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

NIST

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*

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

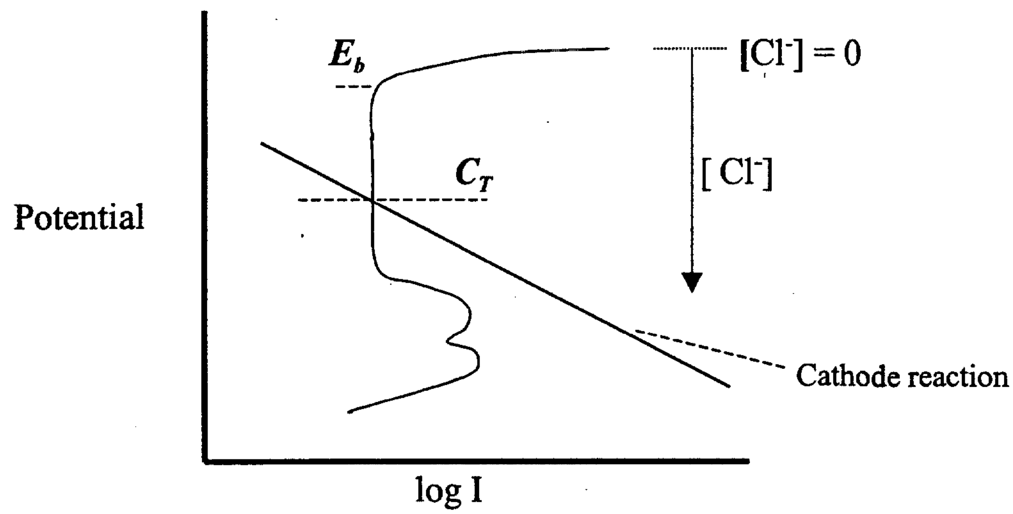

Figure 1. Variation of chloride threshold for corrosion; (E_b is the breakdown potential).

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

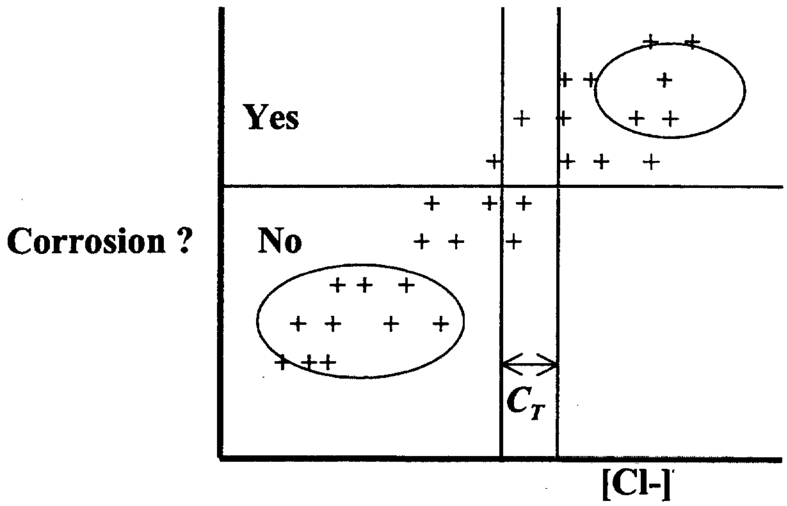

Figure 2. Use of field data in determination of the chloride threshold

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:

	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.