Building for Infrastructure Durability

Constructing in sulfate-rich soil and other corrosive conditions

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WHEN BUILDING INFRASTRUCTURE, THERE IS OFTEN LITTLE, IF ANY, ABILITY TO CONTROL THE ENVIRONMENT IN WHICH THE ROADS, BRIDGES, DRAINAGE CULVERTS, OR OTHER PUBLIC STRUCTURES ARE BUILT. INFRASTRUCTURE MUST BE MADE TO FIT THE ENVIRONMENT, WHICH ALREADY EXISTS TO SUPPORT A HEALTHILY FUNCTIONING SOCIETY. THIS LEAVES CONTRACTORS AND ENGINEERS WITH THE JOB OF CONSTRUCTING BUILDINGS THAT WILL LAST FOR MANY DECADES, IN SPITE OF EXPOSURE TO HARSH CLIMATE, SOIL, AND WATER CONDITIONS.

Engineering consultant companies in Israel are finding many advantages in following a 'performance-based design' approach incorporating migrating corrosion inhibitor technology. This article follows three public works projects on which the performance-based design approach was applied. Each project presented the especially difficult challenge of casting thick pieces of concrete in harsh environmental conditions while seeking to achieve a 100-year service life. Although designed to comply with specifications specific to Europe and Israel, these projects provide an insight into strategies for building infrastructure with greater durability in harsh conditions anywhere in the world.

Performance versus prescriptive specifications

Around the turn of the millennium, the construction industry began realizing buildings were not meeting their planned service life, and therefore introduced the concept of durability in environmental conditions in industry standards. Until then, civil and infrastructure engineers mainly referred to mechanical considerations (tensile and compressive strength, etc.). In Europe, these considerations are reflected within the EN 206-1, *Concrete – Specification, Performance, Production and Conformity, Part 1.*[1] The Israeli equivalent is IS 118, *Concrete: Specification, Performance and Production.*[2] These standards encompass both a 'prescriptive approach' and a 'performance approach.' The American

Concrete Institute (ACI) 318-08, *Building Code Requirements for Structural Concrete and Commentary,* and ACI 301-05, *Specifications for Structural Concrete,* are examples of specifications encompassing prescriptive and performance-based requirements in the United States.[3] While both types of specifications have existed in the United States since the first half of the 20th century, there has also been an increasing realization over the last several decades about the importance of building for durability using a performance-related approach.[4]

Engineers have both a professional and legal obligation to meet standards like these in order to guarantee the quality, safety, and longevity of the construction project. It is the engineer's responsibility to stay updated on current standards and plan accordingly. In Europe and Israel, for example, EN 206-1 and IS 118 standards define several categories of environmental conditions to help engineers plan for durability such as:

- soil composition chemical aggressiveness;
- air with high concentration of chlorides;
- air with high concentration of carbon dioxide (CO_2); and
- the frequent freeze-thaw cycles (freeze-thaw is included in EN 206-1 but is omitted from IS 118 because cold weather almost never occurs in Israel).

The standards give each category a letter code with a range of numbers describing the severity of conditions. After these conditions are identified, both the European and Israeli standards give the construction engineer two options to ensure durability in these circumstances (section 5.3.1 in both standards).

Option 1: Limiting values/prescriptive approach
This approach is intended to improve concrete coverage over rebar, thus delaying ingress of harsh elements through the concrete and extending the corrosion incubation period. After rebar corrosion initiates, corrosion propagation begins—the steel inflates, causing concrete cracking, delamination, and further exposure to corrosion agents and bringing service life to an end.

Option 2: Performance-related design approach
This approach is intended to improve rebar durability and resistance to corrosion, thus raising the chemical concentration threshold at which corrosion initiates (extending the corrosion incubation period), and slowing down the corrosion rate (extending the period of corrosion propagation until cracking begins). This option has several advantages, such as:

- lets engineers reduce the quantity of cement in the mix as compared to the quantity of cement that is needed in the prescriptive approach, which helps minimize thermal and plastic cracking as less cement generates lower heat and results in reduced shrinkage of concrete after casting;
- allows for a shallower concrete coverage on the rebar;
- permits engineers to use smaller amounts of rebar; and
- continues to provide protection if application errors ever occur (no casting is perfect), while Option 1 fails.

The site of the Park of Peace Amphitheater, Mevasset-Zion, Israel, was considered to have a moderately aggressive chemical environment due to direct exposure to the ground.

Photos courtesy Glimmer Industrial Consultation

With a proximity of only 200 m (565 ft) from a main thoroughfare, there was a greater likelihood of early carbonation, which could reduce the naturally high alkaline environment of new concrete that initially protects rebar from corrosion at the Park of Peace Amphitheater site.

Photo courtesy Glimmer Industrial Consultation and Elisar Civil Engineering

A closer look at three specific project environments

Due to its advantages, the performance-based approach played an important role in designing three different infrastructure projects in Israel: an outdoor amphitheater, a stormwater drainage culvert, and a tunnel to capture floodwater. Each of these projects was to be constructed in moderately harsh to severe conditions, while planning for a 100-year service life. Each project opted to follow performance-based concrete design strategies that specified a migrating corrosion inhibitor or its equivalent.

inhibitors play an important role in both delaying time to corrosion initiation and reducing corrosion rates. This technology will be further enhanced by the use of materials and processes to reduce cracking and resist sulfate attack in the first place.

The second-generation migrating corrosion inhibitor admixture specified in these projects is based on salts of amine-carboxylates. This chemistry works its way to the surface of the rebar, where it has an affinity to the metal and forms a protective molecular layer. When the naturally protective alkaline environment of concrete diminishes or when waters, salts, or other corrosives ingress through concrete pores or cracks, this migrating corrosion inhibitor layer disrupts the normal electrochemical process that would otherwise allow a corrosive reaction in the presence of an electrolyte.

Second-generation migrating corrosion inhibitors are said to potentially delay corrosion initiation by two to three times and to reduce corrosion rates after initiation by five to 15 times.[7] The migrating corrosion inhibitor specified in these projects meets ASTM C1582, *Standard Specification for Admixtures to Inhibit Chloride-Induced Corrosion of Reinforcing Steel in Concrete*, physical property results for set time, compressive strength, flexural strength, shrinkage, and freeze/thaw durability (Figure 1, page 46).[8] It also meets corrosion properties under ASTM G180, *Standard Test Method for Corrosion Inhibiting Admixtures for Steel in Concrete by Polarization Resistance in Cementitious Slurries*, (reduced corrosion current by factor of 10, bringing it within the requirements to be $^1/_8$ the value for control specimens) (Figure 2, page 48).[9] It tends to be easy for ready-mixers to work with.

Service life prediction software can help engineers estimate the service life and cost of a structure based on parameters such as climate, mix design, type of reinforcing steel, and corrosion-inhibiting admixtures. Migrating corrosion inhibitors enhance service life by increasing the chloride threshold of the reinforcement, and by slowing down corrosion once it initiates. The migrating inhibitor used increased the chloride threshold in the service life prediction software from 0.05 percent to 0.18 and also increased the propagation period by five times compared to the base case, as a conservative estimate of corrosion rate reduction found in ASTM-G109, *Standard Test Method for Determining Effects of Chemical Admixtures on Corrosion of Embedded Steel Reinforcement in Concrete Exposed to Chloride Environments*, testing of the product.[10]

When running a variety of mix designs for the Israeli infrastructure projects through the software, a concrete mix factoring in the expected performance characteristics of the migrating corrosion inhibitor projected longer service life compared to a denser concrete mix, yet without additional costs. The alternative concrete mix would have required C50/60 strength under the limiting values specification, calling for extra cement and leading to poor workability with a high risk of hydration heating, thermal cracking, and plastic cracking—factors counterproductive to durability. Curing also would have been more complicated with limiting values specifications, and extra rebar would have been needed for crack width control under Eurocode 2, *Design of concrete structures - part 1-1: general rules and rules for buildings*, and IS 466-1, *Concrete code: General principals.*

Instead, the performance-based design allowed the use of C35/45 concrete, requiring less cement and less rebar than for C50/60 concrete. Sulfate-resistant cement was also specified for additional durability of the two projects in a sulfate-rich environment. Incidentally, this cement has a slower strength development, enabling engineers to reduce hydration heat even further. Finally, even in the event of seemingly inevitable construction errors—such as surface cracking, non-constructive segregation, and insufficient concrete cover—the use of a migrating corrosion inhibitor offered an automatic remedy to mitigate the risk of corrosion to save the constructor considerable repair costs in future.

Applying these lessons in the United States

These projects provide insight into building for durability in the United States. Similar conditions are likely to exist in a

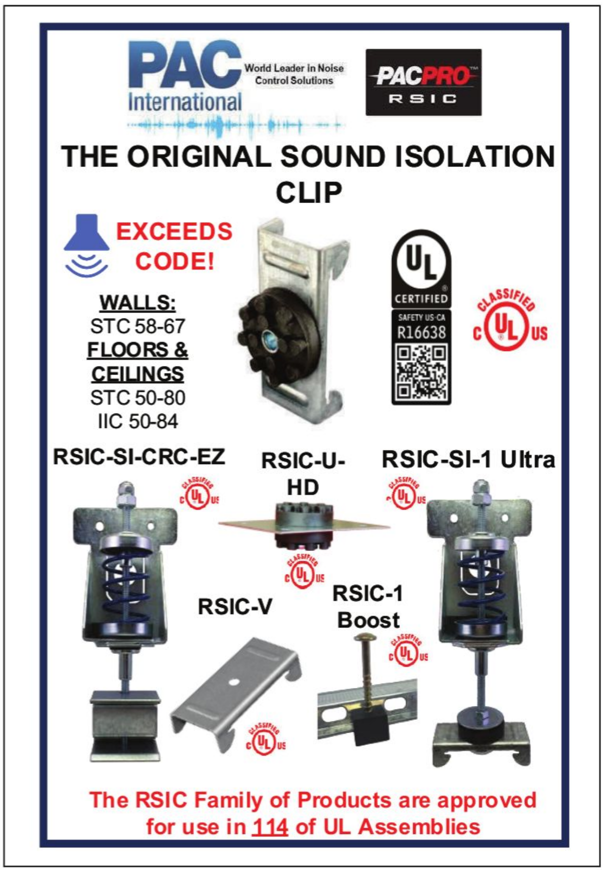

Figure 2

ASTM G180 Results for Biobased Migrating Corrosion Inhibitor Admixture A

Sample	Potential mV (SSC)	R_p (Ohms)	$1/R_p$ (μS/cm^2)	log($1/R_p$)	Area (cm^2)	Dosage (L/m^3)	mean $1/R_p$ (μS/cm^2)	SD $1/R_p$ (μS/cm^2)	Log($1/R_p$)	Log SD
1	-509	8192	23.85	1.38	5.12	0.60	38.91	21.29	1.33	0.29
2	-530.6	3626	53.96	1.73	5.11					
3	-500.2	9373	20.85	1.32	5.12					
4	-457.9	24360	8.10	0.91	5.07					
Controls (13)	-522.9 average					0	394.71	214.21	2.49	0.35

ASTM G180, *Standard Test Method for Corrosion Inhibiting Admixtures for Steel in Concrete by Polarization Resistance in Cementitious Slurries*, Testing of Admixture A. Data taken from "Re: Evaluation of Corrosion Inhibiting Admixture According to ASTM G180," TCG Project 17057, by Tourney Consulting Group in Kalamazoo, Michigan, in May 2017.

Image courtesy Cortec Corp.

southern coastal environment in the country due to high temperatures and the greater likelihood of high sulfate soils.[11] There is also a greater potential for exposure to sea spray with high chloride content. Engineers must take factors like these into account when building in such environments. For example, a structural engineering firm designing a new hotel along the Alabama Gulf Coast considered various durability options before choosing a migrating corrosion inhibitor that allowed them to extend projected service life (compared to epoxy coated rebar) while staying within budget.[12] Judging from the Israeli project examples, future structures facing high sulfate conditions on top of normal marine environments may achieve enhanced durability from the combined use of migrating corrosion inhibitors, sulfate-resistant cement, and C35/45 concrete to reduce cracking without requiring extra rebar.

Even by itself, a migrating corrosion inhibiting admixture can offer increased durability for situations that may be corrosive, although not exposed to marine, high sulfate, or high temperature environments. For instance, northern United States regions that experience harsh winters with lots of snow and ice compensate for the dangerous driving conditions by the heavy application of deicing salts. Roads, bridges, driveways, and parking ramps constructed in these environments are subject to freezing, thawing, cracking, and the ingress of chlorides leading to severe corrosion. Admixing a migrating corrosion inhibitor into the concrete can extend service life with minimal change to the ready-mix other than a slight delay in set time, which is sometimes an advantage for construction workers, but avoidable if necessary.

Another application where migrating corrosion inhibitors contribute to durability is in the risk of stray currents regions (underground re-enforced concrete within 3 km [2 mi] of an electric train, pipes with cathodic protection systems, or high-voltage electric lines). As migrating corrosion inhibitors form a protective molecular insulation layer on rebar, reinforced concrete comprising migrating corrosion inhibitors reduces the rate of corrosion by a factor of three to five.[13]

Conclusion

Building for durability of concrete infrastructure in extremely severe environments is an ongoing challenge. Use of a performance-related design method as was done in three Israeli infrastructure projects offers a good strategy for extending service life by taking a long-term approach to mitigating corrosion. Rather than simply delay corrosion by choosing a strategy that might require additional cement and rebar—with minimal protection once cracking and corrosion have started—the performance-based approach described here minimizes cracking, reduces material needs, and provides ongoing protection against corrosion even after cracking has started. A similar approach can be adapted to concrete infrastructure across the United States for greater durability in marine, sulfate-rich, and harsh winter environments.[14] **CS**

Notes

[1] See EN 206-1:2000, *Concrete – Specification, Performance, Production and Conformity, Part 1*, British Standards Institution, London, United Kingdom.

[2] Consult IS 118:2008, *Concrete: Specification, Performance and Production,* Standards Institution of Israel, Tel Aviv, Israel.

[3] For a brief introduction, see www.nrmca.org/p2p/Guide%20Spec%20Final.pdf.

[4] Read American Concrete Institute (ACI) Committee 329's "ACI 329R-14: Report on Performance-Based Requirements for Concrete" (December 2014) at www.concrete.org/Portals/0/Files/PDF/Previews/329R_14PREVIEW.pdf and "Performance-Based Concrete Mixtures and Specifications for Today" by James M. Shilstone, Sr. and James M. Shilstone, Jr. (February 2002) at ww.shilstone.com/library/Shilstone_CI0202.pdf.

[5] Review "Enhancing Durability at Park of Peace Amphitheater," Case History 650 (December 2019) at www.corteccasehistories.com/?s2member_file_download=access-s2member-level1/ch650.pdf.

[6] Review "Kidron Valley Culvert: Building for 100-Year Service Life," Case History 659 at www.corteccasehistories.com/?s2member_file_download=access-s2member-level1/ch659.pdf.

[7] Read *Improving Durability of Infrastructure with Migratory Corrosion Inhibitors (MCI) Handbook* by Boris Miksic.

[8] Consult "Admixture to Inhibit Chloride-induced Corrosion of Reinforcing Steel in Concrete (ASTM C1582) Concrete Properties Testing Final Report," by Glenn Schaefer.

[9] Read "Re: Evaluation of Corrosion Inhibiting Admixture According to ASTM G180, TCG Project 17057" by Neal S. Burke, PhD.

[10] For more information, visit www.cortecmci.com/wp-content/uploads/2017/09/LIFE-365-Inputs-for-MCI2c-5.27.15.pdf.

[11] See "Soil Survey Technical Note 11: Acid Sulfate Soils in the Coastal and Subaqueous Environment" by the United States Department of Agriculture (USDA) at www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=nrcseprd1461815.

[12] Read "Bio-based Corrosion Inhibitors: Building for resiliency in marine environments" by Julie Holmquist, Andrea Moore, and Casey Heurung in *The Construction Specifier* at www.constructionspecifier.com/bio-based-corrosion-inhibitors-building-for-resiliency-in-marine-environments.

[13] Consult "Corrosion Protection of Reinforcement from Stray Current by MCI 2005/2006 NS Admixtures," by Cortec Corporation. Research is also currently underway at the Israeli National Building Research Institute.

[14] Special thanks to Sen Kang, PhD, senior corrosion engineer, at Cortec Corporation, for technical review and editing.

ADDITIONAL **INFORMATION**

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Key Takeaways

Building for durability of concrete infrastructure in severe environments is an ongoing challenge for contractors and engineers. Using a performance-related design method offers a good strategy for extending service life by taking a long-term approach to mitigating corrosion. Rather than simply delay corrosion by choosing a method requiring additional cement and rebar—with minimal protection once cracking and corrosion have started—the performance-based approach minimizes cracking, reduces material needs, and provides ongoing protection against corrosion even after cracking has started.

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