TECHBRIEF

Improved Concretes for Corrosion Resistance

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FHWA Contact: Paul Virmani, HNR-IO (703) 285-2439

The Structures research and technology program aims to faster increased durability of new bridges and observable increases in the service life of existing structures placing an emphasis on increasing highway safety while preserving the environment The program focuses on researching nondestructive evaluation technologies to identify structural deficiencies and support bridge management systerns. It also uses high-performance materials to repair and rehabilitate the existing inventory of deficient bridges. Thisfind it and fix it program is sup plemented by research which examines all aspects of bridges and foundations, including planning, design, construction, management, maintenance, inspection, and demolition.

Specific expertise areas include bridge coatings, bridge infrastructure, bridge management, nondestructive evaluation, corrosion protection, foundations, scour, geotechnical research, high-performance materials, aerodynamics, seismic research, and structures instrumentation.

U.S. Department of Transportation
Federal Highway Administration

Research and Development
Turner-Fairbank Highway
Research Center
6300 Georgetown Pike
McLean, VA X301-2296

Introduction

The deterioration of various reinforced concrete bridge components containing conventional black steel reinforcement is the most important problem facing U.S. highway agencies. A major cause of this concrete deterioration (cracking, delamination, and spalling) is the corrosion of the embedded steel reinforcement, initiated by chloride ions from deicing salts and saltwater spray that have penetrated the concrete cover.

In response to this situation, the Federal Highway Administration (FHWA) initiated this research project directed at the quantitative identification of the corrosive conditions fostering concrete bridge deterioration and at the identification of concrete materials that consistently provide superior performance when used for bridge deck overlays and for the repair of other concrete bridge members. It was also envisioned that this work would lead to the identification of concretes that are cost-effective for the construction of new bridge members.

Approach

The experimental phase of the research was divided into three tasks:

Task A - Corrosive Environment Studies.
Task B - Concrete Chemical and Physical Properties.
Task C - Long-Term Corrosion Performance.

In task A, laboratory experiments were conducted to characterize the corrosive environment and to establish boundary conditions for moisture content, chloride content, and temperature levels for corrosion initiatin and propagation.

Task B focused on identification of the chemical and physical characteristics of concretes as they relate to the rate of corrosion of embedded reinforcing steel. Corrosive environments used in task B were selected on the basis of results obtained in the task A work.

Task C will provide simulation and measurement of all three of the phenomena that control corrosion-induced deterioration of concrete structures. These include the chloride diffusion rate in the concrete, the rate of corrosion of the steel once corrosion is initiated, and the rate of deterioration of the concrete during the build-up of corrosion products. Task C will encompass long-term testing of small reinforced concrete slabs under conditions that simulate bridge structures in well-defined corrosive environments.

The present interim report describes the methodology used and the results obtained in the task A and task B work.

Results

Task A - Corrosive Environment Studies

The variables included in the task A test matrix were: (1) mortar/concrete mix, (2) reinforcing steel type, and (3) environment. The mortar/concrete variables tested included two mortars (A-2 and B-2) and one concrete (A-5). The only difference in mortar A-2 and concrete A-5 is that concrete A-5 contains coarse aggregate. The two types of reinforcing steel included conventional and prestressed tendons (seven-wire). The environmental variables tested included: (1) chloride concentration, (2) relative humidity, and (3) temperature. The levels were designed to provide low, moderate, and high conditions for each variable. The levels selected were: (1) chloride concentrations of 0.6, 1.8, and 6 kg/m^3 (1, 3, and 10 lb/yd^3); (2) external humidity of 43, 75, and 98 percent; and (3) temperatures of 4, 21, and 38 ^{0}C (40, 70, and 100 ^{0}F).

A full factorial matrix of tests was performed for two mortars (A-2 and B-2) using conventional reinforcing steel specimens. For the concrete (A-51, tests were performed at a single temperature (21 ^{0}C [70 ^{0}F]), two humidities (75 percent and 98 percent), and three chloride concentrations (0.6, 1.8, and 6 kg/m^3 [l, 3, and 10 lb/yd^3]). For the prestressing steel tendons, tests were performed under the same conditions as for concrete A-5.

Figure 1 shows the average corrosion rate for each of the three levels of the three independent variables (temperature, humidity, and chloride concentration). Each independent variable had a significant effect on the corrosion rate for mortar A-2. These effects were quantified by generating a general linear model based on the corrosion rate data. The prestressing steel reinforcement showed similar trends as those for the conventional steel data shown in figure 1, but the magnitudes of corrosion rate for the prestressing steel were generally less than those for the conventional reinforcement. In comparing concrete A-5 to mortar A-2, the corrosion rate of the conventional reinforcement in the concrete was significantly less than that for the mortar. It is speculated that the increased resistance of the concrete, as compared to the mortar, is the cause of the lower corrosion rates measured in the concrete. Similar data were produced for mortar B-2. In general, corrosion rates in mortar B-2 were greater than those measured for mortar A-2. This is attributed to mortar B-2 being a calcium aluminate cement with a lower pH than that for mortar A-2 type I Portland cement.

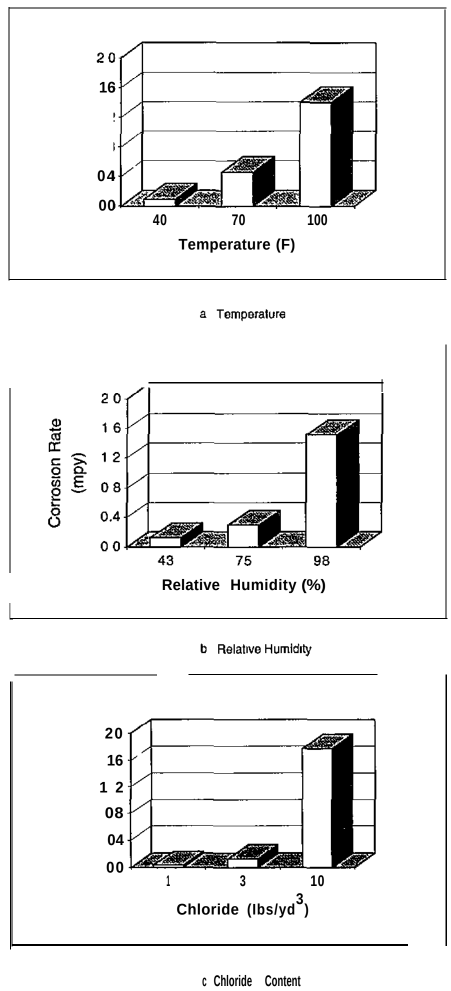
Task B - Concrete Chemical and Physical Properties

The purpose of task B was to characterize the chemical and the physical characteristics of concretes as they relate to the corrosion behavior of embedded reinforcing steel. Based on the results of the task A work, the following two environments were selected:

1. Moderate environment: 21 ^{0}C (70 ^{0}F), 75 percent relative humidity, 1.8-kg/m^3 (3-lb/yd^3) chloride concentration.
2. Aggressive environment: 38 ^{0}C (100 ^{0}F), 98 percent relative humidity, 6-kg/m^3 (10-lb/yd^3) chloride concentration.

The selection of materials and mixture proportions for the concretes was guided by the results of previous studies and by experience with concretes used for the repair and construction of bridges. Although both mortars and concretes were used in task A, only concretes were used in task B (and will be used in task C).

Effect of temperature, humidity, and chloride on corrosion rate for mortar A-2



a Temperature

b Relative Humidity

c Chloride Content

1 mpy = 25.4 um/yr
40°F=4°C,70°F=21 °C, and100°F=38°C
1 lb/yd^3 = 0.6 kg/m^3

Material variables included: (1) cement type, (2) mineral admixture type, (3) fine aggregate type, and (4) coarse aggregate type. Because of the relatively large number of material variables evaluated in the research, it was necessary to limit the concrete mix proportion variables. Water-cement ratios of 0.3, 0.4, and 0.5 were used in these concretes. In addition, air contents were adjusted at 2 percent, 5 percent, and 8 percent.

The experimental design for the task B investigation consisted of 30 concrete mix designs that incorporated all the material and concrete proportion variables previously discussed. In task B, there were too many independent variables (six) with too many levels (six for cement type) to perform sufficient tests to either: (1) perform a full factorial matrix of tests, or (2) determine a model containing interaction and quadratic terms. Therefore, a main effect terms only statistical design was generated.

The dependent variables measured for each of the concrete mix designs were: (1) rapid chloride permeability, (2) compressive strength, (3) electrical resistivity, (4) corrosion rate, (5) corrosion potential, and (6) final chloride concentration at the steel surface.

Table 1 summarizes the effects of the independent variables on the measured dependent variables. Each independent variable had a significant effect on one or more of the dependent variables. In general, cement type and mineral admixture had the most significant effects in terms of magnitude. In addition, general linear models were produced for each dependent variable.

Discussion

The data developed in tasks A and B provide a significant data base to analyze concrete deterioration and to predict corrosion behavior for a range of environments and a range of concrete compositions. No firm conclusions are drawn at this time because confirmatory testing (task C) is ongoing. However several goals were met during the task A and task B research.

A primary focus of task A was to determine the effect of environmental variables on corrosion and to establish boundary conditions necessary for corrosion. Task A examined two mortars in detail: (1) type 1 portland cement (mortar A-2) and (2) calcium aluminate cement (mortar B-2). It is clear that the lower pH of the calcium aluminate cement produced a profound effect on the range in which corrosion is possible and significantly increased the rate of corrosion for a specific environment. For the calcium aluminate cement, significant corrosion occurred, even for several conditions tested for the 0.6-kg/m^3 (1-lb/yd^3) chloride concentration. For the portland cement, only two conditions produced any measurable corrosion at a 0.6-kg/m^3 (1-lb/yd^3) chloride concentration. For those two conditions, the corrosion rate was at the very low end of the corrosion range given. For the portland cement, only minimal corrosion was observed, even at 6 kg/m^3 (10-lb/yd^3) chloride concentration, for the low temperature (4 °C [40 °F]) condition at the low (43 percent) and high (98 percent) relative humidity. Most importantly, predictive models were developed that permit the effect of environmental factors on corrosion of reinforcing steel in concrete to be estimated.

The polarization behavior of a metal in an electrolyte is characterized by plotting potential versus logarithm of current. In task B, a range of concrete compositions were tested in two different environments, and the corrosion rate and corrosion potential were measured. The correlation analysis indicated only weak correlations between the logarithm of corrosion rate and the potential. Furthermore, the data show that for the wide range of concrete conditions investigated in task B, the corrosion rate at any given potential can vary more than two to three orders of magnitude. This makes it impossible to predict corrosion rate from a potential measurement alone. Therefore, concrete cannot be considered a generic material from which general conclusions concerning corrosion behavior can be made. The actual corrosion behavior is dependent on concrete mix components and the environment.

One of the required outputs for tasks A and B was to identify concretes for testing in task C and to select appropriate environments. These concretes will be tested on a larger scale and longer term tests will be performed in task C. Two procedures were used for this purpose: (1) predictions based on the general linear main effect models established in task B and (2) selection of optimum concrete mixes from the test matrix of concretes tested in task B. The task C tests are in progress.

Summary of effects of independence on the measured dependent variables

Independent Variable	Dependent Variable: Rapid Chlonde Permeability	Resistivity	Compressive Strength	Corrosion Rate Moderate	Corrosion Rate Aggressive	Corrosion Potential * Moderate	Corrosion Potential * Aggressive	Chlonde at Steel Surface Moderate	Chlonde at Steel Surface Aggressive
Water-Cement Ratio	▲	▼	▼	▲	▲	▲	▲	◄►	▲
Air Content	◄►	◄►	▼	◄►	▼	▲	▲	◄►	◄►
Coarse Aggregate**	▼	▲	▲	▼	▼	◄►	▲	◄►	◄►
Fine Aggregate**	▼	▲	▲	▼	▼	◄►	◄►	◄►	◄►
Mineral Admixture	▼▲	▼▲	▼▲	▼▲	▼▲	◄►	▼▲	▼▲	▼▲
Cement Type	▼▲	▼▲	▼▲	▼▲	▼▲	▼▲	▼▲	▼▲	▼▲

Decrease in dependent variable with an Increase in Independent variable

I increase in dependent variable with an Increase in Independent variable

◄► No trend in dependent variable with an Increase in independent variable

▼▲ Significant change in dependent variable with change in independent variable

* Increase in corrosion potential is an increasingly more negative potential

** Increasing aggregate refers to increasing absorbent resistance (going from limestone to quartz or glacial sand to quartz increases absorbent resistance)

Moderate Moderate environment (21C (70F) 75% Relative Humidity - 1 8 Kg/m^3 (3 lb/yd^3) chloride)

Aggressive Aggressive environment (38C (100F) - 96% Relative Humidity - 6 Kg/m3 (10 lb/yd^3) chloride)

Researcher: This study was performed by CC Technologies, 6141 Avery Road, Dublin, Ohio, 43016-8761, telephone: (614) 761-1214. Contract no. DTFH61-93-C-00028.

Distribution: This technical summary is being distributed according to a standard distribution. Direct distribution is being made to the Regions and Divisions.

Availability: The publication will be available in July 1997. Copies will be available from the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161. A limited number of copies will be available from the R&T Report Center, HRD-1 I, FHWA, 9701 Philadelphia Court, Unit Q, Lanham, MD 20706, telephone: (301) 577-0818, fax: (301) 577-1421.

Key Words: Bridge decks, chlorides, concrete, corrosion, model predictions, temperature, relative humidity.

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