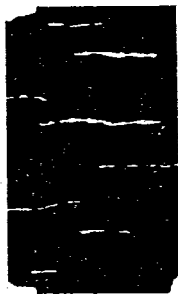
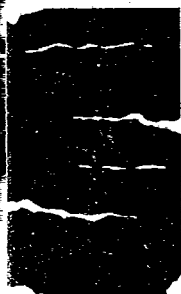


Concrete Durability

Katharine and Bryant Mather
International Conference

John M. Scanlon
Editor



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Volume 1

Concrete Durability

Katharine and Bryant Mather
International Conference

John M. Scanlon
Editor

American Concrete Institute, Detroit

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 December 1, 1987. All discussion approved by the Technical Activities Committee along with closing remarks by the authors will be published in the May-June 1988 issue of either ACI Structural Journal or ACI Materials Journal depending on the subject emphasis of the individual paper.

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PREFACE

Katharine and Bryant Mather have together contributed in excess of 90 years of their careers to investigations and research on the effects of various concreting materials and construction techniques on the ability of hydraulic cement concretes to remain durable under various aggressive exposure conditions found in today's environment. They are recognized throughout the world as authorities on concrete and have contributed greatly to the knowledge of concrete which has resulted in greater use of this, the world's most used construction material. Due to this great contribution, it is fitting that their peers recognize and express appreciation for their accomplishments by organizing this "Katharine and Bryant Mather International Conference on Concrete Durability," held at the Atlanta Marriott Downtown, Atlanta, Georgia, U.S.A., during the period 27 April - 1 May 1987.

The conference was sponsored by the U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, the International Concrete Education Foundation, and the National Bureau of Standards; and co-sponsored by the American Concrete Institute, American Society for Testing and Materials, Canada Centre for Mineral and Energy Technology, Transportation Research Board, U.S.A., and the Portland Cement Association, U.S.A.

Circular 1 announcing the conference and a call for papers was distributed to more than 5,000 individuals and organizations throughout the world in April 1985. As a result, 132 acceptable abstracts were received from individuals residing in 34 countries. During April of 1986, an "Official Invitation to Attend" was distributed to more than 4,000 individuals and organizations throughout the world.

In excess of 150 papers from individuals in 32 countries were received and reviewed in accordance with the policies of the American Concrete Institute (ACI), and were accepted for publication. To all those whose submissions could not be included in the symposium volumes, the Institute and the Conference Organizing Committee extend appreciation for their interest and hard work. The accepted papers are published in two volumes, and papers are divided by subject matter (alkali-aggregate reaction, sulfate attack, freezing and thawing, abrasion, corrosion, and others) as much as possible for the convenience of the reader.

The purpose of the conference was to serve as a forum to bring together outstanding concrete technologists in government, industry, and academia from throughout the world to review the present state of knowledge, to identify and discuss problems and known solutions, and to determine what improvements in practice are needed and how they may be achieved. THE CONFERENCE DID THIS, and a review of the proceedings will make it obvious that the present state of knowledge and anticipated problems have been well documented.

Thanks are extended to the many ACI members and others who helped review manuscripts. With but few exceptions, reviewers responded in a timely manner, and provided very helpful technical and editorial comments which enhanced the authors' papers. We also extend our thanks, and apologize, to those authors whose papers were not accepted, mostly because the papers did not fit the theme of this conference and not because of their technical content. We recommend that they seek other avenues for publication. The cooperation of the authors in accepting and implementing reviewers' suggestions, and in revising their manuscripts accordingly, is greatly appreciated. Particular thanks are extended to Robert Philleo and Thomas Reading for their assistance in carrying out extensive technical and editorial reviews of many of the submitted manuscripts. The assistance of Bryant Mather as the referee for many of the manuscripts is also greatly appreciated.

In addition, I would like to thank some of the unsung heroes: R. K. Dhir, James Pierce, and Joseph Lamond, for the excellent performance of their tasks of reviewing slides prior to the conference. Although too numerous to mention by name, I also thank the individuals who agreed to serve as Session Chairmen for the 45 Technical Sessions presented.

Above all, I want to thank my secretary, Mrs. Princess Nailor, for putting up with me during the preparations for the conference, and for her customary efficiency in handling all of the administrative reviews, announcements, requests, and everything else she had to do beyond the normal call of duty.

JOHN M. SCANLON, Editor
Chairman, CE/ACI
Katharine and Bryant Mather
International Conference on Concrete Durability

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Reflections on Concrete Durability and on International Conferences on Concrete Durability

by K. and B. Mather

Synopsis: The Organizing Committee for this conference requested that we make some remarks and prepare some comments for inclusion in the Proceedings. These words are intended as a basis for the former and to serve as the latter. We observe that: Concrete is international, it is made locally, it has infinite variability, it can be made to be very uniform, and it can be made to last as long as you want it to. An unsolved problem is assessment of the nature and severity of the exposure, so that requirements can be graduated according to severity. Only when this problem is solved will we be able to stamp out specification overkill.

The Organizing Committee also suggested we furnish biographical data and bibliographic data. The standard material accompanying this publication should suffice for the former. An appendix of selected items is provided for the latter purpose.

Keywords: concrete durability; concretes; exposure; specifications; variability

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ACI Honorary Member Katharine Mather, a resident of Clinton, Mississippi, retired from the Waterways Experiment Station, Vicksburg, Mississippi, in 1982 after 40 years of service with the U.S. Army Corps of Engineers. Mrs. Mather received the Anderson Award in 1982, and the Wason Medal in 1955. She has served on the ACI Board of Direction, and is a member of numerous technical committees. She is also an honorary member of ASTM and is a fellow of the Mineralogical Society of America.

Bryant Mather is Chief, Structures Laboratory, Waterways Experiment Station, U.S. Army Corps of Engineers, Vicksburg, Miss., and has been with the Corps since 1941. He is an Honorary Member and a past president of ACI and is a member of several technical committees. He is currently chairman of Committee 116, Notation and Nomenclature. His awards and honors include ACI's Henry C. Turner Medal in recognition of "his many years in improving the quality of concrete work...and for his vigorous personal efforts both inside and outside of that assignment."

INTRODUCTION

During the 44th Annual Meeting of the Highway Research Board (HRB) in 1965, Committee MC-B6 on Basic Research Pertaining to Portland Cement, of which Bill Dolch was Chairman and Katharine Mather was a member, put on the T. C. Powers Symposium on Structure of Portland Cement Paste and Concrete, under the cognizance of the HRB Concrete Division of which Bryant Mather was chairman. Special Report 90, the proceedings of that meeting, is a landmark that all serious workers should have access to and know.

The idea that anyone would put on a "Mather Symposium," in some way analogous to the Powers Symposium, was one that never occurred to either of us and one we found incredible when John Scanlon told us he was going to do it unless we seriously objected. As can be seen, we didn't. I might point out that we have here a "Conference," not a "Symposium." There is a story, once published in the ASTM Bulletin, about how a senior research scientist of a large corporation visited the Chief Executive Officer to request money to support a symposium and the CEO said "What is a symposium?" Whereupon they turned to a dictionary and found, to the dismay of the scientist: "Symposium, fr. Gr. 'symposion' a drinking party..." At that point the CEO said "I approve, nobody needs a drinking party more than you research types." We expect that those of you who desire to participate in a drinking party will not leave Atlanta unsatisfied!

The Organizing Committee has asked that we prepare some comments to go in the Proceedings and to serve as the basis of remarks that we are asked to make on the final day of the

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conference. In view of all that the Organizing Committee has put into making the conference a successful contribution to "durable" concrete and to all of us who have said, in one way or another, that "concrete need not deteriorate," it is with gratitude that we try to comply with its request.

This Conference has again demonstrated a number of fundamental truths and relationships, most of which are quite well known to most of those who participated--especially those more than forty years old. Among them are the following:

Concrete is international and may well be or become intergalactic. Concrete is made everywhere that people build. Concrete is of interest to those who build regardless of their language, their national heritage, their climate, or their cultural heritage. Concrete is like air to breathe, water to drink, earth to grow plants in; it provides for all what Dick Gaynor's 1976 National Ready Mixed Concrete Association's U.S. Bicentennial bumper sticker said: "Concrete - the Foundation of America" and which can be expanded to "Concrete - the Foundation of Civilization."

Concrete is made locally. The mixing water, with negligible exceptions (perhaps when concrete is made on the moon); the aggregates usually; the cement often, is or is made from one or more locally available natural raw materials, in various degrees of processing.

Concrete has infinite variability. The varieties of concrete that are intentionally produced are more numerous than the known varieties of natural sedimentary rocks. Concretes have been--and will be--required to be produced having unit masses from as low as 160 kg/m^3 (10 lb mass per ft^3) to as high as 4800 kg/m^3 (300 lb mass per ft^3); that have unconfined compressive strengths from as low as 0.35 MPa (50 psi) to as high as 275 MPa (40,000 psi); that are of any color--white, black, pink, turquoise, chartreuse, or as one Corps of Engineers' officer demanded: "sand tan"; we await the demand for "olive drab."

Concrete can be made to be very uniform. ACI Committee 214 was organized in 1946. It told concrete makers and users how to use strength tests to measure uniformity of concrete as produced. It is still doing it. In 1979, ASTM Standard Method C 917 for Evaluation of Cement Strength Uniformity was adopted. For many years ASTM Specification C 33 has put rather restrictive limits on uniformity of grading of fine aggregate in terms of fineness modulus. There are uniformity requirements on pozzolans given in ASTM Specification C 618.

Concrete can be made to last as long as you want it to. Even as some relatively fragile sedimentary rocks exist that have survived some hundreds of millions of years, so there are concretes that, if they remain in relatively mild environments, could last forever or at least as close to "forever" as we can measure. The duration



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of the life of a concrete with its relevant properties not sufficiently degraded so as to impair or jeopardize its ability to serve its intended purpose, is not usually a function of the absolute level of any universally relevant property of the concrete such as slump, unit mass, strength, modulus of elasticity, or color but is almost always a function of the interaction of some property or properties, the required levels of which depend on the severity of the environment to which the concrete will be exposed in service. One need not worry much about resistance to freezing and thawing in the tropics, except in facilities using refrigeration; or at the poles, except in facilities using intermittent heating. One need not worry about acid attack, abrasion attack, sulfate attack, attack by burrowing molluscs, or any of the myriad hazards described by Kleinogel, Biczok, or others except where they exist and impact the concrete of interest. And where these potentially destructive influences can be and are brought to bear on the concrete, if their action and its intensity and duration are properly anticipated, the concrete can be rendered adequately resistant so as to merit the designation "Durable," even when as demanded of us by the Nuclear Regulatory Commission, "durable" means not significantly degraded for many centuries or in some cases hundreds of centuries.

The message we have decided to leave with you at this time is (a) that concrete need not deteriorate and (b) that knowledge exists by the use of which concrete can be caused to exist in any of the environments of service for which it may be reasonably proposed with tolerable degradation during its intended service life, if precautions to limit degradation appropriate to the environmental severity are taken.

The Unsolved Problem - The important matter is to know how properly to assess the nature and severity of the environment of service; to get a reasonable estimate of intended service life; to get a reasonable assessment of how much degradation is tolerable structurally and, when relevant, aesthetically. One must then, from these and known relationships of environmental influences and concrete composition and constitution, have procedures and criteria by which to select materials, proportions, and construction practices that will, with reasonable probability of success and compliance with the owner's budget for the work, give concrete that will not deteriorate.

Most of the raw material of knowledge to do this exists, some in relatively quite refined states. But the manner in which this knowledge is used in an attempt to make it an effective tool for makers and users of concrete is primitive. Today we talk about reactive vs non-reactive aggregate and high-alkali vs not high-alkali cement as if all structures, in all environments, involving all ambient temperatures and temperature ranges, in all degrees of moistness from "it rains on the average every 12 years" to the tidal zone in Mombasa, as if all the precautions and restrictions must be taken at 100 percent of the degree we ever need anywhere, everywhere we need to do anything at all. There is no relaxation

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of the 0.60 percent Na_2O limit on cement as a function of environmental severity, reactivity of aggregate, or anticipated level of permeability of concrete. An aggregate is either reactive--or not; if not, nothing need be done, no precautions taken; if "reactive," then the precautions must be taken without reference to degree of reactivity or degree of severity of exposure.

Today we talk about need for resistance to freezing and thawing. If the concrete will ever likely freeze when any of the spaces in it that can hold freezable water are more than 91 percent full, we need air-entrainment, sound aggregate, and protection until moderate maturity is achieved. And, "air-entrainment" means an air content that will give an air-void system with an $\bar{L}$, a bubble spacing factor, less than 0.2 mm (0.008 in.) regardless of whether we have one or one hundred cycles of freezing and thawing per year and regardless of whether the rate of freezing is fast or slow or whether the minimum temperature achieved 10 mm below the exposed concrete surface is minus 5 C or minus 50 C. This topic was elegantly explored by Treval Powers years ago and was brought back to us this week by Bob Philleo.

We have decided to refer to these sorts of approaches as "specification overkill." It involves, much of the time, paying more than needs to be paid to buy a level of protection that, in many cases, can't ever be needed and from which no good can ever be derived. "Ever" in the preceding sentence means not more often than once in a million years. Today we have computers that can be run by most bright junior high school scientists that could be used to take the knowledge that does exist and derive from it reasonable criteria for matching degree of precautions needed or degree of restriction required of the contractor in his exercise of choice among materials, proportions, and practices; so that only limited precautions and light restrictions are called for when the nature and intensity of the anticipated environmental hazards and insults the concrete must resist are slight or of short duration in time. We can then reserve the levels of precautions we now take for all levels of severity for those cases where the hazard is really very severe and protection is needed for a very long time. We might well, by so limiting these requirements in their applicability, be able to increase their degree of protection so as further to minimize the probability that they will be less effective than needed.

Our challenge to all of you therefore is: Since Concrete Need Not Deteriorate, Insure that it Doesn't, but do so without raising the cost more than necessary; stamp out specification overkill.

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APPENDIX

We have selected from the approximately 500 titles in our respective and joint lists of publications the following for the reasons stated.

Mather, Bryant. 1945. "Effect of Type of Test Specimen on Apparent Compressive Strength of Concrete," Proc., ASTM, Vol 45, pp 802-812. Results of tests of 2375 specimens, drilled cores, molded cylinders, modified cubes suggested that factors relating specimen types varied with strength level.

Mather, Katharine. 1947. "Relation of Absorption and Sulfate Test Results on Concrete Sands," American Society for Testing and Materials Bulletin, No. 144 (January 1947), pp 26-31. Test data on samples of 409 sands showed a high correlation of the performance test value and the property test value but this cannot be used as an acceptance criterion for a specific material.

Mather, Bryant. 1948. "Petrographic Identification of Reactive Constituents in Concrete Aggregates," Proc., ASTM, Vol 48, pp 1120-1125. A description of criteria for recognizing opal, chalcedony, tridymite, cristobalite, acid and intermediate volcanic glass in samples of aggregate.

Mather, Katharine and Bryant Mather. 1950. "Methods of Petrographic Examination of Aggregates for Concrete," Proceedings, American Society for Testing and Materials, Vol 50, pp 1288-1313. Also 1950 Preprint, No. 76, 25 pp. The description of the techniques and procedures that became ASTM C 295-54.

Mather, Bryant. 1952. "Cracking of Concrete in the Tuscaloosa Lock," Proc., Hwy Res. Bd., Vol 31, pp 218-233. A report on an extensive investigation primarily by Katharine Mather of what turned out to be the Corps of Engineers' first major example of alkali-silica reaction in a structure in service.

Mather, Katharine. 1953. "Applications of light microscopy in concrete research," Symposium on Light Microscopy, American Society for Testing and Materials Special Technical Publication No. 143, pp 51-70. A review of the development, since 1882, and state-of-the-art including some previously unpublished results of research on mass concrete, selected for the ASTM Sanford E. Thompson Award for 1953.

Kennedy, Thomas B. and Katharine Mather. 1953. "Correlation between laboratory accelerated freezing and thawing and weathering at Treat Island, Maine," Jour. American Concrete Institute, Proceedings Title 50-9, Vol 50, pp 141-172. Also WES Bulletin, 1954. Authors' closure to discussion, ibid (December 1954), pp 172-15 to 172-20. A major attempt to relate laboratory test data to field test data to performance in service. Selected for the ACI Wason Medal for Materials Research for 1955.

Mather, Bryant. 1957. "Laboratory Tests of Portland Blast-Furnance Slag Cements," Jour. ACI, proc., Vol 54, pp 205-232. A report on a study of samples of the product at all six of the plants making portland blast-furnace slag cement in the U.S.A. in 1952.

Mather, Bryant and Katharine Mather. 1958. The Butterflies of Mississippi, Tulane Studies in Zoology, Vol 6, No. 2, New Orleans, La., pp 63-109, 6 figures. Supplements 1, 2, 3 have been published in the Jour. Lepid. Soc. 13:71-72, 1959; 30:197-200, 1976; and 39:134-138, 1985. Recorded occurrence in Mississippi of 150 species of butterflies; increased from 83 to 122 to 144 to 150.

Pepper, Leonard and Bryant Mather. 1959. "Effectiveness of Mineral Admixtures in Preventing Excessive Expansion of Concrete Due to Alkali-Aggregate Reaction," Am. Soc. Testing Mats., Proc. 59, pp 1178-1203. Based on the Waterways Experiment Station Technical Report 6-841 (1958) showed that the amount of pozzolan or slag required to be introduced into a high-alkali cement-reactive aggregate mortar mixture to reduce expansion by 75 percent ranged from 10 to 45 percent and varied as fineness, silica solubility, and silica content changed. Selected for the 1961 ASTM Sanford E. Thompson Award.

Mather, Katharine. 1965. High-Strength, High-Density Concrete, WES MP 6-698, 10 pp; also Journal, Amer. Conc. Inst., Proceedings, Vol 62, No. 8, pp 951-962; reprinted on pp 1587-1596 of ACI SP-34, 1972, Concrete for Nuclear Reactors. Concrete having unit weights of 225-235 lb/ft³ made using each of two sorts of iron ore (magnetite and ilmenite) as high-density aggregate and having water-cement ratios of 0.30 and 0.35 by mass developed strengths of 10,000 to 12,000 psi. Concrete can be simultaneously high-strength and high density.

Mather, Bryant. 1968. "Stronger Concrete," in A Symposium on Concrete Strength, Highway Research Record No. 210, NAS-NAE-NRC Publication 1553, pp 1-28. A state-of-the-art review based on one prepared for the Air Force listing reports of concrete having 10,000-psi strength and higher and factors affecting production of such concrete.

Mather, Bryant. 1968. "Field and Laboratory Studies of the Sulfate Resistance of Concrete," in Performance of Concrete - Resistance of Concrete to Sulphate and Other Environmental Conditions - A Symposium in Honour of Thorbergur Thorvaldson, Canadian Building Series, No. 2, University of Toronto Press, pp 66-76. A review of the chemical reactions involved in sulfate attack and an attempt to relate results of chemical analysis and calculated phase composition of cements to field and laboratory test results.

Mather, Bryant. 1969. "Deterioration of Concrete in Eisenhower Lock," Trans., Ninth International Congress on Large Dams, Vol VI, pp 427-429, Paris. A report to the international dam building

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community that for as severe an exposure as the St. Lawrence Seaway having very sound aggregate and a proper air-void system is not enough; it is also necessary that a degree of maturity be achieved before concrete can, with impunity, be allowed to freeze while critically saturated.

Mather, Bryant. 1969. "Sulfate Soundness, Sulfate Attack, and Expansive Cement in Concrete," in Proceedings, RILEM International Symposium on Concrete Durability, Technical University, Prague, Czechoslovakia, pp C-209 to C-220. A discussion of relations and differences among the phenomenology of the "sulfate" test to predict frost effects; sulfate attack on concrete; and the use of expansive cement. The concept of "crystal growth pressure" is questioned.

Mather, Bryant. 1969. Research on Concrete, Stanton Walker Lecture Series on the Materials Sciences, Lecture No. 7, University of Maryland (National Sand and Gravel Assn., National Ready Mixed Concrete Assn., Washington, D.C.), 15 pp. A review of topics for and benefits of concrete research in which it was concluded that "As humanity tries to cope with the exponential increase in population, pavements, and pollution, research on concrete has an increasingly important role to play in providing the knowledge that will permit society to provide pavements--and other concrete structures--for people and reduce pollution."

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Mather, Katharine. 1981. "Condition of Concrete in Martin Dam After 50 Years of Service," Cement, Concrete, and Aggregates, ASTM, Vol 3, No. 1, pp 53-63. A case history of concrete in a structure with extensive evidence of alkali-silica reaction but which appears to be ready to serve its owner successfully for another half century.

Mather, Katharine. 1981. "Factors Affecting Sulfate Resistance of Mortars," Proceedings of the 7th International Congress on the Chemistry of Cement, Paris, Vol IV, pp 580-585; also WES MP SL-80-17, 18 pp. (CTIAC Report No. 44.) Summarizes recent work showing that some pozzolans are very effective in preventing expansions of mortar made with sulfate susceptible cements, others are not. The ones found effective were silica fume and volcanic glass. The ones found less effective or, in some cases, harmful were fly ashes. A tendency for lignite fly ash to be worse was noted.

Mather, Katharine. 1985. "Preservation Technology: Evaluating Concrete in Structures," Concrete International, Vol 7, No. 10, pages 33-41. This paper prepared and presented at the ACI Convention in Boston in 1975 was intended primarily to share concrete technology with architectural and historic preservation technologists.

Mather, Bryant. 1986. "Selecting Relevant Levels of Quality," Concrete International, Vol 8, No. 3, ACI pp 30-36. Presented at the Abdun-Nur/Cordon Symposium on Quality Concrete in Construction, the intent was to suggest that achieving a given level of quality in concrete in construction is not enough. Also needed are relevant and appropriate criteria for selecting the levels of quality to be achieved.

SP 100-2

Benefits from International Interaction in Concrete Research and Development

by G. Idorn, P. Nerenst, and E. Poulsen

ABSTRACT

The importance for a small European country of early contact with the powerful American research after World War II is described with emphasis on the integration of learning from the behavior of field concrete and from theoretical exploration of the basic nature of concrete.

The tutorial and exchange contributions by K. and B. Mather are discussed, especially about their system approach to investigations of field concrete and their dedication to the development of research and testing.

A survey of the changing conditions for concrete technology and research is outlined, and in conclusion more integration of structural analyses and materials research are recommended.

Keywords: concrete durability; concrete technology; field tests; petrography; research; tests

INTRODUCTION

The story of how contacts were established between the American cement and concrete research and Denmark after World War II is a display of long-term profitable returns for a small country from modest, but dedicated investments in cooperation and exchange.

Denmark, like other European countries, faced after 1945 a serious housing shortage, excessive unemployment rates and exhausted serviceability of marine and infrastructure works, but there was also insatiable desires among young engineers to regain and renew past potentials for technology development and international contacts.

The Danish civil-engineering education with a strong basis in applied sciences and in cement and concrete technology had traditions for continuous updating of news from international research and engineering innovations, primarily through the late Professor E. Suenson's pioneering efforts in teaching, and his own, personal engineering for the development of building design and construction with concrete.

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The social demand for housing and for more employment of workers coupled with insufficient supply of bricks and masons, and no indigenous steel or timber production of significance, created two starters for the new development:

- * A national building research institute, and
- * A strong demand for new knowledge of concrete technology

Winter concreting could double the housing production capacity, and simultaneously reduce the unemployment rate for unskilled workers during the winter seasons.

Consequently, the first publication from the new research institute was a preliminary recommendation for winter concreting practice based upon European experience, and therefore taking attainment of a minimum compressive strength as the requirement for exposure to freezing temperatures.

During a visit to study the concrete research in the US, the director of the materials research of the institute became aware of the discovery of the effects of air-entrainment on the freeze-thaw resistance of concrete, Plum⁽¹⁾. Concurrently the Marshall Aid program was launched as an expression of the outstanding American willingness to supply experience and technical knowledge for the European rebuilding efforts, and to reconstruct international research and technology cooperation. In 1951 Nerenst⁽²⁾ visited all the prominent research institutes and research colleagues in the US, including the USBR, Waterways Experiment Station, Portland Cement Association, US Bureau of Reclamation, National Bureau of Standards and others^(3,4,5).

The new theoretical approach by Powers and colleagues^(3,4,5) to exploration of the physical structure and properties of hardened cement paste was basically different from the prevailing, empiric concepts in European research. The new American theory was applied in the second Danish recommendation for winter concreting, Nerenst, Rastrup, Idorn⁽⁶⁾. A poster for the sited sheds was subsequently issued, which explained the means to monitor the heat/strength development in concrete in low temperatures. Both guidelines applied also the maturity concept and heat transfer theory.

While in the US Nerenst had discussions with K. and B. Mather at WES, and a visit to Th.E. Stanton, the California State Highway Department, was arranged for an introduction to alkali-silica reactions. Upon return to Denmark, Nerenst found suspicious pop-outs of coarse, white aggregates in surfaces of exposed concrete structures, and also extensive map-cracking and gel-exudation on the Vilsund-bridge in N. W. Jutland,⁽²⁾. This was the first "infamous" discovery of deleterious alkali-silica reactions outside N. America. Similar patterns of damage were then also found in marine works on the coasts of W. Jutland, Idorn^(7,8), and also in inland structures.

A comprehensive research program was then initiated in 1954 under the joint auspices of the Academy of technical sciences and the Danish National Building Research Institute, which over the following years issued a special series of research studies, altogether amounting to 22 progress reports. This, and the research on winter concreting, became in effect a profound and lasting response to the new dualistic US-approach: Basic theoretical research concurrent with extensive studies of field concrete behaviour. Besides, the acquaintance with the intensive research and engineering communication and cooperation, and later-on with the profusion of new instrumentation, became essential for the creation of a new generation of concrete research workers.

American cooperation was further extended during E. Poulsen's training in concrete petrography and work with alkali-silica reactions at WES, and with visits to USBR and PCA in 1954. The subsequent Danish school of field concrete investigations and the use of thin sections for appended microscopic examination was founded on the basis of this transfer of experience and methodology for examinations and testing regarding concrete deterioration.

Ever since these early days the Mathers' indefatigable dedication to the development of examination and testing methods, and their tutorial availability for exchange and advice has remained a permanent source of valid and candid education for research in Denmark as well as in other European countries. Their early perception^(9,10,11) of field concrete as "geology alive" and contemporary contributions by others, like Mielenz⁽¹²⁾ and Brown⁽¹³⁾ taught us to take real concrete as the outset for explanatory research and laboratory modelling.

PETROGRAPHY OF CONCRETE

The pioneering American School of investigation of concrete structures, in the creation of which K. and B. Mather played significant roles, introduced experience from the studies of geology in the adapted methodology:

- * First, examination of the structure in the field, with survey and subsequent detailed description of the behaviour of the concrete and of the environments, and of visible evidence of deterioration, if any. Herefrom tentative hypotheses of the cause or causes of observed distress.
- * Next, collection of suitable concrete specimens for close-up laboratory macro-examination, for characterization of the general quality and condition of the concrete and its constituents and also for identification of visible evidence of deleterious alterations, if any. Again a tentative check of the initial interpretation of the field observations.

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- * Third, detailed microscopic, petrographic observations, and supplementary analyses by wet chemical analyses, x-ray, DTA-DTG, infrared, atomic-absorption, SEM and other means for assessment in depth of the microstructural quality of the concrete, and the kinds of physical and chemical/mineralogical alternations observed, if any.
- * Then, eventually, interpretation of the results in pleno of the investigation and concluding statement of the cause or causes of the observed state of the concrete structure. Also assessments of the general state-of-the-art knowledge, and whether the results of investigation are in agreement with this, or present new knowledge.

It is worth mentioning that until the time of elucidation of this methodology the quality of concrete was characterized practically only by the strength of prepared cubes made on construction sites or in research and testing laboratories. The wealth of analytical instrumentation available today did not exist in those days. Petrographic and wet chemical analyses were the primary new tools applied until the 60's, and even for petrography it was difficult to prepare adequate thin sections, so that optical identification in powder mounts of hand-picked minute deposits of a suspicious nature and occurrence became the most used method for assessment of chemical deterioration in concrete. It was the subsequent development of thin sections prepared by polymer impregnation, Poulsen (14), Andersen and Petersen (15), which made it possible also to observe cracking in the micro-structure, and deposition of various phases of hydrated compounds and anhydrous salts in cracks and void spaces etc., resulting from deleterious processes.

The diagnostic value of this new approach became early enhanced in the US because the investigations proved indispensable for identification of alkali-silica reactions, carbonation, sulphate attack and freezing-thawing damage.

IMPACT ELSEWHERE

The increasing awareness of studies of the behaviour of field concrete as complementary to laboratory concrete specimens was early noticed in Canada, where alkali-carbonate reactions were first identified, Swenson (16) and sulphate attack became the subject of much attention, Swenson, Ed.(17).

Assarsson and Sundius (18) and pioneered petrography on cement and cement paste in Scandinavia, followed by Hagerman and Roosaar (19), while Bastiansen et al (20) explored the complex of alum-shale sulphate attack. Elsewhere in Europe workers like Jones, Midgley, Nurse, Gille, Farran, Coutinho and others contributed with exploration of the micro-structure of cement paste in concrete. Partly due to the history of concrete in Europe the attention was much towards cement and concrete

chemistry, Lea (21), Czernin (22), while the American research moved towards higher priority to the physical properties of cement paste and the freeze-thaw resistance of concrete.

The application of new methodology and knowledge in the Danish research on alkali-silica reactions from 1952, and some years' subsequent, intensive investigation of many structures, and of the aggregate resources and the susceptibility of the Danish types of flint resulted in guidelines, issued in 1962, for the making of durable concrete. To prevent alkali-silica reactions it was recommended to use either aggregates without flint (quartz sand and crushed granite being available), or to use a low alkali cement or a low alkali, pozzolanic cement. However, it was also found that the investigations had shown deleterious reactions in field concrete to be an exception and what corresponded to "safe reactions" to be much more common with the generally used aggregates, ordinary portland cement of eqv. Na_2O about 0.7-0.8%, and usual cement contents. A premium price was charged for low alkali cement, and also for the more rare flint-free aggregates. As a consequence, most concrete during the next decade or so was made without special regard to alkali-silica reactions by using ordinary flint-containing aggregates and ordinary portland cement, with a gross national-economy profit, Idorn (23). This is an interesting contrast to the practice in the US, where engineering practice from the mid 40's was offered and used low alkali cements (without premium charge) wherever alkali-aggregate reactivity of aggregates was indicated by the regulatory testing.

Early during the 70's there appeared growing concern in Denmark and also a desire in the US and in a few other countries, e.g. Germany, England and Iceland, for updating of the state of the art of alkali-aggregate reactions. Contacts maintained with K. and B. Mather resulted in an international workshop with 25 invited participants, including several Danish researchers, and organized by Aalborg Portland via the Concrete Research Laboratory, Karlstrup. This meeting initiated the forthcoming international conferences on alkali-aggregate reactions in Reykjavik, Iceland, 1975 (24), at the Cement and Concrete Association, England, 1976 (25), Purdue University, USA, 1978 (26), Cape Town, South Africa, 1981 (27), Copenhagen, Denmark, 1983 (28), and Ottawa, Canada, 1986, with a wealth of continuous updating of our knowledge on this kind of concrete deterioration.

THE CHANGING CONDITIONS

At most of the above and numerous other conferences K. and B. Mather have advocated broader attention to the issues of concrete durability, to proper advance of the appending research, and to the changing engineering conditions. It is of interest for the future to consider the most influential of these.

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B. Mather has suggested that alkali-silica reactions are increasingly happening because the amounts of concrete are increasing, and more concrete is made now than in the past in regions where susceptible aggregates are not yet well identified, and the standards are not updated. Concurrently, however, the modern cement manufacture technology tends to increase the alkali-content in portland cement, and engineering has favored higher content of cement in concrete for the development of structural strength. Also higher C_3S -content and finer grinding have changed cements. Altogether, therewith more types of aggregates than those originally found reactive, are now causing violent or long-term, sneaking alkali-aggregate reactions. Besides, concrete is increasingly being made in regions with severe aggressive environmental conditions, especially in the "sun-belts" of the world.

To match the problems associated with the outlined developments in industry and engineering practice, a wide spectrum of improved testing and control methods, and of chemical and mineral admixtures, have been made available. In fact, there attainable, beneficial effects on the workability of fresh concrete, the curing processing and the durability of hardened concrete, have not been fully brought to bear in practice, despite educational efforts as e.g. by the American Concrete Institute, and intensive research in many countries.

OPPORTUNITIES FOR THE FUTURE

The persistent emphasis in K. and B. Mather's investigations of concrete deterioration on the behaviour of field concrete in service is now subject to broad appreciation. This is because for instance alkali-silica reactions causing cracking and expansions and supplementary damage, may have severe impact on the structural integrity of modern structures and buildings. The appending, general concern about repair and maintenance costs and safety invites research vigorously to exploit the structural effects of the materials degradation rather than concentrating on simplistic refinements of laboratory modelling.

Entering such an updated integration of engineering and basic physico/chemical approaches attention to acknowledged principles in structural analyses and design seems rewarding. Concrete engineering inherited the fundamental safety concept in structural analyses and design from the evolution in practice with masonry and timber as the prevailing materials.

In the recent dedication in research and concrete engineering to attain for instance ultra-high strength or improved durability of concrete as a material, it seems that deliberate application of a safety concept ought to make further progress possible. This would mean elucidation of concise analysis of environmental impacts on hardened concrete - encompassing the deleterious power of the elevated, available energy in hot, saline climates,

as well as the severity of the physico/mechanical impact on structures in the Arctic regions, and moderate, but sometimes long-term, exhausting exposures in between.

Drawing on the application of the safety concepts in structural design it seems that the basic technology research could gain much from integration with structural education and development. Such efforts are faced with several potential pitfalls. One is the temptation to transfer the structural safety concept by ever more refined mathematical models based upon conventional, and too crude empiric materials data. Another risk is, that the technology research concentrates on ever refining analyses and configuration of phenomenological features and reactions in cement paste without knowledge about the engineering and environmental constraints.

The writers feel that rather than different engineering/structural and basic materials technology approaches the future development represents opportunities for integrated progress which are no less challenging than when K. and B. Mather commenced their outstanding contributions to the great American research and engineering development, and to international exchange and cooperation.

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SP 100-3

Why We Have Concrete Durability Problems

by A. Neville

Synopsis: The paper draws attention to some early papers by both the Mathers of particular and lasting significance. Three factors relevant to so many current problems with durability of concrete are reviewed. First, inadequate criteria for acceptance of concrete, strength alone being relied upon in the past. Second, changes in cement properties over the years, which allowed the use of leaner mixes for a given specified strength. The third factor is the corrosion of steel in the concretes used nowadays, particularly severe in hot climates. Finally, recommendations are made for more attention to the composition of the mix and for inspection and maintenance of concrete structures.

Keywords: acceptability; cement compound composition; compressive strength; concrete durability; corrosion; inspection; maintenance; mix proportioning; reinforcing steels

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A state-of-the-art report is not merely a summary of established facts and received wisdom but it should also review our present understanding of the phenomena involved and of their relation to the overall behavior of concrete. It is in increasing the understanding of concrete, a feat so much more difficult than "crunching numbers", that the Mathers' contribution, both Bryant's and Katherine's, has been paramount.

Let me give two examples, one for each of the Mathers, from their early writings. In a 1947 paper (1) on the relation between the weight loss in the sulfate test and absorption of sand, Katherine, having established this relation, says: "statistical prediction is for over-all behavior, not for behavior in individual cases. It is the individual cases - specific aggregates for specific uses - that consumers and producers are both concerned with." How obvious, but how rarely remembered by those who judge an individual material against a formula.

In the same paper, Katherine Mather explains the interpretation of the correlation coefficient. This coefficient is now a daily diet but researchers of the 1940s were little familiar with it. She says: "The coefficient of simple linear correlation, r , measures the degree to which observations of two factors fall on a straight line. When all the observations fall on the line, r equals +1 or -1; when the observations are so scattered that any line is as good as any other, r equals 0." I am ashamed to admit that I could not match this clarity of exposition in a book on statistical methods of which I am a co-author. (2)

Let me now turn to Bryant Mather. While, personally, I found his expositions on expansive reactions within concrete to be the most illuminating, I would, at this stage, like to quote from his 1945 paper (3) on "Effect of type of test specimen on apparent compressive strength of concrete." His intellectual modesty made him say that "he can make no specific suggestion regarding procedures which might be incorporated in existing methods of calculating compressive strength values." He further said that "data of this sort may ultimately provide the basis for the establishment of such correction-factor relationships as are necessary to bring the values for compressive strength of concrete, regardless of the type of specimen used, to parity

with each other." Bryant Mather was right in being so cautious for even today, forty years on, we have not established these relationships and are still struggling with the interpretation of strength values of cylinders, cubes, and cores of different length-diameter ratios.

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This symposium is concerned with concrete durability, and it is tempting to ask why, after all these years of research, there are still so many problems with the durability of concrete. Possibly, there are even more problems these days than, say, fifty years ago. This is not a condemnation of concrete, for structural steel also continues to have the problem of corrosion. Nevertheless, we must ask ourselves: where have we gone wrong?

The topic is too broad to be tackled in a single paper and this author is too narrow to tackle the whole field. I propose therefore to limit myself to reviewing three aspects of "problems with concrete." These are: inadequate criteria for acceptance, changes in cement properties, and corrosion of steel. I must make it clear that I am not concerning myself with external chemical attack as such or with internal chemical disruption.

ACCEPTANCE OF CONCRETE ON THE BASIS OF STRENGTH

At first sight, it may seem strange to consider the use of strength of concrete as a basis of its acceptance to be a "culprit" in durability problems. Let us, however, trace the development of the criterion of strength.

When rational design of concrete structures first became widespread, and this probably coincided with, and indeed was helped by, the establishment of the American Concrete Institute, it was essential to ensure that the concrete used had a certain minimum strength. Cements of the day were of relatively low strength, and it was natural for the structural designer to be concerned with the composition of the mix. This he, and in those days it was never she, did by laying down the proportions of the dry ingredients: cement, sand, and coarse aggregate. Such a prescriptive specification, being based on experience, worked satisfactorily as far as the necessary strength was concerned.

As a by-product, the durability was also satisfactory. I am saying by-product because the durability was not explicitly considered but the concrete was dense. Also, because the strength of concrete was relatively low, the cross-section of concrete members was generally substantial and the cover to reinforcement was generous. If nothing else, we measured it in inches and not in millimeters.

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With time, we found it easy to obtain strength results, using standard test cylinders (or cubes) and, I submit, we became mesmerised by the numbers which were so regularly coming out of the test laboratory.

This fascination continued even when we realized that the 28-day strength, if nothing else, reached the constructor far too late to be of use for control purposes. We sought remedy in the accelerated strength test that would give an early "number" which could be converted to a 28-day strength, known, in our heart of hearts, to be of little value.

We specified nothing, or little, as far as durability was concerned, but believed that strong concrete was durable concrete. So it was to begin with, but later the mathematical identity ceased to be valid. I shall discuss the reasons for this in the next section. At this stage, my point is that we found crunching out strength numbers very easy, and we have been doing so ever since. Despite this preoccupation with strength, I ask every reader how often he has rejected a concrete structure because of inadequate strength.

My submission is that we should have decreased our concern with strength long since and we should have concentrated on developing practical criteria for durable concrete which could be used in specifications. Admittedly, with time, various standards introduced minimum values of cement content and maximum values of water-cement ratio, but these cannot be routinely tested for compliance. So, in the end, we still rely on the 28-day strength and we still believe that acceptance by strength **somehow** guarantees that the cement content and water-cement ratio are satisfactory, and hence the concrete has the necessary durability. Such belief is justified only if everything else about the concrete is immutable but in real life this cannot be taken for granted.

CHANGES IN THE PROPERTIES OF CEMENT

The changes in the properties of cement which have taken place in the last twenty-odd years are, the cement manufacturers would tell us, for the better: the cements are stronger. And yet, concrete placed in the 1970s is much more vulnerable to carbonation than older concretes, on an age-for-age basis.

Moreover, this carbonated concrete is quite highly permeable to moisture and oxygen, although carbonation actually reduces permeability. Both the progress of carbonation and permeability to oxygen and moisture are of course relevant to the protective value of the concrete cover to reinforcement. Inadequate protection leads to corrosion of steel, which is discussed in the next section.

The question is: why has there been this change in the performance of concrete? The simple answer is that the vulnerable modern concrete is less dense than the older concrete. But



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we must look behind this observation and explain how this came about. I would like to do so by quoting from my contribution to a Festschrift for Professor K Wesche. (4)

"There was no change in the **specified** quality of concrete between, say, the early 1960s and 1970s; by this I mean that the structural designer required the same 28-day strength in both periods and, indeed, he was under the impression that his concrete was the same at all times. The specification writer was persuaded that **prescriptive** specifying (for instance, by laying down a 1:2:4 mix) was uneconomical, and **performance** specification became the order of the day: tell us what strength you want and leave the rest to us! Of course, there were many situations where there were specific durability requirements, but I am referring to the run-of-the-mill construction.

So the strength did not change but the composition of the mix did. This was possible because, in the intervening period, there occurred a slow but definite change in the quality of British cement. First, its fineness characteristics changed somewhat, with the consequence of more rapid hydration and therefore more rapid development of strength. Then, more importantly, the chemical composition changed: there was much more triacalcium silicate (C_3S) and much less dicalcium silicate (C_2S); the consequence was also more rapid hydration and more rapid development of strength. One could say that the two strength-age curves for the "old" and the "new" cement intersected one another at 28 days, but beyond that age the curve for the "new" cement showed very little increase while the "old" one used to give us a further increase in strength, perhaps as much as 25 per cent of the 28-day value at one year.

With the "new" cement, it was thus possible to achieve the same 28-day strength as before by using less cement in the mix, that is, by using a leaner mix with a higher water-cement ratio. This, of course, means concrete of lower density and with a higher permeability than before. Such a mix undergoes carbonation much more rapidly and also allows the passage of moisture and of oxygen more readily than the concrete of the 1960s. This statement makes it clear why I gave the same explanation for greater carbonation and for more rapid corrosion.

There was one other consequence of the higher rate of gain of strength of cement. Strengths adequate for removal of formwork were achieved earlier than in the past; in consequence, this gave an excuse



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to discontinue effective curing at an early age. We know that the "skin" (outer few millimeters) of poorly cured concrete is of low quality, and therefore even more permeable than the inner core, and it is the "skin" that is first exposed to the action of carbon dioxide. It is in this way that cement characteristics and **actual** curing are intertwined.

The remarkable thing is that this change occurred without those who ought to know knowing much about it. The cement manufacturers were not doing anything nefarious but were merely improving the burning process in the kiln and increasing the efficiency of cement production. The concrete producers and suppliers were being as economical as possible while adhering strictly to the specification. And so it went on."

I have referred to British cements because I am more familiar with the British scene but, I believe, on this occasion, we are not dealing with a British disease. The root of the problem lies in the fact that cement specifications, in most countries, lay down only **minimum** values of fineness, or C_2S content or strength. Past attempts to include maximum limits have been repulsed on the grounds that this would increase the price of cement. This may be a valid argument but, if we accept that cement properties have a lower bound only, then we should not rely on performance specifications for the strength of concrete. This of course brings us to the conclusions of the preceding section.

CORROSION OF REINFORCEMENT

That steel is subject to corrosion has been known ever since steel was first produced. By embedding it appropriately in concrete, thanks to the highly alkaline environment of the cement paste, we protected the steel and built structures in which the corrosion of steel was minimal and not significant. The problem of corrosion has, however, surfaced in recent years. I am using the word surfaced in both its meanings.

In the literal meaning of the word, I have seen numerous instances of inadequate cover to reinforcement, occasionally so much so that the cover could be described as negative. This is generally due to poor workmanship or to poor supervision which tolerates such workmanship. Clearly, such near-exposed steel can readily corrode, but perhaps the problem should be laid at the door of construction practices rather than of durability problems inherent in concrete. Nevertheless, we should recognise that, occasionally, there are genuine difficulties in achieving the specified cover when the concrete members are slim and unrealistic tolerances are demanded or implied. (I have seen a drawing for a cladding unit 75mm thick,



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with 25mm cover front and rear, and a 20mm reinforcing bar in the middle!)

In the figurative meaning of "surfacing", the corrosion problem has become more widespread, not only in hot countries where it is almost endemic, but even in the temperate (although not always so perceived by the American visitor) climate of Britain. There are several reasons for this.

One is that our claim that concrete, unlike steel, needs no maintenance has caught us out. I am as guilty as the next man in that I preached this view in the 1960s. (5) Perhaps the "old" concrete, dense and used in thick members, was relatively maintenance-free, but this is certainly not the case with modern concretes and modern structures. We must accept that regular, periodic inspection of concrete structures is necessary, and this has to be followed by preventive maintenance and by repairs.

In many structures, a reason for corrosion problems is the use of calcium chloride as an admixture. Again, perhaps the "old" concrete used in members of more substantial cross-section could tolerate more readily the calcium chloride, but there is no doubt that this material leads to corrosion in all but dry concrete. We should have stopped using calcium chloride long ago, but we persisted with it, largely due to commercial pressures, at least in the United Kingdom. It was not until 1977 that the British code of practice for structural concrete clearly recognised the consequences of chloride ion with respect to corrosion.

The use of calcium chloride as an admixture was a self-inflicted wound which could easily have been avoided. This has now been done but there exist numerous structures and, in the United Kingdom, very many domestic buildings in which the consequences of the presence of the chloride ion continue to manifest themselves as a serious corrosion of steel and disruption of concrete. There is no known method of stopping this rot in that we do not know how to remove chloride ions from within the concrete. In consequence, the necessary repair becomes reinstatement, and sometimes demolition is a cheaper solution.

With the development of the developing world, much concrete construction has taken place in hot countries. The usual approach has been to apply our design codes, standards and practices there. We failed to appreciate, among other things, the large effect of temperature on the reactions of corrosion, although chemists tell us that there is approximately a doubling in the speed of these reactions for every 10°C increase in temperature. It is not surprising therefore that, with the average temperature, for instance, in the Gulf, being 20°C higher than in the United Kingdom, many structures there show distress after seven to ten years while here they do so only after 25 or 35 years.

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In many tropical areas, the atmosphere is also particularly aggressive. A factor which I would like to single out is the effect of sea spray and airborne sea water. The chloride from this source has been found, very recently, to penetrate concrete and to reach reinforcement with consequent corrosion. The general mechanism is for the salt-laden moisture to lodge in the pores in the concrete. A hot spell, maybe only of a few hours' duration, results in evaporation of water, with the salt left behind.

On subsequent wetting, the moisture, now carrying the deposited salt, is sucked in deeper; on repeated drying, the water, or much of it, departs, leaving behind an increased amount of salt. Each cycle of wetting and drying repeats this process so that a chloride (and other salts) profile is established, with perhaps as much as 2 per cent of salt by weight of concrete just below the surface and a smaller amount near the reinforcement, but even this is ample for extensive corrosion to occur. It is not surprising, therefore, that many structures from Okinawa to the Gulf have undergone rapid ruin. The underlying reason for this is our lack (until recently) of understanding of ingress of chlorides into concrete superimposed on our lack of appreciation of the effects of higher temperatures in a humid environment.

Delving further into causes of corrosion problems in concrete, we have to admit our imperfect understanding of the progress of corrosion in reinforced concrete. Of course, we do understand the reactions which convert iron into iron oxides, but the real situations involve access of oxygen and of water. We do not know enough about the permeability of different concretes to these agents under practical conditions.

The problem of practical permeability is even more complicated when we take into account the presence of cracks in concrete. Some British work has suggested that the crack width is irrelevant, every crack, wide or narrow, giving equally ready access to oxygen and moisture, but there is evidence that this is not so. (6,7) Perhaps I would be wise not to accept either view, but, clearly, there is a lack of reliable knowledge which would enable us to predict or assess the permeability of concrete cover in so far as the risk of corrosion is concerned.

There is, of course, another approach to tackling the problem of corrosion of steel, and that is protection of the steel itself. Relatively little has been done on this, perhaps because surface treatment of steel is an unpromising approach. The reason for this is that the protective layer is vulnerable to damage under site conditions and it inhibits bending, let alone welding. The external surface of the concrete itself can also be protected by a coating but I doubt that reliable, practical means have yet been achieved.

FUTURE OUTLOOK

Soothsaying is the quickest way to make a technical (or any other) paper obsolete. Nevertheless, it is possible to predict some necessary changes in our attitude to concrete.

First of all, we must admit to ourselves, as well as to the world outside, that structural concrete does not have an indefinite life. The quality of the concrete, in terms of its composition and not of strength measured at 28 days, will determine this life. More than that, maintenance of concrete is needed, and this means regular inspection and occasional repair.

Second, we must take workmanship and supervision much more seriously. The gap between knowledge of concrete and practice is often wide. Our progress in the former has not been matched by improvements in the latter, at least in many cases.

Thirdly, we must be mindful of the fact that

"good practice of the day is based on up-to-date knowledge. But new materials are being developed and new uses for concrete are being found. Often, at first, these changes may be viewed simply as improvements or extensions of **status quo**. This may be so in many respects but, in others, there may lurk an unsuspected side effect, often of the kind that manifests itself only with the passage of time. An intelligent engineer will be on the look-out for the possibilities and will ask himself **all** the necessary questions about possible consequences of any innovation, even those remote from the immediate effect of the change. This was not done in the past when some types of cement and admixture were used or when more efficient methods of compaction allowed a reduction in cement content. The untoward consequences in these cases cost millions of dollars and led to the need for extensive repairs." (8)

With a more intelligent approach, we should be able to avoid these pitfalls.

Having said all that, we must continue to acclaim concrete as an excellent general structural material, and one to which there is no competition in sight. In that, we, concretors, are lucky for we have an assured future, based on a steady progress in knowledge, to which Katherine and Bryant Mather have contributed so enormously.

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SP 100-4

In Situ and Laboratory Investigation of the Degradation of an Old Concrete Quay Wall

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Synopsis : A complete study of the old concrete harbour dam at Zeebrugge (Belgium) is presented. As a basis for material examination an anamnesis study was executed, to establish details of construction techniques, requirements and composition of materials and structure. Mechanical characteristics were determined by diagraphic drilling and by coring. The concrete samples were chemically analysed to determine the cement content and the extent of corrosion.

On the basis of the laboratory results and observations on the site, the repair procedures were determined and subjected to preliminary site tests.

Keywords: cement content; chemical analysis; concrete dams; concrete durability; field tests; repairs; tests

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1. Introduction :

The old harbour dam at Zeebrugge, Belgium, extends into the North Sea over a length of about 2,500 m. The dam was built between 1895 and 1907 and was, at the time, one of the world's most famous civil engineering constructions. Within the framework of the expansion of the sea harbour, the old harbour dam is planned to be the landing-stage for a new car ferry terminal (Figure 1).

The old harbour dam is being integrated into the new harbour construction. During the ninety years of its existence, the dam has suffered considerable damage and deterioration of varying types : chemical and biological corrosion of concrete, erosion of the dam body and the concrete, saggings, damage and repairs from war time bombing. In order to ensure a proper renovation of the structure to meet future requirements, the Ministry of Public Works of Belgium instigated a thorough investigation of a 350 m long part of the dam, including the control of the overall stability of the dam, and the nature and significance of material degradations. The investigation also included the evaluation of possible repair techniques and products involved.

The results of the study served as a basis for the appropriate specifications for the proposed works, which started in early 1986. This paper deals with the investigation of the concrete body of the dam. The relevant results of the anamnesis study will be presented first, in order to allow a correct interpretation of mechanical and chemical analyses results. The mechanical characteristics of the concrete throughout the dam body were determined by means of diagraphic drillings. More detailed information on the concrete at the outer parts was obtained from concrete cores removed from the dam at different locations, covering the underwater zone, the tidal zone and the open air zone.

The relation between exposure data and concrete behaviour was investigated enabling sensible decisions as to whether and where maintenance, repair or strengthening works had to be undertaken.

2. Anamnesis

During the late 19th. Century, King Leopold II decided to undertake the works related to the construction and operation of a port of call at Zeebrugge. This major and, at that time, unique and daring project, also included the construction of an inner and outer harbour connected by a sea lock, and of a seachannel connecting the ports of Brugge and Zeebrugge. The Contractor was also responsible for the design of the scheme. The preferred solution was that of Louis Coiseau, a French contractor, and Jean Cousin, a Belgian contractor. The works were started in 1897 and were completed 10 years later.

The quay wall in which we are interested is a part of the outer

dam project. A cross-section is shown in Figure 2. First the jetty was started. After the construction of the jetty reached a specified length, the construction of the quay wall started and followed that of the jetty. Both structures were designed as a monolithic whole consisting of sunken caissons of 25 m length and variable height, with on top of these caissons concrete blocks of 55 tons cemented to each other. Due to substantial sea bottom erosion, the caissons were mainly founded on willow mattresses and dumped stone. The area between the jetty and the quay wall was filled with material dredged from the access channel to the port of Zeebrugge.

During the two World Wars sections of the quay wall were damaged. For the quay wall section under study we can make a distinction between the concrete used for the caissons and for the blocks of the second and third row (concrete dating from 1900), and concrete used during the repair works carried out between 1945 and 1946 (first row of concrete blocks). No reinforcement was used in or between the blocks. The composition of the structure can be seen in figure 3.

Caissons

The caissons were built in drydock. Concrete was poured into a frame of steel plates of 3 mm thickness (Figure 4). The caissons were situated beneath the low water line. The cement content was theoretically 200 kg/m³ except for the upper half meter where 235 kg/m³ was used. The concrete consisted of : 1 part of slow hardening cement, 3 parts of sand and 5 to 6 parts of granulates (broken stone or natural rounded gravel).

After the caisson was floated into position, it was sunk at low water. The caisson was then filled with concrete poured under water. As can be identified by the corings, the quality of this underwater concrete was relatively low compared with the concrete used to build the caisson walls. A detailed inspection by divers, and corings in these walls, proved that the quality of the concrete here was good. No special concrete repair measures were needed for the caissons in this part of the dam.

On the other hand, and due to the poor accuracy during the sinking operations, the eroded concrete joints between two caissons will have to be made sandtight.

Upper structure (concrete blocks)

The concrete blocks of 55 tons were also prefabricated in drydock. Using the TITAN, a giant crane which was the biggest in the world at that time, these blocks were placed. (Figure 5) Afterwards they were cemented together using a Portland cement mortar. The specification stated that the cement content should be 235 kg/m³ in the following composition : 1 part of slow hardening cement, 3 parts of sand and 5 parts of broken stones or gravel.

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As cement, only normal Portland cement was used. Broken stones from quarries (petit granit, limestone, porphyry) or gravel from the rivers Meuse, Rhine or from the English coast were used. The seaward surface layer of the concrete blocks had to be finished in what was called "special concrete" or "béton granolitique". The particles of the special concrete consist of very small broken porphyry instead of large natural or broken gravel. Although this special concrete was only prescribed for the surface layer it was also found in the mass of the concrete as can be seen in Figure 6.

In order to achieve a monolith structure and to prevent sea water penetrating into the structure, it was also specified that the joints (both vertical and horizontal) between the blocks and between blocks and caissons, should be very carefully filled with mortar using quick hardening cement. This mortar has not resisted the action of time. Mechanical erosion and chemical action on this poor quality cement resulted in open joints. The quay wall was no longer sandtight which resulted in some accidents (sagging of sandfill). The erosion of the joints is most pronounced in the joints in the tidal zone especially in the joints of the second and third row of blocks.

3. Mechanical characteristics

The mechanical characteristics of the dam concrete were investigated by means of diagraphic drilling and by means of mechanical tests on cylindrical samples, cored out of the dam. The location of the different boreholes is indicated in Figure 7. Two vertical corings (KV1 and KV3) were carried out together with one inclined coring (KS2), and four horizontal corings (Kh1 to Kh4). Seven holes were drilled (D1 to D7) using the diagraphic technique.

A diagraphic drilling is a destructive exploratory drilling, where several parameters are recorded during the drilling operation. In this case the following parameters were recorded :

- the instantaneous penetration rate of the drilling tool,
- the compressive force (thrust) on the drill rod,
- the torque applied on the drilling tool.

These parameters are related to the mechanical strength of the concrete and to its cohesion. As an example, the recording of the diagraphic drilling D2 is shown in Figure 8 together with the interpretation of the results.

The advantages of diagraphic drillings are their ease of application, the rapidity of execution and the relatively low cost.

The interpretation of the diagrams was supported by video camera inspection of the boreholes (above and below water).

From the results of the diagraphic drillings it was observed that the concrete of the block layers was of moderate quality, and that the filling concrete of the caissons was of low to moderate quality. The diagrams also indicate that the quality profile is nearly uniform over the thickness of each block or caisson. This result was used to limit the number of cylindrical corings, which are more expensive.

The tensile and compressive strength of the concrete were measured on samples, prepared from the cylindrical corings. The samples were taken in the zones of different quality, as indicated by the diagraphic drillings. Samples for mechanical testing and chemical analysis were taken from the same zones. The mechanical testing was executed, as prescribed by the Belgian Standards NBN B15-211 and 220. The chemical analysis and interpretation were done as prescribed in the standard NBN B 15 - 250.

The results of the compression tests are summarised in Table I, together with the location and dimensions of the samples. The results of the tensile tests are summarised in Table II. The tensile strength was measured by diametrical compression tests on cylindrical cores. No data were found of the originally expected compressive strenghts, which makes a comparison impossible.

There is a clear difference between the quality of the concrete of the caissons and of the blocks. However the quality is sufficiently high as compared to the stresses to which it is subjected in the dam. Exception made for sample KV3 (1.6 m), which was taken at a very porous site, the quality is rather uniformly distributed. As a consequence, no special strengthening treatments are needed for the concrete material.

4. Chemical analysis

The carbonation depth was determined by spraying phenolphthalein indicator liquid on the wetted crack surface. Carbonation depth was about 5 mm. This means that carbonation is one of the aggressive agents, but it must be combined with other agents to explain the erosion of 300 to 400 mm occuring in some places. Therefore, the chemical composition of the concrete at different locations was examined. Eight concrete samples were analysed. The results are summarised in Table III. The analysis and calculation of cement content were executed, as prescribed in the Belgian Standard NBN B 15 - 250. In the Standard, the calculation of the cement content is done by comparison with a mean value of the SiO_2 -sol and CaO -sol content of Portland cement. As the concrete of the dam dates from 1900, the records of the producer "Ciments d'Obourg" were introduced in the formula's. Although only eight samples were analysed, representing a very small proportion of the whole concrete volume of the dam, it can already be shown that no extreme divergenes were found. The greatest differences were found for the sample KV3 (1.6 m), which

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was taken in a nid, and for the sample KH2 (surface), which was very porous, due to a dissolution of the cement at the surface layers. The cement content varies between 233 and 268 kg/m³, which corresponds very well with the prescribed 235 kg/m³. The presence of aggressive ions SO₃²⁻ must be assessed by comparison with the normal content of SO₃²⁻ ions in cement, which can be put at 2,35 % (British Chemical Standards No. 372). The SO₃²⁻ percentages of Table III must be converted into percentages of cement weight, by multiplying by the factor volume density/cement content. So we find the values in Table IV.

The results show a normal sulphate content, except for the samples KH4 and KH2. The samples KH4 were found to be taken from a block, which was repaired after the Second World War bomb damage, using high sulphate resistant cement (HSR-cement). This cement contained at least 5 % of sulphates, and was consistently used in all the post-war repair works at the Zeebrugge dam.

The high sulphate content of sample KH2 (surface) relates to the fact that the analysis was done on the surface layer of the concrete, which was very porous, and had been continually in contact with the sulphate rich seawater.

In order to check the significance of this sulphate contents, the chemical composition of the seawater was analysed. The results are summarised in Table V, and compared with mean values (ref. 7).

The concentration of SO₄²⁻ and Mg⁺⁺ ions appears to be slightly higher than normal, but this difference might be of little importance.

Seawater corrosion is of three types.

The first type is a dissolvent corrosion, where the free lime is dissolved and eroded. It is of most importance in acid water. This type of corrosion occurs in the interior of the dam body. The chemical analyses prove that this corrosion was not important, because the cement content was still good.

The second type is a chemical exchange of ions, between the cement and the aggressive water, by which the Ca (OH)₂ content of the cement is transformed into easily soluble salts or to sulfates, due to a reaction of the Ca (OH)₂ with Na⁺ and Mg⁺⁺ in the seawater. The analyses show an increased sulphate content in the surface layers (see sample KH2), which indicates the importance of this second type of corrosion.

The third type is a chemical-physical action where expansive salt crystals are produced having a destructive effect on the concrete.

The chemical analyses executed on the dam concrete, were not extensive enough to enable a detailed study and evaluation of the chemical corrosion phenomena on the concrete to be carried out.

However, having in mind the small deviations of the concrete and seawater compositions from the norm, it is reasonable to expect a future corrosion rate which will be nearly the same as in the past. Therefore, a more detailed chemical analysis was not pursued.

5. Repairing procedures

After being repaired, the quay wall should fulfill the following requirements

- 1° To make the structure sand-tight (both above and below the waterline) in order to avoid further erosion and sagging of the sandbody behind the quay wall;
- 2° To ensure that the whole structure (quay wall and surrounding soil) has sufficient stability under the actual and expected sea and traffic conditions.
- 3° Forming a monolith retaining wall (as originally designed) by anchoring and cementation of the quay wall blocks.

The above mentioned aims will be attained by using several modern restoration techniques and products, resulting in a "soft" (non-destructive) repairing method. This will lead to a minor interruption of existing harbour activity, to conservation of the historical aspect of the quay wall, as well as to an economical profit compared with building a (partly) new structure.

The preliminary tests and calculations, leading to a detailed work-scheme for the repairs, were numerous and varied. They consisted of :

- visual inspection of the front of the quay wall.
- various measurements of movements of water and structure.
- geotechnical investigation of the sand body behind the quay wall.
- study of the existing and aimed degree of stability of the structure.
- in situ and laboratory tests (chemical and mechanical) on the concrete inside the quay wall. Only these tests are discussed in the present paper.

The procedure adopted is as follows (see figure 9).

Phase 1 : Execution of a vertical continuous longitudinal drainage.

Phase 2 : anchoring of the upper blocks by drilling vertical and oblique concrete anchors.

Phase 3 : Drilling of transverse underwater drains by means of a bathyscaph.

Phase 4 : Cleaning and preparation of the joints between the blocks.

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- Phase 5 : Filling of joints and gaps at the dockside of the quay wall
- Phase 6 : Injection of joints and voids in the internal structure (quay wall and sandbody).
- Phase 7 : Closing of the vertical joints between the caissons.
- Phase 8 : Anchoring of the quay wall to the sand body by means of (passive) ground anchors.
- Phase 9 : Fixing of a protective layer of modified cement mortar on the front surface of the quay wall (under study).

This phasing is not necessary chronological. Certain phases can be executed simultaneously.

The results of this research have lead to the development of several innovative techniques and products which exceed the subject of concrete durability and are more related to marine and coastal engineering.

CONCLUSIONS

The mechanical and chemical analyses of the concrete show a difference between the concrete layers at the outer surface, and the concrete inside the dam. Some extreme values of sulphate contents were explained by the historical study, avoiding incorrect conclusions about the significance of corrosion. Between 1900 and today the chemical corrosion of the concrete was not abnormally high, in contrast with the joints. The surface of the concrete is continuously being eroded by the action of seawater, waves, currents and collisions. The combined chemical and mechanical actions have caused a surface degradation of the concrete of several centimeters, but much more the joint material. Therefore, the main restoration action will be applied to the joints, which will be closed by special techniques. Although the bad view of the quay wall did not give much confidence in the quality of its concrete material, the detailed preliminary investigation of the quay wall showed that no further protective measures concerning concrete durability are needed.

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TABLE I--Compressive Strength of Dam Concrete
(Cylinder Strength = 0.83 x Cube Strength)

*Calculated as a function of Geometric Relations

Coring	Depths m	Dam part	Diameter mm	Strength N/mm ²	Cube strength * (side 200 mm) N/mm ²
KS 2	13.4	caisson	63.3	25.6	22.6
KS 2	11.3	caisson	63.4	20.5	18.3
KS 2	5.2	3rd block	63.2	31.6	28.2
KV 3	3.0	2nd block	63.4	30.5	27.2
KV 3	1.6	1st block	63.4	10.9	9.7
KH 4	0.4	1st block	93.3	31.9	29.3
KH 2	0.6	2nd block	12.2	34.3	31.0

TABLE II--Tensile Strength of Dam Concrete

Coring	Depth m	dam part	diameter mm	tensile strength N/mm ²
KS 2	13.4	caisson	63.3	0.22
KS 2	11.3	caisson	63.3	1.67
KS 2	5.2	3rd block	63.4	5.05
KV 3	3.0	2nd block	63.4	3.86
KV 3	1.6	1st block	63.4	1.37
KH 4	0.4	1st block	93.3	2.18
KH 2	0.6	2nd block	112.4	2.24

TABLE III--Results of Chemical Analyses of Dam Concrete

Sample	KV3 (1.6m)	KV3 (3.7m)	KS2 (6.7m)	KS2 (13.4m)	KH2-surface	KH2 (0.60m)	KH4-surface	KH4 (0.20m)
Volume density (kg/m ³)	1.959,-	2.087,-	2.134,-	2.076,-	1.806,-	2.183,-	2.246,-	2.246,-
Compressive strength (N/mm ²)	9,73	27,17	-	22,60	-	30,99	29,31	29,31
Cement content (kg/m ³)	175,8	233,2	267,8	257,6	187,-	233,4	263,3	233,3
Calcination Loss %	3,42	2,78	3,88	4,43	7,05	3,26	4,07	5,84
SiO ₂ - insoluble %	87,65	86,70	84,32	83,61	76,66	86,63	82,86	80,28
SiO ₂ - soluble %	2,25	2,80	2,99	2,99	2,50	2,61	2,80	2,33
CaO %	5,95	6,83	7,19	7,33	7,51	5,94	7,23	9,33
MgO %	0	0	0	0	1,82	0,02	0,27	0,16
SO ₄ --- %	0,17	0,33	0,26	0,14	1,06	0,25	1,01	0,70
as SO ₃ --- %	0,14	0,28	0,22	0,12	0,88	0,21	0,84	0,58
CO ₂	1,37	0,32	0,45	1,25	2,27	0,39	1,82	3,55

TABLE IV--SO²⁻ Content of Cement

Sample	SO ₃ ²⁻ % w
KV 3 (1.6 m)	1.58
KV 3 (3.7 m)	2.46
KS 2 (6.7 m)	1.73
KS 2 (13.4m)	0.94
KH 2 (surface)	8.53
KH 2 (0.6 m)	1.95
KH 4 (surface)	7.18
KH 4 (0.2 m)	5.62
Reference BGS-372	2.35

TABLE V--Chemical Analysis of Seawater at Zeebrugge

sample	1	2	3	normal (ref 7)
pH	7.79	7.70	7.70	8
SO ₄ ²⁻ (mg/l)	2400	2350	2290	2220
Mg ⁺⁺ (mg/l)	1210	1160	1140	1110
Cl ⁻ (mg/l)	17900	17200	16800	16850