Reinforcing Steel Comparative Durability Assessment and 100 Year Service Life Cost Analysis Report

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Prepared by:

TOURNEY CONSULTING GROUP, LLC

Prepared for:

MMFx STEEL

EXECUTIVE SUMMARY

TCG has reviewed data and literature on MMFX 2 and other concrete reinforcing products (black bar, epoxy-coated reinforcing—ECR, galvanized reinforcing, and UNSS3204 stainless steel reinforcing) to model the service life performance in three scenarios: a bridge deck exposed to deicing salts, a marine pile, and a pile in corrosive soil with high sulfate content. The following is the final report of our evaluation and findings.

The engineering service life analysis included modeling of concrete service life with STADIUM® software. Transport properties of the concrete mixtures were estimated based on data in the TCG and STADIUM data base and our engineering judgment, with the objective of evaluating the expected service life of various reinforcing steel alternatives in a representative concrete mixture placed in specific exposure scenarios.

The following is a summary of the key requirements and findings:

- The concrete service life requirements for the modeling are for 100 years before the onset of spalls that would require repairs to the structures modeled.
- The simulations are based on a “design” concrete cover over the reinforcing. The design cover is the specified cover minus the placement tolerances.
- Numerous technical reports were reviewed for MMFX 2, epoxy-coated, galvanized and stainless steel reinforcing steels. The STADIUM analysis identified a service life greater than 100 years for MMFX 2 (microcomposite) and stainless steel when used with high quality concrete for the concrete elements exposed to chlorides. Black steel and epoxy-coated bars, even at the maximum practical concrete cover could not meet the 100 year service life requirements. Galvanized bars could meet 100 year requirements, but at increased concrete cover compared to MMFX 2 and stainless bars.
- STADIUM provides information on the formation of ettrignite and conversion of monosulfate. The depths to which this would occur for all the structures considered were determined. In all cases, at the 100 year exposure, the reinforcing bars with MMFX 2 or stainless steel would need to be at a minimum cover exceeding what was needed just for prevention of chloride induced corrosion. This negates advantages of the higher chloride threshold value for stainless steel reinforcing bars in uncracked concretes.
- The literature review indicated that there could be additional cost savings in some structural applications by utilizing the enhanced structural performance of the MMFX 2 steel. Reductions in steel contents would need to be determined by a registered structural engineer and confirm to applicable code requirements. A reduction in the amount of steel needed could result in MMFX 2 having an initial cost similar to black bar.
- Prequalification and quality assurance testing should be specified for concrete mixtures and reinforcement proposed for any project to ensure the concrete and reinforcement provided will have material properties required for the 100 year design service life.

MMFX 2 Reinforcing steel
Durability Assessment Report

May 8, 2012

Neal S. Berke, Ph.D.

Tourney Consulting Group, LLC
3401 Midlink Drive
Kalamazoo, MI 49048 USA
(269)384-9980
(269)384-9981 Fax

INTRODUCTION

Tourney Consulting Group, LLC (TCG) was contracted by MMFX Technologies Corporation to assess the 100 year Life Cycle Cost Analysis (LCCA) of MMFX 2 (ASTM A1035/AASHTO MP 18) reinforcing steel in a bridge subjected to deicing salts, a marine pile, and a pile in corrosive soil. The objective of this durability assessment is to demonstrate that MMFX 2 reinforcing steel can meet the 100-year durability design requirements and to compare the service life cost for MMFX 2 bars to alternative concrete reinforcing options for these applications.

Durability Design Basis – The durability objective for this project is to obtain a 100-year service life without structural concrete spalling or structural repairs for the typical structures selected. These elements provide primary road surface or structural support and repairs to these elements define the service life end point.

This durability assessment is based on service life modeling of the concrete using the STADIUM® software program. This software is a state-of-the-art multi-mechanistic concrete degradation model. The assessment included these key components:

Exposure Conditions – Local exposure and climate conditions were researched and the results applied to the service life prediction model.

Concrete Durability Assessment – TCG evaluated the environmental exposure challenges and concrete strength criteria to establish the concrete mixture characteristics required for this project. The mixture characteristics were then used to identify preliminary model input values using our concrete mixtures database. This database provides initial ion transport properties for use in the STADIUM ® software.

Reinforcing Steel Option Assessment – The physical properties and costs of three reinforcing steel alternatives were researched, plain conventional ASTM A615/A706 “black” bars, MMFX 2 ASTM A1035 microcomposite reinforcing bars, epoxy-coated reinforcing bars ASTM A775, galvanized reinforcing bars ASTM A767, and SS2304 ASTM A995 stainless steel reinforcing bars.

Service Life Modeling – TCG analyzed the concrete durability assessment, exposure conditions, and alternative reinforcing steel options in STADIUM ® simulations to develop solutions that will provide 100 years of service life for the structure. The simulation uses computations and the concrete physical properties. As is common for design, the concrete properties without cracks are used for the simulation.

Bridge Model

The bridge used for modeling is representative of a typical structure in the Midwest United States where deicing salts are used and the bridge crosses fresh water.

The concrete in the bridge is exposed to two primary environmental conditions:

1. Deicing zone exposure is the area of the bridge exposed to deicing chemicals used in winter conditions to keep the bridge open for vehicles (freezing rain, snow and ice).

2. "Immersed or Splash" zone exposure is the area of the bridge permanently in the river, or expected to be exposed to normal river level fluctuations. Note that performance in this zone is primarily related as to how well the concrete resists erosion and potentially sulfate or ASR attack, so it will not be considered in modeling the performance of corrosion resistant reinforcement.

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Since MMFX 2 is added to enhance the corrosion resistance the analyses will concentrate on the concrete deck which has the most severe exposure. A schematic of a typical concrete deck, as modeled in the STADIUM® program, is shown in Figure 1.

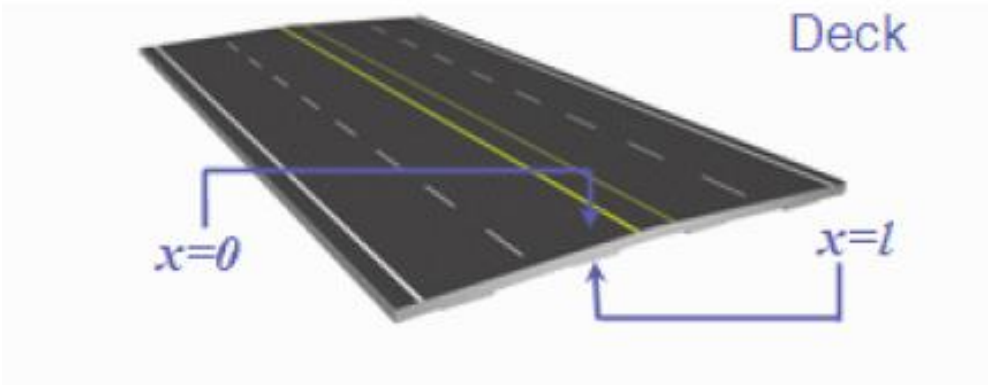


Figure 1 – Typical Concrete Bridge Deck in the Midwest

Marine Model

The most severe exposure in marine environments are typically the piles at the immersed/splash zone location. A typical pile in a marine application, as modeled in the STADIUM® program, is shown in Figure 2.

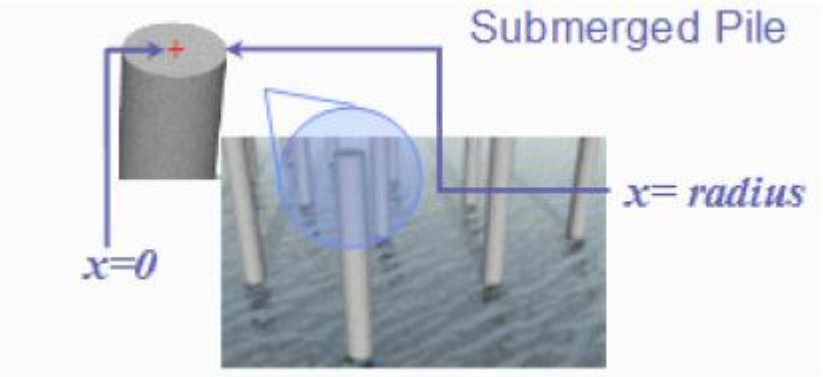


Figure 2 Piles in Marine Application

Soil Pile Model

Concrete building piles usually have good performance in soils with low contents of sulfates and chlorides. However, there are numerous locations where the sulfate and chloride contents in the ground water, and hence soil, could affect the service life of a structure, especially if the design life is 100 years or more. A pile in soils with high water contents of sulfate and chloride will be modeled. A typical reinforcing cage with spacers for use in the Gulf Cooperation Council (GCC) countries is shown in Figure 3.

Figure 3 Reinforcing Cages with spacers (GCC)

Service Life Definition

The service life objective for these structures is defined as 100 years without concrete spalls in critical structural elements.

Service life in this report considers the impact of corrosion of reinforcing steel in the concrete bridge deck due to deicing salts, and corrosion of the outermost steel in the pile for the marine or severe soil applications.

Over the life of a structure reinforced concrete goes through three stages of degradation related to corrosion.

These three stages are defined as follows:

1. Stage one (corrosion initiation) - time for chlorides to penetrate into the concrete to the level of the steel and reach the corrosion threshold level and initiate corrosion.
2. Stage two (propagation) - time from initiation of corrosion to initiation of first concrete spalls.
3. Stage three (repair) - time during the service life interval requiring repairs.

The degradation is shown graphically in Figure 4 for the three stages. For the structures considered in these analyses, the end of Stage 2 defines the end of service life.

The predicted corrosion service life of any concrete structure or component is primarily based on the combination of concrete mixture properties, reinforcing steel properties, element geometry, and environmental conditions. The actual corrosion service life depends on these factors and on installation, operating, and maintenance procedures.

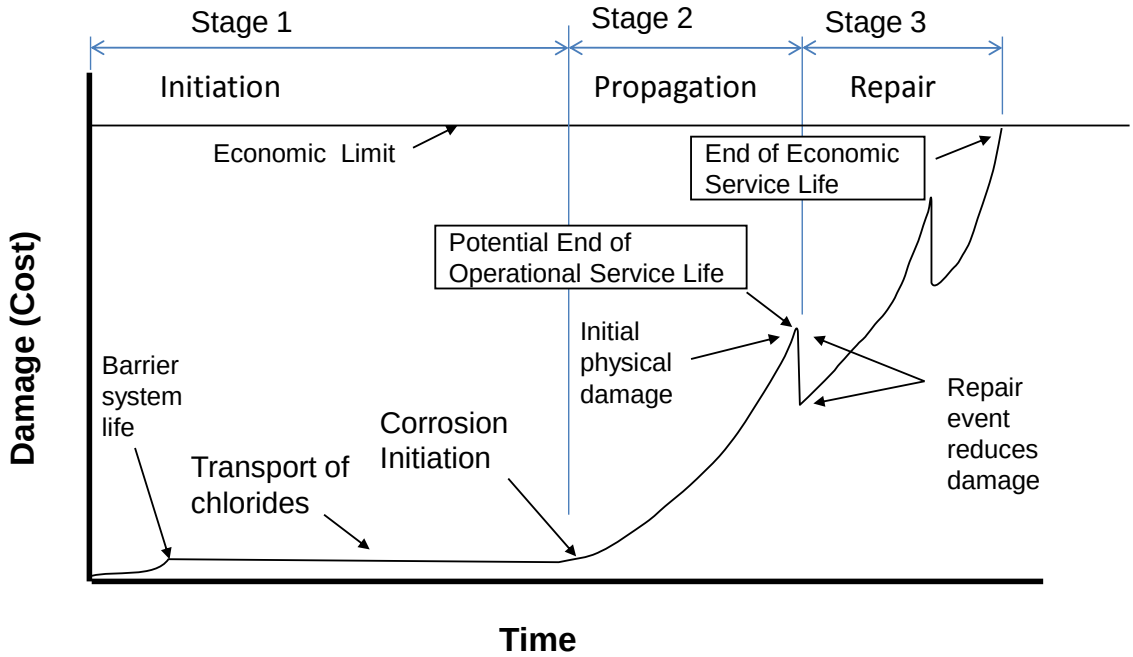


Figure 4 Schematic for reinforced concrete service life.

The predicted service life of components or assemblies can be assessed by one or more methods. Prediction methods[1] include: 1) demonstrated effectiveness, 2) modeling of the deterioration process, and 3) testing. The methods to evaluate service life in this report are based on all three of these methods and include an understanding and application of the principles of building and materials science.

a. Demonstrated effectiveness is essentially using the historical performance of similar concrete components in similar environments to estimate the service life of concrete members and corrosion protection alternatives in the future. The historical perspective gained by past experiences identifies 1) weaknesses in systems 2) synergies gained from combined systems, and 3) engineering strategies that have a proven successful. However, this approach cannot be used for new materials or innovative construction practices, nor can this method account for changes in use or maintenance.

b. Modeling the time to corrosion initiation caused by chloride ion contamination and other chemical degradation mechanisms has been simulated with the STADIUM® software program. This powerful tool allows the user to evaluate the anticipated service life of new materials and concrete mixtures. This tool can be used to model the effect of changing conditions in "what-if" scenarios.

[1] Adapted from Canadian Standards Association CSA S478-95, *Guideline on Durability in Buildings*, CSA, Etobicke, Ontario, Canada.

c. Laboratory testing to validate concrete property estimates and corrosion resistance criteria is necessary to substantiate service life predictions. TCG has conducted testing to verify the ion and a moisture transport property, for typical concretes used in these applications; and has researched reinforcing steel testing programs to justify model inputs. *However, it is recommended that transport properties of the concrete used in STADIUM ® inputs also become part of the concrete and reinforcing bar specifications for quality control. Specifying concrete that conforms to the transport properties will ensure the as-built service life.*

As noted the three stages of corrosion service life analysis are illustrated in Figure 4. These three stages and how they are related to this study are further described below.

1. Stage one (corrosion initiation) is the time concrete naturally protects the embedded reinforcing steel from corrosion. Stage one includes the time it takes chloride ions (from road de-icing salts, or the marine salt water) to penetrate into the concrete to the depth of the steel reinforcement in sufficient quantity (corrosion threshold) to initiate corrosion. We modeled the concrete properties and calculated the time for stage one with the STADIUM ® software. A summary of the results are included in this section of the report. The details of the STADIUM® analysis are included in the Appendix.

   The time to initiation of corrosion will also include the impact of barrier systems to restrict the transport of chlorides into the concrete (barrier protection). The effective life of barriers such as overlays, membranes, or waterproofing systems can be added to the time required to transport chlorides into the concrete. The bridge deck modeling will include a concrete overlay on the newly constructed bridge that will act as a wearing surface and protective barrier for a certain period of time. Since the period of time is expected to be substantially less than the desired 100 year service life, the life of this overlay is conservatively estimated as “zero” for the purpose of this analysis. The overlay’s potential protective features to block chloride ion penetration for a period of time are also conservatively estimated as a zero period of time.

   It is important to note that cracking can “short-circuit” the concrete barrier protection mechanism. Achieving the predicted service life requires effective methods for minimizing cracking and detailing of any cracks and joints. Design and detailing should be provided to prevent excess contamination through cracks or joints that could otherwise leads to premature spalls and repairs.

2. Stage two (corrosion propagation) is the time after corrosion initiation until corrosion produces delaminations and spalls in the concrete. This stage is commonly called propagation. The length of time for this stage is primarily a function of environment, reinforcement type, corrosion rate, concrete cover, and reinforcement layout.

   For conventional reinforcing we estimate the time from corrosion initiation to first spall to be 7 to 11 years for 2” cover and 3” cover respectively. These estimates are based on the calculation procedure described by Liu and Weyers (1998). Hartt (2009), and Morgan (2008) document that alternative reinforcing steels are more resistant to chlorides and corrode at a much slower rate. Scully (2007) confirmed the reduced corrosion rates and showed that the volumetric expansion of corrosion products for alternative reinforcing steels is similar to conventional reinforcing. Considering these facts, TCG used the same propagation period calculation procedure for all systems.

3. Stage three (repairs) includes ongoing repairs (and capital maintenance) required to correct degradation in the concrete slab or tower elements to keep the bridge operational. Since the deck and tower elements are the primary structural elements of the bridge, as are the piles in a marine structure, the structural designers typically stipulate that these elements cannot have structural spalls during the 100 year design service life. Stage 3 for these elements is zero years and the bridge service life ends after stage 2.

MMFX 2 Concrete Reinforcing Steel Bars

MMFX 2 steel bars are a high-strength uncoated corrosion-resistant steel-reinforcing product that meets the specifications of ASTM A 1035/A 1035 M and AASHTO Standard Specification MP 18M/MP 18. The production process and alloy composition combined provide the enhanced corrosion and strength performance.

Table 1 provides the material composition of a typical heat as well as the ASTM and AASHTO specifications. The MMFX 2 is a low-carbon, chromium alloy which provides enhanced corrosion resistance. Corrosion performance is further enhanced by the production process that eliminates most carbide formation and results in a lathe-like structure on a nanoscale that results in a significant improvement in mechanical properties.

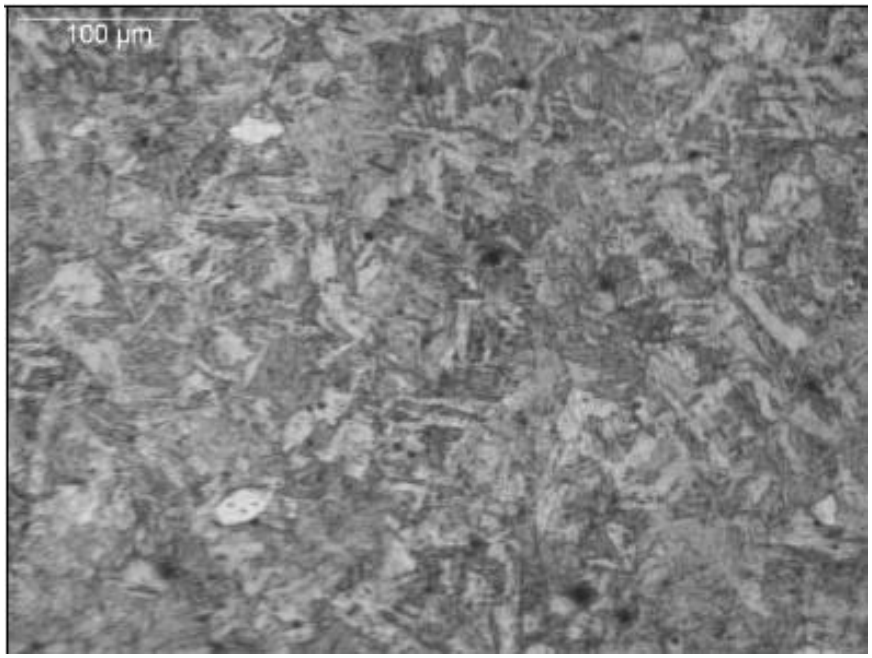
Table 1--MMFX 2 (ASTM A 1035/AASHTO MP 18) Material Composition

(Maximum mass percentage of chemical constituents, except where noted * **)

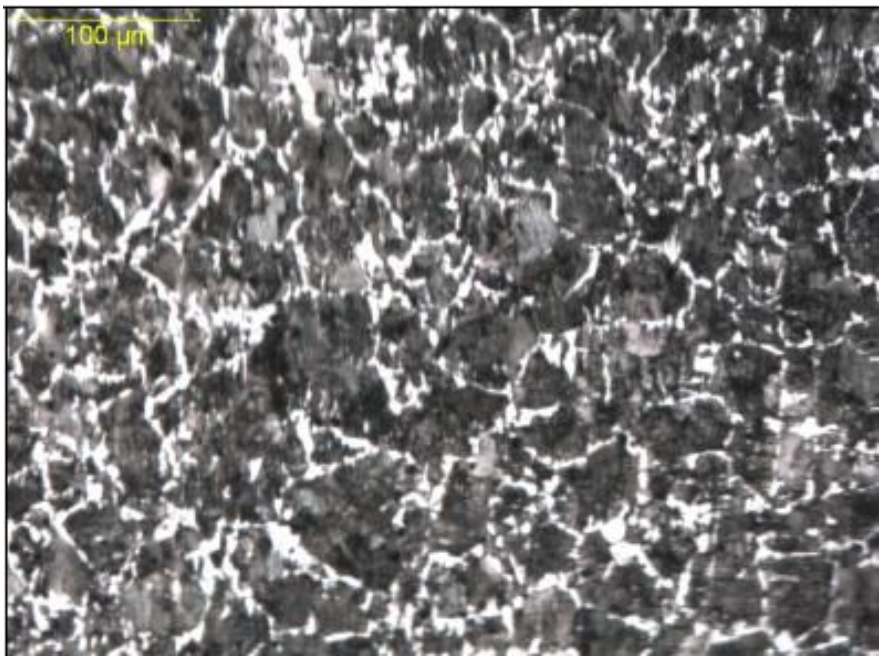
	C	Cr	Mn	Si	S	P	N (ppm)
Average Heat Chemistry	0.07	9.3	0.6	0.15	0.014	0.009	177
ASTM A 1035	0.15	8 to 10.9*	1.5	0.50	0.045	0.035	500
AASHTO MP 18	0.15	9.2**	1.5	0.50	0.030	0.045	200

*Range is given in ASTM A 1035
**Minimum mass percentage

The difference in the microstructure versus A 615 steel bars is shown in Figure 5. The carbides in the normal reinforcing steel act as cathode to the ferrite phase reducing corrosion resistance. The reduction in the carbides results in a lower available cathode to drive the corrosion reactions resulting in longer propagation times to failure once corrosion initiates. The chromium content helps to raise the chloride threshold level in concrete, and with less available cathode it results in upward of a 4-fold increase vs. A 615 steel bars as found by Hartt(2011), Hartt, Powers, Virmani (2009), Tinnea, Hartt, Pianca et al (2006),Ji, Darwin et al (2005), Clemeña and Virmani (2004).



a) MMFX 2 Fine grain martensitic structure
(Water/HCl/HNO_3--Etchant No. 88)



b) ASTM A 615 Grade 60 showing a perlite grain structure with ferrite present along some grain boundaries. (Nital Etchant—No. 74.a)

Figure 5 Microstructure of ASTM A 615 Bar vs. MMFX 2 (ASTM A1035) Bar at a magnification of 250 X.

To meet the specifications of AASHTO MP 18 the MMFX 2 reinforcing steel had to pass severe electrochemical corrosion testing in addition to composition and mechanical property requirements. In these tests corrosion performance was significantly improved compared to ASTM A 615 reinforcing bars, Berke (2011).

The use of MMFX 2 will change the Corrosion Life Service Diagram in Figure 4 by extending the time to corrosion and lowering the corrosion rate once it initiates. The combined effects are illustrated in the modified version of the Corrosion Life Service Diagram which is in Figure 6.

Several reports, not specifically mentioned documenting corrosion performance, are included in the reference section. Reference 28 includes a brief synopsis of several of the articles.

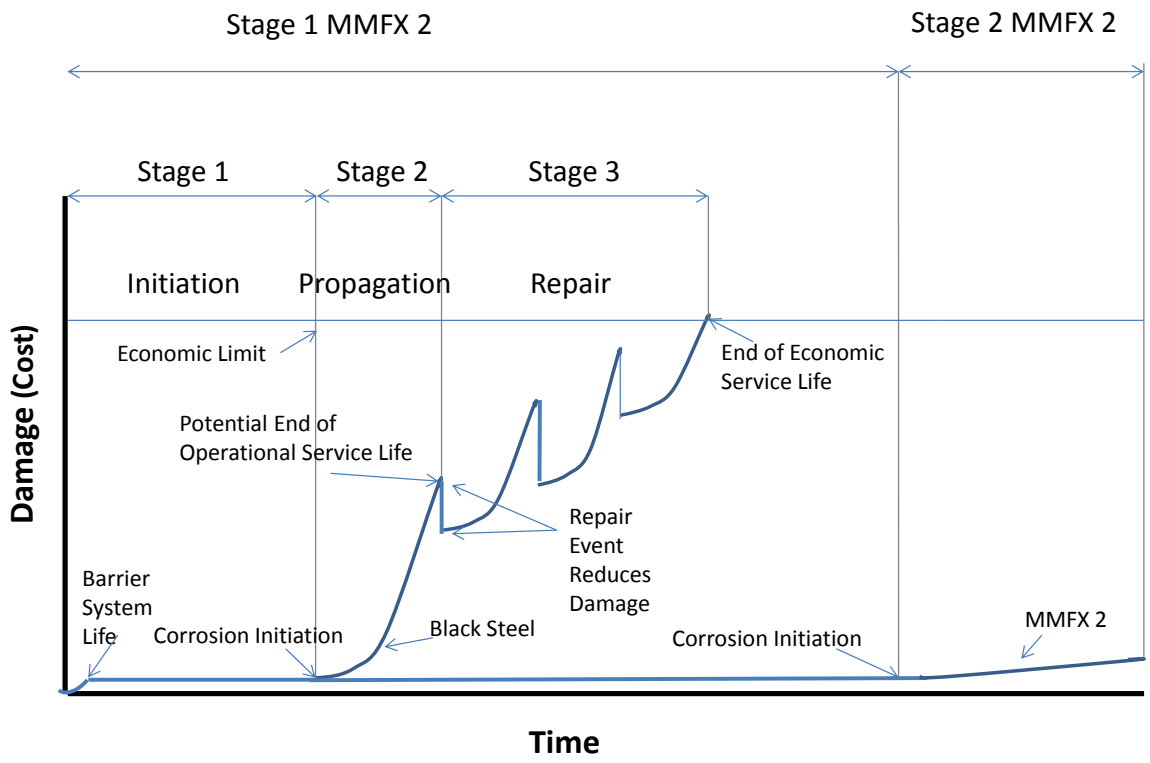


Figure 6 Revised Corrosion Life Service Diagram with MMFX 2

Based upon the references in this report and those in Appendix A, Table 2 was developed to show the improvements of MMFX 2 in corrosion performance models. These values are used in the life cycle modeling. These values are representative of a typical location.

Table 2-Reinforcement Options

Reinforcement Type	Abbreviation	Design Yield Strength (KSI)	Corrosion Threshold (PPM)	Propagation Time[1] (estimated years)	In-Place Unit Cost [2] ($/lb.)
Black Bar	BB	60	500[3]	5 to 7	0.68
Microcomposite Grade 60	MMFX 2-60	60	2000[3]	15 to 20	1.20[5]
Microcomposite Grade 75	MMFX 2-75	75	2000[3]	15 to 20	0.94[5]
Microcomposite Grade 100	MMFX 2-100	100	2000[3]	15 to 20	0.72[5]
Epoxy Coated	ECR	60	500	15	0.78
Galvanized	GS	60	1250[4]	15-20	1.14[7]
UNS S32304 Grade 60	SS 2304-60	60	5000	50 +	2.53[6]
UNS S32304 Grade 75	SS 2304-75	75	5000	50 +	2.08[6]

Notes for Table 2

1. Corrosion Threshold and Propagation Time are estimated from references and literature research.
2. Unit cost represents typical total : material, fabrication, and installation of reinforcing from local sources.
3. FHWA-HRT-09-020 Federal Highway Administration, William H. Hartt, *et al.,* Corrosion Resistant Alloys for Reinforced Concrete, 2009.
4. Galvanized Steel Reinforcement in Concrete, Edited by Stephen R. Yeomans, 2004
5. Cost used is that based on treating the MMFX 2 as Grade 60, 75 or 100 bars. When its Grade 100 properties can be utilized there is up to a 40% reduction in needed steel. This would relate to an equivalent cost/lb. of $0.74. For a Grade 75 use the equivalent cost is $0.98/lb.
6. Cost used is based on treating SS 2304 as a Grade 60 or Grade 75 bars.
7. Galvanized bar cost is based on the 6 to 8% additional weight of the zinc coating on the bar.

The mechanical properties of MMFX 2 are given in Table 3 for the Grade 100 (690 SI units). AASHTO MP 18 has specifications for lower strength Grade 60 (420) and Grade 75 (520) and ASTM A 1035 includes a higher strength Grade 120 (830). The increased ultimate and yield strengths can be utilized by structural engineers to reduce the quantities of reinforcing steel needed. Several references are available that give guidelines as to how this can be performed and are listed in the references. Lucier, Rizkalla, Zia, Hatem (2008) showed that a 33% reduction in reinforcing bars could be achieved in a bridge deck by utilizing high performance MMFX 2 steel reinforcement.

Table 3-MMFX 2 (ASTM A 1035/AASHTO MP 18) Mechanical Properties for Grade 100 (690 SI units).

Property (minimum values)	**Grade 100 (psi)**	**Grade 690 (MPa)**
Tensile Strength	150,000	1030
Yield Strength (0.2% offset)	100,000	690
Stress corresponding to an extension under load of 0.0035 in/in (0.0035 mm/mm)	80,000	550
Elongation in 8 in [200 mm]	**Percent**	
Bar Designation Number		
3 through 11 [10 through 36]	7	
14, 18 [43, 57]	6	

Reducing the required amount of steel to meet structural requirements in addition to lowering Life-cycle costs also facilitates the placement of concrete by reducing reinforcing bar congestion. Additional references on the mechanical properties and using the enhanced properties in structural element are included in the synopsis in Appendix A.

Reinforcing Steel Options Considered

The key performance properties of black bar, epoxy coated bar, galvanized bar, stainless steel bar, and MMFX 2 bar are shown in Table 2. Total installed costs are shown in Table 2. In addition the strength levels are given. The values in the table for MMFX 2 and SS 2304 are for applications where their higher yield stress is not being utilized to reduce the quantity of steel needed. For MMFX 2 total installed costs, when used at the higher grade level, are reduced as less steel is required. UNS S32304 can be used in some cases as Grade 75 so in some applications the amount of steel can be reduced. The other steels have a cost premium associated with a higher grade.

Reinforcing Steel Comparisons

Black Bar

Advantages

- Lowest initial cost
- Good Bond help to minimize crack size

Disadvantages

- Low Corrosion threshold
- Low propagation time
- Service Life estimated less than 100 years for all exposures
- Requires additional protection at cracks

MMFX 2

Advantages

- Low initial cost
- Good bond helps to minimize crack size
- Comparable in initial cost to BB if higher strength can be utilized
- Extended propagation time & raised Corrosion threshold
- Service Life estimated more than 100 years for all exposures
- Increase strength – may reduce reinforcement congestion and in-place costs
- Provides improved corrosion protection at cracks and flexural members
- No special handling procedures, same as black bar

Disadvantages

- Initial Cost premium over BB when used at Grade 60
- May require additional protection at cracks compared to stainless steel

ECR

Advantages

- Low initial cost
- Extended propagation time over BB

Disadvantages

- Low Corrosion threshold
- Possible reduction to Bond
- May increase crack size
- Special storage and handling requirements
- Service Life estimated less than 100 years in all cases

Galvanized

Advantages

- Moderate initial cost
- Extended propagation time & raised Corrosion threshold
- Good bond helps to minimize crack size

Disadvantages

- Service Life estimated less than 100 years accept at higher covers than needed for MMFX 2 and SS 3204 SS
- Requires high performance concrete, admixtures, or barriers to reach service life

- May need isolation from Black Bar
- Additional bar weight from zinc coating
- Requires additional protection at cracks compared to MMFX 2 and SS

Stainless Steels - all

Advantages

- Extended propagation time & high Corrosion threshold
- Service Life estimated more than 100 years
- Provides some corrosion protection at cracks and flexural members

Disadvantages

- Initial Cost premium significantly higher than all other options
- Concrete durability issues (e.g. sulfate attack) could require higher concrete cover than needed for chloride protection eliminating the advantage of having the highest chloride threshold.
- Special storage, fabrication and field handling procedures needed to avoid surface contaminants

Note that for all cases a 100 year service life will require a quality concrete that will provide a sound environment around the reinforcing bars for 100 years.

SERVICE LIFE ASSESSMENTS

PREDICTIVE SERVICE LIFE MODELING APPROACH

Durability modeling combines materials engineering expertise and computer simulations to optimize the reinforced concrete system to achieve a service life goal. Typically this is an iterative process. Each concrete element is evaluated separately based on the exposure conditions with the goal of achieving the required service life.

For the deicing salt exposures, the computer simulations provide the level of chloride contamination at the reinforcing depth as a function of time. For immersed exposures, the simulations provide the depth of deterioration caused by chemical interaction between the concrete and the surrounding water chemistry. The model output is then analyzed to determine if changes to the concrete properties or if alternative reinforcing is required to obtain the service life goal. The program is an excellent tool for evaluating piles in soils with high sulfate and chloride contents in the ground water, as it can predict the level of sulfate attack as well as the chloride profile.

Background on STADIUM Model

SIMCO Technologies Inc. (Quebec, Canada has developed, in collaboration with Laval University, a numerical model, called STADIUM, for the prediction of the degradation of concrete structures exposed to chemically-aggressive environments. In addition to the diffusion of ions and moisture, the model also accounts for the effects of chemical dissolution/precipitation reactions on the transport mechanisms.

During the course of its development, the numerical results yielded by STADIUM were systematically validated on the basis of laboratory test results and field exposure observations (Marchand 2001, Marchand et al. 2001,) and field exposure observations (Marchand et al. 2002a, Marchand et al. 2002b, Marchand et al. 2002c). The model was also used to predict the behavior of numerous existing structures exposed to various forms of chemical degradation phenomena.

Description of STADIUM

STADIUM

Over the past few years, the mechanisms of ionic transport in cement systems have been the subject of a great deal of attention. Most of the reports published on the topic have clearly emphasized the intricate nature of the problem. Given the number of inter-related parameters involved, simple analytical models can hardly describe the process of ionic transport. Numerical modeling is required.

STADIUM is an acronym that stands for Software for Transport and Degradation In Unsaturated Materials.

The main features of the numerical model called STADIUM are described in the following paragraphs. STADIUM predicts the transport of ions in cement-based materials and the chemical modifications occurring to the material as a result of these ionic movements. Currently, STADIUM can only be applied to 1D and axisymmetric problems. The 2D version is nearing completion and will eventually be able to model cracked concrete conditions.

STADIUM is divided in two main modules. The first module accounts for the coupled transport of ions and water without considering any chemical (dissolution/precipitation) reactions. The transport calculation is a volume-averaged version of the extended Nernst-Planck equation. This equation accounts for the electrical coupling between ions as well as for the chemical activity of the various ionic species in solution. The equation is coupled to Poisson's equation, which accounts for the electrical potential of the solution as a function of the local ion concentrations.

The following ionic species are usually considered: OH^-, Na^+, K^+, SO_4^{2-}, Ca^{2+}, $Al(OH)_4^-$, Cl^-.

These ions are related to the predominant chemical degradation phenomena that may affect concrete structures in service: chloride penetration, external sulfate attack, calcium leaching, etc. If needed, additional ionic species can be considered to predict the performance of concrete subjected to various deterioration mechanisms. For example, Mg^{2+} for magnesium sulfate attack, NO_2^- for concrete made with corrosion inhibitor, etc.

To account for the simultaneous transport of water, the previous equations are coupled to Richard's equation. It is a diffusion-type equation that gives the distribution of water content throughout the material. The effect of water movement on ion transport is modeled by adding an advection term to the extended Nernst-Planck equation.

To solve this complex system of nonlinear equations, a numerical algorithm must be used. All the transport equations are solved simultaneously.

The spatial discretization of this coupled system is performed through the finite element method, according to the standard Galerkin procedure. An Euler implicit scheme is used to discretize the transient part of the model. The nonlinear set of equations is solved with a Newton-Raphson algorithm. This second order algorithm gives a good convergence rate and is robust enough to handle the electrical coupling between the ionic species as well as the non-linearities coming from the coupling between the ionic flux and the water movement.

The second module in STADIUM is a chemical equilibrium code. After a transport step, the chemical equilibrium module verifies if the ion concentrations in the pore fluid at each node of the finite element mesh are in equilibrium with the different solid phases of the hydrated cement paste: calcium hydroxide, calcium silicate hydrates, ettringite, and hydrogarnet. If the pore solution is not in equilibrium with the paste, solid phases are either dissolved or precipitated in order to reestablish equilibrium. Solid phases can also be formed as a result of the penetration of aggressive species into the porous network of the material. For example,minerals such as brucite, ettringite, gypsum, Friedel's salt, hydrated sodium sulfate, or halite may precipitate if the right conditions exist.

The dissolution and precipitation of solid phases will lead to a local alteration of the porosity. This local porosity change can affect the transport properties of the material. STADIUM takes this phenomenon into account in its transport module.

Bridge Deck with Deicing Salts

A concrete cover of 2 inches was chosen for the bridge deck with typical tolerances of ± 0.5 inches. A ternary cementitious concrete mixture design was chosen representing a low permeability concrete. The mixture design is shown in Table 4 and designated as Bridge Mix LP.

Table 4 Concrete Mixture Designs for Midwest Bridge Deck

Material	Bridge Mix LP
Cement (lb./yd^3)	420
Silica fume (lb./yd^3)	29
Slag (lb./yd^3)	249
Water (lb./yd^3)	266
Fine aggregate (lb./yd^3)	1124
Coarse aggregate (lb./yd^3)	1750
Design Air Content	7%
W/B ratio	0.38

Transport Properties

TCG estimated concrete transport properties to be used in the STADIUM simulations for the 100 year service life, based upon its in-house data base for similar mixture designs. The values are given in Table 5. The hydration parameter, a, is set at 1 which is consistent with field curing conditions for a bridge deck which would not be in a constant high humidity environment after the curing period.

Table 5 - Transport Properties for STADIUM Simulations Based on TCG Database-Bridge Deck

Mixture	Porosity % (Volume)	Permeability x 10^{-22} m^2/s	IDC* or OH^- Diffusion $(10)^{-11}$ m^2/s	Hydration Parameter a	Hydration Parameter - alpha (1/s)
Bridge Mix LP	12	1	2	1.0	0.0015

A low diffusion coefficient (IDC) means that contaminants such as chlorides will diffuse slower through the concrete. Fly ash, silica fume, and ground granulated blast furnace, and superplasticizers are used to lower the water-to-binder ratios and hence IDC.

Environmental Conditions

The STADIUM software has default values for several locations in North America for both the weather conditions and amounts of deicing salts applied. In addition, if available specific data can be added for a specific location. It is demonstrated below how one would compile the local environmental information needed for a specific location where MMFX 2 would be used.

TCG recently analyzed environmental data and deicing practices at the Indiana/Kentucky border. These data are being used for the simulations and some details as to how the data were obtained follow.

Climate and weather databases were used along with local (Kentucky and Indiana) deicing policies and historical maintenance data to develop STADIUM ® inputs for the different exposure conditions (deicing and immersed in river water).

Temperature and Humidity

The weather exposure conditions used by STADIUM are based on the 40 year history at www.weatherbase.com. Data from this website was also used to estimate the number of deicing applications. Several key metrics are summarized in the following table by month for Louisville Kentucky.

Table 6 - 40-year Mean Monthly Weather Data for Louisville, KY

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average high (°F)	41	46	56	68	77	85	88	87	80	69	56	45	67
Average low (°F)	25	28	36	46	55	64	68	66	59	47	37	29	47
Number of days <32°F	23	19	13	2	0	0	0	0	0	2	10	20	89
Number of days with winter precipitation	11	11	13	12	NA	NA	NA	NA	NA	8	10	11	76
Snow fall (inches)	5.1	4.5	3.2	0.1	NA	NA	NA	NA	NA	0.1	1	2.2	16.2
Annual Precipitation (inches)	3.4	3.4	4.5	4	4.5	3.6	4.2	3.3	3.0	2.6	3.7	3.5	43.6

The average monthly temperature and annual variations are approximated using a sinusoidal function in STADIUM®. For the bridge deck, the range of average monthly ambient temperatures were approximated using an annual mean temperature of 55.4°F with a seasonal swing of ±21.6°F.

The average ambient relative humidity at the bridge deck surface was assumed to be 68% for 9 months, and 100% during the 3-month deicing period.

Based on weather and historical data we would expect 30 to 40 deicing events per year. We used an average of 35 deicing events to estimate the amount of salt applied.

Ion Exposure

Based on data collected from the Indiana and Kentucky highway maintenance departments, salt usage and planned maintenance are summarized as follows:

Kentucky deicing practice is to use between 200 lbs. to 500 lbs./lane mile/event. For 35 annual deicing events, this translates into an annual use rate between 4 to 9 tons/lane mile.

Indiana deicing practices amount to using an historical average of approximately 7 tons/lane mile.

Since bridges are prone to icing faster than roadways, localized deicing salt use on bridges is estimated to be approximately twice the DOT system-wide average. A conservative estimate of 14 tons per lane mile was used for the corrosion service life analysis.

The annual deicing salt use per lane mile is converted into mmoles/L of pore solution for use by STADIUM® simulations. The chloride ion exposure calculated from deicing salt use is listed in Table 7.

Table 7 - Summary of Exposure Conditions for Bridge Deck

Temperature (^{o}F)	Humidity (RH)	Chloride (mM/L)	Time Period for Chloride (days)
55.4 $\pm$ 21.6	68%*	658	90

*****RH is 100% during chloride exposure. Lowest temperature is center of chloride exposure

CORROSION SERVICE LIFE RESULTS

The input parameters listed in Table 4, Table 5 and Table 7, along with the corrosion parameters in Table 2, were used with STADIUM® to perform numerical simulations to estimate the time to corrosion initiation for various reinforcing steel alternatives.

Table 8 provides a summary of the various results. The STADIUM results are in Appendix A.

Table 8 – Corrosion Service Life for Various Reinforcing Steels-Bridge Deck

Concrete Type	Bridge LP	
Exposure	Deicing Salts	
Cover (min.)	1.5	
Reinforcement Type	Estimate to Initiation (y)	1st Repair (y)
Black Bar (BB)	19	25
Microcomposite (MMFX2)	>100	>100
Epoxy Coated (ECR)	19	34
Galvanized (GS)	59	76
UNS S32304 (SS2304)	>100	>100

Table 8 Notes

1. Table Abbreviations: BB = conventional black bar reinforcement, MMFX 2 = micro-composite reinforcement, ECR = epoxy-coated bar, GS = hot-dipped galvanized bars, SS = stainless steel.
2. The service life is the sum of the stage 1 – time to initiation of corrosion and stage 2, propagation time. The stage 1 initiation time is calculated by the STADIUM ® software according to the concrete properties input. The stage 2 time of corrosion propagation varies depending on concrete cover and type of reinforcement. At the end of stage 2 repairs are needed. For a key structure this is often considered to be the end of the service life given costs for repairs and traffic control, or loss of use. For the BB add 6 years to the initiation time to have time to first required repairs. For ECR add 15 years and for GS add 17 years for the time for first repair or end of service life. In the case considered BB, ECR and GS are significantly under the 100 year design life.
3. The service life estimates are based on typical concrete transport properties. For a specific bridge deck the transport properties for the mixtures being considered should be determined.
4. The service life results for the bridge can be validated with concrete testing of the concrete transport properties for concrete mixture design and quality control procedures.

Other Considerations

The STADIUM analysis provided a prediction of the depth of sulfate attack that could be anticipated over the life of the structure. This can be estimated by observing the ettrignite and monosulfate profiles at 100 years (Appendix A). In the deck the half mark was at approximately 1.25-in. Thus, while one can decrease minimum cover to 1.5 inches with MMFX 2 or SS2305 bars, one might not be able to safely go to 1.25 inch of minimum cover or lower. Thus any advantage the SS bars might have for use with a higher chloride threshold, might not be useable.

Marine Pile

Concrete cover of 3 inches was chosen for the marine pile with typical tolerances of ± 0.5 inches. A concrete mixture design representing a low permeability concrete was selected. This mixture design is shown in Table 9 and designated as Pile Mix LP.

Table 9 Concrete Mixture Designs for Marine Pile

Material	Pile Mix LP
Cement (lb./yd^3)	420
Fly ash (lb./yd^3)	211
Silica fume (lb./yd^3)	0
Slag (lb./yd^3)	0
Water (lb./yd^3)	197
Fine aggregate (lb./yd^3)	900
Coarse aggregate (lb./yd^3)	2323
Design Air Content	2%
W/B ratio	0.28

Transport Properties

TCG estimated concrete transport properties to be used in the STADIUM simulations for the 100 year service life, based upon its in-house data base for similar mixture designs. The values are given in Table 10. Note as this is a marine pile there will be significant moisture present to continue the hydration process beyond the initial curing. This is reflected in the hydration parameter (a).

Table 10 - Transport Properties for STADIUM Simulations Based on TCG Database-Marine Pile

Mixture	Porosity % (Volume)	Permeability x 10^{-22} m^2/s	IDC* or OH^- Diffusion $(10)^{-11}$ m^2/s	Hydration Parameter a	Hydration Parameter - alpha (1/s)
Pile Mix LP	12.0	13.4	6	0.2	0.004

A low diffusion coefficient (IDC) means that contaminants such as chlorides will diffuse slower through the concrete. Fly ash, silica fume, and ground granulated blast furnace, and superplasticizers are used to lower the water-to-binder ratios and IDC.

Environmental Conditions

The environmental conditions chosen for this case are based on the US Navy Severe Marine exposure case for Cape Hatteras, NC. The values for temperature, humidity and salt exposure are given in Table 11.

Table 11 - Summary of Exposure Conditions for Marine Pile

Temperature (^oF)	Humidity (RH)	Chloride (mM/L)	Sulfate (mM/L)	Time Period for Chloride (days)
61.7 ± 17.1	100%*	531	27	100

CORROSION SERVICE LIFE RESULTS

The input parameters, listed in Table 9-11, and Table 2 were used with STADIUM® to perform numerical simulations and estimate the time to corrosion initiation for various reinforcing steel alternatives.

Table 12 provides a summary of the various results. The STADIUM generated curves are in Appendix B. Minimum covers of 2 and 2.5 inches corresponding to design covers of 2.5 and 3.0 inches were examined.

Table 12 – Corrosion Service Life for Various Reinforcing Steels-Marine Pile

Concrete Type	Pile Mix LP	Pile Mix LP
Exposure	Marine	Marine
Cover (min.)	2.0	2.5
Reinforcement Type	Service Life Estimate (years)	
Black Bar (BB)	26	37
Microcomposite (MMFX2)	>100	>100
Epoxy Coated (ECR)	35	46
Galvanized (GS)	64	89
UNS S32304 (SS2304)	>100	>100

Table 12 Notes

1. Table Abbreviations: BB = conventional black bar reinforcement, MMFX 2 = micro-composite reinforcement, ECR = epoxy-coated bar, GS = hot-dipped galvanized bars, SS = stainless steel.
2. The service life is the sum of the stage 1 – time to initiation of corrosion and stage 2, propagation time. The stage 1 initiation time is calculated by the STADIUM ® software according to the concrete properties input. The stage 2 time of corrosion propagation varies depending on concrete cover and type of reinforcement. At the end of stage 2 repairs are needed. For a key structure this is often considered to be the end of the service life given costs for repairs and traffic control, or loss of use. For the BB 6 years were added to the initiation time to have time to first required repairs. For ECR 15 years were added and for GS add 17 years were added for the time for first repair or end of service life. In the cases considered BB, ECR and GS (at 2.0 in. minimum cover) are significantly under the 100 year design life. The GS almost makes the 100 year service requirement at the higher 2.5 in. minimum cover.
3. The service life estimates are based on typical concrete transport properties. For a specific marine pile the transport properties for the mixtures being considered should be determined.
4. The service life results for the marine pile can be validated with concrete testing of the concrete transport properties for concrete mixture design and quality control procedures.

Other Considerations

The STADIUM analysis provided a prediction of the depth of sulfate attack that could be anticipated over the life of the structure. This can be estimated by observing the ettrignite and monosulfate profiles at 100 years (Appendix B). In the severe marine exposure the monosulfate at the 2.25-inch level was approximately half the initial value and there is an increased ettrignite level. This indicates that the minimum cover should be higher than 2.25 inches so that the reinforcement is in good quality concrete.

A minimum cover of 2.5 inches is required to provide sound concrete around the reinforcing bars because of the potential depth of sulfate attack in a 100 year period. Thus the higher chloride threshold for the SS2304 can't be utilized to move the bars closer to the surface.

Pile in Severe Soil Exposure

In this example SI units are being used as the conditions used in this example were obtained from conditions in the Gulf Cooperation Council (GCC) countries. Concrete cover of 75 mm was chosen for the soil pile with typical tolerances of ± 12.5 mm. A low permeability concrete mixture with ternary cementitious blend was chosen for this example. The makeup of the ternary blend is 7.5% silica fume, 25% fly ash and the balance being Type 1 cement. The mixture design is shown in Table 13 and designated as Soil Pile Mix LP.

Table 13-Concrete mixture for piles in severe soil exposure.

Material	Soil Pile Mix LP
Ternary Cement (kg/m^3)	425
Water (kg/m^3)	149
Fine aggregate (kg/m^3)	810
Coarse aggregate (kg/m^3)	920
Design Air Content	6.9%

Transport Properties

TCG estimated concrete transport properties to be used in the STADIUM simulations for the 100 year service life, based upon its in-house data base for similar mixture designs. The values are given in Table 14.

Table 14 - Transport Properties for STADIUM Simulations Based on TCG Database-Soil Pile

Mixture	Porosity % (Volume)	Permeability x 10^{-22} m^2/s	IDC* or OH^- Diffusion $(10)^{-11}$ m^2/s	Hydration Parameter a	Hydration Parameter - alpha (1/s)
Soil Pile Mix LP	11	0.96	0.81	0.8	0.005

A lower diffusion coefficient (IDC) means that contaminants such as chlorides will diffuse slower through the concrete. Fly ash, silica fume, and ground granulated blast furnace, and superplasticizers are used to lower the water-to-binder ratios and IDC.

Environmental Conditions

The environmental conditions chosen for this case are based on soil conditions in the GCC at a high rise building site. This is one of the more severe exposures for both chlorides and sulfates. The sulfate and chloride values used are at the upper limit of those measured to have a

conservative approach. The values for temperature, humidity and salt exposure are given in Table 15.

Table 15 - Summary of Exposure Conditions for Soil Pile

Temperature (^oC)	Humidity (RH)	Sulfate (mM/L)	Chloride (mM/L)	Time Period for Exposure (days/y)
32.5 ± 8.5	100	40	423	365

CORROSION SERVICE LIFE RESULTS

The input parameters listed in Table 13-15 and Table 2 were used with STADIUM® to perform numerical simulations and estimate the time to corrosion initiation for various reinforcing steel alternatives and minimum covers. The full results are in Appendix C. Note that though a bridge model was used the pile conditions were representative of a severe soil exposure.

Table 16 provides a summary of the various results.

Table 16 – Corrosion Service Life for Various Reinforcing Steels-Soil Pile

Concrete Type	Soil Pile Mix LP	Soil Pile Mix LP	Soil Pile Mix LP
Exposure	Soil	Soil	Soil
Cover (min.)	37.5	50	62.5
Reinforcement Type	Estimated Service Life to Initiation (years)		
Black Bar (BB)	18	32	48
Microcomposite (MMFX2)	>100	>100	>100
Epoxy Coated (ECR)	18	32	48
Galvanized (GS)	57	96	>100
UNS S32304 (SS2304)	>100	>100	>100

Table 16 Notes

1. Table Abbreviations: BB = conventional black bar reinforcement, MMFX 2 = micro-composite reinforcement, ECR = epoxy-coated bar, GS = hot-dipped galvanized bars, SS = stainless steel.
2. The service life is the sum of the stage 1 – time to initiation of corrosion and stage 2, propagation time. The stage 1 initiation time is calculated by the STADIUM ® software according to the concrete properties input. The stage 2 time of corrosion propagation varies depending on concrete cover and type of reinforcement. At the end of stage 2 repairs are needed. For a key structure this is often considered to be the end of the service life given costs for repairs and traffic control, or loss of use. For the BB add 6 years to the initiation time to have time to first required repairs. For ECR add 15 years and for GS add 17 years for the time for first repair or end of service life. In the case considered BB, ECR and GS (at 37.5-mm minimum cover) are significantly under the 100 year design life.
3. The service life estimates are based on typical concrete transport properties. For a specific soil pile the transport properties for the mixtures being considered should be determined.
4. The service life results for the soil pile can be validated with concrete testing of the concrete transport properties for concrete mixture design and quality control procedures.
5. Note that maintaining specified minimum cover in these conditions can be challenging and both the MMFX 2 and SS 2304 provide a larger safety margin.

Other Considerations

The STADIUM analysis provided a prediction of the depth of sulfate attack that could be anticipated over the life of the structure. This can be estimated by observing the ettrignite and monosulfate profiles at 100 years (Appendix C). In the severe soil exposure the monosulfate at the 25 mm level was approximately half the initial value and there is an increased ettrignite content. This indicates that the minimum cover should be higher than 30 mm so that the reinforcement is in good quality concrete. Thus, while one can decrease minimum cover to 25 mm with SS2305 bars, one might not be able to safely go to a specified 50-mm cover. Thus any advantage the SS bars might have for use with a higher chloride threshold might not be useable.

Impressed current cathodic protection has been considered as an option in these applications. If properly installed and maintained, it might meet the life-cycle requirements. Given the high quantity of steel, rectifier and anode requirements would be high, and initial installation costs could be greater than or comparable to utilizing more expensive SS bars. In addition, over a 100 year projected life, in the severe environment, rectifiers and connections would most likely need to be replaced several times, and maintenance would be high. Over a 100 year period acid produced at the anodes could have a deleterious effect on the concrete.

SERVICE LIFE COSTS

Service life costs are based upon the initial construction costs and costs of subsequent repairs. The repair costs should include traffic control costs as well as lost time and fuel costs to users of the structure to fully capture the costs involved. Even when brought back to a Net Present Value these costs are substantial, and will overshadow minor differences in the initial costs Berke and Li (2007). This is the justification for having no major repairs in the 100 year life used in this study.

Since the black bars can't meet the 100 year service life without spalling their initial cost advantage is not a factor. However, there are potential savings in using MMFX 2 on the initial costs that could actually make these costs comparable to black bars.

As noted in the introduction several studies have been performed that indicate upwards of 33% reduction of Grade 60 black bar can be replaced by MMFX 2 Grade 100. A structural analysis of the specific structure needs to be performed to determine how much less MMFX 2 steel could be safely used.

By substituting MMFX 2 Grade 100 for black bar Grade 60, 1000 tons of black bar could potentially be replaced with 600 tons of MMFX 2 with the same structural capacity in some locations. This reduces the overall cost of the fabricated bar by 40% and would lower job site installation costs as less steel would be handled. Considering only the reduced amount of steel needed gives an equivalent in place cost of $0.74/lb. vs. $0.68/lb. for black bar. Even in applications where MMFX 2 is treated as Grade 75 there still is a reduction in equivalent cost to $0.98/lb. equivalent cost. When installation and handling costs are included, it appears that MMFX 2 is competitive even in initial costs. Note that the level of steel reduction will depend upon applicable code requirements and approval by a registered structural engineer.

Stainless steels could also benefit to a lesser extent in a reduction of steel, but given their cost is over two times that of MMFX 2, MMFX 2 is an attractive alternative

Table 17 shows the increased cost for adding corrosion protection beyond that of black bar as an initial cost and cost of repairs to meet a 100 year service life for a bridge deck. A 4% discount rate was used for the cost of money over time to determine a Net Present Price (NPR) and repairs were assumed to be on 10% of the deck surface at 15 year intervals after the first repairs. Repair and traffic costs are assumed to be $150/ft^2. In addition, there are user costs in extra fuel consumption and time loss. Finally as mentioned earlier there is a negative effect on the environment with the increased fuel consumption and added exhausts from the vehicles.

Table 17-Service Life Analysis for Bridge Deck with Repairs

Concrete Type	Bridge LP				
Exposure	Deicing Salts		Rebar Initial Cost	1st Repair NPR	Total Cost Initial +All Repairs NPR
Cover (min.)	1.5 inches		$/ft^2	$/ft^2	$/ft^2
Reinforcement Type	Estimate to Initiation (y)	1st Repair (y)			
Black Bar (BB)	19	25	8.16	5.62	20.14
Microcomposite (MMFX 2)	>100	>100	14.40	0	14.40
MMFX 2-Gr. 75	>100	>100	11.28	0	11.28
MMFX 2 -Gr. 100	>100	>100	8.64	0	8.64
Epoxy Coated (ECR)	19	34	9.36	3.95	17.79
Galvanized (GS)	59	76	13.68	0.76	14.86
UNS S32304 (SS2304)	>100	>100	30.36	0	30.36
SS2304-Gr. 75	>100	>100	24.96	0	24.96

Notes on Table 17

1. Repairs every 15 years starting at 1st repair at $150/ft^2 (Traffic + Repair)
2. 10% of the surface area is repaired at each time
3. Discount rate at 4%
4. Only MMFX 2 and SS2304 options meet requirement of no significant repairs in 100 years.

The analysis in Table 18 shows that MMFX 2 is the lowest cost solution of the various reinforcing bars used. Utilizing the higher strength, when possible, significantly improves the cost advantages of MMFX 2. MMFX 2 and SS2304 are the only repair free solutions which was the design requirement.

The cost of using corrosion resistant bars is only a small percentage of the total cost of the bridge deck or pile and this is easily recovered by increased service life.

SUMMARY OF FINDINGS

- Concrete mixture data used in the analysis were based on concretes in TCG's database. Transport properties of the concrete mixtures were estimated with the objective of evaluating the expected service life of various reinforcing steel alternatives in a representative concrete mixture placed in project specific exposure conditions. *Prequalification testing should be conducted on concrete mixtures proposed for a specific project to verify the proposed concrete transport properties meet or exceed the estimated values.*
- Numerical simulations were performed using STADIUM® software for the concrete elements and estimated mixture properties evaluated in this study.
- The criteria define the concrete service life requirements as 100 years before the onset of spalling to the top portion of the deck slab or outside of the piles.
- An additional requirement is that the bars be at a depth where the concrete quality is maintained after 100 years of environmental exposure. This is especially important in marine and soil applications where sulfate contents in the water can be elevated.
- The simulations are based on a "design" concrete cover over the reinforcing. The design cover is the specified cover minus the placement tolerances. For the service life analysis 1.5 inches was used for the design concrete cover of the bridge deck to minimize cracking, and 2.0 and 2.5 inches for the marine pile. The pile in corrosive soil used metric minimum covers of 37.5, 50, and 62.5 mm.
- The examples require corrosion resistant steel to achieve the 100 year service life. Numerous technical reports were reviewed on the candidate reinforcing steels and the following is a summary of findings:
    1. MMFX 2 (microcomposite) and stainless steel both provide the required 100 year service life when used with high quality concrete for the concrete elements exposed to deicing, marine and corrosive soil salt exposures at the specified concrete covers.
    2. Solid stainless steel grade 2304 will obtain 100 year service life but have a significantly higher material cost than MMFX 2.
    3. Other degradation mechanisms such as sulfate attack over a 100 year exposure might require higher minimum concrete cover over the reinforcing bars than required for chloride protection. This eliminates the advantage that SS bars have over MMFX bars in uncracked concretes or where cracks have been sealed.
- For elements expected to crack in service that are located in deicing salt exposure, stainless steel or MMFX reinforcing with supplemental protection systems should be considered. The slow corrosion rate of stainless steels coupled with a high chloride threshold will prevent localized corrosion spalls at cracks in low-permeability concrete over the life of this structure. If stainless steel is not used, ACI 224 indicates that for concrete in corrosive environments, with cracks larger than 0.008 inches the cracks should be repaired or treated. Combining MMFX 2 reinforcing with additional protection systems in zones expected to crack could prove to be a cost-effective alternative to stainless steel reinforcing. The supplemental protection system at cracks generally includes materials that provide a barrier at the cracks. The performance of a concrete corrosion inhibitor at cracks has varied in testing and the effectiveness would be uncertain.

- Combining conventional reinforcing with MMFX 2 reinforcing is acceptable because the two steels are electrically similar.
- The structural design may be able to benefit from the higher strength of stainless steel and MMFX2 reinforcing.
- Project service life specifications requirements can be used for concrete mixture prequalification, optimization and quality control. This approach would specify actual concrete transport property testing of the proposed mixture prior to use on the project.

Service Life Design Notes

1. Several factors will affect service life such as: concrete mixture variability, concrete cover, reinforcing steel system, exposure conditions, surface treatments, concrete delivery system, and contractor workmanship. These factors should be addressed in the project design and specifications. .

2. Values for transport properties were approximated using a database of tested concrete mixtures with similar characteristics and with limited testing of local concrete. The simulation results are dependent on initial mixture proportioning and on quality control to maintain concrete quality and the concrete transport properties. .

3. STADIUM® analysis of concrete mixtures provides a method for qualification and quality control of concrete subjected to aggressive environments. This method is based on principles of materials science and is designed to provide a solid basis for decision making for structures that require a long service life.

4. Stadium simulations assume the concrete is macro-defect free (no cracks intersecting the reinforcement). These assumptions are valid when the following occur:

    - Structural systems and concrete reinforcing for bridge decks are designed to minimize cracking.
    - Crack repairs or supplemental protection such as crack sealing or waterproofing system are provided to mitigate adverse effects from cracking that may occur.

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28. **MMFX Product Information - Material Properties and Design Considerations** – MMFX Steel - September 2011

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APPENDIX A

STADIUM® Bridge Deck Results

12033 Bridge Deck Conservative Curing

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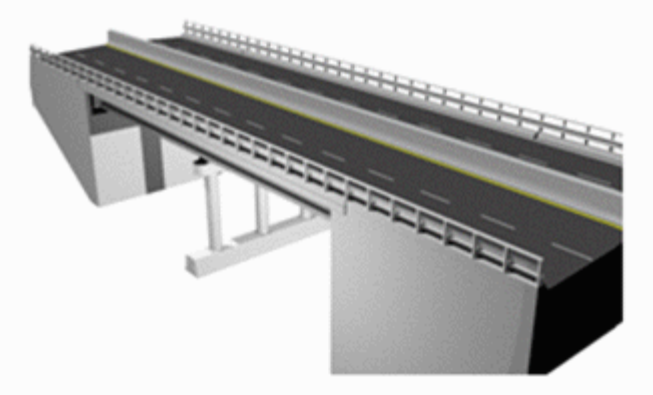
STADIUM® VERSION 2.997

STADIUM® SIMULATION REPORT

Location: Louisville

Structure Type: Bridge

Project Ref.:.....



May. 08, 2012

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Date : 05-08-2012 / 15:47:29
Engineer : .....
Client : .....
Project : .....
Project Ref.: .....

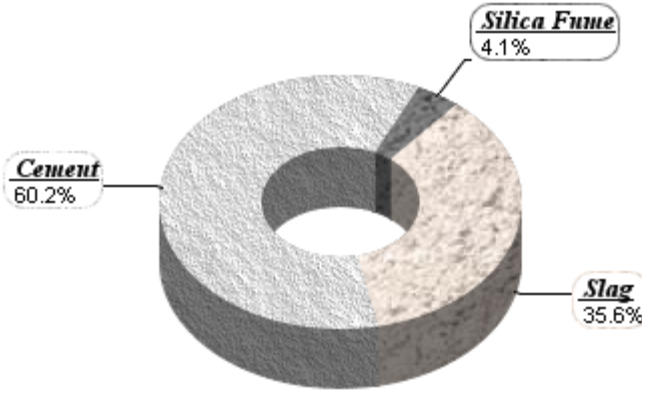
Project Database: [12033 Bridge Deck Conservative Curin

Deck

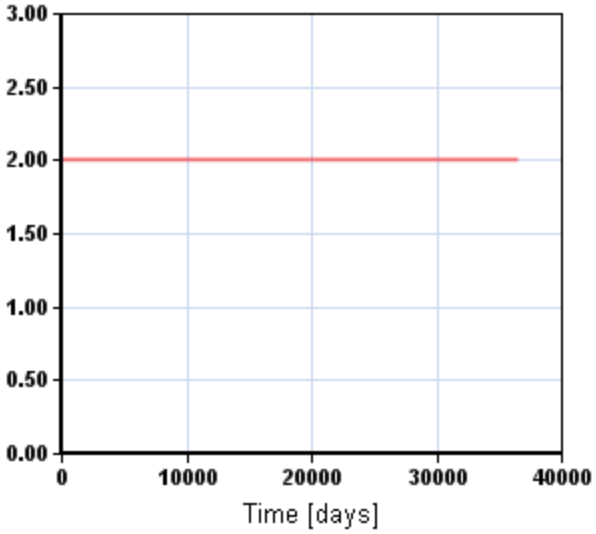
Structure Type: Bridge
Structural Element Type: [Deck]
Material Name:
[Modified Material - for Deck]

Cement Type	TYPE I
Water/Binder Ratio	0.38
Cement Content: (lb/yd³)	421
SCM #1: Slag (lb/yd³)	249
SCM #2: Silica Fume (lb/yd³)	29
SCM #3: None (lb/yd³)	0
Fine Aggregates: (lb/yd³)	1124
Coarse Aggregates: (lb/yd³)	1750
Water: (lb/yd³)	266
Air: [%]	7.0
Material Density: (lb/ft³)	142
Mixture Volume: (ft³)	27.052
Paste Volume: [%]	29.42

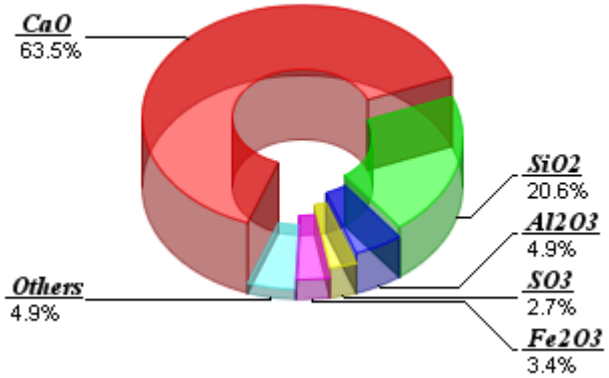
Binder Composition



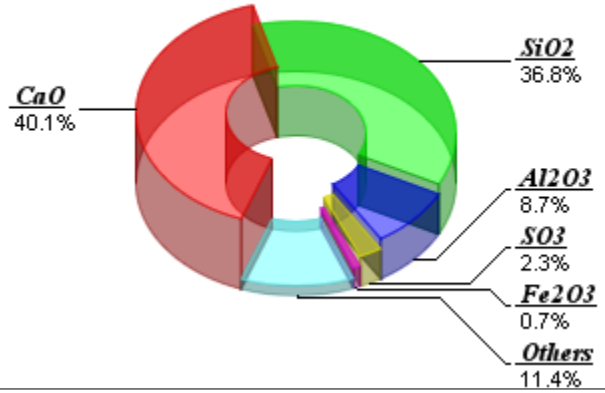
Diffusion Coefficient (e-11 m²/s)- a=1.0 - alpha=1.50E-3



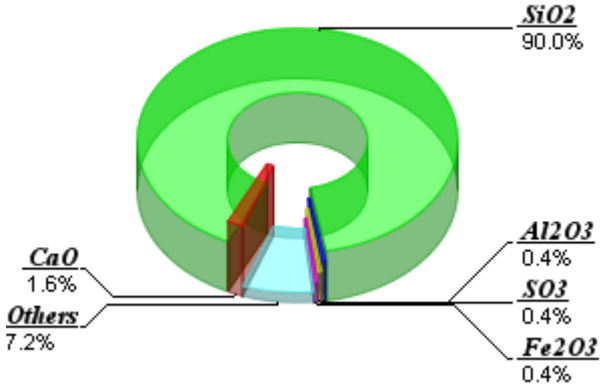
Cement Composition



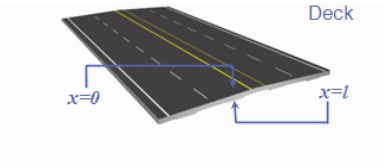
Slag Composition



Silica Fume Composition



Data for project: 12033 Bridge Deck Conservative Curing - Structural element [Deck]



Dimension (in) = 8.
Scenario Duration (years) = 100
Temperature (°F) = 73.4
Water/Binder Ratio = 0.38
Binder Content (lb/yd³) = 699
Total Aggregates (lb/yd³) = 2874
Binder Density (lb/yd³) = 5115
Porosity = 0.12
Cement Type = TYPE I

OH- Diffusion Coeff. (e-11 m²/s)= 2.00
Saturation at 50% R.H.= 0.55
Age of First Exposure (days)= 28
Age at Lab Testing (days)= 28
Hydration Param. - a = 1.
Hydration Param. - alpha (1/s) = 1.500E-03
Thermal Conductivity (W/m.K) = 2.000E+00
Specific Heat (J/kg/K) = 1.000E+03

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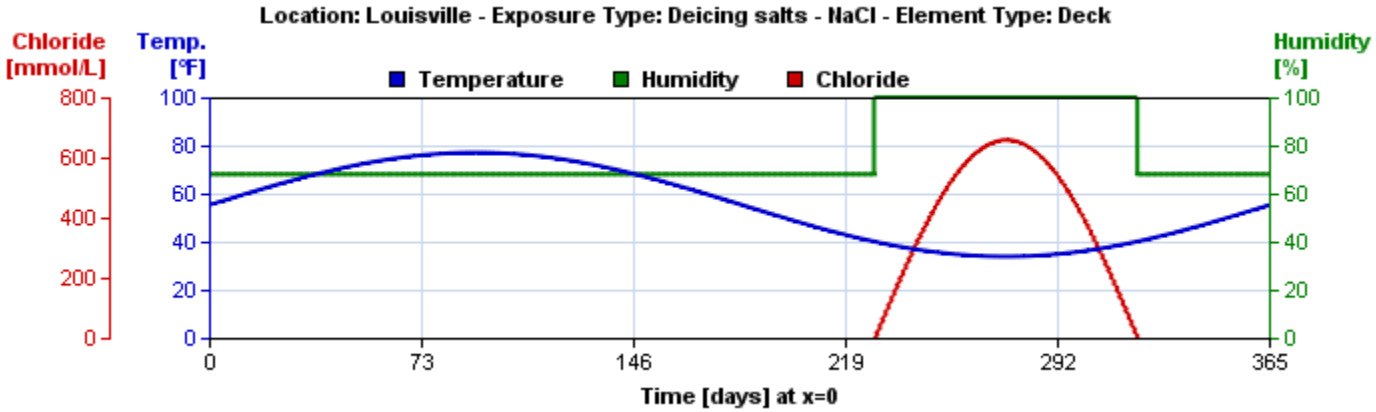
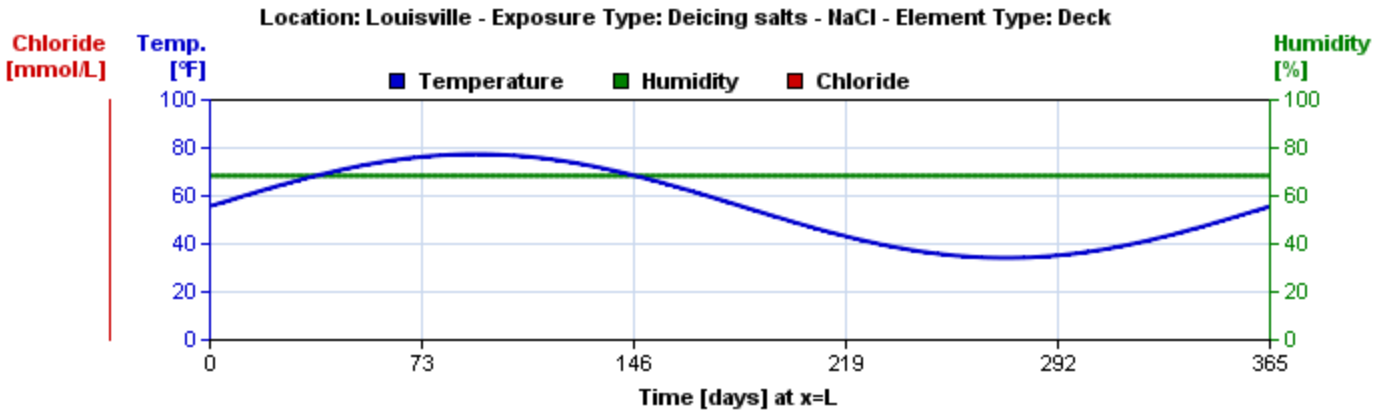
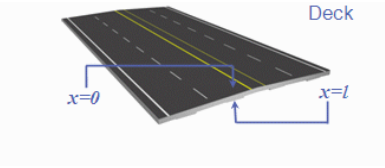




Data for project: 12033 Bridge Deck Conservative Curing - Structural element [Deck] - Scenario: INITIAL



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Age at Lab Testing (days)= 28
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Hydration Param. - alpha (1/s) = 1.500E-03
Thermal Conductivity (W/m.K) = 2.000E+00
Specific Heat (J/kg/K) = 1.000E+03

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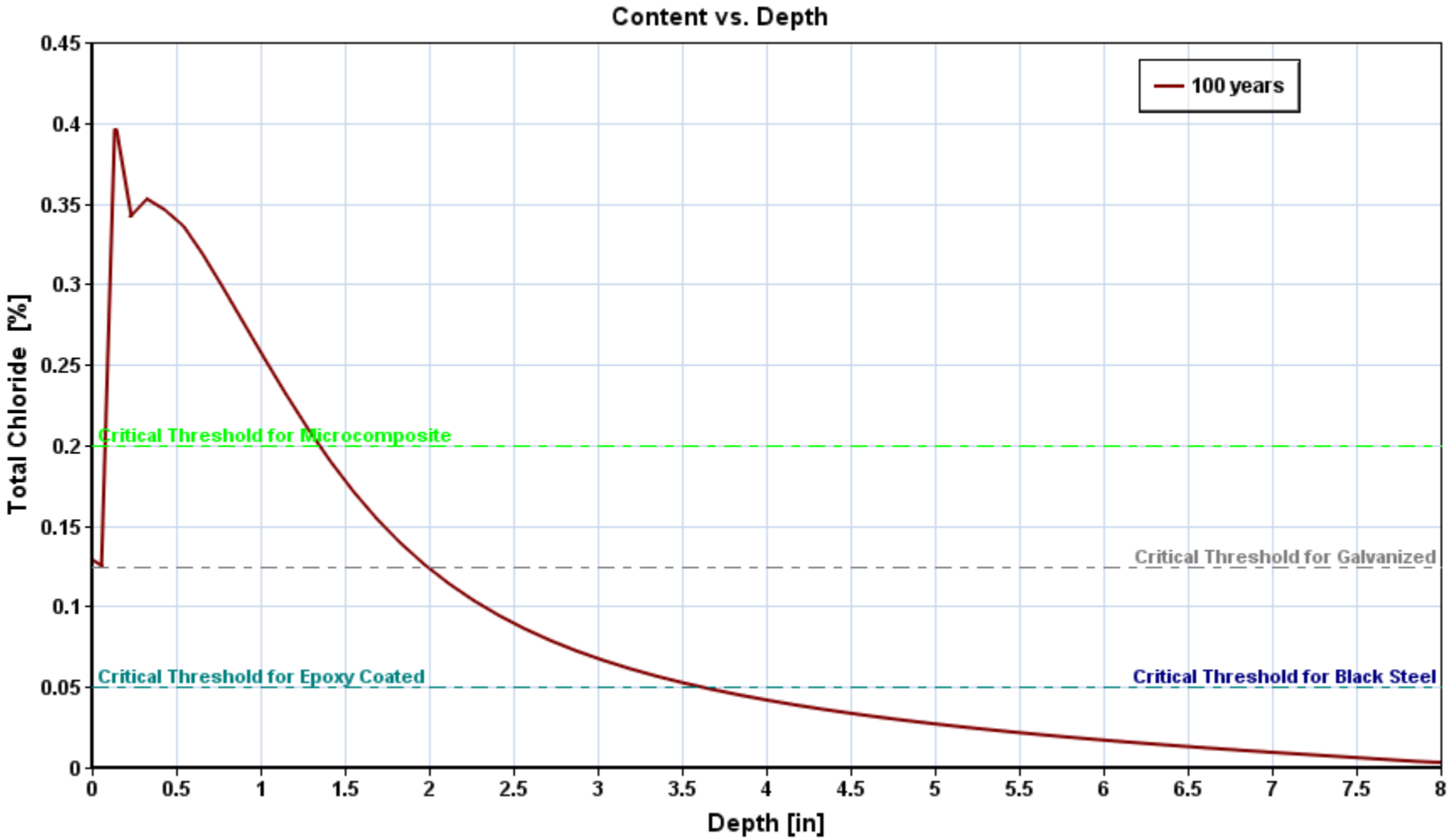
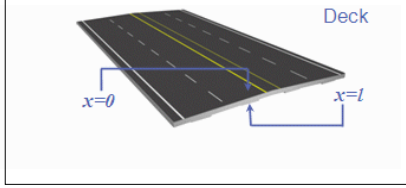


Data for project: 12033 Bridge Deck Conservative Curing - Structural element [Deck]



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Scenario Duration (years) = 100
Temperature (°F) = 73.4
Water/Binder Ratio = 0.38
Binder Content (lb/yd³) = 699
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Saturation at 50% R.H.= 0.55
Age of First Exposure (days)= 28
Age at Lab Testing (days)= 28
Hydration Param. - a = 1.
Hydration Param. - alpha (1/s) = 1.500E-03
Thermal Conductivity (W/m.K) = 2.000E+00
Specific Heat (J/kg/K) = 1.000E+03

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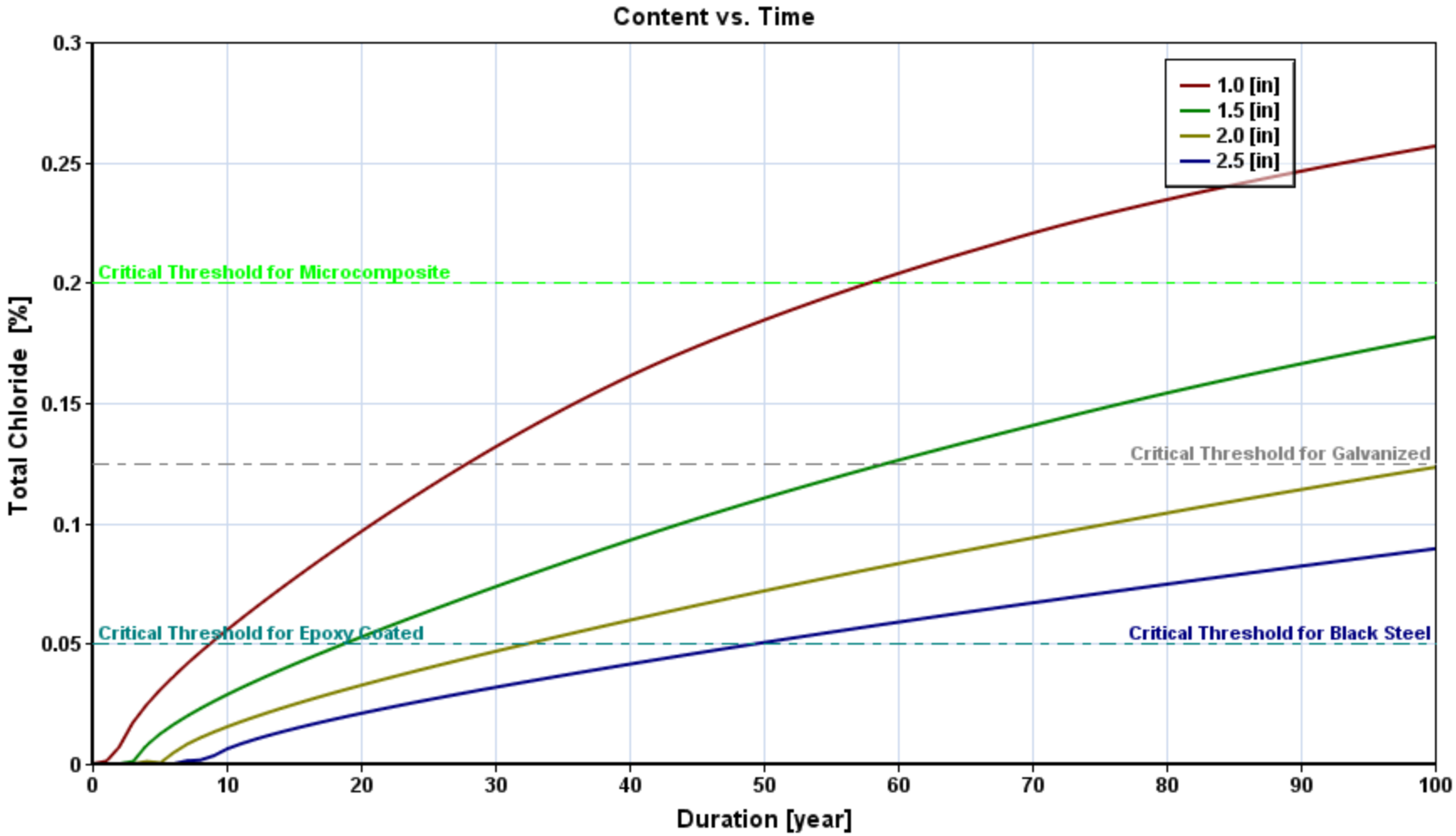
Project Database: [12033 Bridge Deck Conservative Curin



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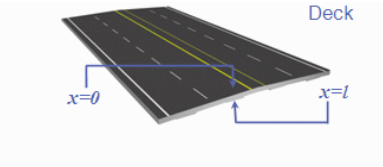

Dimension (in) = 8.
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Temperature (°F) = 73.4
Water/Binder Ratio = 0.38
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Saturation at 50% R.H.= 0.55
Age of First Exposure (days)= 28
Age at Lab Testing (days)= 28
Hydration Param. - a = 1.
Hydration Param. - alpha (1/s) = 1.500E-03
Thermal Conductivity (W/m.K) = 2.000E+00
Specific Heat (J/kg/K) = 1.000E+03

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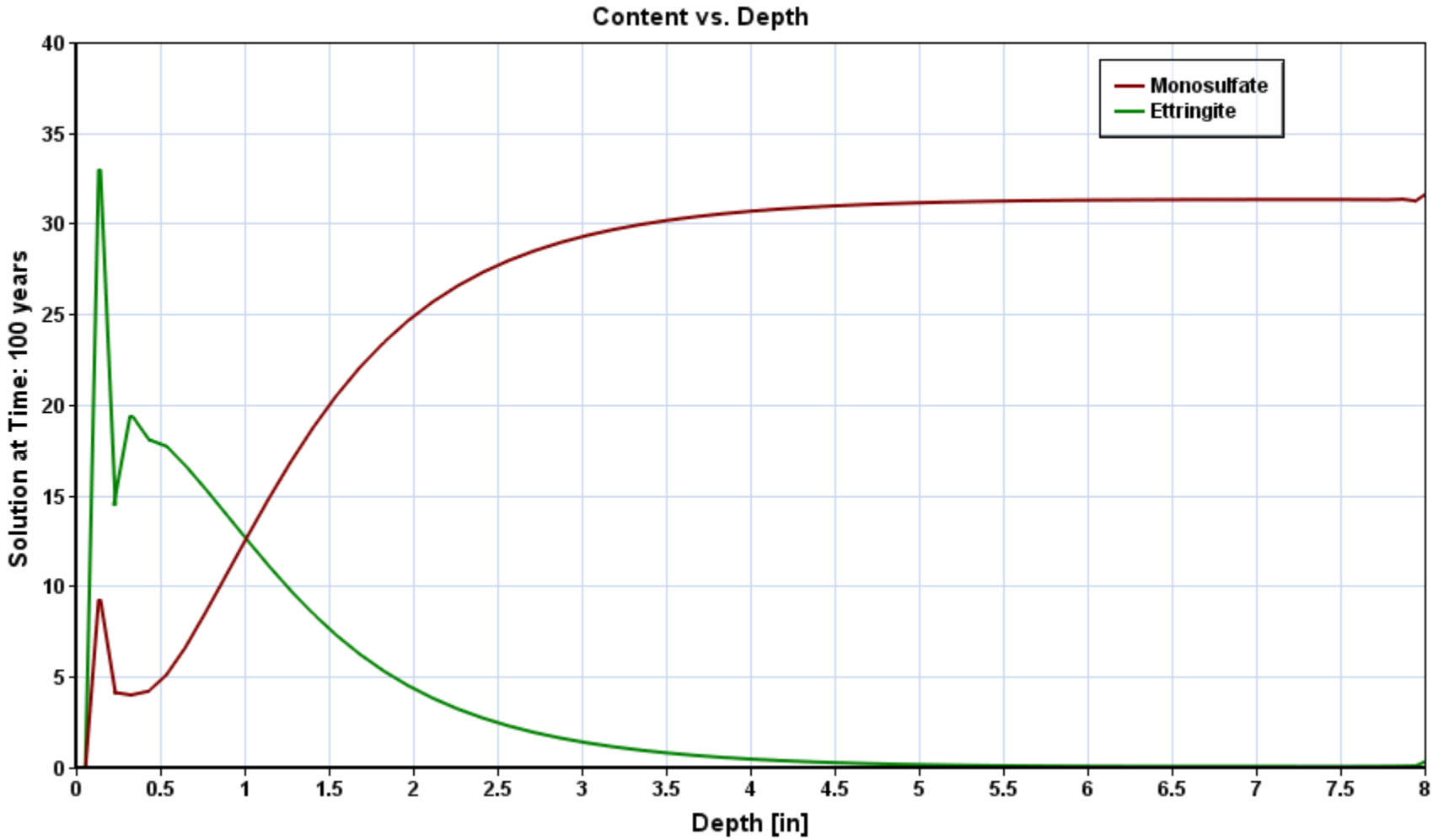

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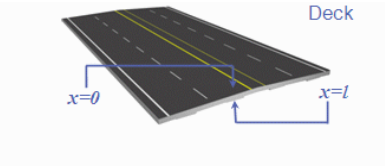

Dimension (in) = 8.
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Saturation at 50% R.H.= 0.55
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Age at Lab Testing (days)= 28
Hydration Param. - a = 1.
Hydration Param. - alpha (1/s) = 1.500E-03
Thermal Conductivity (W/m.K) = 2.000E+00
Specific Heat (J/kg/K) = 1.000E+03

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APPENDIX B

STADIUM® Marine Pile Results

Marine Pile HP

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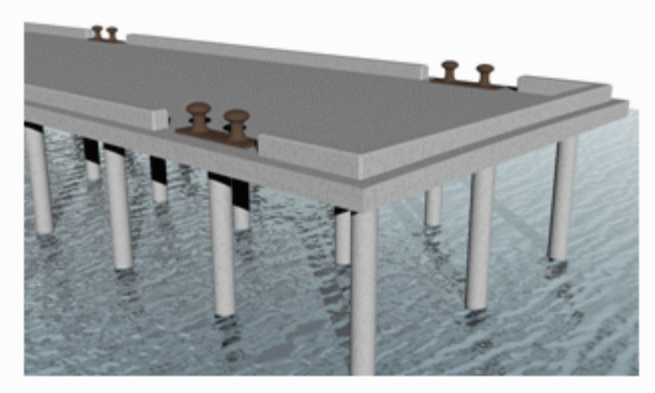
STADIUM® SIMULATION REPORT

Location: Cape Hatteras

Structure Type: Marine

Project Ref.:.....



May. 08, 2012

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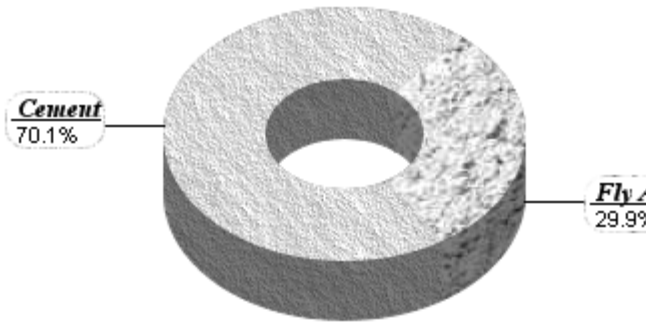
Pile

Structure Type: Marine
Structural Element Type: [Pile]
Material Name:
[Modified Material - for Pile]

Cement Type	TYPE I
Water/Binder Ratio	0.28
Cement Content: (lb/yd³)	494
SCM #1: Fly Ash F (lb/yd³)	211
SCM #2: None (lb/yd³)	0
SCM #3: None (lb/yd³)	0
Fine Aggregates: (lb/yd³)	900
Coarse Aggregates: (lb/yd³)	2323
Water: (lb/yd³)	197
Air: [%]	2.0
Material Density: (lb/ft³)	153
Mixture Volume: (ft³)	26.819
Paste Volume: [%]	25.94

Binder Composition



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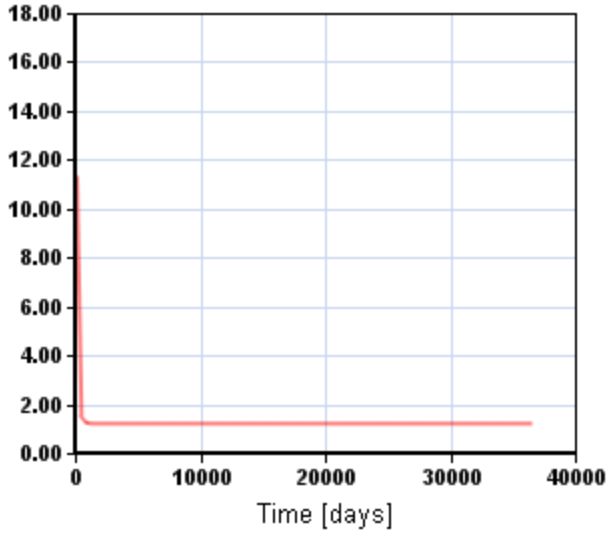
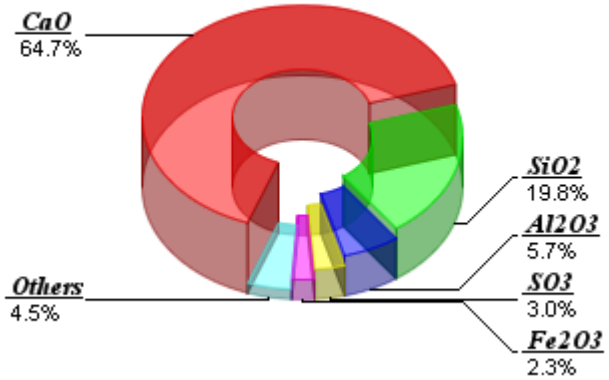
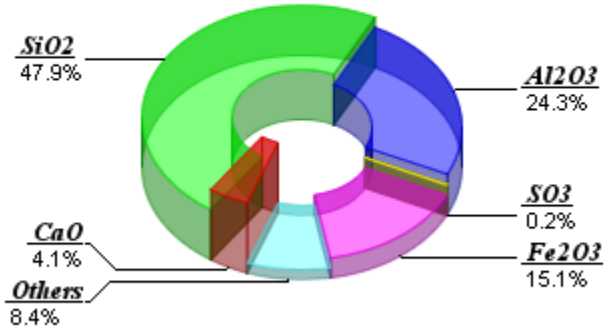


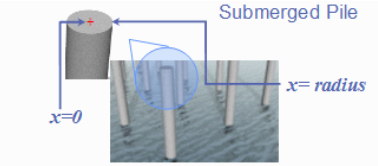
Cement Composition



Fly Ash F Composition



Data for project: Marine Pile HP - Structural element [Pile]



Dimension (in) = 8.
Scenario Duration (years) = 100
Temperature (°F) = 73.4
Water/Binder Ratio = 0.28
Binder Content (lb/yd³) = 705
Total Aggregates (lb/yd³) = 3223
Binder Density (lb/yd³) = 4956
Porosity = 0.12
Cement Type = TYPE I

OH- Diffusion Coeff. (e-11 m²/s)= 6.00
Saturation at 50% R.H.= 0.58
Age of First Exposure (days)= 28
Age at Lab Testing (days)= 28
Hydration Param. - a = 0.2
Hydration Param. - alpha (1/s) = 4.000E-03
Thermal Conductivity (W/m.K) = 2.000E+00
Specific Heat (J/kg/K) = 1.000E+03

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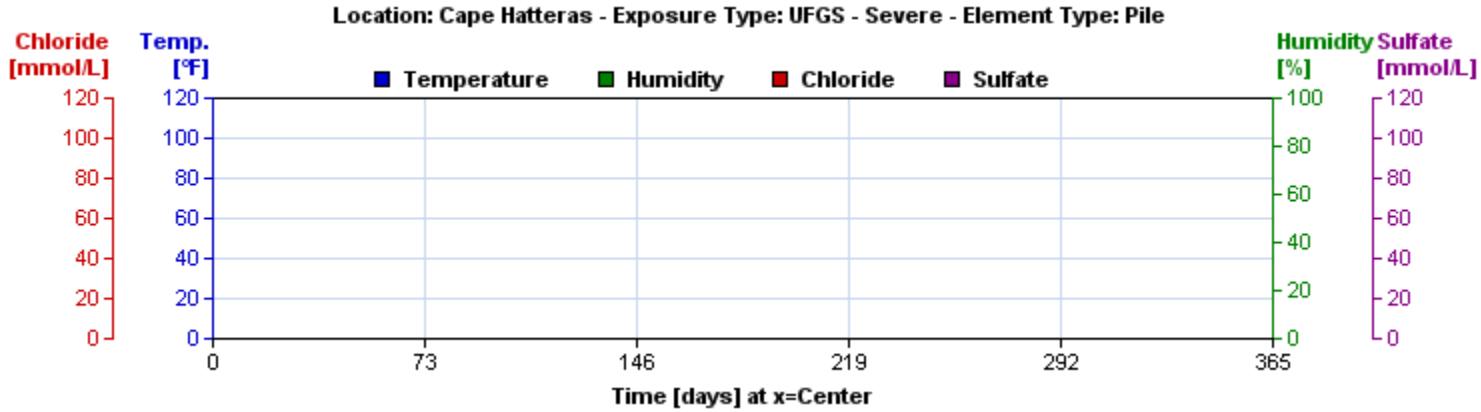
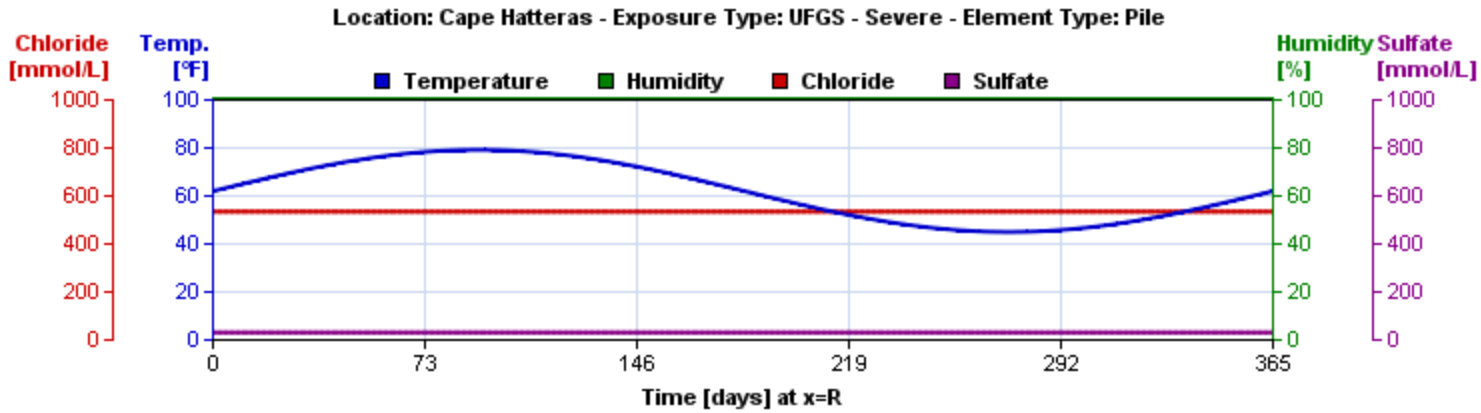
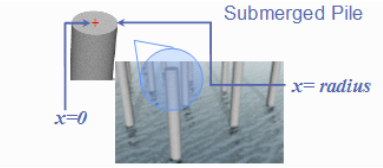
Date : 05-08-2012 / 16:08:43
Engineer : .....
Client : .....
Project : .....
Project Ref.: .....

Project Database: [Marine Pile HP.sdb]





Data for project: Marine Pile HP - Structural element [Pile] - Scenario: INITIAL



Dimension (in) = 8.
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Hydration Param. - a = 0.2
Hydration Param. - alpha (1/s) = 4.000E-03
Thermal Conductivity (W/m.K) = 2.000E+00
Specific Heat (J/kg/K) = 1.000E+03

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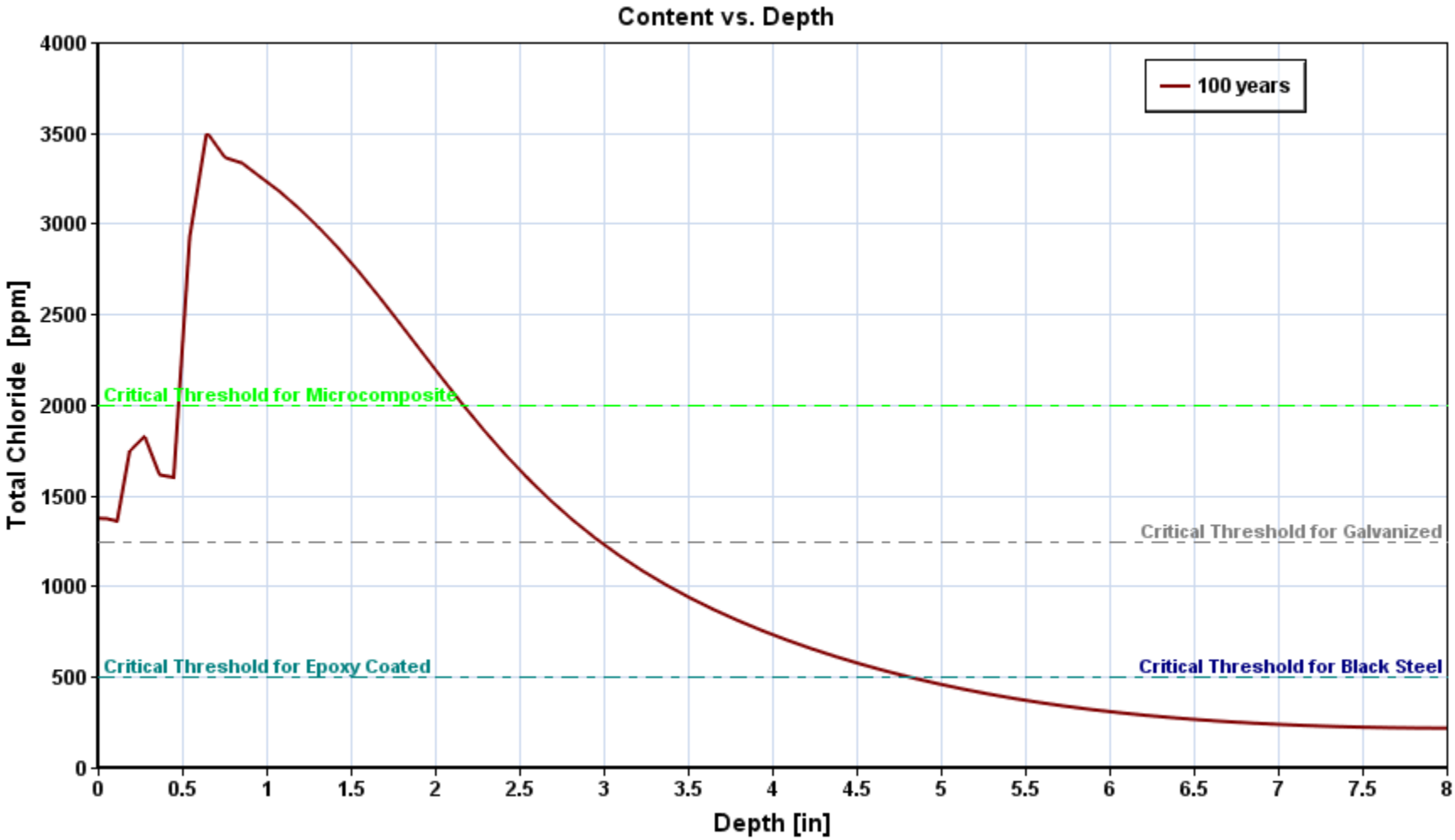
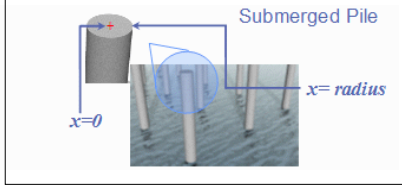
Project Database: [Marine Pile HP.sdb]



Data for project: Marine Pile HP - Structural element [Pile]



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Scenario Duration (years) = 100
Temperature (°F) = 73.4
Water/Binder Ratio = 0.28
Binder Content (lb/yd³) = 705
Total Aggregates (lb/yd³) = 3223
Binder Density (lb/yd³) = 4956
Porosity = 0.12
Cement Type = TYPE I

OH- Diffusion Coeff. (e-11 m²/s)= 6.00
Saturation at 50% R.H.= 0.58
Age of First Exposure (days)= 28
Age at Lab Testing (days)= 28
Hydration Param. - a = 0.2
Hydration Param. - alpha (1/s) = 4.000E-03
Thermal Conductivity (W/m.K) = 2.000E+00
Specific Heat (J/kg/K) = 1.000E+03

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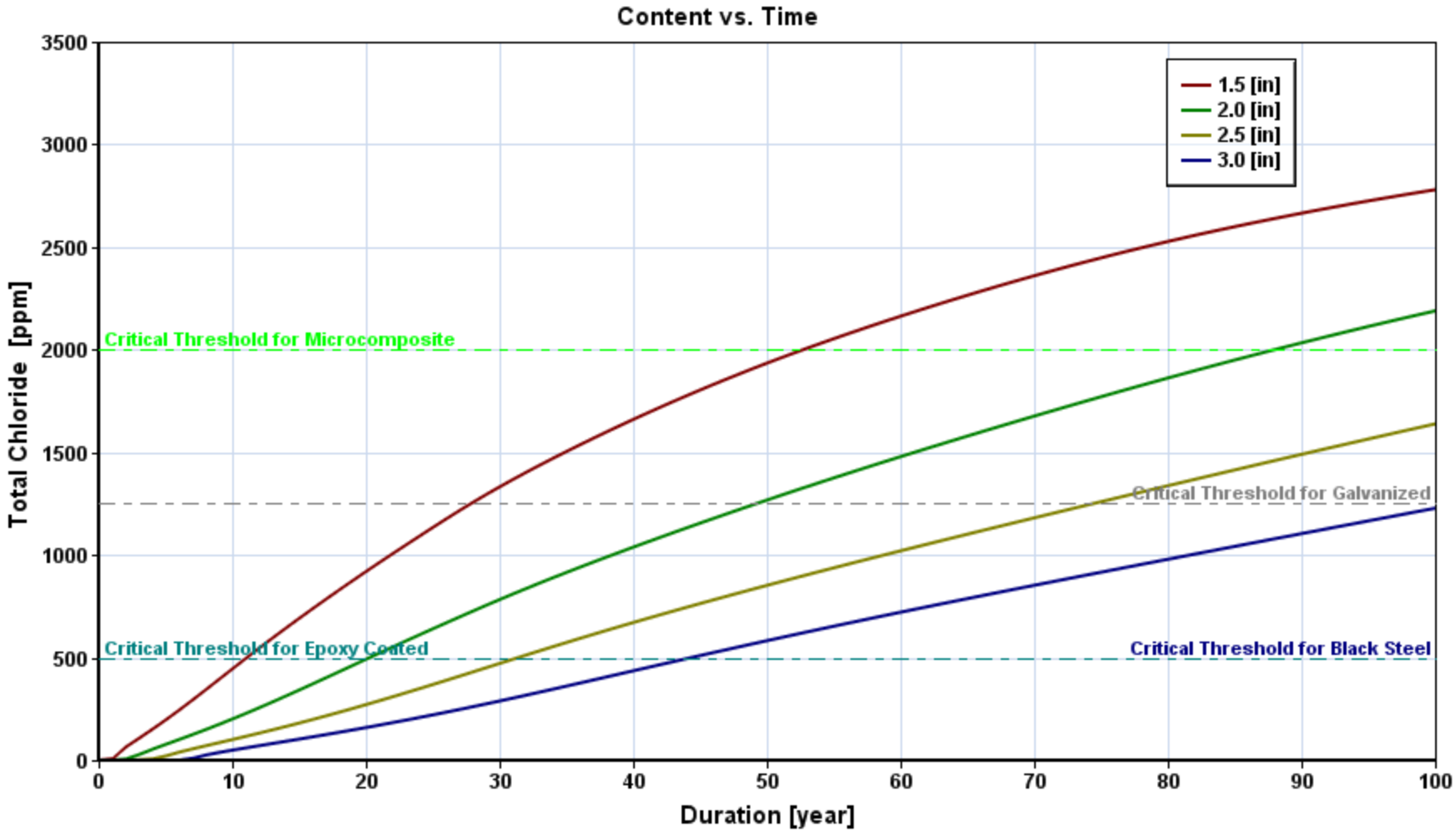
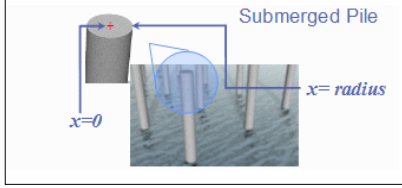


Data for project: Marine Pile HP - Structural element [Pile]



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Binder Density (lb/yd³) = 4956
Porosity = 0.12
Cement Type = TYPE I

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Saturation at 50% R.H.= 0.58
Age of First Exposure (days)= 28
Age at Lab Testing (days)= 28
Hydration Param. - a = 0.2
Hydration Param. - alpha (1/s) = 4.000E-03
Thermal Conductivity (W/m.K) = 2.000E+00
Specific Heat (J/kg/K) = 1.000E+03

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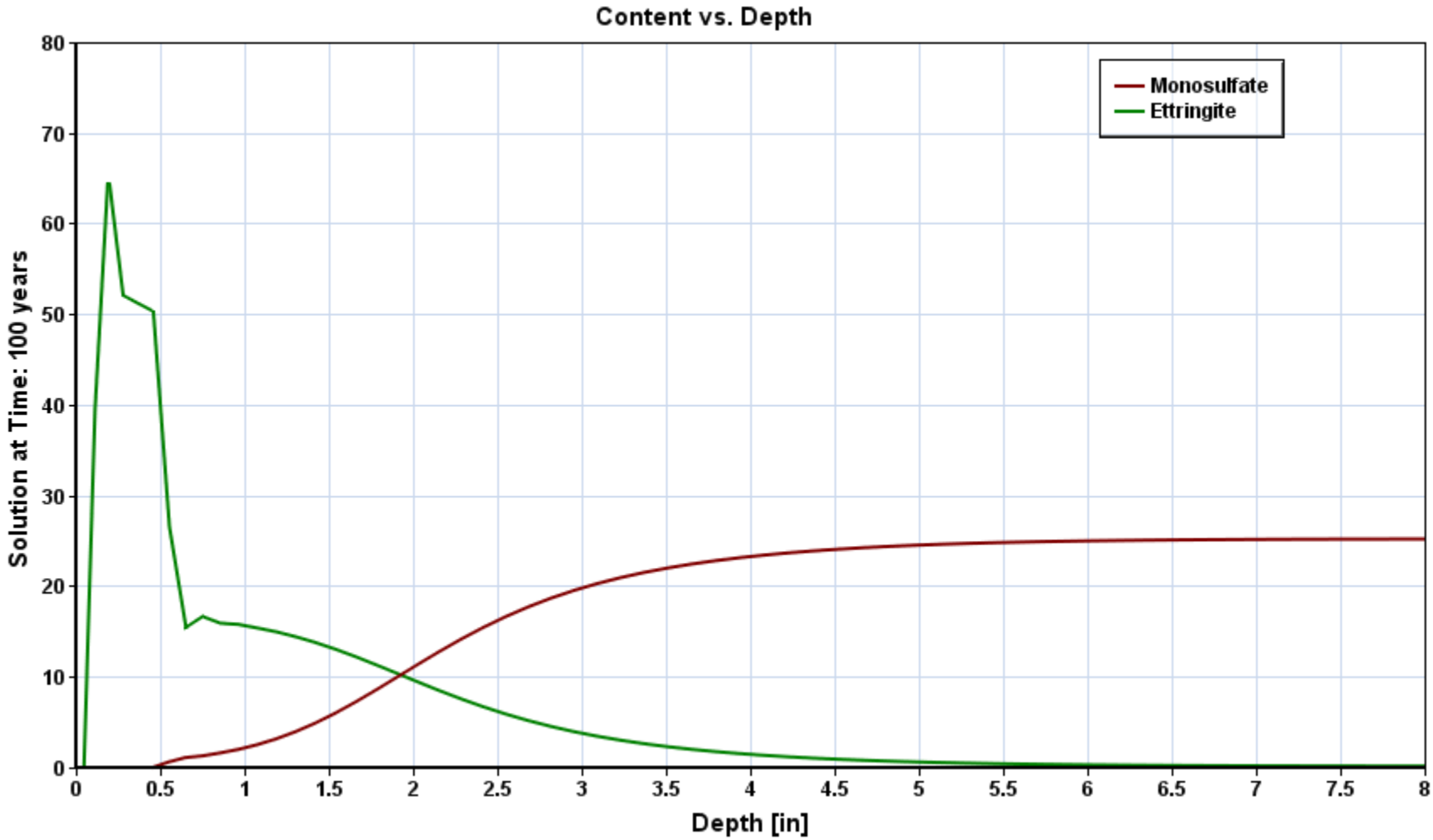

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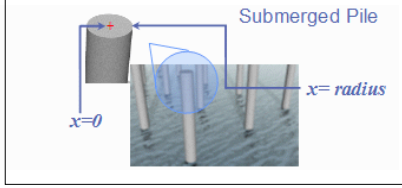

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Thermal Conductivity (W/m.K) = 2.000E+00
Specific Heat (J/kg/K) = 1.000E+03

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APPENDIX C

STADIUM® Soil Pile Results

Severe Soil Plle

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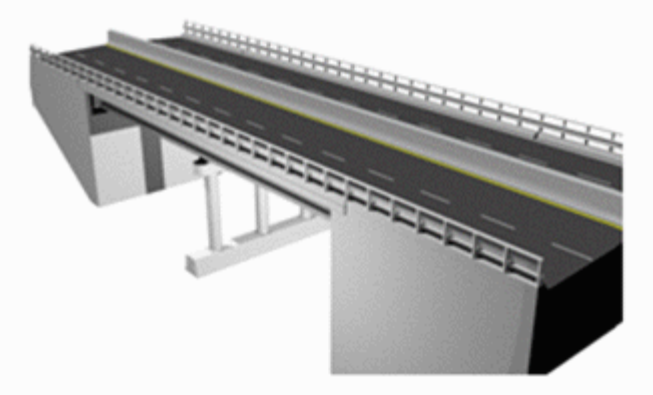
STADIUM® SIMULATION REPORT

Location: Saudii Arabia

Structure Type: Bridge

Project Ref.:.....



May. 08, 2012

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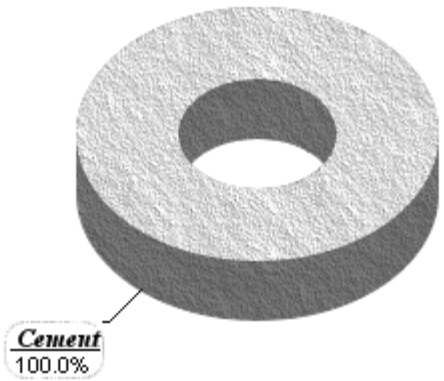
Pile - Column

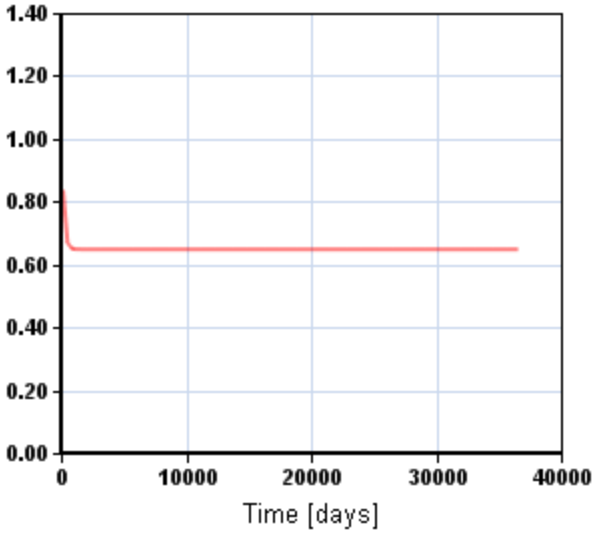
Structure Type: Bridge
Structural Element Type: [Pile - Column]
Material Name:
[Modified Material - for Pile - Column]

Cement Type	Pre-Blended Ternary
Water/Binder Ratio	0.35
Cement Content: (kg/m³)	425
SCM #1: None (kg/m³)	0
SCM #2: None (kg/m³)	0
SCM #3: None (kg/m³)	0
Fine Aggregates: (kg/m³)	810
Coarse Aggregates: (kg/m³)	920
Water: (kg/m³)	149
Air: [%]	6.9
Material Density: (kg/m³)	2304
Mixture Volume: (m³)	1.016
Paste Volume: [%]	30.05

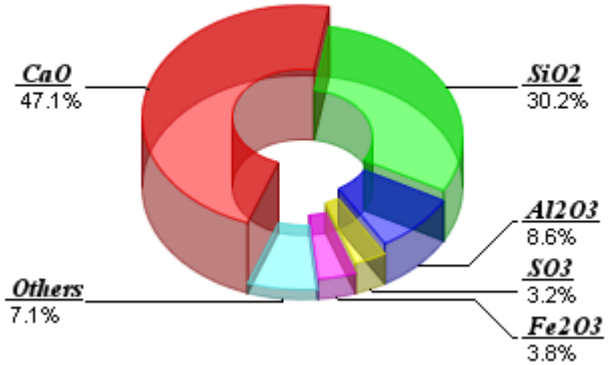
Binder Composition



Diffusion Coefficient (e-11 m²/s)- a=.8 - alpha=5.00E-3



Cement Composition



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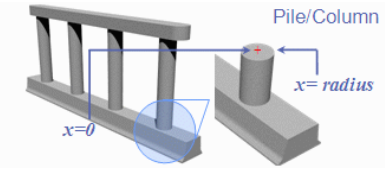

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Scenario Duration (years) = 100
Temperature (°C) = 23.0
Water/Binder Ratio = 0.35
Binder Content (kg/m³) = 425
Total Aggregates (kg/m³) = 1730
Binder Density (kg/m³) = 2800
Porosity = 0.109
Cement Type = Pre-Blended Ternary

OH- Diffusion Coeff. (e-11 m²/s)= 0.81
Saturation at 50% R.H.= 0.66
Age of First Exposure (days)= 28
Age at Lab Testing (days)= 28
Hydration Param. - a = 0.8
Hydration Param. - alpha (1/s) = 5.000E-03
Thermal Conductivity (W/m.K) = 2.000E+00
Specific Heat (J/kg/K) = 1.000E+03

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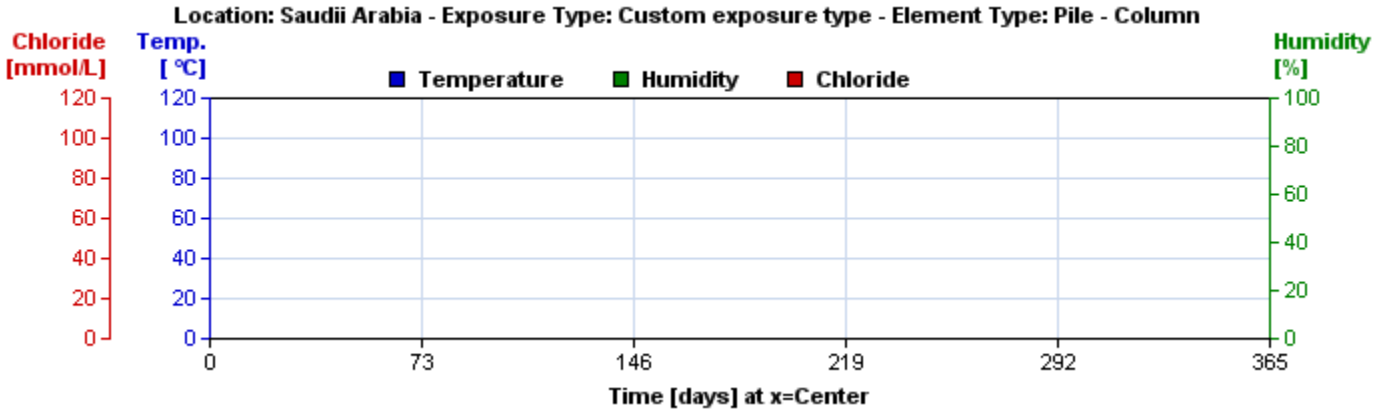
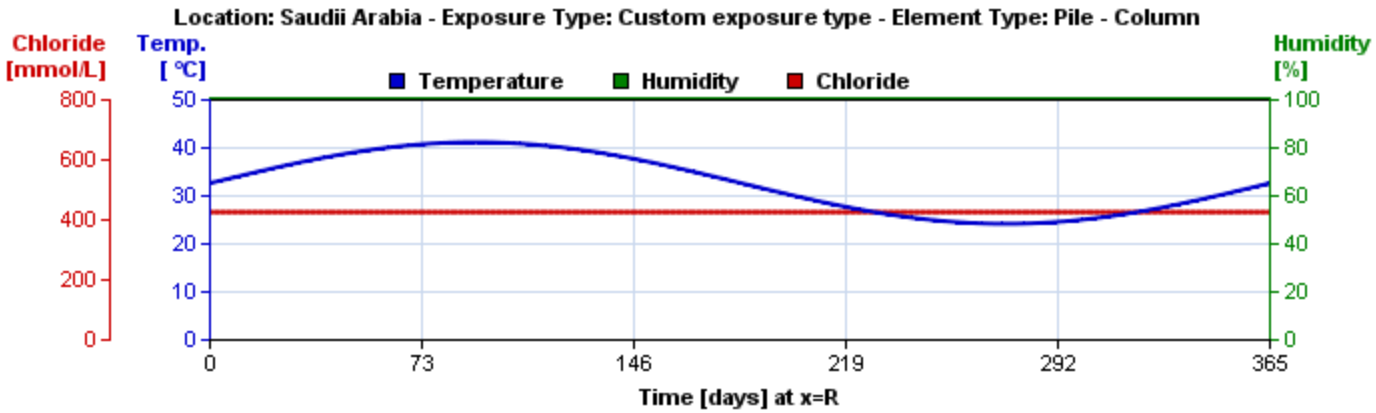
This Product is licensed to: NBerke2
Date : 05-08-2012 / 16:15:11
Engineer : .....
Client : .....
Project : .....
Project Ref.: .....

Project Database: [Severe Soil PIle.sdb]





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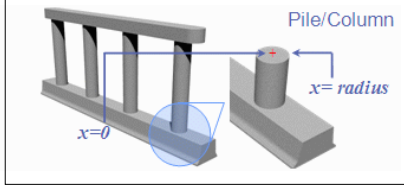

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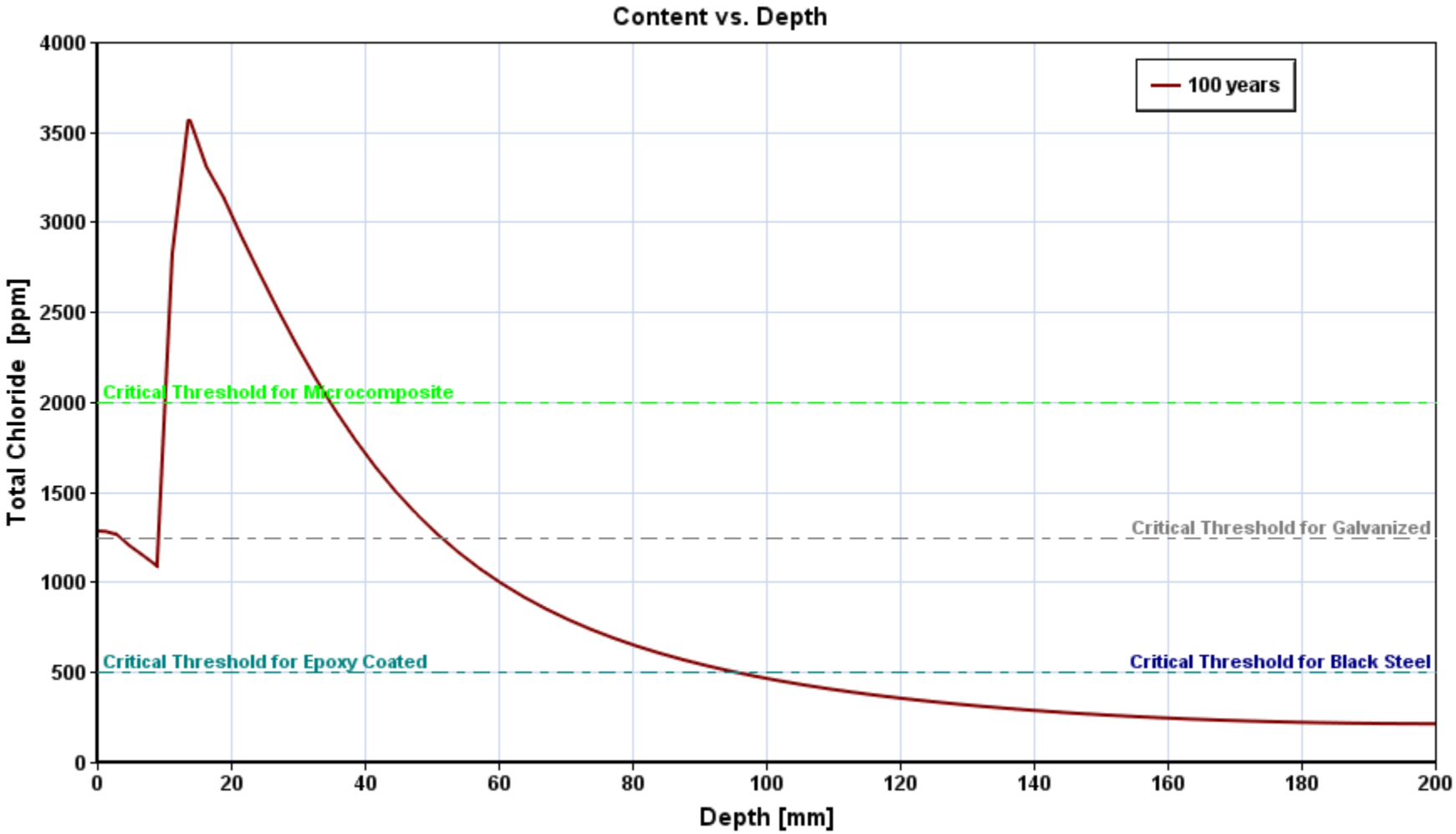

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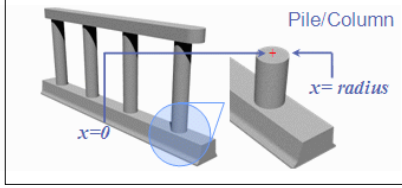

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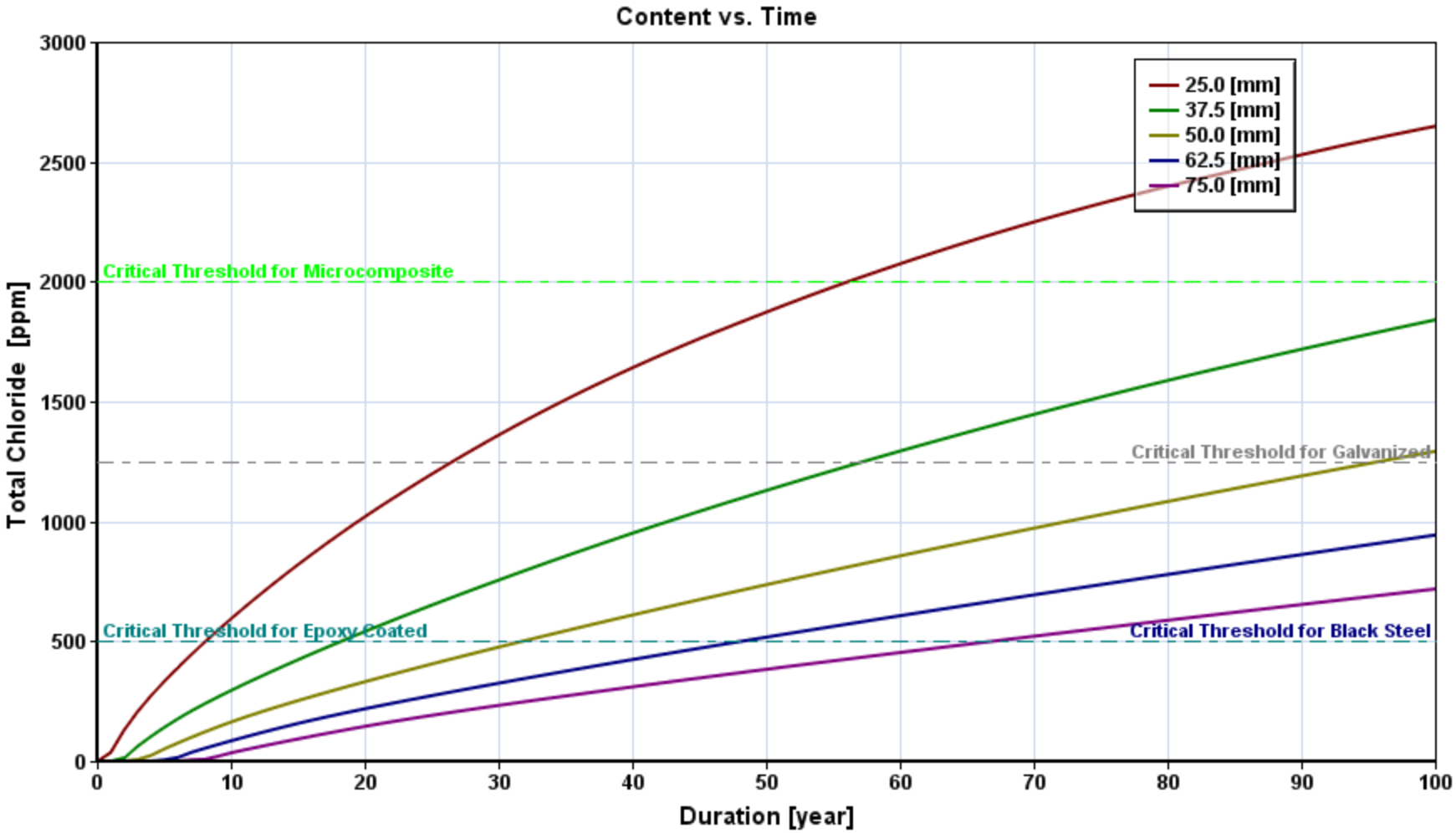

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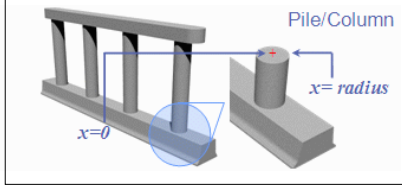

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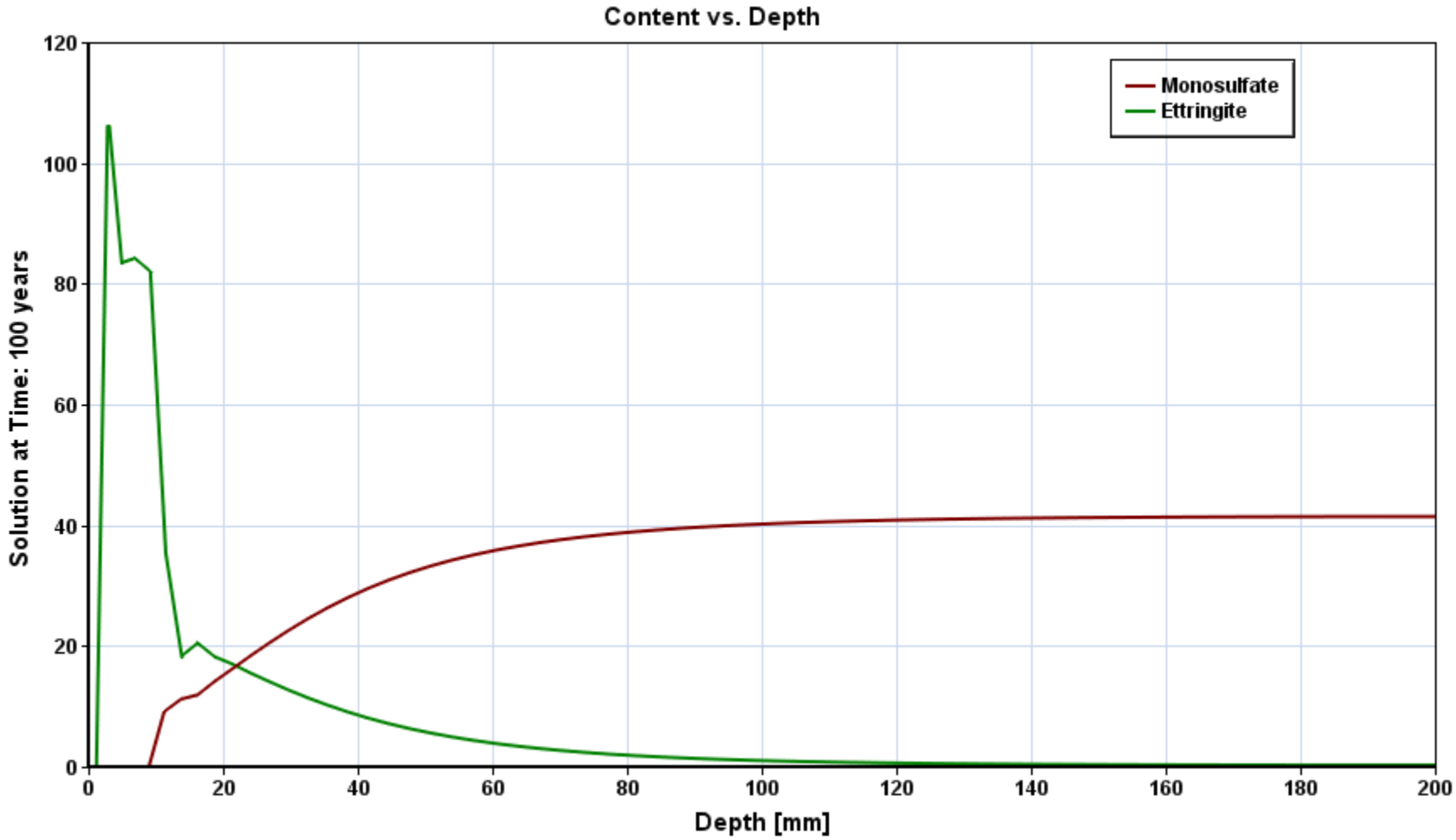

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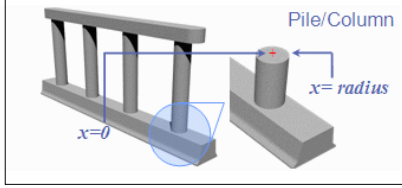

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APPENDIX D

Key Degradation Mechanisms

Durability Challenge – Numerous concrete distress mechanisms must be addressed in order to obtain the 100-year service life defined above. Almost universally, concrete distress mechanisms are related to the ingress of moisture. All the distress mechanisms common in the warm, humid, river regions produce cracks in the concrete which then accelerates moisture and chemical ingress and further distress. The durability challenge is to mitigate the multiple distress mechanisms described below while optimizing cost and performance.
The following list of degradation mechanisms are common and were addressed within the TCG durability analysis.

Reinforcement Corrosion – Reinforcement corrosion is the most prevalent and costly distress mechanism for concrete structures. Normally, reinforcing steel is protected by a passive iron hydroxide surface film that forms in the alkaline environment inside Portland cement concrete. However, this protection can be broken when aggressive contaminates such as chloride ion penetrate into the concrete, or the pH inside the concrete drops due to ingress of carbon dioxide in the air, or from localized leaching of the alkali hydroxides at cracks.

Once this passive film is broken, the reinforcing steel begins to corrode and produce expansive rust products. These iron oxides occupy a volume that is between 4 to 7 times the volume of the steel consumed, so corrosion occurs for several years without any outward sign of damage to the concrete. Eventually the iron oxide expansion builds enough pressure to crack the concrete and cause spalling.

Two types of corrosion are common, general corrosion of the steel caused by carbonation (chemical reaction with carbon dioxide gas), and pitting corrosion commonly associated with localized attack by chloride ion or leaching at cracks.

General corrosion normally occurs when the concrete cover to the reinforcing steel is inadequate, or when porous concrete ages to a point where the depth of carbonation reaches the reinforcing. General corrosion is best mitigated by using low permeability concrete and enforcing concrete cover requirements during construction. If a structure suffers from carbonation, the concrete alkalinity can be restored through chemical treatments.

Pitting corrosion is the most common distress mechanism effecting reinforced concrete with chloride ion contamination. There are numerous techniques to mitigate pitting corrosion, and each has an associated cost and performance limitations.

The most common corrosion mitigation techniques include:

- Increase concrete cover depth,
- reduce concrete permeability,
- corrosion-inhibiting admixtures,
- corrosion-resistant reinforcing steel / alloys, galvanized reinforcing,
- Crack and shrinkage control,

- Flexural cracking control in design and structural system selection,
- Curing extended 3 or 7 days,
- Barrier coatings or sealers on the concrete,
- Cathodic protection.

Fresh Water and Seawater Attack – Freshwater attack is not relevant in these analyses. Freshwater exposure distress is characterized by increased porosity and flaking of the surface in and below the zone from low to high water. This distress is a complex process involving calcium leaching and carbonation.

Seawater attack is the phenomena associated with the gradual deterioration of the surface in seawater. This distress is characterized by increased porosity and flaking of the surface in and below the tidal zone. This distress is a complex process involving a combination of calcium leaching, sulfate attack, salt crystallization distress, and microbial attack. Sulfate attack mitigation techniques are effective against seawater attack.

Delayed Ettringite Formation (DEF) – Delayed ettringite formation is a phenomenon that occurs when concrete overheats. If the internal concrete temperature exceeds 72 degrees C, the ettringite crystals that form in the early stages of cement hydration begin to dissolve or melt. These dissolved crystals then disperse within the cement paste and reform in voids after the concrete cools. Unfortunately, ettringite crystal formation is a very expansive reaction. Normally this expansion has little impact when the concrete is in the plastic state, but it is extremely disruptive once the concrete has hardened.

DEF is not common, because it is easily mitigated through temperature controls. Ettringite crystal expansion is often associated with sulfate attack.

Volume Change / Cracking – Concrete undergoes chemical and thermal volume change during the exothermic chemical reactions known as cement hydration; elastic volume change in response to changes in temperature; and drying shrinkage once hardened. If this volume change is restrained, either externally or internally by temperature or moisture gradients tensile stress is developed within the concrete, which can cause cracking.

During the first few days after casting concrete undergoes radical changes in temperature at a time when it has very little strength. As the cementitious materials hydrate, heat is liberated and strength increases.

The temperature rise in the concrete is directly related to the volume to surface area ratio and the quantity of cementitious materials and their chemical heat of hydration. If the concrete element is thin and has a large surface area, such as a slab, the temperature rise is small. However, if the concrete elements are massive, very little heat is lost from the core of the placement so the temperature rise can reach 70 degrees F or more. Since heat is dissipated from the surface through evaporation, a temperature differential develops between the surface and the core.

Elastic volume changes directly related to the temperature differential can cause both small and large cracks to occur at the surface. These cracks can occur any time in the first month after casting, but are more frequent in the first week or so when construction operations, such as form removal increase the temperature differential.

The most common techniques to mitigate thermal cracking are related to mixture proportioning, temperature monitoring and timing of construction practices. Reducing the core temperature rise through cement reduction and replacement with supplementary cementitious materials is the most common mixture proportioning practice.

Timing construction operations to avoid thermal shock is essential to producing macro-defect free mass concrete. One key principal is to slowly cool the concrete, which may require covering or insulating the surface. Maintaining the heat from cement hydration also allows more rapid strength gain, and permeability reduction.

Drying shrinkage is primarily related to the evaporation of water from the concrete after hardening. The magnitude of this volume change is a function of the cement paste volume the water-to-cement ratio, and the aggregate quality. If drying shrinkage volume change is restrained, cracks develop.

Methods to mitigate the influence of drying shrinkage cracks include: reducing sources of restraint, providing control joints, reducing the total cementitious materials content, keeping the water to cement ratio between 0.35 and 0.43, and / or use of shrinkage reducing admixtures. Drying shrinkage cracks often negate the low permeability of high strength concrete that is proportioned with high cementitious content and a low water to cement ratio. Minimizing the cement paste volume, using good aggregate, and providing sufficient water for hydration are the keys to minimizing drying shrinkage cracking.

<u>Sulfate attack</u> – Sulfate contamination from ground water, gypsum-contaminated soils, brackish water, and chemical process industries causes expansion to occur. Sulfate attack occurs when external sulfate ion combines with aluminate phases of the cement to form ettringite in the presence of moisture. Ettringite crystal expansion produces progressive failure, commonly from the exposed surface inward. This distress relates to a loss of protective concrete cover over the reinforcing system.

Techniques used to mitigate sulfate attack are reducing permeability, concrete strength greater than 4500 psi (31 MPa), limiting water ingress, ensuring proper consolidation, extended moist curing, and using sulfate resistant cements.

The soils in Louisville Kentucky and Utica Indiana can be tested for sulfates in the groundwater and soil.

<u>Alkali-aggregate reaction</u> – Certain minerals commonly found in aggregates chemically react with the alkali hydroxides in cement. There are two primary classifications alkali-silica reaction (ASR), and alkali-carbonate reaction (ACR). Alkali-silica reaction is by far the most prevalent form of distress, as most aggregate minerals contain silica.

The alkali hydroxides in cement dissolve the silica and form a gel that expands when it comes in contact with water. This gel expansion first fills cracks and voids in the aggregate and cement paste until there is no further room to expand. Further gel expansion develops internal stress in the concrete and causes cracking in both the paste and aggregate. AS such, ASR distress is characterized by an induction period with little outward sign of distress, followed by progressive cracking with gel exudation, followed by progressive spalling and generally slow deterioration of the concrete. Typical service lives of structures effected by ASR range from 15 to 50 years.

The ASR chemical reaction occurs at various rates depending on the combination of cementitious materials, aggregate minerals, temperature, and exposure to water. Because of the almost infinite possible combinations of materials, there is no recognized procedure for predicting the life expectancy for structures suffering from ASR. The best predictor for ASR service life is service history of the aggregate placed in similar concrete mixtures and environment.

Alkali-aggregate reaction is best mitigated by identifying reactive aggregates prior to mixture proportioning. If an aggregate is found to be reactive, the concrete mixture can be modified by replacing a portion of cement with supplementary cementitious materials, and/or admixing lithium nitrate solution. Once a structure is built and is found to be suffering from ASR, there is not much that can be done other than topical treatment or injection with lithium nitrate, which only hinders the expansive reaction in the treated area at the surface.

For massive structural elements in a wet environment, ASR must be mitigated prior to placement if a 100-year service life is to be expected. The aggregates proposed for concrete should also be tested before including in concrete mixtures. Project specifications should include these minimum requirements for ASR testing.

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