Concrete Mix Design for Durability

Integration of Technologies

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Protection of the steel in reinforced concrete structures is of prime significance in the design and construction of a durable structure, especially in chloride environments. Specifications and standards such as ACI 318 provide special guidelines for structures exposed to marine environment and cold climates, where the chloride penetration is the result of wetting of the structures by sea water or treatment with chloride salts to prevent freezing. The standards usually specify the required cover thickness and the mix composition. The cover thickness is usually in the range of 50 to 75 mm for severe exposures, and the mix design calls for a maximum water-to-cement (w/c) ratio of 0.40 or 0.45. In practice, however, durability problems sometimes occur even if the requirements of the codes are apparently met. This has resulted in a trend to push for concretes of lower w/c ratios, which are more impermeable (i.e. high-strength concretes). However, these concretes are more sensitive to cracking and there is a need to take this into account in the structural design.

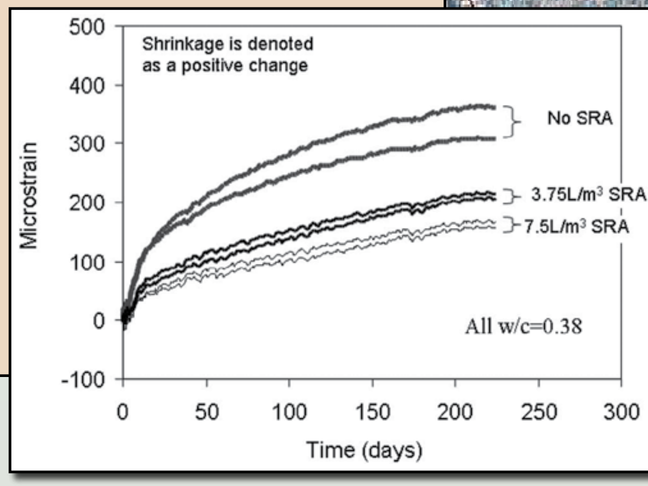

Figure 1: Effect of shrinkage-reducing admixture on the shrinkage strains developed over time for 0.38 w/c ratio concrete

This article explores an alternative strategy, which is intended to mobilize more than one mechanism to combat corrosion, as well as mitigate through cracks without the need to modify the structural design. Such an approach can be potentially more cost-effective, particularly when there is a need for extended service life beyond 50 years, which is often required in infrastructure construction. The approach taken here considers two main issues: (i) penetration through the cracks, and (ii) penetration through the concrete matrix itself.

It is well known that cracking is an inherent characteristic of reinforced concrete structures, and cannot be eliminated unless post-tensioned concrete is used. However, there is mounting evidence that if the crack width is maintained below 0.1 to 0.2 mm, the permeability of the concrete is not much greater than that of the non-cracked matrix. This results, to a large extent, from the fact that the crack should not be viewed as a parallel-wall "canyon", but rather as two tortuous surfaces that are interacting with each other, as long as the crack opening is not too large. This shows up in the mechanical performance by the ability of cracks to transfer some loads across their surfaces (strain softening behavior) and "self-heal" as water penetrates into them.

The approach to protecting the steel in the concrete "between the cracks" can consist of several mechanisms: (i) making the concrete impermeable, (ii) reducing the build-up of chloride on the concrete surface, and (iii) providing protection to the steel at its surface by means of inhibitors. The effectiveness of each of these approaches, or some combination thereof, can be estimated and quantified by modeling service life and life-cycle cost. For that purpose, the Life-365 model will be applied.

Control of Cracking

The codes usually call for control of cracking in the range of 0.1 to 0.3 mm, depending on the corrosive environment in which the structure is to serve. Attention is given in the structural design for this control, yet cracking can often arise from numerous other effects, particularly shrinkage. This is an especially significant issue in thin structures like bridge decks. There are several strategies to mitigate this type of cracking: (i) add more steel, (ii) change the properties of the concrete to reduce its shrinkage by incorporation of shrinkage reducing admixtures, or (iii) make it tougher using technologies such as fiber reinforcement. The modifications of the concrete properties can be quantified in terms of changes in the concrete material properties, reduced shrinkage (*Figure 1*), or enhancement of the strain softening behavior of the concrete, i.e., its ability to carry loads after cracking has occurred. Fibers, which provide bridging effects over cracks, can enable load transfer even under cracking. This is visualized graphically by curves of stress vs. crack width. Such curves can be used to model the behavior of the material in the post-cracking zone, which follows the pre-cracking zone that is modeled as an elastic behavior.

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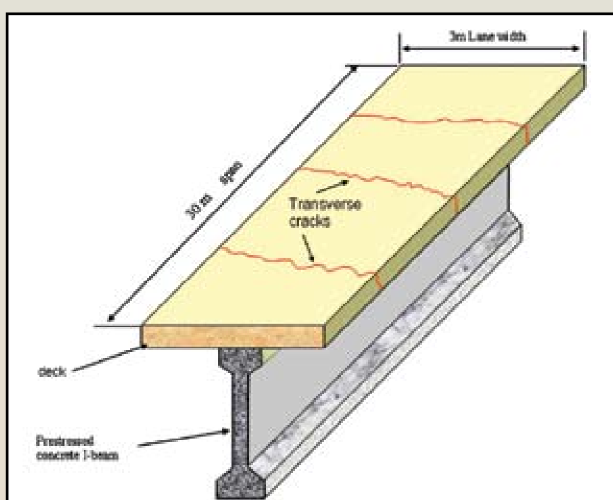


Figure 2: Bridge deck structure modeled for cracking due to shrinkage effects

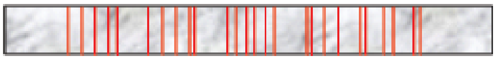
Mix	Deck Steel Density	Deck Cracking pattern after 180 days*	Total # of Cracks	Time to 1st Cracking	Average Crack Width (mm)
Control	Normal		8	112 days	0.47
7.5 *L/m*³ SRA	Normal		No cracking after 180 days		
Control	Double		26	77 days	0.12

*Figure 3: The effect of SRA and steel reinforcement density on mitigating the cracking in the bridge deck, modeled by 2-D finite element software. *Drawing from left to right represents a 36 m long and 228 mm thick concrete deck (not to scale). Each vertical line represents a crack in the deck.*

Quantification of the effects of various technologies on properties of the concrete is only the first stage in an evaluation process, by which their influence on the actual performance of the structure should be assessed. For that purpose, it is possible to use emerging models which can serve as design tools to consider the processes that take place over time. Stresses due to environmental effects such as shrinkage and thermal deformations are calculated to determine the time of onset of cracking, when their magnitude exceeds the strength of the concrete. Such tools can simultaneously take into account structural issues (such as the restraint built into the structure), construction practices, and special mechanical properties of concrete such as strain softening and visco-elastic behavior (e.g., creep), and their change over time.

A 36-meter long bridge deck structure (*Figure 2*) was modeled with such a design tool (FEMASSE) to compare the performance achieved by using shrinkage reducing admixture (SRA). In this case, a 3-meter wide deck is cast on a steel beam and the shrinkage strains developed at the deck are restrained by the underlying beam, leading to tensile stresses in the deck and eventually to cracking. The results of such calculations are presented in *Figure 3*, showing the number of cracks along the deck and their width. Each spike in *Figure 3* represents a crack, and the height of the spike represents its width. It can be seen that technologies that are employed to induce changes in the concrete properties (reduced shrinkage or increased toughness) can be as effective as doubling of the steel for bringing the crack width into the acceptable range (*Figure 4*).

Figure 4: Effectiveness of mix design using SRA to control the cracking in bridge decks

Control of Chloride Ingress and Corrosion Protection

After assuring crack control to meet durability/serviceability requirements, there is a need to assure the protection of the steel in the concrete itself, "in between the cracks". For that purpose, three technologies are considered: to enable control of diffusion, control chloride build-up on the surface, and protect of the steel itself.

Means to reduce diffusion of chlorides are based on the concept of making a concrete with reduced porosity and reduced interconnection between pores. This is well documented, in particular with respect to the effect of reduction of w/c ratio and incorporation of supplementary cementitious materials such as fly ash and silica fume. A database for effective diffusion coefficients based on laboratory and field tests was developed, and some typical data is shown in *Table 1*.

A high concentration of chlorides on the concrete surface is of concern in exposure conditions, where wetting/drying cycles are prevalent. Reducing the wetting characteristics of the concrete by water repelling agents, which lead to reduced capillary absorption, was found to be an effective means for reducing this build-up (*Figure 5*). The data in *Figure 5* is based on 15 cycles of wetting and drying, where the drying is at 35°C/20%RH, similar to the Southern Exposure test. The reduction in the chloride build-up on the surface is roughly proportional to the reduction in the capillary absorption coefficient determined by the ASTM C1582 test. The results are based on the chloride penetration profiles obtained after the wetting/drying cycles (*Figure 6*).

w/c ratio	Silica fume content, %wt. of cement	Diffusion coefficient, $m^2/s \times 10^{-12}$
0.48	0	11
0.38	0	2
0.48	15	0.7
0.38	15	0.3

Table 1: Effect of various technologies on the effective diffusion coefficient of concretes

The curves in *Figure 6* may lead to the erroneous conclusion that water repelling admixtures are effective in reducing the diffusion coefficient of concrete. However, conditions leading to the profiles in *Figure 6* are wetting/drying, whereas in tests where the penetration mechanism is "purely" diffusion (i.e., the surface is kept continuously in contact with a chloride solution), penetration curves are similar in the concretes with and without admixtures, and the diffusion coefficients are practically the same. All range from 2.7×10^{-11} to 2.9×10^{-11} m^2/s. This discussion highlights the need to take precaution in the interpretation of the Southern Exposure test. This is not a mere academic issue, but one of practical significance, if one uses this test to determine meaningful parameters that are intended to be used for life-cycle modeling.

Technologies to mitigate penetration of chlorides into concrete are not always sufficient to eliminate eventual ingress of chlorides to the steel surface. In such instances, there is room to consider the

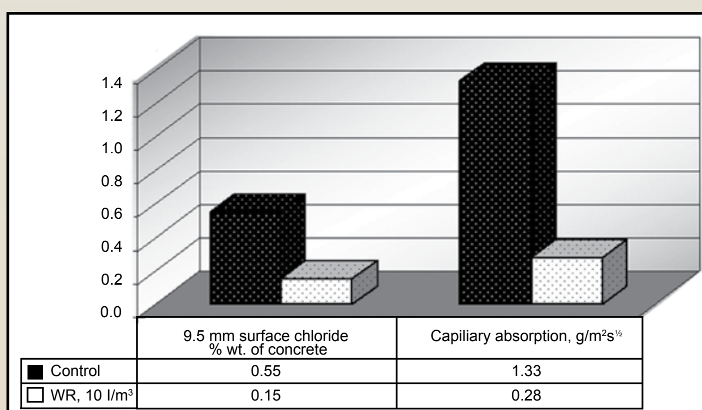


Figure 5: Effect of water repellent admixture on the build-up of chlorides on the surface of concrete in wetting/drying tests

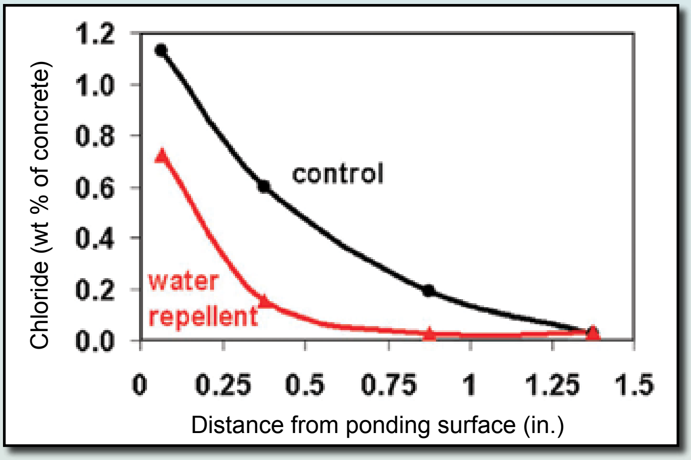


Figure 6: Effect of water repellent admixture (10 l/m3) on the profiles of chlorides penetration after 15 cycles of wetting/drying

protection of the steel itself. One of the options for this purpose, based on modifying the concrete composition, is the use of corrosion inhibitors. The effect of corrosion inhibitors was studied extensively and, based on the data accumulated, a "safe envelope" curve can be constructed (*Figure 7*). As long as the chloride content level is below the line, corrosion is unlikely. Therefore, the values on the line in *Figure 7* represent the threshold chloride values and they are a function of the corrosion inhibitor content.

Integration of Technologies

The effectiveness of simultaneous application of several technologies was assessed by calculation using the Life-365 model, with inputs derived from the studies outlined above. The ultimate quantification of effectiveness is the life-cycle cost (LCC). Yet, to provide for overall judgment of different alternatives, the initial cost and time for corrosion initiation are also reported. This is demonstrated for a bridge deck in a cold environment of 10°C average yearly temperature. The base case calculation for the structure followed the requirement in the codes, 65 mm cover and 0.40 w/c ratio concrete for the bridge deck.

The technologies considered were: (i) fly ash and silica fume replacement to reduce the effective diffusion coefficient, (ii) water repelling additions to reduce chloride build up, and (iii) corrosion inhibitor to increase the chloride threshold, as outlined below:

- 30% and 40% fly ash substitution, marked FA/30 and FA/40
- 10% silica fume replacement, marked SF/10
- 10, 15, and 20 *l/m³* addition of water repellent admixtures, of two types (DP1 and DP2), marked DP1/10 and DP2/10, with the value following the slash line representing the content added; DP1 at 10 *l/m³* dose reduced the chloride build up on the surface by a factor of 3, and DP2 at 10 *l/m³* dose reduced it by a factor of 5.
- 10 to 20 *l/m³* addition of corrosion inhibitor, $Ca(NO)_2$.

Unless marked differently, the w/c was that of the base case. In some instances this ratio was reduced to 0.40 (in the case of the marine wall), but not below it, to eliminate the issue of autogenous shrinkage, which can be of particular concern in hot conditions.

Results of this calculation are shown in *Figure 8*. For purposes of comparison only, costs above those of the base concrete were considered. Therefore, the initial cost of the base concrete in *Figure 8* is taken as zero. The design according to the specifications will result in a need for repair well before the design life, and life-cycle costs will be relatively high. The application of a single technology can improve the situation (reduce LCC and increase initiation time). However, none of them will change the situation drastically. Only a combination of technologies, preferably all three, can result in a drastic reduction of LCC and an initiation time approaching the design life or even longer. To achieve this favorable state of affairs, the initial cost will go up by about $20/m².

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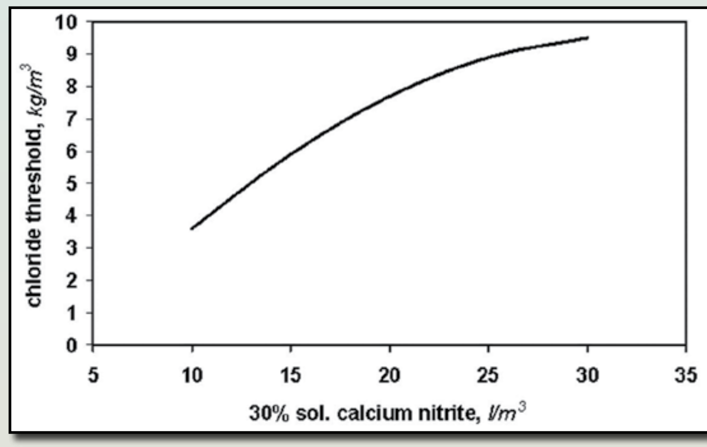

Figure 7: Ca(NO)2 corrosion inhibitor protection curve for chlorides

Conclusions

The conventional approach of improving the resistance to steel corrosion in concrete by reducing the diffusivity of concrete requires the use of high-strength/low w/c ratio concretes, with accompanied difficulties associated with early age cracking. Even then, extended durability performance at a reasonable LCC is difficult to achieve.

An integrated approach, which is based on the combined use of several technologies to mitigate chloride corrosion, can be much more effective in achieving an extended service life as high as 100 years, at a reasonable LCC.

The integrated technologies that result in such durability performance can be based on concretes that are less prone to cracking (i.e. w/c ratio of 0.40 to 0.45 with fly ash), with added means to reduce chloride surface build-up using water repelling admixtures (which are effective in wetting/drying conditions where capillary absorption is dominant) and technologies to enhance the steel passivation by corrosion inhibitors.

There is a need for precaution when evaluating such systems using standard test methods, such as the Southern Exposure test. Interpretation of the results of wetting/drying tests in terms of diffusion coefficients calculated from chloride penetration curves can be misleading with respect to the influence of technologies such as water repelling admixtures: overestimation of their influence on reduction in diffusion coefficients and ignoring their influence on reduction of the chloride surface build–up. Resolution between such influences is essential for adequate modeling and quantitative assessment of technologies of this kind, and their integration.▪

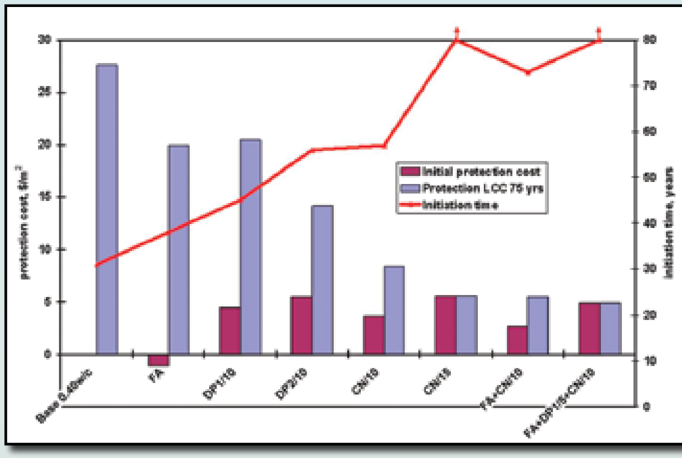

Figure 8: Prediction of costs (initial and life-cycle) and corrosion initiation times for a bridge deck with 75-year design life

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