NISTIR 6327

Modelling Service Life and Life-Cycle Cost of Steel-Reinforced Concrete

Report from the NIST/ACI/ASTM Workshop held in Gaithersburg, MD on November 9-10, 1998

Geoffrey Frohnsdorff

Building and Fire Research Laboratory
Gaithersburg, Maryland 20899

United States Department of Commerce
Technology Administration
National Institute of Standards and Technology

NISTIR 6327

Modelling Service Life and Life-Cycle Cost of Steel-Reinforced Concrete

Report from the NIST/ACI/ASTM Workshop held in Gaithersburg, MD on November 9-10, 1998

Geoffrey Frohnsdorff

May 1999

Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

United States Department of Commerce
William M. Daley, *Secretary*
Technology Administration
Gary R. Bachula, *Acting Under Secretary for Technology*
National Institute of Standards and Technology
Ray Kammer, *Director*

ABSTRACT

The NIST / ACI / ASTM workshop on "Modelling Service Life and Life-Cycle Cost of Steel-Reinforced Concrete" was focused on possibilities for developing and standardizing such models, specifically for chloride-exposed concrete. The report includes summaries of nine presentations by model developers and reports from working groups that addressed i) chloride transport mechanisms and test methods, ii) chloride thresholds for corrosion initiation, iii) corrosion rate and time to rehabilitate or replace, and iv) life-cycle cost and service life prediction models. Several models for chloride transport to the steel were well advanced, but modelling of chloride thresholds and corrosion rates poses difficulties that still need to be overcome. Economic models for life-cycle costing are in place and ready to use with service life models as they are developed. It was agreed that standard models for service life prediction and life-cycle costing are necessary . It was recommended that a simple, but useful model could and should be developed and standardized in the short term, with a more scientifically sound model being a longer term objective. The model development would need to be supported by development of some new standard test methods and databases containing appropriate and reliable data. Standardization of the models would be expected to be carried out in ACI committees and standardization of test methods in ASTM. NIST's Partnership for High-Performance Concrete Technology would contribute to the development of models, test methods, and data.

Keywords: Chlorides; concrete; corrosion; corrosion threshold; economics; models; reinforcement; service life; transport processes.

ACKNOWLEDGMENTS

The success of the workshop described in this report was due to the collective efforts of many persons. We wish to thank the following for their contributions:

- The Steering Committee for deciding on the workshop objectives, the workshop structure, and the list of invitees;
- The invited speakers for providing essential background information and a perspective for the working group discussions;
- The chairs, co-chairs and recorders for giving direction to the discussions and ensuring that the main ideas were captured;
- All the participants for providing the viewpoints that the workshop was set up to obtain; and
- NIST staff members Nancy Wilkin and Romayne Hines for the excellence of the arrangements, and for providing friendly help wherever it was needed during the workshop.

We are grateful to the sponsoring organizations, the American Concrete Institute and the American Society for Testing and Materials, for lending their support to the workshop.

Special thanks and appreciation are due to the W.R. Grace and Master Builders companies for sharing in expenses for the workshop, including underwriting the costs of refreshments and the workshop dinner.

TABLE OF CONTENTS

APPENDICES

EXECUTIVE SUMMARY

A workshop cosponsored by ACI, ASTM and NIST was held in Gaithersburg, Maryland, on November 9-10, 1998. The subject was "Modelling Service Life and Life-Cycle Cost of Steel-Reinforced Concrete." The workshop resulted from a discussion within the Strategic Development Council of ACI in May 1998 concerning the need for standards for the subject of the workshop.

The workshop objectives were:

1. To review current models for determining the service life and life-cycle cost of steel-reinforced concrete subjected to chloride-induced corrosion of the steel:
2. To reach agreement on an approach to development of a comprehensive model that would provide a suitable basis for standardization;
3. To identify new data and test methods, if any, needed to support development of the model; and
4. To recommend actions to be taken to develop the model and propose it for standardization.

The workshop began with ten invited presentations, several from experts from other countries, that provided an overview of current modelling activities. The first presentation reviewed the purpose and activities of the RILEM Technical Committee TMC, Modelling Chloride Penetration in Concrete, and the later presentations described service life models developed in Canada (2), Denmark (1), Sweden (1), and the United States (4), and life-cycle cost models developed in the United States (2). The service life models were all based on calculations of time to initiation of corrosion of the reinforcing steel.

The invited presentations were followed by two breakout sessions in each of which four working groups discussed assigned topics. In the first session, all four groups addressed the question, "How could a framework for development of a standard, or standards, for service life and life-cycle cost of chloride-exposed, steel-reinforced concrete best be developed?" In the second session, each group had a different assignment, the four assignments being 1) chloride transport mechanisms and test methods, 2) chloride thresholds for corrosion initiation, 3) corrosion rate and time to rehabilitate or replace, and 4) service life prediction and life-cycle costing.

Among the results from the first four working group discussions were agreement that there was an urgent need for service life and life-cycle cost models for chloride-exposed, steel-reinforced concrete and that the model or models developed immediately on the basis of current knowledge should be followed by development over the long term of a more comprehensive model reflecting sound scientific knowledge of the corrosion process. Suggested criteria to be met by a model to meet the immediate need were that it should:

- Be verifiable by comparison of its outputs with actual data, e.g., the model should be able to make accurate predictions of chloride contents
- Be well-documented and have background material clearly presented, with assumptions and limitations being clearly stated

- Offer help on input values
- Have a statistical basis for assumptions (with respect to input values, diffusion coefficients (d_a), surface concentrations, and environment)
- Have the smallest possible number of adjustable coefficients
- Deal with as many known mechanisms as practical
- Provide data for economic analysis

The more comprehensive "scientific" model to be developed over the longer term should:

- Meet all the criteria for the immediate model
- Incorporate lesser-known transport mechanisms
- Incorporate multiple deterioration mechanisms
- Correlate service conditions and microclimates
- Link microclimate to macroclimate
- Include preventive maintenance
- Include corrosion propagation.

It was pointed out that a database incorporating appropriate and reliable data will be needed to support model development. The data is needed for determination of apparent diffusion coefficients, for testing and verification of existing models, and the selection of one or more models for further development. The database should include surface chloride concentrations and chloride contents for at least five different locations (depths), mixture designs, age (at least up to ten years), and temperature. It was emphasized that if the mixture proportions were not recorded, other data would be of little value.

Chloride transport mechanisms and test methods

In the second breakout session, the group discussing chloride transport mechanisms and test methods emphasized the need for good sampling if good data is to be obtained from the field. Guidelines on sampling are needed and as a minimum, they should cover coring, profiling, and analytical procedures, with the sampling being appropriate to the situation. Examples of different situations are a bridge deck, a sea wall, and a tunnel wall. Many factors must be considered in studies of transport mechanisms including: i) binding of chloride, ii) age dependance, iii) temperature dependance, iv) surface barriers, and v) cracks, with diffusion, convection and unsaturated flow being transport mechanisms that must all be addressed.

Chloride thresholds for corrosion initiation

The working group on chloride thresholds for corrosion initiation pointed out the need for an accepted, mechanism-free definition of the "corrosion threshold." It recommended that the definition should be:

> *The chloride threshold, C_T, is the mass of total chloride per unit volume of concrete that results in permanent depassivation of the steel (for a specific set of mixture proportions, history, and environmental factors).*

It also recommended that there be consistency in the units used for expressing the chloride threshold. The most reliable method for determination of the threshold is that based on field survey data. Results from slow ingress of chloride into concrete (usually over several years) is useful but not as reliable and, unfortunately, results obtained from immersion of the steel in simulated concrete pore solution, while easiest to obtain, do not correlate well with data from field surveys. Chloride thresholds appear to depend on many factors including: chloride concentration, concrete ingredients (type and source of aggregate, type of pozzolan, type of cement, and types of chemical admixtures), mixture proportions, consolidation (voids, settlement around the rebar, interfacial porosity), finish and cure, local environment (temperature, moisture content, oxygen, pH, CO_2, solutes, and chloride source), electrical potential, time, the reinforcing metal, and the intrinsic variability of concrete.

Corrosion rates and time to rehabilitate or replace

The working group addressing corrosion rates and time to rehabilitate or replace believed that modelling of corrosion rates should be possible, though more data is needed to support the model development. Data, such as on the mechanical properties of rust, is needed for modelling relationships between corrosion rate, stress in rust, and stress in concrete. The problem is complex and its solution will require a fracture mechanics approach. Another need is for methods for characterizing damage levels, since those that now exist only account indirectly for the factors that determine the need to repair. The FHWA rating system should be used as a starting point. It must be recognized that different steels are different in their susceptibilities to chloride-induced corrosion, and knowledge is needed on the effects on corrosion rate of factors such as mill scale, cracks, and crevice corrosion. Modelling the corrosion of epoxy-coated rebars will involve localized corrosion, and agreement should be sought on damage functions for epoxy-coated bars and for systems containing corrosion inhibitors. Data is needed on such systems to help evaluate damage in them. Regarding existing models, they do not address all critical aspects of time to failure; for example, few, if any, cover corrosion rates. A question that must be asked is, What constitutes failure and how can it be modelled? Is it failure of the bond and deterioration of the concrete? Or loss of tensile capacity due to the reduced cross-section of the steel? For modelling purposes it will be necessary to separate new construction from repair, with verification of information taking place during the design phase.

Service life prediction and life-cycle cost

The working group on service life prediction and life-cycle cost concluded that there is enough information to be able to make a stab at producing a useful model and for life-cycle cost modelling, the methodology is already in place in ASTM E917. In the short term, models may have to include ‘fudge factors” but, for the long term, a comprehensive service life model should be the goal; among the requirements for such a model is that the corrosion initiation portion should have a probabilistic base. A task group should be set up to allow public input to the model development and standardization. Within the task group, there should be working groups on a) “empirical” modelling of transport, b) “scientific” modelling of transport, c) the corrosion threshold (models and test methods), and d) life-cycle cost. There will be several barriers -- some technical, some institutional -- to overcome in developing and gaining acceptance for the desired models. Among them will be code committee members who will not be comfortable with inclusion of diffusion coefficients in concrete codes, and the current lack of standard test methods needed to develop a common database. For the most rapid progress, different organizations should each play a part. Test methods and specifications would be expected to be addressed in ASTM and CEN, with guides and codes being addressed by ACI and RILEM. Momentum built at the present workshop should be maintained through a continuing series of workshops.

Recommendations

Following the breakout sessions, a final plenary session heard reports from the working groups and ended with a general discussion leading to several key recommendations.

The key recommendations from the workshop were:

1. A subcommittee on modeling of service life and life-cycle cost of reinforced concrete should be established in ACI Committee 365, Service Life Prediction. The subcommittee should establish guidelines for the models and, using the current state of knowledge, develop a baseline corrosion service life and life-cycle cost model as rapidly as possible.
2. The baseline model should be made available to the industry for testing and implementation and then placed on the Web, possibly with a list of other models and links to them. The possibility of forming an on-line discussion group should be considered.
3. Over a longer term, a comprehensive model based on scientific understanding should be developed through the joint activities of an industry-government consortium and the relevant standards organizations. Test method standards should be developed in ASTM Committee C09, Concrete and Concrete Aggregates, and ASTM Committee G01, Corrosion.
4. An organization such as NIST should be given responsibility for maintaining the model on the Web and for making necessary updates as further developments occurred.

Conclusion

In response to the first recommendation, a subcommittee was set up in ACI Committee 365, Service Life Prediction, with the purpose of carrying out the recommendations. Michael Thomas of the University of Toronto was invited to become chairman of the new subcommittee and he accepted the appointment.

A TRIBUTE TO JAMES CLIFTON (1933 - 1999)

James Roger ("Jim") Clifton died unexpectedly on January 19 after an illustrious career devoted to advancing knowledge of the materials science and durability of inorganic construction materials. He was an important contributor to the workshop that is the subject of this report – a subject to which he had made many important contributions over the last thirty years. For example, he led the early research on epoxy-coated reinforcing bars which became the foundation for a new industry and for which he and Robert Mathey received the Lindau Award from the American Concrete Institute in 1986. As chairman of ACI Committee 222 on Corrosion of Metals in Concrete from 1985 to 1989, he led the drafting of the Committee's state-of-the-art report published in 1989 and later, as chairman of ACI Committee 365 on Service Life Prediction from 1993 until his death, he led the drafting of that Committee's state-of-the-art report. Jim also contributed at least as greatly to the field through his leadership of the Inorganic Building Materials Group in NIST's Building and Fire Research Laboratory – a Group that has led in the application of computational materials science to concrete and related cement-based materials, an example of which is provided by the 1996 paper, Service Life Prediction of Chloride-Exposed Steel-Reinforced Concrete, of which he was a co-author.

Jim spent about the last thirty years of his professional career (1970 – 1999) at the National Institute of Standards and Technology (formerly the National Bureau of Standards), first as a Research Physical Scientist and then, from 1981 on, as Leader of the Inorganic Building Materials Research Group. In 1978, he began the computational cement research which led to the developments for which the team he built, and in which he took great pride, is now world-famous.

Jim was a good friend and colleague. He was generally open-minded, sometimes impatient, and quick to express an opinion if he thought someone was wrong. We had occasional disagreements which we were always able to resolve amicably – and we had many laughs together. Jim liked to write and he wrote fluently and well. However, his handwriting was often illegible, so he and his colleagues welcomed the advent of word processors. Jim bought enthusiastically into the electronic age in other ways, too, as in his pioneering work with Larry Kaetzel in the development of knowledge-based expert systems and CIKS (computer-integrated knowledge systems) for concrete. A measure of the significance of the work is that the expert system, HWYCON (a decision-support system for HighWaY CONcrete), issued in 3000 copies by the Transportation Research Board in 1993, and it is now used in virtually all of the Nation's state departments of transportation.

Jim was a good leader who was encouraging to his staff in their work, and seriously concerned about their welfare and professional growth. He looked for excellent performance, but was understanding and helpful when unforeseen problems arose. He recognized the importance of secretaries and was grateful for the good secretaries he had.

Jim was highly-motivated, and worked hard and productively. He was much appreciated by sponsors of his research because he could be relied on to fulfill his obligations faithfully and on time. He earned the trust of sponsors and often became friends with them.

Though Jim worked hard, he always went home promptly at the official end of the workday. He was a private person, but he obviously enjoyed being at home with his wife, Eva, to whom he had been married for 31 years, and he was proud of his son, Michael.

In his first years at NIST, Jim was one of the softball gang -- I did not see him play, but I heard he played with the enthusiasm he showed in most things he chose to do. He had a hobby of building and flying model airplanes and I remember an occasion on which he was very upset when he lost one that crashed in a cornfield and could not be found.

Jim liked to travel to new places and, as an authority on the preservation of historic stone and adobe structures, his work gave him opportunities to do so. As examples, he visited archeological sites in Arizona and New Mexico as a consultant to the National Park Service, and he was a member of a UNESCO team that visited the site of the ancient city of Mohenjo-Daro in Pakistan to advise on its preservation. Because of his knowledge of stone preservation, he was consulted on the treatment of the stone used in the restoration of the West Front of the U.S. Capitol.

Through his chairmanship of several technical committees or subcommittees in ACI, ASTM, and RILEM, Jim found opportunities to collaborate with persons from other organizations, not only in drafting committee documents, but also in co-authorship of other publications. He had an outstanding publication record with at least 140 publications to his credit. Among awards received for his writings and his research were the Silver medal of the U.S. Department of Commerce in 1975, the Communicator Award of the NIST Building and Fire Research Laboratory in 1976, the P.H. Bates Award (which I was proud to share with him) from the ASTM Committee on Cement in 1978, and the Lindau Award from ACI in 1993. Jim was elected to the Fellowship of the American Concrete Institute in 1993.

Over the years, Jim and I wrote several papers together, and we planned to co-author the present report. Unfortunately, it was not to be. However, I felt it fitting to include this tribute to him -- as a fine person, a good friend, a dedicated and highly motivated civil servant and scientist, and a major contributor to the field that this report is intended to help advance. It is noteworthy that Jim left his mark on one of the last actions of the workshop when, in rapid response to one of the workshop recommendations, he approved the setting up of a new subcommittee in the ACI Committee (ACI 365, Service life Prediction) that he chaired.

Jim is survived by his wife, Eva, his son, Michael, and his sister. I am grateful that we were able to share him with them.

Geoffrey Frohnsdorff

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
CEN	European Standards Organization
CIKS	Computer-integrated knowledge system
CGI	Common Gateway Interface
CSE	Copper sulfate electrode
CTH	Chalmers University of Technology
FHWA	Federal Highway Administration
HPC	High-performance concrete
ISO	International Organization for Standards
NDE	Non-destructive evaluation
NT	Nordic Test
OPC	Ordinary portland cement
RCPT	Rapid chloride penetration test
RILEM	International Union of Research and Testing Laboratories for Materials and Structures
SHRP	Strategic Highway Research Program
SI	International System of Units
WG	Working Group

1. INTRODUCTION

The workshop was held in the Hilton Hotel, Gaithersburg, Maryland, on November 9 and 10, 1998. NIST was asked to take the lead in organizing the workshop at a meeting of ACI's Strategic Development Council in May, 1998, in which the need for standards for modeling service life and life-cycle cost was pointed out. NIST accepted the task and formed a steering committee the members of which are listed in Appendix 1. The steering committee drafted the objectives for the workshop and drew up the initial invitation list. The list included persons who i) had contributed models on the corrosion of steel in concrete, ii) were users or potential users of models, and iii) were viewed as representatives of standards-writing committees that might be expected to be asked to establish the standards that would be needed. The list of the 40 persons who participated in the workshop is also given in Appendix 1.

The objectives for the workshop were:

1. To review current models for determining the service life and life-cycle cost of steel-reinforced concrete subjected to chloride-induced corrosion of the steel;
2. To reach agreement on an approach to development of a comprehensive model that would provide a suitable basis for standardization;
3. To identify new data and test methods, if any, needed to support development of the model; and
4. To recommend actions to be taken to develop the model and propose it for standardization.

The agenda for the workshop is given in Appendix 2. After welcoming remarks, the workshop began with a presentation from Marta Castellote of the Eduardo Torroja Institute of Construction Sciences, Spain, who reviewed the objectives and plans for RILEM Technical Committee TMC, Testing and Modelling Chloride Penetration in Concrete; (RILEM is the International Union of Research and Testing Laboratories for Materials and Structures). The RILEM committee is chaired by Carmen Andrade of the Eduardo Torroja Institute. There followed a series of nine invited presentations concerning models for prediction of the service life and life-cycle cost of chloride-exposed, steel-reinforced concrete from leaders in the field from Canada, Denmark, Sweden, and the United States. The presentations helped ensure that all participants had an appreciation of types of model that had been, or were being, developed.

The formal presentations were followed by two half-day working group (WG) sessions, with four working groups in each. In the first session, all four groups, WGs 1 through 4, were asked to address the question, "How could a framework for development of a standard, or standards, for service life and life-cycle cost of chloride-exposed, steel-reinforced concrete best be developed?" In the second working group session, each of the four groups had a different assignment, as indicated by their names: WG5, Chloride Transport Mechanisms and Test Methods; WG6, Chloride Thresholds for Corrosion Initiation; WG7, Corrosion Rate and Time to Rehabilitate or Replace; and WG8, Service Life Prediction and Life-Cycle Cost.

The memberships of the groups are given in Appendix 3, with designations of the chairman, co-chairman, and a NIST staff member assigned as a recorder and to assist as needed.

In this report, summaries of the invited presentations are given first; they are followed by working group reports and a report from the closing session at which recommendations for action were made. Additional sections before the appendixes are a summary of the results of the workshop and a list of references supplementing the summaries of the invited presentations. Appendices 4, 5 and 6 are abstracts submitted by three invitees who were unable to attend the workshop.

On a sad note, it must be mentioned that James (Jim) Clifton, who played an important part in the workshop, died suddenly on January 19. Because of his many contributions to concrete science and technology, Jim was well known to most of the workshop participants. It therefore seemed fitting to include a tribute to Jim at the front of this report.

2. SUMMARIES OF INVITED PRESENTATIONS

2.1 RILEM TECHNICAL COMMITTEE TMC, TESTING AND MODELLING CHLORIDE PENETRATION IN CONCRETE

Marta Castellote, Eduardo Torroja Institute of Construction Sciences, Spain

Concrete, was established in 1997. Its scope and objectives [1]* are similar to those of the present workshop. The committee was established because of the increasing need for internationally-accepted methods for evaluating the durability of concrete and the lack of performance tests the results of which could be used to predict the long-term behavior of concrete in chloride-containing environments. The lack of suitable test methods is attributable, at least in part, to uncertainties about factors controlling the ingress of chlorides into concrete.

The scope of the RILEM Committee includes: mechanisms of chloride ingress into concrete; definition of terms; identification of important parameters; and the significance of different "diffusion coefficients." Test methods used in different countries are to be identified and models for predicting chloride ingress by different mechanisms evaluated. Consensus will be sought on test methods appropriate for use in the design phase and those applicable to existing structures. While the models identified may have different levels of sophistication, understanding of each will be sought to enable evaluation of their usefulness for predictive purposes.

The Committee's work is expected to take about five years. It will begin with preparation of a state-of-the-art report, and this will be followed by a two-part program:

1. Tests
    - 1.1 Identification and comparison of existing methods and testing variables.
    - 1.2 Round robin tests on selected methods.
    - 1.3 If needed, production of RILEM Technical Recommendations.
2. Models
    - 2.1 Analysis of the background of the different models, and of the initial and boundary conditions of the different solutions of Fick's law.
    - 2.2 Discussion on the limits of application of the models for predictive purposes; and round robin tests for comparative predictions.
    - 2.3 Optimum framework of a model.
    - 2.4 Simplified models for design purposes.
    - 2.5 A state-of-the-art report and, if possible, a RILEM Recommendation on the use of models.

---

* Numbers in [ ] are for references listed in Section 5.

The test methods to be recommended in 1999 will address: sampling and profiling; modelling and calibration; and determination of the chloride threshold for initiation of corrosion. The goal to be achieved in 2002 is a recommended international approach to modelling chloride penetration into concrete which can take into account all climates and environmental conditions. The Committee's state-of-the-art reports should be of particular interest to academics and testing laboratories, while its recommendations should be important to testing laboratories, practicing engineers, and standards bodies.

On behalf of Committee Chairperson, Carmen Andrade, Dr. Castellote invited other interested persons to join the RILEM Committee. (For those who may need it, Dr. Andrade's e-mail address is: Andrade@fresno.csic.es .)

2.2 MODEL FOR A QUANTITATIVE CORROSION DAMAGE FUNCTION FOR A REINFORCED CONCRETE MARINE SUBSTRUCTURE

Alberto Sagüés, University of South Florida

A damage function approach has been applied in predicting the course of corrosion in (mostly) marine structures. It has been applied in two ways [2,3], one simple and one more sophisticated. In the first, knowledge of the distribution of the thickness of the concrete cover over the reinforcing steel and of the surface chloride concentrations is used in calculations for each of three ranges of elevation with respect to sea level – the tidal zone, the lower splash zone, and the upper zone. Diffusion is assumed to be the only transport mechanism, and it is also assumed that each elevation has its own threshold concentration of chloride to initiate corrosion. From the results, if the cost of repair per unit area is known, the repair cost can be calculated. This model blends uncertainty with variability.

The first approach was used in forecasting the extent of corrosion of the reinforcement in two 31 year-old, parallel concrete bridges in a marine environment in northern Florida. A preliminary inspection showed that the chloride concentration at the depth of the reinforcement in the cylindrical piling was approaching the level normally associated with the onset of corrosion. Future traffic projections required deciding between alternatives that included expanding the present structures or rebuilding. To select the most appropriate alternative, an investigation was conducted to develop an approximate forecast of future corrosion development. The investigation included assessing the present condition, and developing a quantitative corrosion deterioration model. The corrosion condition was assessed by visual observation, direct examination of reinforcement, and electrochemical corrosion measurements. Chloride-penetration profiles were obtained from extracted concrete cores. Reinforcement cover was measured by direct observation. The chloride profile data were analyzed to obtain apparent chloride ion diffusivities, surface concentrations and bulk concentrations. The deterioration model used the statistical distributions of concrete cover, diffusion coefficient and surface concentration to estimate the distribution of times for corrosion initiation and appearance of external damage on the bridge substructure. The output of the model was a damage function indicating the amount and location of repairs needed as a function of bridge age.

The model outputs showed a period of no significant corrosion damage followed by gradual deterioration afterwards. The shapes of the curves for each elevation range reflect the assumed dispersion of model parameters (concrete cover, surface concentration, and diffusivity) around their average values. An assumption of no dispersion would have resulted in a sharp step damage function for each range, with damage starting at the time corresponding to that dictated by the average parameter values plus the assumed propagation time. The model outputs project that the most damage will take place in the tidal zone during the next few decades. Detailed cost estimates for rehabilitation were prepared based on the repair/rehabilitation alternatives considered.

The model is not an absolute prediction tool. It should be viewed as a means of providing quantitative projections to assist in comparing repair and future construction alternatives. The output is highly sensitive to the assumed values of key parameters, such as the chloride concentration threshold (C_T), which are subject to much uncertainty. The overall modeling assumptions involve numerous simplifications that ignore important issues such as effective diffusivity and surface concentration variations with time, the effect of chloride ion binding on diffusion, alternative chloride transport mechanisms, effect of potential on C_T, non-flat surfaces, and the factors altering the length of the propagation stage. Improvement is also needed to discern between actual variability and measurement uncertainty in the parameters (concrete cover, diffusivity, surface concentration) used as distributed values.

The second approach [4] is more complicated; it uses a propagation stage model that incorporates oxygen diffusion, corrosion, and a concentration- and potential-controlled threshold into computations of macrocell corrosion; it can take into account the effects of corrosion inhibitors and anodic protection. The approach includes a method of generating a quantitative corrosion damage function given the concrete properties, the configuration of the substructure, and basic assumptions about corrosion mechanisms. The output of the model is the amount of damage requiring repair at different elevations in the substructure as a function of time. The model is illustrated for a partially submerged marine substructure column. The damage function is developed for three sequential computational model modules concerning chloride ion transport, corrosion distribution, and evaluation of surface damage. The quantitative model output is illustrated for the different stages of deterioration of the system and for corrosion protection alternatives.

The entire system is initially considered to be in the passive state, and the open circuit potential is not a strong function of elevation. Chloride ions begin to penetrate to different extents at various elevations, depending on the local surface chloride content. The evolution of chloride concentration as a function of potential and time is calculated by means of a *chloride transport module* that assumes diffusional chloride transport. Eventually, the chloride threshold, C_T, is reached at an elevation where chloride accumulates rapidly and causes local depassivation of the steel. This, in turn, causes a local potential change, and formation of a corrosion macrocell that depresses potential at the active spot and in the passive steel nearby. The redistribution of potentials and resulting corrosion rates are calculated using a *corrosion distribution module* based on a previously developed computation methodology. Since C_T is potential dependent, steel depassivation is not likely to happen next at spots immediately adjacent to the region of potential depression, but rather at other places with the appropriate combination of sufficiently high potential and chloride contamination. Every time an additional spot becomes active, the potential distribution becomes readjusted and so does the C_T distribution. As each spot enters the active corrosion condition, the corrosion distribution module calculates the local corrosion rate. The rate is integrated as a function of time and converted into local corrosion penetration with a value M_{crit} assumed to result in concrete cover spalling for the combination of steel (rebar) diameter and concrete cover used at that location of the system. When M_{crit} is reached at a given element of the system, the element is declared damaged and its projected area on the external concrete surface counted as damaged area. The sum of damaged area for the entire system as a function of time is defined as the *damage function* of the system.

2.3 PRESENT LIMITATIONS IN SCIENTIFICALLY-BASED PREDICTION MODELS FOR CHLORIDE INGRESS INTO SUBMERGED CONCRETE

Lars-Olof Nilsson, Chalmers University, Sweden

Most current prediction models for chloride ingress into concrete are empirical and depend on fitting curves to measured chloride profiles. Since the models do not have firm physical and chemical foundations, predictions are made by extrapolation from existing data. The results of the extrapolations are uncertain because of large scatter in the data and uncertainties in the models. Chalmers University of Technology has developed scientifically-based models that use current knowledge of the physical and chemical processes involved in the transport of chlorides in concrete. They have concentrated mostly on chloride ingress and a little on the corrosion threshold. They have used a lot of literature data, some from people at the present workshop. The model runs in a WINDOWS environment.

This study described [5] had the objective of determining the possibilities and the limits of the Chalmers University (CTH) model for predicting the penetration of chloride ions into concrete. The diffusion of chloride is established from Fick's first law and a diffusion coefficient is determined by the CTH Migration Test. The effects of temperature, age of the concrete, and the variation of the diffusion coefficient as a function of depth have been examined. The interactions between chlorides and the concrete are represented as a function of concentration of free chloride, temperature, and pH of the pore solution. Leaching of alkalis is included in the model to predict the pH at different depths.

The results of the predictions for different cases have been compared with results of measurements made in the laboratory and the field. Differences between predictions and the results of accelerated immersion tests at elevated temperatures appear to be due to the fact that the diffusion coefficient depends on concentration. The effect of unsaturation of the submerged concrete is illustrated by some examples and its consequences are analyzed.

Predictive models that are described as "scientific" should be based on relevant and decisive physical and chemical parameters such as mass balance equations, a genuine flux equation, chloride binding relationships, the effect of material characteristics, and the effect of environmental conditions. Such a model, ***ClinConc***, has been developed by Tang [6]. Features of the model are:

- non-linear binding isotherms, $c_b(c, T, [OH^-])$, including the significant effects of both pH and temperature;
- a chloride diffusion equation with free chloride concentration as the driving potential,
- a chloride diffusion coefficient, D_{CTH} (t, T, X), that is a function of age, temperature, distance to the cast surface, etc.;
- a method for measuring the chloride diffusion coefficient, D_{CTH} , in an independent chloride migration test; and
- leaching of alkali hydroxides by a separate mass balance equation.

The model predicts total and free chloride distributions and the distribution of hydroxides. Comparison with measured chloride profiles has shown that, with but a few exceptions, predictions made with the model are accurate. The exceptions are:

- the predicted penetration is too high when compared with that measured after exposure to the Scandinavian NT Build 443 immersion test [7]; in this test, the chloride concentration is much higher than in normal exposures;
- the effect of unsaturated pores has not yet been considered in a completely correct way; a number of measurements have shown that good concrete is far from saturated in the submerged zone, even after long exposure times;
- the effect of temperature on chloride binding is still unclear; experimental results do not agree with theory, and this causes a large uncertainty; (in summer, temperature effects cause increases in the free Cl^- concentration);
- the effect of temperature on the diffusion coefficient is also uncertain, since data on the steady-state diffusion coefficient are rare; and
- predicted chloride contents close to the exposed surface are somewhat low in some cases; a number of surface effects that could influence binding have not been considered.

It is concluded that the ***ClinConc*** model for chloride penetration is very promising for predicting actual chloride profiles in submerged parts of structures. The demands for input data are small and short-term tests can provide the data. The inputs include mixture proportions, workmanship, and exposure conditions, and the only parameter to be measured is D_{CTH} . This can be obtained from a simple test using silver nitrate applied to a split concrete sample. A good rapid test for chloride diffusion is needed, but the AASHTO test is not suitable.

The predicted results are meant to be used for direct comparison with measured profiles without the need for curve-fitting. Any discrepancies found immediately indicate where the most important knowledge is lacking. So far predicted chloride profiles coincide fairly well with measured ones, with the only exceptions being immersion tests with high chloride concentrations close to the exposed concrete surface. Possible improvements have been identified. The next steps in improving the scientific models should be: 1) a concentration-dependent diffusivity, $D_{Fl}(c)$, and 2) a saturation-dependent diffusivity, $D(S)$, where S is the degree of saturation.

In regard to the subject of the workshop, questions to be asked include: What is the required performance? What is meant by service life? Is reduced load-carrying capacity acceptable?

It was pointed out that many reports will issue from the three-year European project that is developing the Duracrete Chloride Penetration Model and will end soon.

2.4 CHLORIDE EXPOSED RC-STRUCTURES: CHLORIDE INGRESS AND LIFETIME PREDICTION BY THE HETEK MODEL

Ervin Poulsen, AEC Laboratory, Denmark

In the design, construction, and maintenance of marine reinforced concrete structures different persons have different needs for information. The <u>structural engineer</u> needs an estimate in which the basic parameters of chloride ingress are based on a knowledge of the concrete, reinforcement, and the environment in order to plan and design marine structures. The <u>entrepreneur</u> (i.e., the contractor) needs the concrete to be accepted or rejected by pre-testing and trial casting before the construction of a marine structure starts. The <u>building owner</u> needs to be warned, on the basis of inspection and examination of the marine structure, in due time before corrosion starts,. The basic HETEK model can assist the structural engineer and the entrepreneur in obtaining the information they need from knowledge of the concrete composition, the rebar cover, and the environment, but owners of structures also need field data which differs depending on whether the structure is new or old. The HETEK model is based on observations at the Träslövsläge Marine Exposure Station in Sweden. It is the result of cooperation between the University of Gothenberg's Department of Materials and the Cementa Company in Sweden, and the AEC Laboratory and the Department of Mathematics of the Technical University of Denmark in Denmark. The model uses data obtained with the Scandinavian NT Build 443 test method. The main result of the work is a model for chloride ingress into concrete and prediction of the initiation period before corrosion of the steel reinforcement begins. The model applies to marine structures of reinforced concrete, as well as to reinforced concrete structures exposed to traffic splash containing chlorides. Inputs to the model are: the mixture proportions of the concrete; the class of chloride environment; and the thickness of the cover over the reinforcement bar in question. The outputs are the chloride profile at any time and the initiation period. Prediction of service lives is being addressed, but it is complicated by the need to know the criterion for initiation of corrosion (i.e., the threshold value of chloride in concrete) and the failure criterion, and the difficulty in predicting corrosion rates.

In marine environments chloride ingress has to be considered in a) submerged sections, b) sections in the splash zone, and c) sections exposed in the marine atmosphere above the splash zone. If proper care is taken, useful data on chloride distribution can be obtained from profile grinding of concrete cores. Chloride profiles can also be obtained from *insitu* measurements on drilled dust or by use of the CorroWatch[*] multiprobe [9] embedded in field

---

[*] Certain trade names and company products are mentioned in the text or identified in an illustration to adequately specify the experimental procedure and equipment used. In no case does such an identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

concrete. The probe has four anodes at different distances from the surface; using the time for corrosion observed at each anode, the model can estimate the chloride profile at any time and predict the initiation period if the thickness of cover is known. For existing concrete, required information about the ingress of chloride can be obtained by the method of inverse cores [10]. In this method, a core cut from the concrete is put back in place with the virgin part exposed to the environment; the ingress into the virgin surface is followed by measurements made at suitable intervals.

The chloride profile is characterized by four parameters – exposure time, t; surface ordinate (i.e., the chloride concentration at the surface), C_s; the initial chloride content of the concrete, C_i; and the diffusion coefficient, $D = a^2 / \pi t$, where a is the distance that chloride would have penetrated if the chloride concentration gradient was constant and had the value of the gradient at the concrete surface. The surface chloride content changes with time and the distribution depends on the direction of the prevailing wind and the distance above sea level. Also, for structures on the seashore, distance from the shore influences chloride ingress.

Penetration of chloride ions into concrete is affected by the heterogeneity of the material; it occurs through defects and the cement matrix. The potential diffusion coefficient can be determined as a function of. w/c ratio and concrete maturity using the NT Build 443 test method. For supplementary binding materials such as fly ash and blastfurnace slag, the binder's *factor of efficiency* is the mass of cement that can replace 1 kg of the binder without changing the chloride diffusivity of the concrete.

Examination of concrete specimens exposed to seawater at the Träslövsläge Marine Exposure Station provided data on chloride ingress; the parameters were: environments (marine atmosphere, splash zone, submerged), concrete composition (4 types of cement; 2 types of silica fume; 2 types of fly ash; $0.25 \leq w/b \leq 0.75$), and exposure periods from about 6 months to 5 years.

Service lifetime prediction by the HETEK method involves a 10-step spread-sheet calculation. It is described, and examples of initiation time predictions are given, in Reference [11]. The predicted initiation times were comparable to those made by Clifton's model [12] (e.g., Clifton, 30 years; HETEK, 25 years). Estimates of the parameters of the HETEK model were made using Mejlbro's Lambda functions [13].

Some other references to the work of Poulsen and his colleagues are [14,15,16].

2.5 MODELLING CHLORIDE INGRESS BY THE COMBINED PROCESSES OF DIFFUSION AND CONVECTION

Michael Thomas, University of Toronto, Canada (with Evan Bentz)

The University of Toronto (U of T) model [17] was developed by Bentz and Thomas. Their purpose was to provide a model that would be useful to engineers. The specific application was for reinforced concrete tunnel lining sections. The WINDOWS-based model addresses chloride ingress by diffusion, wicking, and permeability, with positive pressure heads, evaporation, convection, and chloride binding being taken into account. For wicking, the Buenfeld model [18] was adopted.

Input parameters in the U of T model are: surface concentration, diffusion coefficient and its change with time, activation energy of the diffusion process, the initial chloride profile, permeation coefficient and its change with time, a viscosity correction, binding coefficients, porosity, and the temperature profile. The output is the chloride (total or free) concentration profile at any selected time interval. The model was calibrated using Bamforth's data from OPC (ordinary portland cement) concrete blocks that the Taywood Company had exposed on the shore of the English Channel above the high-tide level; some of the blocks were of fly-ash-containing concrete. Chloride binding was represented by either the Langmuir isotherm or the Freundlich isotherm, and diffusion coefficients were determined for OPC and fly ash concretes.

The governing equation, and equations for chloride binding, diffusion coefficient, and hydraulic conductivity, follow.

The governing equation is:

$$dC_f / dt = D \,.\, d^2C_f / dx - v_{avg} \,.\, dC_f / dx \qquad (1)$$

where C_f = 'free' Cl in solution; D = diffusion coefficient; and v_{avg} = average linear velocity, which is given by:

$$v_{avg} = Q / n \,.\, A = -(k/n) \,.\, (dh/dx) \qquad (2)$$

with Q = flow rate; n = porosity; A = cross-sectional area; k = hydraulic conductivity (permeability); and h = hydraulic head.

The alternative isotherms used to represent chloride binding were:

the Langmuir isotherm: $C_b = \alpha \,.\, C_f / (1 + \beta \,.\, C_f)$ (3)

and the Freundlich isotherm: $C_b = \alpha \,.\, C_f^{-\beta}$ (4)

where C_b = concentration of bound chloride; and α and β = binding coefficients.

The diffusion coefficient, $D(t,T)$, at time t and temperature T, is given by:

$$D(t,T) = D_{ref} \,.\, (t_{ref} / t)^m \,.\, \exp[(U/R) \,.\, (T_{ref}^{-1} - T^{-1})] \qquad (5)$$

where D_{ref} = diffusion coefficient at a reference time t_{ref} and temperature T_{ref}; m = a constant (depends on mixture proportions); U = activation energy of the diffusion process; and R = the gas constant; (the temperatures are in degrees Kelvin).

The hydraulic conductivity is:

$$k(t,T) = (k_{ref} / Z) \,.\, (t_{ref}/t)^{r} \qquad (6)$$

where $k(t,T)$ = permeability at time t and temperature T; k_{ref} = permeability at time t_{ref} and temperature T_{ref}; Z = viscosity temperature correction factor; and r = a constant (depends on mixture proportions), To facilitate its use, the model provides default values for quantities for which actual data may not be available. As can be seen from the plots in Figure 1, the model appears to provide a good fit to data for OPC concrete. Comparable results have been obtained for concretes containing blast furnace slag and fly ash.

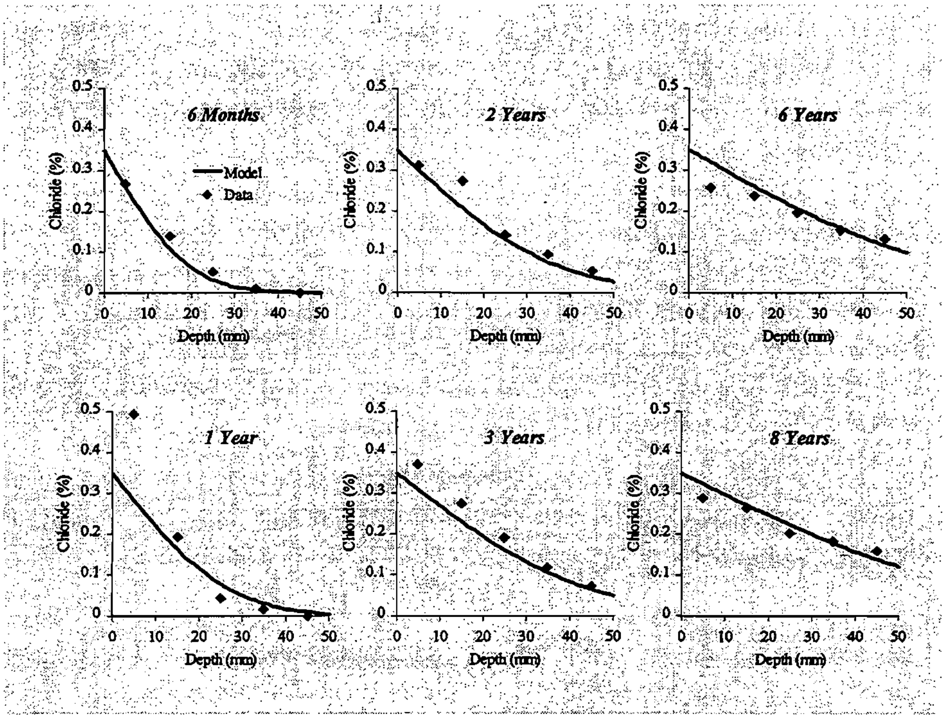

Figure 1. Comparison between U of T Model outputs and experimental data

2.6 MODELING ION TRANSPORT IN CEMENT-BASED MATERIALS

Jacques Marchand, Laval University, Canada (with E. Samson and Y. Maltais)

Over the past few years, the mechanisms of ionic transport in cement systems have been the subject of a great deal of attention. Most of the reports published on the topic have clearly emphasized the intricate nature of the problem. Given the number of parameters involved, the process of ionic transport cannot be described by analytical models, and numerical modeling is required.

The main features of a numerical model that predicts the mechanisms of ionic transport in reactive porous media were described in the presentation. An important original feature of the model is that it accounts for the electrical coupling (diffusion potential) between the various species in solution.

The model is divided into four parts: ionic diffusion, moisture transport, chemical reactions, and chemical damage. The transport of ions by diffusion is modeled by solving the extended

Nernst-Planck / Poisson set of equations. The diffusion of all ionic species present in the system can be accounted for by the model. It also accounts for chemical activity effects.

The transport of water by capillary suction is described by a diffusion-type equation, and the variation of the water diffusion coefficient is described by an exponential equation. The water content of the solid serves as the state variable for this part of the model.

Chemical reactions are modeled through a series of sink and source terms. The non-linear nature of each chemical reaction process is accounted for by a number of interaction isotherms. The influence of on-going chemical reactions on the material transport properties is accounted for. The effects of the chemically-induced alterations are described in terms of porosity variations.

To solve such a complex system of non-linear equations, a numerical algorithm must be used. All the equations are solved simultaneously. The spatial discretization of this coupled system is performed through the finite element method using the standard Galerkin procedure. An Euler implicit scheme is used to discretize the transient part of the model. The non-linear set of equations is solved with the Newton-Raphson algorithm. The second order algorithm gives a good convergence rate and is robust enough to handle the electrical coupling between the ionic flux and the water movement.

The model can be used to follow any changes in the concrete pore solution chemistry to obtain a precise description of the materials solid phase distribution. The model has been successfully applied to cases of degradation by sulfates and by chlorides.

2.7 THE DURAMODEL® FOR THE DESIGN OF COST-EFFECTIVE CONCRETE STRUCTURES

Paul Tourney, W.R. Grace Company

Systems for the corrosion protection of reinforcing steel in concrete have three possible effects: 1) reduction of the ingress of chloride, 2) increase of the chloride level at which corrosion initiates; and 3) reduction of the corrosion rate once corrosion initiates. The performance of a protection system needs to be evaluated in light of these effects. Once these are documented, one can determine the initial costs of the protection system and then project the time to corrosion for first and subsequent repairs. The future repair costs are converted to present day costs using a net present value analysis. Examples have shown that eliminating corrosion protection at the design stage is an expensive long-term option.

The Grace model [19] describes each of the three possible effects mathematically. The model is WINDOWS-based and the inputs include the type of structure and application, and the exposure conditions – temperature, surface chloride, thickness, chloride build up/year, and the corrosion threshold. Outputs include the service life with repair and the costs for various protective systems. Evaluation of the performance of a protection system as related to the three effects requires data from accelerated and long-term field and laboratory tests, and the evaluation requires an understanding of corrosion mechanisms as well as protection mechanisms; the same accelerated testing techniques cannot be used for all methods.

Since many protection systems affect the rate of diffusion or the chloride levels needed for corrosion, the prediction of chloride ingress is critical for life-cycle analyses. The exact rate of chloride diffusion through concrete cannot be calculated due to the heterogeneous nature of concrete and the differences between concreting materials. However, an approximate value can be obtained with sufficient accuracy for estimating the ingress of chloride into concrete structures in the field as a function of exposure conditions.

Fick's second law of diffusion can be used to calculate an effective diffusion coefficient, D_{eff}, if the chloride concentration at any time is known as a function of depth. A more rigorous approach would determine chloride binding and calculate the diffusion coefficient independent of chloride binding. To minimize effects of sorption, longer test periods are also recommended. However, work in the Grace laboratory and by others has shown that the effective diffusion coefficient can be used to predict chloride profiles, when it is determined after at least one or two years of exposure, since this exposure allows opportunity for both sorption and diffusion processes to occur. Hence, D_{eff} takes account of mechanisms other than pure diffusion. Diffusion coefficients and surface concentrations are determined by solving the equation from Fick's second law. Solutions for this equation, $\partial c/\partial t = \nabla^2 c(t)$, are given in the model for: a) a semi-infinite slab – applicable to cases in which the chloride ingress is from one side only, such as walls or decks under severe marine exposures, or submerged walls or slabs subject to constant chloride exposure, and b) cases in which chloride ingress is two-dimensional and chloride diffuses into the concrete from two sides, such as a square concrete pile.

Chloride concentration profiles from numerous laboratory and field studies have shown that a typical chloride diffusion coefficient for quality concrete is about 2×10^{-12} m^2/s, but may be an order of magnitude higher for a low-quality concrete, and be significantly lower for quality concretes containing supplementary cementitious materials. Diffusion coefficients can be adjusted for different environmental temperatures.

To develop a chloride profile, it is necessary to know the surface concentration. Typical values for the surface concentration are 18 kg/m^3 for severe marine environments in the splash/tidal zone. When bridge decks are exposed to deicing salts, chlorides build up at a rate of about 0.6 kg/m^3 per year until about 14 kg/m^3 is reached and further increase stops due to surface saturation and the washing effect of rain.

From typical values noted in the SHRP program [20], it appears that corrosion damage needing repairs tends to occur five years after initiation of corrosion. However, when epoxy-coated rebar is used for both top and bottom mats of steel, the time to repair is estimated to be 20 years after corrosion initiation; (more research is needed to better define this value). Assuming that there is no increase in chloride threshold values for epoxy-coated rebar, the 20-year value reflects a 75% reduction in the corrosion rate. Corrosion inhibitors result in an increase in the chloride threshold value.

Life cycle cost analysis – Life-cycle costs of corrosion protection scenarios were examined [19]. For the bridge deck example, the costs did not include extra expenses associated with the handling of epoxy-coated rebar and traffic control; user delay costs and other loss-of-use costs should also be included in the analyses. If these costs were included, only systems without repairs would make economical sense.

2.8 CREATING A STANDARD CORROSION SERVICE LIFE PREDICTION METHOD

Matthew A. Miltenberger, Master Builders Inc., Cleveland, Ohio

In order to model chloride diffusion, it is necessary to select appropriate boundary conditions and to have the necessary input parameters. The input parameters are the effective diffusion coefficient, the chloride loading, the depth of cover over the reinforcement and, perhaps, a temperature correction. Insight into the boundary conditions can be obtained by studies of buildup of chlorides at the concrete surface and by ponding experiments. Solutions to Fick's second law have been obtained for cases of buildup and constant chloride content.

In research at Master Builders, a chloride flux test cell, a chloride migration test cell, and ponding experiments have been used in the determination of diffusion coefficients for concretes with and without silica fume. (With the chloride flux test cell, it takes two to three years to obtain data for high-performance concrete.) For conductivity measurements in the migration test cell, the specimens were saturated with chloride solution prior to making the measurements. Plots of measured versus predicted diffusion coefficients showed reasonably good agreement. Among the comparisons made were: a) typical ponding test results – chloride content vs. depth from surface (measured and Fick's 2nd law); b) complete chloride profile -- chloride content vs. depth from surface (measured and Fick's 2nd law); c) combined transport mechanisms -- chloride content vs. depth from surface (measured and Fick's 2nd law using D from flux test).

Standardization issues -- The standardization of a model, or models, for service life prediction will be a complex problem. Among matters that need to be addressed are: a) establishment of a common terminology, b) definition of calculation procedures, c) identification of applicable transport mechanisms, d) standardization of test methods, and e) provide guidance to all who need it. Ultimately the standard, or standards, to be drafted should help designers.

Standardization of terminology is important for improving communication and reducing confusion and, in this connection, units of measurement should be standardized and not left as they are, e.g., m^2/s, cm^2/s, mm^2/yr, in^2/yr.

As for the model calculations, among the issues are:

- Should the L-R (Load-Resistance) format be adopted?
- Should a model incorporate reduction factors to account for other distresses (e.g., cracking)?
- Should corrosion propagation be included?
- Should equation(s) for multiple chloride transportation modes be included?
- How should the model(s) be validated?

- If a Nernst-Einstein temperature correction is to be used, is an activation energy (*U*) determined from studies on cement paste applicable to concrete?

Among the transport issues are those relating to the definition of the environmental loads, i.e., the driving force(s) behind chloride ingress:

- Diffusion -- The effective surface concentration
- Wicking – Relative humidity and the moisture gradient
- Sorption – Wet/dry cycle frequency
- Hydraulic permeation – Pressure head

Other transport issues concern definition of corrosion resistance parameters (such as the chloride threshold) and parameters related to the pore structure and its connectivity (such as the diffusion coefficient, water vapor diffusivity, sorptivity, and the hydraulic permeability). Then there is the question of identification of appropriate test methods and whether values should be estimated from mixture proportions.

In connection with model inputs, designers will need guidance to select reasonable values for diffusion coefficients, surface concentrations, buildup coefficients, and environmental factors. In connection with environmental factors, Master Builders has developed a chloride loading map for the United States based on data obtained from the Salt Institute [22], publications from the Strategic Highway Research Program [e.g., 20], and the Florida Department of Transportation [23], and measurements on concrete in parking garage structures.

In summary, a service life standard(s) should define common nomenclature, follow the familiar L-R format, include multiple chloride transport mechanisms, identify appropriate test methods, provide graphical guidance where appropriate, and be validated with data from real structures.

2.9 PREDICTING SERVICE LIFE OF CHLORIDE-EXPOSED STEEL-REINFORCED CONCRETE

Dale Bentz, National Institute of Standards and Technology

A computer-integrated knowledge system (CIKS) provides a means of combining a wealth of information into a coherent system useful to both the academic and commercial communities. For the concrete community, a subject of vital interest is the service life of concrete structures. For corrosion of reinforcing steel, the diffusion rate at which chloride can reach the steel is one of the controlling factors in determining how long a structure will last. A prototype CIKS for use in predicting the service life of steel-reinforced concrete exposed to chloride ions has been developed [24]. Starting from the mixture proportioning process, the system proceeds to predict chloride ion diffusivity coefficients and finally to predict the ingress profiles and the time-to-initiation of corrosion for a reinforced concrete exposed in a specific environment. The CIKS integrates into a single coherent system a number of computer models -- some previously developed, some new.

A starting point is the mixture proportioning of the concrete. The current ACI guidelines for proportioning ordinary-strength (ACI 211.1-94) and high-strength (ACI 211.4R-93) concrete have been computerized using a combination of HyperText Markup Language (HTML) forms and CGI programs written in the C programming language. If this starting point is selected, the system user is presented with forms for trial proportioning of the concrete mixture to which the user supplies the needed parameters and data according to the appropriate ACI guidelines. For ordinary strength concretes, choices include: slump; pozzolanic replacement method: (volume or mass basis); pozzolanic replacement material (silica fume, fly ash, or blastfurnace slag); aggregate surface property (angular or rounded); construction type (reinforced foundation, footing, beam and wall, column, pavement, mass concrete, thin section, or predetermined slump); air entrainment (no or yes); ASTM cement Type (I, II, III, IV, or V); and exposure condition (mild, moderate, severe, or salt or sulfate). The choices are different for high-strength concrete -- the additional items to be specified are: slump, use or absence of high-range water-reducing agent, and strength after 28 days or 56 days of curing. The completed form is submitted and the resultant trial mixture proportions are returned, together with a predicted value for the chloride ion diffusivity (***D***) of the in-place concrete, and an estimate of the maximum expected temperature increase under adiabatic conditions.

The prediction of chloride ion diffusivity from mixture proportions is based on a statistically-designed computer experiment which identified water-cement ratio (w/c), volume fraction of aggregates, and degree of hydration as the three major variables influencing the diffusivity of a conventional concrete mixture without mineral admixtures. An equation for estimating chloride ion diffusivity coefficients using these three variables was developed. In addition, the CIKS returns an estimate of the 90 percent confidence limits for the estimated D value, based on regression of the developed equation to the computer experiment data. Values for w/c and volume fraction of aggregates are directly available from the trial mixture proportioning process. The long-term degree of hydration is estimated as 90 % of the theoretical maximum achievable hydration based on the w/c.

Once a D value has been estimated, it can be used in a model to predict the service life of a reinforced concrete structure exposed to an external source of chlorides. The simplest approach, implemented as a menu item, is to use Fick's second law and solve for t in the following equation:

$$C_{corr} / C_{ext} = erfc\,[x / 2(Dt)^{1/2}] \qquad (1)$$

where C_{corr} is the concentration of chloride ions needed at the reinforcement to initiate corrosion, C_{ext} is their external concentration, x is the depth of the reinforcement, D is the chloride ion diffusivity, t is the predicted service life, and $erfc\ (x) = 1 - erf\ (x)$. An alternative to the simple *erf* solution of Fick's second law is to employ a one-dimensional finite difference solution incorporating the time-dependent variability of the exposure environment and the performance differences between the bulk and surface layer concrete. This optional analysis is implemented by selection of a separate menu item from the CIKS.

Several prototype databases are included in the current version of the CIKS. The first is a bibliographical listing of recent articles dealing with the penetration of chloride ions into cement-based materials. The fact that the database resides on a different computer than the CIKS itself illustrates the feasibility of a distributed knowledge system using the World Wide Web. The second database is a compilation from the literature of concrete chloride ion diffusivity coefficients, along with mixture proportions and curing times, when provided.

The prototype shows the potential of employing a CIKS in the design process. A variety of different trial mixture proportions can be evaluated quickly with respect to their expected service life for chloride-ion-induced corrosion, and also with respect to their susceptibility to thermal cracking via the projected adiabatic temperature rise. The diffusion coefficients predicted by the computer can be compared to those in the existing experimental results database.

The potential of the Web for disseminating knowledge of concrete technology appears promising. Updating a CIKS on the Web, such as the prototype described, will become much simpler and quicker since only information on the server machine will need to be changed. Thus responses to user feedback will be able to be greatly expedited.

2.10 USING CONCRETE SERVICE LIFE PREDICTION MODELS TO ESTIMATE THE LIFE-CYCLE COSTS OF CONCRETE STRUCTURES

Mark Ehlen, National Institute of Standards and Technology

NIST's Building and Fire Research Laboratory has developed several economic techniques applicable to construction that have become ASTM standards. These include techniques for life-cycle costing and analytical hierarchical decision-making. The techniques have been applied in the development of the life-cycle costing software, BridgeLCC [25], for use in comparing new technology and traditional materials and systems for bridges on a common life-cycle economic basis. In the first instance, BridgeLCC was applied to bridge applications of fiber-reinforced polymer composites but, as part of NIST's Partnership for High-Performance Concrete Technology program, it is now being applied by several State Departments of Transportation to life-cycle costing of high-performance concrete (HPC) in bridges. The service life input is provided by the model described in the presentation.

BridgeLCC incorporates the NIST-developed life-cycle costing standard, ASTM E 917, Practice for Measuring Life-Cycle Costs of Buildings and Building Systems [26], and uses the NIST cost classification scheme. It can be used for sensitivity analyses, including Monte Carlo simulations. Examples of applications are: In building a new bridge, should steel, or conventional concrete, or high-performance concrete, be used in the girders? Or, for an existing bridge, should it be repaired or replaced? Should it be painted now or painted later? In applying BridgeLCC to the life-cycle cost of a bridge, the model addresses all bridge-related costs that occur during construction, e.g., maintenance and repair, and disposal of the structure (whether incurred by the agency, by the users of the bridge, or by affected "non-users"). All costs are discounted to a single number in present-day dollars using an interest rate formula.

The ASTM E 917 life-cycle costing standard covers a wide range of applications. Using a user-friendly, step-wise procedure, performance-based criteria allow evaluation of new materials and designs. Using the NIST classification scheme in a top-down approach insures that all costs can be accounted for. Using the scheme bottom-up, all costs can be properly placed, and the calculations can start with the engineer's estimate. The NIST cost categories are:

Characteristic 1: Who pays? The agency; the user; or a third party?

Characteristic 2: When does the cost occur? In initial construction? In operation, maintenance, and repair (OM&R)? Or in disposal?

Characteristic 3: What part of the project causes the cost? An element? A non-elemental factor (e.g., mobilization)? Or introduction of new technology (e.g., beam load test, NDE)?

Applying the NIST classification scheme in BridgeLCC, the technical advantages and disadvantages of a material can be assessed in economic terms. It should also be noted that BridgeLCC can be used to assess life-cycle costs on a probabilistic basis.

In an example, life-cycle analysis was carried out to compare a conventional concrete bridge with an high-performance concrete bridge and determine the life-cycle cost savings of using HPC instead of conventional concrete. It also showed how use of HPC would affect the initial construction costs and repair costs. For the HPC bridge, savings would result from use of fewer beams and from a longer-lasting deck.

3. WORKING GROUP REPORTS

3.1 Working Groups 1 - 4. Standards for Service Life and Life-Cycle Cost

In this session, all four working groups were asked to address the question, "How could a framework for development of a standard, or standards, for service life and life-cycle cost of chloride-exposed, steel-reinforced concrete best be developed?" This section combines comments from the four working groups.

The WG discussions were broad-ranging and included comments on the need for standard models as well as direct responses to the question posed. The discussions may be summarized as follows.

The Need -- It is known that the Nation's economic losses attributable to corrosion are enormous. In the case of corrosion of steel in concrete, we cannot afford not to develop a standard model when designers have so much need for guidance. A standard method is needed, even if it is not perfect -- "Any system is better than anarchy!" Standard models would help: a) promote good concrete practices, b) provide credible evidence of the efficacy of products, and c) ensure that taxpayers' dollars were wisely spent. Because a coherent system would help improve concrete in the long term, we should reaffirm the need for development and standardization of a model in accord with the workshop objectives.

The Approach -- Model development should be carried out by a committee with subcommittees working on different aspects of the model. The modelling activity should define the limitations of the model and identify research needed for its improvement. To start to fill the need, a useful model should be produced as soon as possible, with an improved model being produced over a longer term. Among related activities, it will be necessary to define terms so as to avoid confusion, and databases in standard formats such as those outlined by ACI 126, Database Formats for Concrete Material Properties, should be established to help with model development and validation.

The Workshop Objectives -- The objectives as presented at the start of the workshop were generally satisfactory, but one WG stated that it would have been better if the need for both short-term and long-term objectives and for definitions had been recognized. The WG would have liked Objectives 2, 3 and 4 to be modified, and a fifth objective added so that the objectives would have been:

1. To review current models for determining the service life and life cycle cost of steel-reinforced concrete subjected to chloride-induced corrosion of the steel (no change)
2. To agree on basic parameters and issues for modelling service life prediction and life cycle costs.
3. To identify and, if necessary, develop and standardize test methods needed to support development and validation of models.
4. To recommend actions to be taken with a time frame for developing models for potential standardization.
5. To disseminate information (i.e., transfer technology) to the professional community.

Workshop Scope – It should be emphasized that transport of chlorides in concrete is not only by diffusion. While it is possible to force fit data to get an apparent diffusion coefficient, it is better to look at all transport mechanisms. Indeed, the main cause of corrosion may be cracking which allows chloride to reach and depassivate the steel. This should be covered in the later WG discussions.

Criteria for an acceptable model

An important subject in the discussions concerned criteria to be met by acceptable models. It was suggested that two sets of criteria were needed, one for a model that would be developed quickly to satisfy the immediate need, and one for the preferred model that would be developed over the long term. To support development of both models, a unified, reference database should be established.

Criteria for a model to meet the immediate need – The model should:

- Be verifiable by comparison of its outputs with actual data, e.g., the model should be able to make accurate predictions of chloride contents
- Be well-documented and have background material clearly presented, with assumptions and limitations being clearly stated
- Offer help on input values
- Have a statistical basis for assumptions (with respect to input values, diffusion coefficients (d_a), surface concentrations, and environment)
- Have the smallest possible number of adjustable coefficients
- Deal with as many known mechanisms as practical
- Provide data for economic analysis (i.e., for life-cycle costing)

It was commented that the W.R. Grace model might be a suitable starting point for a model to meet the immediate need.

Criteria for the preferred (long term) model – The model that is the ultimate goal should:

- Meet all the criteria for the immediate model:
- Incorporate lesser-known transport mechanisms
- Incorporate multiple deterioration mechanisms
- Correlate service conditions and microclimates
- Link microclimate to macroclimate
- Include preventive maintenance
- Include corrosion propagation.

It was also suggested that any standard model would have to have a strong component of testing.

Criteria for the database – Appropriate and reliable data will be needed to support model development. The data is needed for determination of apparent diffusion coefficients, for verification of existing models and the selection of one or more models for further development. It should include surface chloride concentrations. The database should include chloride contents for at least five different locations (depths), temperature, mixture proportions, and age (at least up to ten years). It was emphasized that other data would be of little value if the mixture proportions were not recorded.

3.2 Working Group 5. Chloride Transport Mechanisms and Test Methods

Sampling -- Good data is needed if knowledge of chloride transport mechanisms is to be advanced most rapidly. A critical issue to be addressed is the development of guidelines on sampling techniques. As a minimum, the guidelines should cover coring, profiling, and analytical procedures, with the sampling being appropriate to the situation. This can be appreciated by considering a few different scenarios:

a) For a bridge deck, or a deck in a parking garage, subjected to deicing salts, the salt may be intentionally applied to the concrete surface or be splashed on to it. The subsequent transport of chloride into the concrete will be affected by drying and by wetting by rain. Mechanisms to be considered must include: wicking, absorption, diffusion, and evaporation.

b) For a sea wall, the problem is more complicated. Below the water line where the concrete remains submerged, diffusion will be the dominant mechanism. Above the water line, the concrete will be subjected to salt fog, rain, and splashing from waves, and the transport mechanisms to be considered must include: wicking, absorption, diffusion, and evaporation. The transition zone will be subject to repeated immersion from waves and tides, and all transport mechanisms must be considered: wicking, absorption, diffusion, evaporation.

c) For the wall of a tunnel with a dry interior and surrounded by a wet salty environment, permeability, diffusion and evaporation must all be considered.

Many factors must be considered in studies of transport mechanisms. They include:

- Binding of chloride – Important work on chloride binding isotherms has been carried out. It is also possible to estimate the chloride binding from a single measurement of the apparent diffusion coefficient, D_a, and an assumed isotherm.
- Age dependence – Data from laboratory D_a tests at different ages neglect environmental effects. Some data have been obtained from field specimens of different ages which have been exposed to similar environments.
- Temperature dependence -- There is some data on bulk D at different temperatures and concentrations.
- Surface barriers -- A Danish test has provided information on the effectiveness of surface barriers.
- Cracks -- In the case of cracked concrete, it is important that measurements be made at points between cracks.

Test methods that can be useful in studies of different transport processes are listed in Table 1. For in-situ tests (on both new and existing structures), multi-probe corrosion detection sensors can be used to get "field" measurements of the time to initiation of corrosion.

Table 1. Chloride Transport Processes and Appropriate Tests

CHLORIDE TRANSPORT PROCESSES	LABORATORY TEST METHODS
• Diffusion	• Bulk diffusion, NORDTEST 443 • Rapid migration test (CTH) * ➢ steady state migration ➢ resistivity / conductivity (RCPT **, AC impedance)
• Convection (movement of Cl^- with H_2O) ➢ permeation	• Darcian permeability test (CRD 163)
• Unsaturated flow	• Vapor diffusion (for wicking) • "Sorption" (as per C. Hall and L. Parrott)

* CTH = Chalmers University of Technology
** RCPT = Rapid chloride penetration test

3.3 Working Group 6. Chloride Thresholds for Corrosion Initiation

For general understanding, it is important to have an accepted, mechanism-free, definition of the "corrosion threshold." In general, the chloride threshold is the point of metal depassivation and it is a function of the structures of the concrete and the metal (usually "black" steel), and of the environment. U.S. practice, as adopted by the FHWA, is to use a single number, between about 0.7 kg/m^3 and 1.2 kg/m^3 (1.2 lb/yd^3 and 2 lb/yd^3), for the chloride threshold; this is probably too simplistic and it might be better to take a statistical approach in determining the threshold.

The chloride threshold, C_T, (Figure 1), appears to depend on many factors including:

- chloride concentration
- concrete ingredients (type and source of aggregate, type of pozzolan, type of cement, and types of chemical admixture)
- mixture proportions
- consolidation (voids, settlement around rebar, interfacial porosity), finish, cure

- local environment (temperature, moisture content, oxygen, pH, CO_2, solutes, chloride source)
- potential ("normal", about -100 mv CSE), prior corrosion elsewhere, oxygen availability
- time -- (Does the threshold vary with time?)
- reinforcing metal – plain steel (surface condition, alloys mod., heat treatment), pre-stress (post tensioning, oil on surface), stainless, galvanized
- intrinsic variability of concrete

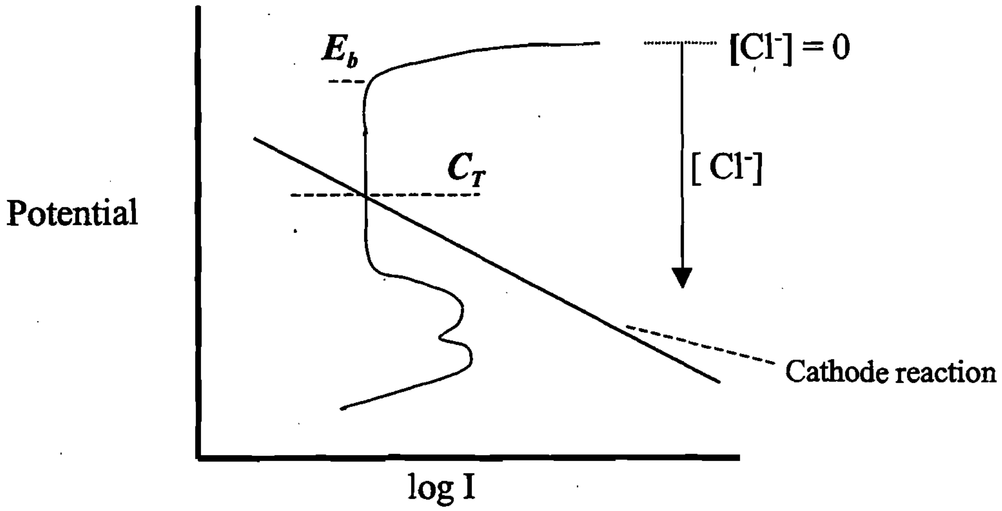

Figure 1. Variation of chloride threshold for corrosion; (E_b is the breakdown potential).

For reinforcement other than plain black steel, additional factors have to be taken into account. Among them are:

- the threshold for galvanized steel may be twice as high as that for black steel, or it may be non-existent
- the threshold for stainless steel may be 5 to10 times higher than for black steel
- epoxy-coated steel needs its own model (propagation) to address "debonding" time, though conditions for depassivation may be the same as for black steel.

Test methods are needed to measure the chloride threshold under different conditions such as: a) pre-existing chlorides in the concrete materials (as opposed to chloride ingress from an external source); b) carbonation of the concrete; c) the chloride source (e.g., NaCl vs. $CaCl_2$); and d) the local chloride distribution at the steel surface.

Definition of chloride threshold – It is important to recognize that a) total chloride; b) free chloride; c) water-soluble chloride; and d) the $[Cl^-]$ / $[OH^-]$ ratio, are not necessarily closely-related. While total chloride is easiest to measure, the $[Cl^-]$ / $[OH^-]$ ratio is most important for initiation of corrosion. This is why the "chloride threshold" must be defined appropriately. The WG recommended that the definition should be, essentially:

> *The chloride threshold, C_T, is the mass of total chloride per unit volume of concrete that results in permanent depassivation of the steel (for a specific set of mixture proportions, history, and environmental factors).*

In addition to adoption of an appropriate definition for C_T, there should be consistency in the choice of units used for expressing it. At present there is no consistency. Some units used are: lb/yd^3, lb/lb, kg/m^3, and kg/kg. In accord with the recommended definition, the preferred SI unit should be kg/m^3.

The threshold may be represented as:

$C_T = f$ (mixture proportions, construction practices, metal type, corrosion inhibitors, the environment, E, t)

where construction practice affects concrete quality, E is the local electrical potential of the reinforcing metal, and t is time.

Values of C_T for use in a model -- It is a difficult to know how to choose C_T for use in a model. One approach is to select a base C_T and modify it by multipliers for different cases. Suggested multipliers are:

Factor affecting C_T	Suggested multiplier for C_T
mixture proportions	the Poulsen formula
construction practice	nothing (factor < 1)
environment	(wet, dry) Poulsen
E	nothing
t	nothing
the metal:	
black steel	1
stainless steel	> 1

Determination of C_T from field survey data

At present, the most trustworthy method for determination of the threshold is analysis of field survey data as illustrated in Figure 2.

Determination of C_T from immersion in simulated pore solutions

The simplest and most rapid method of attempting to determine C_T is to immerse the steel in simulated concrete pore solutions containing different concentrations of chloride and different [Cl$^-$] / [OH$^-$] ratios. Unfortunately, the results do not correlate well with field data.

As a result, the method is only useful as a screening tool to weed out unsatisfactory new materials. It is generally agreed that allowing the slow ingress of chloride into concrete over several years provides a better basis for determination of C_T, though still greater reliance is placed on the data from field surveys. To summarize, the usefulness of the different types of test can be represented:

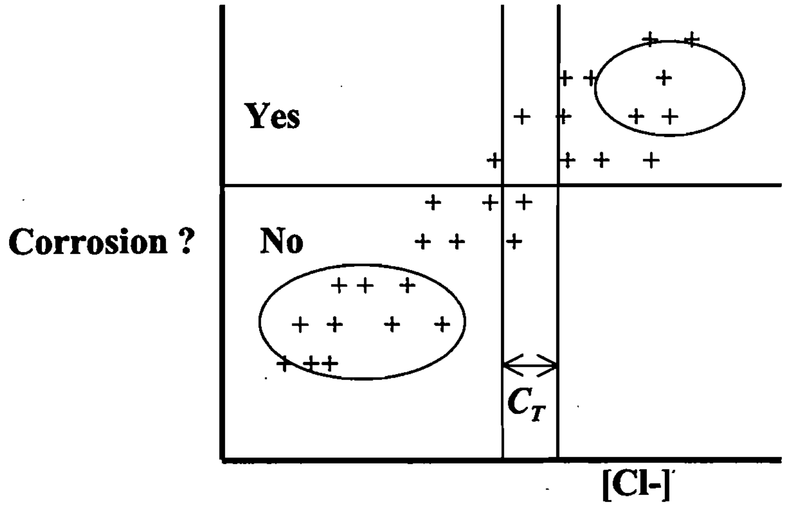

Figure 2. Use of field data in determination of the chloride threshold

	Applications of the Test		
Test Method	All	New rebar	Screening
Extensive field survey	x	-	-
Slow Cl^- ingress test (years)	x	x	-
Simulated pore solution tests	x	x	x

3.4 Working Group 7. Corrosion Rate and Time to Rehabilitate or Replace

Modelling of rates of corrosion should be possible; however, more data is needed to support the modelling. In considering time to rehabilitate or replace, questions that must be asked are: "What constitutes failure?", and "How can failure be modelled?"

Regarding corrosion rate and crack propagation, there is a need for more information on mechanical properties of rust, and a need to know if the expansion is pressure-dependent? This information is needed for modelling relationships between corrosion rate, stress in rust, and stress in concrete; the problem is complex and a fracture mechanics approach will have to be taken. There is also a need for methods for characterizing damage levels. Those we have now only account indirectly for factors (e.g., chloride level, percent spalling, cracks, etc.) that determine the need to repair. Methods for characterization of damage level include:

- number and orientation of cracks
- size of cracks
- percent delamination caused by corrosion
- half-cell potentials
- rates of corrosion.

The FHWA rating system should be adopted as a starting point. Data from the bridge inventory database should be used and a statistical analysis of historical data should be considered. For new structures, a good (reliable) set of constants based on material properties is needed. The properties of the (steel - paste) interfacial zone should be included.

Regarding modelling of corrosion of reinforcing steel in concrete, modelling of the rate of corrosion should not be too ambitious. It should be within our means, though more data is needed, especially on newer systems such as epoxy-coated rebars and concrete containing corrosion inhibitors.

Other materials must be distinguished from "black steel" and from each other. For example, comparing A706 and A615 steels, A706 is more susceptible to chloride-induced corrosion. Knowledge is needed about the effects on corrosion rate of factors such as mill scale, cracks, and crevice corrosion; an assumption of uniform corrosion may not be valid. Modelling the corrosion of epoxy-coated rebars will involve localized corrosion, and agreement should be sought on damage functions for epoxy-coated rebars and for systems containing corrosion inhibitors. Data is needed on such systems to help evaluate damage in them.

An SHRP (Strategic Highway Research Program) [20] report exists for "black steel." It includes useful information on corrosion rates and on predicting time to repair, and it provides a methodology.

Existing models do not address all critical components of time to corrosion. For example:

- few (if any) cover corrosion rates
- existing methods for field determination of corrosion rates need improvement; they are difficult to use on vertical surfaces, and they do not work well with prestressing steel
- overestimation of corrosion rates may be a potential problem in modeling
- improved correlation between laboratory and field measurements of corrosion rates may be needed before a reliable approach to modeling is developed; (small sensors being developed for in situ corrosion rate measurements may help).

A question that must be asked is, What constitutes failure and how can it be modelled? Is it failure of the bond and deterioration of concrete? Or loss of tensile capacity due to the reduced cross-section of the steel?

For modelling purposes it will be necessary to separate "new construction" from "repair", with verification of information taking place during the design phase. Overall, there will probably be three decision points: design stage; fresh concrete; and some time later.

3.5 Working Group 8. Service Life Prediction and Life-Cycle Costing

There is now enough information to be able to make a stab at producing useful service life and life-cycle cost models. The life-cycle cost methodology is in place and standardized in ASTM E 917. For the short term, the models may have to include "fudge factors." For the long term, a comprehensive service life model should be the goal and the requirements for such a model should be laid out. A fundamental requirement for the corrosion initiation model is that it should have a probabilistic base.

A task group, perhaps a joint one between ACI and AASHTO, should be established to allow public input to the model development and standardization. Within ACI, the task group should be in one of two committees – either Committee 365 on Service Life Prediction, or Committee 222 on Corrosion of Metals in Concrete. Further, the task group should be set up in time for its first meeting to take place during ACI's Spring 1999 Convention. Within the task group, there should probably be four working groups to address: a) "empirical" modelling of transport, b) "scientific" modelling of transport, c) the corrosion threshold (models and test methods), and d) life-cycle cost. Some of the considerations are indicated in Table 2.

Table 2. Some interrelationships among boundary conditions, transport processes, and transport modifiers

Boundary Conditions	**Transport Process**	**Transport Modifiers**
e.g. saturated unsaturated external pressure temperature threshold limits	e.g. diffusion absorption hydraulic effect evaporation	e.g. binding α (or time) * temperature surface barriers steel coatings cracks

* α = degree of hydration of the cement

For expediency, "empirical" models will have to be developed first. They should apply to plain concrete, surface protection, and impregnated concrete in both new and existing structures. "Scientific" models should replace the empirical models as the desired scientific understanding of the factors affecting the rate of corrosion is gained.

Barriers – There are several barriers to overcome in developing and gaining acceptance of the desired models. Some of the barriers are institutional, some technical. Among them are:

a) code committee members who may not be comfortable with inclusion of diffusion coefficients in concrete codes, b) lack of the standard test methods needed to develop a common database, c) lack of a standardized approach to modelling, and d) lack of standards for relevant chloride analyses.

For the most rapid progress, several different organizations should play a part. Test methods and specifications would be expected to be addressed in ASTM and CEN, with guides and codes being addressed by ACI and RILEM.

As a result of its discussions, the WG recommended that:

- A standards organization should provide a home for the service life and life-cycle cost model development activities. Within ACI, an appropriate committee would be ACI 365 or ACI 222.
- Momentum built at the present workshop should be maintained through a continuing series of workshops.

4. FINAL DISCUSSION AND RECOMMENDATIONS

4.1 Workshop Recommendations

Discussion in the closing session showed a strong measure of agreement among the participants that there was a good basis for preparation of a state-of-the-art report and for development of a model or models. Specific recommendations were:

The key recommendations from the workshop were:

1. A subcommittee on modeling of service life and life-cycle cost of reinforced concrete should be established in ACI Committee 365, Service Life Prediction. The subcommittee should establish guidelines for the models and, using the current state of knowledge, develop a baseline corrosion service life and life-cycle cost model as rapidly as possible.
2. The baseline model should be made available to the industry for testing and implementation and then placed on the Web, possibly with a list of other models and links to them. The possibility of forming an on-line discussion group should be considered.
3. Over a longer term, a comprehensive model based on scientific understanding should be developed through the joint activities of an industry-government consortium and the relevant standards organizations. Test method standards should be developed in ASTM Committee C09, Concrete and Concrete Aggregates, and ASTM Committee G01, Corrosion.
4. An organization such as NIST should be given responsibility for maintaining the model on the Web and for making necessary updates as further developments occurred..

Regarding Recommendation 1, because the two key persons needed to approve the recommended action -- Jim Clifton, Chairman of ACI 365, and Terry Holland, Chairman of ACI's Technical Activities Committee – were present and were in agreement, they announced that the proposed subcommittee would be established. Further, they announced that Mike Thomas of the University of Toronto had accepted their invitation to chair the subcommittee. The announcement was applauded. Thomas invited persons interested in joining the subcommittee to contact him at: mthomas@attcanada.net .

4.2 Workshop Summary

The workshop began with an invited presentation on the status of international efforts in RILEM to standardize service life prediction of reinforced concrete. The RILEM committee expects to complete its development of standardized methodologies (modelling and test methods) by the end of the year 2002. Nine other invited speakers gave presentations on the characteristics of empirical and analytical models for predicting the time to initiation of corrosion of steel in reinforced concrete.

In the workshop, working groups discussed the various aspects of service life modelling of reinforced concrete and related testing and identified the following main points in response to the workshop objectives:

Chloride transport:

- Transport mechanisms must include diffusion, wicking and sorptivity.
- Service environments must be adequately characterized; this includes the development of a comprehensive "isochloride" map.
- The most appropriate test methods for obtaining data to support the modelling appear to be bulk diffusion and DC-driven methods; resistivity test methods, such as RCPT, are most suitable for quality control assessments; procedures for sampling field concrete need to be standardized.

Chloride threshold for corrosion initiation:

- Test methods are needed to determine threshold values for steel in reinforced concrete with various corrosion protection systems.

Corrosion rate/propagation:

- A more detailed understanding of factors affecting corrosion rate and corrosion propagation needs to be developed.
- Correlations between laboratory and field data should be established.
- A database of field performance data for all corrosion protection systems should be developed.
- Define and quantify "damage" levels for the different types of damage, e.g., cracking and spalling.

Service life and life-cycle cost models:

- "Initiation" stage models should be able to be standardized in view of the work that has been done in this area.
- In the near term, a model should be developed that accounts fully for corrosion initiation.
- An "initiation" model should allow for corrosion propagation as an empirical input to account for the "damage" level at which corrective action needs to be taken by the user/owner.
- Over a longer term, when corrosion propagation issues are much better understood, an initiation/propagation model should be developed.

The subcommittee of ACI Committee 365, Service Life Prediction, that was established at the end of the workshop should be a focus for work to meet the needs identified in the above list. The subcommittee should establish task groups to address the different aspects of knowledge needed to support the development of standard models for service life prediction and life-cycle costing of steel-reinforced concrete. Because the workshop was organized at the suggestion of ACI's Strategic Development Council, a report on the workshop should be given to the SDC at its next meeting. Support should be sought for formation of an industry-government consortium to focus resources on development of the desired standard models. Organizations that should be interested in participating in a consortium are suppliers of concrete materials, engineering and construction companies, governmental construction agencies and research laboratories (federal and state), and academic research groups. In North America, the proposed standardization activities related to concrete practice would logically take place in ACI, while test method standards would be developed in ASTM. On the international level, RILEM is already involved in prestandardization activities and ISO TC71, Concrete and Reinforced Concrete, should be the relevant standards organization; in this connection, it may be noted that ACI is the secretariat for ISO TC71.

In view of the need for large amounts of well-organized data to support the model development, standard database formats should be adopted. If ACI Committee 126, Database Formats for Concrete Material Properties, has already developed suitable formats, those formats should be used; if it has not, ACI 126 should be asked to develop the needed formats.

5. REFERENCES

1. RILEM Technical Committee TMC, Testing and Modelling Chloride Penetration into Concrete, Annual Report, RILEM, Cachan, France, 1997, pp. 11-12.

2. Sagüés, Alberto A., and Kranc, S.C., Model for a Quantitative Corrosion Damage Function for Reinforced Concrete Marine Substructure (Summary Paper), in Rehabilitation of Corrosion Damaged Infrastructure, P. Castro, O. Traconis, C. Andrade (eds.), Chapter IV: Modeling, Methods, Techniques and Technologies, pp. 268-276, 1998, NACE International.

3. Sagüés, A.A., Scannell, W., and Soh, F.W., Development of a Deterioration Model to Project Future Concrete Reinforcement Corrosion in a Dual Marine Bridge, Proceedings, International Conference on Corrosion and Rehabilitation of Reinforced Concrete Structures, Orlando, Florida, December 8-11, 1998.

4. Kranc, S.C., and Sagüés, A.A., Computation of Reinforcing Steel Corrosion Distribution in Concrete Marine Bridge Substructures, Corrosion, v. 50, p. 50 (1994).

5. Nilsson, Lars-Olof, and Tang, Luping, Present Limitations in Scientifically Based Prediction Models for Chloride Ingress into Submerged Concrete, in Proceedings, First International Meeting, Materials Science and Concrete Properties, Toulouse, March 5-6, 1998.

6. Tang, L., Chloride Transport in Concrete – Measurement and Prediction, Ph.D. Thesis, Report P-96:6, Dept. of Building Materials, Chalmers University of Technology, Goteborg, Sweden, 1996.

7. NT Build 443, Concrete Hardened: Accelerated Chloride Penetration, Approved 1995-11, NordTest Register, Esbo, Finland, 1996.

8. Poulsen, E., Frederiksen, J.M., and Mjelbro, L., Chloride-Exposed RC Structures: Chloride Ingress and Lifetime Prediction by the HETEK-Model (visuals for the NIST/ACI.ASTM Workshop, 41 images: a copy can be made available upon request).

9. CorroWatch: Embeddable Multiprobe for Corrosion Monitoring in Concrete Structures, Force Institute, Copenhagen (promotional literature).

10. Poulsen, E, and Frederiksen, J.M., The Method of Inverse Cores, AEC Laboratory (notes for the NIST/ACI/ASTM Workshop, 7 pp; a copy can be made available upon request).

11. Maage, M., Helland, S., Poulsen, E., and Carlsen, J.E., Service Life Prediction of Existing Conccrete Structures Exposed to a Marine Environment, ACI Materials Jrnl., v. 93, No. 6, pp. 602-608, 1996.

12. Clifton, J., Predicting the Service Life of Concrete, ACI Materials Jrnl., v. 90, pp. 611-617, 1993.

13. Mejlbro, Leif, The Complete Solution of Fick's Second Law of Diffusion with Time-Dependent Diffusion Coefficient & Surface Concentration, MAT-Report No.1996-18.

14. Poulsen, Ervin, Estimation of Chloride Ingress and Service Life Prediction in RC Structures Exposed to Marine Environment, Mario Collepardi Symposium, ACI Venice, Italy, October 1997 (19 pages).

15. Frederiksen, J.M., and Poulsen, E., HETEK: Chloride Penetration into Concrete Manual, Report No. 123, Road Directorate, Ministry of Transport, Copenhagen, Denmark, 1997 (48 pages).

16. Mejlbro, L., Estimates of Parameters of the HETEK-Model (notes for the NIST / ACI / ASTM Workshop (note for the NIST / ACI / ASTM Workshop, 12 pages)

17. Bentz, E.C., Evans, C.M., and Thomas, M.D., Chloride Diffusion Modeling fpr Marine Exposed Concrete, 4th International Symposium on Corrosion of Reinfocement in Concrete Construction, C. Page, P. Bamforth and J. Figg (eds.), SCI, Cambridge, U.K., 1996, pp. 176-188.

18. Buenfeld, N.R., Shurafa, M.-T., and McLoughlin, I.M., Chloride Transport Due to Wick Action in Concrete, RILEM International Workshop on Chloride Penetration into Concrete, Domaine Saint Paul, St. Remy-les-Chevreuse, France, 1995.

19. Berke, N.S., Hicks, M.C., Macdonald, A., Tourney, P., Use of the DuraModel® for the Design of Cost-Effective Concrete Structures, Proceedings, International Conference on Corrosion and Rehabilitation of Concrete Structures, Orlando, Florida, Dec. 7-11, 1998.

20. Weyers, R.E., Fitch, M.G., Larsen, E.P., Al-Quadi, I.L., Chamberlin, W.P., and Hoffman, P.C., Service Life Estimates (Report SHRP-S-668), Strategic Highway Research Program, National Research Council, Washington, D.C., 1993.

21. Johnson, D.A, Miltenberger, M.A., and Amey, S.L., Determining Chloride Diffusion Coefficients for Concrete Using Accelerated Test Methods, 3rd CANMET / ACI International Conference on Concrete in Marine Environments, St. Andrews-by-the-Sea, New Brunswick, Canada, Aug. 4-9, 1996. Supplementary Papers, pp. 95-114.

22. State Department of Transportation Salt Use Survey, Salt Institute, 1983.

23. Structure Design Guidelines, Chapter 7, Florida Department of Transportation

24. Bentz, Dale P., Clifton, James R., and Snyder, Kenneth A., A Prototype Computer-Integrated Knowledge System: Predicting Service Life of Chloride-Exposed Steel-Reinforced Concrete, Concrete International, pp. 42-47, December 1996.

25. Ehlen, M.A., Life Cycle Costs of New Construction Materials, J. Infrastructure Systems, Dec. 1997, pp. 129-133.

26. ASTM E 917, Practice for Measuring Life-Cycle Costs of Buildings and Building Systems, Annual Book of Standards, v. 04.11, American Society for Testing and Materials, Philadelphia, 1998.

27. Berke, N.S., and Hicks, M.C., Control of Corrosion of Steel in Concrete: The Infrastructure Issue, Topical Research Symposium '98, R. Latanision (ed.), NACE, Houston, Texas, 1998.

APPENDIX 1

Steering Committee and Workshop Participants

Steering Committee

Geoff Frohnsdorff	Building and Fire Research Laboratory, NIST
Shuaib Ahmad	American Concrete Institute
Emmanuel Attiogbe	Master Builders, Inc.
Neal Berke	W.R. Grace Company
Dan Falconer	American Concrete Institute
Doug Hooton	University of Toronto
Paul Johal	Prestressed/Precast Concrete Institute
Colin Lobo	National Ready Mixed Concrete Association

Workshop Participants

Shuaib Ahmad	American Concrete Institute
Antonio Aldekiewicz	W.R. Grace Company
Stephen Amey	Master Builders Inc.
Emmanuel Attiogbe	Master Builders Inc.
Dale Bentz	Building and Fire Research Laboratory, NIST
Evan Bentz	University of Toronto, Canada
Neal Berke	W.R. Grace Company
Nick Carino	Building and Fire Research Laboratory, NIST
Marta Castellote	Eduardo Torroja Inst. of Construction Sciences, Spain
Jim Clifton	Building and Fire Research Laboratory, NIST
Mark Ehlen	Building and Fire Research Laboratory, NIST
Geoff Frohnsdorff	Building and Fire Research Laboratory, NIST
Ed Garboczi	Building and Fire Research Laboratory, NIST
David Gustafson	Concrete Reinforcing Steel Institute
Terry Holland	Silica Fume Association; and Chairman, ACI / TAC

Workshop Participants (continued)

Doug Hooton	U. of Toronto, Canada
Paul Johal	Precast/Prestressed Concrete Institute
Paul Kelley	Simpson, Gumpertz and Heger
Alistair MacDonald	W.R. Grace Company
Bryan Magee	Purdue University
Jaques Marchand	Laval University, Canada
Nick Martys	Building and Fire Research Laboratory, NIST
Matthew Miltenberger	Master Builders Inc.
George Muste	National Ready Mixed Concrete Association
Ted Neff	Consultant
Lars-Olaf Nilsson	Chalmers University, Sweden
Charles Nmai	Master Builders Inc.
Jan Olek	Purdue University
Ed O'Neil	U.S. Army Corps of Engineers / WES
Michael Ortlieb	Carl Walker, Inc.
Clauss Germann Petersen	Germann Instruments, Denmark
Mark Postma	Carl Walker, Inc.
Ervin Poulsen	AEC, Denmark
Alberto Sagüés	South Florida University
Michael Sprinkel	Virginia Transportation Research Council
Michael Thomas	University of Toronto, Canada
Paul Tourney	Grace Construction Products
David Trejo	University of Texas
Alex Vaysburd	Structural Preservation Systems
Paul Virmani	Federal Highway Administration

APPENDIX 2

THE NIST / ACI / ASTM WORKSHOP ON MODELS FOR PREDICTING THE SERVICE LIFE AND LIFE-CYCLE COST OF STEEL-REINFORCED CONCRETE

AGENDA

DAY 1 (November 9)

7:30 Continental Breakfast

Plenary Session 1

8:00 Welcome and review of the workshop goals — Geoffrey Frohnsdorff, BFRL/NIST

RILEM Technical Committee TMC, Testing and Modelling Chloride Penetration in Concrete – Goals and Plans

8:10 Marta Castellote, Eduardo Torroja Institute of Construction Sciences, Spain

Presentations on Models for Predicting Service Life and Life-Cycle Cost of Steel-Reinforced Concrete

8:40 Alberto Sagues, University of South Florida

9:10 Lars-Olof Nilsson, Chalmers University, Sweden

9:40 Ervin Poulsen, AEC, Denmark

10:10 COFFEE BREAK

10:25 Michael Thomas, University of Toronto, Canada

10:55 Jacques Marchand, Laval University, Canada

11:25 Paul Tourney, W.R. Grace Company

11:55 Matthew Miltenberger, MasterBuilders Company

12:25 BUFFET LUNCH

1:25 Dale Bentz, Building Materials Division, BFRL/NIST

1:55 Mark Ehlen, Office of Applied Economics, BFRL/NIST

Working Group Activities

2:25 Instructions to Working Groups

2:40 BREAK

Working Group Session 1

3:00 Working Group discussions (WG 1 through WG 4)

5:30 Adjournment

6:30 DINNER

8:00 Meeting of Steering Committee with Working Group Chairs/Co-Chairs

* * * * * * * * * * *

<u>DAY 2</u> (November 10, 1998)

7:30 Continental Breakfast

Plenary Session 2

8:00 Reports from chairs of WGs in Working Group Session 1

Working Group Session 2

9:00 Working Group discussions (WG 5 through 8)

10:30 COFFEE AVAILABLE

12:00 BUFFET LUNCH

Plenary Session 3

12:45	Reports from chairs of WGs in Working Group Session 2	Terry Holland, Consultant
2:40	Final discussion and recommendations for action	Terry Holland, Consultant

3:00 Adjournment

APPENDIX 3

Working Group Assignments

Working Group 1

Doug Hooton, Chair
Shuaib Ahmad, Co-Chair
Nick Martys, Recorder
Mark Ehlen
Terry Holland
Alistair MacDonald
Jacques Marchand
Lars-Olof Nilsson
Charles Nmai
Ervin Poulsen

Working Group 2

Albert Sagues, Chair
Neal Berke, Co-Chair
Dale Bentz, Recorder
Stephen Amey
Evan Bentz
Paul Kelley
George Muste
Michael Ortlieb
Mike Sprinkel
David Trejo

Working Group 3

Jan Olek, Chair
Paul Johal, Co-Chair
Ed Garboczi, Recorder
Marta Castellote
Geoff Frohnsdorff
Matthew Miltenberger
Clauss Germann Petersen
Mark Postma
Paul Tourney
Alex Vaysburd

Working Group 4

Mike Thomas, Chair
Emmanuel Attiogbe, Co-Chair
Nick Carino, Recorder
Anthony Aldykiewicz
James Clifton
Dave Gustafson
Bryan Magee
Ted Neff
Ed O'Neill
Paul Virmani

Working Group Assignments (continued)

Working Group 5

Doug Hooton, Chair
Shuaib Ahmad, Co-Chair
Nick Martys, Recorder
James Clifton
Paul Kelley
Alistair MacDonald
Matthew Miltenberger
Ted Neff
Lars-Olof Nilsson
Clauss Germann Petersen
David Trejo

Working Group 6

Alberto Sagues, Chair
Neal Berke, Co-Chair
Dale Bentz, Recorder
Marta Casellote
Geoff Frohnsdorff
Bryan Magee
Charles Nmai
Mark Postma
Alex Vaysburd

Working Group 7

Jan Olek, Chair
Paul Johal, Co-Chair
Ed Garboczi, Recorder
Anthony Aldykiewicz
Stephen Amey
Dave Gustafson
Jacques Marchand
Ed O'Neill
Ervin Poulsen
Paul Virmani

Working Group 8

Mike Thomas, Chair
Emmanuel Attiogbe, Co-Chair
Nick Carino, Recorder
Evan Bentz
Mark Ehlen
Terry Holland
George Muste
Michael Ortlieb
Mike Sprinkel
Paul Tourney

APPENDIX 4

New, Formable, Corrosion-Improved, Low-Carbon Steels for Concrete

(An abstract provided by Gareth Thomas, University of California,
Berkeley and San Diego, who was unable to attend the workshop)

Reinforced concrete structures are an integral part of everyday life. Inadequacies in the overall design perspectives of reinforced concrete structures, which pay insufficient attention to durability – mainly corrosion resistance – result in many structures deteriorating well before their life expectancy. The result is enormous costs for repair and rehabilitation of highway structures due to corrosion damage, amounting to billions of dollars.

An important challenge is to involve the principles of Materials Science and Engineering, to design by microstructural control, through processing, steels which are economically attractive, and which provide superior mechanical and corrosion resistance properties. This paper describes such an approach using the principles of low carbon dual phase steel (DFM).

In this system, the microstructure is designed to avoid carbide particles which in the presence of ferrite, or other phases, localizes the anodic-cathodic coupling in a galvanic situation. Since all structural steels in current use have carbides in their structure, they are all susceptible to galvanic attack. Thus, the design of steels with ferrite-martensite structures (DFM), in the absence of carbides, allows us to easily attain mechanical property requirements for reinforcements, with greatly improved corrosion resistance.

In all cases, the DFM steels show superior properties, are easily welded and show excellent formability, e.g., in wire drawing, corrosion results show that in the long-term weight loss data, a smooth bar showed no detectable corrosion after one year, and the short-term tests in chloride solutions, dramatically shows the superior corrosion resistance of DFM to A-615 rebars; the latter are almost completely destroyed after three weeks exposure.

- The original paper, by Gareth Thomas of the University of California and David Trejo of Michigan State University, was presented at the Workshop on Materials for the Infrastructure, La Jolla, California, April 1-3, 1998. The workshop was sponsored by the Institute for Mechanics and Materials (IMM), University of California, San Diego (UCSD), and the National Science Foundation. The workshop proceedings were published as Report No. 98-1 from the IMM, UCSD, 9500 Gilman drive, Dept. 0404, La Jolla, CA, 92093-0404.

APPENDIX 5

Loading Effect on Corrosion of Reinforcing Steel

(Abstract provided by Surendra Shah of Northwestern
University who was unable to attend the workshop)

A great deal of research on corrosion of reinforcing steel in concrete has been done regarding material properties, mix proportions, corrosion protection, repair and retrofitting, as well as service life prediction. Limited work has been done clearly illustrating the mutual interaction among loading, cracking, and corrosion damage. The objective of the present research is to investigate this interaction. Reinforced concrete beams, (10 x 10 x 110) cm, were prepared and subjected to different levels of flexural loading: (0, 45, 60, and 75) % of the ultimate load. They were also exposed to a laboratory environment with ponding and wetting / drying cycling at room temperature. Half cell potential and galvanic current measurements were taken daily to monitor the corrosion of the reinforcing steel. After corrosion initiation, external current was applied to the beams to accelerate the corrosion. The beam deflections and crack characteristics were recorded during the entire test. The remaining loading capacity of the beams was evaluated at the end of the experiment. The results indicate that loading has a significant effect on the corrosion rate of reinforcing steel. Corrosion increases beam deflection. Loading level has a considerable effect on the initiation of corrosion, but the effect reduces after corrosion initiation. The beams under load had much higher corrosion rates than those which had been preloaded and then unloaded. The present research may provide another look into current service life predictions of concrete.

---

* The abstract was of a paper submitted to the ACI Spring Convention in Chicago in March 1999. The authors are Sang-chun Yoon, Hyung-rae Kim, Kejin Wang, Jason Weiss, and Surendra P. Shah, NSF Center for Advanced Cement-Based Materials, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208.

APPENDIX 6

Chloride Penetration into Concrete with Light Weight Aggregates

(Abstract provided by Magne Maage of Selmer ASA, Trondheim,
who was unable to attend the workshop) *

The experimental work started as a part of the Lightcon project with the objective of studying chloride ingress into practical LWA concretes depending on many variables as well as giving input to the model for service life prediction developed in the same project. Eight concretes have been tested, two by two were identical except that half of the cement content was replaced by slag in one of the two. All mixes had 5 % to 10 % silica fume by weight of cement plus slag. The most important variables were: (1) curing time before exposure, (2) curing time (20, 65 and 95) °C, (3) exposure temperature (5, 20 and 35) °C, (4) exposure time, (5) type of exposure (submerged, splash, spray), (6) salt concentration in exposure water (1, 4 and 10) %, (7) type of binder (OPC and OPC + slag).

The most important conclusion was that the results fitted very well to the hypothesis for service life prediction. Additionally, the following main conclusions may be mentioned:

Surface chloride content, C_s , is the environmental load and it increases with exposure time during the first years, reduces with increased curing time and introduction of slag, and independent / inconsistent correlation to curing and exposure temperature.

The achieved diffusion coefficient, D_s , is independent of curing and exposure temperature, decreases with exposure time and introduction of slag.

The parameter, α , expresses the time dependency of D_i with exposure time; a is independent of curing time, curing and exposure temperature, and increase somewhat with increased salt concentration in the exposure water and introduction of slag.

---

* This abstract is from a draft report by M. Maage, S. Helland, and J.E. Carlsen, Chloride Penetration into Concrete with Light Weight Aggregates, Report 3.X, SINTEF, Trondheim, Norway, scheduled for publication at the end of 1998.