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

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William M. Daley, *Secretary*
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Gary R. Bachula, *Acting Under Secretary for Technology*
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Ray Kammer, *Director*

- 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