concrete and will point to possibilities of technological interventions in the structure of concrete. Each of the three processes of media penetrating the concrete can be defined by well-known physical laws, and mathematical connection can be found between the concentration of aggressive media per concrete depth and the potential service life of the structure. These relationships could serve as a basis for engineering computing the structure service life and designing the reinforcement protection. Four typical engineering tasks in design of concrete cover are presented.

STRUCTURE OF CONCRETE COVER

Processes of absorption, diffusion and flow, under external pressure i.e. of transport of media through concrete depend on the pore system and the amount of water in the pores. Concrete contains pores ranging from centimetres to nanometres (Fig.1). Setzer /1/ has conveniently divided the pores according to their size and role in the transportation processes. These are voids from inadequate compaction or subsequent bleeding; specific pores due to aeration, capillary pores, and the minute gel pores. The great differences in pore size result in the structure of water and the water behaviour in the pores. For example, on the surface of the gel particles, water which is several molecules thick, due to the surface forces, has the density which is double to that in the capillaries or of free water in the voids. In the micropore area the dominant phenomena can be described only by physical laws of surface forces. The greater the pores, the greater the influence of macroscopic physical regularities, properties depending on the total volume of water in the pore, or on pore size. In larger pores, the influence of surface forces is smaller. In capillaries, this results in the well-known capillary suction and capillary elevation, and in the largest pores, the influence is negligible. In the largest pores, water transports only under head.

Gel pores, i.e. micro pores and mezo pores are constant (~ 28%) for the hydrated part of the cement stone, and their amount cannot be influenced. All other pores can be influenced by technological measures in the phase of mix design, compacting and curing (Fig.1).

In the interface area all kinds of oriented pores form /3/. This zone apparently presents the weakest part of the concrete structure, both concerning the mechanical properties and the durability. The pores between aggregate grains and cement stone are the ways of least resistance to the penetration of water and other media into concrete.

Aggregate pores have quite different character from pores in hydrated cement stone. Most aggregates have granular structure

24 Ukrainčik and Bjegović

permeable to liquids. Their pores are usually much larger, and with the porosity of aggregates of about 1%, the rock permeability coefficient is approximately equal to that of cement stone of 50% porosity. On the aggregate grain surface, however, these pores are filled with cement stone of lower permeability. This may be the reasons why aggregate grains are not the main way for water and other media to penetration into concrete.

The quality of concrete depends very much on its surface layer known as concrete skin. Three skins of concrete can be defined /4 and 5/: cement (depth about 0.1 mm), mortar (depth about 4 mm) and concrete one (depth about 30 mm). Depth of the skins depends on the wall effect, sedimentation and segregation, compacting method, and penetration and evaporation of water into the concrete and out of it. The consequences of these phenomena are variations of water /cement and aggregate/ cement ratios and increased porosity of the concrete surface layers.

These are the reasons why concrete skin in aggressive environments should be improved. Each subsequent action on the concrete cover should include the removal of the cement or mortar skins. This practically means that in the preparation of the substrate, the surface layer of concrete 2-3 mm deep has to be removed.

PHYSICAL LAWS OF LIQUID AND GAS TRANSPORTATION IN CONCRETE

Penetration of media into concrete can be described by three processes: diffusion, absorption and head flow.

a) Diffusion

Transport of media through concrete due to chemical or moisture or temperature potential is diffusion, and for transient (not steady state) phenomena the process is described by Fick's second law

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2}, \text{ where} \quad (1)$$

$\frac{\partial C}{\partial t}$ = concentration change in time

$\frac{\partial^2 C}{\partial x^2}$ = concentration change per cross-section

D = diffusion coefficient (m²/s)

The most influencing gradient is that of the moisture concentration, but it is often in combination with gradients due to different solution concentrations or temperature differences. as well.

Diffusion coefficient is a parameter of the material, but it is different for each media diffusing through the concrete. The passage of most media through concrete change the structure of the concrete, which in turn changes the diffusion coefficient. There are suggestions on the dependence of diffusion

coefficient on humidity, but they are still unreliable for practical application. Prognoses on the basis of constant D give satisfactory results so far - no worse than those obtained by taking functionally changeable D .

There are good correlations between gas permeability coefficient according to Darcy and diffusion coefficient /6/. Having data for D , Fick's diffusion equation can be solved numerically for actual boundary and initial conditions. For simple geometrical forms like those in Fig.2 /7/ the solutions are possible in closed form:

$$C_x = C_0 \left(1 - \operatorname{erf} \frac{x}{\sqrt{2 D \cdot t}} \right) \quad (2)$$

b) Absorption

In capillary absorption, two phenomena are important: capillary pressure and the resistance to capillary flow. Both of these phenomena depend on the pore size diameter. In the water that rises in the capillary, subpressure appears (p_k). It is defined by the surface tension of the water (σ) and the wetting angle (δ) on the boundary of the liquid air and capillary wall. Laplace's equation for capillary pressure can be applied:

$$p_k = \sigma \left(\frac{1}{R_1} + \frac{1}{R_2} \right) = \frac{2 \sigma \cos \delta}{r} \quad (3)$$

In expression (3), Laplace's equation is calculated for the capillary radius (r) and wetting angle /8/. If water is taken to completely wet the surface, equals zero. With this assumption, capillary elevation in concrete pores is calculated /1/ (Fig.3). In their final position capillary forces raising water are in balance with the water weight.

$$p_k = \rho \cdot g \cdot h$$

Actual capillary elevation greatly depends on the changeable geometry of the capillary pores and on whether the concrete is being wetted or dried /9/.

In order to obtain a balance of capillary forces and water column weight a certain time is necessary because water raising is resisted by friction against the walls.

Water absorption speed depends only on capillary porosity and is proportional to the capillary absorption coefficient A

$$q_a = \frac{A}{2} \sqrt{\frac{1}{t}} \quad (4)$$

Capillary absorption coefficient is determined experimentally /9/.

26 Ukrainčik and Bjegović

c) Flow under hydrostatic pressure

Water flow under external pressure is possible through capillary and larger pores (Fig.1). It is described by the Darcy's law

$$\frac{dq}{dt} = k \frac{h \cdot A}{l} \quad (5)$$

where

- q - flow volume (m³)
- k - permeability coefficient for the considered medium (m/s)
- h - pressure change on length l (m of water column)
- A - area (m²)
- l - length (m)

During the water flow the pore size and the viscosity coefficient (η) radically change. It is a well know fact with concrete hydraulic structures, that most often water permeability decreases due to advanced hydration, concrete swelling, carbonatization and capillary blocking in narrow places by water transported particles. Water permeability coefficient, therefore, is not a suitable parameter for concrete characterization. Standard tests can distinguish only very bad concrete from good concrete.

For flow of gasses, it is suitable to introduce specific permeability coefficient according to the Hagen-Poiseuille equation:

$$K = \frac{k \cdot \eta}{\rho \cdot g} \quad (m^2)$$

Test of gas permeability, give a more reliable insight into the open and connected porosity of concrete. The influence of the kind of cement, w/c ratio and above all the curing of concrete on the gas permeability coefficient is very clearly illustrated by Fig.4. Badly cured concrete can have the coefficient of gas permeability which is 100 times greater than the normal one, which can result in halved service life. Methods are developed /11/ for testing the concrete gas permeability in laboratory and in situ. The gas permeability testing procedure is effectively used in determining the value of repair materials /12/. Good correlations are found between gas permeability of concrete and some other parameters for transport processes of media into concrete /11/.

COVER DESIGN

For engineering purpose, in calculating the durability and designing the structure regarding the corrosion protection of the reinforcement, four typical tasks (Fig.5) should be solved.

- I. Diagnosis of the condition of the existing reinforced concrete structure. By testing samples taken from the structure, flow of aggressive media (Cl⁻, CO₂, etc.) per cover depth (c) and

around the reinforcement is obtained. This and the actual age of the structure (t) serve as a basis to calculate the diffusion coefficient (D), absorption (A), permeability coefficient (k) and to forecast the structure service life (t).

- II Calculation of permeability parameters D , A , k for the expected structure service life (t) and the given dimensions of the cover (c).
- III Designing the cover depth (c) for the expected structure service life and the given parameters D , A , k .
- IV Parameters D , A , k and the cover depth (c) are optimized for a given service life.

The real service life of numerous structures, especially bridges, industrial objects and some public objects is doubtlessly too short. On the other hand, in the design and the construction there is still no notion of the "designed service life" except for the wish for a structure to last "indefinitely". Between these two extremes, some minimum values of service life will soon have to be agreed upon, where routine checks and maintenance would enable the designed function of the structure.

The following proposal /13/ is a good example:

Structure	Expected service life (years)
Airport runways	30 - 50
Bridges (BS 5400)	120
Dams	50 - 100
Residential buildings	60
Harbours	80
Factories	26 - 50
Offices, shops	50 - 100

In designing the service life, damage risk degree as a function of time can be shown in a simplified way in two characteristic phases by the scheme in Fig.6. Data on material parameters (D, A, k) are available from laboratory and in situ tests, hence practical calculations and evaluations of concrete cover are possible /14/. Designed depth of the concrete cover (c) can greatly exceed that common in present practice and existing regulations, especially in slender structures with greater spans. The depths of 70 and 80 mm are quoted as necessary /15/. A good substitute could be subsequently but timely applied thin layers of polymer modified cement mortars. With great adhesiveness such mortars have gas permeability which is about ten times smaller than that of concrete skin /12/.

If subsequent examinations of concrete structure show insufficient protective value of the concrete cover or some lower concentration of aggressive media in the concrete, the reinforcement in the concrete can be protected by means of additional layers of mortars based on portland cement with polymer admixtures, or

28 Ukrainčik and Bjegović

only polymers, or polymer mortars. This is strengthening of concrete cover. Additional problems appear there: preparation and properties of the substrate, permeability properties of additional layer materials (selection), adhesion and compatibility and realisation.

Reinforcement cover saturated with aggressive media above the critical amount must be completely removed and replaced by a new one, which has adequate permeability properties. Special problems are similar to those strengthening the cover.

In both cases, correct diagnosis and categorization of the damage degree as well as the selection of adequate repair measures are very important.

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PORES IN CONCRETE			TECHNOLOGICAL INFLUENCES	MEDIA TRANSPORT LAWS	
r (m)	KIND			CEMENT/AGGREGATE INTERFACE	D I F F U S I O N
10-9	GEL 28%	MICRO PORES	CEMENT HYDRATION		
10-8		MEZO PORES			
10-7	CAPILLARY 0-10 %	MICRO CAPILL.	w/c RATIO		
10-6		CAPILLARIES			
10-5					
10-4	0-8% AIR PORES	MACRO CAPILL.	A.E.A.		
10-3					
10-2	VOIDS	LARGE OPEN PORES	COMPACTION AND "BLEEDING"	D I F F U S I O N	F L O W

Fig. 1--Pore distribution and technological influences

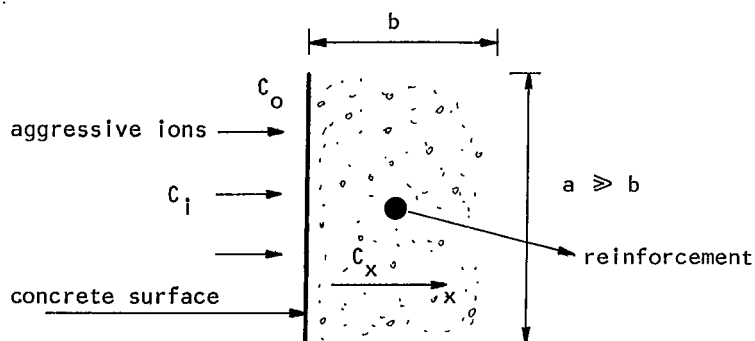


Fig. 2--Model of chloride ion transport into concrete

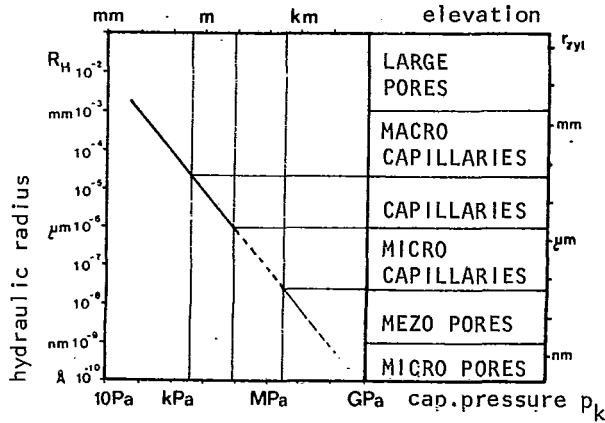
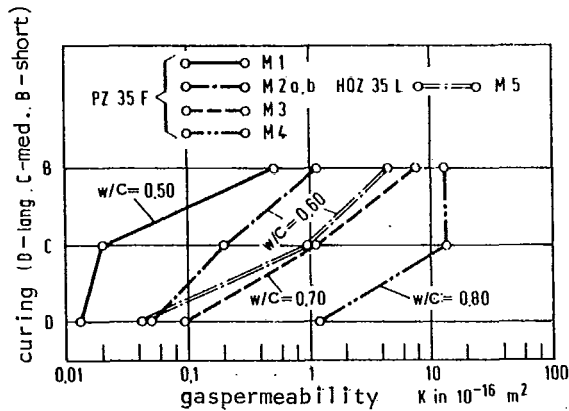


Fig. 3--Computed capillary elevation, i.e., pressure as a function of capillary radius $/3/$



PZ 35 F similar to type III ASTM C 150
 HOZ 35 F similar to type IS ASTM C 595
 Mi designates watercement ratio

Fig. 4--Interdependence of curing, water cement ratio, kind of cement and concrete permeability $/10/$

32 Ukrainčik and Bjegović

ENGIN. TASKS VARIABLES	I	II	III	IV
c	x ↑	GIVEN ○	DESIGNED ↑	DESIGNED ↑
D, A, k	xx ↑	DESIGNED ○	xx ↑	DESIGNED ↑
c_o ; c_x	x ↓	○	GIVEN ○	○
t	DESIGNED ↓	GIVEN ○	○	GIVEN ○

x as measured
 xx as calculated

○ as required
 ○○ as allowed

Fig. 5--Scheme of four tasks

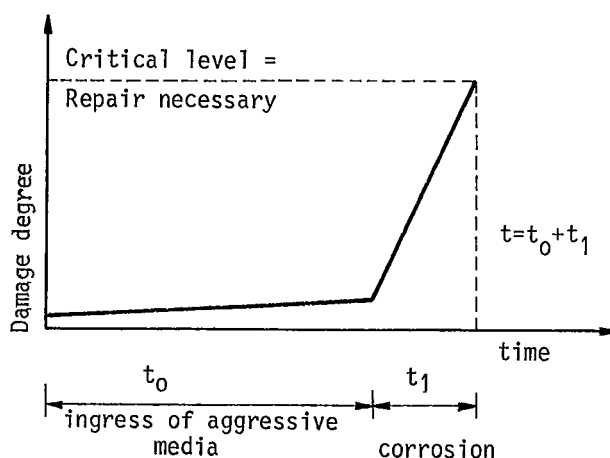


Fig. 6--Reinforcement damage degree versus time.

 t_0 is the time necessary for critical contamination around reinforcement t_1 is the time necessary for steel corrosion

SP 131-2

An Holistic Approach to the Corrosion of Concrete in Aqueous Environments Using Indices of Aggressiveness

by J.J. Basson and B.J. Addis

SYNOPSIS

Mechanisms of corrosion of concrete have been extensively studied and elucidated by various workers, but rate-determining factors have been neglected as have the interactions between different corrodents. However, by considering all relevant influences as part of the total corrosive environment, it is possible to quantify aggressiveness as indices and to use these in order to select the appropriate technology for the circumstances under consideration.

Keywords: Cements; coatings; corrosion; deterioration; environments; leaching; salts; spalling; tests; water; water cement ratio

34 Basson and Addis

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INTRODUCTION

Although codes of practice for concrete work used in various parts of the world deal with the question of aggressiveness of water to concrete, a study of these codes shows that:

- They generally consider individual parameters such as sulphate content in isolation and do not allow for the combined effects of various ionic species.
- They give widely divergent permissible limits of ionic concentrations.
- They are often based on water-treatment technology while corrosion technology would be more appropriate.

The engineer who has to specify concrete in an aggressive aqueous environment is therefore able to find only limited, and sometimes questionable, guidance from existing codes and other technical literature.

The authors believe that realistic guidelines are necessary to enable the engineer to specify concrete for exposure to aggressive water. This paper attempts to address this requirement by developing a set of indices to quantify the aggressiveness of water to concrete, and by providing corresponding recommendations for countermeasures.

To the authors' knowledge, this is the first time a rational attempt has been made to develop a design methodology for durability of concrete in natural waters.

This paper is divided into two sections. The first section, which forms the bulk of the paper, deals with the deterioration of concrete itself. The second section deals with the corrosion of steel embedded in the concrete.

SCOPE

The contents of this paper are intended to be used primarily for assessing the corrosivity of waters of natural origin (such as lakes, streams, subterranean aquifers, etc). The indices are therefore not necessarily applicable to industrial effluents and other wastes. Sampling is not discussed but the analytical tests deemed necessary are tabulated.

CORROSION OF CONCRETE

Mechanisms of corrosive attack on concrete by water

Concrete is a complex conglomerate of components which differ radically in their susceptibility to corrosive attack. The aggregates normally used are generally more resistant to attack than is the cementitious binder, which is the most vulnerable component because of its greater chemical reactivity. As a result of the vital role that it plays in maintaining the integrity of the entire matrix, it will be appreciated that any degradation of the binder undermines the soundness of the concrete.

From the point of view of understanding the corrosion reactions involved, the binder can be considered to be a mixture of hydrated di- and tri-calcium silicates, tri-calcium aluminates and tetra-calcium aluminoferrites, together with hydrated calcium and magnesium oxides and alkali metals, chiefly sodium and potassium. The common denominator is the presence of calcium and its compounds and the chemistry of this element therefore tends to dominate the mechanisms of corrosion.

The most important mechanisms of corrosive attack on concrete are leaching and spalling.^[1] These are further discussed below.

Leaching corrosion of a concrete can result either from the direct dissolution of one or more of the components of the concrete into the water or by the conversion of any of such components into more soluble forms as a result of interactions with the solutes present in the water. It is manifested by etching, roughening and general loss of material, starting at the exposed surfaces and progressing inwards.

"Spalling corrosion" is the term used in this paper for the various destructive effects that occur as a result of expansive reactions between one or more of the components of the concrete with solutes present in the water. The progression is usually weakening of the matrix, followed by cracking and eventually spalling.

36 Basson and Addis

Properties of water responsible for leaching attack**Solvency**

Water comes very close to being the universal solvent. All the materials found in concrete are soluble in water: some (eg calcium hydroxide) are fairly soluble, others (eg aggregates) are very sparingly soluble. However, a solubility of only a few micrograms per litre can mount up to an appreciable quantity of dissolved material when one considers the number of megalitres per unit area that a structure such as a breakwater or spillway is subjected to during its service life of a century or longer.

The acidity of the water

With rare exceptions the materials normally found in concrete have a higher solubility in acidic than in alkaline waters. In acidic waters more material can therefore be dissolved before saturation occurs.

Properties of water responsible for spalling attack**The nature of dissolved salts**

The salts dissolved in water are almost invariably dissociated into their component ions, which are then free to participate independently of their original partners in various chemical reactions. The most important of these in the context of corrosion of concrete are those ion-exchange reactions where an ion present in the liquid phase is exchanged for one present in the solid phase. Thus for example, if sodium sulphate is present in the water, it can exchange ions with the calcium hydroxide present in the concrete to give sodium hydroxide (which remains in the liquid phase) and calcium sulphate (which is a new and deleterious ingredient of the solid phase). Of equal importance are the ion-addition reactions that can occur within the concrete. The sulphate ion in the example just given can also react directly with the calcium aluminates to form monosulphates and ettringite, which is a sulphoaluminate with double the molecular volume of the original compounds. This in turn sets up expansive stresses far higher than the tensile strength of the concrete and leads to cracking and spalling failure of the structure. (See Reference 2 for a more detailed treatment of this topic.)

A large number of these ion-exchange and ion-addition reactions are possible, depending on which ions are present in the liquid phase. Both anions and cations may be involved in these reactions: hydroxyl ions may be exchanged for sulphate ions as in the example above, but magnesium may also be exchanged for calcium, with equally disastrous consequences. The importance

of these reactions lies in the changes in molecular volumes, crystal habits, solubilities or pH that occur either immediately or as a result of secondary reactions. In most cases the end result is either an expansive change or loss of cementitious properties, both of which undermine structural integrity. It is these factors that make such reactions so destructive.

FACTORS THAT DETERMINE THE RATE OF CORROSION

Composition of water

- **The concentration gradient between the solid and liquid phases**

The direction of chemical reactions is always towards establishing an equilibrium. If a large disparity in concentration is present between two phases, the reaction will proceed rapidly in the direction required to establish parity. In the case of concrete wetted by water, the concentration of calcium compounds in the solid phase is usually many orders of magnitude higher than that of these compounds in the liquid phase. In the case of distilled or very soft water the concentration of dissolved calcium salts in the liquid phase is almost zero and the concentration gradient becomes very large. The resultant dissolution rate can consequently be very high and rapid attack will take place.

This explains the extremely aggressive behaviour of distilled and very soft waters towards concrete, which can result in the rapid leaching out of the components described above, especially calcium hydroxide, the presence of which is essential for maintaining the integrity of the binder.^[3] On the other hand where water already contains high concentrations of the compounds present in the concrete, the concentration gradients are lower and can disappear when saturation of the aqueous phase is achieved. This explains the mitigating role of "hardness" in waters that have passed through calciferous strata and have picked up appreciable quantities of calcium salts, and also why very pure or very soft waters are often aptly termed "hungry" waters by corrosion technologists.

- **Ionic species**

The rate of corrosion depends on which ionic species are present in solution in the water. Spalling is usually associated with the presence of sulphate ions and the rate of corrosion depends on the cations associated with them. Where ammonium ions are associated with sulphate ions the rate of attack is enhanced by the volatility of the

38 Basson and Addis

reaction products. Where the ammonium ion is exchanged for calcium in the concrete, it is converted to ammonium hydroxide, which, when exposed to the very alkaline conditions present in the concrete phase, is volatilized and lost as ammonia. The net result is the formation of voids in the concrete and a loss of alkalinity (or rise in acidity) of the water, which then becomes even more corrosive. It is the combined effect of these reactions that makes the presence of ammonium salts so much more deleterious than that of its alkali-metal counterparts. The attack by sulphate is also enhanced because of the greater solubility of calcium sulphate in ammonium sulphate solutions.

- The presence of dissolved gases

Dissolved carbon dioxide gas is essential for the formation of the more highly soluble calcium bicarbonates from the relatively insoluble carbonates originally present on carbonated concrete surfaces, and its presence is therefore an accelerating influence.

- The concentration of dissolved salts

For a given combination of ionic species, corrosion is a function of concentration.

ENVIRONMENTAL FACTORS

- The temperature of the water

Chemical reaction rates are temperature dependent and generally double for every 10-degree rise in the Kelvin temperature. Warm waters will therefore have higher corrosion rates than cold waters.

- The movement of the water relative to the concrete

In the absence of any movement of the water layer in immediate contact with the concrete surface, any corrosive action will soon cease because of the depletion of reactants and establishment of equilibrium conditions. Corrosion rates will become diffusion dependent and proceed much more slowly under stagnant conditions than would be the case if the water were in motion and the interface layer were to be constantly replenished. Wave movements in tidal zones or turbulent flow in pipelines are therefore accelerating agents by virtue of their effective mixing action.

FIXING OF ACCEPTABLE LIMITING VALUES

This requires an evaluation of which characteristics of the water are significant in assessing its aggressiveness and what the limiting values of such characteristics should be under "standard conditions", which, for the purpose of this study, are defined as follows:

- A prevailing water temperature of 20 °C.
- Laminar flow conditions (ie gentle, non-turbulent flow, with a velocity sufficient to ensure that the replenishment of corrosive agents is not diffusion-rate limited).
- All corrosive ions present in their least corrosive form.

The first column of Table 1 shows those properties of the water which have been chosen as being significant in terms of its corrosiveness. The following points should be noted:

- Because pH and calcium content alone were found not to be a sufficient measure of the leaching propensities of waters, a simple but powerful test (see Appendix 1) was developed to serve as an additional measure of this mode of attack.
- Total ammonium ion content comprises the sum of both free and saline ammonia plus albuminoid ammonia expressed as ammonium ion content. (The rationale for this approach is that both the existing ammonium ions, as well as those that can be formed from the decay of any organic matter that may be present, should be measured to assess the actual corrosive potential of the water).
- Total sulphate ion content comprises the sum of both existing sulphate ions plus those that can be derived from the oxidation of any sulphides present. (The rationale is once again to ensure that microbiological changes are taken into consideration when assessing the full corrosive potential of a water).

Other columns of Table 1 reflect details of the analytical methods used and show the recommended limits for assessing the aggressiveness of water. The values so derived have been termed "normalized" values and those shown in the column headed "EXCESSIVE" as the "normalized limiting values" used in Appendix 3 for the derivation of indices of aggressiveness.

The need to standardize on strictly defined normalized values will be evident from a study of Appendix 2, in which some national standards are compared. The wide differences and apparent contradictions in the recommendations are probably due largely to the fact that these national limits have been fixed for very dissimilar local conditions having vastly divergent water temperatures, flow regimes and ionic species. Indeed, if some credible assumptions are made in respect of these environmental characteristics and the corrections discussed in Appendix 3 are applied to the data shown, the disparity lessens and the values so "normalized" move closer to those adopted in this paper.

Corrosion index

This is defined as a measure of the corrosiveness of a water and is derived from the sub-indices, which are in turn derived from the analytical properties of the water.

The derivation of the individual indices and correction factors from normalized limiting values are dealt with in detail in Appendix 3, but the most important parameters are summarized on the next page for convenient cross-reference.