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THE UNIVERSITY OF TEXAS AT AUSTIN

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ConcreteWorks Implementation: Final Report

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16. Abstract
Under TxDOT Project 0-4563, researchers at The University of Texas at Austin developed an innovative software package known as ConcreteWorks, which gives laboratory technicians, engineers, inspectors, and contractors a tool that combines concrete design, analysis, and performance prediction to improve and guide TxDOT to better designs. Although ConcreteWorks has been very well received at the national and international levels, it has not yet been implemented into standard TxDOT practice. Through a combination of training and implementation support, the goal of this project will be to spur the implementation of ConcreteWorks within TxDOT.

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Chapter 1. Introduction

1.1 Background

The hydration of cement and water is an exothermic reaction capable of generating significant amounts heat. During curing, excessive temperatures can prevent the normal formation of a hydration product known as ettringite, only to allow its formation once the concrete has already hardened. While somewhat rare in the field, this condition is known as Delayed Ettringite Formation (DEF). Concrete expansion caused by DEF is substantially greater than any other concrete durability-related issue. A more common problem during curing is the development of large thermal gradients capable of cracking the concrete. Thermal gradients can arise out of rapidly increasing internal temperatures or even by stripping forms in cold weather. While thermal cracks aren't nearly as large as those caused by DEF, they allow chlorides to quickly and easily penetrate deep into the concrete to the rebar. For these reasons, controlling early-age temperatures is a critical part of ensuring long term durability. The current TxDOT mass concrete temperature specification is TxDOT Item 420.4.G14:

> *Mass placements are defined as placements with a least dimension greater than or equal to 5 ft., or designated on the plans. For monolithic mass placements, develop and obtain approval for a plan to ensure the following during the heat dissipation period:*
>
> - *The temperature differential between the central core of the placement and the exposed concrete surface does not exceed 35°F and the temperature at the central core of the placement does not exceed 160°F.*
> - *Base this plan on the equations given in the Portland Cement Association's Design and Control of Concrete Mixtures. Cease all mass placement operations and revise the plan as necessary if either of the above limitations is exceeded. Include a combination of the following elements in this plan:*
> - *Selection of concrete ingredients including aggregates, gradation, and cement types, to minimize heat of hydration;*
> - *Use of ice or other concrete cooling ingredients;*
> - *Use of liquid nitrogen dosing systems;*
> - *Controlling rate or time of concrete placement;*
> - *Use of insulation or supplemental external heat to control heat loss;*
> - *Use of supplementary cementing materials; or*
> - *Use of a cooling system to control the core temperature.*
>
> *Furnish and install 2 sets of temperature recording devices, maturity meters, or other approved equivalent devices at designated locations. Use these devices to simultaneously measure the temperature of the concrete at the core and the surface. Maintain temperature control methods for 4 days unless otherwise approved. Maturity meters may not be used to predict strength of mass concrete.*

While the specification recognizes that concrete temperature and durability are related, it does very little to help prevent excessive temperatures. The calculations found in the Portland Cement Association's *Design and Control of Concrete Mixtures* are difficult, guidance is vague, and the result is inaccurate. Information in literature regarding temperature rise of materials is dispersed and irrelevant to local materials. The problem becomes even more difficult when cracking tendency is considered, which the specification does not even address.

In light of the deficiencies of the TxDOT mass concrete temperature specification, researchers at The University of Texas at Austin developed an innovative software package under TxDOT Project 0-4563. Known as ConcreteWorks, the software gives laboratory technicians, engineers, inspectors, and contractors a tool to improve and guide TxDOT to better designs. ConcreteWorks is a free stand-alone Microsoft Windows based software suite capable of assisting with ACI211 mix design, temperature prediction, cracking probability classification, and chloride-diffusion service-life analysis.

1.2 Research Objective

Although ConcreteWorks has been very well received at the national and international levels, it has yet to be integrated into standard TxDOT practices. The goal of this research is to spur the implementation of ConcreteWorks within TxDOT by accomplishing four objectives: (1) develop training materials for ConcreteWorks, (2) deliver training courses to selected TxDOT districts, (3) implement ConcreteWorks on TxDOT projects, and (4) make minor modifications to ConcreteWorks.

1.3 Scope of Report

Following this introductory chapter, Chapter 2 briefly covers the development of a curriculum and training materials to teach TxDOT engineers, inspectors, and contractors how to incorporate ConcreteWorks into their standard design and construction practices.

Chapter 3 provides an explanation of the laboratory and field testing that was performed to characterize each of the case studies in ConcreteWorks.

Chapter 4 presents two unique case studies in precast concrete temperature prediction. Instrumentation and laboratory testing results for each case study are explained and used to compare observed temperatures with ConcreteWorks analyses. Observations made while in the field are also discussed.

Chapter 5 presents two case studies in mass concrete temperature prediction. Instrumentation and laboratory testing results for each case study are explained and used to compare observed temperatures with ConcreteWorks analyses.

Chapter 6 discusses work performed in anticipation of a future case study in chloride diffusion service-life prediction.

Chapter 7 presents conclusions regarding the results of this research and provides recommendations for future research related to early-age temperature prediction.

Chapter 2. ConcreteWorks Training

The first task of this research was to develop a curriculum and training course that would train TxDOT employees how to use the ConcreteWorks software program. The course was designed to teach the basic principles of ACI 211 mix design, temperature prediction, cracking probability classification, and chloride-diffusion service-life analysis. While the goal was to keep ConcreteWorks from being a black box, trainees needed to be able to leave the classroom feeling comfortable with understanding the inputs and using the program.

2.1 Austin Pilot Course

The ConcreteWorks curriculum originated as an 8-hour course consisting of seven modules. The typical format of the modules was approximately 45 minutes of presentation-based instruction followed by a 15-minute demonstration of the actual program relating to the material taught in the module. One module consisted of a 1-hour hands-on case study in which trainees were to design a concrete element to meet several performance specifications outlined in the assignment. Overall, the Austin pilot course was determined to be too long, too hands-off, and too difficult to follow due to its emphasis on teaching the theory behind ConcreteWorks. What was needed was an interactive course that would engage trainees and get them comfortable with using the program. The Austin Pilot Course slides can be found in Appendix A.1.

2.2 Standard Training Course

Several drastic changes were made to the ConcreteWorks curriculum based on the outcome of the Austin Pilot course. Two modules were removed from the course and the remaining modules were redesigned to emphasize hands-on use of the program. The general format of each module was 10 minutes of instruction-based presentation followed by 25 minutes of instructor-led demonstration and hands-on exercise. In total, the course consisted of approximately 1 hour of lecture-style training and 3 hours of hands-on use of the program. This new format kept trainees fully engaged and enabled them to ask questions rather than be buried in complex theory.

In total, the course was delivered to six districts including Austin, Corpus Christi, Dallas, El Paso, Fort Worth, Houston, and Lubbock. Although the course was custom tailored to meet the needs of each individual district, a standard course guide with the presentation slides and hands-on assignments can be found in Appendix A.2.

Chapter 3. Laboratory Testing Results

Temperature prediction of a concrete member involves several interrelated mechanisms, none of which have a closed-form solution. Each mechanism must be modeled, and a solution determined iteratively. As seen in Figure 3.1, the analysis may be divided into three main components: heat generation from the hydration process, heat transfer through the concrete, and heat exchange between the element and the outside environment (Riding, 2007). Characterizing each process and comparing the results with field observations requires a complex laboratory and field testing program.

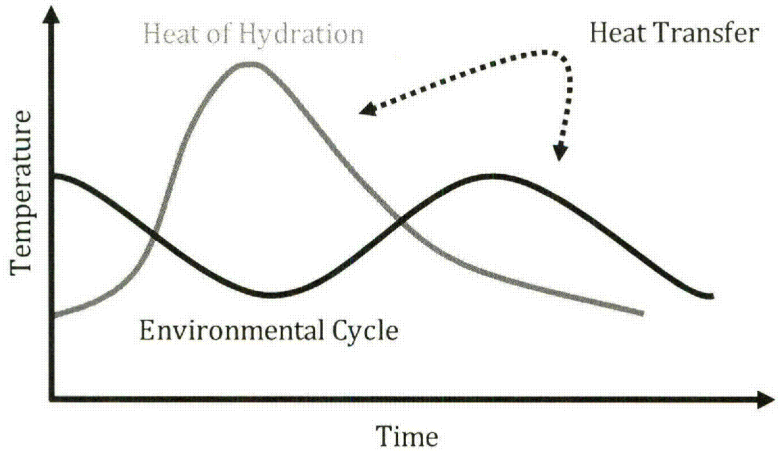


Figure 3.1: Temperature Prediction Processes

3.1 Field Testing Program

One of the concerns that arose early in the project was that of a sensitivity analysis. After all, ConcreteWorks allows each process to be described to varying degrees of accuracy. If very little is known about a certain process, ConcreteWorks has a built-in predictive or statistical model to calculate the variables it needs to perform the calculations. Some examples include the built-in 30-year historical weather model, the use of cement chemistry typical of the cement type, the ability to calculate hydration parameters from the cement chemistry, and finally the model for calculating heat transfer constants based on aggregate classification. In all cases, the program allows for overwriting programmatically determined values with results attained from laboratory testing. Doing so should theoretically improve the overall accuracy of the resulting temperature prediction. One of the objectives of field implementation was to determine how much accuracy could be gained by putting in the effort to determine these inputs.

A systematic method for gauging ConcreteWorks' response to various inputs was created with the development of four levels of detail as outlined in Figure 3.2. Each level of detail (LOD) represents an increase in effort to characterize the case studies. What follows is an explanation of the laboratory testing performed for each LOD.

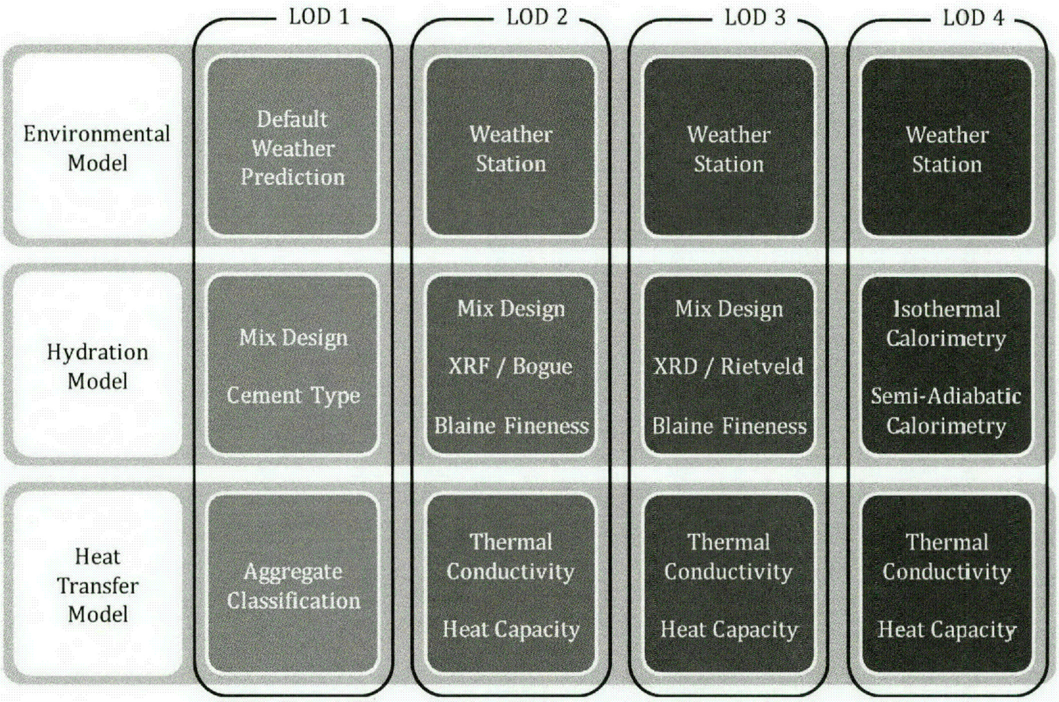


Figure 3.2: Levels of Detail (LOD) in Process Characterization

3.2 Environmental Cycle

The default ConcreteWorks weather prediction is based on hourly 30-year average weather data calculated from the National Climatic Data Center (NCDC) Solar and Meteorological Surface Observational Network (SAMSON) CDs (Riding, 2007). With weather data for almost every major city in all 50 states, selecting the closest city to the project site is usually sufficient to get an accurate prediction of the weather. At LOD 1, the time, date, and location of each case study were specified, allowing ConcreteWorks to refer to its built-in 30-year historic weather data to determine the environmental cycle.

3.2.1 Weather Station

For the purposes of this research, a commercial weather station was installed at the site of each case study to generate the same environmental cycle in ConcreteWorks as observed in the field. The weather station was programmed to record temperature, relative humidity, solar radiation, and wind speed on 15-minute intervals for the duration of each case study. By removing the environmental cycle as a variable, a fair comparison could be made between LOD 2, 3, and 4.

Analyzing the results of the weather station to produce a table of inputs was fairly straightforward aside from one small caveat. The weather station measures solar radiation, whereas ConcreteWorks uses percent cloud cover as an input to calculate solar radiation. A conversion to back-calculate percent cloud cover was necessary and so was a deeper understanding of how ConcreteWorks determines solar radiation.

ConcreteWorks assumes a linear relationship between solar radiation and cloud cover according to Equation 3.1 (Riding 2007):

$$E_H = \left(0.91 - (0.7 \cdot C)\right) \cdot E_{TOA} \tag{3.1}$$

where E_{TOA} is the horizontal solar radiation at the top of earth's atmosphere (W/m^2) and E_H is the surface horizontal solar radiation (W/m^2). Radiation is defined as "energy emitted by matter that is at a finite temperature" (Riding, 2007); thus the total daily solar radiation would appear to capture the total energy emitted by mechanisms of solar radiation. Percent cloud cover was calculated on the basis that the total daily solar radiation ($W/m^2/day$) predicted by ConcreteWorks should equal that measured by the weather station. As the relationship in Equation 3.1 is linear, ConcreteWorks was used to predict solar radiation based on zero percent cloud cover. Assuming zero percent cloud cover, Equation 3.1 becomes:

$$E_{TOA} = \sum \frac{E_{H_{0\%\,CC}}}{0.91} \tag{3.2}$$

where $E_{H,0\%CC}$ is ConcreteWorks' predicted daily total surface horizontal solar radiation ($W/m^2/day$) with zero percent cloud cover and E_{TOA} is now the total daily horizontal solar radiation at the top of the earth's atmosphere ($W/m^2/day$). Substituting Equation 3.2 back into Equation 3.1 and solving for percent cloud cover, C, yields:

$$C = 1.3 \cdot \left(1 - \frac{\sum E_{OBS}}{\sum E_{H_{0\%\,CC}}}\right) \tag{3.3}$$

where E_{OBS} is the total daily surface horizontal solar radiation ($W/m^2/day$) observed by the weather station. Equation 3.3 was used to directly calculate the daily cloud cover based on the total daily solar radiation predicted by Concrete Works at zero percent cloud cover and that observed in the field.

3.3 Hydration Model

The heat evolution of a particular concrete mixture can be modeled by an S-shaped curve requiring only three parameters to describe. It is important to realize that heat produced by any given concrete mixture is mix specific, so any changes to the mix proportions, cement, or other materials will alter the shape of the heat signature curve, seen in Figure 3.3.

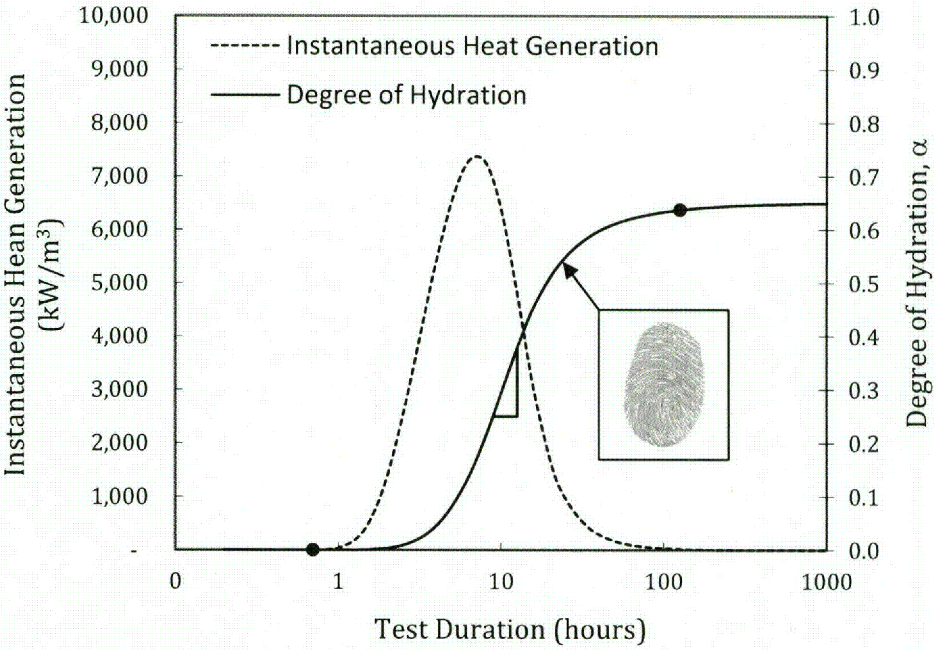


Figure 3.3: Mix-specific Heat Signature

The parameters describing the shape of the heat signature curve are α, β, and τ. In the order they are shown in Figure 3.4, these parameters describe the ultimate degree of hydration, the reaction rate, and the timing of the reaction.

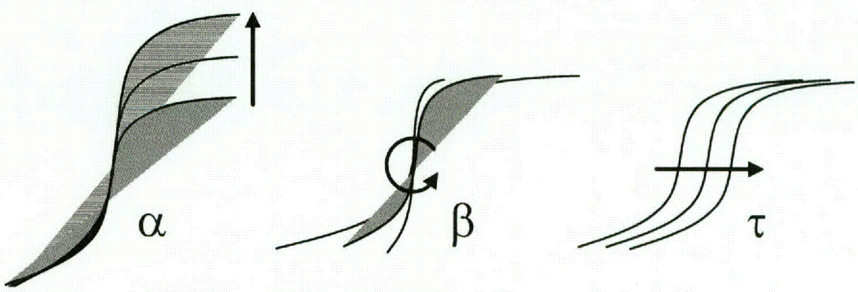


Figure 3.4: Hydration Parameters

As α, β, and τ are merely shape factors, a few additional variables are necessary to define the actual heat output of the concrete mixture. Hu, with units of J/gram of cementitious materials, defines total heat available in a concrete mixture based on the cement chemical composition as well as the addition of any supplementary cementitious materials (SCMs). Activation Energy, E_a, defines the temperature dependency of the hydration reaction. Essentially, Activation Energy is used to scale the hydration reaction based on the concrete temperature.

What follows is an explanation of the laboratory testing performed to characterize the heat generation properties for each case study as well as the empirical formulas used by ConcreteWorks to determine E_a, α, β, τ, and Hu.

3.3.1 Blaine Fineness

Blaine fineness was performed on each of the cements sampled from case studies using ASTM C204 (2007). Table 3.1 summarizes the results.

Table 3.1: Blaine Fineness for Case Study Cements

Blaine Fineness, m^2/kg		
Bexar (Alamo)	Type III	486.3
Bexar (Capitol)	Type III	519.8
Eagle Lake	Type III	517.5
WBSB 8	Type I/II	385.2
WBSB 9	Type I/II	389.3

3.3.2 Bogue Composition

Cement crystalline phases were determined using Bogue calculations according to ASTM C150 (2011). While Bogue isn't the most reliable method of determining the cement phases, it is readily available on cement mill certificates. Mill certificates, however, are usually only a monthly estimation of the cement properties. To improve the relevance of the ConcreteWorks simulations, X-Ray Fluorescene (XRF) was performed to more accurately determine the chemical composition of the cements. The Alamo cement used at Bexar ConcreteWorks in San Antonio as well as Eagle Lake contained limestone additions, necessitating a Thermal Gravimetric Analysis (TGA) to determine the amount of free lime. The product of these results is shown in Table 3.2.

Table 3.2: Cement Bogue Composition by Case Study

	Alamo	Capitol	Eagle Lake	WBSB 8	WBSB 9
C_3S	46.39%	61.47%	60.33%	32.56%	48.77%
C_2S	24.64%	10.82%	14.31%	38.60%	23.36%
C_3A	6.39%	10.76%	6.20%	12.16%	11.42%
C_4AF	11.28%	4.63%	10.64%	5.81%	5.20%
Free Lime	0.90%	0.00%	1.47%	0.00%	0.00%
SO_3	3.56%	4.37%	0.66%	3.72%	3.80%
MgO	0.66%	1.30%	3.57%	1.33%	1.27%
Na_2O	0.06%	0.11%	0.03%	0.14%	0.13%
K_2O	0.66%	0.48%	0.68%	0.53%	0.54%

With the mix design, Blaine fineness, and Bogue composition available, ConcreteWorks derives E_a, τ, β, α, and Hu using the following empirical formulas developed from previous research (Poole, 2007):

$$E_a = \begin{array}{c} 41{,}230 + 8{,}330 \cdot \left[\left(p_{C_3A} + p_{C_4AF} \right) \cdot p_{cement} \cdot p_{gypsum} \right] \\ -3{,}470 \cdot Na_2O_{eq} - 19.8 \cdot Blaine + 2.96 \cdot p_{FlyAsh} \cdot p_{FlyAsh-CaO} \\ +162 \cdot p_{GGBFS} - 516 \cdot p_{SF} - 30{,}900 \cdot WRRET - 1{,}450 \cdot ACCL \end{array} \quad (3.4)$$

$$\tau = exp\begin{pmatrix}2.68 - 0.386 \cdot p_{C_3S} \cdot p_{cem} + 105 \cdot p_{Na_2O} \cdot p_{cem} + 1.75 \cdot p_{GGBFS} \\ -5.33 \cdot p_{FA} \cdot p_{FA-CaO} - 12.6 \cdot ACCL + 97.3 \cdot WRRET\end{pmatrix} \quad (3.5)$$

$$\beta = exp\begin{pmatrix}-0.494 - 3.80 \cdot p_{C_3A} \cdot p_{cem} - 0.594 \cdot p_{GGBFS} \\ +96.8 \cdot WRRET + 39.4 \cdot LRWR + 23.2 \cdot MRWR \\ +38.3 \cdot PCHRWR + 9.07 \cdot NHRWR\end{pmatrix} \quad (3.6)$$

$$\alpha_u = \frac{1.031 \cdot w/cm}{0.194 + w/cm} + exp\begin{pmatrix}-0.885 - 13.7 \cdot p_{C_4AF} \cdot p_{cem} \\ -283 \cdot p_{Na_2O_{eq}} \cdot p_{cem} \\ -9.90 \cdot p_{FA} \cdot p_{FA-CaO} \\ -339 \cdot WRRET - 95.4 \cdot PCHRWR\end{pmatrix} \quad (3.7)$$

$$H_u = H_{cem} \cdot p_{cem} + 550 \cdot p_{GGBFS-120} + 1800 \cdot p_{FA-CaO} \cdot p_{FA} \quad (3.8)$$

$$H_{cem} = \begin{matrix}500 \cdot P_{C_3S} + 260 \cdot p_{C_2S} + 866 \cdot p_{C_3A} + 420 \cdot p_{C_4AF} \\ +624 \cdot p_{SO_3} + 1186 \cdot p_{FreeCa} + 850 \cdot p_{MgO}\end{matrix} \quad (3.9)$$

where p_{C3S}, p_{C2S}, p_{C3A}, p_{C4AF}, p_{FreeCa}, p_{SO3}, p_{MgO}, p_{Na2O}, p_{gypsum} are the respective percent C_3S, C_2S, C_3A, C_4AF, Free Lime, SO_3, MgO, Na_2O, and gypsum in the Portland cement; p_{Na2Oeq} is the percent Na_2O_{eq} ($Na_2O + 0.658 \cdot K_2O$) in the Portland cement; p_{cem}, p_{FlyAsh}, $p_{GGBFS-120}$, and p_{SF} are the respective percent Portland cement, fly ash, slag, and silica fume of the total cementitious materials content; $p_{CaO-FlyAsh}$ is the percent CaO in the fly ash; *Blaine* is the Blaine fineness of the Portland cement [m^2/kg]; LRWR is an ASTM Type A water reducer, MRWR is a mid-range water reducer, NHRWR is a Type F naphthalene high range water reducer, PCHRWR is an ASTM Type F polycarboxylate based high range water reducer, *WRRET* is an ASTM Type A&D water reducer/retarder, and *ACCL* is an ASTM Type C calcium-nitrate based accelerator (Riding, 2007). The chemical admixture dosages are in percent solids by weight of cementitious materials; however, they aren't specified in the mixture proportions. Instead, ConcreteWorks assumes typical dosages for each type of admixture indicated in the mixture proportions.

3.3.3 X-Ray Diffraction

Quantitative X-Ray Diffraction (XRD) was performed on each cement sample in order to fulfill the needs of the LOD 3 ConcreteWorks simulation. Rietveld analysis was then used to define the cement chemical composition, as summarized in Table 3.3

Table 3.3: Cement Rietveld Analysis by Case Study

	Alamo	Capitol	Eagle Lake	WBSB 8	WBSB 9
Alite	55.0%	70.0%	65.0%	64.4%	59.0%
Belite	8.6%	5.7%	11.0%	5.3%	6.1%
Aluminate	5.2%	9.9%	4.2%	10.4%	10.3%
Ferrite	8.0%	2.3%	8.8%	2.0%	2.5%
Gypsum	6.9%	9.4%	10.7%	17.3%	14.5%

Using the results of the Rietveld analysis, ConcreteWorks determines the hydration parameters according to Equations 3.10 through 3.15:

$$E_a = \begin{matrix} 39{,}200 + 107 \cdot [(P_{Aluminate}) \cdot p_{cem} \cdot (p_{CaSO_4xH20} + p_{Arcanite}) \cdot p_{cem}] \\ -12.2 \cdot Blaine + 1.24 \cdot p_{FlyAsh} \cdot p_{FlyAsh-CaO} + 120 \cdot p_{GGBFS} \\ -533 \cdot p_{SF} - 30{,}100 \cdot WRRET - 1{,}440 \cdot ACCL \end{matrix} \quad (3.10)$$

$$\tau = exp\begin{pmatrix} 2.95 - 0.972 \cdot p_{Alite} \cdot p_{cem} + 152 \cdot p_{Na_2O} \cdot p_{cem} + 1.75 \cdot p_{GGBFS} \\ -4.00 \cdot p_{FA} \cdot p_{FA-CaO} - 11.8 \cdot ACCL + 95.1 \cdot WRRET \end{pmatrix} \quad (3.11)$$

$$\beta = exp\begin{pmatrix} -0.418 - 2.66 \cdot p_{Aluminate} \cdot p_{cem} - 0.864 \cdot p_{GGBFS} \\ +108 \cdot WRRET + 32.0 \cdot LRWR + 13.3 \cdot MRWR \\ +42.5 \cdot PCHRWR + 11.0 \cdot NHRWR \end{pmatrix} \quad (3.12)$$

$$\alpha_u = \frac{1.031 \cdot w/cm}{0.194 + w/cm} + exp\begin{pmatrix} -0.297 - 9.73 \cdot p_{Ferrite} \cdot p_{cem} \\ -325 \cdot p_{Na_2O_{eq}} \cdot p_{cem} \\ -8.90 \cdot p_{FA} \cdot p_{FA-CaO} \\ -331 \cdot WRRET - 93.8 \cdot PCHRWR \end{pmatrix} \quad (3.13)$$

$$H_u = H_{cem} \cdot p_{cem} + 550 \cdot p_{slag} + 1800 \cdot p_{FA-CaO} \cdot p_{FA} + 330 \cdot p_{SF} \quad (3.14)$$

$$H_{cem} = \begin{matrix} 500 \cdot p_{Alite} + 260 \cdot p_{Belite} + 866 \cdot p_{Aluminate} + 420 \cdot p_{Ferrite} \\ +624 \cdot p_{Sulfate} + 1186 \cdot p_{Lime} + 850 \cdot p_{Periclase} \end{matrix} \quad (3.15)$$

where p_{Alite}, p_{Belite}, $p_{Aluminate}$, $p_{Ferrite}$, $p_{Periclase}$, p_{Lime}, and $p_{Sulfate}$ are the respective percent alite, belite, aluminate, ferrite, periclase, and sulfate in the Portland cement; p_{Na2Oeq} is the percent Na_2O_{eq} (Na_2O + 0.658 · K_2O) in the Portland cement; $CaSO_4{\cdot}xH_2O$ is the total percent by mass of gypsum, hemihydrates, and anhydrite; p_{cem}, p_{FlyAsh}, $p_{GGBFS-120}$, and p_{SF} are the respective percent Portland cement, fly ash, slag, and silica fume of the total cementitious materials content; $p_{CaO-FlyAsh}$ is the percent CaO in the fly ash; *Blaine* is the Blaine fineness of the Portland cement [m^2/kg]; LRWR is an ASTM Type A water reducer, MRWR is a mid-range water reducer, NHRWR is a Type F naphthalene high range water reducer, PCHRWR is an ASTM Type F polycarboxylate based high range water reducer, *WRRET* is an ASTM Type A&D water reducer/retarder, and *ACCL* is an ASTM Type C calcium-nitrate based accelerator (Poole, 2007).

3.3.4 Calorimetry

Rather than rely on a derivation of the hydration parameters for LOD 4, E_a, α, β, and τ were directly obtained using isothermal and semi-adiabatic calorimetry. As with the previous simulations, Hu was still calculated using Equation 3.8.

Activation energy (E_a) was calculated based on a modified ASTM 1074 approach using isothermal calorimetry. Isothermal calorimetry was performed on paste samples at 15, 38, and 60 °C (59, 100, and 140 °F) over 72 hours using an eight-channel isothermal calorimeter.

Semi-adiabatic calorimetry was performed on a sample of the concrete from each case study to determine α, β, and τ. Semi-adiabatic calorimetry is a very simple test in which a 6 inch x 12 inch cylinder of fresh concrete is placed in an insulated drum that measures the temperature of the concrete as well as the outside environment. Because the calorimeter is not completely adiabatic, some heat is lost to the outside environment. This is accounted for by using a calibrated correction factor to determine the actual heat generated by the concrete. The calorimeter was place in an air-conditioned space shortly after sampling and samples were run for approximately 120 hours.

3.3.5 Hydration Property Results

A summary of the hydration parameters produced at each LOD for each case study is presented in Table 3.4 through Table 3.8.

Table 3.4: Alamo Hydration Model by LOD

		LOD 1	LOD 2	LOD 3	LOD 4
E_a	J/mol	33636	34240	37236	26335
τ	hours	18.568	18.032	15.463	
β	-	1.026	0.962	0.975	
α_u	-	0.665	0.667	0.674	
H_u	J/kg	456649	413390	392056	392056

Table 3.5: Capitol Hydration Model by LOD

		LOD 1	LOD 2	LOD 3	LOD 4
E_a	J/mol	33636	34018	41343	27416
τ	hours	18.568	17.177	13.862	
β	-	1.026	1.076	1.071	
α_u	-	0.665	0.709	0.694	
H_u	J/kg	456649	450276	460635	460635

Table 3.6: Eagle Lake Hydration Model by LOD

		LOD 1	LOD 2	LOD 3	LOD 4
E_a	J/mol	29157	26774	32719	29573
τ	hours	16.013	14.050	12.321	23.669
β	-	1.026	0.958	0.956	0.940
α_u	-	0.649	0.654	0.656	0.687
H_u	J/kg	456736	452389	438586	438586

Table 3.7: WBSB 8 Hydration Model by LOD

		LOD 1	LOD 2	LOD 3	LOD 4
E_a	J/mol	35958	36594	48838	27122
τ	hours	16.231	19.801	13.481	18.480
β	-	0.965	1.138	1.097	1.032
α_u	-	0.748	0.768	0.782	0.806
H_u	J/kg	448602	410244	469159	469159

Table 3.8: WBSB 9 Hydration Model by LOD

		LOD 1	LOD 2	LOD 3	LOD 4
E_a	J/mol	35959	36332	46722	26914
τ	hours	16.207	17.786	14.034	18.494
β	-	0.965	1.116	1.095	0.812
α_u	-	0.748	0.772	0.780	0.932
H_u	J/kg	448776	436329	443901	443901

3.4 Heat Transfer Model

The transfer of heat through a concrete element is defined by two properties: thermal conductivity and heat capacity. Thermal conductivity, k [W/m/°C], is the ability of a material to transfer heat. Heat capacity, Cp [J/kg/°C], dictates the energy required to raise the temperature of a material. Based on literature, ConcreteWorks automatically adjusts both values according to the mix design and the course and fine aggregate types. Like the hydration model, however, they may also be overwritten with values acquired from testing.

3.4.1 Thermal Conductivity and Heat Capacity

Heat transfer was characterized by separately measuring the thermal conductivity and effusivity of paste, coarse aggregate, and fine aggregate samples from each mix. Each component's thermal properties were then multiplied by its respective mass fraction of the total concrete mixture. Summing the results yielded the heat transfer characteristics of the concrete.

Testing was performed with a Mathis TCi Thermal Conductivity Analyzer. Samples were polished smooth and then placed on the sensor using water as a contact agent. The instrument was then set to subject the samples to a series of 3-second heating cycles followed by 57-second cooling cycles. By measuring the temperature of the sample at the end of each cycle, the instrument determines its thermal conductivity and effusivity. Figure 3.5 shows the sensor.

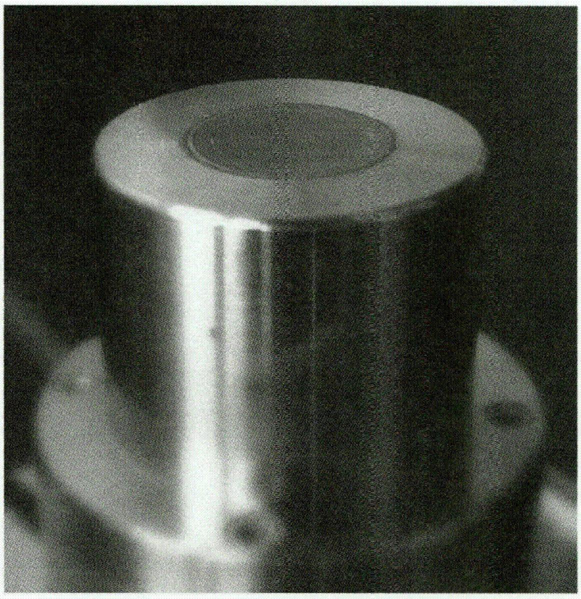


Figure 3.5: Mathis Thermal Conductivity Sensor

Heat capacity was calculated using Equation 3.16. Because the Mathis TCi requires water as a contact agent, samples were stored in water and tested in the fully saturated state. Density of the coarse and fine aggregates was determined according to ASTM C127 and C128 respectively and the saturated density was used as the basis for the calculation of Cp in equation 3.16. Density of the paste samples was determined gravimetrically.

$$C_P = \frac{e^2}{k \cdot \rho} \qquad (3.16)$$

Coarse aggregates were prepared by sampling approximately 10 stones large enough to cover the surface of the heating surface. As evidenced by the difficulty of finding suitable samples from the precast plant aggregates, 3/4-inch maximum sized aggregate is the smallest feasible sample size for normal testing. Stone selected for testing were ground flat on one side and then polished to a glassy finish.

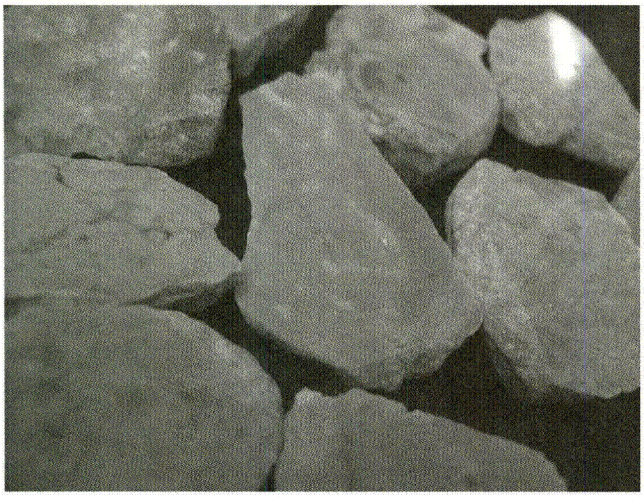


Figure 3.6: Polished Course Aggregate Samples

Paste samples were prepared by combining 30 grams (~1 oz.) of materials in a 10-oz. epoxy mixing cup. After 12 hours of curing, the paste samples were removed from the cups and polished smooth for testing. In the event that solids had settled, both the top and bottom of the samples were tested and averaged to determine the heat transfer properties.

Fine aggregates were too small to be tested individually and were prepared as mortars instead. Similar to the paste samples, mortar samples were also prepared in 10-oz. epoxy mixing cups. Once cured, they were ground and polished. Both sides were analyzed and the result was averaged to account for any settling of the fine aggregate within the paste. As the thermal properties of the paste component of the mortar mix was already known, the properties of the fine aggregate were back calculated from the mortar test result. Table 3.9 summarizes the results of the heat transfer testing.

Table 3.9: Heat Transfer Results

	k	Cp
Alamo	1.67	0.20
Capitol	1.67	0.20
Eagle Lake	1.91	0.20
WBSB 8	2.46	0.20
WBSB 9	2.45	0.20

3.5 Mechanical Testing

From each case study, 4-inch x 8-inch inch cylinders were cast for mechanical testing. The aim of the testing program was to gather compressive strength, maturity, elastic modulus, and splitting tensile strength at ½, 1, 3, 7, 14, and 28 days after concrete placement. Mechanical properties for each case study can be seen in Table 3.10 through Table 3.14.

Table 3.10: Alamo Mechanical Properties

Test	f'c	f'st	E	CTE
Time	psi	psi	ksi	$10^{-6}/°C$
12-hr	2432	-	-	3.18
1-Day	5984	-	-	
3-Day	8676	1086	4563	
7-Day	9853	1279	4796	
14-Day	10391	1043	5227	

Table 3.11: Capitol Mechanical Properties

Test	f'c	f'st	E	CTE
Time	psi	psi	ksi	$10^{-6}/°F$
12-hr	3479	-	-	3.16
1-Day	6111	-	-	
3-Day	8347	1031	4296	
7-Day	9557	1103	4819	
14-Day	10170	1079	4948	

Table 3.12: Eagle Lake Mechanical Properties

Test	f'c	f'st	E	CTE
Time	psi	psi	ksi	$10^{-6}/°C$
1-Day	7047	999	5109	6.03
3-Day	8550	1048	5336	
7-Day	9916	1191	5701	
14-Day	10904	1240	6025	
28-Day	11910	1236	6214	

Table 3.13: WBSB 8 Mechanical Properties

Test	f'c	f'st	E	CTE
Time	psi	psi	ksi	$10^{-6}/°C$
12-Hr	164	53	11	4.91
1-Day	1712	476	3485	
3-Day	4235	794	4826	
7-Day	4990	839	5116	
14-Day	5643	961	5432	
28-Day	6634	978	5739	

Table 3.14: WBSB 9 Mechanical Properties

Test	f'c	f'st	E	CTE
Time	psi	psi	ksi	$10^{-6}/°C$
12-Hr	292	90	796	5.08
1-Day	2117	463	3536	
3-Day	4039	821	4768	
7-Day	4879	899	4916	
14-Day	5748	967	5250	
28-Day	6454	1102	5641	

Chapter 4. Precast Concrete Temperature Prediction

4.1 Research Significance

Concrete mixtures in the precast industry are designed around maximizing production. The primary objective is to achieve release strength as soon as possible so that forms can be stripped and prepared for the next beam. Accomplishing this objective usually means utilizing a combination of high cement content, highly reactive Type III cement, and accelerating admixtures to ensure high early strength. However, accelerating hydration also accelerates heat generation and excessive temperatures are a common problem that can lead to delayed ettringite formation, cracking, and other durability related issues.

U-beams are particularly prone to overheating due to the solid-concrete end blocks at each end of the beam. While the end blocks are typically only 18 to 24 inches thick, they are usually lined with foam on one side which insulates the concrete and retains heat. The thickness of the foam varies depending on the length of the beam, but it is usually between 2 and 6 inches. In addition to making minor adjustments to the thickness of the end blocks possible, the foam also provides a compliant barrier for easy removal of the formwork.

ConcreteWorks predicts temperatures on a vertical plane through the center of the end block, where temperatures are the highest. Figure 4.1 shows the installation of a U54. Figure 4.2 illustrates the cross section of a typical U54 beam as well as where ConcreteWorks predicts temperatures.

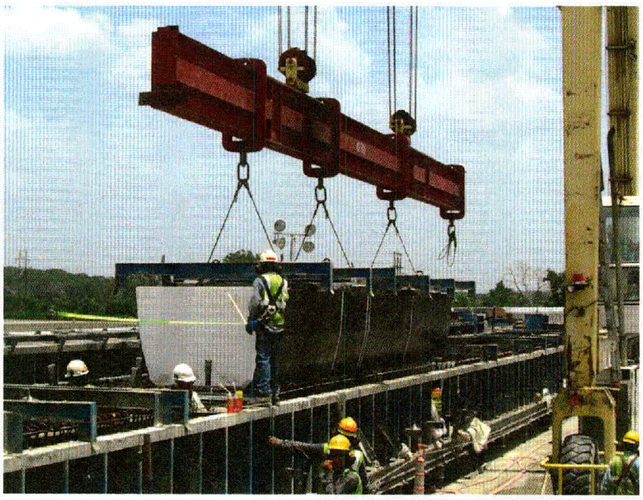


Figure 4.1: Installation of U54 Male Formwork

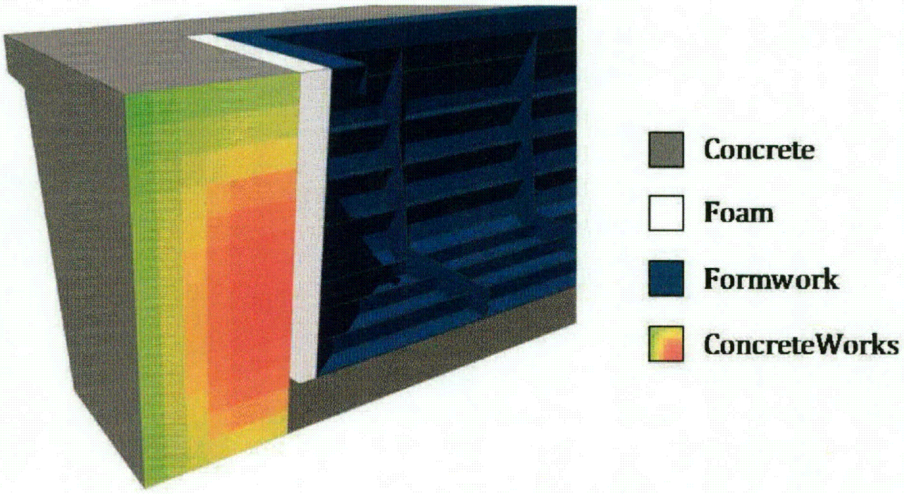


Figure 4.2: Cross Section of a Typical U Beam

4.2 Case Study: Bexar Concrete Works

Two 54-inch-tall U-beams were instrumented with temperature sensors at Bexar Concrete Works on September 27, 2010. Located on Loop 1604 north of downtown San Antonio, Bexar Concrete Works is an impressive operation. At the time of this project, the company sourced its aggregates from Vulcan Materials, located on the west side of Bexar Concrete's property. On the east side of the property is Alamo Cement, one of their primary sources of cement. Bexar Concrete was also sourcing cement from Capitol Aggregates, located just a few miles south of the precast plant.

This project presented a unique research opportunity because two identical beams with identical mixture proportions were poured within approximately 1 hour of each other on the same day. The only difference between the beams was the source of cement. One beam contained Type III cement produced by Alamo. The other beam employed Type III cement produced by Capitol Aggregates. The two cements have significantly different chemical properties. The plant had reported temperatures varying by 20 degrees simply by switching the cement. The goal of this project was to monitor the two beams and replicate the field observations using ConcreteWorks' temperature prediction software.

4.2.1 Materials and Mixture Proportions

The paste fraction entailed a reasonable cementitious content of 815 pounds, 25% of which was Class F fly ash. Both the fine and course aggregates were crushed limestone manufactured by Vulcan Materials. Sika products were used for workability and set retardation. The mix design used for the beams is presented in Table 4.1. Samples of all the raw materials used in the concrete mixtures were collected on the day following the pour and brought back to the Concrete Durability Center for laboratory testing.

Table 4.1: Bexar Precast Mix Design

Raw Materials		Amount
Cement	Type III	611.0 lb
SCM	Class F Fly Ash	204.0 lb
Water	.32 W/C	256.0 lb
Coarse Aggregate	3/4" Limestone	1817.0 lb
Fine Aggregate	Limestone	1089.0 lb
Admixtures		**Amount**
Water Reducer	Sika ViscoCrete 4100	5.50 fl oz/cwt
Retarder	Sika Plastiment	2.50 fl oz/cwt

4.2.2 Instrumentation

Thermochron iButtons made by Dallas Semiconductor were used to collect temperature data in the beams. An iButton consists of an onboard thermocouple, battery, and a memory chip capable of storing over 2,000 data points and is capable of logging temperature readings every 5 minutes for a period of 7 days. Each beam was instrumented with 12 temperature sensors, all of which were placed on one side of the end block. Six sensors were placed as close as possible to the center of the end block for comparison with ConcreteWorks. Six more sensors were placed near the sides to get a better idea of the temperature distribution throughout the end block. For the purposes of this research, discussion will focus on the six sensors placed near the center of the end block. Figure 4.3 illustrates the approximate location of the sensors within the end block as measured after installation.

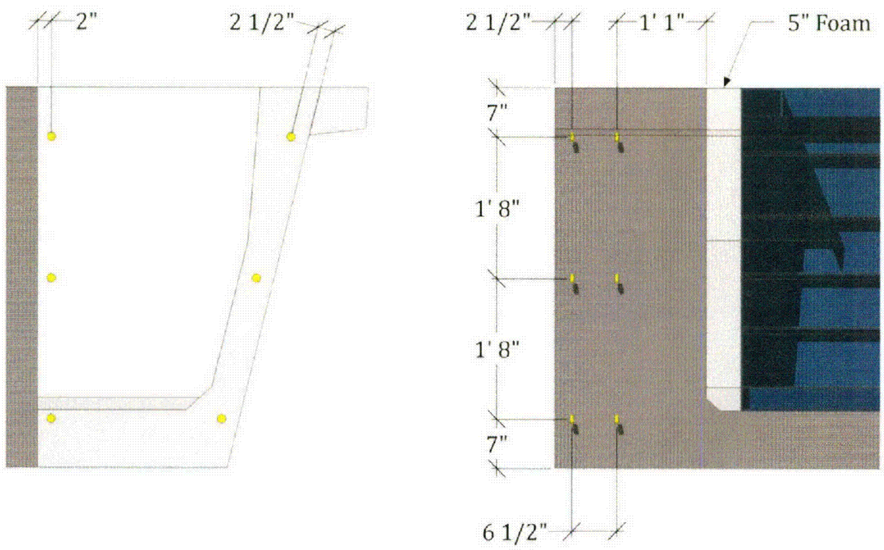


Figure 4.3: Bexar Precast—Approximate Location of Sensors

Comparing the installed location of the sensors with the output file generated by ConcreteWorks raised a few questions concerning the dimensions of the end block as modeled by the software program. Unless there is an error in the output file, it appears as if a 54-inch U beam end block is modeled as 48-inches tall. Whereas typical end blocks range between 18 and 24 inches thick, the modeled end block is 27 inches thick. The beams instrumented on site were approximately 22 inches thick. There is no option in ConcreteWorks to specify the thickness of the end block.

Despite these complications, an analysis was conducted of the temperatures observed in the field and those predicted by ConcreteWorks. The output for ConcreteWorks, illustrated by Figure 4.4, consists of a two-dimensional array of points in the end block at which temperatures are predicted on a 5-minute interval. To produce predicted temperatures at the same locations at which iButtons were installed, bilinear interpolation of predicted temperatures surrounding each iButton was performed. This was done for each time step and plots of the observed and predicted temperatures were developed. Figure 4.4 also presents a naming scheme for the sensors, with B, M, and T representing the bottom, middle, and top rows of sensors respectively.

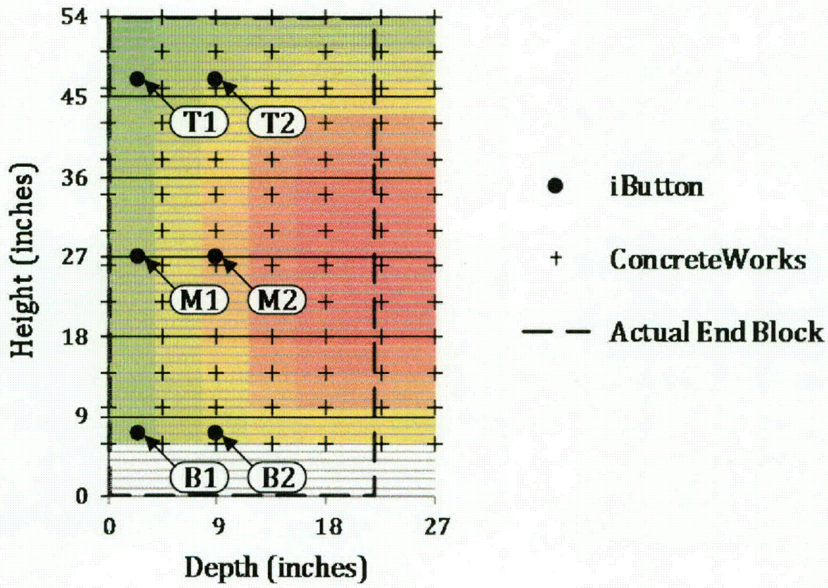


Figure 4.4: Bexar Precast—End Block Instrumentation Schematic

4.2.3 Field Observations

A commercial weather station was set up on site the morning of the pour and programmed to record temperature, relative humidity, solar radiation, and wind speed on a 15-minute interval. Table 4.2 summarizes the observed weather conditions at the site. A detailed comparison between the observed weather and ConcreteWorks predicted weather can be found in Appendix B.1.

Table 4.2: Bexar Precast Weather Station Data

Date	Temperature Max	Temperature Min	Wind Speed	Cloud Cover	Relative Humidity Max	Relative Humidity Min
-	°F	°F	m/s	%	%	%
9/27/2010	80.1	58.0	5.3	22	86.0	28.4
9/28/2010	87.3	50.3	5.3	22	91.7	24.9
9/29/2010	91.4	56.1	6.7	25	89.9	23.2
9/30/2010	88.1	55.7	6.7	25	87.3	27.0

Casting of the Alamo beam began at approximately 3:30 p.m., soon followed by the Capitol beam at 5:00 p.m. Both mixtures arrived at approximately 88 °F. The fast setting time of the concrete allowed for only 26 cylinders to be collected from each beam. Q-Drums were prepared and placed in an office on site for the next several days. Both beams were stripped of their forms at approximately 25 hours.

Data was collected from the sensors 7 days after casting. The Capitol beam reached 180.5 °F and maintained above 170 °F for approximately 12 hours. The Alamo beam reached a maximum temperature of 162.5 °F. Despite almost identical conditions for both beams, the Capitol beam reached 18 °F higher than the Alamo beam.

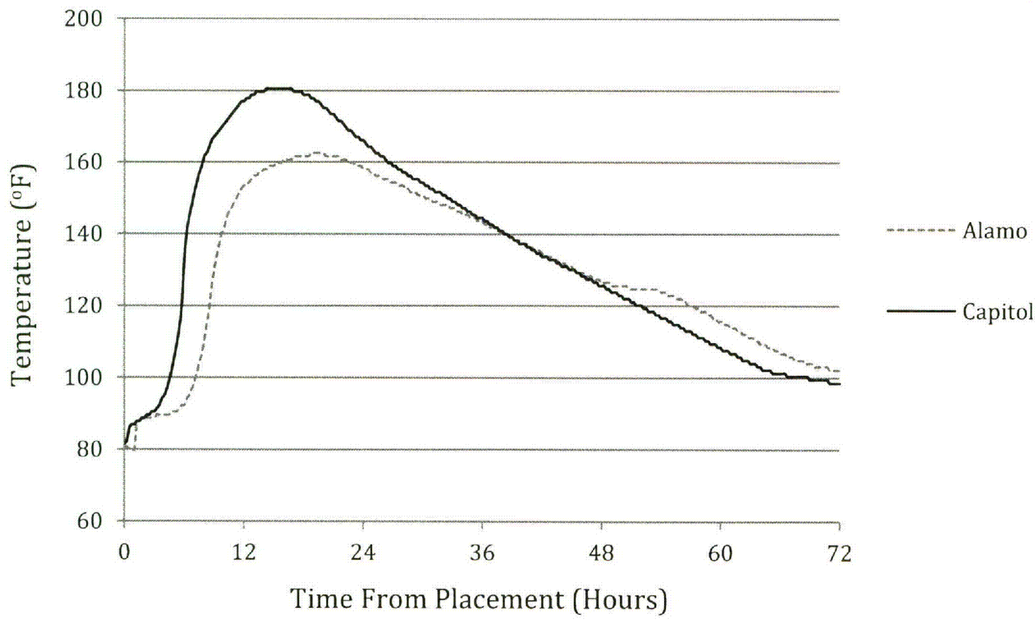


Figure 4.5: Maximum Observed Temperature (Alamo vs. Capitol)

4.2.4 Observed and Predicted Temperatures

ConcreteWorks was used to simulate the beams for each of the levels of detail outlined in Chapter 3. What follows is a plot of each of the six central iButtons compared with ConcreteWorks' predicted temperatures (Figures 4.6–4.17). The figures begin with the bottom temperature sensors and progressing, with the Capitol beam being presented first.

Capitol

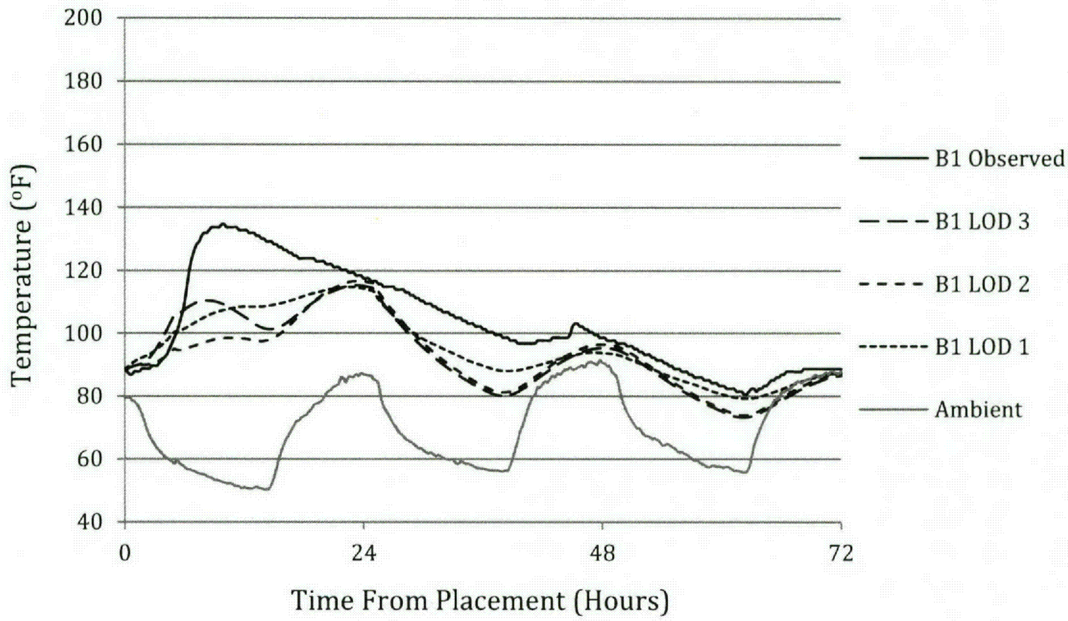


Figure 4.6: Capitol ConcreteWorks Analysis (Sensor B1)

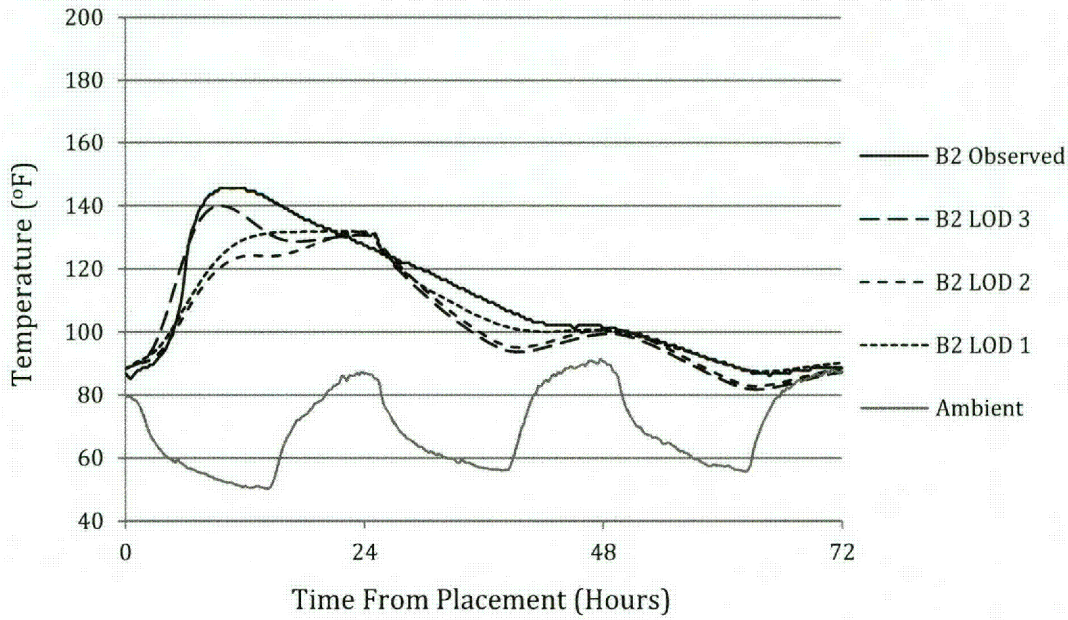


Figure 4.7: Capitol ConcreteWorks Analysis (Sensor B2)

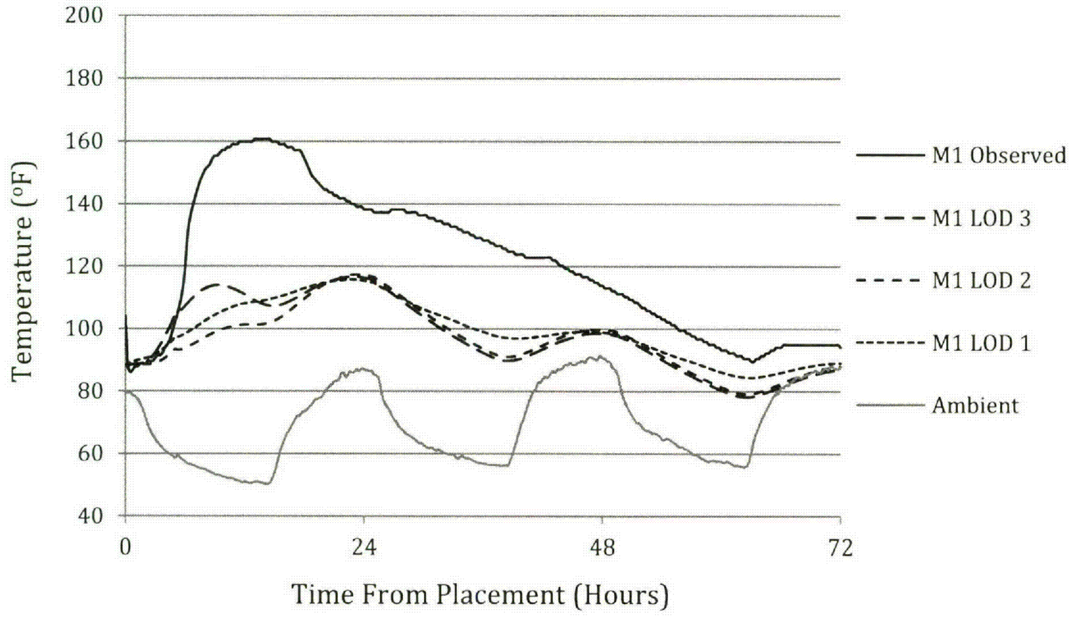


Figure 4.8: Capitol ConcreteWorks Analysis (Sensor M1)

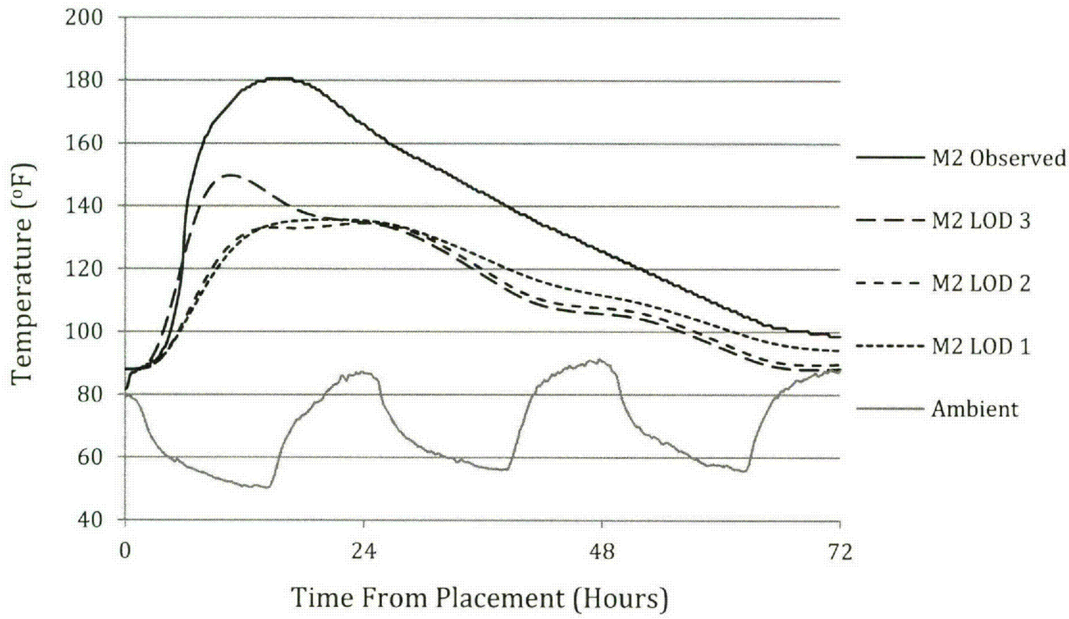


Figure 4.9: Capitol ConcreteWorks Analysis (Sensor M2)

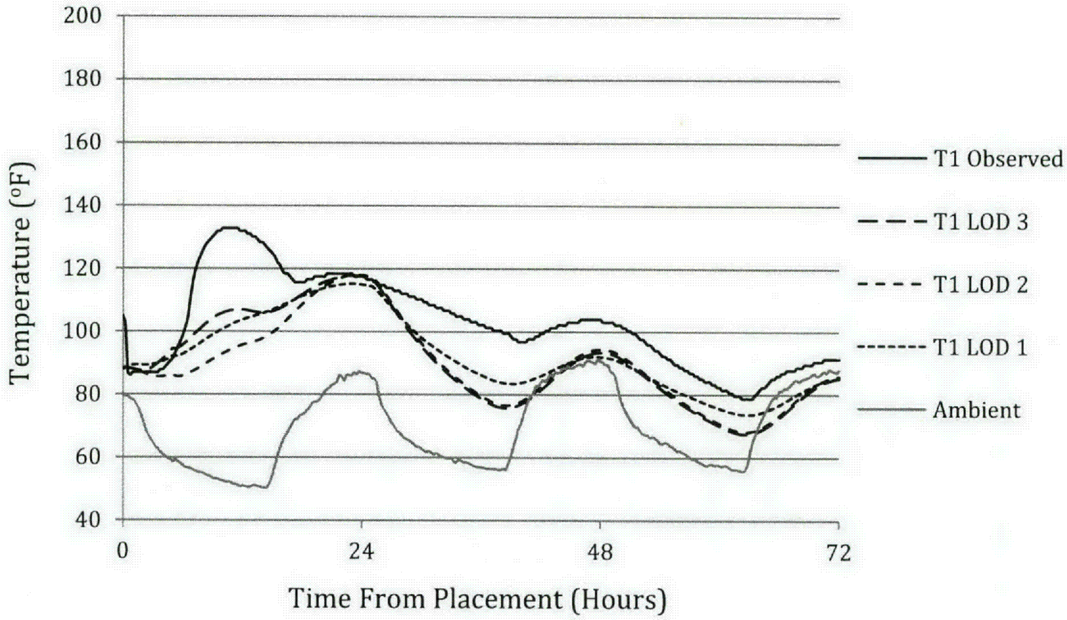


Figure 4.10: Capitol ConcreteWorks Analysis (Sensor T1)

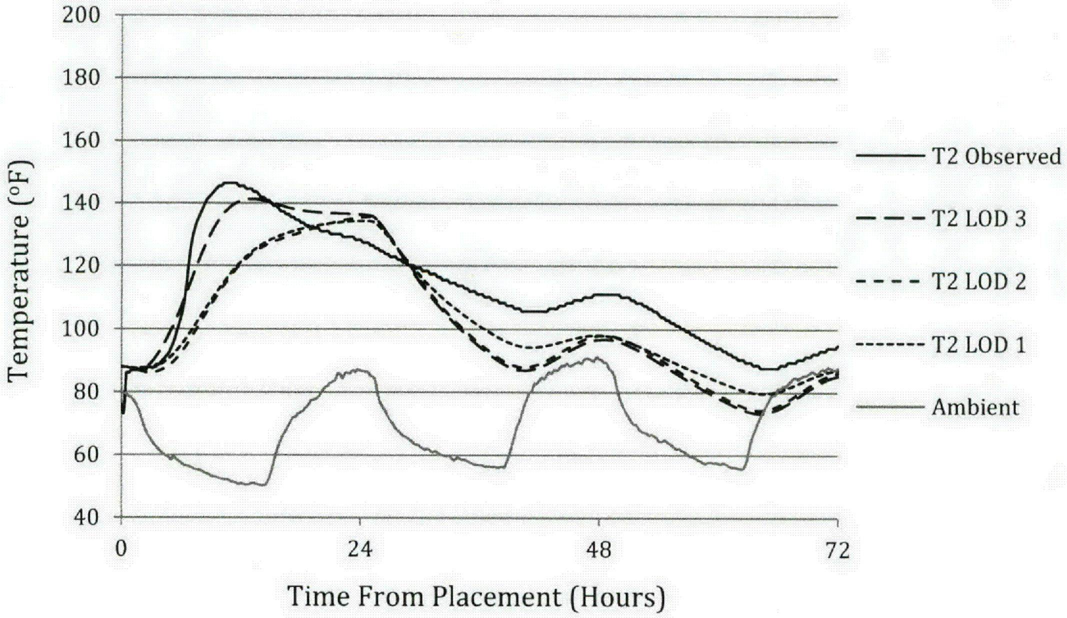


Figure 4.11: Capitol ConcreteWorks Analysis (Sensor T2)

Alamo

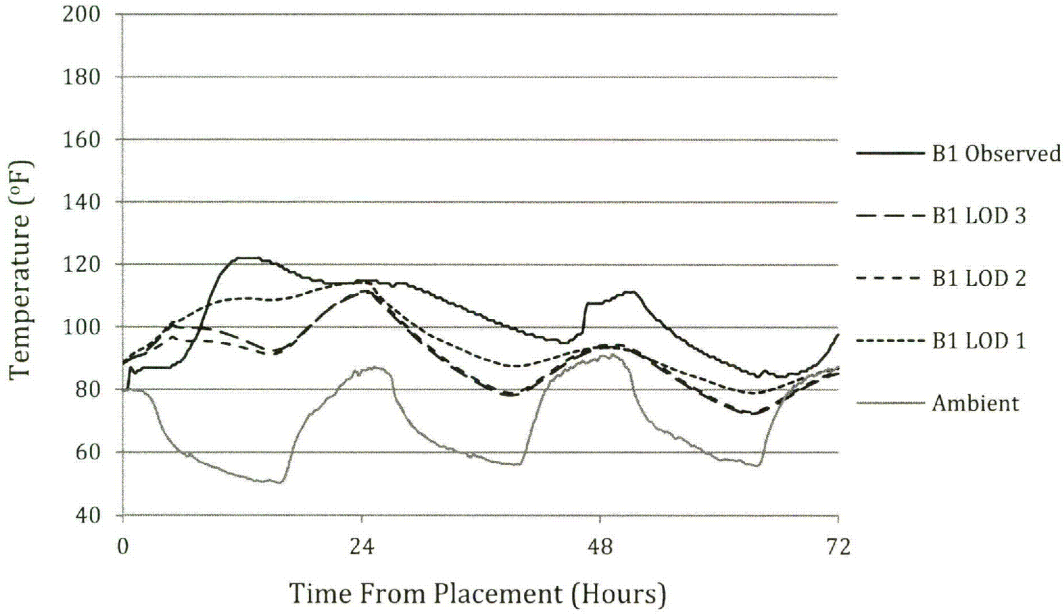


Figure 4.12: Alamo ConcreteWorks Analysis (Sensor B1)

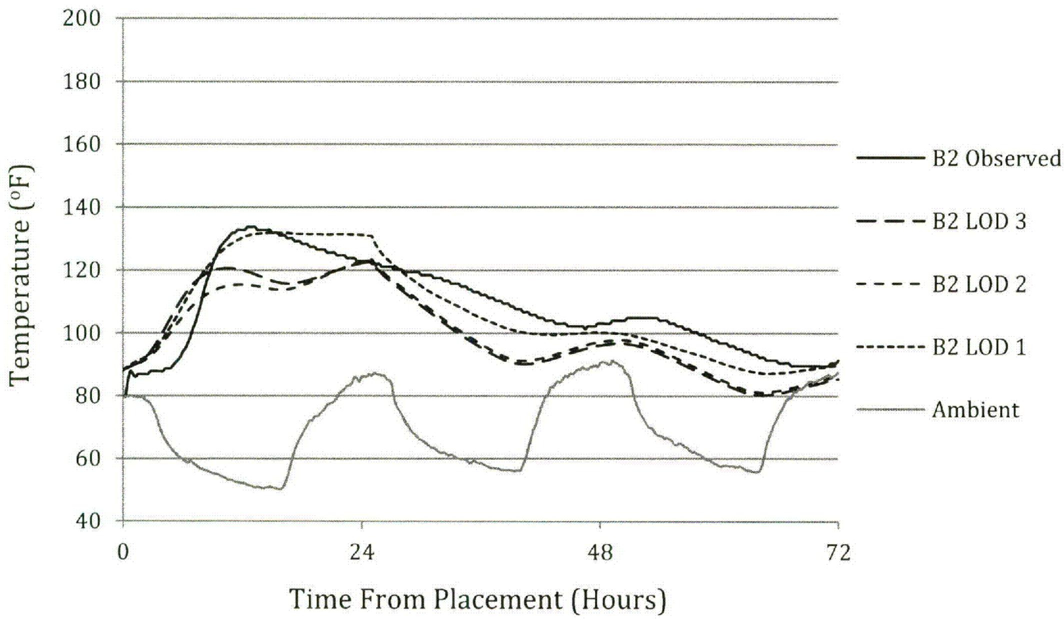


Figure 4.13: Alamo ConcreteWorks Analysis (Sensor B2)

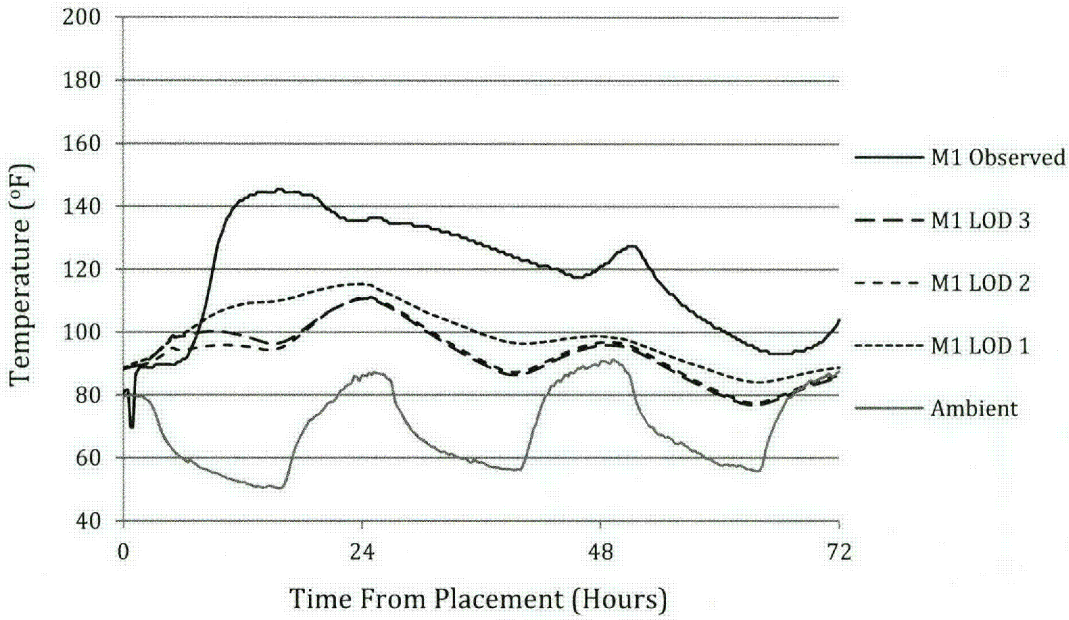


Figure 4.14: Alamo ConcreteWorks Analysis (Sensor M1)

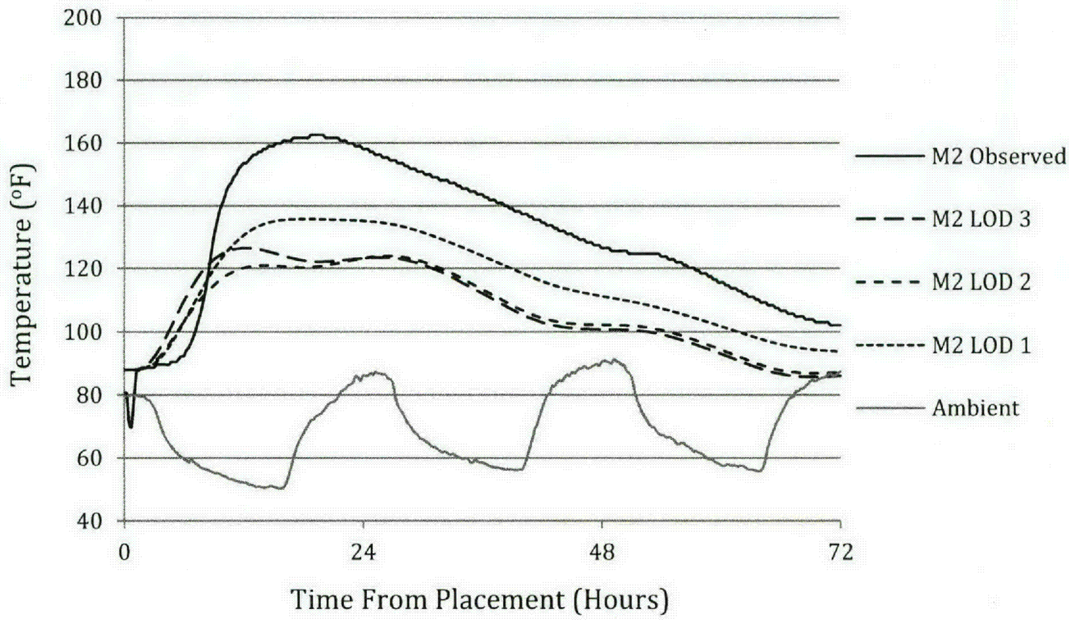


Figure 4.15: Alamo ConcreteWorks Analysis (Sensor M2)

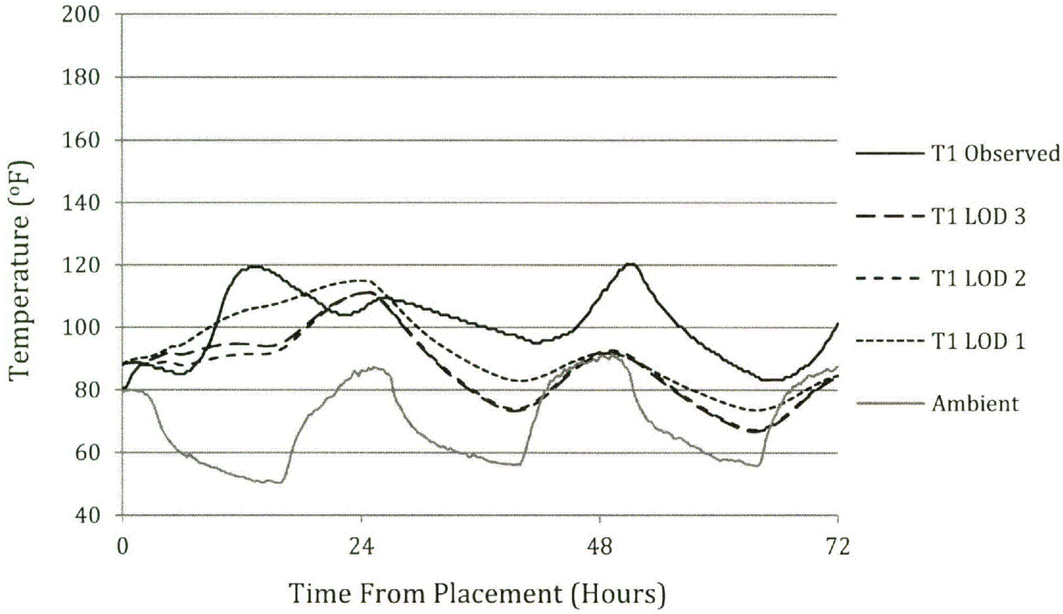


Figure 4.16: Alamo ConcreteWorks Analysis (Sensor T1)

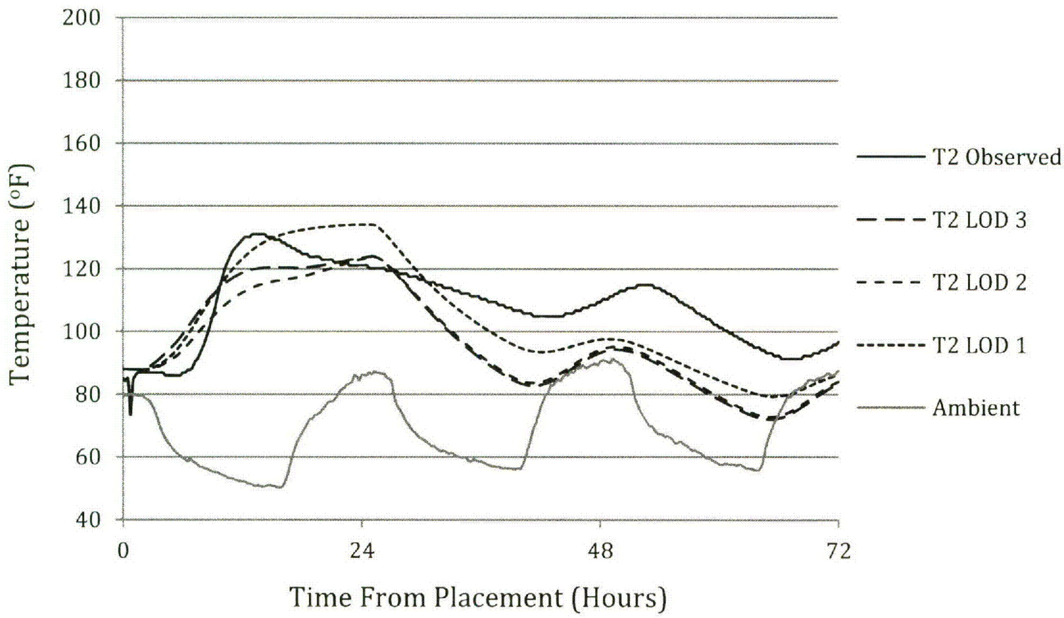


Figure 4.17: Alamo ConcreteWorks Analysis (Sensor T2)

4.3 Case Study: Valley Prestress Products

Maintaining adequate temperatures is so difficult that some precast producers install water cooling pipes in the end blocks of U-beams. Valley Precast, located in Eagle Lake, Texas, recently began installing water cooling pipes to control temperatures. Although ConcreteWorks is currently unable to model cooling pipes, both a water-cooled and a non-water-cooled beam were instrumented.

4.3.1 Structural Plans

A commercial weather station was set up at the precast plant at approximately 10:00 a.m. on the day of the pour. Located just a few hundred yards away from the beams, the station was programmed to record temperature, relative humidity, solar radiation, and wind speed on a 15-minute interval. For unknown reasons, the weather station failed to collect relative humidity, in which case daily relative humidity statistics were acquired from a nearby weather station in Wharton, TX. Aside from a brief afternoon shower on the first two days of the monitoring period, conditions were consistent with southeast Texas weather: hot and humid. A summary of the observed conditions may be seen in Table 4.3. For a detailed comparison between the weather observed at Eagle Lake and ConcreteWorks predicted weather, see Appendix C.1.

Table 4.3: Eagle Lake Weather Station Data

Date	Temperature Max	Temperature Min	Wind Speed	Cloud Cover	Relative Humidity Max	Relative Humidity Min
-	°F	°F	m/s	%	%	%
7/1/2011	94.8	75.0*	10.1	45	94.0*	39.0*
7/2/2011	97.6	76.5	5.9	19	94.0*	30.0*
7/3/2011	97.0	74.9	4.6	24	94.0*	27.0*
7/4/2011	96.0	74.5	4.4	27	94.0*	32.0*

* collected from wunderground.com

4.3.2 Materials and Mixture Proportions

The same mix design, summarized in Table 4.4, was used for both the water-cooled and non-water-cooled beam. The mix was a high-performance self-consolidating concrete (SCC). To characterize the concrete, cylinders were taken on site during construction for mechanical testing and raw materials were acquired from the batch plant on the day of the pour for laboratory testing.

Table 4.4: Eagle Lake Mix Design

Raw Materials		Amount
Cement	Alamo Type III	700.0 lb
SCM	Class F Fly Ash	233 lb
Water	0.30 W/C	269 lb
Coarse Aggregate	1/2" River Gravel	1527 lb
Fine Aggregate	River Sand	1269 lb
Admixtures		**Amount**
Water Reducer	Sika ViscoCrete 2110	5.25 fl oz/cwt
Retarder	Sika Plastiment	1.25 fl oz/cwt
Accelerator	Sika CNI	16.44 fl oz/cwt
VMA	Sika 4R	2.15 fl oz/cwt

4.3.3 Instrumentation

To speed up instrumentation, six temperature bars (see Figure 4.18) were fabricated for each end block using 1/4-inch diameter steel tubing and three iButtons evenly spaced at 8 1/8 inches. Because the end block thickness wasn't known at the time of fabricating the temperature bars, they were made longer than necessary. Once on site, the bars were cut to size and the ends were injected with fast curing epoxy for waterproofing. While the cutting and capping of temperature bars added a little more complication to the instrumentation process, the benefits were invaluable. The temperature bars ensured precise placement of sensors in the end block as well as a rigid point of attachment to the surrounding rebar. The temperature bars also make it very easy to have several sensors grouped to a single multi-conductor wire, which greatly reduces confusion regarding which wire belongs to which sensor after the concrete has been poured.

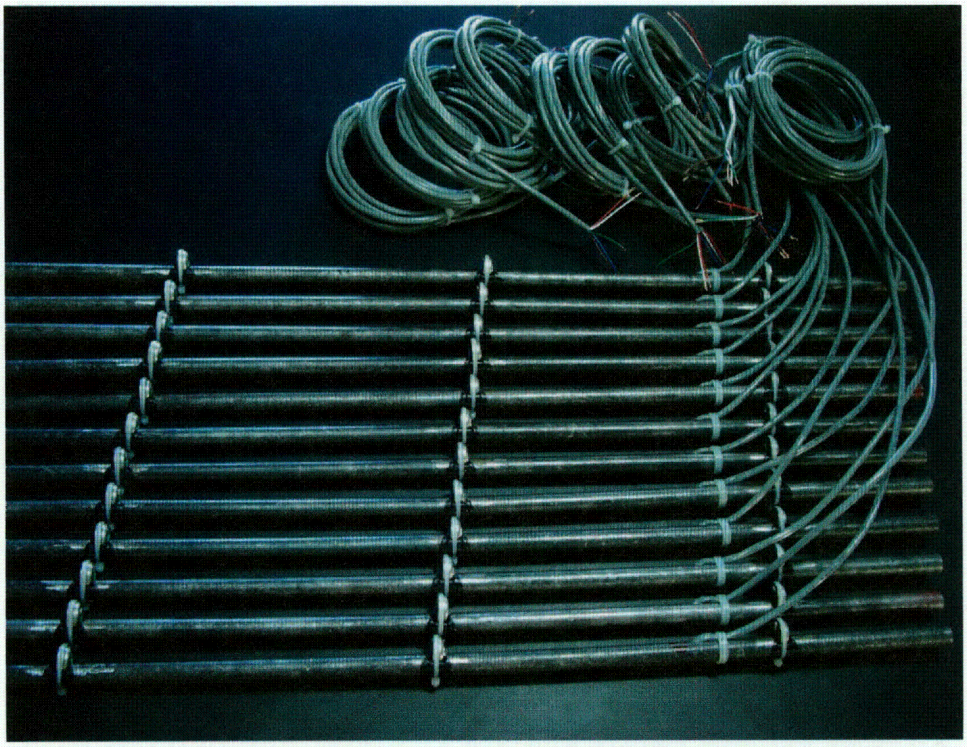


Figure 4.18: Eagle Lake Temperature Bars

Similarly to the Bexar Precast beams, half the sensors were placed as close as possible to the center of the end block for comparison with ConcreteWorks. The remaining nine sensors were placed near the sides to get a better idea of the temperature distribution throughout the end block. Figure 4.19 shows the approximate location of the sensors within the end block as measured after installation.

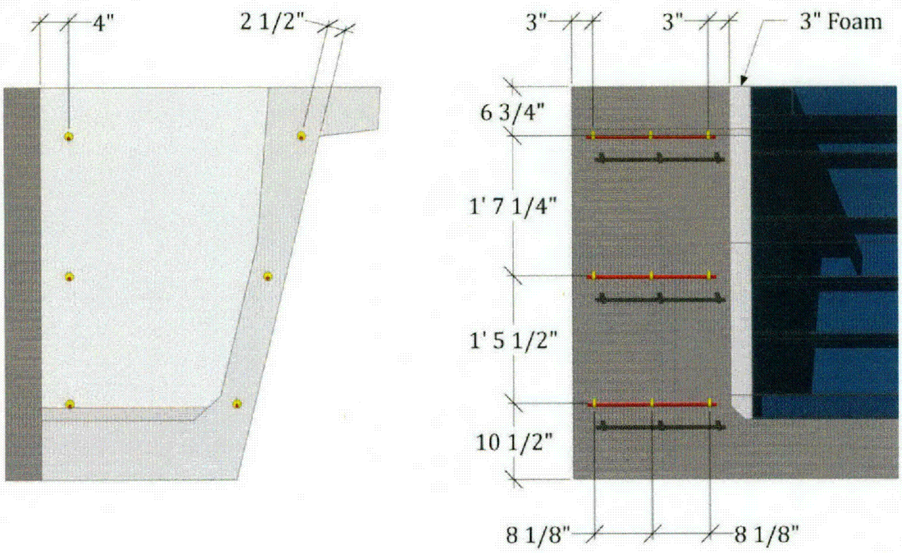


Figure 4.19: Installed Sensor Locations

The same complications regarding the modeled end block size apply to the modeling of the Eagle Lake beam. A 54-inch U beam end block is modeled as 48 inches tall and 27 inches thick. The beams instrumented on site were approximately 22 inches thick. There is no option in ConcreteWorks to specify the thickness of the end block.

An analysis was conducted of the temperatures observed in the field and those predicted by ConcreteWorks. The output for ConcreteWorks, illustrated by Figure 4.20, consists of a two-dimensional array of points in the end block at which temperatures are predicted on a 5-minute interval. To produce predicted temperatures at the same locations at which iButtons were installed, bilinear interpolation of predicted temperatures surrounding each iButton was performed. This was done for each time step and plots of the observed and predicted temperatures were developed. Figure 4.20 also presents a naming scheme for the sensors, with B, M, and T representing the bottom, middle, and top rows of sensors respectively.

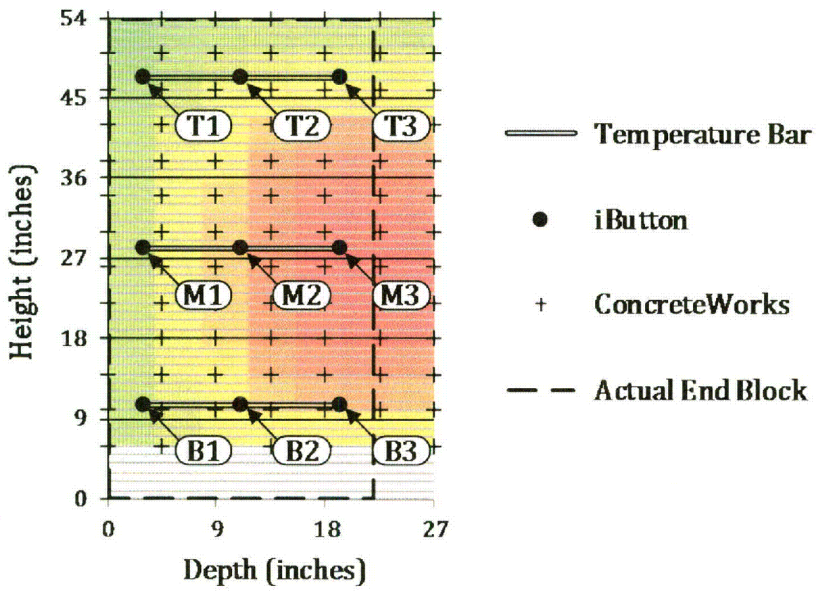


Figure 4.20: Eagle Lake—End Block Instrumentation Schematic

4.3.4 Observed and Predicted Temperatures

The following figures (Figure 4.21 through Figure 4.29) present the temperatures observed in the field by each of the nine sensors at the center of the end block as well as their corresponding temperatures predicted by ConcreteWorks.

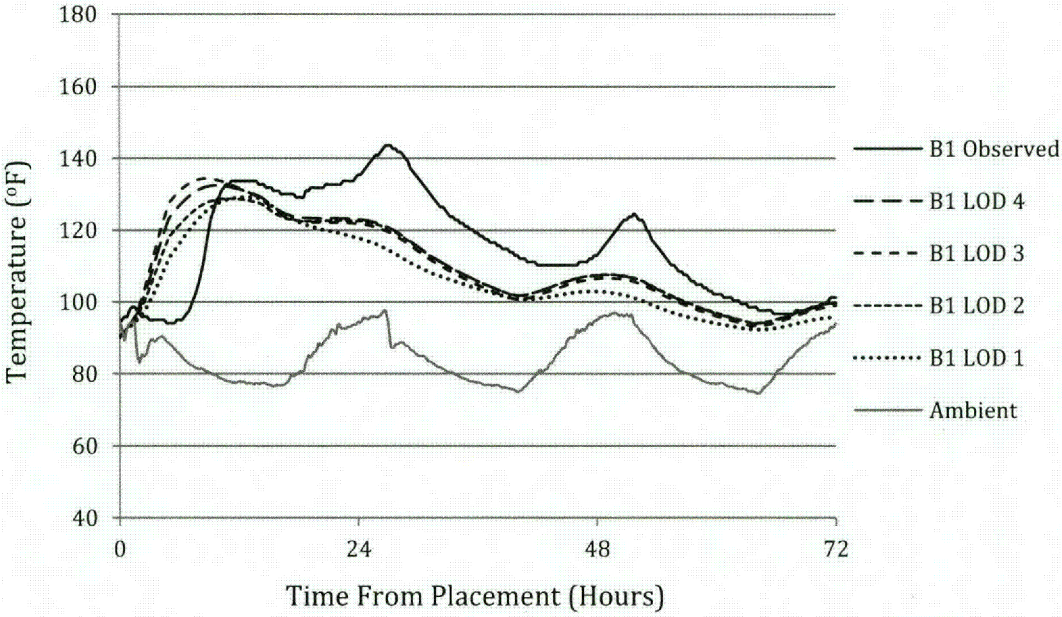


Figure 4.21: Eagle Lake—ConcreteWorks Analysis (Sensor B1)

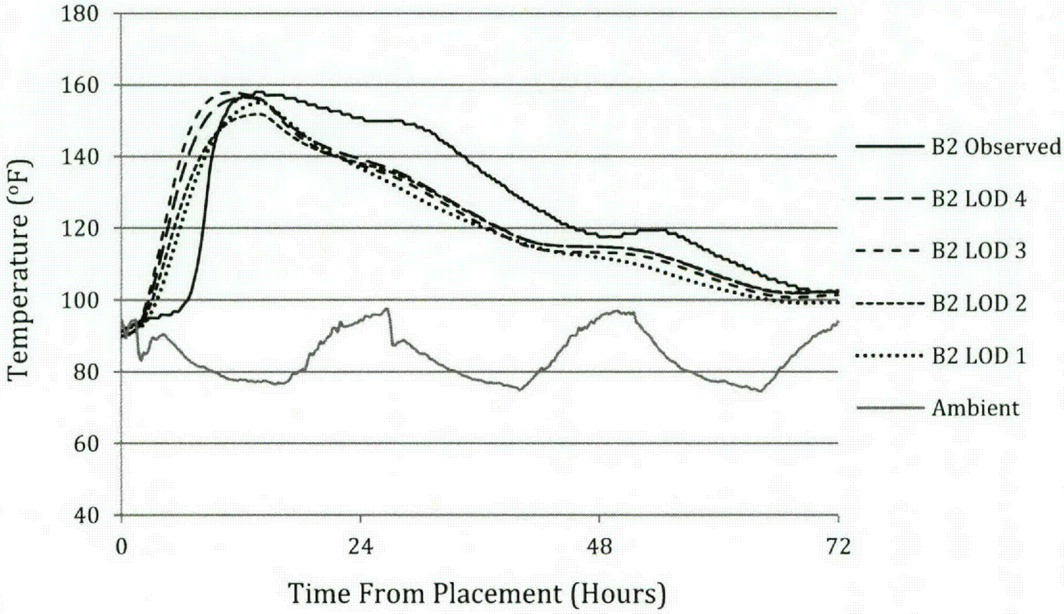


Figure 4.22: Eagle Lake—ConcreteWorks Analysis (Sensor B2)

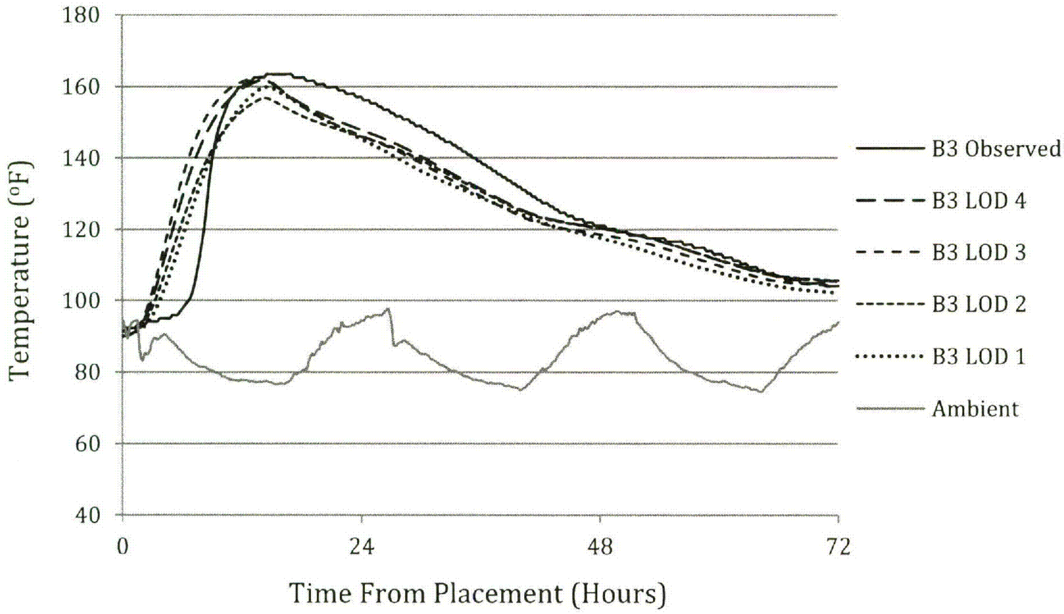


Figure 4.23: Eagle Lake—ConcreteWorks Analysis (Sensor B3)

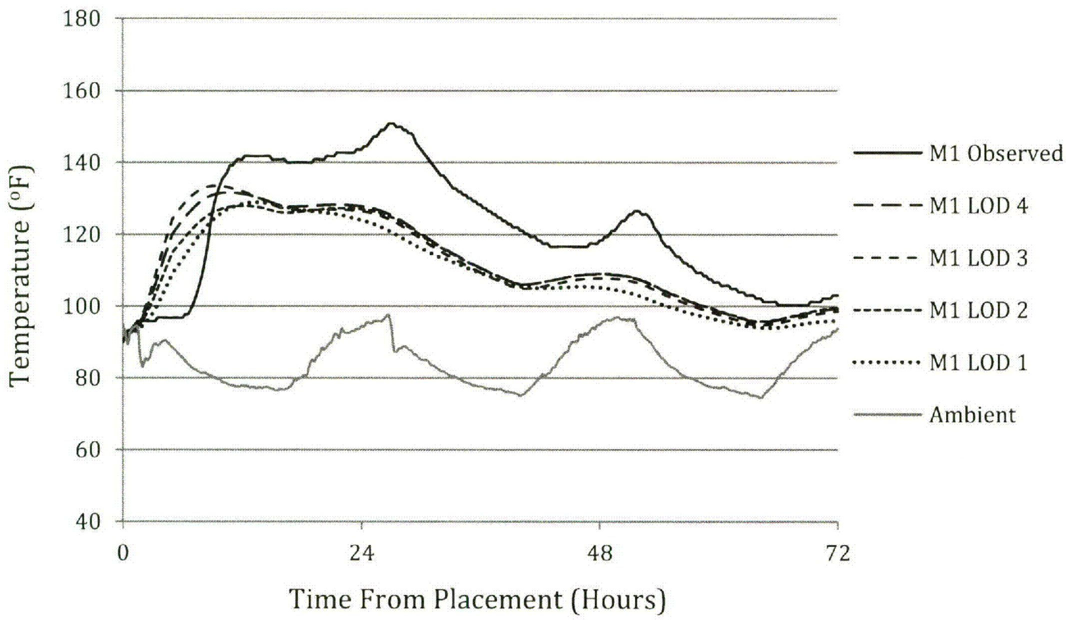


Figure 4.24: Eagle Lake—ConcreteWorks Analysis (Sensor M1)

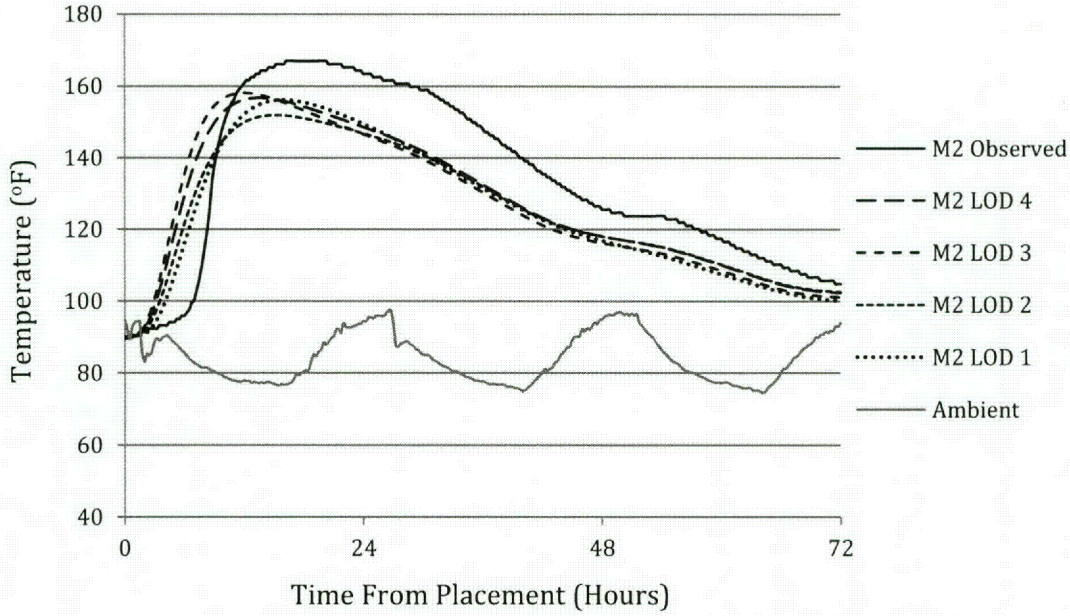


Figure 4.25: Eagle Lake—ConcreteWorks Analysis (Sensor M2)

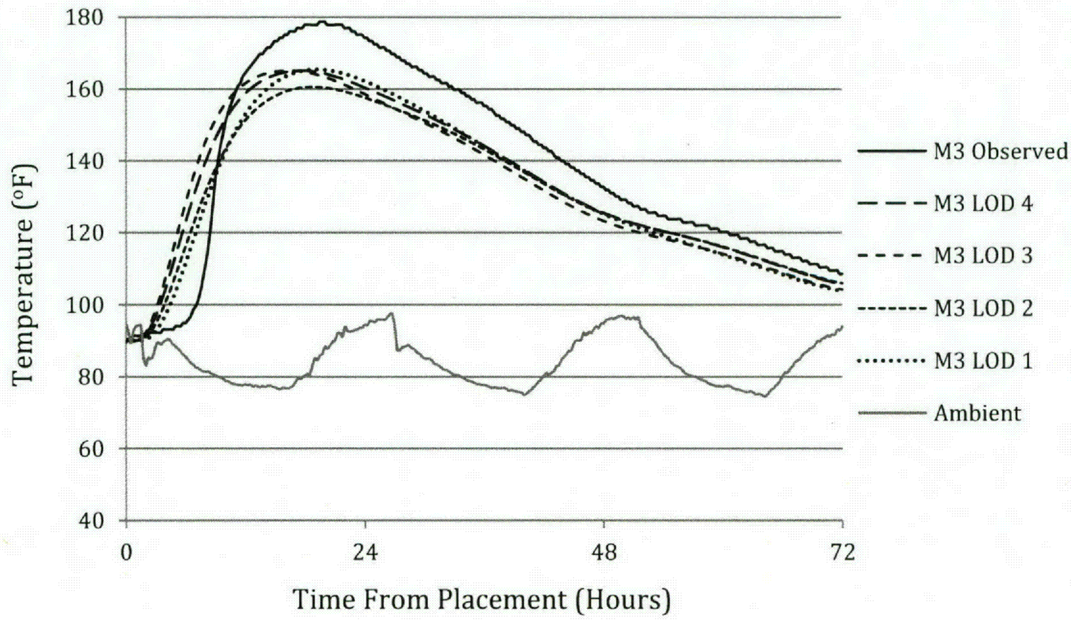


Figure 4.26: Eagle Lake—ConcreteWorks Analysis (Sensor M3)

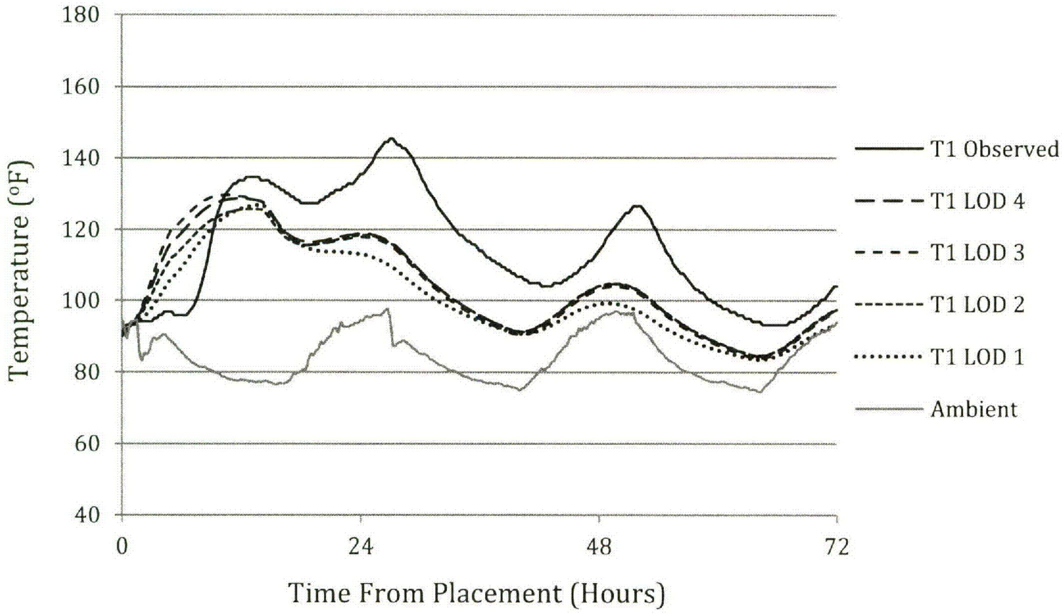


Figure 4.27: Eagle Lake—ConcreteWorks Analysis (Sensor T1)

Figure 4.28: Eagle Lake—ConcreteWorks Analysis (Sensor T2)

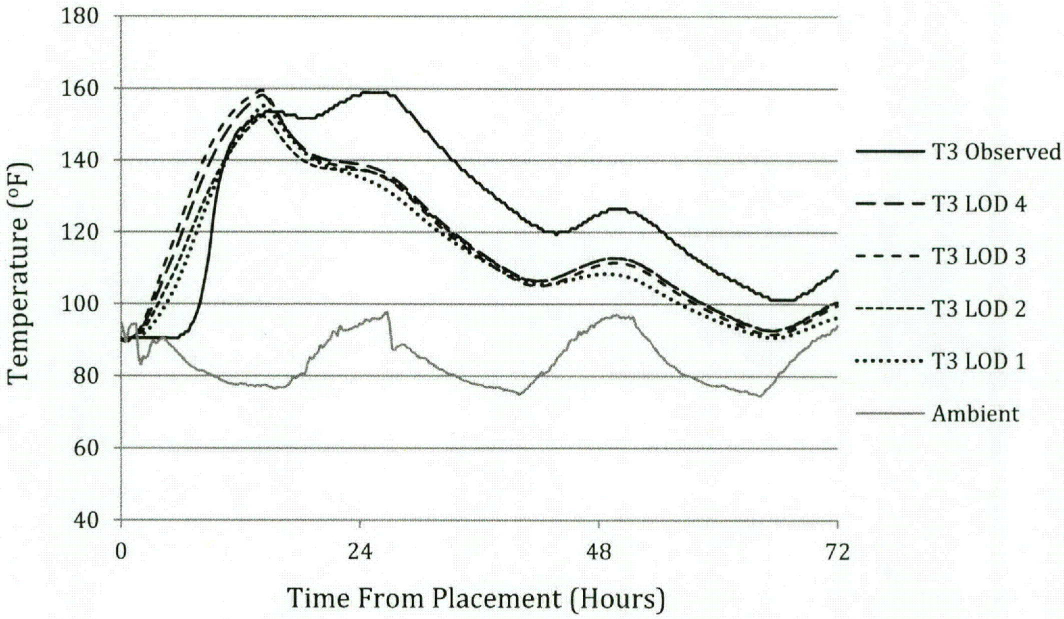


Figure 4.29: Eagle Lake—ConcreteWorks Analysis (Sensor T3)

4.3.5 Additional Observations

Although ConcreteWorks does not model water cooling pipes, a water-cooled beam was instrumented to document the effects on thermal behavior and the results certainly make a strong case for adding this functionality to the software program.

4.3.6 Water Cooled End Block

In addition to instrumenting a regular U 54 beam, an identical water cooled beam was also instrumented using the same mix design and poured within an hour of the non-water cooled beam. The beam was cooled by installing a 4-inch pipe straight down the center of the end block, illustrated in green in Figure 4.30.

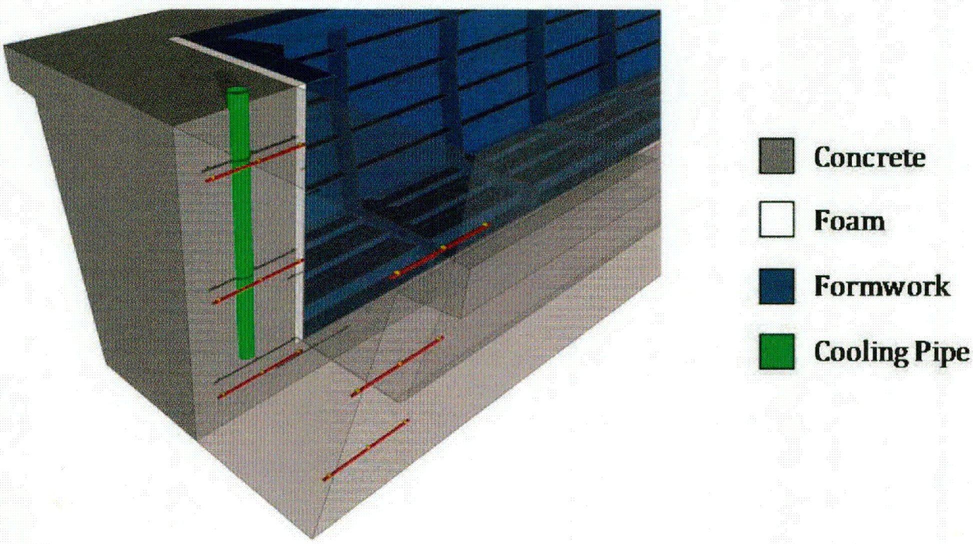


Figure 4.30: Eagle Lake—Water Cooled Beam

Rather than allow the water to run through one end of the pipe and out the other like a typical water cooling system, the pipe was capped at the bottom end and a hose was dropped into the top. The water simply fills the pipe and overflows out of the top, carrying excess heat away from the center of the end block. The design is brilliant because it's very easy to install, unobtrusive, and targets the hottest part of the end block. The instrumentation of the two beams showed that the water cooling pipe reduced the maximum temperature 21.6 °F. Whereas the non-water-cooled beam reached a maximum temperature of 178.7 °F, the water-cooled beam only reached 157.1 °F. A plot of the two hottest sensors (M2 and M3) is shown in Figure 4.31. Sensor M2 WC is particularly interesting as it is located just 2 inches away from the water cooling pipe. At 14 hours, the water was turned off and forms were stripped. The concrete responded with rapid temperature rise as the hydration reaction was in full swing. Cooling the end block for the first 14 hours, however, had already ensured the beam was in no danger of overheating.

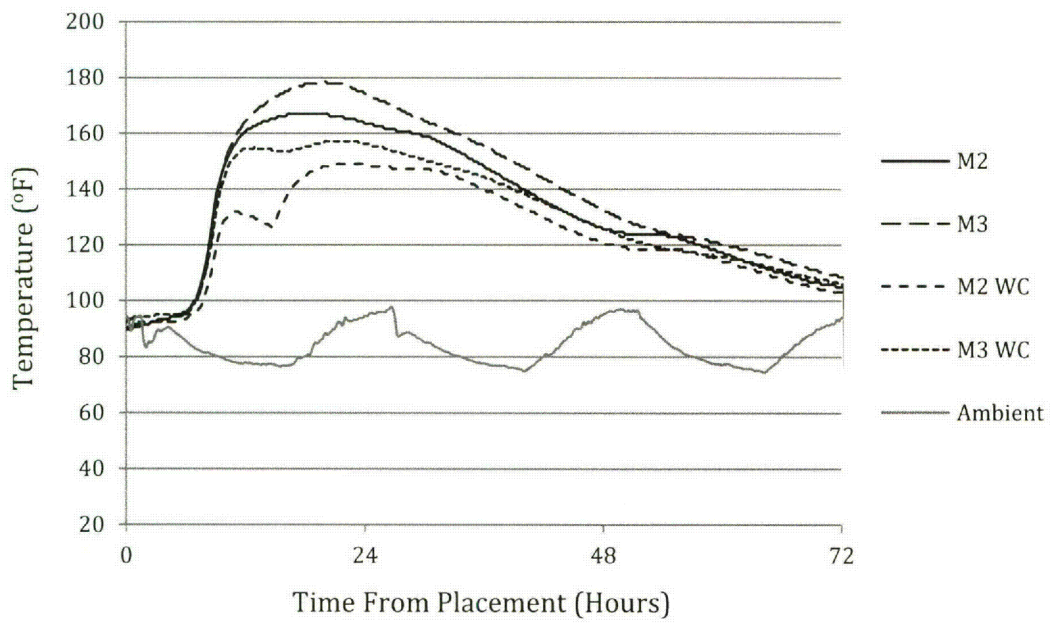


Figure 4.31: Eagle Lake—Observed Temperature (Water Cooled Beam)

4.3.7 Diaphragm Temperature

A few spare iButtons were brought along in anticipation of any sensor failures detected before concrete casting. After instrumentation, all 36 sensors installed in the two beams were confirmed functional. With no need for the spares, one was installed at the center of a diaphragm in the beam. Diaphragms are concrete bulkheads poured between the beam's midpoint and each end. As seen in the design drawing in Figure 4.32, the diaphragms may range between 6 and 12 inches thick. The instrumented diaphragm was 7 inches thick.

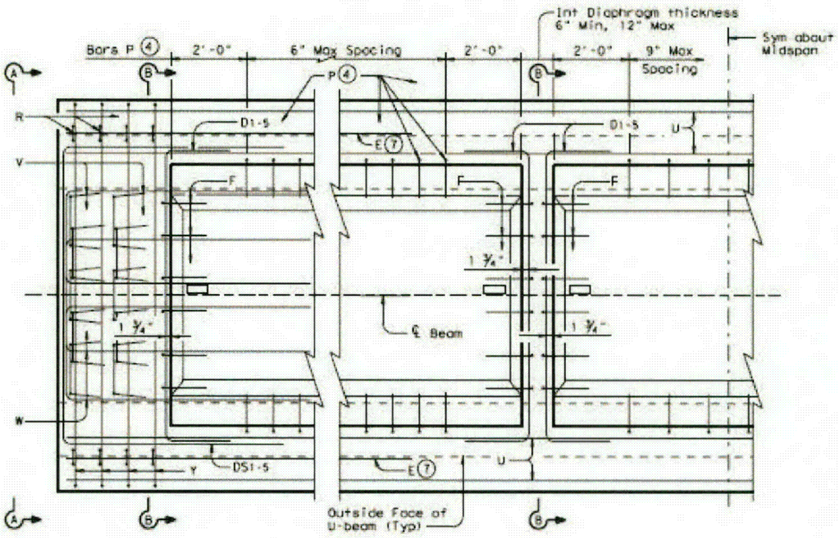


Figure 4.32: Diaphragm iButton

Although a 7-inch thick concrete section seems very unlikely to overheat, it was sandwiched between a layer of 3-inch thick foam on one side and 2-inch thick foam on the other side. Figure 4.33 illustrates the instrumentation of the diaphragm. No dimensions are available as the sensor was very rudimentarily placed by eye.

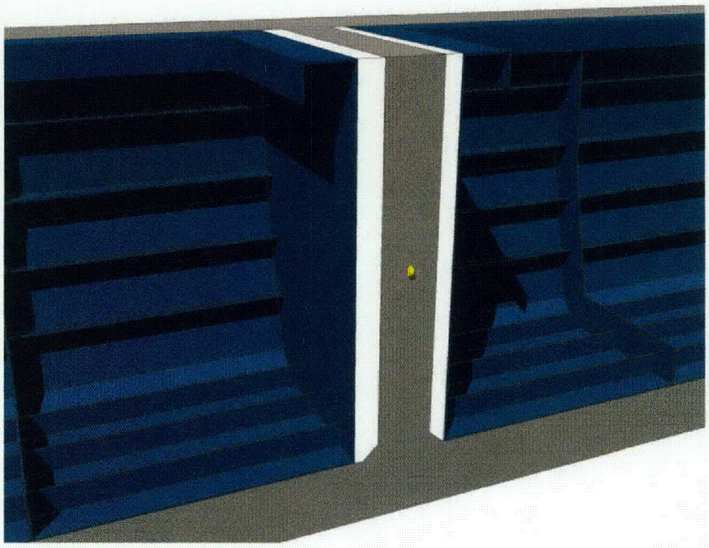


Figure 4.33: Diaphragm iButton

Despite the insulation provided by the foam, what the iButton captured was nothing short of surprising. As seen in Figure 4.34, concrete temperatures in the diaphragm behaved semi-adiabatically, rising to a temperature of 169.7 °F. That's 12.6 °F higher than the maximum concrete temperature observed in the water cooled end block!

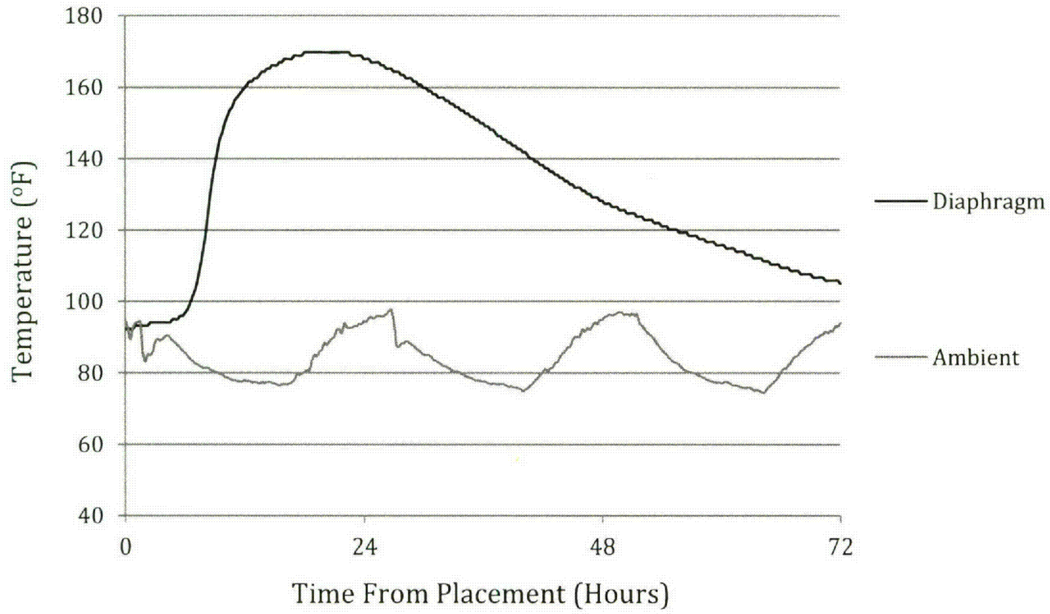


Figure 4.34: Eagle Lake—Observed Temperature (Diaphragm)

4.4 Discussion

The temperature predictions developed for each of the precast case studies reveal much information regarding the difficulty in replicating observed temperatures. While a large portion of the error is likely due to the incorrect size of the modeled end block as discussed earlier, it has always been known that ConcreteWorks' Achilles heel is temperature prediction near the surface of the concrete. Temperatures near the surface can be very erratic depending on ambient weather conditions, stripping of the forms, and changes to the boundary conditions caused by curing. This doesn't bode well for an element in which the greatest dimension along a viable path of heat transfer is only two feet. Essentially, almost any point in a precast element is near an exterior surface.

Despite some of the difficulties with modeling smaller elements, the case studies provide good indicators of opportunities for improvement in the software. One discrepancy between the temperature models and the iButton data was the end block's response to the stripping of forms. When the forms were stripped, the iButton data for all three beams shows the concrete responded with a decrease in temperature as heat was lost to the environment. The same effect is seen with the modeled temperatures, however, to a much greater degree. The top sensors installed in the Eagle Lake beam illustrate this behavior particularly well as the forms were stripped at the coolest point in the day at only 14 hours after placement. ConcreteWorks assumes that curing blankets are placed on top of the beam until forms are stripped. Once that occurs, the curing blankets are assumed to be removed unless specified otherwise in the construction inputs. In the field trials, curing blankets were permanently removed once the beam was taken off the production line. The predicted rapid temperature decrease with form removal indicates that the heat conduction between the exposed concrete and the surrounding environment is overestimated by ConcreteWorks. Consequently, this could also explain why the predicted maximum temperatures are significantly lower than the observed maximum temperatures.

One example of varying construction methods observed in the field was the formwork used for the exterior face of the end blocks. With the opposite side of the end block completely insulated with foam, the exterior face is one of the primary locations of heat transfer to the environment. Accurately defining the boundary conditions here could result in much better modeling of the thermal behavior of the system. Figure 4.35 shows the reinforced plywood formwork used by Bexar Concrete Works on the left and the structural steel formwork used by Eagle Lake on the right. Another example seen in the case studies was the varying thicknesses of foam used on the end blocks. Currently, ConcreteWorks has no options to specify the foam thickness or the type of formwork used on the exterior face of the end block.

Figure 4.35: Exterior Formwork—Bexar (Left) and Eagle Lake (Right)

While near-surface thermal prediction will never be perfect, the software program had a chance to highlight its greatest strength with the Alamo vs. Capitol comparison: hydration. The most impressive result of precast thermal predictions was the software program's ability to replicate the difference in maximum temperature between the Alamo and Capitol beams cast at Bexar Concrete Works. This effect can't be captured by LOD 1 as there were no specified inputs with which to differentiate the two cements. LOD 2, however, specified the Bogue-calculated cement composition for the cement used in each beam and yielded a 10.5° difference as seen in Table 4.5. LOD 3, in which the cement composition was more accurately defined by Rietveld analysis, achieved a correspondingly higher accuracy in predicting the difference, with a predicted temperatures varying by 23 °F.

Table 4.5: Maximum Temperature (Alamo vs. Capitol)

	Observed	LOD 3	LOD 2	LOD 1
Capitol	180.5	149.7	134.5	135.6
Alamo	162.5	126.5	124.0	135.7
Difference	18.0	23.2	10.5	-0.1

4.5 Conclusion and Recommendations

A reliable method was developed for instrumenting precast elements and four U54 beams were outfitted with several sensors each. Various methods of characterizing the case studies were compared in ConcreteWorks using the observed temperatures as a baseline. Some recommendations for future research are as follow:

- Investigation into the importance of adding inputs to specify the type of formwork used on the exterior face of the end block as well as a comparison between the modeling of varying foam thicknesses
- Corrections to ConcreteWorks modeled end block dimensions

Chapter 5. Mass Concrete Temperature Prediction

5.1 Research Significance

It is well known that freshly poured concrete in the central portion of a large column is capable of reaching very high temperatures. The center of the column is well insulated by surrounding concrete and temperatures behave semi-adiabatically. At the exterior of the column, temperatures closely mimic the outside air temperature. The difference in temperature between the center of the column and its outer reaches presents internal stresses caused by variations in thermal expansion. A very large temperature difference isn't enough to crack concrete, however. The temperature variation has to occur over a short enough distance. In other words, the temperature gradient causes the stresses. Thermal gradients can occur for several reasons. If the concrete is particularly hot or very fast reacting, the center of the column can heat up enough to cause an excessive gradient. Alternatively, gradients can be caused by stripping forms in a cold environment. Similar to dropping an ice cube in a glass of water, quickly subjecting a hot concrete element to cold surroundings can present a thermal shock capable of severe cracking. If a gradient is large enough, the induced thermal stresses may results in severe cracking.

The maximum thermal gradient is likely to occur at two locations. One possible location is the center of a column's widest face as this point represents the shortest path from the center of the column to the exterior. At the corners of the column, two surfaces are available to transfer heat to the outside environment, making for rapid heat loss and consequently high potential for crack inducing thermal gradients.

5.2 Case Study: IH 35/SH 71 WBSB Column 8

The Interstate Highway 35/State Highway 71 (IH 35/SH 71) is located in southeast Austin. This construction project is a phase 2 effort that adds remaining connector ramps not included in the original highway interchange construction in 2002/2003. The structures being built are of particular interest to this research as they qualify as mass concrete placements. The westbound SH71 to southbound IH35 connector, the tallest flyover at the site, has several columns exceeding 5 feet least dimension and standing 100 feet tall.

Coincidentally, some of the original columns of the IH 35/SH 71 interchange were used as a test bed for the initial development of ConcreteWorks. Unfortunately, history often repeats itself and some of the same instrumentation problems faced by Kyle Riding and Jonathan Poole reoccurred several years later.

5.2.1 Project Details

The structure of interest is Column 8, located at the northeast corner of the interchange. Column 8 connects westbound SH 71 to southbound IH 35. While it's not the largest structure on the site, Column 8 was chosen for instrumentation due to its simple rectangular geometry and safe and easy access from the surrounding frontage roads. Temperature sensors were to be installed in the upper half of the column and the frontage road provided access at about mid height. Figure 5.1 shows the site layout surrounding Column 8. The column measures 10' 2" x 7' 6" as shown by Figure 5.2.

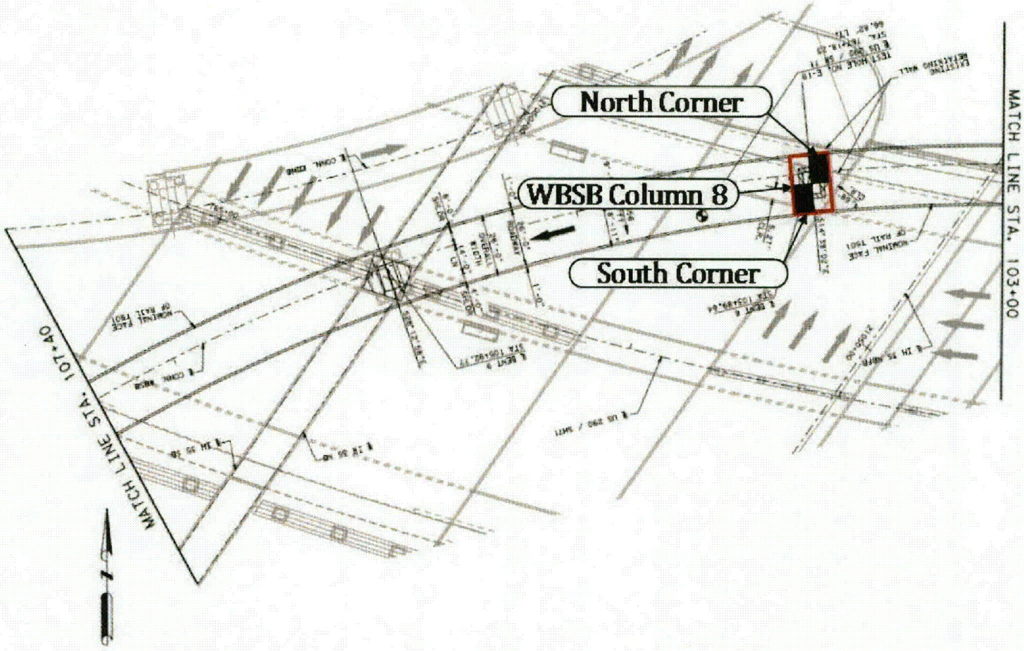


Figure 5.1: WBSB 8 Site Layout

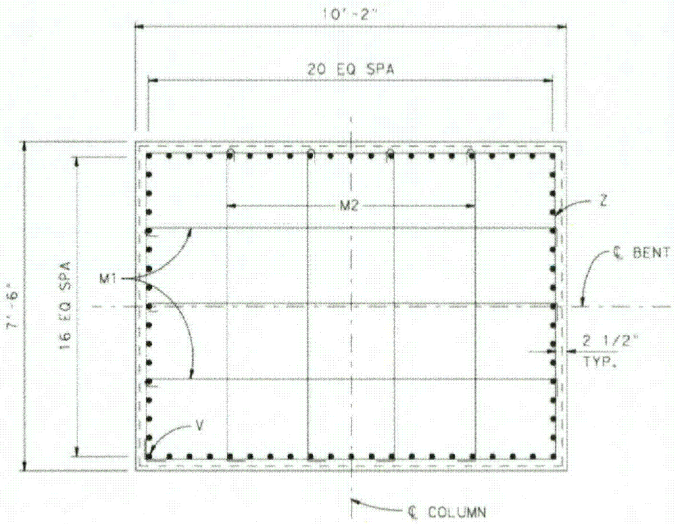


Figure 5.2: WBSB 8 Design Drawing

Column 8 was poured in two stages. Stage 1 occurred on Saturday November 13, and involved the placement of approximately 45 feet of concrete. Stage 2, which occurred on Thursday, November 18, saw the placement of the remaining 63 feet of the column, bringing it to its final height of 108 feet. Sensors were installed before Stage 2, at approximately 55 feet off the ground.

5.2.2 Materials and Mixture Proportions

Concrete was supplied by Lauren Concrete, specifically from batch plant #1 located on McKinney Falls Parkway, just a few miles southeast of the site. The paste fraction involved a mixture of Type I/II cement manufactured by Capitol, 25% Class F fly ash, and water-to-cementitious-materials ratio of 0.42. Coarse aggregate was a manufactured dolomitic limestone originating from Marble Falls, Texas, and the fine aggregate was siliceous river sand. Sika 2100 high range water reducer was added for workability and Sika 930 for set retardation. A copy of the batch sheet was acquired for the concrete specifically placed at the height of the sensors. Table 5.1 summarizes the mix design.

Table 5.1: WBSB 8 Mix Design

Raw Materials		Amount
Cement	Capitol Type I/II	428.0 lb
SCM	Class F Fly Ash	107.5 lb
Water	0.42 W/C	231.2 lb
Coarse Aggregate	1 1/2" Dolomitic Lime	1934.0 lb
Fine Aggregate	River Sand	1356.0 lb
Admixtures		**Amount**
Water Reducer	Sika ViscoCrete 2100	3.70 fl oz/cwt
Retarder	Sikatard 930	2.60 fl oz/cwt

5.2.3 Instrumentation

Installation of the sensors took place after the entire 100 feet of the formwork and steel rebar cage had been erected. At this point, approximately 45 feet of the column had been poured below, leaving 53 feet of column in addition to a 10 foot capitol remaining. The column was accessed by taking a man lift to the top of the formwork and climbing down 60 feet to a location approximately 10 ft above the concrete surface created by the placement of Stage 1. The purpose of placing the sensors so high in the column was to eliminate the effects of the shade created by the northbound deck of IH 35. The communication wires were routed through a hole in the steel formwork, allowing the sensors to be programmed and read at any time from a safe location on the ground. Figure 5.3 presents a view from half way up inside the column.

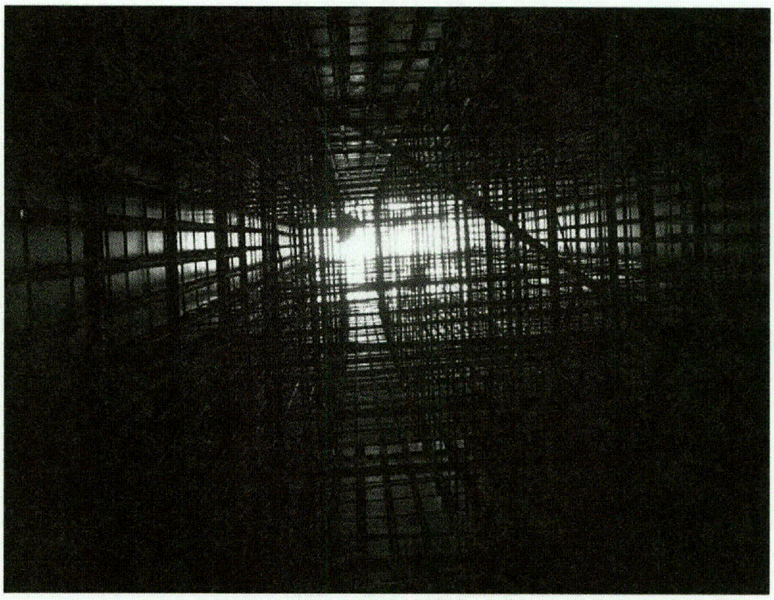


Figure 5.3: Looking up from Inside WBSB 8

The temperature sensors used were Thermochron iButtons, made by Dallas Semiconductor. With an onboard thermocouple, battery, and a memory chip capable of storing over 2,000 data points, the iButtons are capable of logging temperature readings every 5 minutes for a period of 7 days. The only downside of utilizing these iButtons is that they must be installed in the concrete where they are exposed to the construction environment and rendered irretrievable. Great consideration was put into protecting the sensors from being stepped on by construction workers, being battered by concrete vibrators, and having water forced into openings (consequently short-circuiting the electronics). In the interest of making the sensors durable as well as minimizing installation time on site, the temperature sensors were preinstalled on four short lengths of rebar. With seven iButtons per rebar length, the sensors were then coated with epoxy for waterproofing.

In the event of sensor failures, two opposite quadrants of the column were instrumented for redundancy. The placement of sensors can be seen in Figure 5.4.

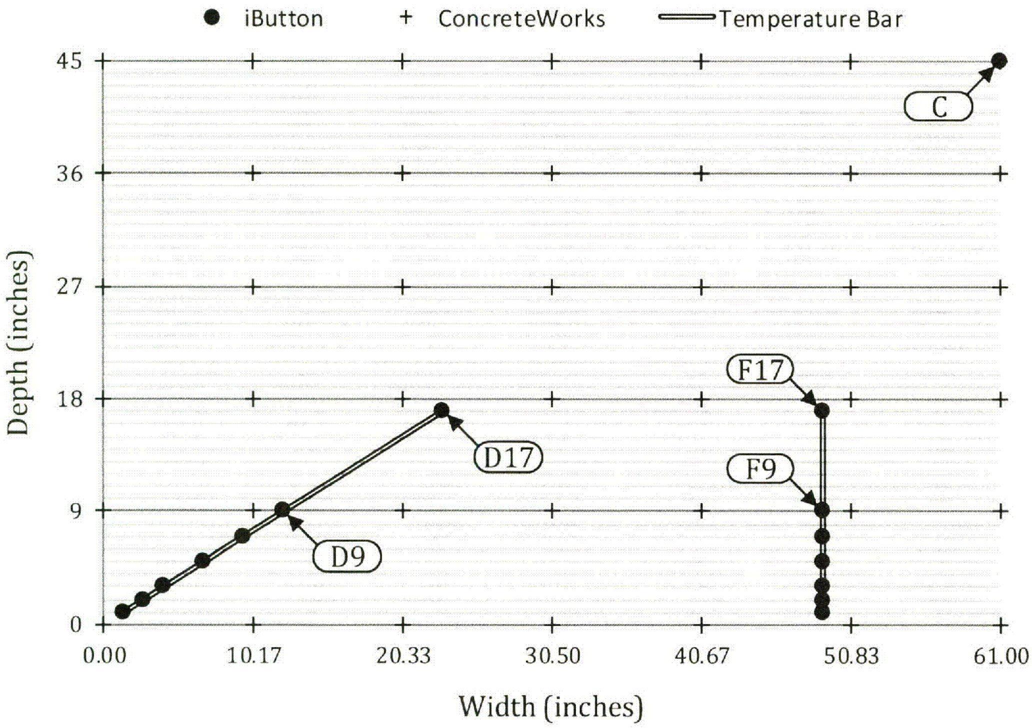


Figure 5.4: Column 8 Instrumentation Schematic

Figure 5.4 illustrates the instrumentation of one quadrant of the column where the axes form the outside faces of the column with point (0,0) representing the corner and point (61,45) representing the center of the column. Two strings of sensors are present, showing the installed location of the iButtons. The diagonal string of sensors, aligned radially from the center of the column straight towards the corner, is temperature bar D. This temperature bar was intended to measure thermal gradients resulting from heat loss through the corner of the column. The second string of sensors extending toward the widest face of the column is temperature bar F. Sensors are named according to the bar on which they are located: D for the diagonal bar and F for the bar extending towards the face of the column. The number following the bar label indicates the sensors depth from the widest face of the column. Sensor D17, for example, is located on the diagonal temperature bar 17 inches from the face of the column. Finally, a single sensor was placed at the center of the column to measure the maximum temperature. The figure also shows how ConcreteWorks divides an element up into a grid, reporting predicted temperatures at evenly spaced nodes represented by the + symbols.

To prevent the concrete from segregating during placement, it was poured into a chute at the top of the column. The chute was installed at the right where the central temperature bars (bar F) were intended to go. As a result, the temperature bars had to be offset by about a foot from the centerline of the column. Figures 5.5 and 5.6 show the temperature bars in WBSB 8.

Figure 5.5: Diagonal Temperature Bar in WBSB 8

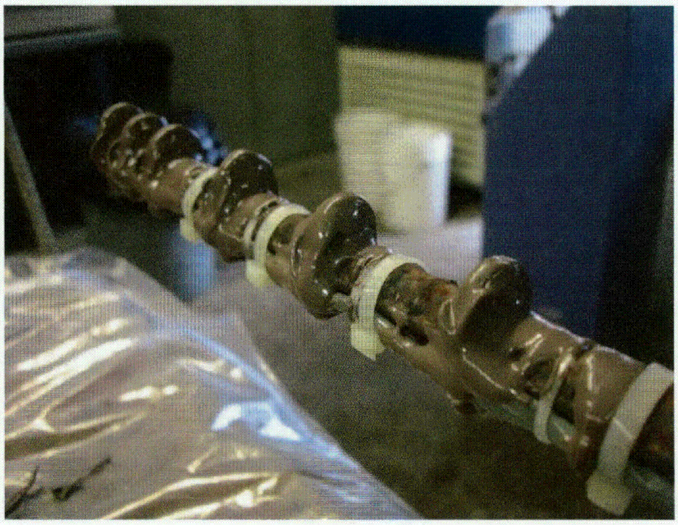


Figure 5.6: WBSB 8 Temperature Bar

Despite measures to protect the sensors against the construction environment, the temperature bars had a few flaws. First of all, wires running the length of the temperature bars made it difficult to completely seal the sensors from water intrusion. The epoxy did not bond well to the wire insulation; under enough pressure, it's possible the connecting wires actually acted as a direct path for water intrusion into the sensors. Additionally, the epoxy exhibited very brittle behavior; if brought into contact with a concrete vibrator, the epoxy could have chipped, leaving the sensor completely exposed to the surrounding elements.

5.2.4 Field Observations

A commercial weather station was set up on site prior to the concrete pour and programmed to record temperature, wind speed, solar radiation, and relative humidity on a 15-minute interval. The daily conditions are summarized in Table 5.2. Refer to Appendix D.1 for a detailed comparison of the observed weather data with ConcreteWorks' default weather model as well as the model adjustments based on the observed conditions.

Table 5.2: WBSB 8 Weather Station Data

Date	Temperature		Wind Speed	Cloud Cover	Relative Humidity	
-	MAX	MIN	MAX	AVG	MAX	MIN
11/18/2010	65.2	44.7	12.6	14%	69.7	28.4
11/19/2010	70.8	43.6	7.1	18%	74.2	23.8
11/20/2010	76.0	49.1	8.0	74%	93.5	51.6
11/21/2010	81.6	68.1	11.0	66%	88.0	47.8
11/22/2010	82.3	69.6	11.9	69%	84.6	48.9
11/23/2010	82.6	70.8	7.3	69%	85.8	52.4
11/24/2010	84.4	71.7	12.2	53%	84.9	45.6
11/25/2010	79.1	45.5	14.2	99%	82.6	29.0

On November 18, 2010, at 2:00 a.m., all 29 sensors were confirmed operational. An hour and a half later at 3:30 a.m., concrete was placed at the sensor location, the semi-adiabatic calorimeter was prepared, and cylinders were cast for mechanical testing. At 6:00 a.m., cementitious materials were obtained from the batch plant and taken to the Concrete Durability Center for testing.

5.2.5 Observed and Predicted Temperatures

For several reasons already discussed, 22 of 29 sensors installed in the column failed prematurely. Of those 22 sensors, 16 failed to even read, thus providing no data. As a result, no data was collected from the sensors located at the faces of the column and several sensors on the diagonal temperature bars failed a few days into the monitoring period. In total, only seven sensors survived the full 7-day period. Figures 5.7 and 5.8 present the majority of the data that was collected. The sensors that failed during the monitoring period can be seen dropping off of the plot.

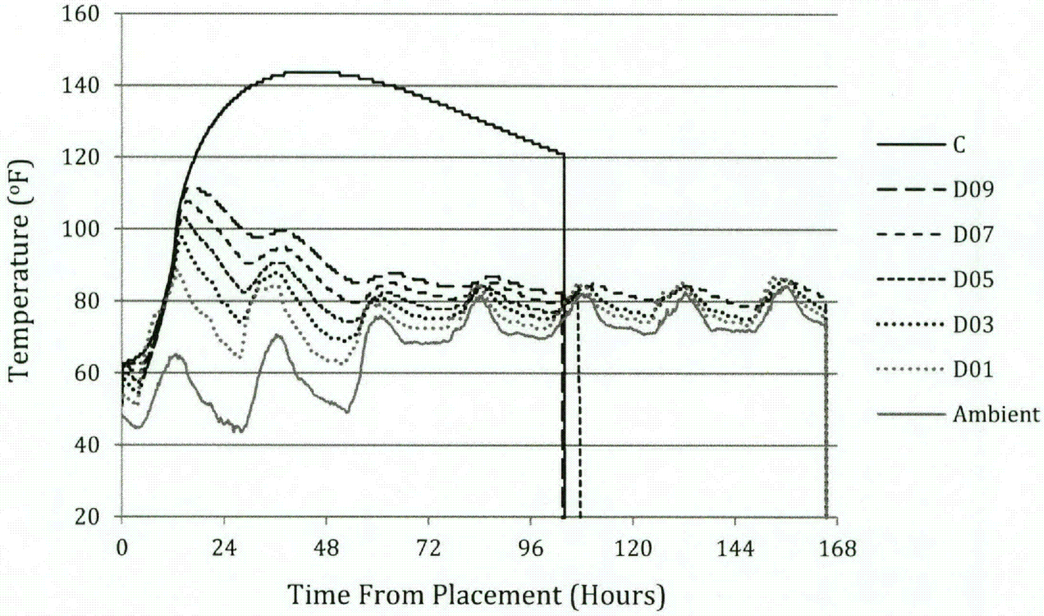


Figure 5.7: WBSB 8 Observed Data (Temperature Bar D—South)

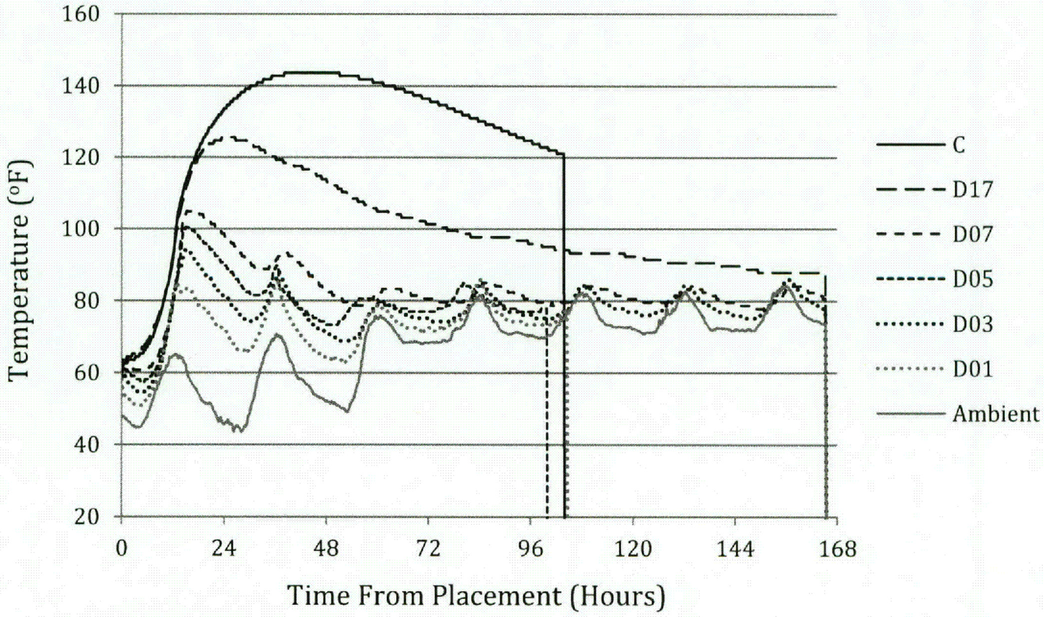


Figure 5.8: WBSB 8 Observed Data (Temperature Bar D—North)

ConcreteWorks simulations were performed for each LOD and compared with the observed data. For a detailed look at the ConcreteWorks simulations, refer to the screen prints documented in Appendix D.2. Bilinear interpolation of ConcreteWorks' temperature output was used to solve for the temperature at each iButton based on its location and the predicted temperatures of the four surrounding nodes. This method was performed at each 5-minute time step and allowed ConcreteWorks' prediction to be directly compared with data gathered from the field.

Maximum Temperature

The maximum temperature recorded in Column 8 was 143.6 °F. The most accurate ConcreteWorks simulation was LOD 3, which came within 5.8 °F of the observed maximum temperature. Figure 5.9 and Table 5.3 present the results.

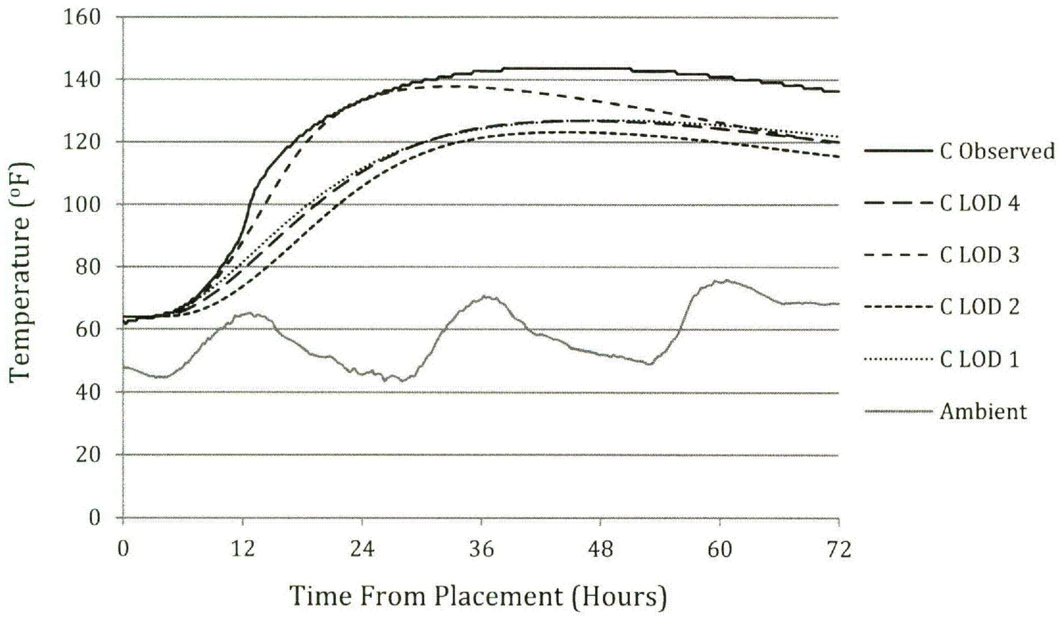


Figure 5.9: WBSB 8 Sensor C Comparison

Table 5.3: WBSB 8 Maximum Temperature Summary

MAX	OBS	LOD 4	LOD 3	LOD 2	LOD 1
Temperature, °F	143.6	126.9	137.8	123.2	127.0
Differential, °F	81.0	59.9	71.9	56.2	63.0

Thermal Gradients

Tables 5.4 and 5.5 present thermal gradient data.

Table 5.4: WBSB 8 Maximum Thermal Gradients (°F/inch)—Temperature Bar D

REGION	OBS (S)	OBS (N)	LOD 4	LOD 3	LOD 2	LOD 1
C - D17	-	0.76	0.57	0.65	0.53	0.59
D17 - D09	-	-	1.26	1.67	1.19	1.35
D09 - D07	2.67	-	1.71	2.24	1.61	1.66
D07 - D05	2.67	3.74	1.93	2.54	1.81	1.87
D05 - D03	2.94	2.94	1.67	2.19	1.57	1.59
D03 - D02	3.74	3.74	1.48	1.93	1.39	1.37
D02 - D01	4.27	3.21	1.35	1.76	1.27	1.23

Table 5.5: WBSB 8 Maximum Thermal Gradients (°F/inch)—Temperature Bar F

REGION	OBS (S)	OBS (N)	LOD 4	LOD 3	LOD 2	LOD 1
C - F17	-	-	0.62	0.70	0.57	0.64
F17 - F09	-	-	1.46	1.85	1.36	1.63
F09 - F07	-	-	2.37	3.14	2.23	2.54
F07 - F05	-	-	2.37	3.14	2.23	2.54
F05 - F03	-	-	2.37	3.14	2.23	2.54
F03 - F02	-	-	2.37	3.14	2.23	2.54
F02 - F01	-	-	2.37	3.14	2.23	2.54

5.3 Case Study: IH 35/SH 71 WBSB Column 9

The Interstate Highway 35/State Highway 71 (IH 35/SH 71) interchange is located in southeast Austin. The original interchange was constructed in 2003. This construction project is a phase 2 effort that adds remaining connector ramps not included in the original highway interchange. The WBSB ramp connects westbound SH 71 to southbound IH 35. It's the tallest ramp on site, with several mass-concrete columns exceeding 100 feet in height. At the center of this ramp and at the very center of the entire interchange is Column 9. Situated between the northbound and southbound lanes of IH 35 as well as the eastbound and westbound lanes of SH 71, Column 9 is a massive 11' 10" x 7' 6" column that rises 111 feet from its base.

5.3.1 Project Details

Similarly to Column 8, two quadrants of the column were instrumented for redundancy. As seen in Figure 5.10, Column 9 is oriented such that the south corner gets significantly more solar radiation than any other corner. To compare the impact this had on temperatures, the southern-most and northern-most quadrants were chosen for instrumentation.

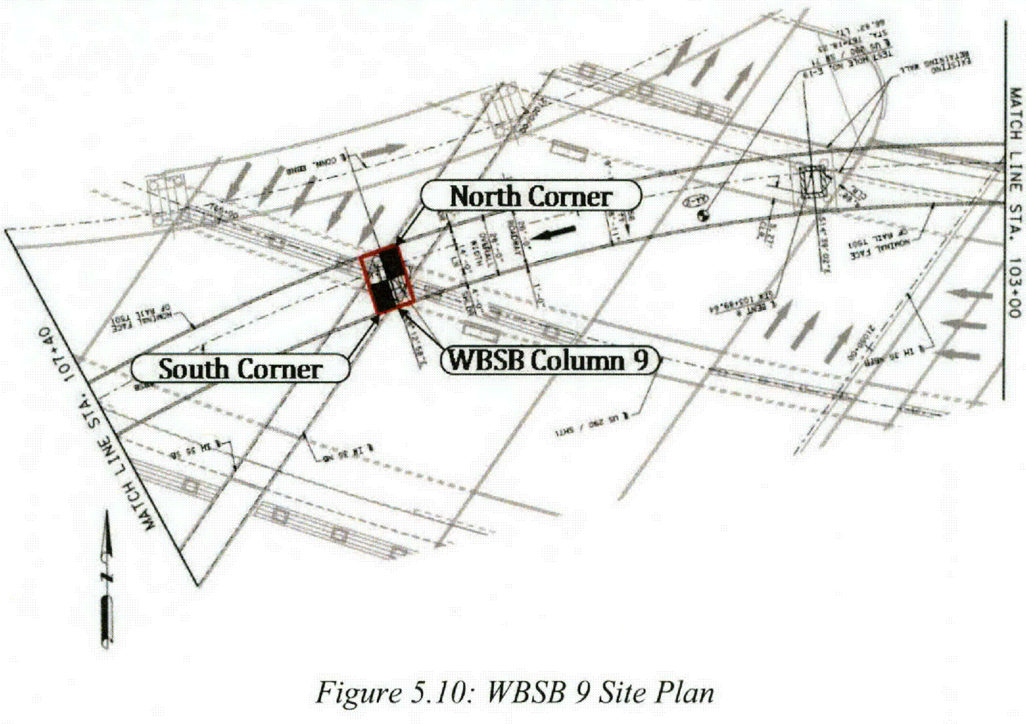


Figure 5.10: WBSB 9 Site Plan

Column 9 differs from Column 8 in that it isn't a simple rectangular column. Each of the two widest faces has a 3-foot wide x 3-inch deep architectural inset. Unfortunately, ConcreteWorks does not model complex shapes, so a decision had to be made on how model the insets most accurately. The formwork for the insets, as seen in Figure 5.11, is important because, as will be seen from the sensor data, it provided significant insulation and caused even the concrete near the surface to behave semi-adiabatically.

Figure 5.11: WBSB 9 Inset Formwork

Two possibilities were available for trying to model the impact of the insets in ConcreteWorks. The actual dimensions of the column, as shown in Figure 5.12, are 11' 10" x 7' 6". One option was to model the structure as an 11' 10" x 7' column with architectural form liners across the width. Form liners, just like the insets, tend to minimize the exchange of heat between the concrete and the environment. On the actual column, the insets cover a relatively small portion of the width. By modeling the column with the full width insulated, the entire column would behave semi-adiabatically, the maximum predicted temperature would be artificially high, and thermal gradients would be significantly reduced. The simplest solution, and probably the best representation of the actual column, was to ignore the insets and model the structure as an 11' 10" x 7' 6" rectangular column.

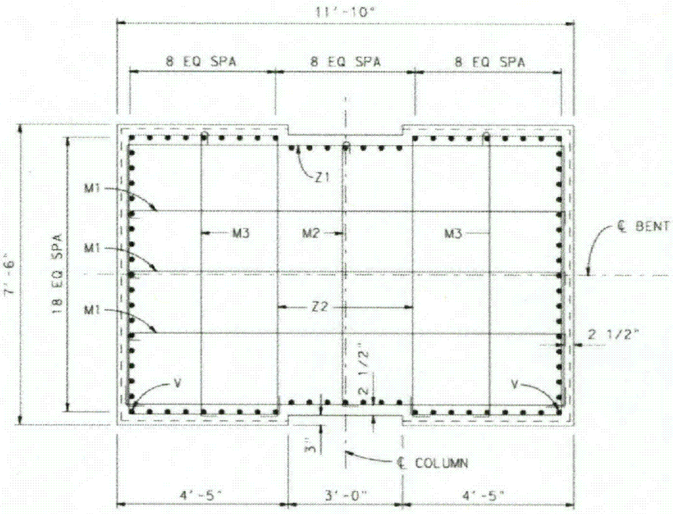


Figure 5.12: WBSB 9 Design Drawing

As seen in Figure 5.13, access to the upper half of the column was available from the roadway deck of IH 35. Concrete barriers were installed along the left shoulder of the southbound deck, allowing for a well-protected workspace. The structure was poured in three stages: 0 to 50 feet for Stage 1, 50 to 100 feet for Stage 2, and the capitol on Stage 3. To minimize pressure head from the concrete poured above, sensors were installed midway up Stage 2 at approximately 75 feet from the base of the column. This also eliminated the effects of the shade created by the IH 35 roadway decks.

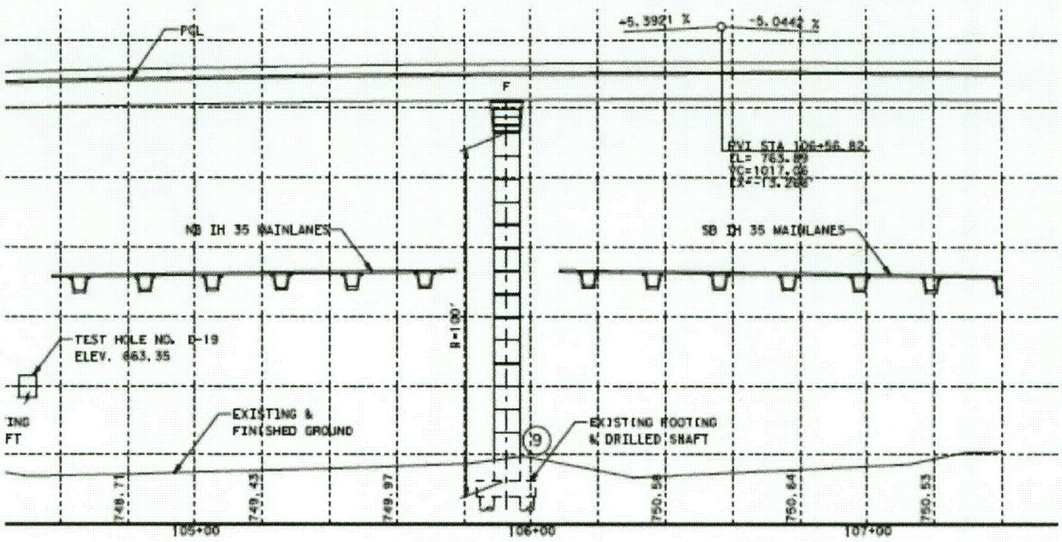


Figure 5.13: Column 9 Profile View

5.3.2 Materials and Mixture Proportions

Concrete was supplied by Lauren Concrete batch plant #1, located just a few miles southeast of the site on McKinney Falls Parkway. The mix design used for Column 9 is essentially the same as that used for Column 8. The paste fraction involved a mixture of Type I/II cement produced by Capitol, 25% Class F fly ash, and a water-to-cement ratio of 0.42. Coarse aggregate was a manufactured dolomitic limestone originating from Marble Falls, Texas, and the fine aggregate was siliceous river sand. Sika 2100 high range water reducer was added for workability and Sika 930 for set retardation. Table 5.6 summarizes the mixture proportions as per the batch sheet acquired for the concrete placed at the location of the sensors.

Table 5.6: WBSB 9 Mix Design

Raw Materials		Amount
Cement	Capitol Type I/II	431.5 lb
SCM	Class F Fly Ash	107.5 lb
Water	0.42 W/C	231.2 lb
Coarse Aggregate	1 1/2" Dolomitic Lime	1906.0 lb
Fine Aggregate	River Sand	1348.0 lb
Admixtures		**Amount**
Water Reducer	Sika ViscoCrete 2100	3.00 fl oz/cwt
Retarder	Sikatard 930	2.60 fl oz/cwt

5.3.3 Instrumentation

Due to the problems experienced with Column 8, an entirely new approach was taken to the fabrication of temperature bars. Instead of using rebar, 1/4-inch diameter hollow steel tubing was adopted as the new platform. Overall, the hollow steel tubing provided many advantages. It was easier to cut and shape. The notches, which provide a stable place to seat the iButtons, were very easily cut and widened in either direction to accurately place sensors at exactly 1, 2, 3, 5, 7, 9, and 17 inches. All of the communication wires were routed internally through the tube. The notches were cut slightly large, providing access for the wires to be soldered to the sensors. Finally, a much tougher epoxy was found. To prevent water intrusion, the sensors were coated with the epoxy on the outside and the tubes were injected with epoxy at each end. The result of all these changes was a very lightweight and rugged system with very few potential entry points for water. The only downside to the hollow tubes is that they bend easier if stepped on. This risk was mitigated by installing the temperature bars on the underside of rebar whenever possible. Figure 5.14 shows one of the temperature bars being assembled.

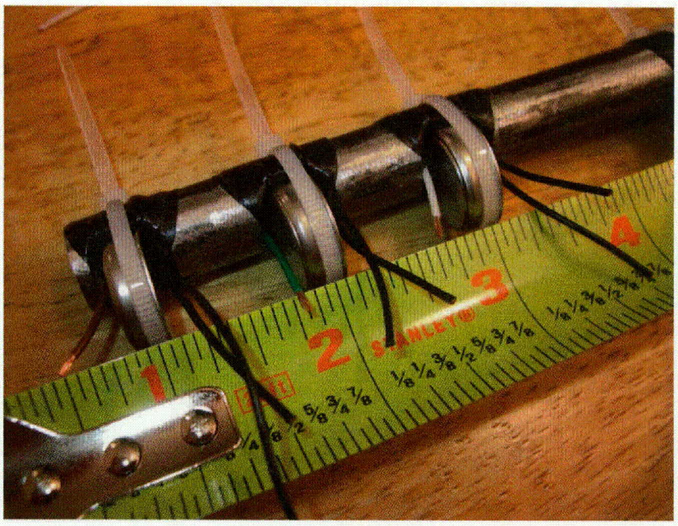


Figure 5.14: Fabrication of New Temperature Bar

Temperature bars were strategically placed to capture the maximum thermal gradient and a single sensor was placed at the center of the column to measure the maximum temperature. Placement of the temperature bars is depicted by Figure 5.15, which illustrates one quadrant of the column. The axes represent the exterior faces of the column, where point (0,0) is the corner and point (71,45) is the center of the column. ConcreteWorks predicted temperatures are reported at the nodes indicated by the + symbols. The iButton locations as installed in the column are also illustrated.

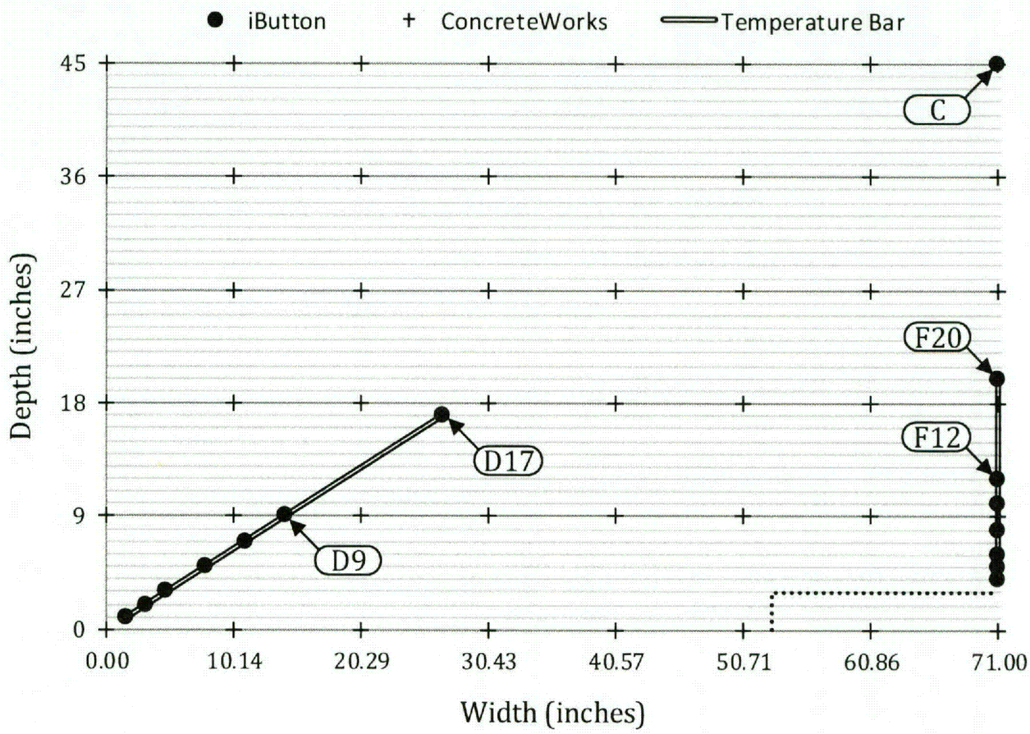


Figure 5.15: WBSB 9 Detailed Instrumentation Scheme

The same naming scheme used for Column 8 also applies to Column 9. D represents the diagonal temperature bar extending toward the corner of the column, where sensor D7, for example, designates the sensor on the diagonal temperature bar located 7 inches away from the column's widest face. F represents the temperature bar extending toward the widest face, where sensor F4, for example, denotes the sensor on the central temperature bar located 4 inches from the concrete surface. It's important to note that with the architectural insets, F4 is only located one inch from the concrete surface of the actual column. The naming scheme applies to the column as it is modeled. To avoid confusion, the architectural insets are shown as a dotted line on the figure above. Finally, C represents the single sensor placed at the center of the column. Figures 5.16 and 5.17 show the completed installation of sensors in one quadrant of the column.

Figure 5.16: WBSB 9 Completed Instrumentation

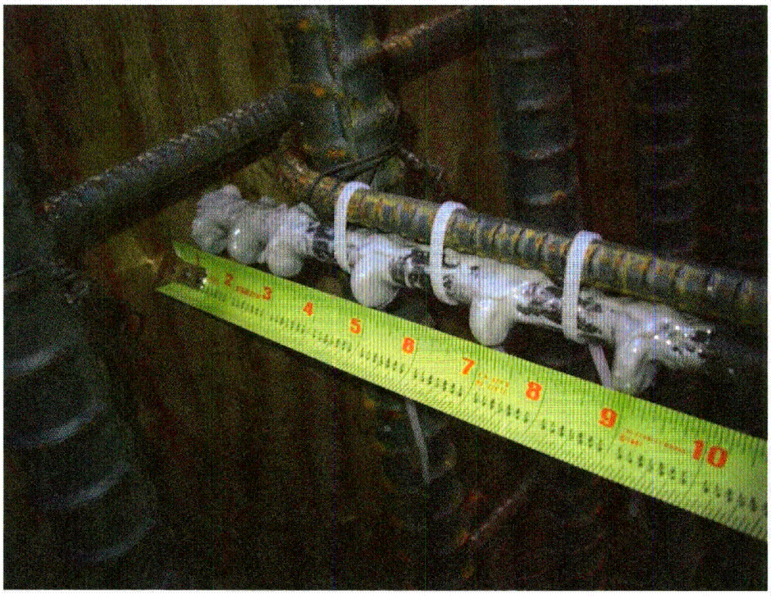


Figure 5.17: WBSB 9 Instrumentation

5.3.4 Field Observations

A commercial weather station was set up on site prior to the pour and programmed to record temperature, wind speed, relative humidity, and solar radiation on a 15-minute interval. The daily conditions are summarized in Table 5.7. For detailed comparisons between the actual weather, ConcreteWorks' predicted weather, and adjustments made to ConcreteWork's predicted weather, refer to Appendix E.1.

Table 5.7: WBSB 9 Weather Station Data

Date	Temperature		Wind Speed	Cloud Cover	Relative Humidity	
-	MAX	MIN	MAX	AVG	MAX	MIN
12/20/2010	74.9	51.1	9.8	55%	90.7	50.6
12/21/2010	77.3	62.6	9.0	56%	88.4	52.9
12/22/2010	64.7	53.7	8.5	100%	93.0	48.1
12/23/2010	64.9	52.7	7.9	99%	71.0	53.8
12/24/2010	65.9	45.5	14.4	100%	93.1	71.5
12/25/2010	45.8	35.5	14.2	56%	80.2	50.4
12/26/2010	50.3	29.0	6.2	17%	80.8	32.8
12/27/2010	59.1	31.8	9.5	32%	85.2	44.2

On December 20, 2010, at 8:00 a.m., Stage two of the concrete pour began and raw materials were acquired from the batch plant for laboratory testing. At 12:30 p.m., concrete was placed at the sensors, cylinders were cast for mechanical testing, and the semi-adiabatic calorimeter was setup and taken to a climate controlled space at the Pickle Research Campus in North Austin. Cement and fly ash were acquired from the batch plant on the morning of the pour for physical and chemical analysis.

5.3.5 Observed Predicted Temperatures

Figures 5.18 and 5.19 show the effect of the architectural insets, as temperatures behaved semi-adiabatically.

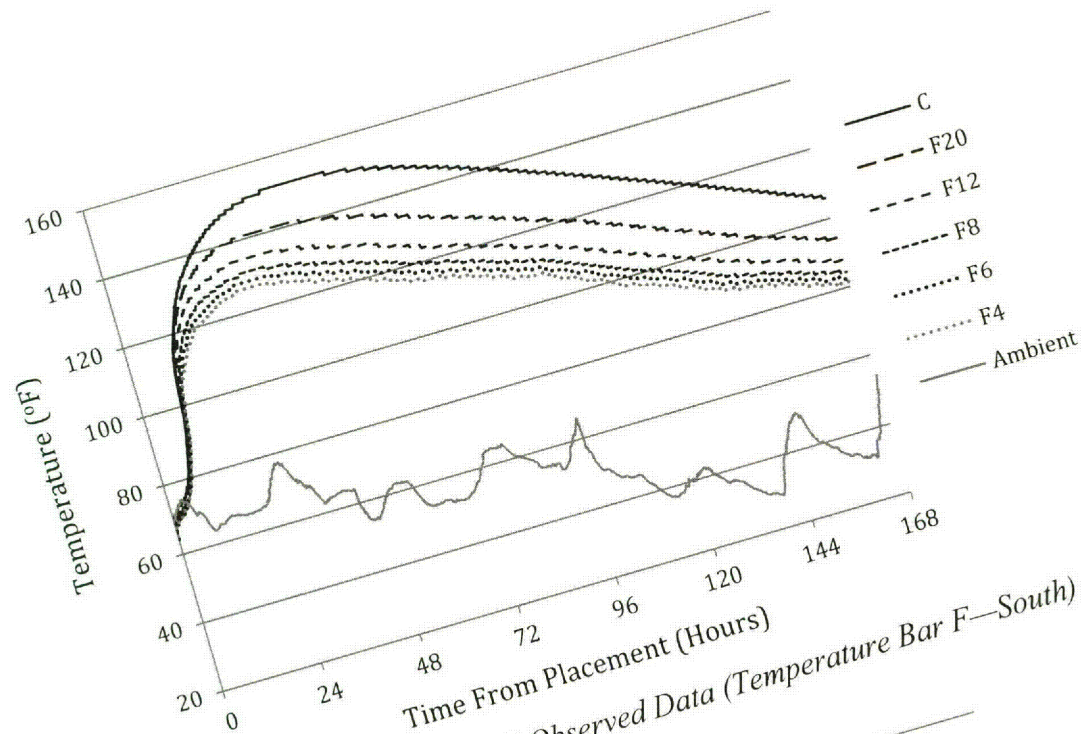


Figure 5.18: WBSB 9 Observed Data (Temperature Bar F—South)

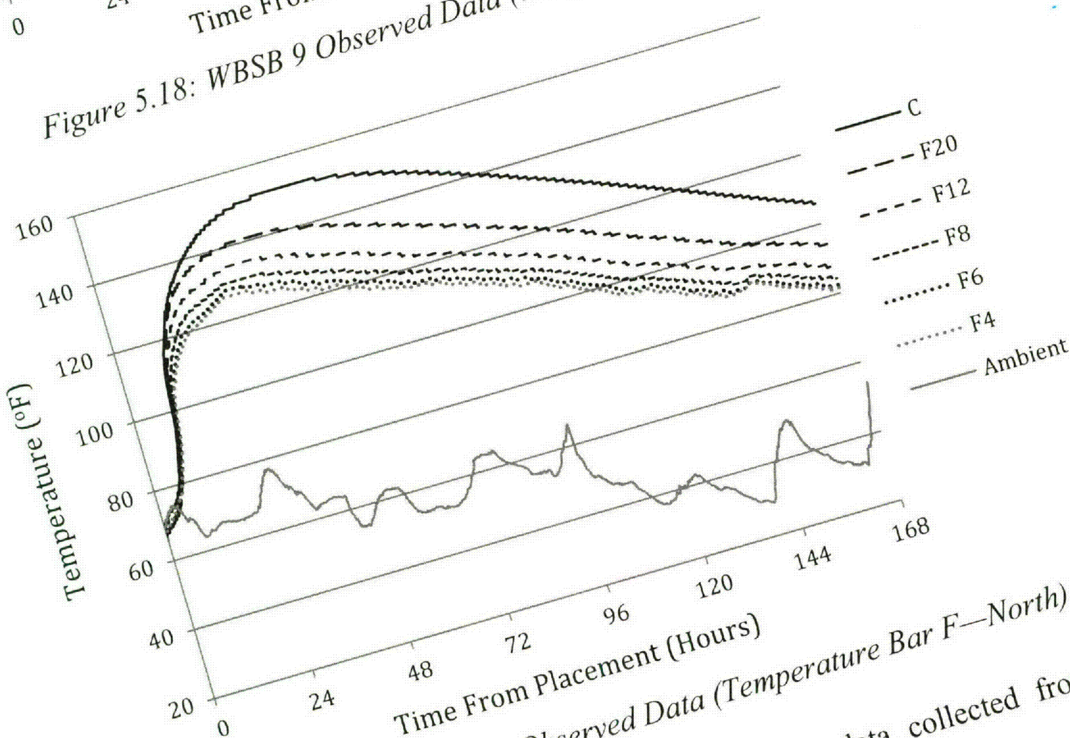


Figure 5.19: WBSB 9 Observed Data (Temperature Bar F—North)

Figures 5.20 and 5.21 show the majority of the data collected from the diagonal temperature bars.

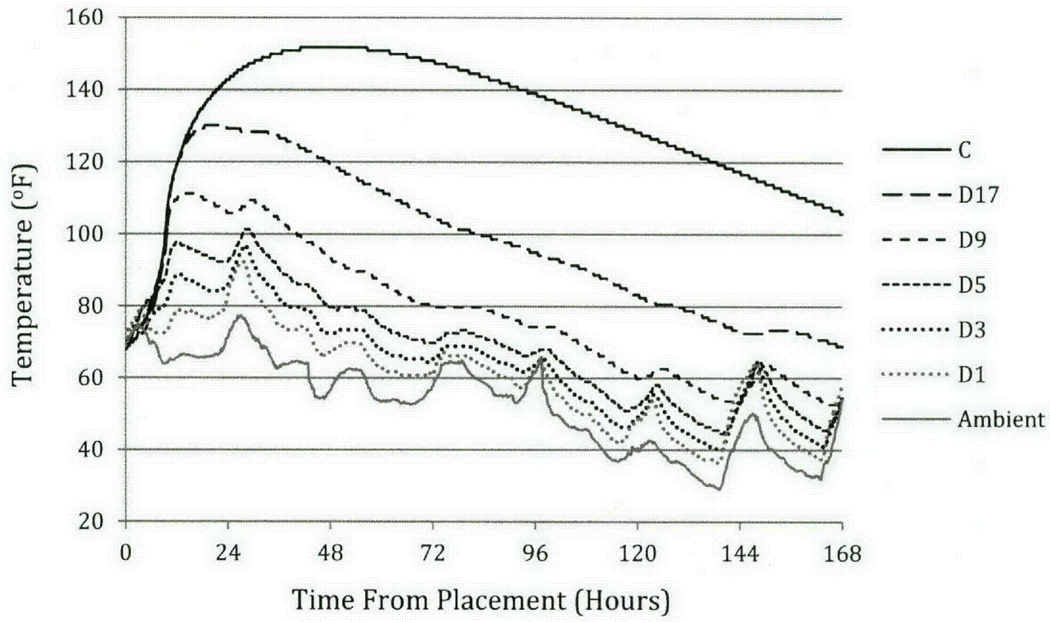


Figure 5.20: WBSB 9 Observed Data (Temperature Bar D—South)

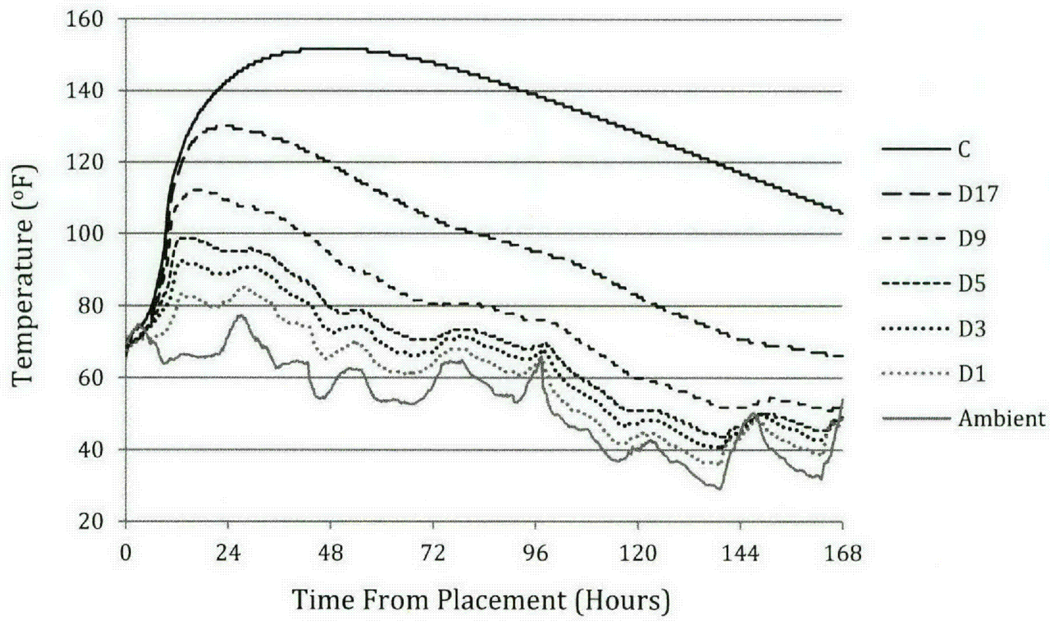


Figure 5.21: WBSB 9 Observed Data (Temperature Bar D—North)

Predicted Maximum Temperature

Figure 5.22 and Table 5.8 present sensor comparison and thermal performance data.

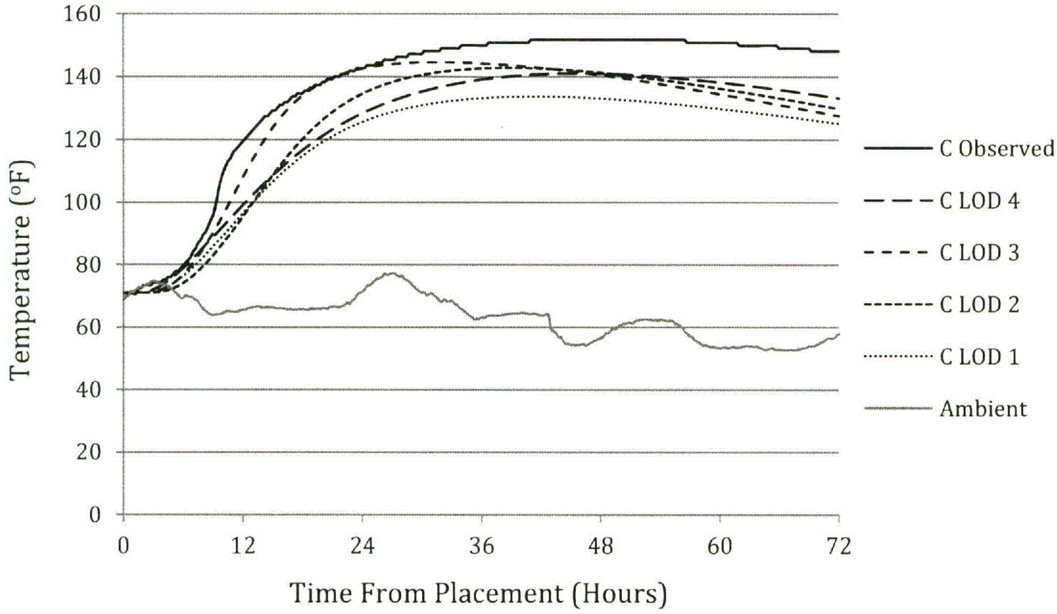


Figure 5.22: WBSB 9 Sensor C Comparison

Table 5.8: WBSB 9 Thermal Performance Summary

MAX	OBS	LOD 4	LOD 3	LOD 2	LOD 1
Temperature, °F	151.7	141.1	144.6	142.8	133.7
Differential, °F	89.1	71.3	70.7	69.9	75.7

Thermal Gradients

The maximum temperature difference recorded by the iButtons was 89.1 °F. The maximum gradient measured between any two sensors was 6.30 °F/inch (Tables 5.9 and 5.10). In relation to tables discussing gradients, the "region" column represents C for center, D for diagonal, and F for Face. The numbers following the prefix are the distance (inches) from the widest face of the column.

Table 5.9: Maximum Thermal Gradients (°F/inch)—Temperature Bar F

REGION	OBS (S)	OBS (N)	LOD 4	LOD 3	LOD 2	LOD 1
C - F20	0.61	0.65	0.68	0.65	0.66	0.71
F20 - F12	1.13	1.13	1.66	1.65	1.63	1.80
F12 - F10	1.35	1.35	1.81	1.83	1.81	2.00
F10 - F08	1.35	1.80	2.19	2.25	2.25	2.50
F08 - F06	1.80	1.80	2.67	2.71	2.73	3.04
F06 - F05	1.80	2.25	2.67	2.71	2.73	3.04
F05 - F04	1.80	4.05	2.67	2.71	2.73	3.04

Table 5.10: WBSB 9 Absolute Max Gradients (°F/inch)—Temperature Bar D

REGION	OBS (S)	OBS (N)	LOD 4	LOD 3	LOD 2	LOD 1
C - D17	0.88	0.89	0.63	0.61	0.61	0.65
D17 - D09	1.81	1.75	1.36	1.40	1.40	1.51
D09 - D07	2.17	2.17	1.64	1.68	1.68	1.80
D07 - D05	2.17	1.93	1.82	2.02	1.90	2.01
D05 - D03	2.89	2.17	1.71	1.93	1.79	1.87
D03 - D02	2.89	2.89	1.50	1.70	1.57	1.61
D02 - D01	2.89	3.37	1.36	1.54	1.42	1.43

5.4 Discussion

Temperatures predicted by ConcreteWorks were a little lower than temperatures observed in the field. However, there is concern that cementitious materials were contaminated during collection from the batch plant.

Whereas the mass concrete specification limits temperature differences to 35 °F or less, both observed columns as well as the ConcreteWorks models produced temperature differences varying between 70 °F and 80 °F. Regardless, structures in the field exhibited no signs of cracking.

5.5 Conclusion and Recommendations

Recommendations are as follows:

- Investigation into the implications of a maximum thermal gradient instead of a maximum temperature difference.
- A better method of acquiring cementitious materials from a batch plant is needed. Cross contamination is too likely when collecting materials from the primary chute. It is believed that cementitious materials collected for Column 8 and Column 9 were contaminated with fairly high amounts of fly ash, very likely causing a significant impact on the results for XRF, XRD, and isothermal calorimetry testing.

Chapter 6. Chloride Service Life

6.1 Case Study: Copano Bay Bridge

The Copano Bay Bridge is located on SH 35, just a few miles north of Fulton, Texas (Figure 6.1). Constructed in 1967, the causeway was the replacement of a narrow two-lane structure built of timber and concrete around 1930. After 45 years, the new structure is the latest casualty to be claimed by the harsh coastal environment. With construction of the third structure soon underway, the purpose of this portion of the research is to provide guidance on the selection of materials and mixture proportions to achieve a 75-year minimum design life.

Figure 6.1: Copano Bay Bridge (Looking Northeast)

On April 12, 20011, 6 concrete cores were extracted from the Copano Bay Bridge. Three different zones were targeted with two cores each: the tidal zone, splash zone, and spray zone. Specifically, two cores were pulled below the tie beams at water level (tidal zone); two cores were pulled from the tie beam a couple feet above the water level (splash zone); and two cores were pulled from the roadway (spray zone). Two additional cores were taken from the concrete deck of the original causeway, which is currently used as a fishing pier.

6.1.1 Field Observations

Access to the piers was made possible by boat. The opportunity was taken while on the boat to survey some of the degradation of the causeway's substructure, seen in Figures 6.2–6.6.

Figure 6.2: Corrosion of Tie Beam and Column

Figure 6.3: Cracking of Tie Beam and Column

Figure 6.4: Cracking of Tie Beam

Figure 6.5: Corrosion of Precast Concrete Piling

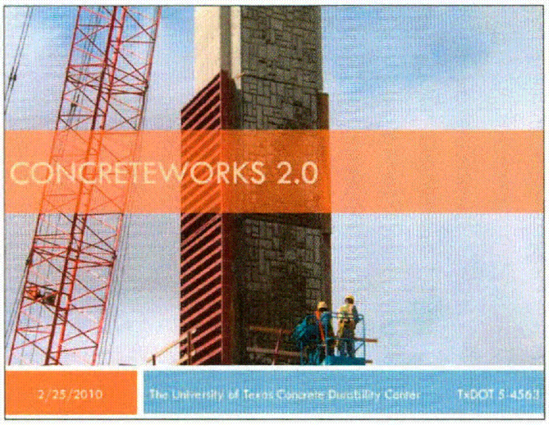
Figure 6.6: Corrosion of Concrete Slab and Girder Span

Chapter 7. Conclusion

The ability exists to engineer concrete to achieve not only strength and workability requirements, but thermal requirements as well. Materials and mixture proportions can be specifically selected to attenuate early age heat evolution or minimize it altogether. Aggregates can be selected based on their ability to minimize thermal gradients at the expense of maximum temperature or vice versa. Materials and mixture proportions have major implications on the heat evolution of a concrete mixture as well as the transfer of heat through the structure during curing. ConcreteWorks has the capability to model these variables and more, however it still needs more exposure within the Texas Department of Transportation to gain traction. A 4-hr ConcreteWorks training course was developed and delivered to TxDOT engineers, inspectors, and contractors throughout the state of Texas. Additionally, this research equates to a complete guide on how to instrument field structures, what information is needed to model those structures, and how to use ConcreteWorks to compare the results. If ConcreteWorks is to succeed as a critical component of the mass concrete specification, it needs more opportunities to be applied in the field by TxDOT employees.

Appendix A: ConcreteWorks Training

Austin Pilot Class



Purpose

- Enhance Knowledge And Use Of ConcreteWorks Across TxDOT Districts
- Identify And Train TxDOT Districts With Upcoming Projects Suitable For ConcreteWorks Implementation
- Provide Technical Support For Districts Interested In Implementing ConcreteWorks On Upcoming Projects
- Specification Approach For ConcreteWorks

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Purpose

Implementation

- Up To Four Projects
- Technical Support And Guidance
- On Site Instrumentation And Testing
  - Semi-Adiabatic Calorimetry
  - Isothermal Calorimetry
  - Maturity
- Validation Of ConcreteWorks

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Purpose

Implementation

- Preferred Projects
  - Mass Concrete
    - Rectangular Columns
    - Thermal Cracking Tendencies
  - Service-Life Prediction
    - Marine Structures
    - Exposure to Deicing Salts

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Agenda

Start		End	Topic
9:00 AM	-	9:25 AM	ConcreteWorks Overview
9:25 AM	-	10:10 AM	Mix Design and Proportioning
10:10 AM	-	10:25 AM	Break
10:25 AM	-	10:45 AM	Demonstration
10:45 AM	-	11:30 PM	Heat of Hydration and Thermal Stress Analysis
11:30 PM	-	12:00 PM	Demonstration & Questions
12:00 PM	-	1:00 PM	Lunch
1:00 PM	-	1:45 PM	Chloride Service-Life Modeling
1:45 PM	-	2:00 PM	Demonstration
2:00 PM	-	2:20 PM	Other Durability Related Issues
2:20 PM	-	2:30 PM	Group Project - Overview and Instructions
2:30 PM	-	3:00 PM	Group Project - Case Study
3:00 PM	-	3:15 PM	Break
3:15 PM	-	3:30 PM	Group Project - Presentations
3:30 PM	-	4:00 PM	Implementation of ConcreteWorks

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ConcreteWorks 2.0 Overview

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Item 420.4.G4 (2004)

- Mass placements are defined as placements with a least dimension greater than or equal to 5 ft., or designated on the plans. For monolithic mass placements, develop and obtain approval for a plan to ensure the following during the heat dissipation period:
  - the temperature differential between the central core of the placement and the exposed concrete surface does not exceed 35°F and
  - the temperature at the central core of the placement does not exceed 160°F.
- Base this plan on the equations given in the Portland Cement Association's Design and Control of Concrete Mixtures. Cease all mass placement operations and revise the plan as necessary if either of the above limitations is exceeded. Include a combination of the following elements in this plan:
  - selection of concrete ingredients including aggregates, gradation, and cement types, to minimize heat of hydration;
  - use of ice or other concrete cooling ingredients;
  - use of liquid nitrogen dosing systems;
  - controlling rate or time of concrete placement;
  - use of insulation or supplemental external heat to control heat loss;
  - use of supplementary cementing materials; or
  - use of a cooling system to control the core temperature.
- Furnish and install 2 sets of temperature recording devices, maturity meters, or other approved equivalent devices at designated locations. Use these devices to simultaneously measure the temperature of the concrete at the core and the surface. Maintain temperature control methods for 4 days unless otherwise approved. Maturity meters may not be used to predict strength of mass concrete.

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Why All The Trouble?

- ...and why the specification?
  - Concrete temperature and concrete durability are related
  - ConcreteWorks can help provide high quality, durable, crack-free concrete

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Why Do We Need A Program?

- The calculations are difficult
- Guidance provided by ACI and PCA is vague
- Information in literature concerning temperature rise of various materials is dispersed
- The problem becomes even more difficult when cracking tendency is considered. The specification does not even address this!

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ConcreteWorks

- User-friendly software package for the design, analysis, and performance prediction of structural concrete
  - Mass Concrete
  - Bridge Decks
  - Concrete Pavements
  - Precast Concrete Members

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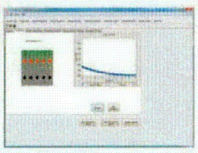
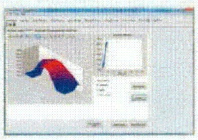
ConcreteWorks





- Mass Concrete
  - Temperature Prediction
  - Cracking Probability
  - Chloride Service-life Analysis
- Bridge Decks
  - Temperature Prediction
  - Chloride Service-life Analysis
- Pavements
  - Temperature Prediction
- Precast/Prestressed Members
  - Temperature Prediction

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ConcreteWorks

- Put In
  - Materials and Mix Design Inputs
  - Geometry of Structural Element
  - Type of Formwork, Base, Etc.
  - Time and Date of Project Placement
    - Weather Conditions
- Get Out
  - Maximum Temperature Prediction
  - Temperature Distribution Throughout Element
  - Maximum Temperature Differential
  - Other Goodies: ASR, DEF, and Sulfate Attack Susceptibility

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ConcreteWorks

- Advantages
  - Evaluation of Concrete Before Poured
  - Prevent Problems Before they Occur
    - No Need to Repair Later
  - Save Consultant Fees $$$$
    - Program Development Paid Now
    - Software is Intended to be Free
  - Save Mix Designs Digitally Forever
    - No Need for Keeping Bulky Paperwork

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ConcreteWorks

How Do We Do It?

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We Bombard You With Equations

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How It Works

- Concrete Hydration Heat Generation
  - (Schindler, 2002)

$$q'(t) = H_u C_c \left(\frac{\tau}{t_e}\right)^{\beta} \left(\frac{\beta}{t_e}\right) \alpha(t_e) \frac{E}{R} \left(\frac{1}{273 + T_r} - \frac{1}{273 + T_c}\right)$$

- Heat Transfer to the Environment
  - (DeWitt, 2002)

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + q' = \rho c_p \frac{\partial T}{\partial t}$$

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How It Works

- Numerical Approximation Methods
- Finite Difference/Control Volume → Energy Balance
  - (Patankar, 1980)
    - Add Rate of Energy Entering the Control Volume
    - Subtract Rate of Energy Leaving the Control Volume
- Result?
  - Change in Stored Energy
    - $\Delta E_{STORED} = E_{IN} - E_{OUT}$

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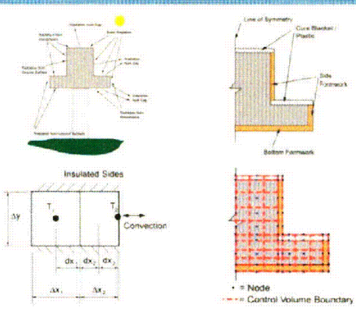
How It Works



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Navigation

What Goes into Modeling a Concrete Structure?

- Member Type
- General Inputs
- Shape Inputs
- Member Dimensions
- Mixture Proportions
- Material Properties
- Mechanical Properties
- Construction Inputs
- Environmental Inputs
- Corrosion Inputs
- Input Check

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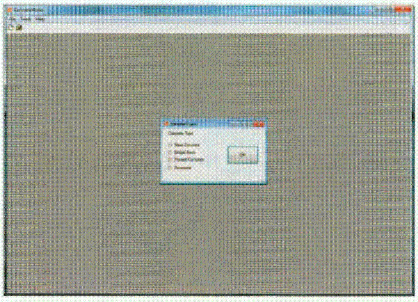
Navigation

Member Type



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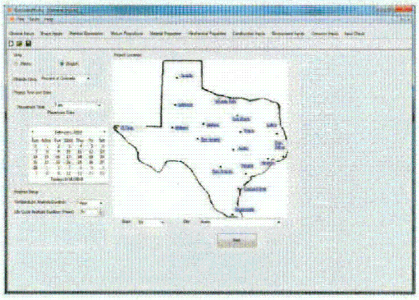
Navigation

General Inputs



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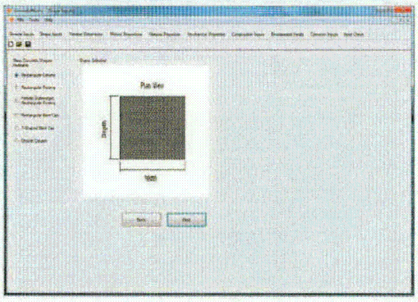
Shape Inputs



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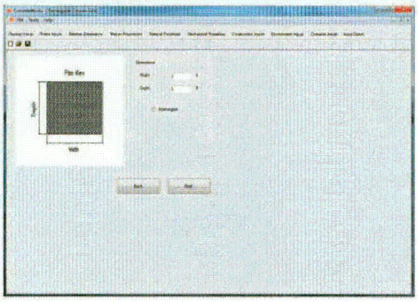
Navigation

Member Dimensions



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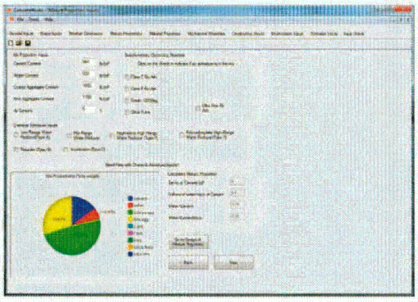
Navigation

Mixture Proportions



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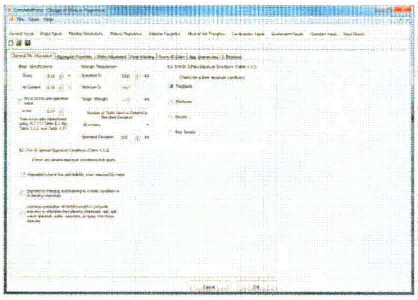
Navigation

Mixture Proportions – General Mix Information



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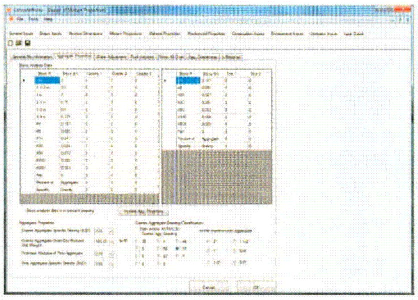
Navigation

Mixture Proportions – Aggregate Properties



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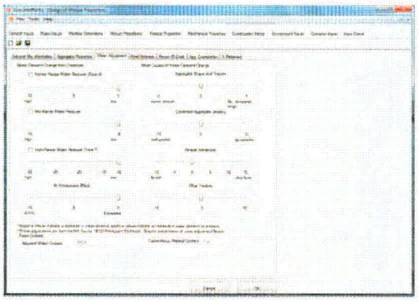
Mixture Proportions – Water Adjustment



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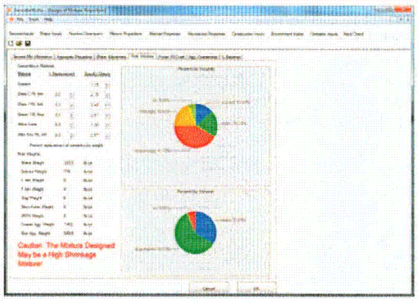
Navigation

Mixture Proportions – Final Volumes



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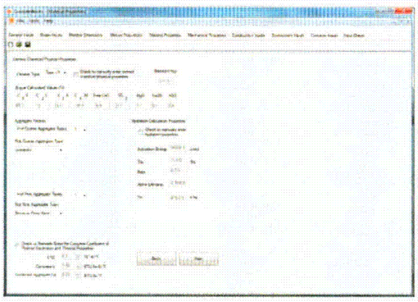
Navigation

Material Properties



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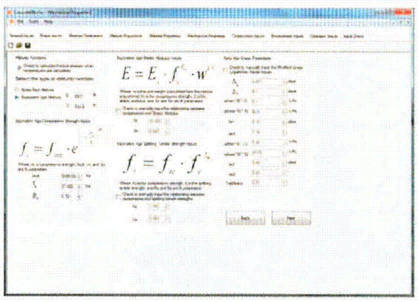
Navigation

Mechanical Properties



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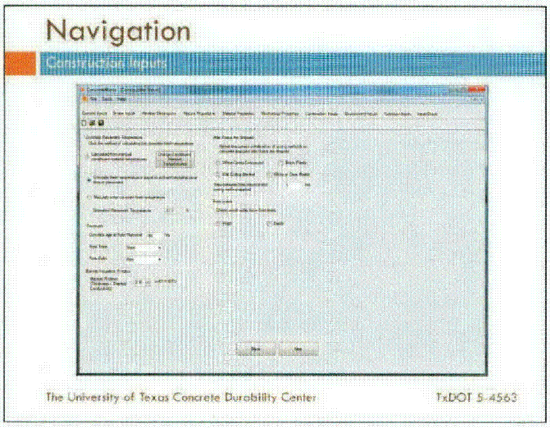
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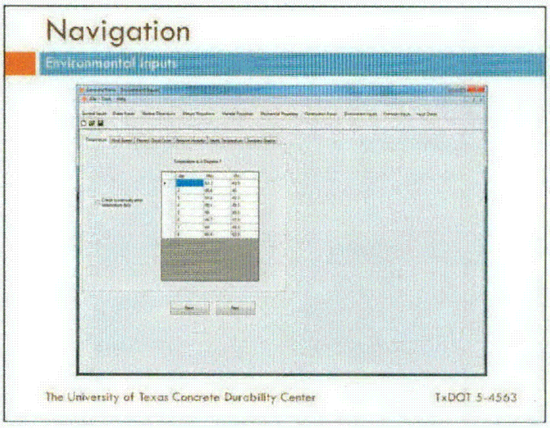
Construction Inputs
The University of Texas Concrete Durability Center
TxDOT 5-4563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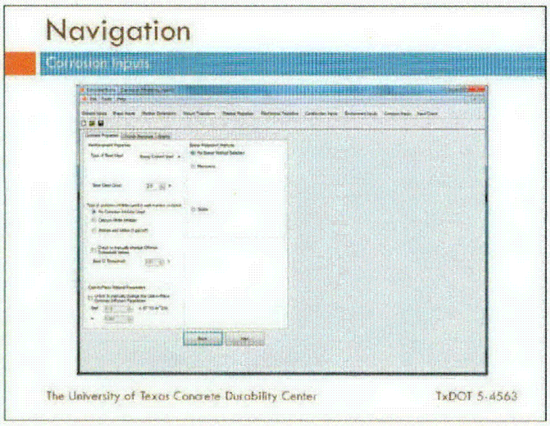
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The University of Texas Concrete Durability Center
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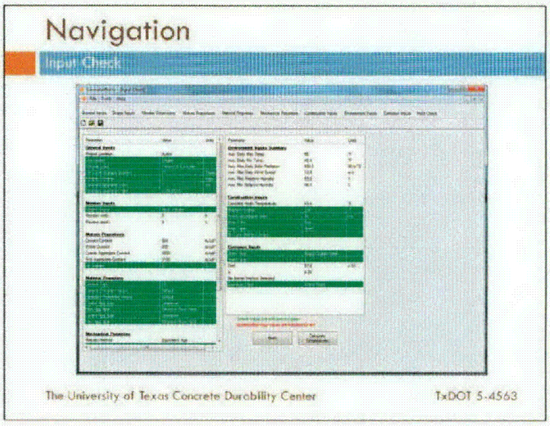
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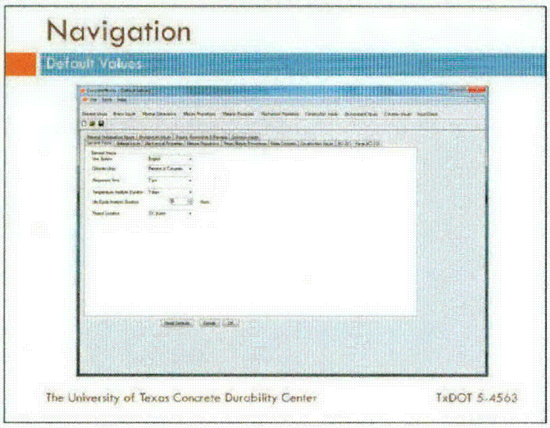
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Default Values
The University of Texas Concrete Durability Center
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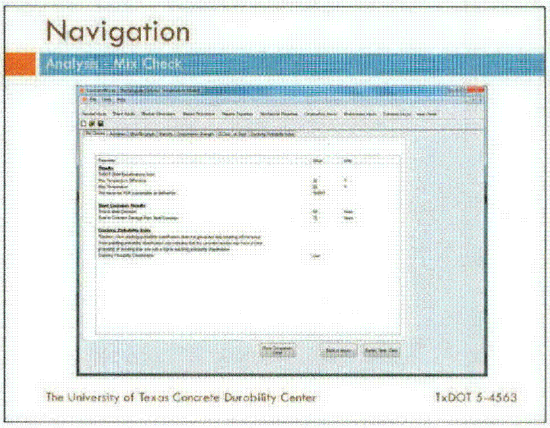
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Analysis - Mix Check
The University of Texas Concrete Durability Center
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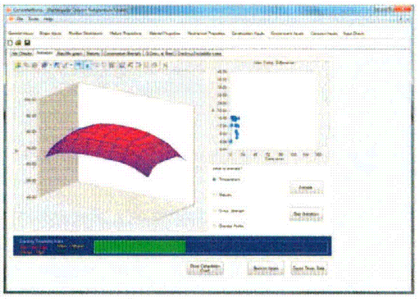
Navigation

Analysis - Animations



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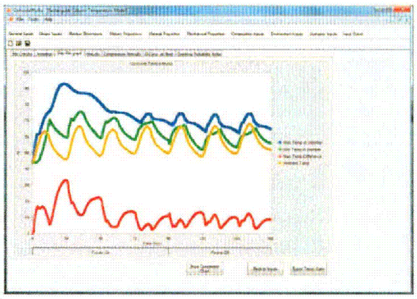
Navigation

Analysis - Temperature Graphs



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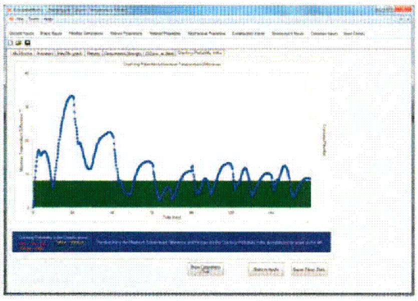
Navigation

Analysis - Cracking Probability Index



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ConcreteWorks

Conclusion

- Benefits
  - Evaluation of Concrete Before Poured
  - Design Mixes With Minimal Crack Susceptibility
  - Improve Longevity of Structures
  - Reduce Replacement and Repair of Structures
  - Reduce Field Discussions Concerning Placement Time and Weather Extremes

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ConcreteWorks

Conclusion

- What it Won't Do:
  - Account for Precipitation
  - Freeze Events
  - Recommend 22% or 23% Fly Ash
  - Model Odd Shaped Concrete Members

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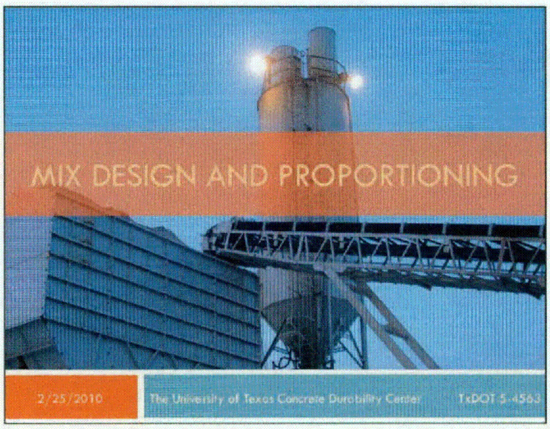

Mix Design And Proportioning

Introduction

- Essential Properties When Designing Concrete:
  - Workability
  - Performance
    - Durability
    - Strength
    - Uniform Appearance
  - Economy

Mix Design & Proportioning

THE ACI 211 METHOD

ACI 211 Mix Design

Overview

- ACI Method Is Based On Comprehensive Laboratory Testing Of Concrete
- Materials Used To Develop The ACI Method Are Likely Different From Local Materials
- It Is Expected That Your Mixture Will Not Perform Exactly As Designed
- Concrete Mixtures In Practice Always Adjusted To Take Advantage Of Local Materials

ACI 211 Mix Design

Overview

- Step 0: Assemble Information
- Step 1: Slump
- Step 2: Maximum Size Aggregate
- Step 3: Water and Air Content
- Step 4: Water to Cement Ratio
- Step 5: Cement Content
- Step 6: Coarse Aggregate Content
- Step 7: Fine Aggregate Content
- Step 8: Aggregate Moisture Content Adjustment
- Step 9: Trial Batch

ACI 211 Mix Design

Step 0: Assemble Information

- From Specifications
  - Slump
  - Member Dimensions
  - Nominal Maximum Size Aggregate
  - Required Air Content
  - Minimum Cementitious Materials Content
  - Specified Strength
  - Maximum Water to Cement Ratio

ACI 211 Mix Design

Step 0: Assemble Information

- Exposure Conditions
  - Freeze-Thaw
  - Marine Environment
  - Sulfates

The University of Texas Concrete Durability Center — TxDOT 5-4563

ACI 211 Mix Design

Step 0: Assemble Information

- Materials
  - Specific Gravities of Cementitious Materials
  - Bulk Specific Gravities of Aggregates
  - Dry-Rodded Unit Weights of Aggregates
  - Aggregate Gradations and Maximum Size
  - Fineness Modulus of Fine Aggregate
  - Aggregate Absorption
  - Aggregate Moisture Content

The University of Texas Concrete Durability Center — TxDOT 5-4563

ACI 211 Mix Design

Step 0: Assemble Information

- Other Requirements (TxDOT Item 421.4.A.6 Mix Design Options)
  - Option 1 - Replace 20 to 35% of the cement with Class F fly ash.
  - Option 2 - Replace 35 to 50% of the cement with GGBFS.
  - Option 3 - Replace 35 to 50% of the cement with a combination of Class F fly ash, GGBFS, or silica fume. However, no more than 35% may be fly ash, and no more than 10% may be silica fume.
  - Option 4 - Use Type IP or Type IS cement (Up to 10% of a Type IP or Type IS cement may be replaced with Class F fly ash, GGBFS, or silica fume).
  - Option 5 - Replace 35 to 50% of the cement with a combination of Class C fly ash and at least 6% of silica fume, UFFA, or metakaolin. However, no more than 35% may be Class C fly ash, and no more than 10% may be silica fume.
  - Option 6 - Use a lithium nitrate admixture at a minimum dosage of 0.55 gal. of 30% lithium nitrate solution per pound of alkalis present in the hydraulic cement.
  - Option 7 - When using hydraulic cement only, ensure that the total alkali contribution from the cement in the concrete does not exceed 3.50 pcy.
  - Option 8 – For any deviations from options 1-7, test aggregates for expansion according to ASTM C 1260

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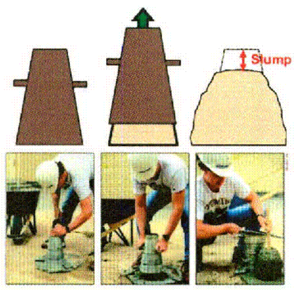
ACI 211 Mix Design

Step 1: Slump



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ACI 211 Mix Design

Step 1: Slump

- Minimize Slump While Maintaining:
  - Ease Of Placement
  - Workability
  - Finishability

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ACI 211 Mix Design

Step 1: Slump

Types of Construction	Slump, in.	
	Max	Min
Reinforced Foundation Walls and Footings	3	1
Plain Footings, Caissons, and Substructure Walls	3	1
Beams and Reinforced Walls	4	1
Building Columns	4	1
Pavements and Slabs	3	1
Mass Concrete	2	1

ACI 211 Table 6.3.1

Rule of Thumb: 1" of Slump ≈ 10 lb/yd^3 of Water

The University of Texas Concrete Durability Center — TxDOT 5-4563

ACI 211 Mix Design

Step 2: Maximum Size Aggregate

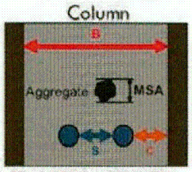
- Maximum Size Aggregate (MSA)
  - Determined By:
    - Formwork Clearance
    - Concrete Member Thickness
    - Reinforcement Spacing
    - Cover Over Steel Reinforcement
  - Affects Workability, Cost, And Performance
  - Sieve Size On Which 5 - 15% Of Coarse Aggregate Is Retained (typically 15)

The University of Texas Concrete Durability Center TxDOT 5-4563

ACI 211 Mix Design

Step 2: Maximum Size Aggregate

Column

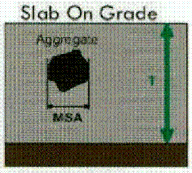


Distance Between Forms (B): $MSA \leq B/5$

Reinforcement Spacing (S): $MSA \leq \frac{3}{4}S$

Cover (C): $MSA \leq \frac{3}{4}C$

Slab On Grade



Thickness of Slab (T): $MSA \leq 1/3$

Pumped Concrete:

$MSA \leq 1/3$ Dia. of Hose

$MSA \leq 1\frac{1}{2}$ in.

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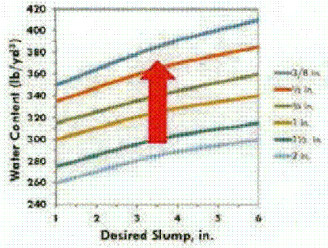
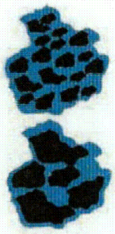
ACI 211 Mix Design

Step 3: Water And Air Content

Reducing The Maximum Aggregate Size Increases Water Content





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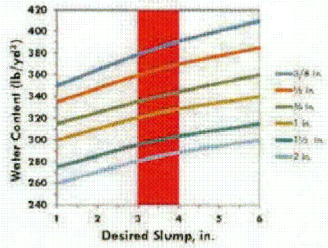
ACI 211 Mix Design

Step 3: Water And Air Content

Desired Slump: 3 - 4 in.
Maximum Sized Aggregate: 1 1/2 in.



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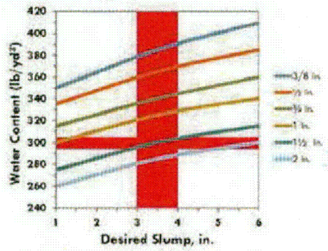
ACI 211 Mix Design

Step 3: Water And Air Content

Desired Slump: 3 - 4 in.
Maximum Sized Aggregate: 1 1/2 in.



Water Content: ~ 295 to 305 lb/yd³

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ACI 211 Mix Design

Step 3: Water And Air Content

Non Air-Entrained Concrete

Mixing Water, lb/yd³ for Indicated Slump and Maximum Size of Aggregate								
Slump, in.	3/8 in.	½ in.	¾ in.	1 in.	1½ in.	2 in.	3 in.	6 in.
1 to 2	350	335	315	300	275	260	220	190
3 to 4	385	365	340	325	300	285	245	210
6 to 7	410	385	360	340	315	300	270	-
Entrapped Air, percent (Approx.)	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.2

ACI 211 Table 6.3.3

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ACI 211 Mix Design

Step 3: Water And Air Content

Air-Entrained Concrete

Mixing Water, lb/yd³ for Indicated Slump and Maximum Size of Aggregate								
Slump, in.	3/8 in.	½ in.	¾ in.	1 in.	1½ in.	2 in.	3 in.	6 in.
1 to 2	305	295	280	270	250	240	205	180
3 to 4	340	325	305	295	275	265	225	200
6 to 7	365	345	325	310	290	280	260	-
Exposure	Recommended Total Air Content, percent							
Mild	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
Moderate	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0
Severe	7.5	7.0	6.0	6.0	5.5	5.0	4.5	4.0

ACI 211 Table 6.3.3

The University of Texas Concrete Durability Center TxDOT 5-4563

ACI 211 Mix Design

Step 4: Water To Cement Ratio

28-Day Compressive Strength, psi	Water-Cement Ratio by Weight	
	Non-Air-Entrained	Air-Entrained
6000	0.41	-
5000	0.48	0.40
4000	0.57	0.48
3000	0.68	0.59
2000	0.82	0.74

ACI 211 Table 6.3.4(a)

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ACI 211 Mix Design

Step 4: Water To Cement Ratio

- Supplementary Cementitious Materials (SCMs)
  - Accounted for by Converting the W/C Ratio Based on the SCM Content and SCM Specific Gravity
  - Weight Equivalency (ACI 211 6.3.4.1)
    - Same Weight of Cementitious Materials
    - Larger Total Volume (Due to Lower SG of SCMs)
  - Absolute Volume Equivalency (ACI 211 6.3.4.2)
    - Same Volume of Cementitious Materials
    - Lower Total Weight of Cementitious Materials

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ACI 211 Mix Design

Step 5: Cement Content

- Calculate Based On Selected Water Content And Water-Cement Ratio

$$\text{Cement } (lb/yd^3) = \frac{\text{Water } (lb/yd^3)}{\text{Water - Cement Ratio}}$$

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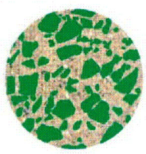
ACI 211 Mix Design

Step 6: Coarse Aggregate Content



- Coarse Aggregate
  - Larger Than 3/8"
  - Up to 6" or More
  - Usually 30-40% of Mix
    - By Volume or Mass
- Gravel
  - Typically Round or Subangular
- Crushed Stone
  - Angular

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ACI 211 Mix Design

Step 6: Coarse Aggregate Content

Volume of Coarse Aggregate per Unit Volume of Concrete				
Nominal Maximum Size of Aggregate	Fine Aggregate Fineness Modulus			
	2.40	2.60	2.80	3.00
3/8 in.	0.50	0.48	0.46	0.44
1/2 in.	0.59	0.57	0.55	0.53
3/4 in.	0.66	0.64	0.62	0.60
1 in.	0.71	0.69	0.67	0.65
1½ in.	0.75	0.73	0.71	0.69
2 in.	0.78	0.76	0.74	0.72
3 in.	0.82	0.80	0.78	0.76
6 in.	0.87	0.85	0.83	0.81

ACI 211 Table 6.3.6

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ACI 211 Mix Design

Step 6: Coarse Aggregate Content

- Coarse Aggregate Factor
  - Intended to Provide Consistent Workability
    - Empirical Basis
  - Multiplied by Dry-Rodded Unit Weight of Coarse Aggregate to Get Coarse Aggregate Content

CA Content = CA Factor x Dry Rodded Unit Weight

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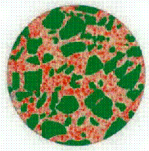
ACI 211 Mix Design

Step 7: Fine Aggregate Content

- Fine Aggregate
  - Sand
  - Crushed Stone
  - 100% Passing 3/8" Sieve
  - Usually 35-45% of Mix
    - By Volume or Mass
  - Only Remaining Volume to be Determined



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ACI 211 Mix Design

Step 7: Fine Aggregate Content

- Calculate Fine Aggregate On Per Cubic Yard Basis

	27 (Unit Volume)	(ft^3)
-	Volume Of Mixing Water	(ft^3)
-	Volume Of Air	(ft^3)
-	Volume Of Portland Cement	(ft^3)
-	Volume Of Coarse Aggregate	(ft^3)
	Volume Of Fine Aggregate	(ft^3)

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ACI 211 Mix Design

Step 8: Moisture Content Adjustment

- Aggregate Volumes Based on Oven-Dry Weights
- Aggregates Pulled From Stock Piles Contain Some Amount Of Moisture
  - Net Change In Water Content And Water-Cement Ratio
  - Need To Adjust For Actual Aggregate Moisture Content

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ACI 211 Mix Design

Step 8: Moisture Content Adjustment

- Mix Design Obtained Following ACI 211:
  - Cement: 564 lb/yd^3
  - Water: 220 lb/yd^3
  - Coarse Aggregate: 1800 lb/yd^3
  - Fine Aggregate: 1100 lb/yd^3

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ACI 211 Mix Design

Step 8: Moisture Content Adjustment

- Mix Design Obtained Following ACI 211:
  - Cement: 564 lb/yd^3
  - Water: 220 lb/yd^3
  - Coarse Aggregate: 1800 lb/yd^3
  - Fine Aggregate: 1100 lb/yd^3
- Aggregate Properties:
  - Coarse Aggregate
    - Absorption: 0.5% (by mass)
    - Moisture: 0.3% (by mass)
  - Fine Aggregate
    - Absorption: 0.9% (by mass)
    - Moisture: 1.3% (by mass)

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ACI 211 Mix Design

Step 8: Moisture Content Adjustment

- Aggregate Water Contribution
  - CA (0.3% - 0.5%) x 1800 lb/yd = -3.6 lb water
  - FA (1.3% - 0.9%) x 1100 lb/yd = +4.4 lb water
- Net Result
  - 4.4 – 3.6 = 0.8 lb water added by aggregates
  - Adjusted mix water = 220 – 0.8 = **219.2 lb/yd^3**

ACI 211 Mix Design

Step 9: Trial Batch

- ACI 211 Mix Design Process is Intended for Trial Batch Only
- You Are Responsible for Making Necessary Adjustments

Mix Design & Proportioning

CONCRETEWORKS MIX DESIGN

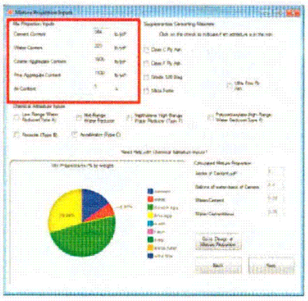
ConcreteWorks Mix Design

Overview

- How Does ConcreteWorks Use Mix Proportions?
  - Heat Signature Of Concrete
  - Diffusion Coefficient For Chloride Service Life
  - Risk Of Shrinkage, ASR, DEF, And Sulfate Attack
  - Many, Many Other Reasons…

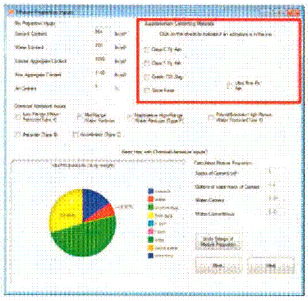
ConcreteWorks Mix Design

Mixture Proportion Inputs



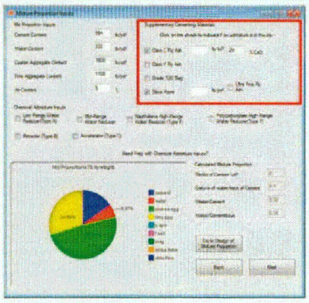
ConcreteWorks Mix Design

Mixture Proportion Inputs – Supplementary Cementing Materials



ConcreteWorks Mix Design

Mixture Proportion Inputs – Supplementary Cementing Materials



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ConcreteWorks Mix Design

Mixture Proportion Inputs – Supplementary Cementing Materials

- Default Free Lime (CaO)
  - Materials
    - Class C Fly Ash – 29% (typical: 22-30%)
    - Class F Fly Ash – 19% (typical: 8-14%)
  - Basis
    - Typical Maximum Free Lime Contents
    - Most Conservative Analysis for Heat of Hydration

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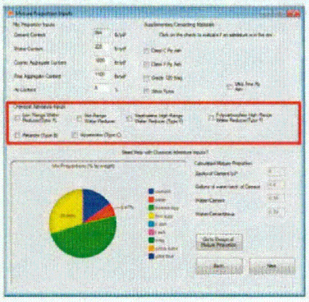
ConcreteWorks Mix Design

Mixture Proportion Inputs – Chemical Admixtures



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ConcreteWorks Mix Design

Mixture Proportion Inputs – Chemical Admixtures

- Chemical Admixtures
  - ConcreteWorks Assumes Typical Dosages
    - Affects Time At Which Heat Is Generated
    - Minimal To No Effects Otherwise

Chemical Admixture	Dose, percent by Mass of Cementitious Materials
LRWR	0.29
WRRET	0.35
MRWR	0.32
NHRWR	0.78
PCHRWR	0.68
ACCL	1.30

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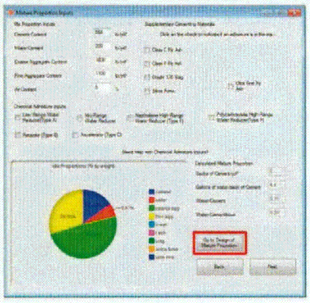
ConcreteWorks Mix Design

Mixture Proportion Inputs – Mix Design



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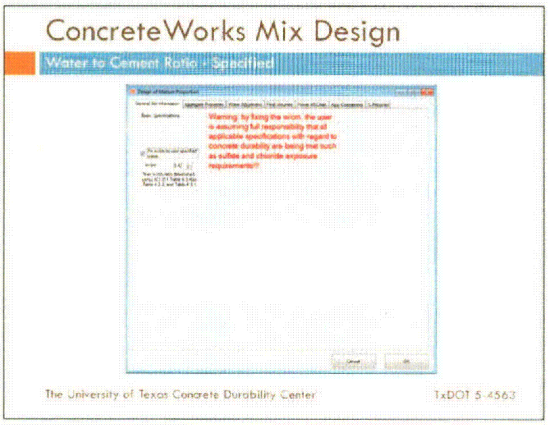
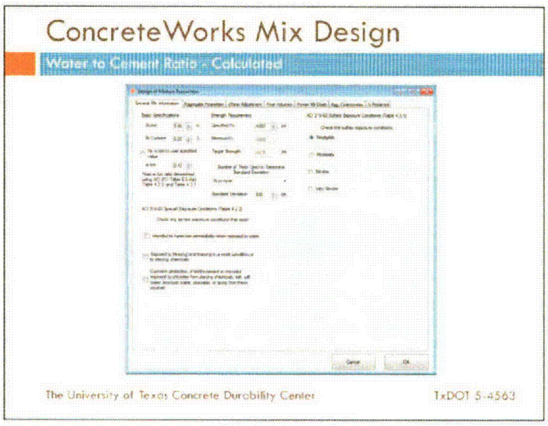
ConcreteWorks Mix Design

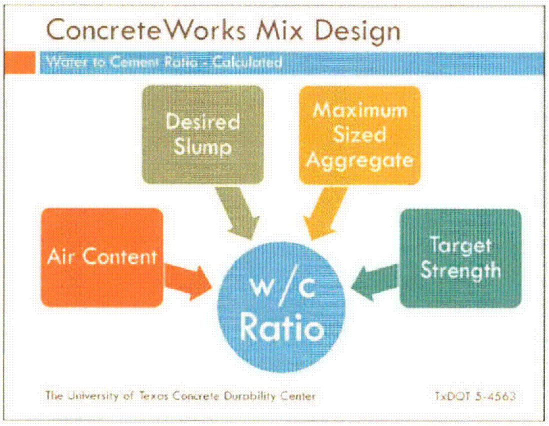
Water to Cement Ratio

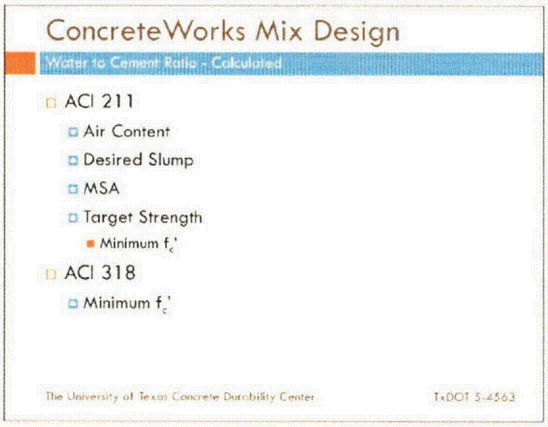
- Specified
- Calculated
  - Desired Slump
  - Air Content
  - Max Sized Aggregate
  - Target Strength
    - Sample Standard Deviation
    - Sample Size
    - Exposure Conditions
      - Sulfates
      - Freeze-Thaw
      - Corrosion
      - Water

The University of Texas Concrete Durability Center TxDOT 5-4563


ConcreteWorks Mix Design
Water to Cement Ratio - Specified
The University of Texas Concrete Durability Center
TxDOT 5-4563


ConcreteWorks Mix Design
Water to Cement Ratio - Calculated
The University of Texas Concrete Durability Center
TxDOT 5-4563


ConcreteWorks Mix Design
Water to Cement Ratio - Calculated
Desired Slump
Maximum Sized Aggregate
Air Content
Target Strength
w/c Ratio
The University of Texas Concrete Durability Center
TxDOT 5-4563


ConcreteWorks Mix Design
Water to Cement Ratio - Calculated
ACI 211
Air Content
Desired Slump
MSA
Target Strength
Minimum f'c
ACI 318
Minimum f'c
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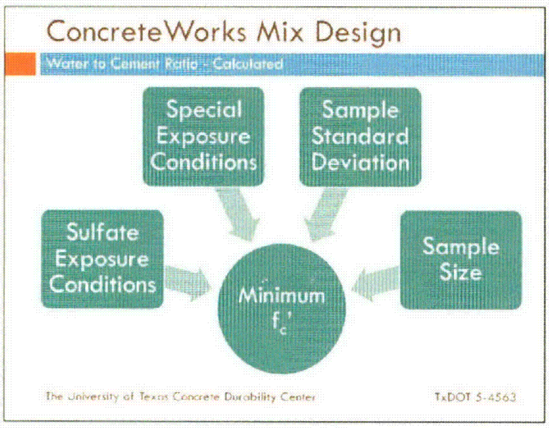
ConcreteWorks Mix Design
Water to Cement Ratio - Calculated
Special Exposure Conditions
Sample Standard Deviation
Sulfate Exposure Conditions
Sample Size
Minimum f'c
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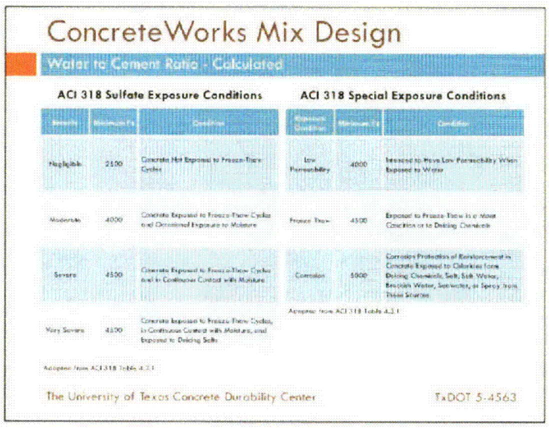
ConcreteWorks Mix Design
Water to Cement Ratio - Calculated
ACI 318 Sulfate Exposure Conditions
Negligible 2500 Concrete Not Exposed to Freeze-Thaw Cycles
Moderate 4000 Concrete Exposed to Freeze-Thaw Cycles and Occasional Exposure to Moisture
Severe 4500 Concrete Exposed to Freeze-Thaw Cycles and in Continuous Contact with Moisture
Very Severe 4500 Concrete Exposed to Freeze-Thaw Cycles, in Continuous Contact with Moisture, and Exposed to Deicing Salts
Adapted from ACI 318 Table 4.2.1
ACI 318 Special Exposure Conditions
Low Permeability 4000 Intended to Have Low Permeability When Exposed to Water
Freeze Thaw 4500 Exposed to Freeze-Thaw in a Moist Condition or to Deicing Chemicals
Corrosion 5000 Corrosion Protection of Reinforcement in Concrete Exposed to Chlorides from Deicing Chemicals, Salt, Salt Water, Brackish Water, Seawater, or Spray from These Sources
Adapted from ACI 318 Table 4.2.1
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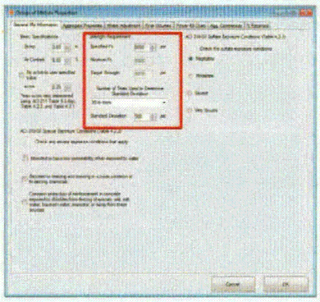
ConcreteWorks Mix Design

Water to Cement Ratio - Calculated



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ConcreteWorks Mix Design

Water to Cement Ratio - Calculated

- Target Strength, f'_{cr}
  - Overdesign to Ensure Minimum Specified Strength Is Achieved
  - Based On Extent And Accuracy of Previous Testing of Similar Mixes
  - Function Of:
    - Sample Standard Deviation
    - Number of Tests
    - Minimum Specified Strength, f'_c

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ConcreteWorks Mix Design

Water to Cement Ratio - Calculated

No. of Tests	Sample Standard Deviation Modification Factor
Less than 15	Use Table 5.3.2.2
15	1.16
20	1.08
25	1.03
30 or More	1.00

ACI 318-08 Table 5.3.1.2

s_s = (std. dev.) x (modification factor)

Specified Compressive Strength, psi	Target Strength, psi
$f'_c < 3000$	$f'_{cr} = f'_c + 1000$
$3000 \le f'_c \le 5000$	$f'_{cr} = f'_c + 1200$
$f'_c > 5000$	$f'_{cr} = 1.10f'_c + 700$

ACI 318-08 Table 5.3.2.2

Specified Compressive Strength, psi	Target Strength, psi
$f'_c \le 5000$	Use larger of: $f'_{cr} = f'_c + 1.34s_s$, $f'_{cr} = f'_c + 2.33s_s - 500$
$f'_c > 5000$	Use larger of: $f'_{cr} = f'_c + 1.34s_s$, $f'_{cr} = 0.90f'_c + 2.33s_s$

ACI 318-08 Table 5.3.2.1

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ConcreteWorks Mix Design

Water to Cement Ratio - Calculated

- ACI 318 vs TxDOT Item 421 Table 6
  - Target Strengths Identical for Most Strengths, Test Quantities, and Standard Deviations
  - At High Strengths and High Standard Deviations, ACI 318 Provides Somewhat Higher Target Strengths

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ConcreteWorks Mix Design

Water to Cement Ratio - Calculated

- Target Strength Translated to w/c Ratio Using ACI 211
- Interpolates Between Values When Necessary

28-Day Compressive Strength, psi	Water-Cement Ratio by Weight	
	Non-Air-Entrained	Air-Entrained
6000	0.41	-
5000	0.48	0.40
4000	0.57	0.48
3000	0.68	0.59
2000	0.82	0.74

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ConcreteWorks Mix Design

Water to Cement Ratio - Calculated

- More Testing Equals
  - Smaller Sample Standard Deviation
  - Reduced Target Strength
- It Pays to Test Often and Accurately

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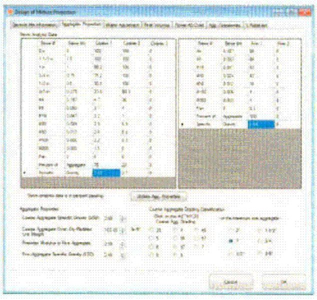
ConcreteWorks Mix Design

Aggregate Properties



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ConcreteWorks Mix Design

Aggregate Properties

- Aggregate Analysis
- Aggregate Optimization (Optional)
  - Benefits
    - Reduce Water
    - Improve Workability
    - Minimize Finishing
    - Improve Consolidation
    - Minimize Heat
    - Improve Durability
  - Downside
    - May Require Use of Three or More Aggregate Sizes

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ConcreteWorks Mix Design

Aggregate Properties

- Aggregate Gradation Optimization
  - 0.45 Power Chart
  - Coarseness Factor
  - Combined Percent Retained
- Refer to Tex-470-A for Greater Detail

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ConcreteWorks Mix Design

Aggregate Properties – Gradation Optimization

- 0.45 Power Chart
  - Overview
    - Theoretically Densest Gradation Possible
    - Historically Used For Asphalt Applications
  - Method

$$\% \text{ Passing} = \left(\frac{d}{D}\right)^{0.45}$$

d = Sieve Size Being Considered

D = Nominal Maximum Sieve Size

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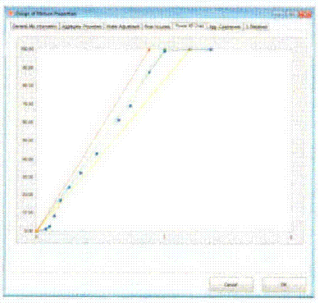
ConcreteWorks Mix Design

Aggregate Properties – Gradation Optimization



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ConcreteWorks Mix Design

Aggregate Properties – Gradation Optimization

- Aggregate Coarseness Factor
  - Plot of Workability vs. Coarseness Factor
  - Assumes Round Or Cubic Shaped Aggregate Particles
  - Use Judgment For Flat Or Elongated Aggregates

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ConcreteWorks Mix Design

Aggregate Properties – Gradation Optimization

- Aggregate Coarseness Factor
  - Method

$$\text{Coarseness Factor} = \left(\frac{S}{T}\right) x\,100$$

Workability Factor = 1 - T

S = Cumulative % Retained on 3/8 in. Sieve

T = Cumulative % Retained on No. 8 Sieve

Adjust WF for Every Cementitious Materials Content

+ 2.5% for Every 94 pcy in excess of 564 pcy

- 2.5% for Every 94 pcy below 564 pcy

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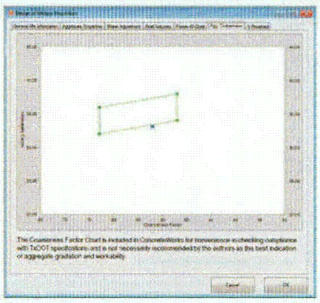
ConcreteWorks Mix Design

Aggregate Properties – Gradation Optimization



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ConcreteWorks Mix Design

Aggregate Properties – Gradation Optimization

- Combined Percent Retained
  - Plot of CA Retained on Each Individual Sieve
- TxDOT Tex-470-A Method
  - Sum of Any Two Adjacent Sieves ≥ 13%
  - Excludes First and Last Sieves to Retain Material

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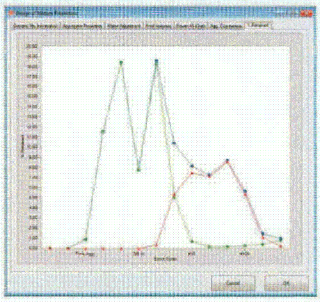
ConcreteWorks Mix Design

Aggregate Properties – Gradation Optimization



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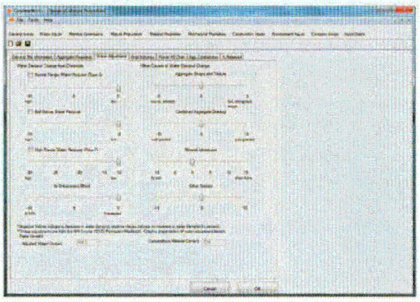
ConcreteWorks Mix Design

Water Adjustment



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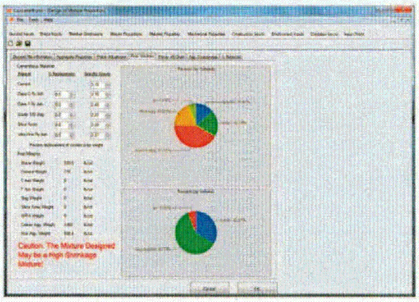
ConcreteWorks Mix Design

Final Volumes



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ConcreteWorks Mix Design
Final Volumes
Again - Mix Design is Intended for Trial Batch Only
You Are Responsible for Making Necessary Adjustments
Hopefully ConcreteWorks Resulted in a More Satisfactory Result the First Time Around
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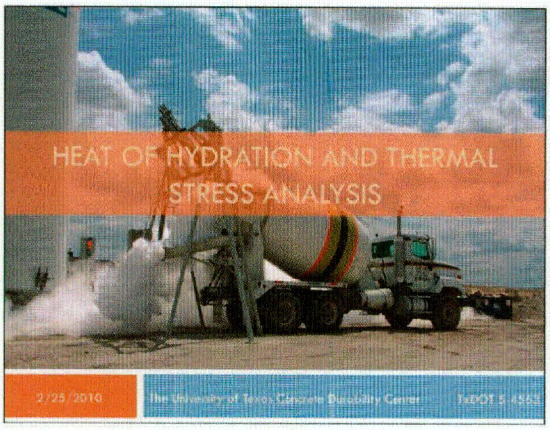

Overview

- Introduction
- Temperature Prediction
  - Heat Transfer Model
  - Hydration Model
- Thermal Stress Analysis
  - Free Shrinkage and Mechanical Properties
  - Elastic Stress and Degree of Restraint
  - Early-Age Creep Model
  - Cracking Potential
- Cracking Potential
- Application

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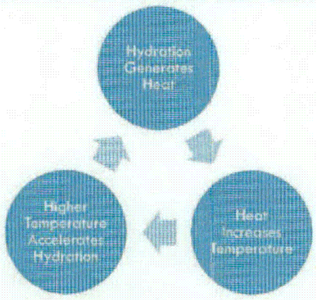
Introduction

Concrete Temperature Dependence



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Introduction

Potential Risks in Mass Concrete Elements

- High Temperature
  - Delayed Ettringite Formation (DEF)
- Thermal Gradients
  - Thermal Cracking
- Avoid/Control the Following
  - Excessive Temperatures (> 158 °F)
  - Large Temperature Gradients (> 35 °F)

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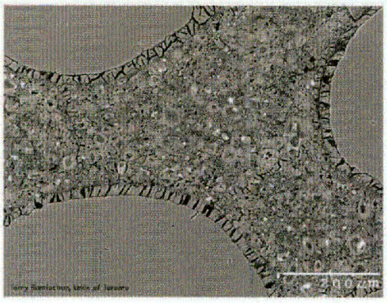
Introduction

Delayed Ettringite Formation (DEF)



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Introduction

Delayed Ettringite Formation (DEF)

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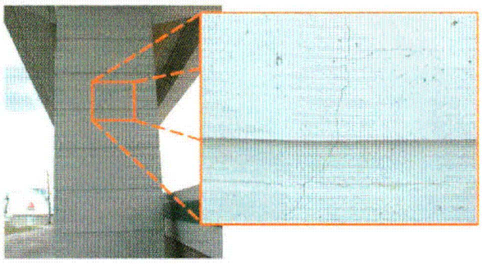
Introduction

Thermal Cracking in Mass Concrete Elements



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Introduction

Current Spec: TxDOT Item 420 (paraphrased)

- Mass placements are defined as placements with a least dimension greater than or equal to 5 ft., or designated on the plans. For monolithic mass placements, develop a plan to ensure the following:
  - Temperature at central core not exceed 160°F
  - Temperature differential between central core and exposed surface not to exceed 35°F
- Base this plan on the equations given in the PCA's Design and Control of Concrete Mixtures. Include a combination of the following elements in this plan:
  - Selection of concrete ingredients including aggregates, gradation, and cement types, to minimize heat of hydration
  - Use of ice or other concrete cooling ingredients
  - Use of liquid nitrogen dosing systems
  - Controlling rate or time of concrete placement
  - Use of insulation or supplemental external heat to control heat loss
  - Use of supplementary cementing materials
  - Use of a cooling system to control the core temperature
- Furnish and install 2 sets of temperature recording devices, maturity meters, or other approved equivalent devices at designated locations. Use these devices to simultaneously measure the temperature of the concrete at the core and the surface. Maintain temperature control methods for 4 days unless otherwise approved. Maturity meters may not be used to predict strength of mass concrete.

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Introduction

Why Do We Need a Program?

- The Calculations are Difficult
- Guidance Provided by ACI and PCA is Vague
- Information Regarding Thermal Properties of Different Materials is Dispersed
- Problem Becomes Even More Difficult When Cracking Tendency is Considered
  - Not Even Addressed by the Spec

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Introduction

ConcreteWorks Accounts For

- Variable Concrete Properties
- Temperature Sensitivity of Hydration
- Material Hydration Properties
- Environment Conditions
- Construction Process
- Boundary Conditions

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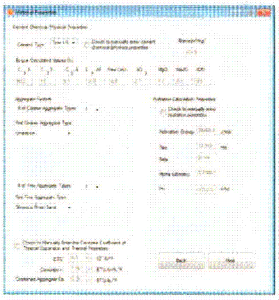
Introduction

ConcreteWorks Preview



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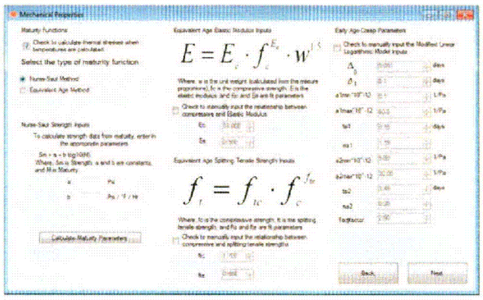
Introduction

ConcreteWorks Preview



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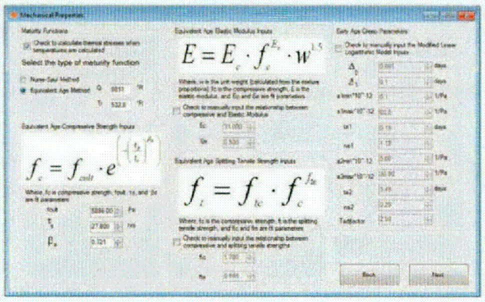
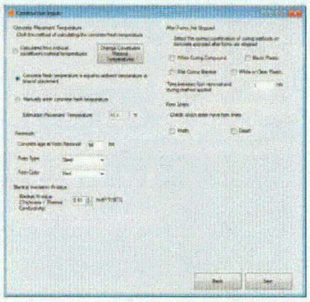
Introduction

Concrete Works Preview



Introduction

Concrete Works Preview



Temperature Prediction

Fundamentals

- Energy Balance

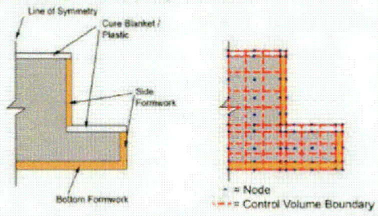
$$\Delta E = E_{in} - E_{out} + E_{gen} \qquad \text{[Watts]}$$

  - Where:
    - E_{in} = Thermal Energy Entering Control Volume
    - E_{out} = Thermal Energy Leaving Control Volume
    - E_{gen} = Thermal Energy Generated Within Control Volume
- Heat Transfer (E_{in} - E_{out})
- Heat of Hydration (E_{gen})

Temperature Prediction

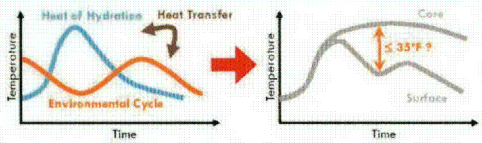
Fundamentals

- Control Volume
  - Transfer of Heat Between Control Volumes
  - Modeling of Boundary Conditions



Temperature Prediction

Fundamentals



Heat of Hydration	Environmental Cycle	Heat Transfer
Cement Composition	Air Temperature	Element Geometry
Effect of SCMs	Wind Speed	Element Size
Cement Fineness	Relative Humidity	Submerged ??
Amount of Cement	Cloud Cover	Form Properties
Chemical Admixtures	Solar Radiation	Curing Method
w-cm Ratio	Air Pressure	Surface Color
Mix Temperature		Aggregate Type

Temperature Prediction

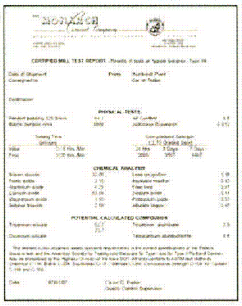
Hydration Model

- Hydration Reaction is Exothermic
  - Gives Off Heat
  - E_{gen} Term in Temperature Prediction Model
- Heat Generation
  - Function of Chemical/Physical Properties of Cementitious Materials
    - Cement Chemical Composition
      - Bogue
      - Rietveld
    - Fineness
    - SCM Content
  - Chemical Admixtures

Temperature Prediction

Hydration Model

- Cement Chemical Composition - Bogue
  - Commonly Used
    - Alite
    - Belite
    - Tricalcium Aluminate
    - Tetracalcium Aluminoferrite
    - Free Lime
    - Sodium Oxide
    - Magnesium Oxide
    - Potassium Oxide
    - Calcium Oxide



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Temperature Prediction

Hydration Model

- Cement Chemical Composition - Rietveld
  - Better Quantification of Cement Composition than Bogue
  - Requires Advanced Techniques Such as X-Ray Diffraction (XRF)
    - Consequently, Rietveld is Not as Common
  - Preferred Technique if Available
    - Alite
    - Belite
    - Aluminate
    - Ferrite
    - Gypsum
    - Bassanite
    - Anhydrite
    - Periclase
    - Arcanite
    - Calcite

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Temperature Prediction

Hydration Model

- Calorimetry – Measure of Heat Released
  - Adiabatic Calorimetry
    - No Heat Loss
  - Semi-Adiabatic Calorimetry
    - Heat Loss Measured and Accounted For
    - Characterizes Materials Very Well
  - Isothermal Calorimetry
    - Specimen Kept at Constant Temperature
    - Great for Studying Specific Causes and Effects
    - Doesn't Mimic Real Life

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Temperature Prediction

Hydration Model – Isothermal Calorimetry

- Test Details
  - Run on Cement Pastes (Typically ~40g)
  - Sample Maintained at Constant Temperature
  - Calorimeter Measures Energy Required to Keep Sample at Constant Temperature
    - Watts / Gram of Cementitious Materials
- Purpose
  - Useful for Testing Effects on Reaction Rate of:
    - Various Cements
    - Supplementary Cementitious Materials (SCMs)
    - Chemical Admixtures
  - Temperature Dependency of Reaction
    - Activation Energy, E_a (Characterizes the Response of a Reaction to Changes in Temperature)

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Temperature Prediction

Hydration Model – Isothermal Calorimetry

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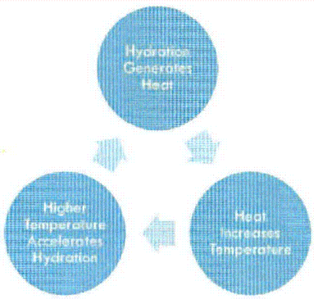
Temperature Prediction

Hydration Model – Isothermal Calorimetry



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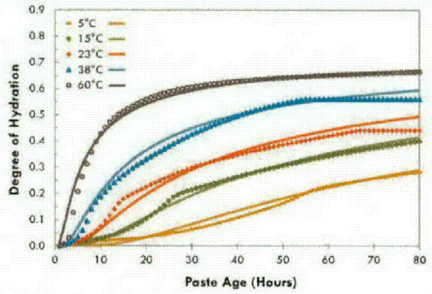
Temperature Prediction

Hydration Model – Isothermal Calorimetry



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Temperature Prediction

Hydration Model – Isothermal Calorimetry

$$\ln k = \ln A - \frac{E_a}{RT}$$

- Activation Energy (Brown and Ma, 1994)
  - Where
    - k = rate of reaction
    - A = constant (=0)
    - R = Universal gas constant (8.314)
    - T = reference temperature
    - E_a = Activation Energy

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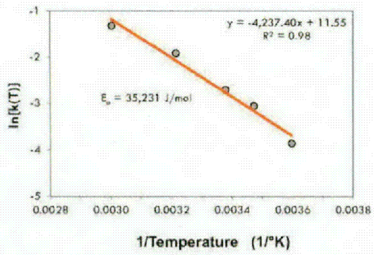
Temperature Prediction

Hydration Model – Isothermal Calorimetry

- Apparent Activation Energy, E_a



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Temperature Prediction

Hydration Model – Semi-Adiabatic Calorimetry

- Test Details
  - Typical Test Duration is 1 Week
  - Insulated Chamber to Retain Heat
    - 6" x 12" Cylinder
  - Heat Allowed to Build in System
    - Progressively Increases Reaction Rate
  - Must Measure and Account for Heat Loss
- Purpose
  - Mimics Real Life Conditions Very Well
  - Material Characterization

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Temperature Prediction

Hydration Model – Semi-Adiabatic Calorimetry

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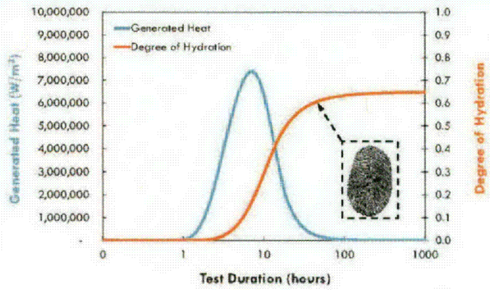
Temperature Prediction

Hydration Model – Semi-Adiabatic Calorimetry



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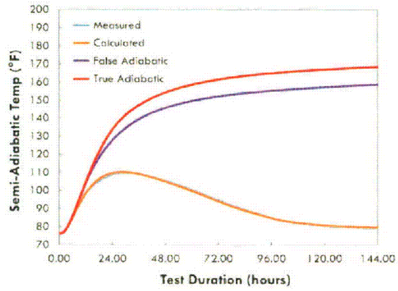
Temperature Prediction

Hydration Model – Semi-Adiabatic Calorimetry



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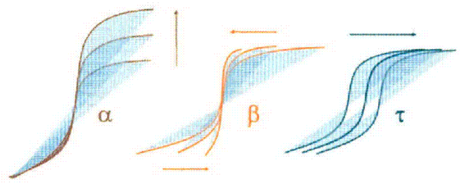
Temperature Prediction

Hydration Model – Semi-Adiabatic Calorimetry

- Semi-Adiabatic Hydration Calculation Parameters



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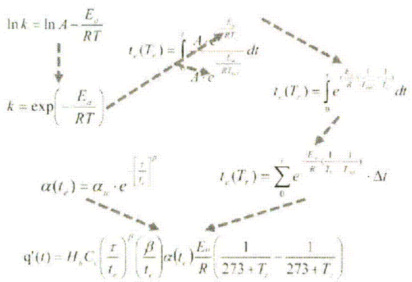
Temperature Prediction

Hydration Model



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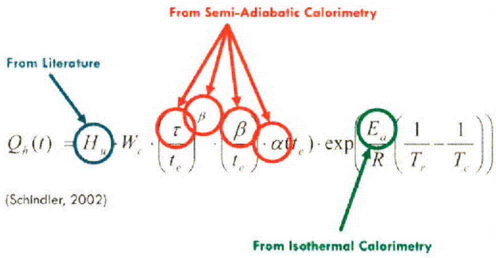
Temperature Prediction

Hydration Model



(Schindler, 2002)

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Temperature Prediction

Heat Transfer Model

- Developed from Existing Theory
- Wide Body of Literature
- Various Boundary Conditions
- No Closed-Form Solution Available
  - Must Use Finite Element or Finite Difference Methods
  - Finite Difference Chosen for Computation Speed

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Temperature Prediction

Heat Transfer Model

- Heat Transfer Mechanisms
  - Radiation
    - Solar Radiation
    - Atmospheric Radiation
    - Radiation from Surrounding Surfaces
    - Irradiation
  - Convection
    - Free Convection
    - Forced Convection
  - Conduction
    - Soil, Formwork, Curing Mat, Etc.

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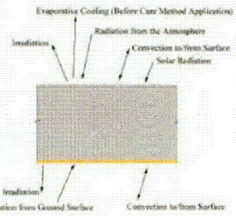
Temperature Prediction

Heat Transfer Model

- Heat Transfer Mechanisms



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Temperature Prediction

Heat Transfer Model

- Environment
  - Temperature
  - Relative Humidity
  - Percent Cloud Cover
  - Wind Speed
  - Yearly Temperature

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Temperature Prediction

Heat Transfer Model

- Member Geometry
  - Bridge Deck
  - Column
  - Footing
  - Bent Cap

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Temperature Prediction

Heat Transfer Model

- Construction
  - Concrete Placement Temperature
  - Formwork Type/Material
  - Form Liners
  - Time at Which Forms are Stripped
  - Blanket Insulation R-Value

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Temperature Prediction

Heat Transfer Model

- Concrete Thermal Properties
  - Thermal Conductivity
    - Ability of a Material to Transfer Heat
  - Specific Heat
    - Characterization of the Energy Required to Increase the Temperature of a Material
- Must Be Updated Every Time Step

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Temperature Prediction

Heat Transfer Model

- Thermal Conductivity
  - Ability of a Material to Conduct Heat
- Changes With:
  - Aggregate Content
  - Aggregate Type
  - Porosity
  - Density
  - Moisture Content
  - Temperature

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Temperature Prediction

Heat Transfer Model

- Specific Heat
  - Energy Required to Increase Temperature of Material
- Changes With:
  - Degree of Hydration
  - Mixture Proportions
  - Temperature

$$C_p = \frac{1}{\rho} \cdot \left(W_c \cdot \alpha \cdot (8.4 \cdot T_c + 339) + W_c \cdot (1-\alpha) \cdot C_c + W_A \cdot C_A + W_W \cdot C_W \right)$$

Temperature Prediction

Field Sites

Temperature Prediction

Field Sites

Temperature Prediction

Field Sites

- Hydration Model Based On (To Date):
  - Semi-Adiabatic Calorimetry - 139 Tests
  - Isothermal Calorimetry – 630 Tests
- Field Calibrated With:
  - 33,626 Hrs of Temperature Data
  - 137 Temperature Sensors from 12 Concrete Members
  - Average R^2 Value of 0.90

Temperature Prediction

Field Sites

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Austin	US 71/I 35	Dec-02	Column	7x12x50	Steel	Limestone
Austin	Loop 1/SH 45	Jun-03	Column	6x10x30	Steel	Limestone
Austin	Loop 1/SH 45	Jun-03	Footing	24x26x7.3	Steel	Limestone
Austin	Loop 1/SH 45	Jul-03	Column	6x10x67	Steel	Limestone
Austin	Loop 1/SH 45	Aug-03	Footing	10x10x6	Soil	Limestone
South Padre	Queen Isabella Causeway	Feb-04	Dolphin	16x16x9	Steel/PCC	River Gravel
Wichita Falls	Scott St. & FW&D Railroad	Mar-04	Bent Cap	3.3x3.3	Wood	Granite
Austin	Loop 1/SH 45	Jun-04	Column	8.5x10x80	Steel	Limestone
Austin	Loop 1/SH 45	Jun-04	Footing	9.5x10.5x5.5'	Steel	Limestone
Austin	Loop 1/SH 45	Jun-04	Bent Cap	Min 2'	Steel	Limestone
Galveston	Galveston Causeway	Aug-04	Footing	66x13x6.5	Steel	River Gravel
South Padre	Queen Isabella Causeway	Sep-04	Dolphin	16x16x9	Steel/PCC	River Gravel

Temperature Prediction

Field Sites

Concrete Member	Maximum Temperature Recorded (°F)	Maximum Temperature Difference Recorded (°F)
Column 1	154.0	86.0
Column 2	136.0	35.0
Column 3	136.0	40.0
Column 4	163.4	60.3
Footing 1	161.0	72.0
Footing 2	133.0	45.0
Footing 3	135.5	41.4
Dolphin 1	145.4	72.0
Dolphin 2	123.8	45.9
Rect. Bent Cap	128.3	27.9
T Bent Cap	153.5	65.7
Pedestal	165.2	43.2

What???

Field Sites

- Apparently Cracking is Not Directly Related to Maximum Temperature Or Maximum Temperature Differential
- Just About All Mass Concrete Elements Exceeded Temperature Limits Without Cracking
- Need a Better Method of Crack Prediction

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Thermal Stress Analysis

Basic Problem Statement

- Quantify the Effects that Cause Early-Age Cracking in Texas Mass Concrete Mixtures
- Early-Age Cracking is Primarily Caused By:
  - Thermal Gradients
  - Drying Shrinkage
  - Autogenous Shrinkage

  } + Degree of Restraint
- Must Account for Creep
- Integrate Heat Prediction Model With Thermal Cracking Behavior
  - Thermal Stress Analysis

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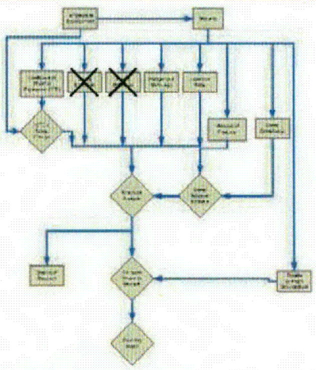

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Thermal Stress Analysis

Fundamentals

- Changing Early-Age Material Properties
  - Modulus of Elasticity
  - Strength
  - Poisson's Ratio
  - Coefficient of Thermal Expansion (CTE)
  - Creep
  - Differential Temperature Development

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Thermal Stress Analysis

Free Shrinkage and Mechanical Properties

- A Three Parameter Model is Used to Describe Hydration (Freiesleben Hansen and Pedersen , 1985)
- Where
  - $H(t)$ = Heat Evolved at Time t
  - H_u = Total Amount of Heat Available
  - α = Degree of Hydration

$$\alpha = \frac{H(t)}{H_u}$$

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Thermal Stress Analysis

Free Shrinkage and Mechanical Properties

- A Three Parameter Model is Used to Describe Hydration (Freiesleben Hansen and Pedersen , 1985)
- Where
  - $H(t)$ = Heat Evolved at Time t
  - H_u = Total Amount of Heat Available
  - t_e = Equivalent Age
  - α_u, τ, β are determined from semi-adiabatic calorimetry

$$\alpha = \frac{H(t)}{H_u}$$

$$\alpha(t_e) = \alpha_u \cdot e^{-\left[\frac{\tau}{t_e}\right]^{\beta}}$$

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Thermal Stress Analysis

Free Shrinkage and Mechanical Properties

$$H_u = H_{cem} \cdot p_{cem} + 461 \cdot p_{slag} + 1800 \cdot p_{FA-CaO} \cdot p_{FA}$$

From Kishi and Maekawa (1994), Schindler (2004)

$$H_{cem} = 500 \cdot p_{C_3S} + 260 \cdot p_{C_2S} + 866 \cdot p_{C_3A} + 420 \cdot p_{C_4AF}$$
$$+ 624 \cdot p_{SO_3} + 1186 \cdot p_{FreeCa} + 850 \cdot p_{MgO}$$

From Bogue (1955), Schindler (2004)

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Thermal Stress Analysis

Free Shrinkage and Mechanical Properties

- Equivalent Age
  - Time-Temperature History
    - Semi-Adiabatic Calorimetry
      - α_u, τ, β
- What Does it Mean
  - Allows Us to Compare Apples to Apples
  - Concrete Cured for 10 Hours Under HOT Conditions May Have a Theoretical Age of 14 Hours

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Thermal Stress Analysis

Free Shrinkage and Mechanical Properties

- Strength Development
  - Tensile
  - Compressive
  - Elastic Modulus

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Thermal Stress Analysis

Free Shrinkage and Mechanical Properties

- Elastic Modulus Development
  - Link Between Restrained Strains and Stresses
  - Default Constants Come from ACI 318 Building Code

$$E = k(f_c)^n$$

$$k = 0.043(w_c)^{1.5}$$

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Thermal Stress Analysis

Free Shrinkage and Mechanical Properties

- Concrete Maturity
  - Time-Temperature History
  - Maturity Functions
    - Nurse-Saul Method
      - Used by TxDOT
    - Equivalent Age Method
  - Mix Specific
  - Required for Cracking Prediction

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Thermal Stress Analysis

Free Shrinkage and Mechanical Properties

- Poisson Ratio
  - Necessary for Modeling Stresses in Two and Three Dimensional Elements
  - Decreases with Hydration
  - Equivalent in Tension and Compression
  - Assumed to be Independent of State of Stress

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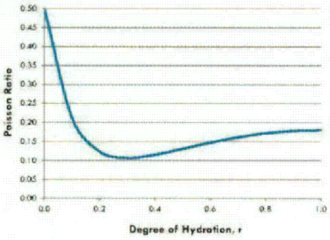
Thermal Stress Analysis

Free Shrinkage and Mechanical Properties

- Poisson Ratio



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Thermal Stress Analysis

Free Shrinkage and Mechanical Properties

- Early-Age Free Shrinkage
  - Coefficient of Thermal Expansion (CTE)
  - Autogenous Shrinkage
  - Drying Shrinkage
  - Plastic Shrinkage
- Drying and Plastic Shrinkage
  - Currently Unaccounted for in ConcreteWorks
  - Negligible in Mass Concrete
    - Low Surface Area / Volume Ratio
  - Currently in Development Under TxDOT 6332
    - Thermal Stress Analysis of Bridge Decks

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Thermal Stress Analysis

Free Shrinkage and Mechanical Properties

- Coefficient of Thermal Expansion
  - Primarily a Function of Constituent Materials
    - Coarse Aggregate
    - Fine Aggregate
    - Paste

$$\alpha_{cteh} = \frac{\alpha_{ca}V_{ca} + \alpha_{fa}V_{ca} + \alpha_{p}V_{p}}{V_{ca} + V_{fa} + V_{p}}$$

  - Assumed to be Constant
    - CTE Decreases Rapidly Before Time of Set
    - Accurate for Normal to High w/cm Ratios

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Thermal Stress Analysis

Free Shrinkage and Mechanical Properties

- Autogenous Shrinkage Model
  - Caused by Internal Drying Associated with Low w/c Ratio
    - Chemical Shrinkage

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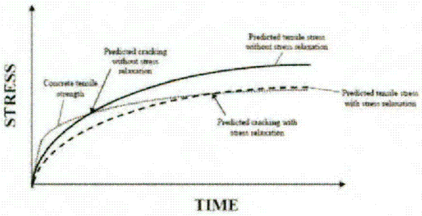
Thermal Stress Analysis

Early-Age Concrete Creep Model

- **Time dependence of restrained shrinkage and creep (Mehta, 1993)**



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Thermal Stress Analysis

Cracking Potential

- Many Proposed Methods of Estimating Cracking Risk
  - Temperature Difference Requirements
  - Stress – Strain Based Failure
- ConcreteWorks Cracking Susceptibility Criterion
  - Tensile Stress vs. Tensile Strength

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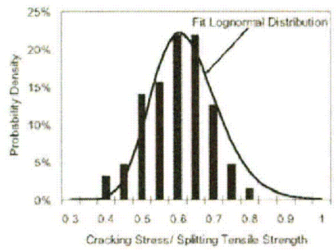
Thermal Stress Analysis

Cracking Potential



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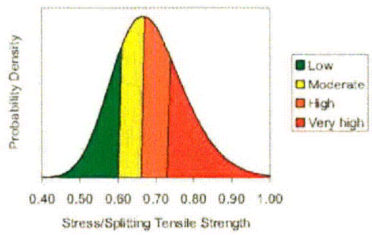
Thermal Stress Analysis

Cracking Potential



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Summary

- ConcreteWorks has been shown to accurately predict thermal distributions in field structures.
- Concrete can be used to predict cracking susceptibility – needs to be validated in the field!!
- More information later on how to implement ConcreteWorks and incorporate into TxDOT specifications…

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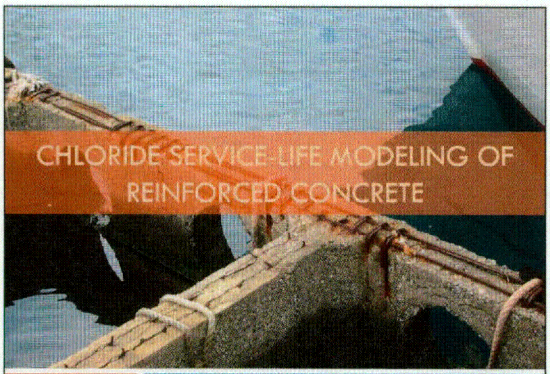

CHLORIDE SERVICE-LIFE MODELING OF REINFORCED CONCRETE

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Overview

- Introduction
- Mechanics of Corrosion
- Role of Chlorides in Corrosion
- Diffusion Coefficient
- Prevention and Mitigation of Steel Corrosion

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Introduction

Basic Mechanism of Corrosion

- Why Does Steel Corrode?
  - Steel is Not Naturally Occurring
    - Manufactured from Iron Ore
  - Prefers to Revert Back to Natural State in Form of Iron Oxide (Rust)
  - Speed Governed by Rate of Ionic Solution Movement
  - Rust Occupies Greater Volume than Original Steel
  - Induced Tensile Stresses
- Why is This a Problem for Concrete?
  - Cracking, Spalling, and Delamination of Concrete

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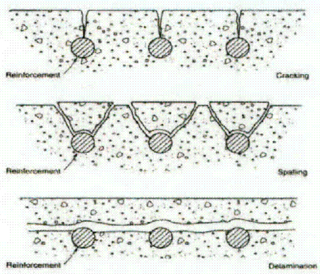
Introduction

Basic Mechanism of Corrosion



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Introduction

Basic Mechanism of Corrosion

- Stages of Corrosion
  - Penetration and Accumulation of Chlorides
  - Chloride Threshold Reached – Initiation of Corrosion
  - Corrosion Induced Tensile Stress Build
  - Cracking, Spalling, and/or Delamination Occurs
  - Structure Loses Load-Carrying Capacity

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Introduction

Basic Mechanism of Corrosion

- Stages of Corrosion (ConcreteWorks)
  - Penetration and Accumulation of Chlorides
  - Chloride Threshold Reached – Initiation of Corrosion
  - Degradation of Reinforcement
    - For Rebar: 6 Years
    - For Prestress: Immediate Failure

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Introduction

Basic Mechanism of Corrosion

- Corrosion Protection Strategies
  - Non-Corrosive Reinforcement
  - Coatings on Steel
  - Membranes or Sealers
  - Chemical Corrosion Inhibitors
  - Non-Chloride De-Icers
  - Increased Concrete Cover
  - Low Permeability Concrete

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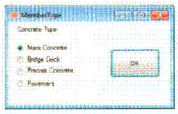
Introduction

Supported Member Types

- Critical Structures
  - Bridge Decks
  - Parking Garages
  - Marine Structures
- Supported Members
  - Mass Concrete
  - Bridge Decks



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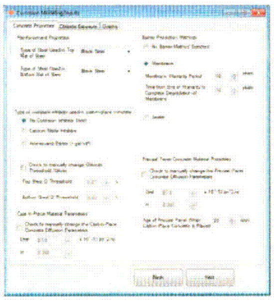
Introduction

Corrosion Modeling Inputs



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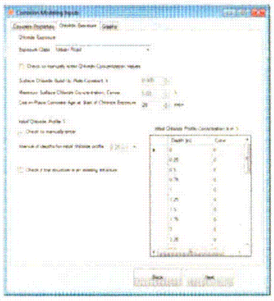
Introduction

Corrosion Modeling Inputs



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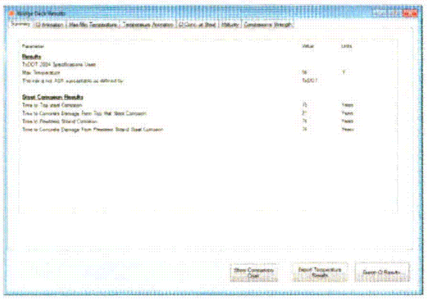
Introduction

Corrosion Modeling Results



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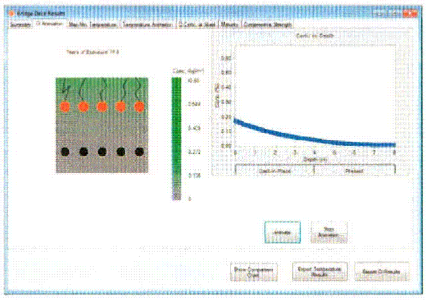
Introduction

Corrosion Modeling Results



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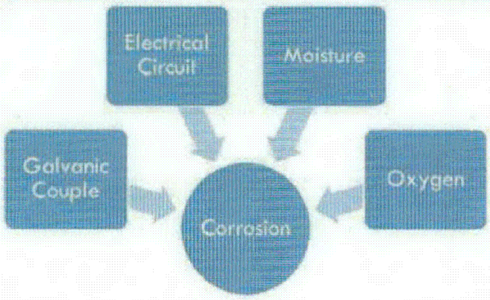
Mechanics of Corrosion

Requirements for Corrosion



Mechanics of Corrosion

Requirements for Corrosion

- Galvanic Couple
  - Anodic and Cathodic Areas With Different Potential
- Electrical Circuit
  - Metallic and Electrolytic Continuity Between Anode and Cathode
- Moisture
  - For Cathodic Reaction
  - To Provide Electrolyte
- Oxygen
  - For Cathodic Reaction

Mechanics of Corrosion

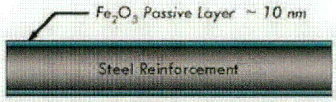
Passivation of Steel Reinforcement

- Pore Solution Composition
  - Dominated by Sodium, Potassium, and Hydroxyl Ions
    - Alkalis (Na^+, K^+) Represent Small Proportion of Cement
    - 90% of Alkalis End Up in Pore Solution
  - Hydroxyl Ions Forced Into Solution to Balance Charge
  - Result: Very High pH ~ 13 - 14

Mechanics of Corrosion

Passivation of Steel Reinforcement

- Alkaline Conditions Prevail in Concrete
- Above pH of Approximately 12.1
  - Formation of Iron Oxide Film, Passive Layer, on Surface of Embedded Steel Reinforcement
    - Prevents Anode from Forming
    - Keeps Oxygen and Moisture from Reaching Steel



Mechanics of Corrosion

Passivation of Steel Reinforcement

- All Requirements for Corrosion Are Generally Met Without Passive Layer
  - Problem of Corrosion Arises When Passive Layer is Compromised or Depassivated

Mechanics of Corrosion

Depassivation of Steel Reinforcement

- Two Mechanisms of Depassivation
  - Chloride Diffusion
    - Primary Cause of Corrosion in Marine Environment
    - Chlorides from De-Icing Salts Penetrate Through Concrete
    - Breakdown of Passive Layer
  - Carbonation
    - CO_2 from the Atmosphere Penetrates Through Concrete
    - Reduction in the pH
      - Steel is Only Effectively Passivated in High-pH Environment

Mechanics of Corrosion

Depassivation of Steel Reinforcement

- Two Mechanisms of Depassivation
  - Chloride Diffusion
    - Primary Cause of Corrosion in Marine Environment
    - Chlorides from De-Icing Salts Penetrate Through Concrete
    - Breakdown of Passive Layer
  - Carbonation
    - CO_2 from the Atmosphere Penetrates Through Concrete
    - Reduction in the pH
      - Steel is Only Effectively Passivated in High pH Environment
  - Carbonation Not Considered in ConcreteWorks

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Role of Chlorides in Corrosion

Effect of Chlorides

- Cl^- Ions Incorporate Themselves Into the Passive Film
  - Replace Oxygen
  - Increase Solubility
  - Increase Ionic Conductivity
- A Local Phenomenon
  - Chloride Ions Rarely Distributed Homogenously Over Steel Surface
  - Random Imperfections in Passive Layer
  - Large Cathode-Anode Ratios
  - Resulting Pitting Corrosion

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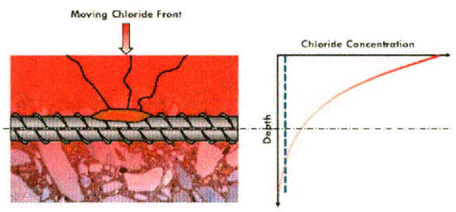
Role of Chlorides in Corrosion

Rate of Chloride Ingress

- First Line of Defense - Slow Down Rate at Which Chlorides Reach Steel



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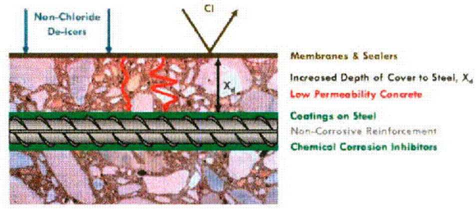
Role of Chlorides in Corrosion

Rate of Chloride Ingress

- First Line of Defense
  - Slow Down Rate at Which Chlorides Reach Steel



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Role of Chlorides in Corrosion

Rate of Chloride Ingress

- Chloride Ingress Is a Factor of:
  - Chloride Surface Concentration, C_s
    - Severity of the Environment
  - Temperature
    - Chlorides Penetrate Quicker in Warmer Climates
  - Depth of Cover to Steel, X_d
  - Corrosion Threshold, Ct
    - Chloride Concentration Required to Initiate Corrosion
    - Typically 0.05 – 0.1% (by mass) or 2 – 4 pcy
  - Diffusion Coefficient, D
    - Concrete Permeability

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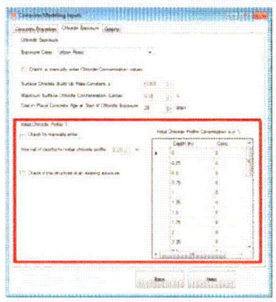
Role of Chlorides in Corrosion

Initial Chloride Profile



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Chloride Surface Concentration

Internal Sources of Chlorides in Concrete

- Chloride-Containing Chemical Admixtures
  - $CaCl_2$-Based Accelerators
    - Not Allowed in Any TxDOT Work
- Aggregates
  - Sea-Dredged Sand
  - Presence of Mineral Halite
- Mixing Water
  - Chloride Limits per TxDOT Item 421 Table 1
    - Bridges & Prestress: 500 ppm
    - All Other Concrete: 1000 ppm

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Chloride Surface Concentration

External Sources of Chlorides in Concrete

- Seawater
  - Marine Structures, Oil Platforms, Coastal Bridges, Etc.
- Groundwater
  - Piles, Tunnels, Foundations, Footings
- De-Icing Chemicals
  - Rock Salt Used on Paving Surfaces

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Chloride Surface Concentration

Chloride Surface Concentration Buildup

- Easy to Model for Constant Boundary Conditions
  - Marine Exposure
- Typically Varying Concentration Otherwise
  - With Season
    - Application of Deicer Salts in Winter
    - Washing Away of Deicer Salts in Summer
  - Within Same Structure
    - Local Differences in Slope
    - Proximity to Drains
    - Relative Location to Deicer Salt Application

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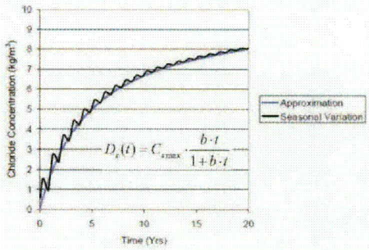
Chloride Surface Concentration

Chloride Surface Concentration Buildup

- Approximated as Smooth Curve



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Chloride Surface Concentration

Chloride Surface Concentration Buildup

- $C_s(t)$ A Function Of:
  - C_{smax} = Maximum Chloride Surface Concentration
  - b = Chloride Surface Concentration Build-Up Rate
  - t = Time (t_0 = Concrete Age at First Chloride Exposure)
- C_{smax} and b Selected by ConcreteWorks Based On:
  - Location (City and State)
  - Exposure Class
- Variables May Also be Manually Entered

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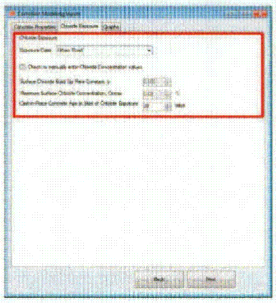
Chloride Surface Concentration

Chloride Surface Concentration Buildup

- Structural Classification
  - Rural Road
  - Urban Road
  - Parking Garage
- Location Classification
  - Splash Zone
  - Spray Zone
  - Within 0.8km of Ocean
  - Within 1.5km of Ocean



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Chloride Surface Concentration

Membranes & Sealers

- Membranes
  - Chloride Surface Concentration Assumed 0
    - 100% Effective for Duration of Warranty Period
  - Degrade Linearly After End of Warranty Period
    - 0% Effective at End of Degradation Period
- Sealers
  - Degrade Linearly from Time of Application
    - 100% Effective at Time of Application
    - 0% Effective at End of Degradation Period

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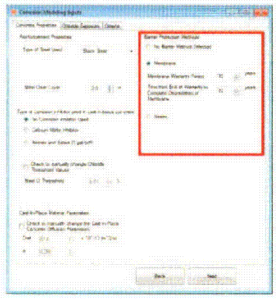
Chloride Surface Concentration

Membranes & Sealers



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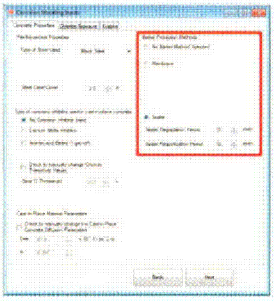
Chloride Surface Concentration

Membranes & Sealers



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Temperature

- Increased Temperature Accelerates Diffusion of Chlorides Into Concrete
- Automatically Accounted for in ConcreteWorks

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Depth of Cover to Steel

- Extend the Time it Takes for Chlorides to Reach Reinforcement
- Bridge Deck:
  - Defined on Member Dimensions Screen
- Mass Concrete
  - Defined on Corrosion Inputs Screen

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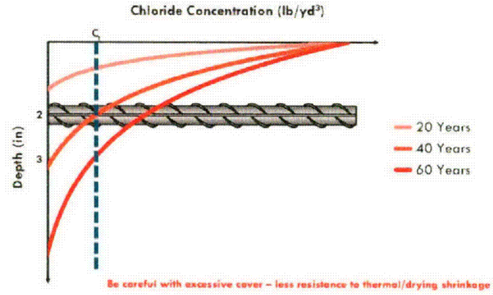
Depth of Cover to Steel



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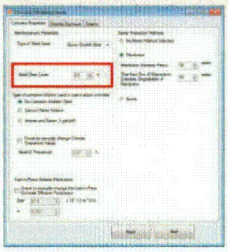
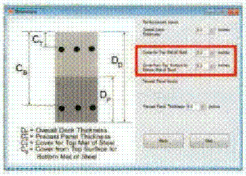
Depth of Cover to Steel

Mass Concrete | **Bridge Deck**





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Chloride Threshold

- Concentration Required to Initiate Corrosion
  - Corrosion Will Not Begin Until Corrosion Threshold is Reached
  - Increasing Threshold Allows for Greater Accumulation of Chlorides Before Onset of Corrosion
- Ways to Increase Corrosion Threshold
  - Chemical Corrosion Inhibitors
  - Corrosion Resistant Reinforcement

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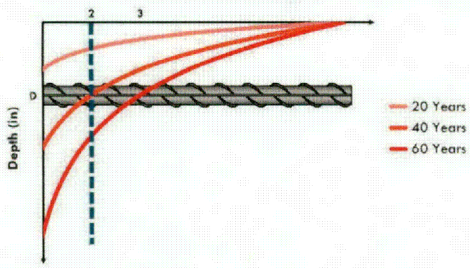
Chloride Threshold



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Chloride Threshold

Chemical Corrosion Inhibitors

- Calcium Nitrite
  - User-Defined Dosage
- Amines & Esthers
  - Fixed Dosage: 1 gal/yd^3
- Manually Defined Chloride Threshold

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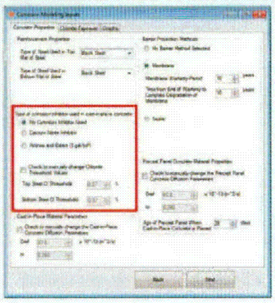
Chloride Threshold

Chemical Corrosion Inhibitors



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Chloride Threshold

Non-Corrosive Reinforcement

- Alternative Reinforcement Options
  - Epoxy Coated Steel
  - Grade 316 Stainless Steel
- Manually Defined Chloride Threshold
  - Value Largely Dependent on Reinforcement Material
  - Non-Corrosive Reinforcement Has a Larger Threshold than Standard Steel Reinforcement
  - No Rule of Thumb, However, Lower Value is More Conservative

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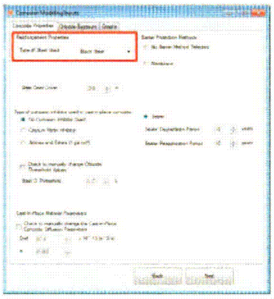
Chloride Threshold

Non-Corrosive Reinforcement



Diffusion

"Ions Don't Fly, They Swim!!"

-P.K. Mehta

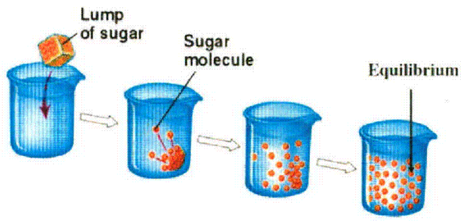
Diffusion

Definition

- Diffusion
  - Molecules in Water Are in Constant Random Motion
  - This Motion Causes These Molecules to Move From Regions of High to Low Concentration
  - This Process is Called **Diffusion**
  - When Molecules are in Equal Concentration in All Regions, the Substance is Said to Be In **Equilibrium**

Diffusion

Definition



Diffusion

Diffusion Coefficient

- Contributing Factors
  - Time
  - Temperature
  - Mix Design
    - SCMs
    - W/C Ratio

$$D_{28} = 2.17 \cdot 10^{-12} \cdot e^{\frac{w/c}{0.279}}$$

$$D_{28-UFFA} = D_{28} \cdot \left(0.170 + 0.829 e^{\left(\frac{-UFFA}{6.07}\right)}\right)$$

$$D_{28-SF} = D_{28} \cdot \left(0.206 + 0.794 e^{\left(\frac{-SF}{2.51}\right)}\right)$$

$$m = 0.26 + 0.4 \cdot \left(\frac{FA}{50} + \frac{SG}{70}\right)$$

$$D_{ult} = D_{28} \cdot \left(\frac{28}{36500}\right)^m$$

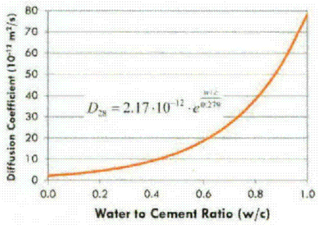
$$D_i(t) = D_{28} \cdot \left(\frac{28}{t}\right)^m + D_{ult} \cdot \left(1 - \left(\frac{28}{t}\right)^m\right)$$

$$D_{it}(t,T) = D_i(t) \cdot \exp\left[\frac{U}{R} \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right]$$

Diffusion

Effects of Mix Design

- Water to Cement Ratio
  - Porosity & Permeability Decrease w/ Decreasing W/C



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Diffusion

Effects of Mix Design

- SCMs – Ultra Fine Fly Ash and Silica Fume
  - Reduced Porosity
  - Smaller Particle Sizes
    - Particle Packing
    - More Surface Area = Faster Pozzolanic Reaction

$$D_{28-UFFA} = D_{28} \cdot \left(0.170 + 0.829 e^{\left(\frac{-UFFA}{6.07}\right)}\right)$$

$$D_{28-SF} = D_{28} \cdot \left(0.206 + 0.794 e^{\left(\frac{-SF}{2.51}\right)}\right)$$

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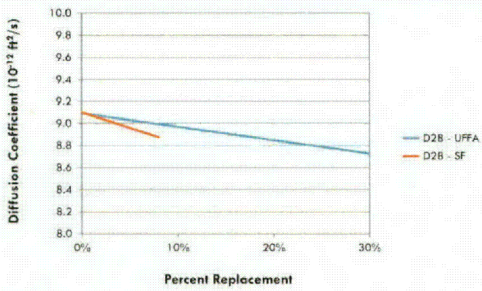
Diffusion

Effects of Mix Design



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Diffusion

Effects of Mix Design

- SCMs – Slag and Fly Ash
  - No Change in 28-Day Diffusion Coefficient
  - Reduction in Later-Age Diffusion Coefficient
    - Pozzolanic Reaction
    - Filling of Pores with Hydration Products

$$m = 0.26 + 0.4 \cdot \left(\frac{FA}{50} + \frac{SG}{70}\right)$$

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Diffusion

Effects of Time

- As Hydration Progresses:
  - Decreasing Total Porosity
  - Disconnectivity of Pore Network
  - Decreasing Concrete Permeability/Diffusivity
- Decays Asymptotically to Ultimate Value

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$$D_{28-PC} = 2.17 \cdot 10^{-12} \cdot e^{\frac{w/c}{0.279}}$$

$$D_{28-UFFA} = D_{28-PC} \cdot \left(0.170 + 0.829 e^{\left(\frac{-UFFA}{6.87}\right)}\right) \qquad D_{28-SF} = D_{28-PC} \cdot \left(0.206 + 0.794 e^{\left(\frac{-SF}{2.51}\right)}\right)$$

$$D_{ult} = D_{28} \cdot \left(\frac{28}{36500}\right)^m \qquad m = 0.26 + 0.4 \cdot \left(\frac{FA}{50} + \frac{SG}{70}\right)$$

$$D_t(t) = D_{28} \cdot \left(\frac{28}{t}\right)^m + D_{ult} \cdot \left(1 - \left(\frac{28}{t}\right)^m\right)$$

$$D_T(t,T) = D_t(t) \cdot \exp\left[\frac{U}{R} \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right]$$

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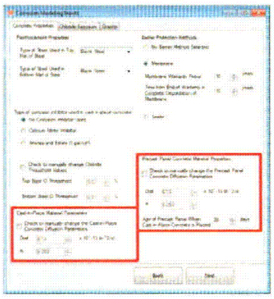
Diffusion

Diffusion Coefficient



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Diffusion

Measuring Diffusion in Concrete

- Bulk Diffusion
  - Fairly Long Term Test
    - At Least 35 Days
    - Can be 90+ Days
  - Somewhat Complex Analysis

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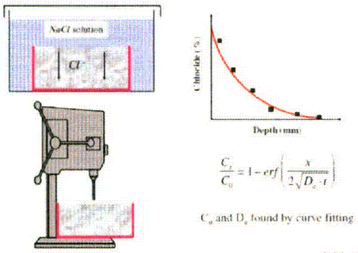
Diffusion

Measuring Diffusion in Concrete



Life-365

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Diffusion

Measuring Diffusion in Concrete

- Rapid Chloride Permeability Test (RCPT)
  - Doesn't Directly Measure Diffusivity
    - Measures Resistivity
    - Cumulative Charge Passed Over 6 Hour Period
- Drawbacks of RCPT
  - Temperature of Sample Increases During Test
    - Decreasing Resistivity
  - Requires 4"x8" Cylinder to Be Cut Down to 2" Length
  - Takes 6 Hours

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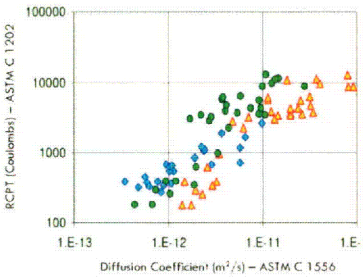
Diffusion

Measuring Diffusion in Concrete



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Application

Assumptions of Service-Life Model

- Concrete
  - Uncracked
  - Saturated
  - Constant Density
  - Diffusion the Only Transport Mechanism
    - Mass Transport from any Temperature Gradient or Pressure Gradient is Negligible
- Reinforcement
  - Corrosion Degradation Period
    - Rebar: 6 Years
    - Prestress: Immediately

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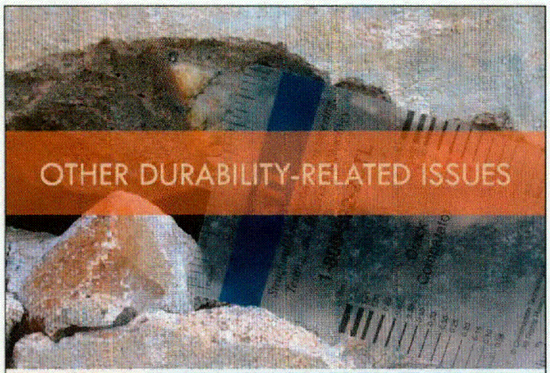

OTHER DURABILITY-RELATED ISSUES

2/25/2010 The University of Texas Concrete Durability Center TxDOT 5-4563

Overview

- Introduction
- Alkali-Silica Reaction (ASR)
- Sulfate Attack
- Delayed Ettringite Formation (DEF)

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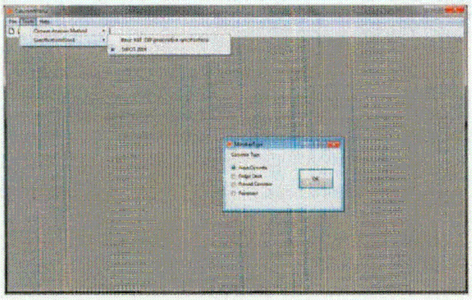
Introduction

Specifications for Durability



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Introduction

Specifications for Durability

- Fulfillment of Specification Requirements For:
  - ASR
  - DEF
  - Sulfates
- Prescriptive Spec
  - Mix Design
- Performance Spec (Predicted)
  - Temperature

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Alkali-Silica Reaction (ASR)

Outline

- Definitions
- Mechanism and Symptoms
- Contributing Factors
- Mitigation Strategies
- Application to ConcreteWorks

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Alkali-Silica Reaction (ASR)

Definition

- Reaction between the alkalis (sodium and potassium) in portland cement and certain siliceous rocks or minerals present in some aggregates
- Products of the reaction may cause abnormal expansion and cracking of concrete in service

ACI 116

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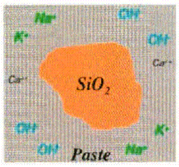
Alkali-Silica Reaction (ASR)

Mechanism and Symptoms

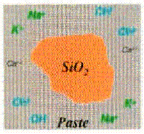
- Concrete Model Showing:
  - Cement Paste
  - Reactive Siliceous Aggregate
  - Pore Solution Dominated By:
    - Sodium, Na^+
    - Potassium, K^+
    - Hydroxyl, OH^-
    - Minor Amounts of Ca^{2+}

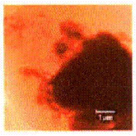


Alkali-Silica Reaction (ASR)

Mechanism and Symptoms

- Siliceous Aggregate Attacked
  - First by Hydroxyl, OH^-
  - Then by K^+ and Na^+
- Formation of Alkali-Silica Gel
  - Composed of Na, K, and Si

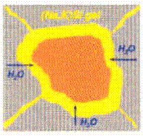




Alkali-Silica Reaction (ASR)

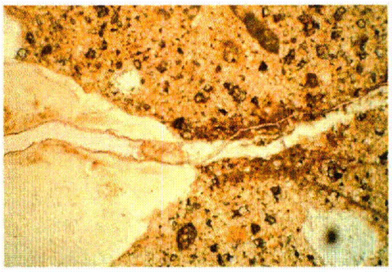
Mechanism and Symptoms

- Gel Absorbs Water
  - From Cement Paste
- Resulting Expansion
  - Internal Stresses
  - Eventual Cracking



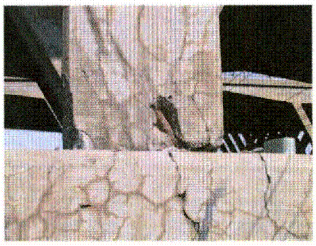
Alkali-Silica Reaction (ASR)

Mechanism and Symptoms



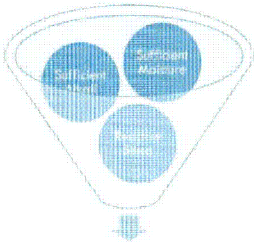
Alkali-Silica Reaction (ASR)

Mechanism and Symptoms



Alkali-Silica Reaction (ASR)

Contributing Factors



ASR

Alkali-Silica Reaction (ASR)

Mitigation Strategies

- Non-Reactive Aggregates
  - TxDOT Considers All Aggregates Reactive
  - See 8 Mix Design Options per TxDOT Item 421.4.A.6
- Minimize Total Alkali Content of Concrete

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Alkali-Silica Reaction (ASR)

Application to Concrete Works

- TxDOT Item 421 (2004)
  - Minimum SCM Content
  - Lithium Nitrate Admixture
  - Maximum Alkali Content

$$Na_2O_{eq} = Na_2O + 0.658K_2O$$

$$Alkali\ [pcy] = \frac{cement\ [pcy] \times Na_2O_{eq}\ [\%]}{100} \leq 3.5\ pcy$$

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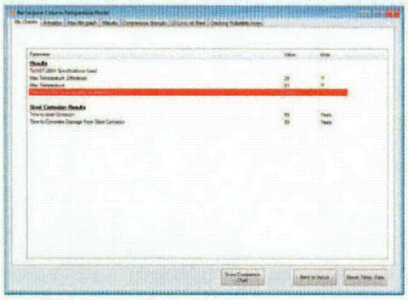
Alkali-Silica Reaction (ASR)

Application to Concrete Works



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Sulfate Attack

Outline

- Definition
- Mechanism and Symptoms
- Contributing Factors
- Mitigation Strategies
- Application to Concrete Works

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Sulfate Attack

Definition

- Deterioration of Concrete Through the Actions of Sulfate Salts and/or Acids, Chemically or Physically
  - Internal
    - Source of Sulfate is Internal to Concrete
  - External
    - Source of Sulfate is External to Concrete
      - Ground Water
      - Soil
      - Industry Waste
      - Fertilizer
      - Atmospheric SO3
  - Physical vs. Chemical

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Sulfate Attack

Mechanism and Symptoms - Physical

- Cyclical Transformation of Sodium Sulfate Between Anhydrous and Hydrous States With Change in Temperature and Humidity
  - Similar in Nature to Freeze-Thaw
- Hydrous Form Occupies Much Greater Volume
  - Induced Tensile Stresses on Concrete
  - Fatigue

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Sulfate Attack

Mitigation Strategies - Physical

- Low Permeability Concrete
- Epoxy Coatings or Sealants

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Sulfate Attack

Mechanism and Symptoms - Chemical

- Result of Chemical Reactions Involving Sulfate Anion, SO_4^{2-}, Which Forms Ettringite and/or Gypsum
  - Ettringite Formation, Followed by Water Absorption, Leads to Expansion and Cracking
  - Gypsum Formation Leads to Loss of Cohesion and "Mushy" Consistency of Cement Paste

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Sulfate Attack

Contributing Factors - Chemical

- C_3A Content of Cement
  - Chemistry/Minerology of Fly Ash
- Form of Sulfate
- Sulfate Concentration
- Sulfate Ion Availability to Reactants
- Availability of Moisture Inside Concrete
  - Ions Don't Fly, They Swim!

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Sulfate Attack

Mitigation Strategies - Chemical

- Reduce Sulfate Penetration
- Lower C_3A With Type II or Type V Cements
- Incorporation of SCMs
- Good Construction Practice

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Sulfate Attack

Mitigation Strategies

ACI 318 Sulfate Exposure

Severity	Minimum [illegible]	Condition
Negligible	2500	Concrete Not Exposed to Freeze-Thaw Cycles
Moderate	4000	Concrete Exposed to Freeze-Thaw Cycles and Occasional Exposure to Moisture
Severe	4500	Concrete Exposed to Freeze-Thaw Cycles and in Continuous Contact with Moisture
Very Severe	4500	Concrete Exposed to Freeze-Thaw Cycles, in Continuous Contact with Moisture, and Exposed to Deicing Salts

Adapted from ACI 318 Table 4.3

TxDOT 421 Sulfate Exposure

Option	Condition
1	Replace 20 to 35% of the Cement With Class F Fly Ash
2	Replace 35 to 50% of the Cement With GGBFS
3	Replace 35 to 50% of the Cement With a Combination of Class F Fly Ash, GGBFS, or Silica Fume. However, No More Than 35% May Be Fly Ash, and No More Than 10% May Be Silica Fume
4	Use Type IP or Type IS Cement (Up to 10% of a Type IP or Type IS Cement May be Replaced With Class F Fly Ash, GGBFS, or Silica Fume)

TxDOT 421.4.A.6

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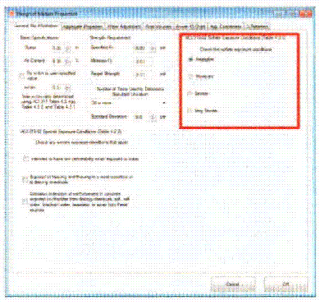
Sulfate Attack

Application to ConcreteWorks



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Delayed Ettringite Formation (DEF)

Outline

- Definition
- Mechanism and Symptoms
- Contributing Factors
- Mitigation Strategies
- Application to Concrete Works

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Delayed Ettringite Formation (DEF)

Definition

- Internal Sulfate Attack
  - Damage (Expansion & Cracking) of Concrete Due to Formation of Ettringite After Concrete Has Already Hardened
  - Result of Excessive Temperatures During Curing Which Prevent the Normal "Early" Formation of Ettringite

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Delayed Ettringite Formation (DEF)

Mechanism and Symptoms

- At High Temperature
  - Early Stages
    - Incongruent Dissolution of Ettringite
    - Sulfate & Alumina Enveloped in Rapidly Forming Inner CSH
  - Later Stages - Upon Cooling
    - Ettringite Formation in Fine Pores of Outer CSH
    - Resulting Expansion of Hardened Cement Paste
    - Ettringite Causes Paste to Expand Away From Aggregates

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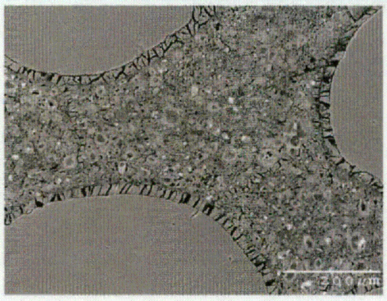
Delayed Ettringite Formation (DEF)

Mechanism and Symptoms



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Delayed Ettringite Formation (DEF)

Mechanism and Symptoms

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Delayed Ettringite Formation (DEF)

Contributing Factors

- Excessive Temperatures During Curing
  - Prevents Normal "Early" Formation of Ettringite
  - Type III Cement Susceptible to DEF
- Late Release of Sulfate From High-sulfate Clinkers

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Delayed Ettringite Formation (DEF)

Mitigation Strategies

- Sulfate-Resistant Cement
- SCMs
- Good Construction Practice

Delayed Ettringite Formation (DEF)

Application to ConcreteWorks

- TxDOT Item 421 (2004)
  - Minimum SCM Content
  - T_{max} Predicted ≤ 158° F
  - ΔT_{max} Predicted ≤ 35° F

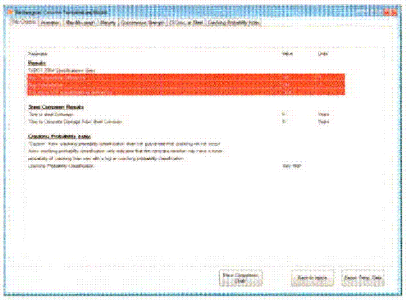
Delayed Ettringite Formation (DEF)

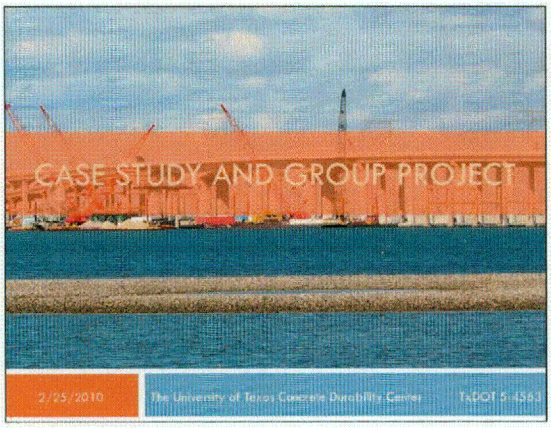
Application to ConcreteWorks

- Basic DEF Prescriptive Spec
  - ConcreteWorks Only Flags 158 F Max
- User Needs to Be Aware of TxDOT Specs
  - TxDOT Spec is:
    - 170 for Cement + Fly Ash
    - 150 for Precast
    - 158 for Mass Concrete

Delayed Ettringite Formation (DEF)

Application to ConcreteWorks





Case Study and Group Project

Objective

- The objective of this assignment is for you and your colleagues to work in groups to design a concrete mixture for a large, rectangular column that meets all technical requirements described herein.
- Your group's assignment is to design a concrete mixture for large rectangular column to be placed in an aggressive environment in Galveston, TX.

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Case Study and Group Project

Objective

- Using ConcreteWorks, select an option that meets the technical requirements and also is practically and economically feasible. Each group will be asked to give a 10-15 minute presentation, briefly summarizing your proposed mixture proportion and construction plan.
- *Be innovative and have fun!! Be sure to have a name for your group and maybe even a theme (e.g., sustainability, innovation, speed, technology, etc.). In your group presentation, please give justification for your group's approach and back this up with output from ConcreteWorks).*

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Case Study and Group Project

Construction Details

- Casting date – December 29, 2010
- Casting time – 7 am (but time of pour can be shifted five hours earlier or later, if necessary)
- Temperature analysis duration = 7 days
- Life cycle analysis duration = 75 years
- Column dimensions = 5' x 6' (non-submerged)
- Steel forms, stripped at 96 hours (you can try to strip earlier provided you meet mass concrete requirements for maximum temperature and maximum thermal gradient)
- Crushed ice and liquid nitrogen are available to reduce fresh concrete temperature

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Case Study and Group Project

Exposure Conditions and Durability Requirements

- Exposure Classification: Splash Zone
  - Use Default Values for Chloride Concentrations
- Corrosion of reinforcing steel must be avoided for 75 years!!

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Case Study and Group Project

Mass Concrete - Specifications

- Maximum fresh concrete temperature = 75 °F
- Maximum temperature anywhere in column = 158 °F (to avoid Delayed Ettringite Formation or "DEF")
- Maximum temperature gradient in column = 35 °F (to avoid thermal cracking)

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Case Study and Group Project

Available Materials

- Maximum cementitious materials content = 600 lbs/yd³ (as per DOT requirements for mass concrete)
- Portland cement (ASTM C 150)
  - Type I
  - Type I/II
  - Type II
- Fly ash (ASTM C 618)
  - Class F fly ash (CaO = 5.0%)
  - Class C fly ash (CaO = 25.0%)
- Ground granulated blast-furnace slag (Grade 120)
- Silica fume (densified)

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Case Study and Group Project

Available Materials

- Chemical admixtures
  - Water reducer
  - Mid-range water reducer
  - Retarder
  - Accelerator
  - Air-entraining agent
  - Corrosion inhibitor – calcium nitrite (to raise chloride threshold value)
- Aggregates
  - Siliceous river sand or manufactured sand (limestone)
  - Siliceous river gravel or crushed limestone (1" max size)

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Overview

- Project Tasks
- Objectives
- Mass Concrete
- Chloride-Service Life
- Discussion

Project Tasks

- Task 1 – Training Materials for ConcreteWorks
- Task 2 – Delivery of Training Courses
- Task 3 – Implementation of ConcreteWorks
- Task 4 – Minor Modifications to ConcreteWorks

Objectives

Path Forward

- Implementation of ConcreteWorks
  - Mass Concrete
  - Pavement Applications
    - Sufficient Research Currently in Progress
  - Service-Life Prediction
  - Bridge Decks
    - In Progress Under TxDOT 6332
- Development of Specification Approach

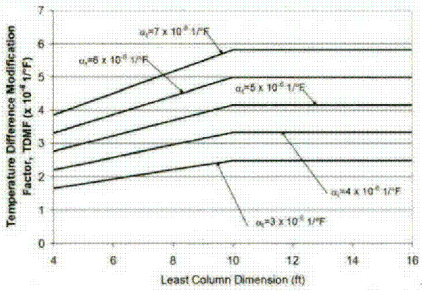
Mass Concrete

Specification Approach

- Temperature Difference Modification Factor (TDMF)
  - Determined By:
    - Compressive Strength Development
    - Concrete Member Size
    - Concrete Coefficient of Thermal Expansion
  - Limited Max Temperature Difference : 20 - 60° F

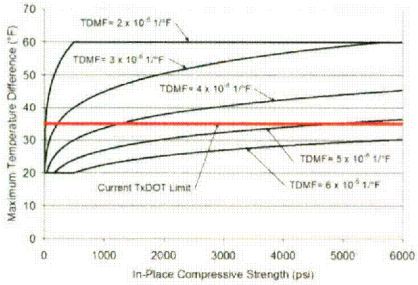
Mass Concrete

Specification Approach



Mass Concrete

Specification Approach



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Mass Concrete

Specification Approach

- Maximum Temperature Deviation From a Concrete Thermal Stress Analysis

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Mass Concrete

Specification Development

- Proof of Compliance With Job Specification
  - Requisite Data Collection
  - Instrumentation and Monitoring
  - Format and Language
  - Ensure Use of Accurate Analysis Parameters

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Mass Concrete

Tech Support

- Testing of Job-Specific Materials
  - Isothermal Calorimetry
  - Semi-Adiabatic Calorimetry
  - Maturity
  - Other Material Properties Essential to ConcreteWorks
- Preliminary Evaluation
  - Modeling of Project in ConcreteWorks
- Instrumentation Plan
  - Data to Collect
  - Where to Put Sensors
  - How Many
- Calibration/Validation of ConcreteWorks

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Service Life

Objectives

- 75-year Design Life
- Marine or Deicing Salt Exposure

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Service Life

Technical Support

- Determination of Relevant Material Properties
- Diffusion Modeling
- Validation of Diffusion Modeling
- Correlation of Diffusion Coefficients with RCPT

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Service Life

Field Support

- Monitoring
- Collect and Analyze Materials and Mixes
- Visual Inspection
- Cores from Job and Cylinders at Job Site (for RCPT and other tests)

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Got Any Jobs for Us?

- Time Frame
- Change Orders

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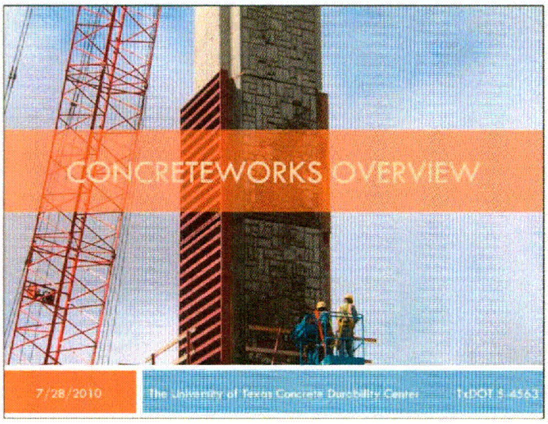
Standard Class



ConcreteWorks Overview

Purpose

- Enhance Knowledge And Use Of ConcreteWorks Across TxDOT Districts
- Identify And Train TxDOT Districts With Upcoming Projects Suitable For ConcreteWorks Implementation
- Provide Technical Support For Districts Interested In Implementing ConcreteWorks On Upcoming Projects
- Specification Approach For ConcreteWorks

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ConcreteWorks Overview

Implementation

- Up To Four Projects
- Technical Support And Guidance
- On Site Instrumentation And Testing
  - Semi-Adiabatic Calorimetry
  - Isothermal Calorimetry
  - Maturity
- Validation Of ConcreteWorks

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ConcreteWorks Overview

Implementation

- Preferred Projects
  - Mass Concrete
    - Rectangular Columns
    - Thermal Cracking Tendencies
  - Service-Life Prediction
    - Marine Structures
    - Exposure to Deicing Salts

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ConcreteWorks Overview

Agenda

Start		End	Topic
8:00 AM	-	8:10 AM	ConcreteWorks Overview
8:10 AM	-	8:20 AM	Mix Design and Proportioning
8:20 AM	-	8:45 AM	Demonstration and Hands-On Exercise
8:45 AM	-	8:55 AM	Temperature Prediction
8:55 AM	-	9:20 AM	Demonstration and Hands-On Exercise
9:20 AM	-	9:30 AM	Crack Prediction
9:30 AM	-	9:55 AM	Demonstration and Hands-On Exercise
9:55 AM	-	10:10 AM	15 Minute Break
10:10 AM	-	10:20 AM	Chloride Service-Life
10:20 AM	-	10:45 AM	Demonstration and Hands-On Exercise
10:45 AM	-	11:00 AM	Case Study – Overview & Instructions
11:00 AM	-	11:30 AM	Case Study – Group Work
11:30 AM	-	12:00 PM	Case Study – Presentations

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ConcreteWorks Overview

Item 420.4.G4 (2004)

- Mass placements are defined as placements with a least dimension greater than or equal to 5 ft., or designated on the plans. For monolithic mass placements, develop and obtain approval for a plan to ensure the following during the heat dissipation period:
  - the temperature differential between the central core of the placement and the exposed concrete surface does not exceed 35°F and
  - the temperature at the central core of the placement does not exceed 160°F.
- Base this plan on the equations given in the Portland Cement Association's Design and Control of Concrete Mixtures. Cease all mass placement operations and revise the plan as necessary if either of the above limitations is exceeded. Include a combination of the following elements in this plan:
  - selection of concrete ingredients including aggregates, gradation, and cement types, to minimize heat of hydration;
  - use of ice or other concrete cooling ingredients;
  - use of liquid nitrogen dosing systems;
  - controlling rate or time of concrete placement;
  - use of insulation or supplemental external heat to control heat loss;
  - use of supplementary cementing materials; or
  - use of a cooling system to control the core temperature.
- Furnish and install 2 sets of temperature recording devices, maturity meters, or other approved equivalent devices at designated locations. Use these devices to simultaneously measure the temperature of the concrete at the core and the surface. Maintain temperature control methods for 4 days unless otherwise approved. Maturity meters may not be used to predict strength of mass concrete.

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ConcreteWorks Overview

Why All The Trouble?

- ...and why the specification?
  - Concrete temperature and concrete durability are related
  - ConcreteWorks can help provide high quality, durable, crack-free concrete

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ConcreteWorks Overview

Why Do We Need a Program?

- The calculations are difficult
- Guidance provided by ACI and PCA is vague
- Information in literature concerning temperature rise of various materials is dispersed
- The problem becomes even more difficult when cracking tendency is considered. The specification does not even address this!

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ConcreteWorks Overview

- User-friendly software package for the design, analysis, and performance prediction of structural concrete
  - Mass Concrete
  - Bridge Decks
  - Concrete Pavements
  - Precast Concrete Members

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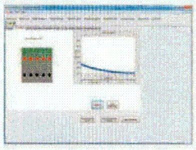
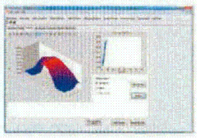
ConcreteWorks Overview





- Mass Concrete
  - Temperature Prediction
  - Cracking Probability
  - Chloride Service-life Analysis
- Bridge Decks
  - Temperature Prediction
  - Chloride Service-life Analysis
- Pavements
  - Temperature Prediction
- Precast/Prestressed Members
  - Temperature Prediction

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ConcreteWorks Overview

- Put In
  - Materials and Mix Design Inputs
  - Geometry of Structural Element
  - Type of Formwork, Base, Etc.
  - Time, Date and Location of Project Placement
- Get Out
  - Maximum Temperature Prediction
  - Temperature Distribution Throughout Element
  - Maximum Temperature Differential
  - Cracking Susceptibility
  - Other Goodies: ASR, DEF, and Sulfate Attack Susceptibility

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ConcreteWorks Overview

- Advantages
  - Evaluation of Concrete Before Poured
  - Prevent Problems Before they Occur
    - No Need to Repair Later
  - Save Consultant Fees $$$$
    - Program Development Paid Now
    - Software is Intended to be Free
  - Save Mix Designs Digitally Forever
    - No Need for Keeping Bulky Paperwork

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ConcreteWorks Overview

- Other Benefits
  - Design Mixes With Minimal Crack Susceptibility
  - Improve Longevity of Structures
  - Reduce Replacement and Repair of Structures
  - Reduce Field Discussions Concerning Placement Time and Weather Extremes

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ConcreteWorks Overview

- What it Won't Do:
  - Account for Precipitation
  - Freeze Events
  - Recommend 22% or 23% Fly Ash
  - Model Odd Shaped Concrete Members

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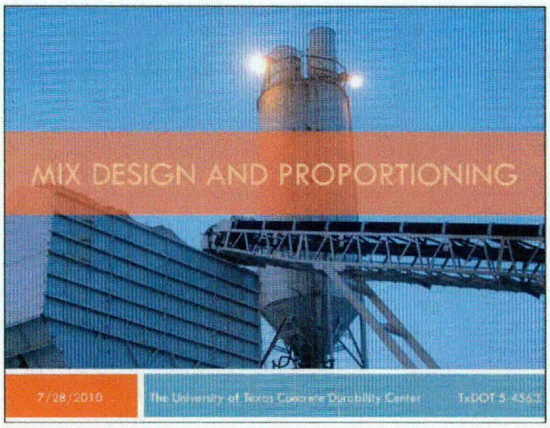

Mix Design And Proportioning

Step 0: Assemble Information

- Specifications
  - Slump
  - Specified Strength
  - Maximum Water to Cement Ratio
  - TxDOT Item 421.4.A.6
- Exposure Conditions
  - Freeze-Thaw
  - Marine Environment
  - Sulfates
- Material Properties
  - Specific Gravities of Cementitious Materials
  - Bulk Specific Gravities of Aggregates
  - Dry-Rodded Unit Weights of Aggregates
  - Aggregate Gradations and Maximum Size
  - Fineness Modulus of Fine Aggregate
  - Aggregate Absorption
  - Aggregate Moisture Content

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Mix Design And Proportioning

Step 1: Slump

Types of Construction	Slump, in. Max	Slump, in. Min
Reinforced Foundation Walls and Footings	3	1
Plain Footings, Caissons, and Substructure Walls	3	1
Beams and Reinforced Walls	4	1
Building Columns	4	1
Pavements and Slabs	3	1
Mass Concrete	2	1

ACI 211 Table 6.3.1

Rule of Thumb: 1" of Slump ≈ 10 lb/yd^3 of Water

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Mix Design And Proportioning

Step 2: Maximum Size Aggregate

- Maximum Size Aggregate (MSA)
  - Determined By:
    - Formwork Clearance
    - Concrete Member Thickness
    - Reinforcement Spacing
    - Cover Over Steel Reinforcement
  - Affects Workability, Cost, And Performance
  - Sieve Size On Which 5 - 15% Of Coarse Aggregate Is Retained (typically 15)

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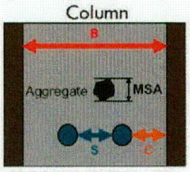
Mix Design And Proportioning

Step 2: Maximum Size Aggregate

Column

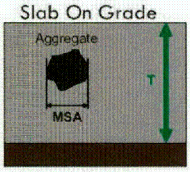


Distance Between Forms (B): MSA ≤ B/5

Reinforcement Spacing (S): MSA ≤ ¾S

Cover (C): MSA ≤ ¾C

Slab On Grade



Thickness of Slab (T): MSA ≤ T/3

Pumped Concrete: MSA ≤ 1/3 Dia. of Hose

MSA ≤ 1 ½ in.

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Mix Design And Proportioning

Step 3: Water And Air Content

Non Air-Entrained Concrete

Mixing Water, lb/yd^3 for Indicated Slump and Maximum Size of Aggregate								
Slump, in.	3/8 in.	½ in.	¾ in.	1 in.	1½ in.	2 in.	3 in.	6 in.
1 to 2	350	335	315	300	275	260	220	190
3 to 4	385	365	340	325	300	285	245	210
6 to 7	410	385	360	340	315	300	270	-
Entrapped Air (approx.)	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.2

ACI 211 Table 6.3.3

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Mix Design And Proportioning

Step 3: Water And Air Content

Air-Entrained Concrete

Mixing Water, lb/yd³ for Indicated Slump and Maximum Size of Aggregate								
Slump, in.	3/8 in.	½ in.	¾ in.	1 in.	1½ in.	2 in.	3 in.	6 in.
1 to 2	305	295	280	270	250	240	205	180
3 to 4	340	325	305	295	275	265	225	200
6 to 7	365	345	325	310	290	280	260	-
Freeze/Thaw	Recommended Total Air Content, percent							
Mild	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
Moderate	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0
Severe	7.5	7.0	6.0	6.0	5.5	5.0	4.5	4.0

ACI 211 Table 6.3.3

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Mix Design And Proportioning

Step 4: Water To Cement Ratio

28-Day Compressive Strength, psi	Water-Cement Ratio by Weight	
	Non-Air-Entrained	Air-Entrained
6000	0.41	-
5000	0.48	0.40
4000	0.57	0.48
3000	0.68	0.59
2000	0.82	0.74

ACI 211 Table 6.3.4(a)

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Mix Design And Proportioning

Step 5: Cement Content

- Calculate Based On Selected Water Content And Water-Cement Ratio

$$Cement\ (lb/yd^3) = \frac{Water\ (lb/yd^3)}{Water\ to\ Cement\ Ratio}$$

- Consider SCMs
  - % Replacement by Weight (ACI 211 6.3.4.1)
  - % Replacement by Volume (ACI 211 6.3.4.2)

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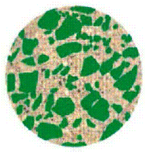
Mix Design And Proportioning

Step 6: Coarse Aggregate Content



- Coarse Aggregate
  - Larger Than 3/8"
  - Up to 6" or More
  - Usually 30-40% of Mix
    - By Volume or Mass
- Gravel
  - Typically Round or Subangular
- Crushed Stone
  - Angular

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Mix Design And Proportioning

Step 6: Coarse Aggregate Content

Volume of Coarse Aggregate per Unit Volume of Concrete				
Nominal Maximum Size of Aggregate	Fine Aggregate Fineness Modulus			
	2.40	2.60	2.80	3.00
3/8 in.	0.50	0.48	0.46	0.44
1/2 in.	0.59	0.57	0.55	0.53
3/4 in.	0.66	0.64	0.62	0.60
1 in.	0.71	0.69	0.67	0.65
1½ in.	0.75	0.73	0.71	0.69
2 in.	0.78	0.76	0.74	0.72
3 in.	0.82	0.80	0.78	0.76
6 in.	0.87	0.85	0.83	0.81

ACI 211 Table 6.3.6

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Mix Design And Proportioning

Step 6: Coarse Aggregate Content

- Coarse Aggregate Factor
  - Intended to Provide Consistent Workability
    - Empirical Basis
  - Multiplied by Dry-Rodded Unit Weight of Coarse Aggregate to Get Coarse Aggregate Content

$$CA\ Content = CA\ Factor \times Dry\ Rodded\ Unit\ Weight$$

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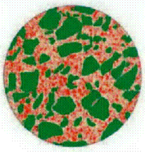
Mix Design And Proportioning

Step 7: Fine Aggregate Content

- Fine Aggregate
  - Sand
  - Crushed Stone
  - 100% Passing 3/8" Sieve
  - Usually 35-45% of Mix
    - By Volume or Mass
  - Only Remaining Volume to be Determined



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Mix Design And Proportioning

Step 7: Fine Aggregate Content

- Calculate Fine Aggregate On Per Cubic Yard Basis

	27 (Unit Volume)	(ft^3)
-	Volume Of Mixing Water	(ft^3)
-	Volume Of Air	(ft^3)
-	Volume Of Portland Cement	(ft^3)
-	Volume Of Coarse Aggregate	(ft^3)
	Volume Of Fine Aggregate	(ft^3)

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Mix Design And Proportioning

Step 8: Moisture Content Adjustment

- Mix Design Obtained Following ACI 211:
  - Cement: 564 lb/yd^3
  - Water: 220 lb/yd^3
  - Coarse Aggregate: 1800 lb/yd^3
  - Fine Aggregate: 1100 lb/yd^3
- Aggregate Properties:
  - Coarse Aggregate
    - Absorption: 0.5% (by mass)
    - Moisture: 0.3% (by mass)
  - Fine Aggregate
    - Absorption: 0.9% (by mass)
    - Moisture: 1.3% (by mass)

Does Moisture Content Exceed Absorption Capacity of Aggregate?

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Mix Design And Proportioning

Step 8: Moisture Content Adjustment

- Aggregate Water Contribution
  - (Moisture – Absorption) x Aggregate Content
  - CA (0.3% - 0.5%) x 1800 lb/yd = -3.6 lb water
  - FA (1.3% - 0.9%) x 1100 lb/yd = +4.4 lb water
- Net Result
  - 4.4 – 3.6 = 0.8 lb water added by aggregates
  - Adjusted mix water = 220 – 0.8 = **219.2 lb/yd^3**

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Mix Design And Proportioning

Step 9: Trial Batch

- ACI Method Is Based On Comprehensive Laboratory Testing Of Concrete
- Materials Used To Develop The ACI Method Are Likely Different From Local Materials
- Concrete Mixtures In Practice Always Adjusted To Take Advantage Of Local Materials
- ACI 211 Mix Design Process is Intended for Trial Batch Only
- You Are Responsible for Making Necessary Adjustments

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Mix Design And Proportioning

Hands-On Demonstration of Mix Design and Proportioning in ConcreteWorks!

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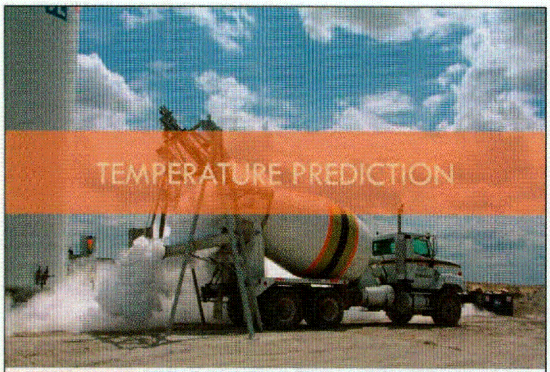
Hands-On Exercise
Mix Design and Proportioning

1. **Open a new mass concrete project in ConcreteWorks**
2. **General Inputs**
   a. Select English units
3. **Mixture Proportion Inputs**
   a. Click Go to Design of Mixture Proportion
   b. General Mix Information
      i. Compressive strength = 4000 psi
      ii. Slump = 4 in
      iii. Number of test used to determine standard deviation = 15-19
      iv. Standard deviation = 600
   c. Aggregate Properties
      i. Enter aggregate gradation properties as seen in the table below

	Coarse 1	Coarse 2	Fine 1
2 in	100	100	-
1 ½ in	100	100	-
1 in	98.2	100	-
¾ in	75.2	100	-
½ in	38.5	100	-
3/8 in	23.5	98.3	-
#4	4.7	36	99
#8	3.7	4	84
#16	3.2	1	63
#30	2.9	0.9	43
#50	2.6	0.8	19
#100	2.2	0.3	4
#200	1.5	0	1
Pan	0	0	0
SG	2.7	2.6	2.7

      ii. Coarse Aggregate Oven-Dry-Rodded Unit Weight = 105 lb/ft^3
      iii. Try various coarse aggregate percentages to optimize the gradation
      iv. Make sure to select "Update Aggregate Properties" each time you make changes
   d. Water Adjustment
      i. Add in a type F high range water reducer and assume it reduces water demand by 25%
      ii. Assume your optimized gradation reduces water demand by 5%
   e. Final Volumes
      i. Add 30% Class F Fly Ash - assume 3% water reduction per 10% fly ash
      ii. Add 8% Silica Fume - assume 2% water demand per 1% silica fume



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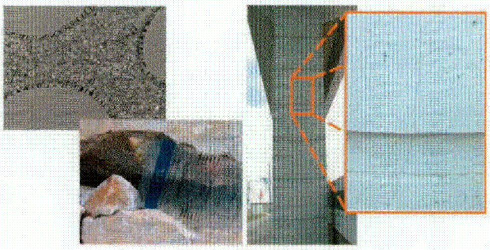
Temperature Prediction

Potential Risks in Mass Concrete Elements

High Temperature | Thermal Gradients



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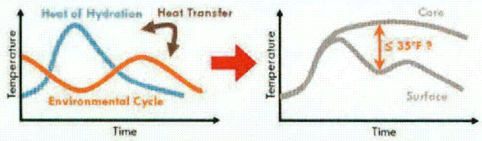
Temperature Prediction

Introduction



Heat of Hydration	Environmental Cycle	Heat Transfer
Cement Composition	Air Temperature	Element Geometry
Effect of SCMs	Wind Speed	Element Size
Cement Fineness	Relative Humidity	Submerged ??
Amount of Cement	Cloud Cover	Form Properties
Chemical Admixtures	Solar Radiation	Curing Method
w-cm Ratio	Air Pressure	Surface Color
Mix Temperature		Aggregate Type

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Temperature Prediction

Hydration Model

- Hydration Reaction is Exothermic
  - Gives Off Heat
- Heat Generation Characterized By:
  - Cement Chemical/Physical Properties
    - Chemical Composition
      - Bogue
      - Rietveld
    - Blaine Fineness
  - Calorimetry
  - Cement Content
  - Chemical Admixtures

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Temperature Prediction

Hydration Model

- Cement Chemical Properties
  - Oxide Analysis
    - Calcium Oxide, CaO
    - Silicon Dioxide, SiO_2
    - Ferric Oxide, Fe_2O_3
    - Aluminum Oxide, Al_2O_3
    - Free Lime, CaO
    - Sulphur Trioxide, SO_3
    - Magnesium Oxide, MgO
    - Sodium Oxide, Na_2O
    - Potassium Oxide, K_2O
  - Calculated Compounds Using Bogue Equations
    - Alite, C_3S
    - Belite, C_2S
    - Tricalcium Aluminate, C_3A
    - Tetracalcium Aluminoferrite, C_4AF

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Temperature Prediction

Hydration Model

$CaO = CaO - \textit{Free Lime}$

$C_3S = 4.0710 \cdot CaO - 7.6024 \cdot SiO_2 - 1.4297 \cdot Fe_2O_3 - 6.7187 \cdot Al_2O_3$

$C_2S = 8.6024 \cdot SiO_2 + 1.1 \cdot Fe_2O_3 + 5.0683 \cdot Al_2O_3 - 3.0710 \cdot CaO$

$C_3A = 2.6504 \cdot Al_2O_3 - 1.6920 \cdot Fe_2O_3$

$C_4AF = 3.0432 \cdot Fe_2O_3$

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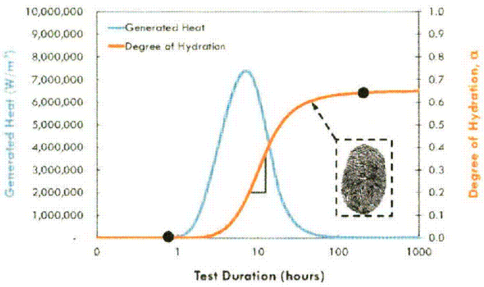
Temperature Prediction

Hydration Model



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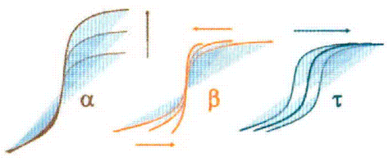
Temperature Prediction

Hydration Model

- Calorimetry
  - Heat Generation Characteristics



  - Activation Energy
    - Temperature Dependency of Hydration Reaction

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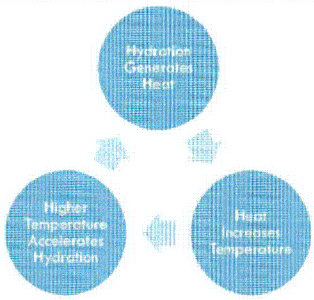
Temperature Prediction

Hydration Model



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Temperature Prediction

Heat Transfer Model

- Concrete Thermal Properties
  - Thermal Conductivity
  - Specific Heat
- Environmental Conditions
  - Temperature
  - Wind Speed
  - Cloud Cover
  - Humidity
- Boundary Conditions
  - Formwork
  - Curing

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Temperature Prediction

Heat Transfer Model

- Concrete Thermal Properties
  - Coefficient of Thermal Expansion
  - Thermal Conductivity
    - Ability of a Material to Transfer or Conduct Heat
  - Combined Aggregate Specific Heat
    - Energy Required to Increase Temperature of Material

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Temperature Prediction

Heat Transfer Model

- Energy Balance

$$\Delta E = E_{in} - E_{out} + E_{gen} \quad \text{[Watts]}$$

  - Where:
    - E_{in} = Thermal Energy Entering Control Volume
    - E_{out} = Thermal Energy Leaving Control Volume
    - E_{gen} = Thermal Energy Generated Within Control Volume
- Heat Transfer (E_{in} - E_{out})
- Heat of Hydration (E_{gen})

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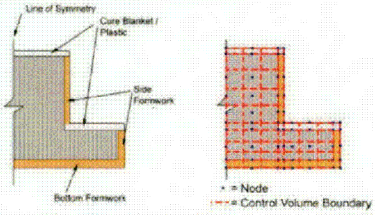
Temperature Prediction

Heat Transfer Model

- Control Volume
  - Transfer of Heat Between Control Volumes
  - Modeling of Boundary Conditions



Temperature Prediction

Field Work

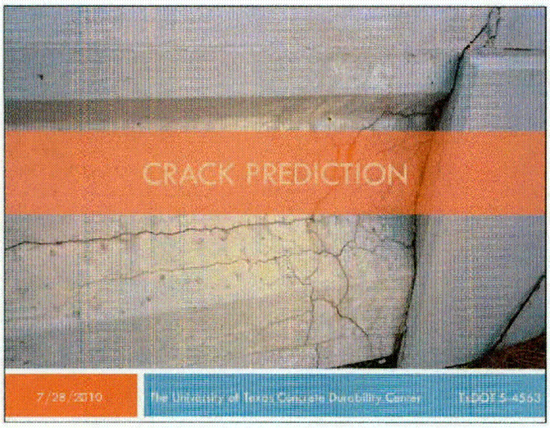
- Hydration Model Based On (To Date):
  - Semi-Adiabatic Calorimetry - 139 Tests
  - Isothermal Calorimetry – 630 Tests
- Field Calibrated With:
  - 33,626 Hrs of Temperature Data
  - 137 Temperature Sensors from 12 Concrete Members
  - Average R^2 Value of 0.90

Temperature Prediction

Hands-On Demonstration of Temperature Prediction in ConcreteWorks!

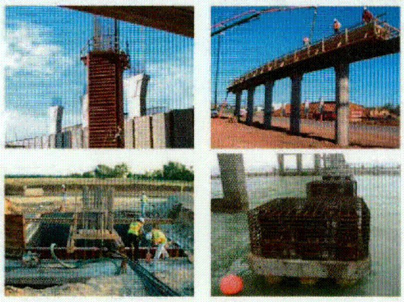
Hands-On Exercise
Temperature Prediction

1. **Open a new mass concrete project in ConcreteWorks**
2. **General Inputs**
    a. Select English units
    b. Placement time = 10 am
    c. Temperature analysis duration = 7 days
    d. Project Location = Fort Worth
3. **Shape Inputs**
    a. Rectangular Column
4. **Member Dimensions**
    a. Width = 5 ft
    b. Depth = 5 ft
5. **Mixture Proportion Inputs**
    a. Click Go to Design of Mixture Proportion
    b. Compressive strength = 5000 psi
6. **Input Check**
    a. Calculate Temperatures
7. **Results**
    a. Select "Show Comparison Chart"
    b. Rename Series 1 to "Straight Cement @ 10 am"
    c. Close the comparison window
8. **Modify the Mix Design and Placement Time**
    a. Go to the General Inputs Screen and change the placement time to 10 pm
    b. Go to Design of Mixture Proportion on the Mix Proportion tab and replace cement with 35% F Ash
    c. Click the Water Adjustment tab and adjust the following sliders:
        i. High Range Water Reducer (Type F): -20
        ii. Aggregate Shape and Texture: -2
        iii. Combined Aggregate Grading: -5
        iv. Mineral Admixtures: -10
    d. Give the F Ash a CaO content of 10%
    e. Manually enter the concrete fresh temperature: 60 F
9. **Repeat step 6 and 7 - name the series "Revised Mix @ 10 pm"**
    a. Compare your results



Crack Prediction

Field Work



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Crack Prediction

Field Work

Concrete Member	Maximum Temperature Recorded (°F)	Maximum Temperature Difference Recorded (°F)
Column 1	154.0	86.0
Column 2	136.0	35.0
Column 3	136.0	40.0
Column 4	163.4	60.3
Footing 1	161.0	72.0
Footing 2	133.0	45.0
Footing 3	135.5	41.4
Dolphin 1	145.4	72.0
Dolphin 2	123.8	45.9
Rect. Bent Cap	128.3	27.9
T Bent Cap	153.5	65.7
Pedestal	165.2	43.2

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Crack Prediction

Introduction

- Concrete Cracks When Stress Exceeds Strength
  - Variable Early-Age Properties
    - Compressive Strength
    - Tensile Strength
    - Modulus of Elasticity
    - Coefficient of Thermal Expansion
    - Poisson's Ratio
    - Shrinkage
    - Creep
- Need to Know Progress of Cement Hydration
  - Maturity

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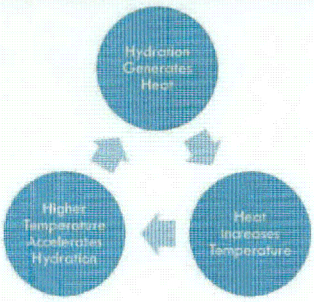
Crack Prediction

Concrete Maturity



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Crack Prediction

Concrete Maturity

- Method of Comparing Hydration Progress at Different Temperatures
  - Samples of Concrete Mixture of Same Maturity Should Have Similar Properties Regardless of the Combination of Time and Temperature Yielding that Maturity
  - Generally Used for Determining In-Place Strength Development in Variable Temperature Conditions
- Maturity Functions (ASTM C 1074)
  - Nurse-Saul Method
    - Time-Temperature-Strength Relationship from Laboratory Testing
    - Linear Temperature-Strength Gain Relationship
  - Equivalent Age Method
    - Originated as a General Concept for all Chemical Reactions
    - Exponential Temperature-Strength Gain Relationship

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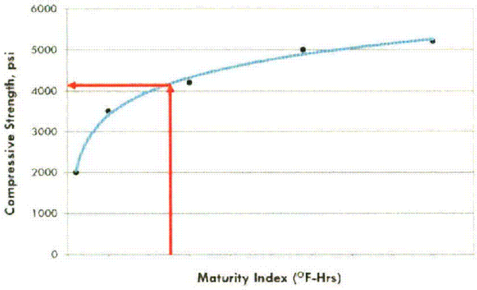
Crack Prediction

Concrete Maturity



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Crack Prediction

Elastic Modulus Development

- Relates Compressive Strength to Elastic Modulus
- Default Values Come from ACI 318 Building Code

$$E = E_c \cdot f_c^{E_e} \cdot w^{1.5}$$

Where :

E = Elastic Modulus

f_c = Compressiv e Strength

w = Unit Weight

E_c and E_e are Fit Paramaters

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Crack Prediction

Tensile Strength Development

- Relates Compressive Strength to Tensile Strength
- Default Values Come from ACI 318 Building Code

$$f_t = f_{tc} \cdot f_c^{f_{te}}$$

Where :

f_{tc} = Splitting Tensile Strength

f_c = Compressiv e Strength

f_{tc} and f_{te} are Fit Paramaters

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Crack Prediction

Thermal Stress Analysis

- Integrate Heat Prediction Model With Thermal Cracking Behavior
  - Thermal Stress Analysis
- Early-Age Cracking is Due to Strains Primarily Caused By:
  - Thermal Gradients
  - Drying Shrinkage
  - Autogenous Shrinkage

  } + Degree of Restraint
- Must Account for Creep
  - Stress Relaxation

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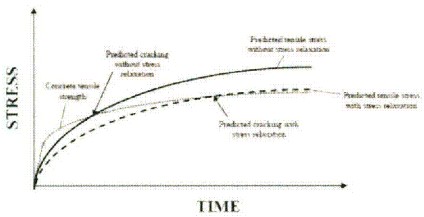
Crack Prediction

Early-Age Concrete Creep Model

- Time Dependence of Restrained Shrinkage and Creep (Mehta, 1993)



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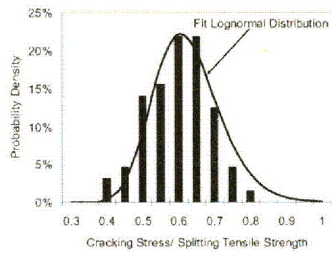
Crack Prediction

Cracking Potential



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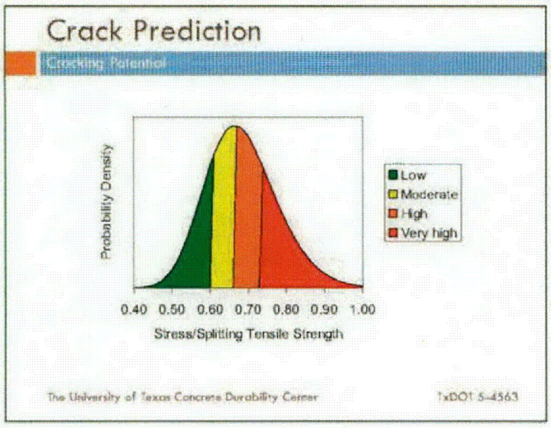
Crack Prediction
Cracking Potential
Probability Density
Low
Moderate
High
Very high
0.40 0.50 0.60 0.70 0.80 0.90 1.00
Stress/Splitting Tensile Strength
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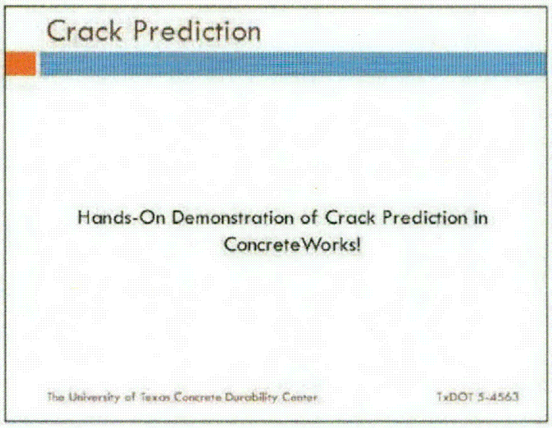
TxDOT 5-4563


Crack Prediction
Hands-On Demonstration of Crack Prediction in ConcreteWorks!
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TxDOT 5-4563

Hands-On Exercise
Crack Prediction

1. **Open a new mass concrete project in ConcreteWorks**
2. **General Inputs**
    a. Select English units
    b. Set the location to Forth Worth, TX
    c. Temperature analysis duration = 3 days
3. **Shape Inputs**
    a. Rectangular column
4. **Rectangular Column Dimensions**
    a. Width = 3 ft
    b. Depth = 3 ft
5. **Material Properties**
    a. Coarse aggregate type = siliceous river gravel
    b. Fine aggregate type = siliceous river sand
6. **Mechanical Properties**
    a. Check to calculate thermal stresses
    b. Maturity function = Nurse-Saul
    c. Nurse-Saul Strength Inputs
        i. a = -5450 psi
        ii. b = 2850 psi/°F/hr
7. **Input Check**
    a. Calculate Temperatures
8. **Modify the Material Properties**
    a. Coarse aggregate type = limestone
9. **Input Check**
    a. Calculate Temperatures
    b. Compare Results

CHLORIDE SERVICE-LIFE

7/28/2010 The University of Texas Concrete Durability Center TxDOT 5-4563

Chloride Service-Life

Basic Mechanism of Corrosion

- Why Does Steel Corrode?
  - Steel is Not Naturally Occurring
    - Manufactured from Iron Ore
  - Prefers to Revert Back to Natural State in Form of Iron Oxide (Rust)
  - Speed Governed by Rate of Ionic Solution Movement
- Why is This a Problem for Concrete?
  - Rust Occupies Greater Volume than Original Steel
  - Cracking, Spalling, and Delamination of Concrete

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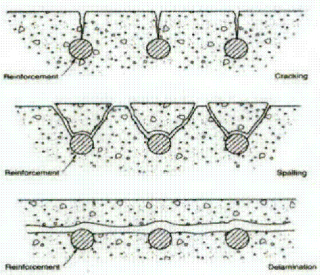
Chloride Service-Life

Basic Mechanism of Corrosion



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Chloride Service-Life

Basic Mechanism of Corrosion

- Stages of Corrosion
  - Penetration and Accumulation of Chlorides
  - Chloride Threshold Reached – Initiation of Corrosion
  - Degradation of Reinforcement
    - For Rebar: 6 Years
    - For Prestress: Immediate Failure

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Chloride Service-Life

Internal Sources of Chlorides in Concrete

- Chloride-Containing Chemical Admixtures
  - $CaCl_2$-Based Accelerators
    - Not Allowed in Any TxDOT Work
- Aggregates
  - Sea-Dredged Sand
  - Presence of Mineral Halite
- Mixing Water
  - Chloride Limits per TxDOT Item 421 Table 1
    - Bridges & Prestress: 500 ppm
    - All Other Concrete: 1000 ppm

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Chloride Service-Life

External Sources of Chlorides in Concrete

- Seawater
  - Marine Structures, Oil Platforms, Coastal Bridges, Etc.
- Groundwater
  - Piles, Tunnels, Foundations, Footings
- De-Icing Chemicals
  - Rock Salt Used on Paving Surfaces

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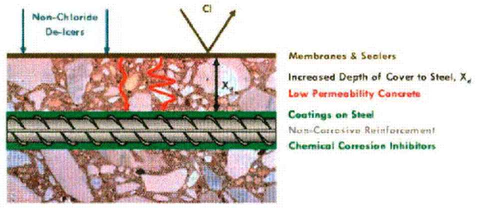
Chloride Service-Life

Corrosion Prevention Methods



Chloride Service-Life

Prevention Methods

- First Line of Defense
  - Slow the Rate at Which Chlorides Reach Steel
- Second Line of Defense
  - Increase the Chloride Threshold
    - Chloride Concentration Required to Initiate Corrosion
    - Typically 0.05 – 0.1% (by mass) or 2 – 4 pcy

Chloride Service-Life

Slow the Rate of Chloride Ingress

- Surface Concentration
  - $C_s(t)$ A Function Of:
    - C_{smax} = Maximum Chloride Surface Concentration
    - b = Chloride Surface Concentration Build-Up Rate
    - t = Time (t_0 = Concrete Age at First Chloride Exposure)
  - C_{smax} and b Selected by ConcreteWorks Based On:
    - Location (City and State)
    - Exposure Class
  - Variables May Also be Manually Entered

Chloride Service-Life

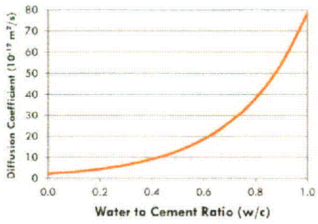
Slow the Rate of Chloride Ingress

- Membranes
  - Chloride Surface Concentration Assumed 0
    - 100% Effective for Duration of Warranty Period
  - Degrade Linearly After End of Warranty Period
    - 0% Effective at End of Degradation Period
- Sealers
  - Degrade Linearly from Time of Application
    - 100% Effective at Time of Application
    - 0% Effective at End of Degradation Period

Chloride Service-Life

Slow the Rate of Chloride Ingress

- Low Permeability Concrete
  - Porosity & Permeability Increase w/ Increasing W/C



Chloride Service-Life

Increase the Chloride Threshold

- Concentration Required to Initiate Corrosion
  - Corrosion Will Not Begin Until Corrosion Threshold is Reached
  - Increasing Threshold Allows for Greater Accumulation of Chlorides Before Onset of Corrosion
- Ways to Increase Corrosion Threshold
  - Chemical Corrosion Inhibitors
  - Corrosion Resistant Reinforcement

Chloride Service-Life

Increase the Chloride Threshold

- Chemical Corrosion Inhibitors
  - Calcium Nitrite
    - User-Defined Dosage
  - Amines & Esthers
    - Fixed Dosage: 1 gal/yd^3

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Chloride Service-Life

Increase the Chloride Threshold

- Alternative Reinforcement Options
  - Epoxy Coated Steel
  - Grade 316 Stainless Steel
- Manually Defined Chloride Threshold
  - Value Largely Dependent on Reinforcement Material
  - Non-Corrosive Reinforcement Has a Larger Threshold than Standard Steel Reinforcement
  - No Rule of Thumb, However, Lower Value is More Conservative

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Chloride Service-Life

Assumptions of Service-Life Model

- Concrete
  - Uncracked
  - Saturated
  - Constant Density
  - Diffusion the Only Transport Mechanism
    - Mass Transport from any Temperature Gradient or Pressure Gradient is Negligible
- Reinforcement
  - Corrosion Degradation Period
    - Rebar: 6 Years
    - Prestress: Immediately

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Chloride Service-Life

Hands-On Demonstration of Chloride Service-Life in ConcreteWorks!

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Hands-On Exercise
Chloride Service-Life

1. **Open a new bridge deck project in ConcreteWorks**
2. **General Inputs**
    a. Select English units
    b. Set the location to Fort Worth, TX
3. **Shape Inputs**
    a. Deck w/ Precast Panels
4. **Member Dimensions**
    a. Overall Deck Thickness = 8 inches
    b. Cover for Top Mat of Steel = 2 inches
    c. Cover from Top Surface for Bottom Mat of Steel = 6 inches
    d. Precast Panel Thickness = 4 inches
5. **Mix Design**
    a. Compressive Strength = 4000 psi
    b. Click the Water Adjustment tab and adjust the following sliders
        i. Mid Range Water Reducer: -12
        ii. Aggregate Shape and Texture: -3
6. **Corrosion Inputs**
    a. Exposure Class = Urban Road
7. **Input Check**
    a. Calculate Temperatures
8. **Modify the Mix Design & Corrosion Inputs**
    a. 5% Silica Fume
    b. 30% Class F Fly Ash
    c. Sealer (10 years degradation and 10 year reapplication period)
9. **Recalculate and Compare Your Results**

Case Study and Group Project

The objective of this assignment is for you and your colleagues to work in groups of 3 to 5 to design a large rectangular column to meet the challenging requirements and specifications outlined below.

Using ConcreteWorks, select a mix design and construction plan that meets the technical requirements and is also practical and economically feasible. Each group will be asked to give a 5-10 minute presentation, briefly summarizing your proposed design. Give justification for your group's approach and back it up with output from ConcreteWorks.

Just a word of advice - minimize temperatures before calculating cracking probability. Otherwise you will waste lots of time waiting for the program to calculate.

Be innovative and have fun! Be sure to have a name for your group and maybe even a theme (e.g., sustainability, innovation, speed, technology, etc.).

1. **Construction Details**
   - A. Column dimensions = 7' x 7' (non-submerged)
   - B. Casting date = July 28, 2010
   - C. Casting time = 6 am (can be shifted five hours earlier or later if necessary)
   - D. Location = Fort Worth
   - E. Chloride exposure = urban road
   - F. Temperature analysis duration = 7 days
   - G. Formwork = steel (stripped at 72 to 120 hours)

2. **Performance Requirements**
   - A. Temperature Specifications
     - I. Maximum fresh concrete temperature = 75 °F
     - II. Maximum temperature = 158 °F (to avoid delayed ettringite formation)
     - III. Maximum temperature gradient = 35 °F (to avoid thermal cracking)
   - B. Serviceability / Durability
     - I. Low cracking probability index
     - II. 75 year chloride service-life
3. **Mix Design**
   - A. Basic Specifications
     - I. Air Content = 6.00%
     - II. Slump = 4.00 in
   - B. Strength Requirement
     - I. 28-day compressive strength = 4000 psi
     - II. Number of tests used to determine standard deviation = less than 15

C. Mix Design Options
   I. Replace 20 to 35% of the cement with Class F fly ash
   II. Replace 35 to 50% of the cement with Grade 120 slag
   III. Replace 35 to 50% of the cement with a combination of Class F fly ash, Grade 120 slag, or silica fume. However, no more than 35% may be fly ash, and no more than 10% may be silica fume.

D. Water Adjustment
   I. Mid-range water reducer: 12% water reduction
   II. High-range water reducer: 25% water reduction
   III. Class F fly ash: 3% water reduction per 10% ash
   IV. Grade 120 slag: no impact
   V. Silica fume: 2% water increase per 1% silica fume

4. Available Materials

A. Portland cement (ASTM C 150)
   I. Type I
   II. Type I/II
   III. Type II

B. Supplementary cementitious materials
   I. Class F fly ash (CaO = 19.0%)
   II. Grade 120 slag
   III. Silica fume

C. Chemical admixtures
   I. Mid-range water reducer
   II. High-range water reducer
   III. Retarder
   IV. Accelerator

D. Aggregates
   I. Coarse
      1. Siliceous river gravel
      2. Dolomite
      3. Limestone
   II. Fine
      1. Siliceous river sand

E. Crushed ice and liquid nitrogen are available to reduce fresh concrete temperature (minimum of 60 °F)

5. Mechanical Properties

A. Maturity Function = Nurse-Saul

B. Below 35% SCMs

   I. A = -5450 psi

   II. B = 2830 psi/°F/hr

C. Above 35% SCMs

   I. A = -7450 psi

   II. B = 2950 psi/°F/hr

Appendix B: Bexar Concrete Works

Weather Data

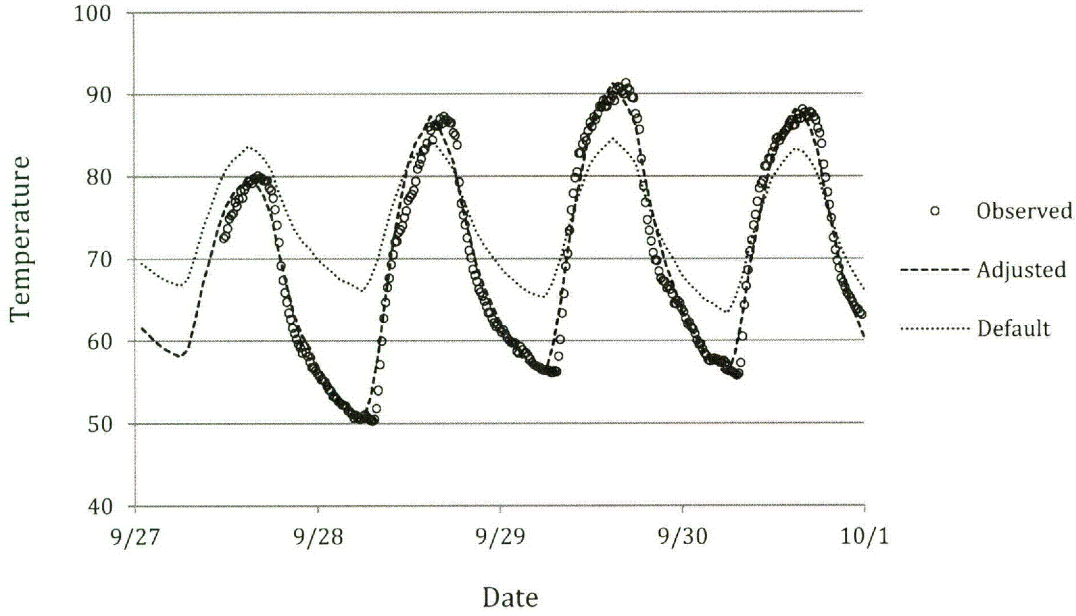

Figure B-1 – Ambient Temperature

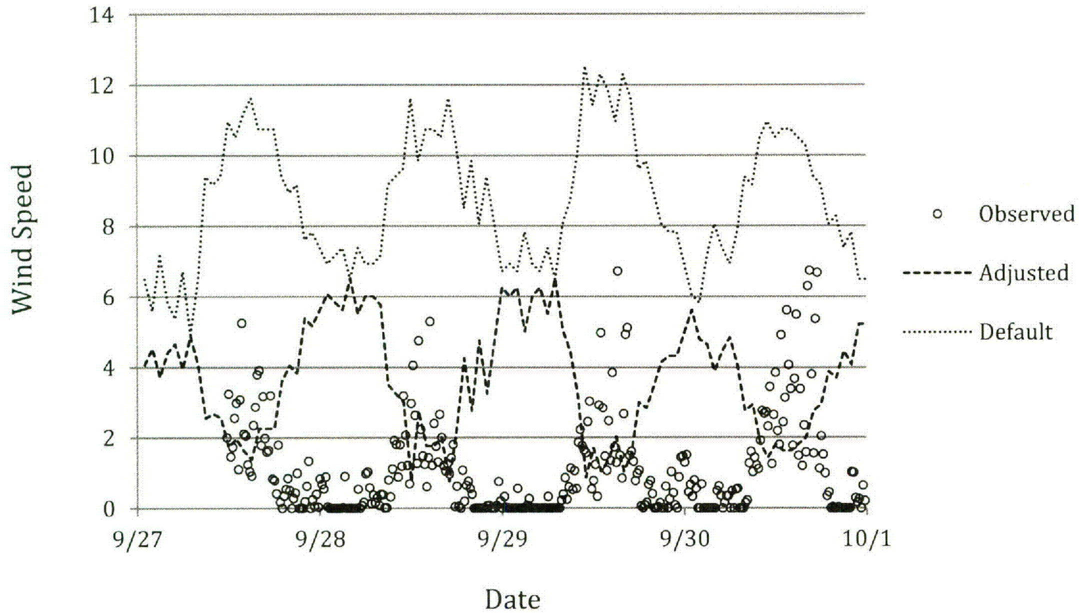

Figure B-2 – Wind Speed

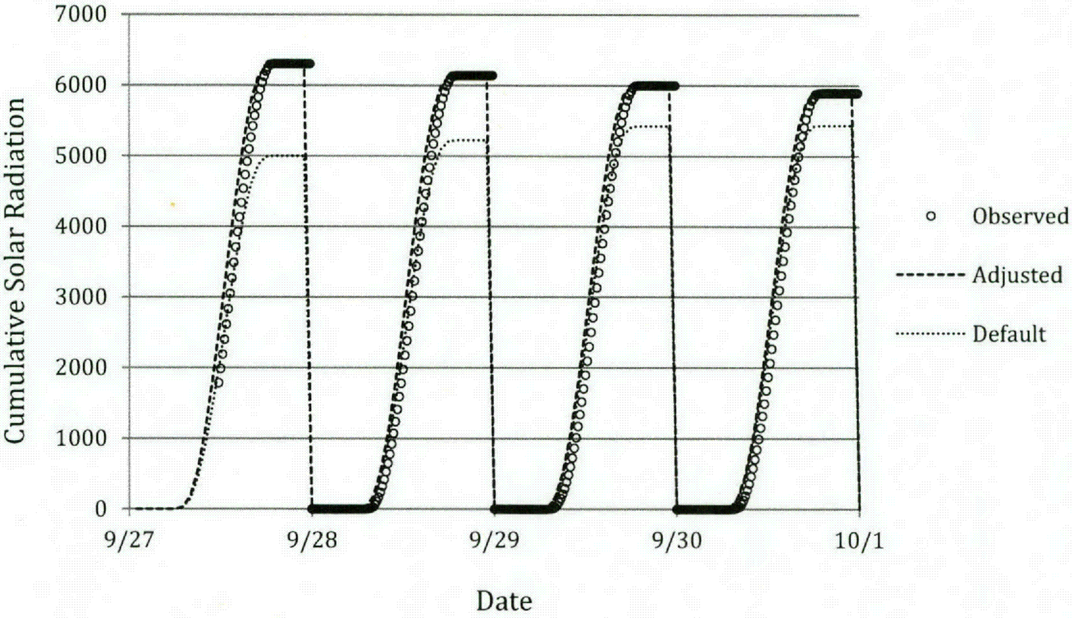

Figure B-3 – Bexar Precast Solar Radiation

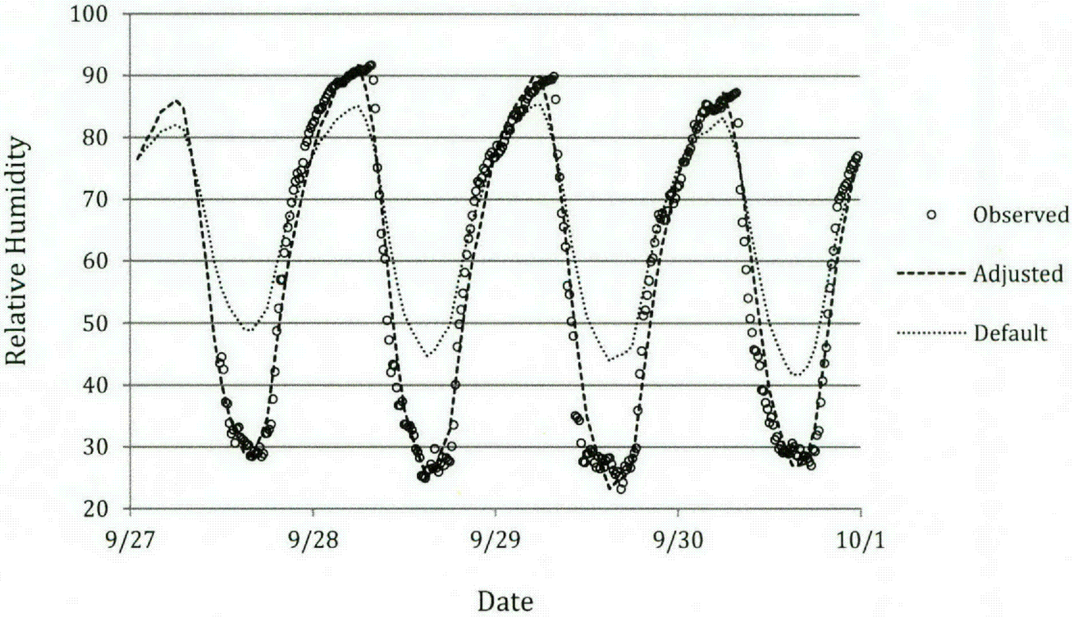

Figure B-4 – Bexar Precast Relative Humidity

ConcreteWorks Screen Prints

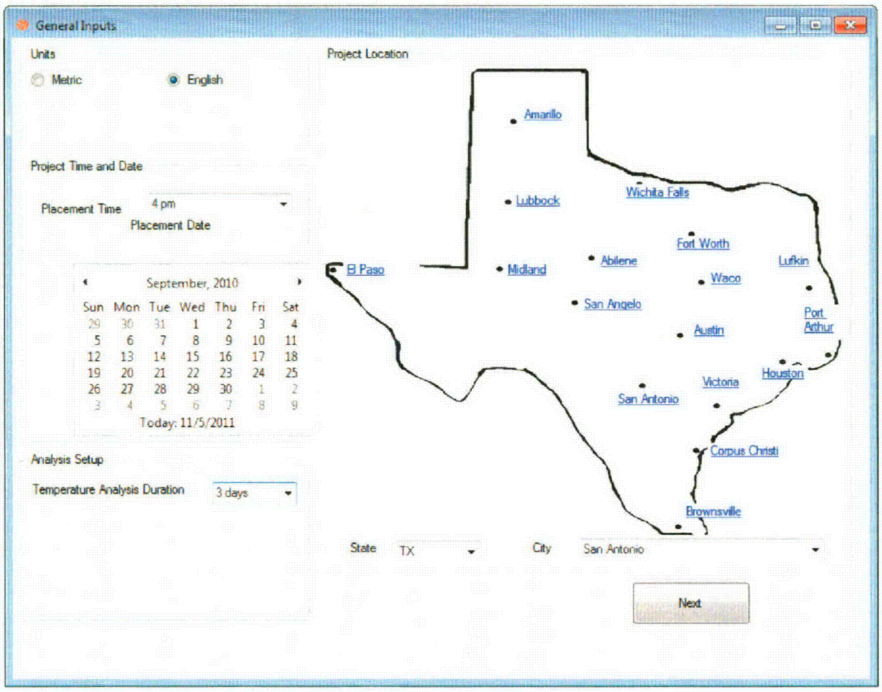

Figure B-5 – Alamo General Inputs

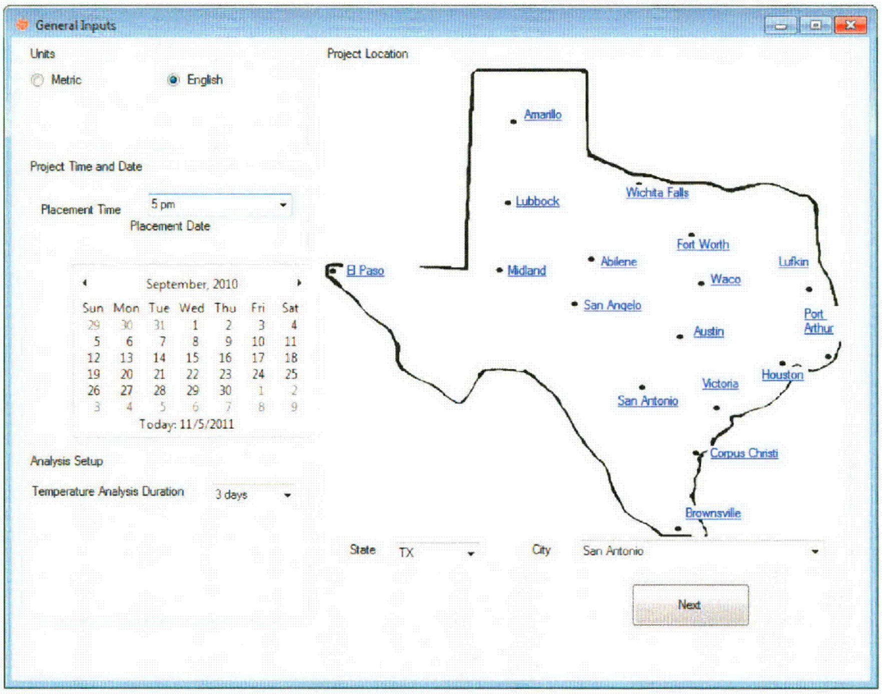

Figure B-6 – Capitol General Inputs

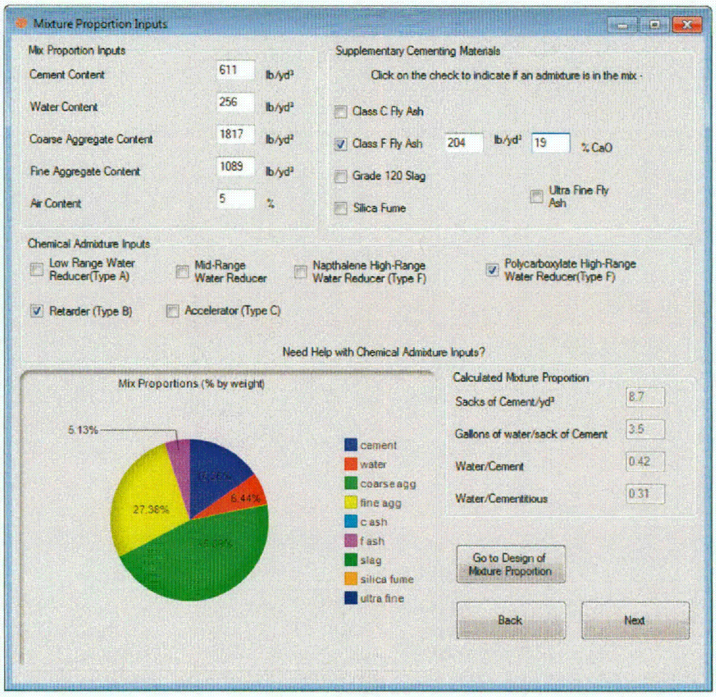

Figure B-7 – Bexar Mixture Proportions

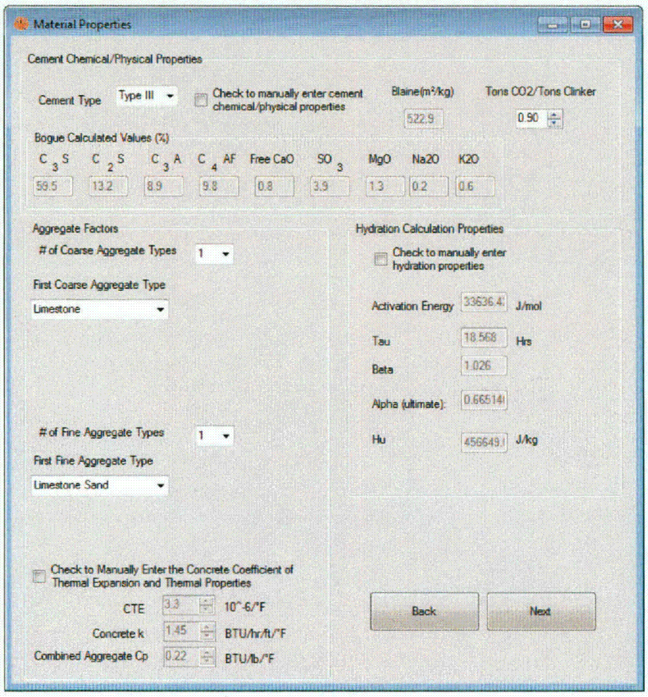

Figure B-8 – Alamo Material Properties (LOD 1)

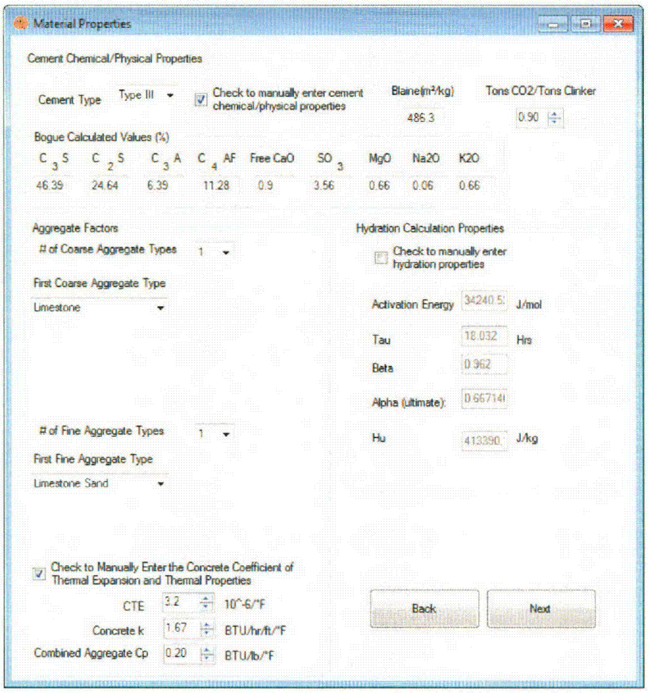

Figure B-9 – Alamo Material Properties (LOD 2)

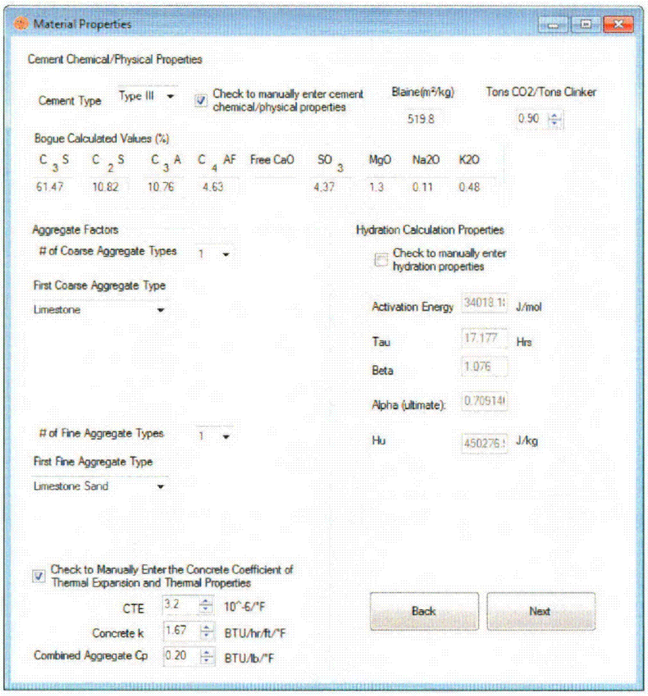

Figure B-10 – Capitol Material Properties (LOD 2)

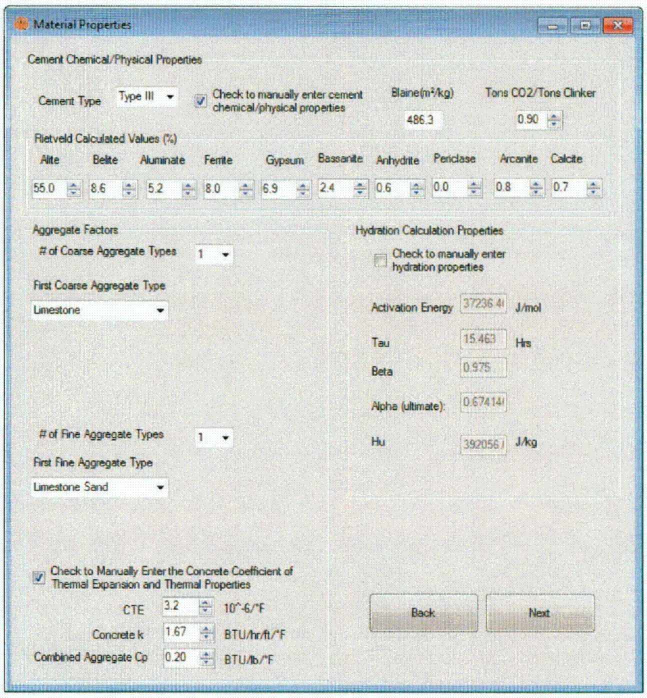

Figure B-11 – Alamo Material Properties (LOD 3)

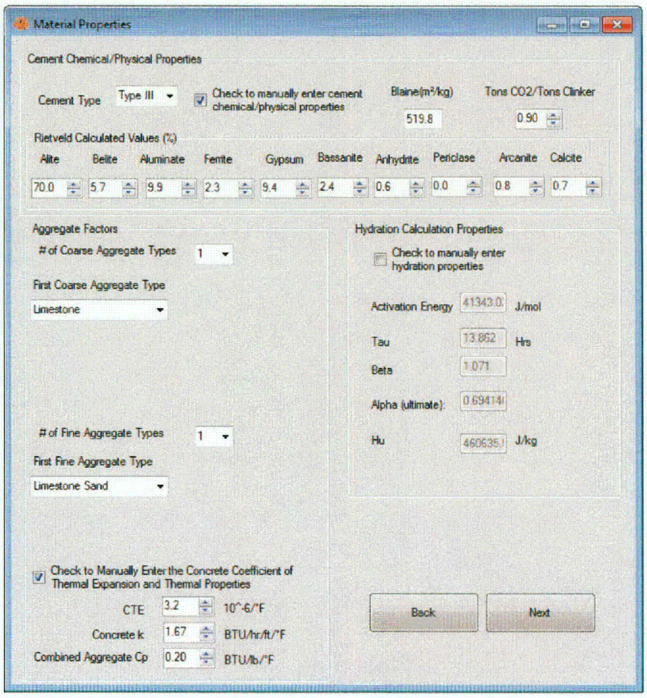

Figure B-12 – Capitol Material Properties (LOD 3)

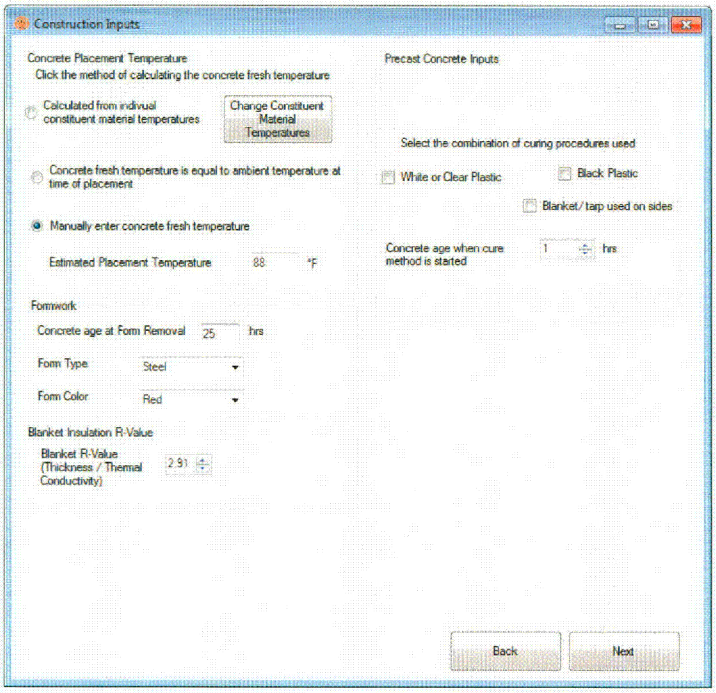

Figure B-13 – Bexar Construction Inputs

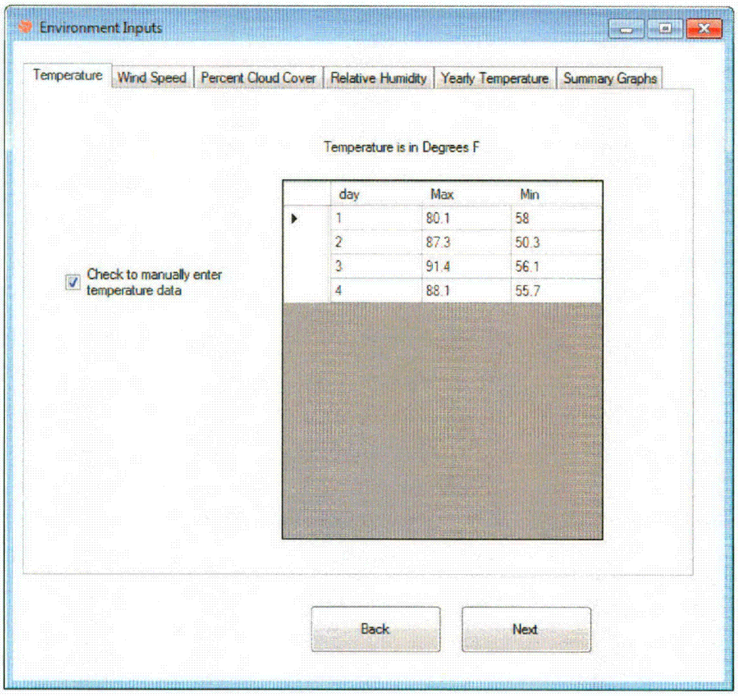

Figure B-14 – Bexar Environmental Inputs (Temperature)

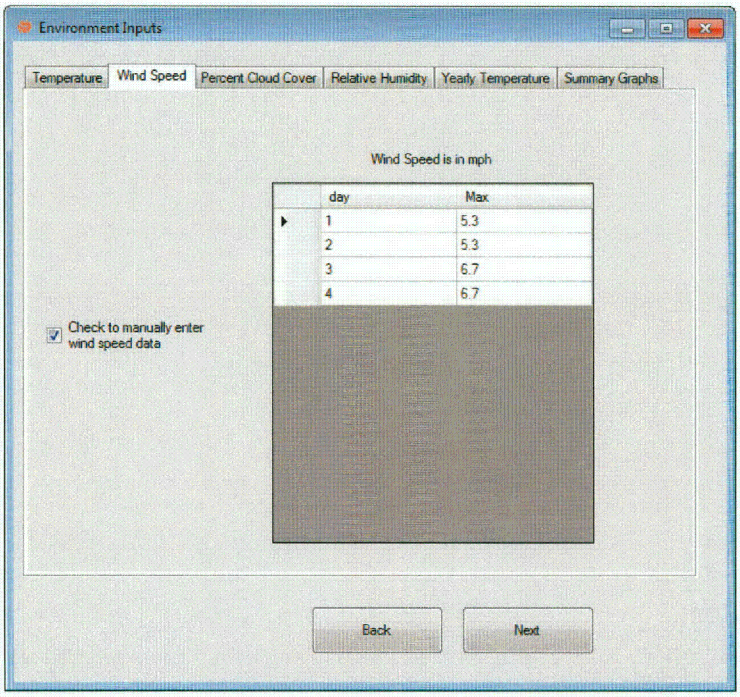

Figure B-15 – Bexar Environmental Inputs (Wind Speed)

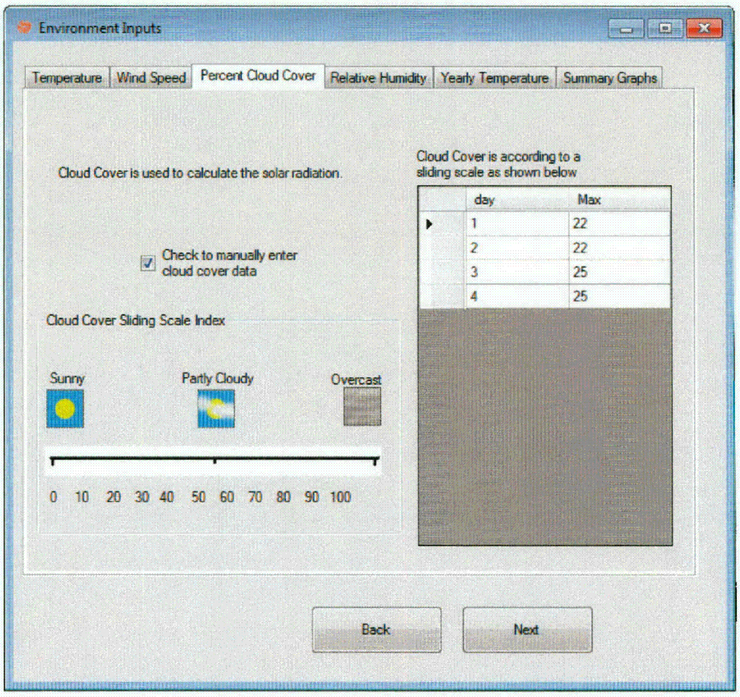

Figure B-16 – Bexar Environmental Inputs (Cloud Cover)

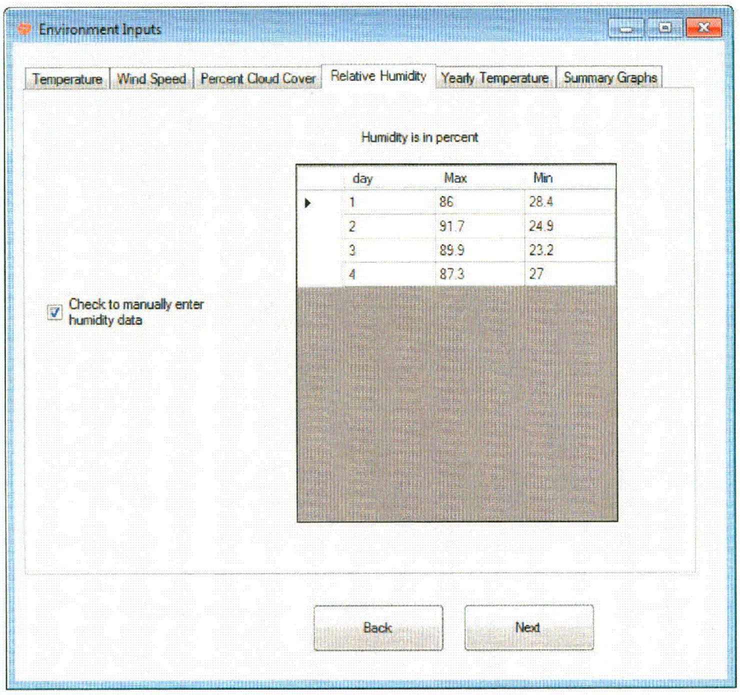

Figure B-17 – Bexar Environmental Inputs (Relative Humidity)

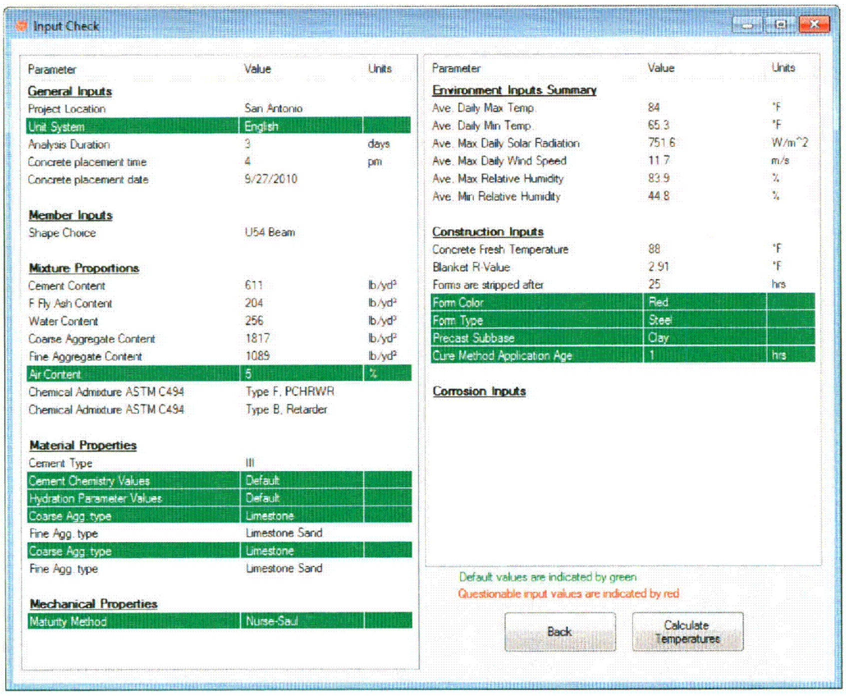

Figure B-18 – Alamo Input Check (LOD 1)

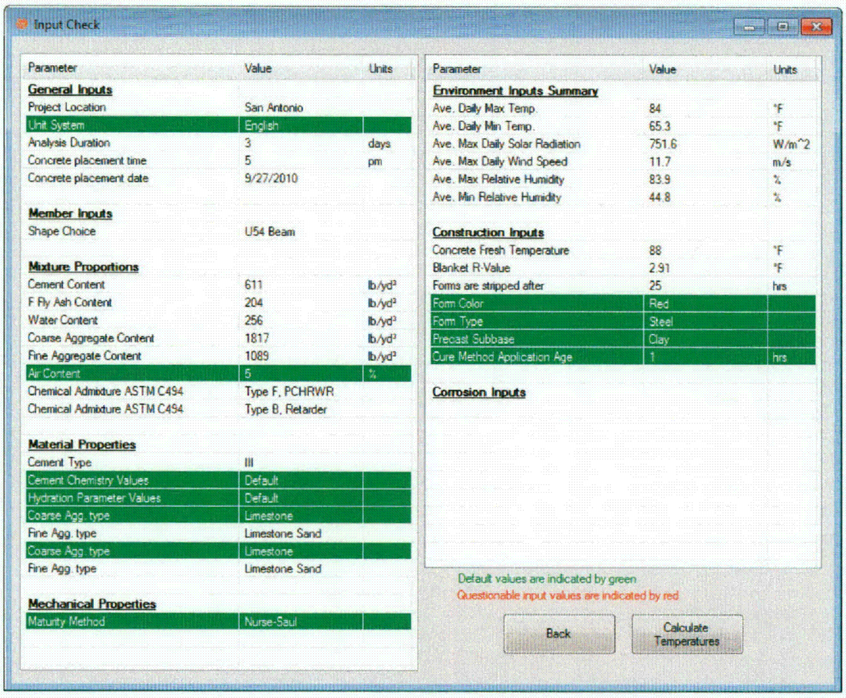

Figure B-19 – Capitol Input Check (LOD 1)

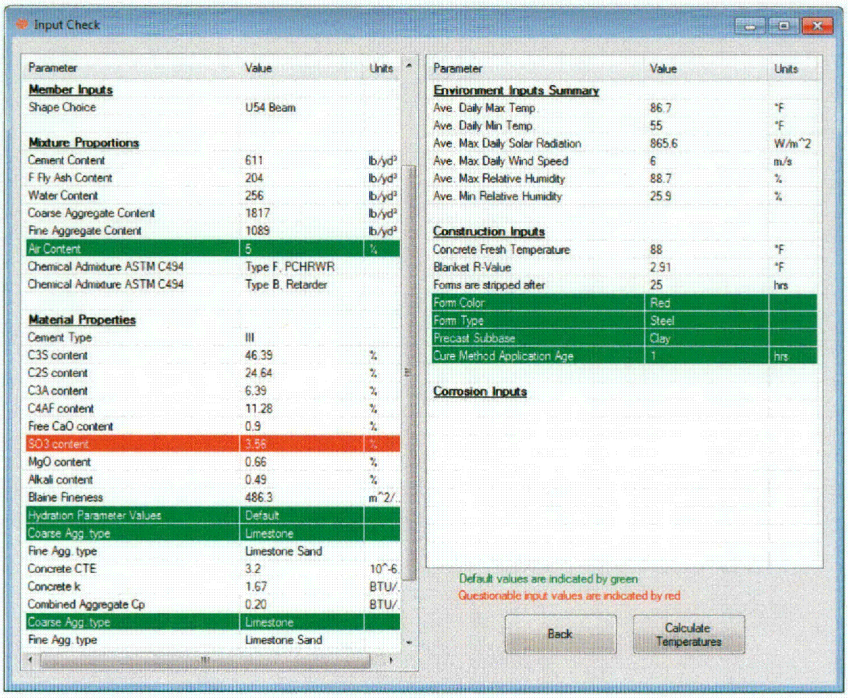

Figure B-20 – Alamo Input Check (LOD 2)

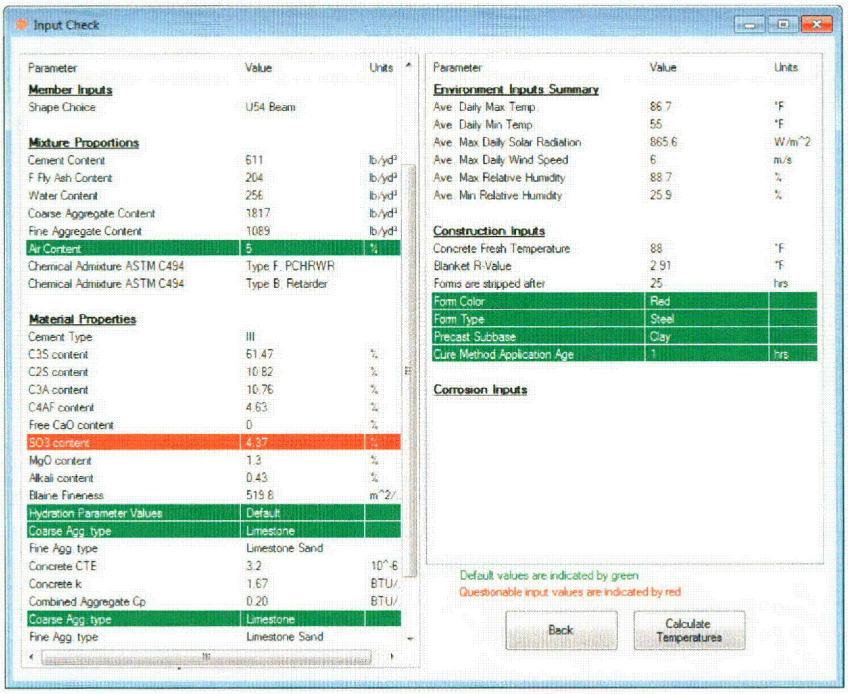

Figure B-21 – Capitol Input Check (LOD 2)

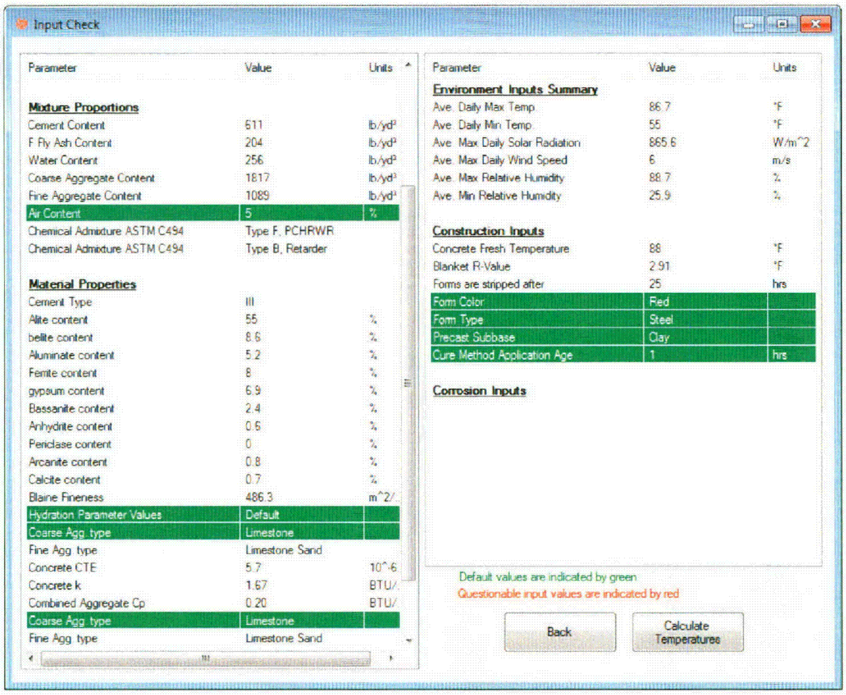

Figure B-22 – Capitol Input Check (LOD 3)

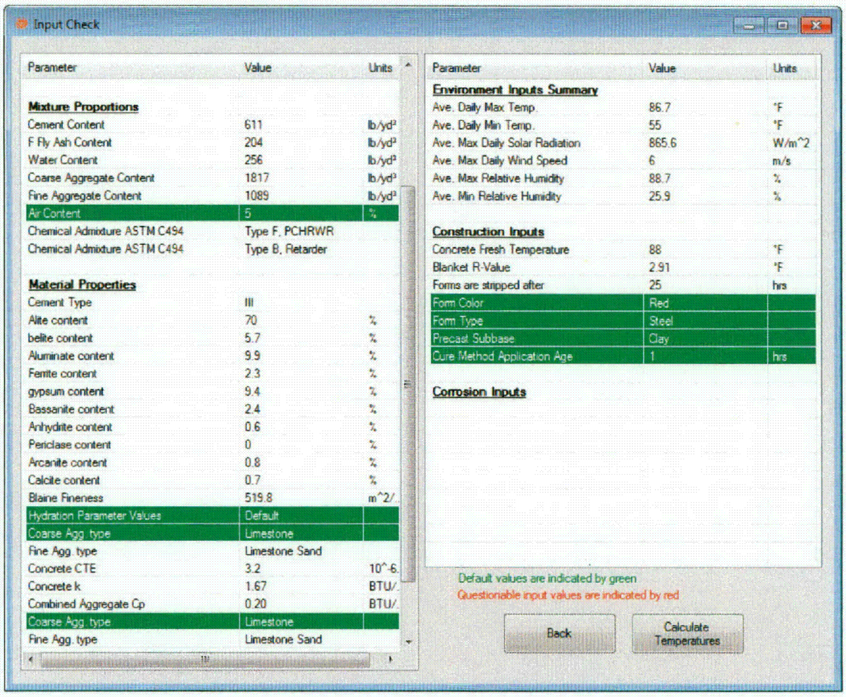

Figure B-23 – Capitol Input Check (LOD 3)

Appendix C: Valley Prestress Products

Weather Data

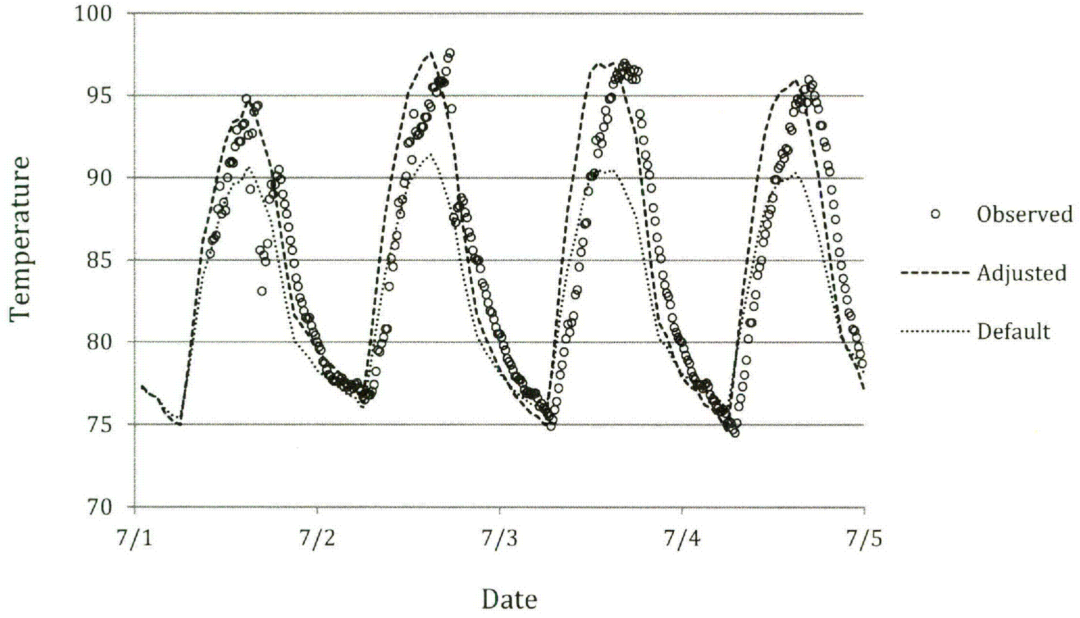

Figure C-1 – Eagle Lake Temperature

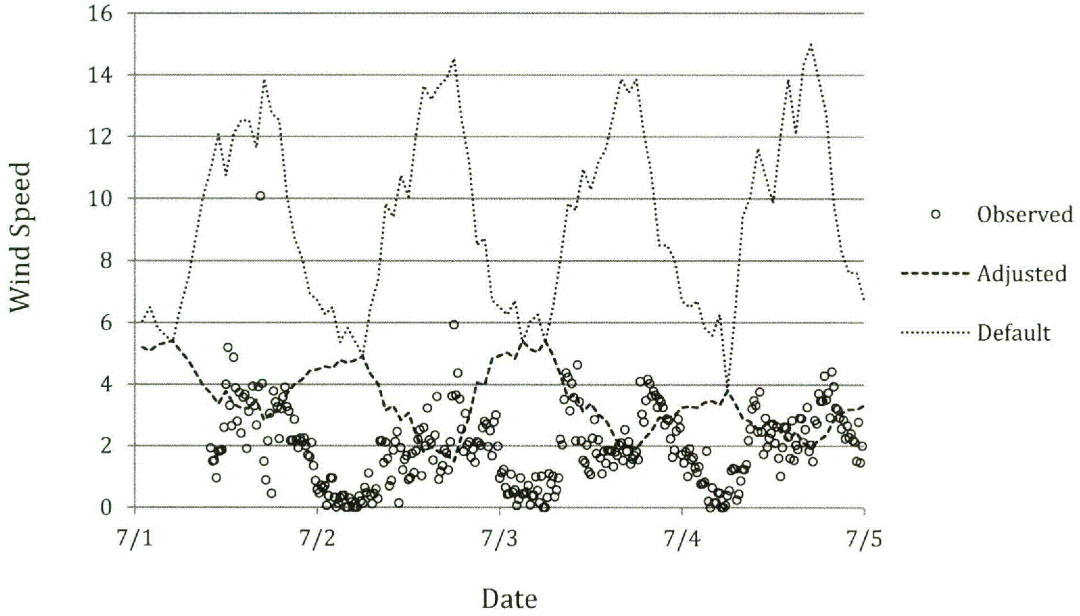

Figure C-2 – Eagle Lake Wind Speed

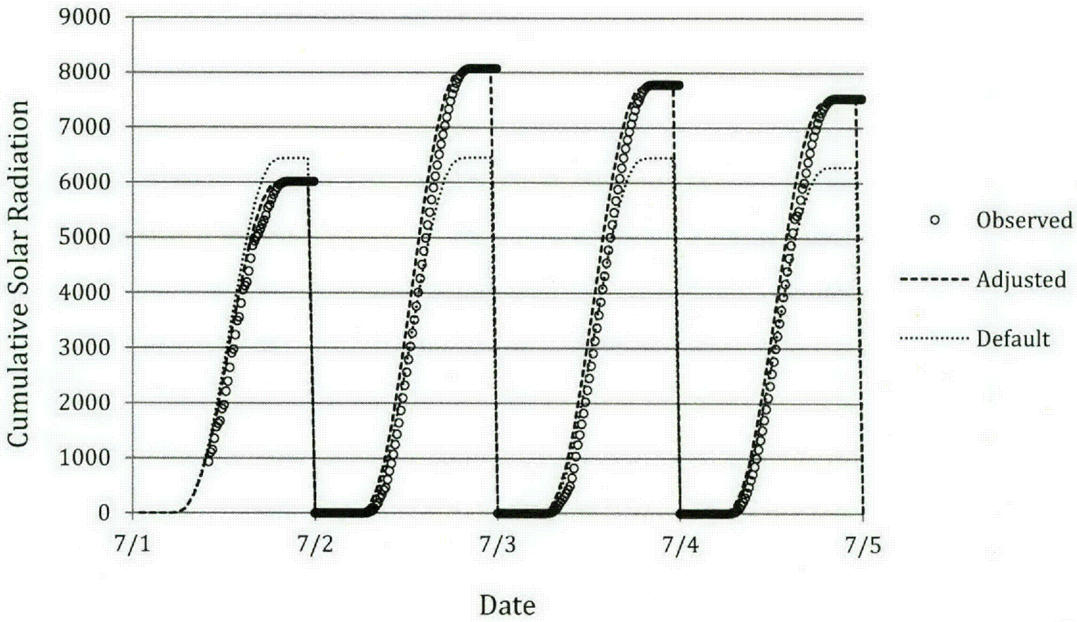

Figure C-3 – Eagle Lake Solar Radiation

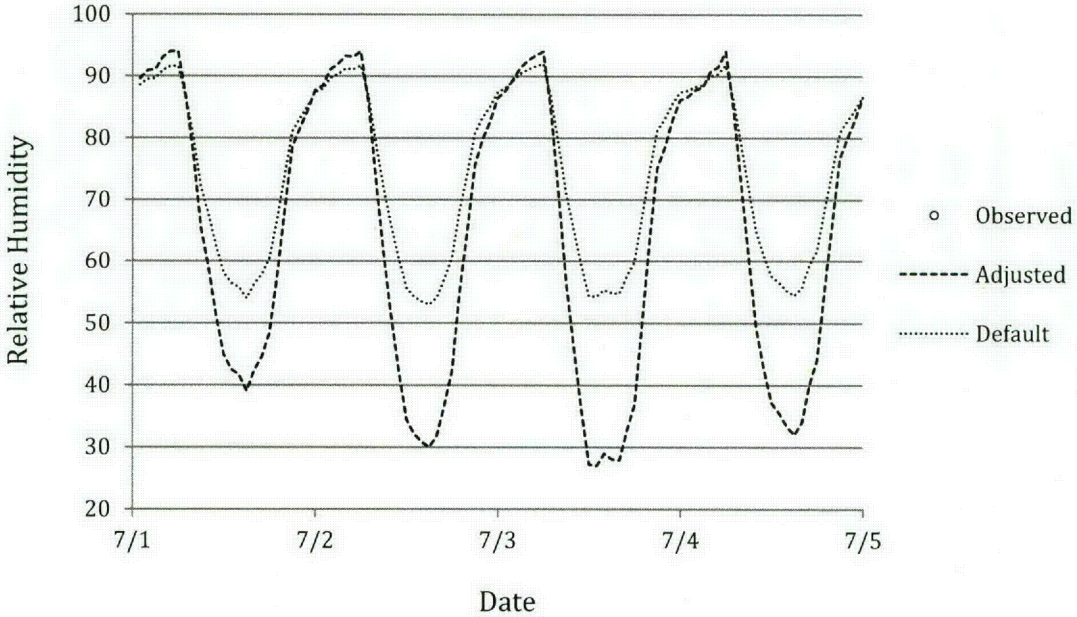

Figure C-4 – Eagle Lake Relative Humidity

ConcreteWorks Screen Prints

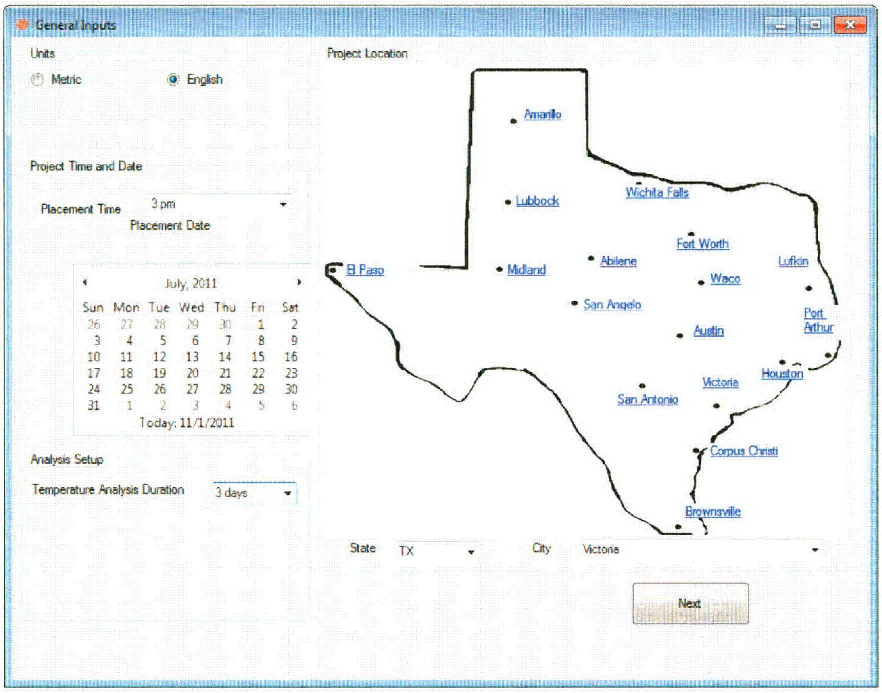

Figure C-5 – Eagle Lake General Inputs

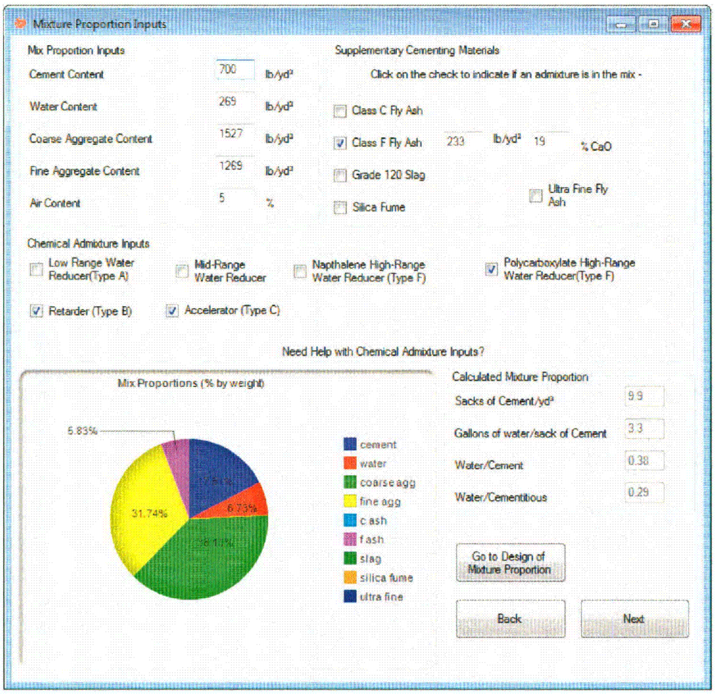

Figure C-6– Eagle Lake Mixture Proportions

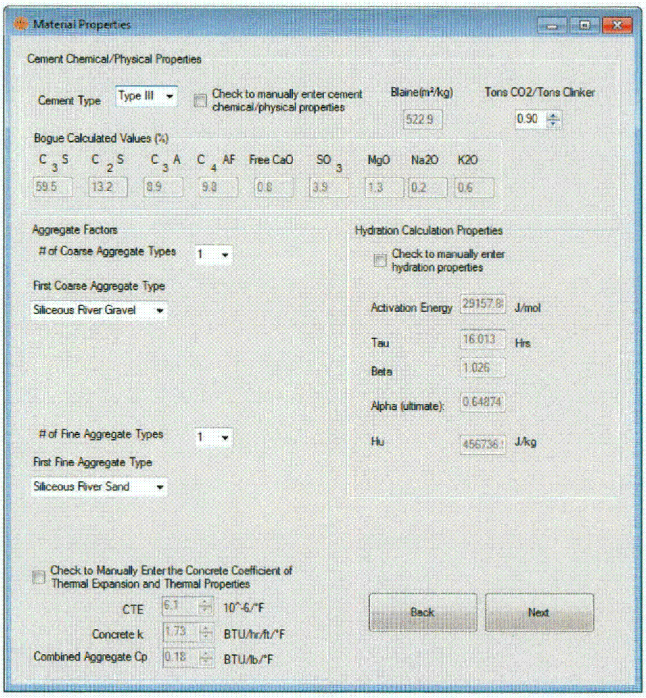

Figure C-7 – Material Properties (LOD 1)

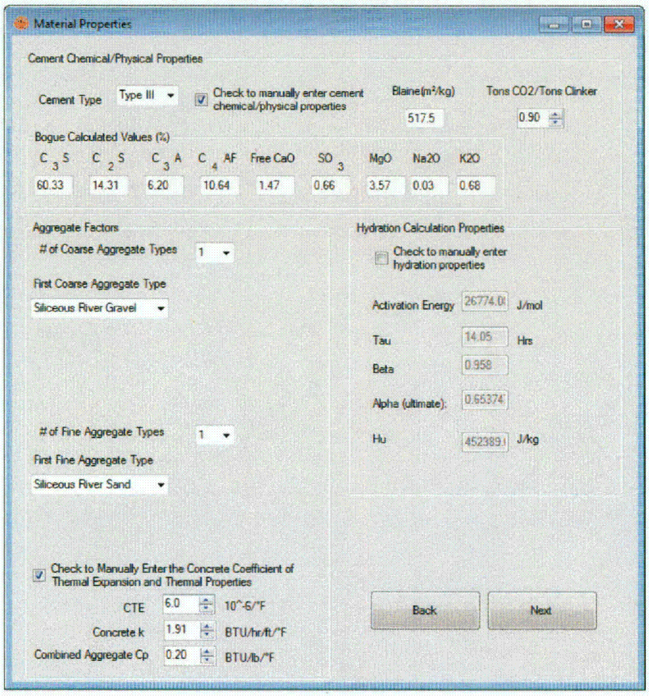

Figure C-8 – Material Properties (LOD 2)

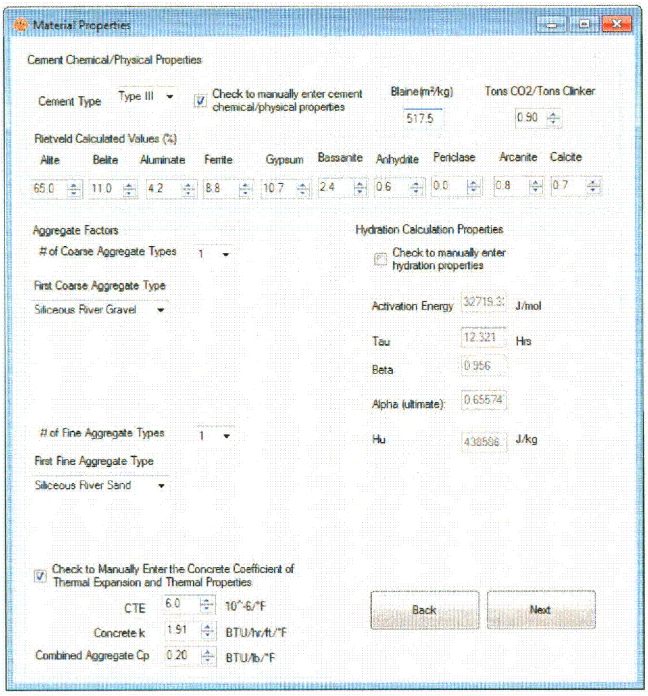

Figure C-9 – Material Properties (LOD 3)

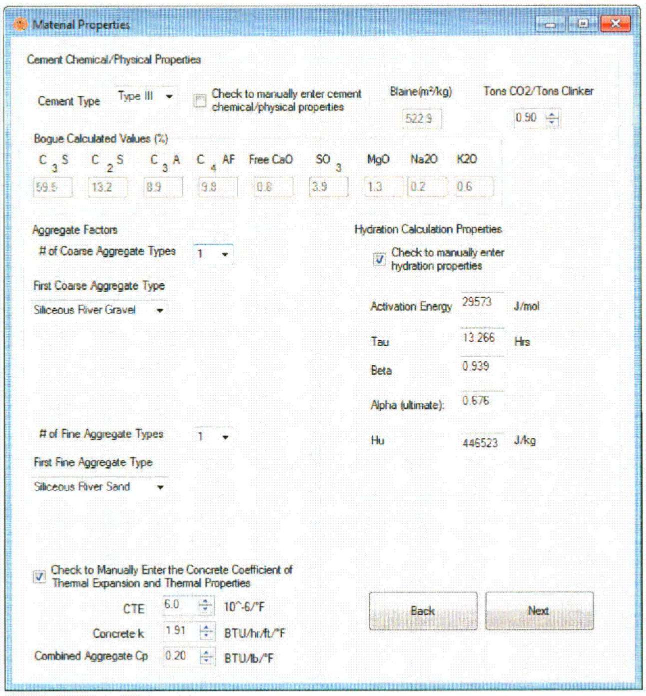

Figure C-10 – Material Properties (LOD 4)

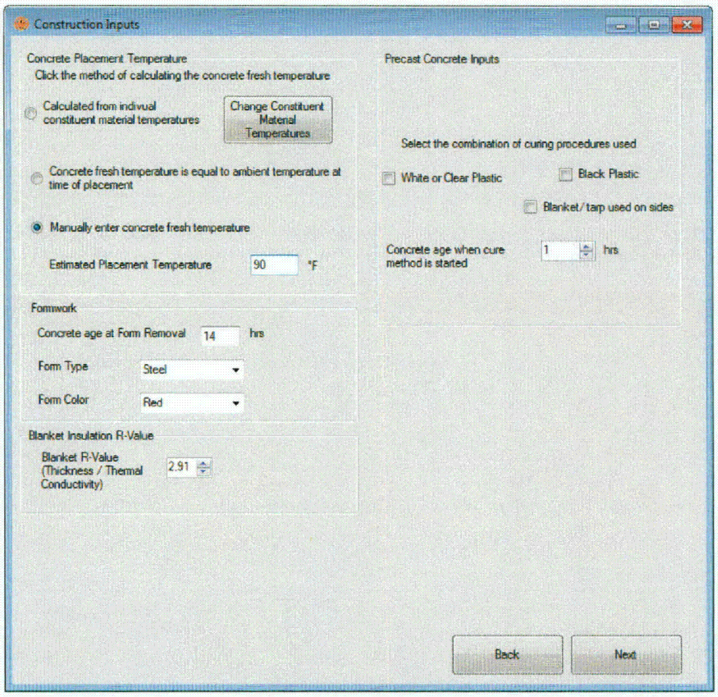

Figure C-11 – Eagle Lake Construction Inputs

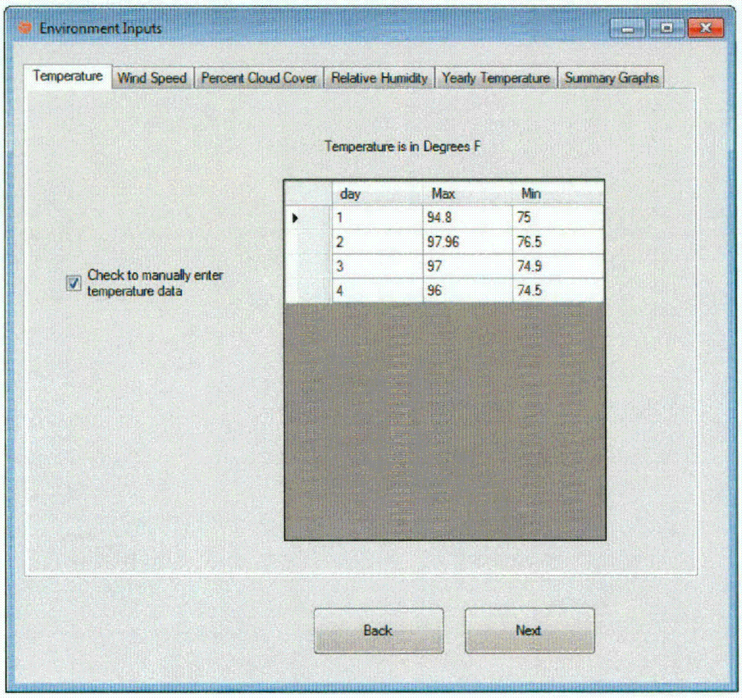

Figure C-12 – Eagle Lake Environmental Inputs (Temperature)

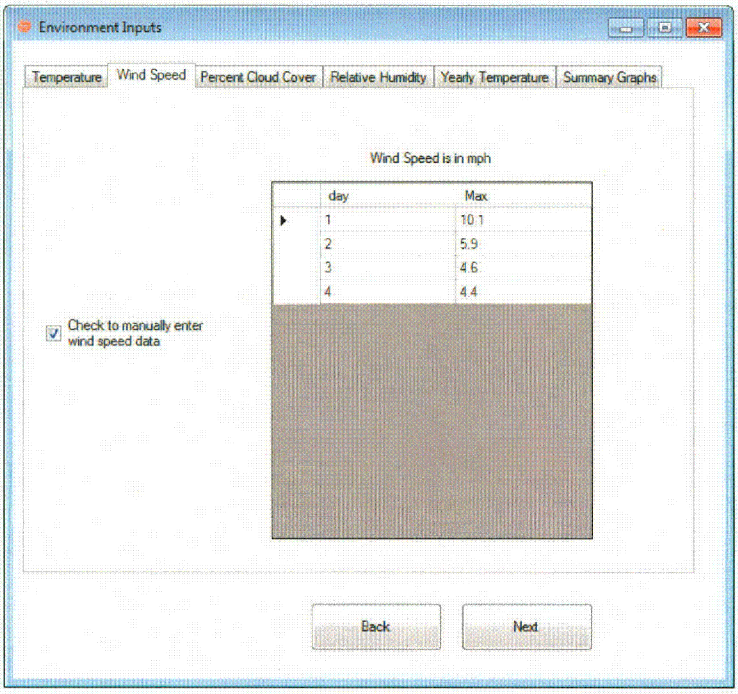

Figure C-13 – Eagle Lake Environmental Inputs (Wind Speed)

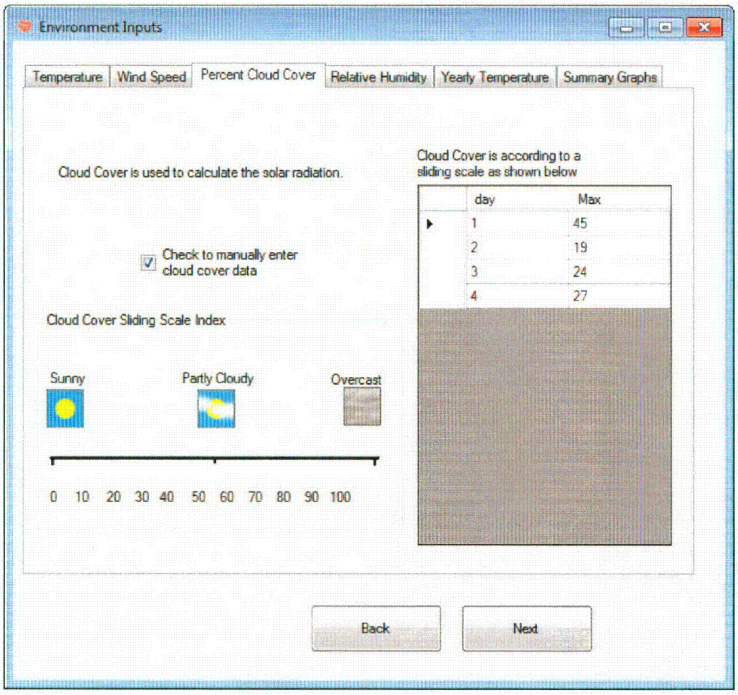

Figure C-14 – Eagle Lake Environmental Inputs (Cloud Cover)

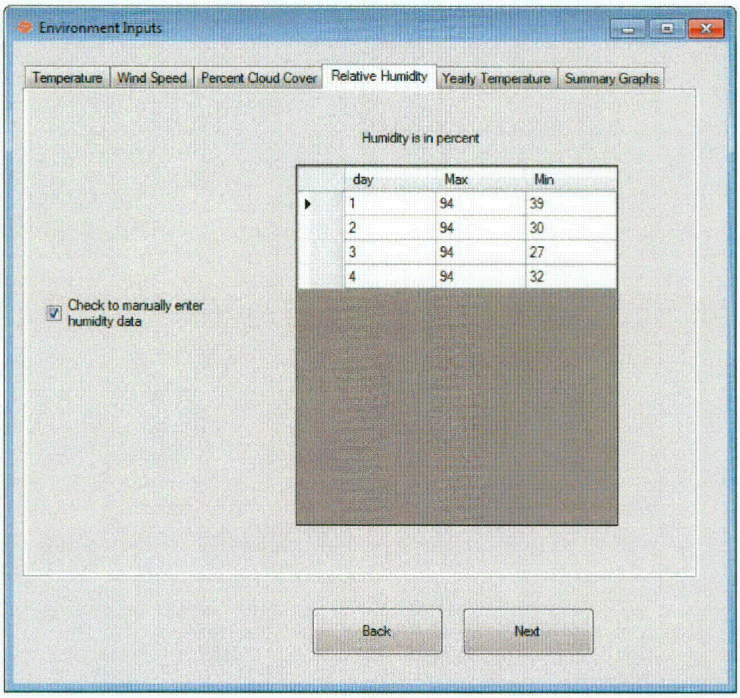

Figure C-15 – Eagle Lake Environmental Inputs (Relative Humidity)

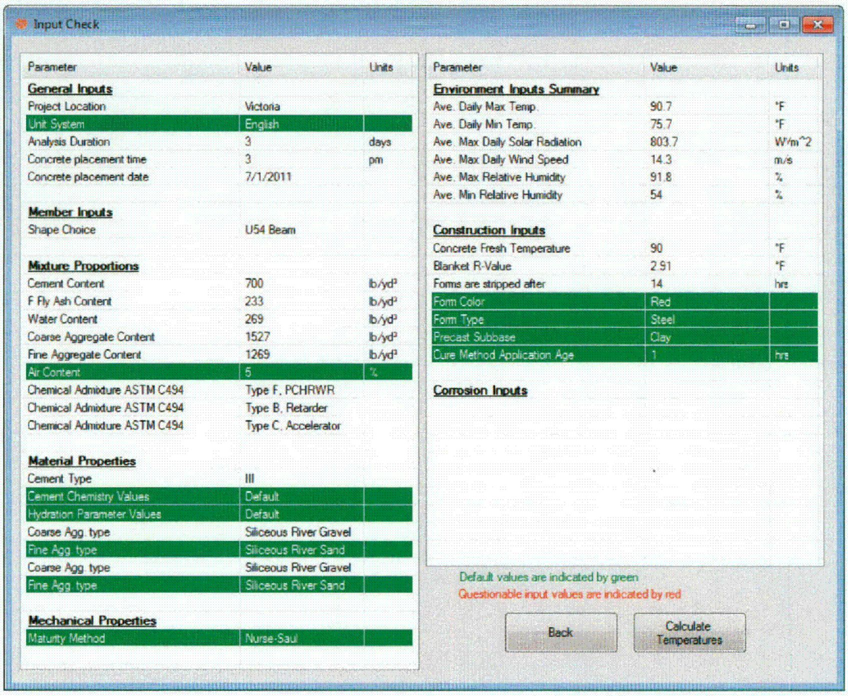

Figure C-16 – Eagle Lake Input Check (LOD 1)

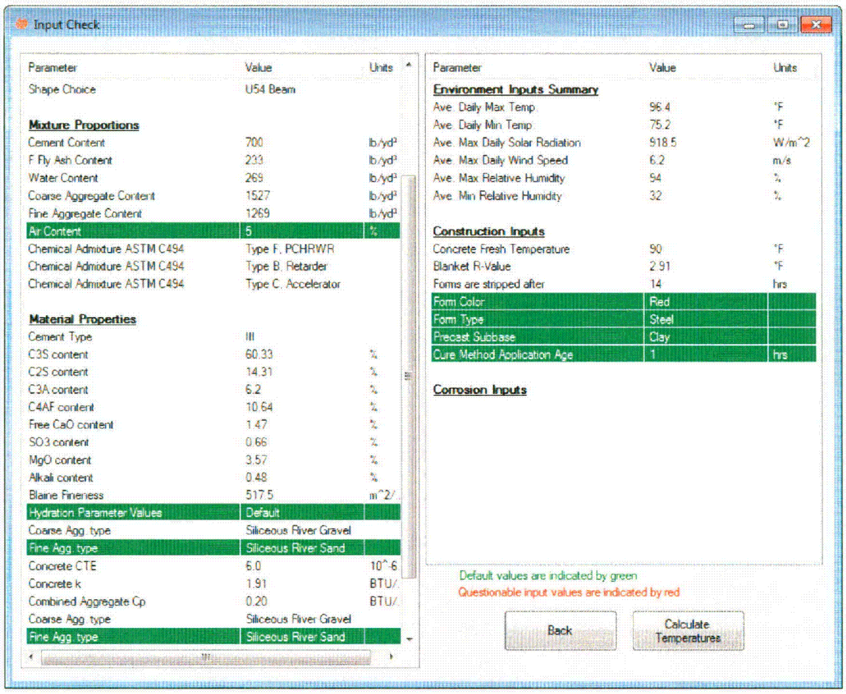

Figure C-17 – Eagle Lake Input Check (LOD 2)

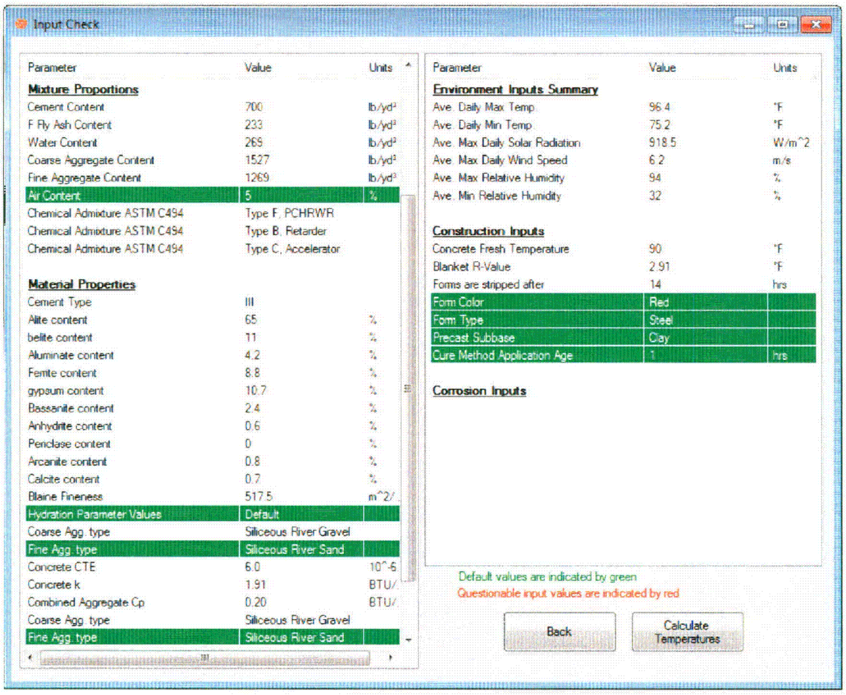

Figure C-18 – Eagle Lake Input Check (LOD 3)

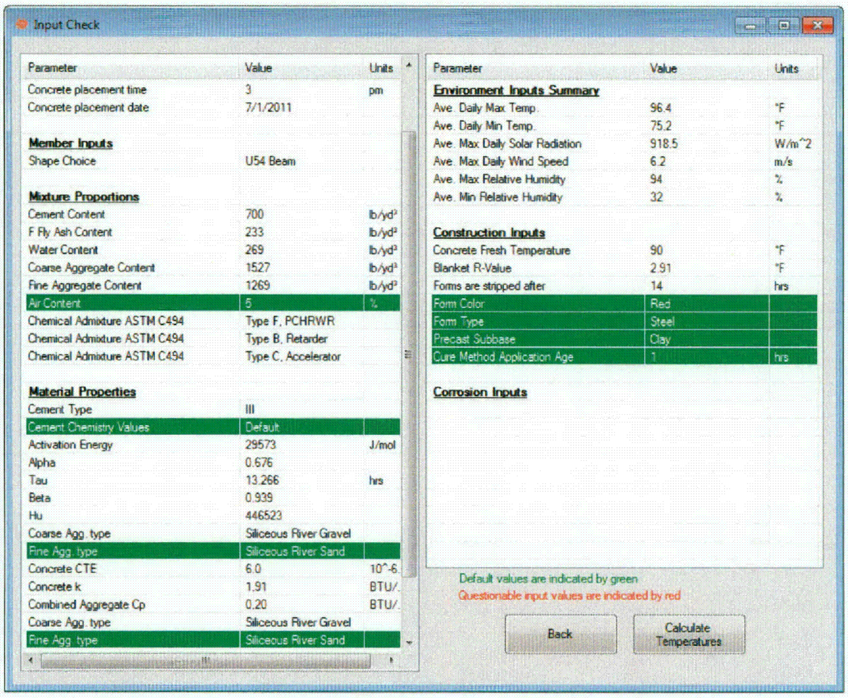

Figure C-19 – Eagle Lake Input Check (LOD 4)

Appendix D: IH35/SH71 WBSB Column 8

Weather Data

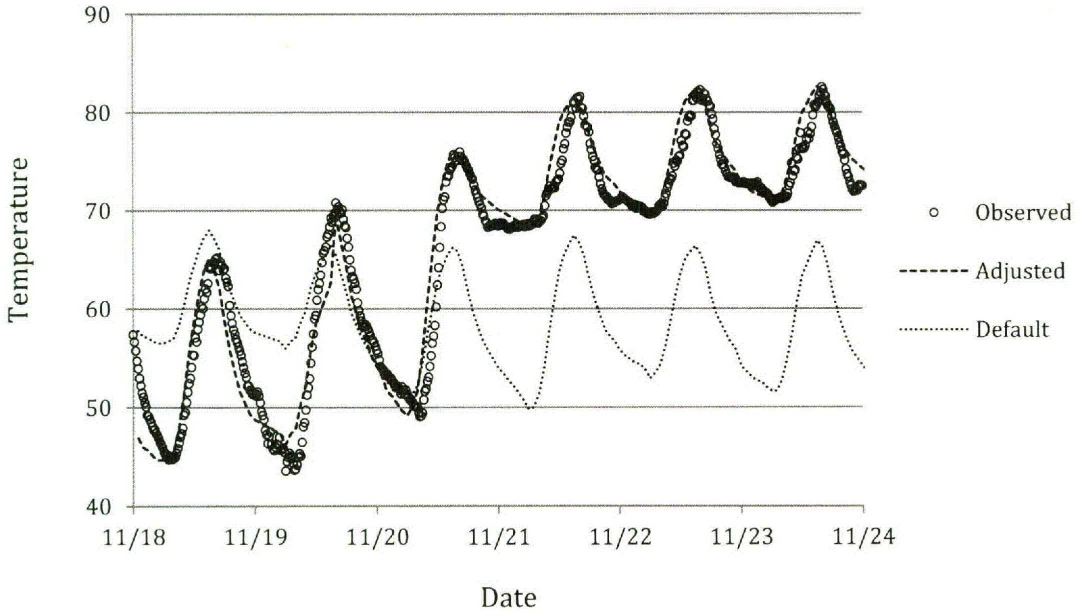

Figure D-1 – WBSB 8 Temperature

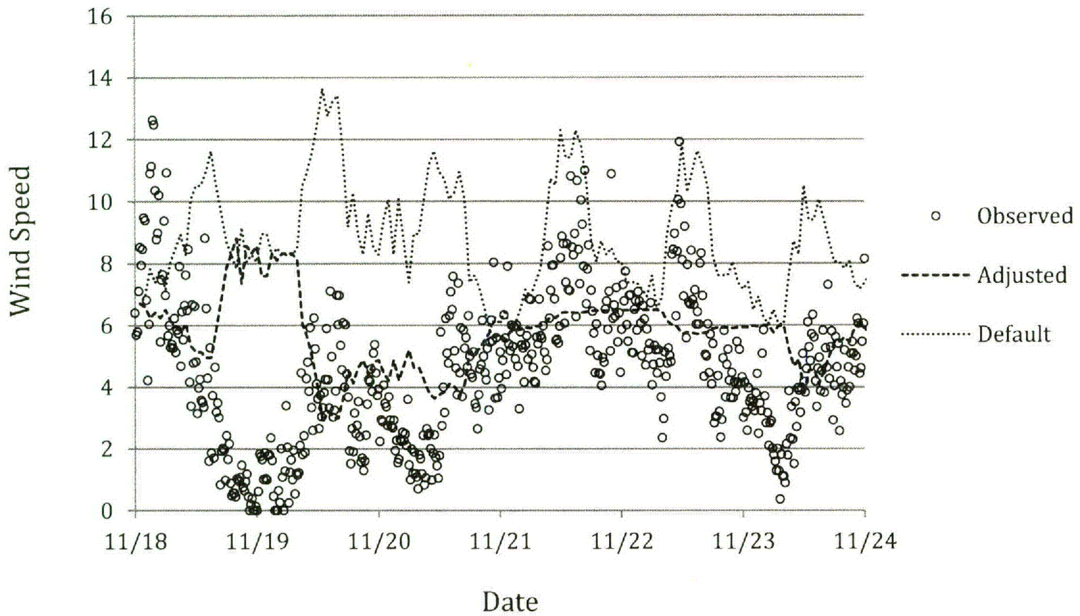

Figure D-2 – WBSB 8 Wind Speed

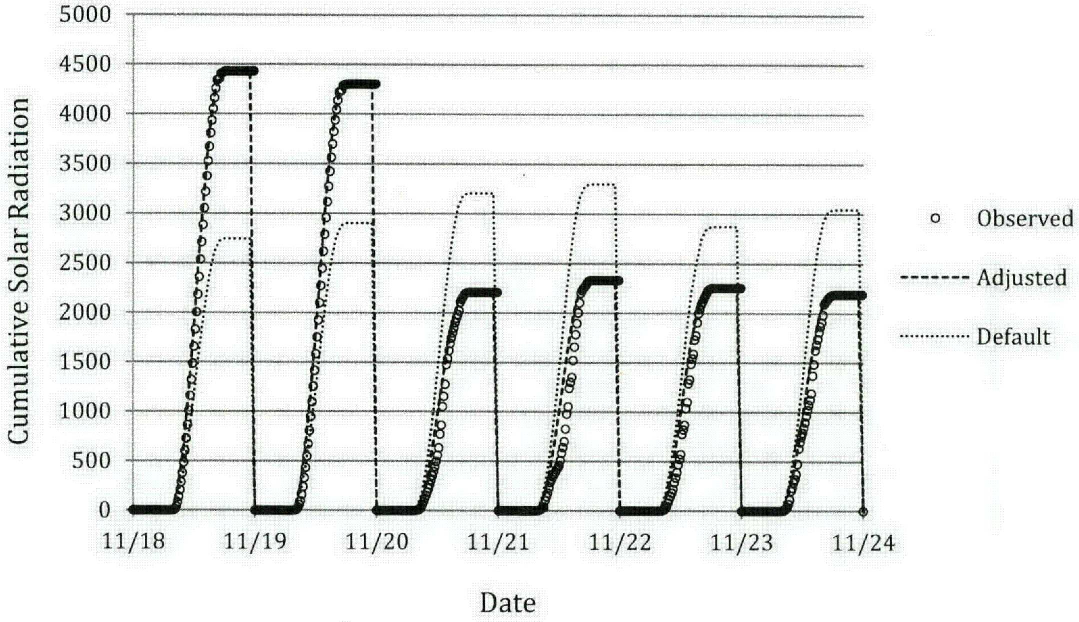

Figure D-3 – WBSB 8 Solar Radiation

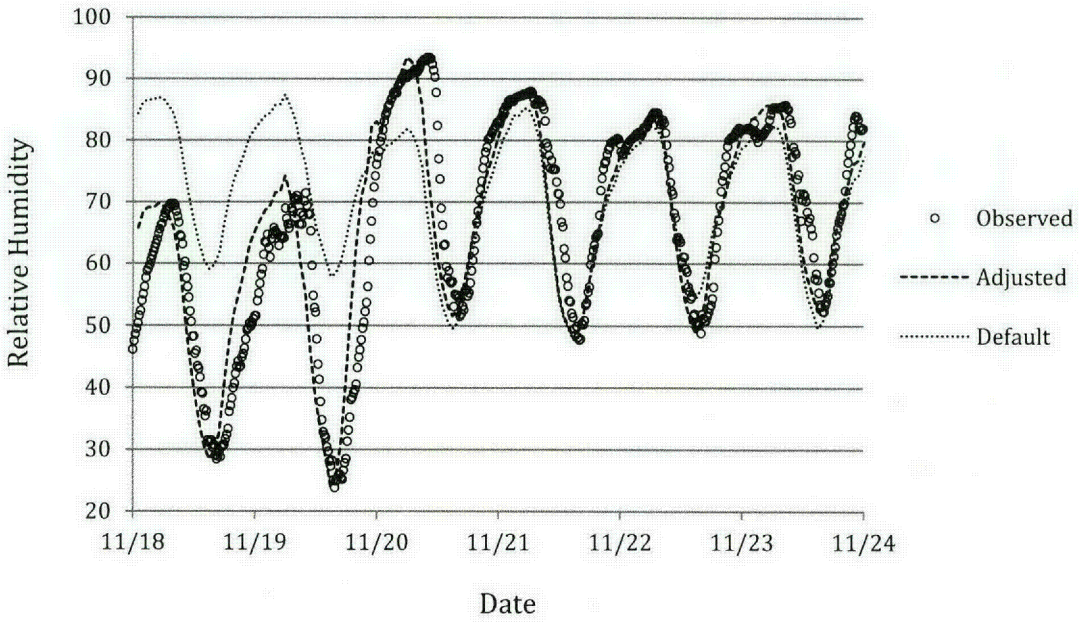

Figure D-4 – WBSB 8 Relative Humidity

ConcreteWorks Screen Prints

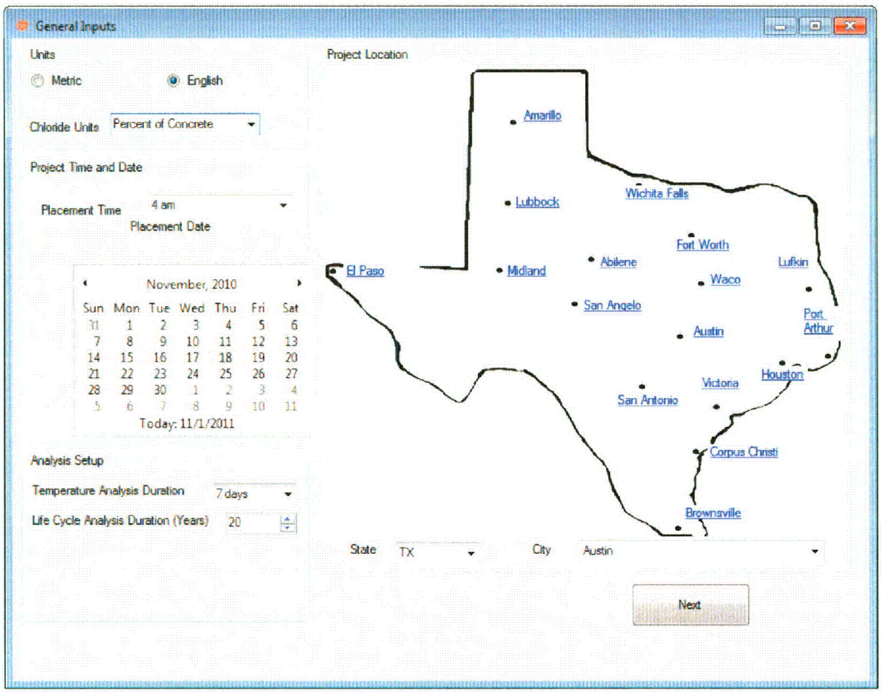

Figure D-5 – WBSB 8 General Inputs

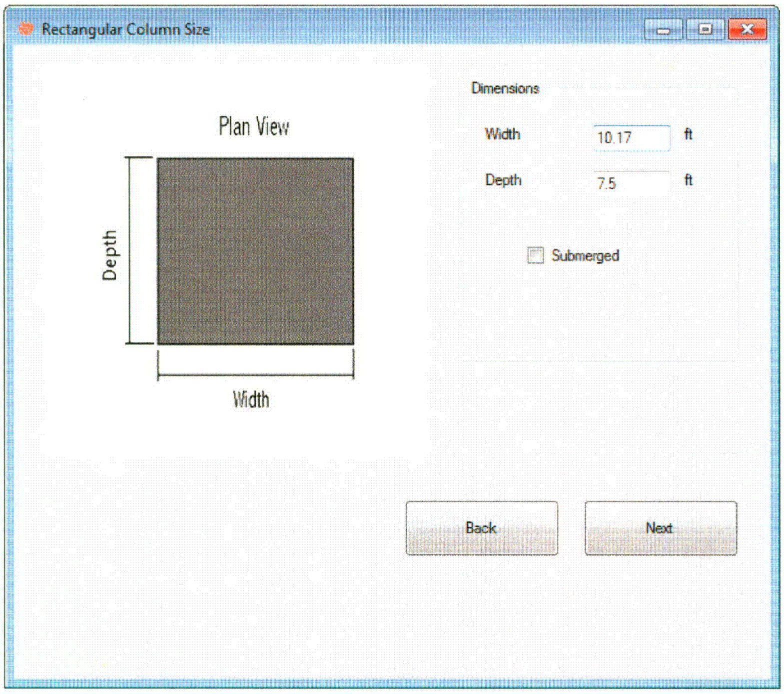

Figure D-6 – WBSB 8 Member Dimensions

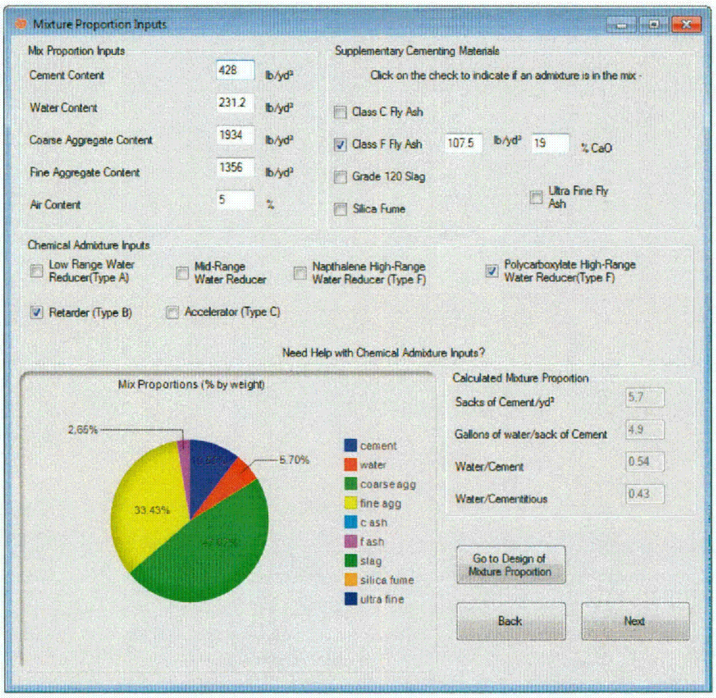

Figure D-7 – WBSB 8 Mixture Proportions

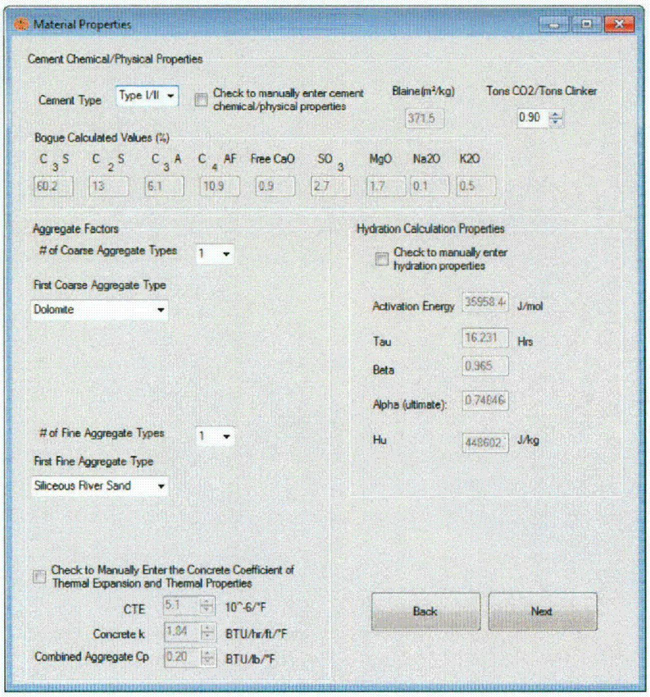

Figure D-8 – WBSB 8 Material Properties (LOD 1)

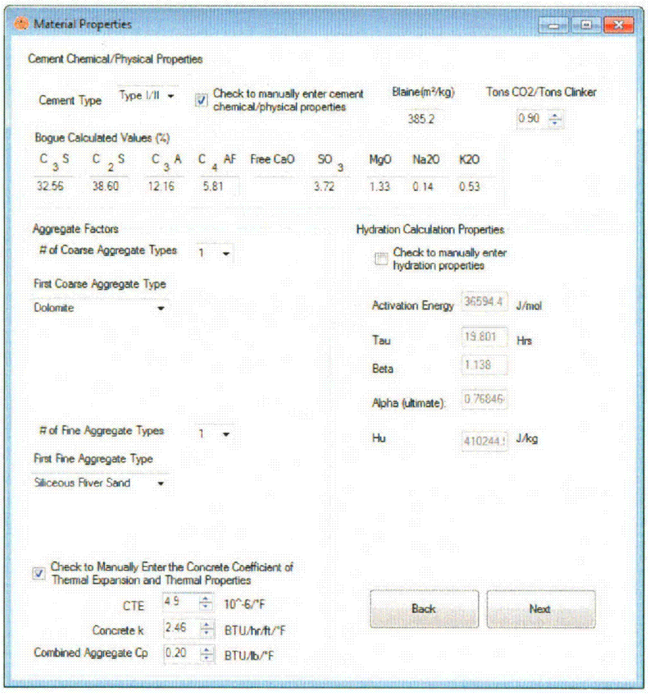

Figure D-9 – WBSB 8 Material Properties (LOD 2)

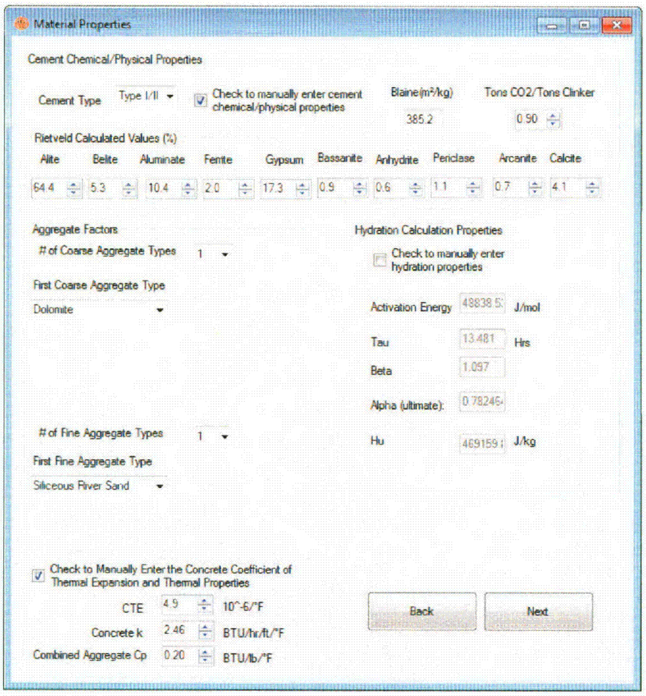

Figure D-10 – WBSB 8 Material Properties (LOD 3)

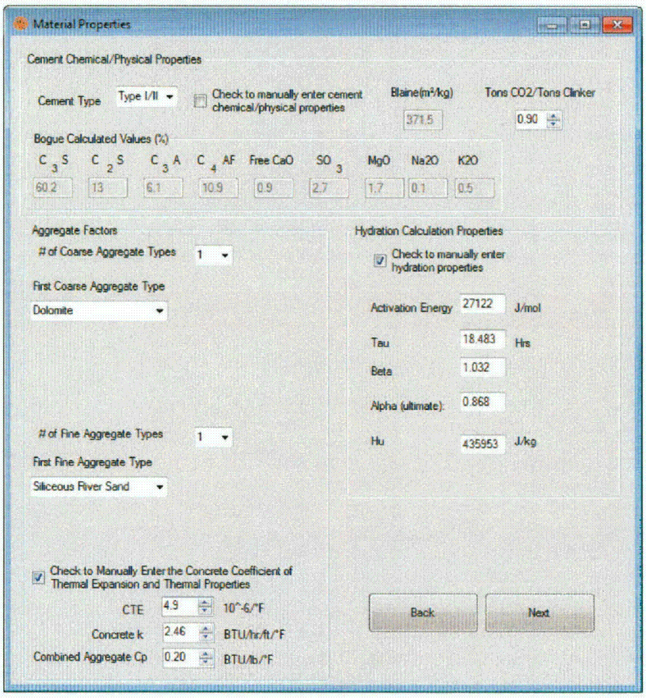

Figure D-11 – WBSB 8 Material Properties (LOD 4)

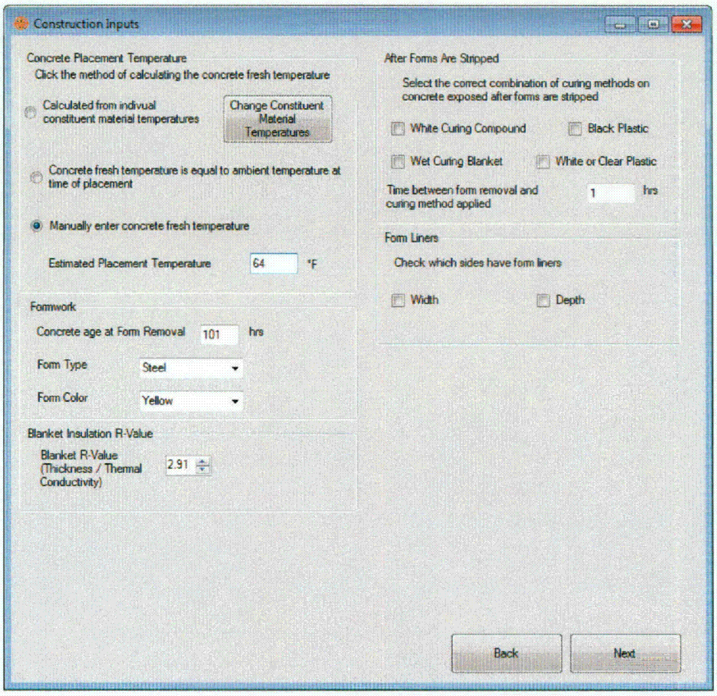

Figure D-12 – WBSB 8 Construction Inputs

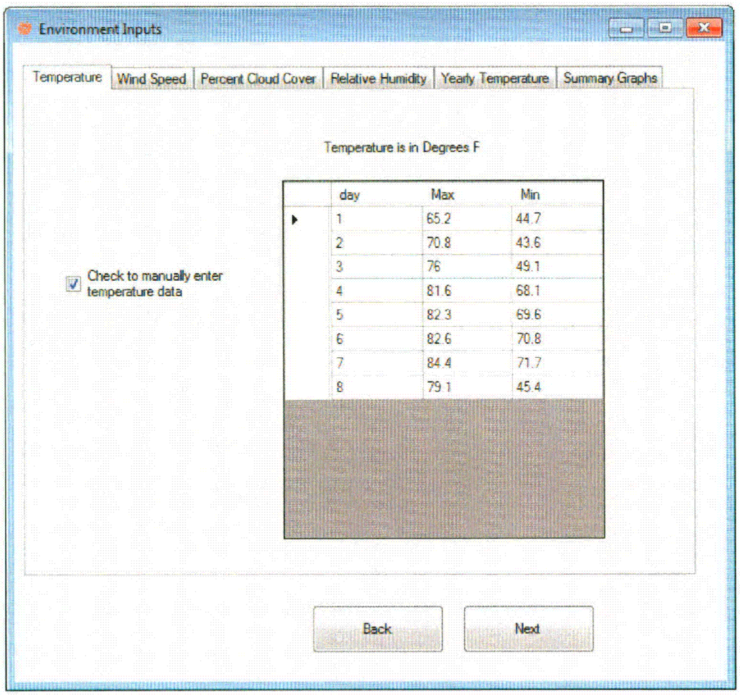

Figure D-13 – WBSB 8 Environment Inputs (Temperature)

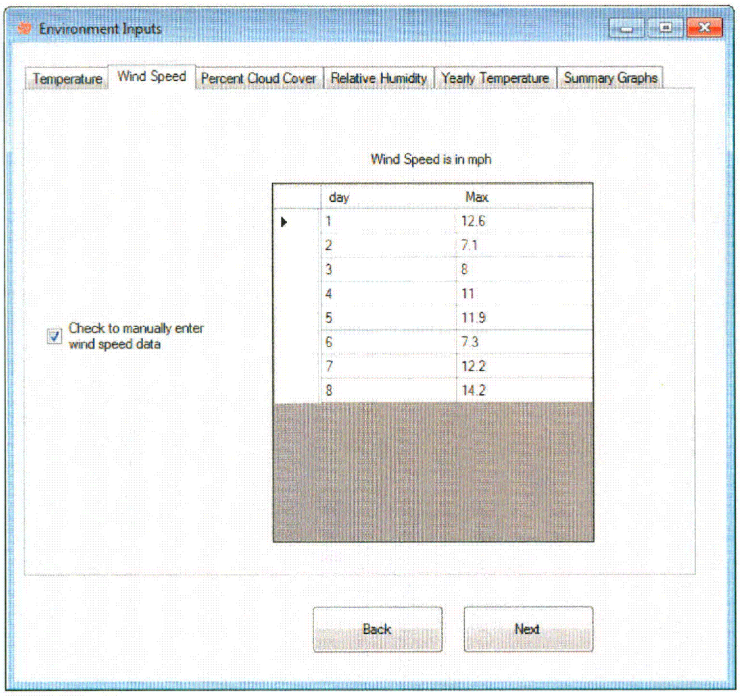

Figure D-14 – WBSB 8 Environment Inputs (Wind Speed)

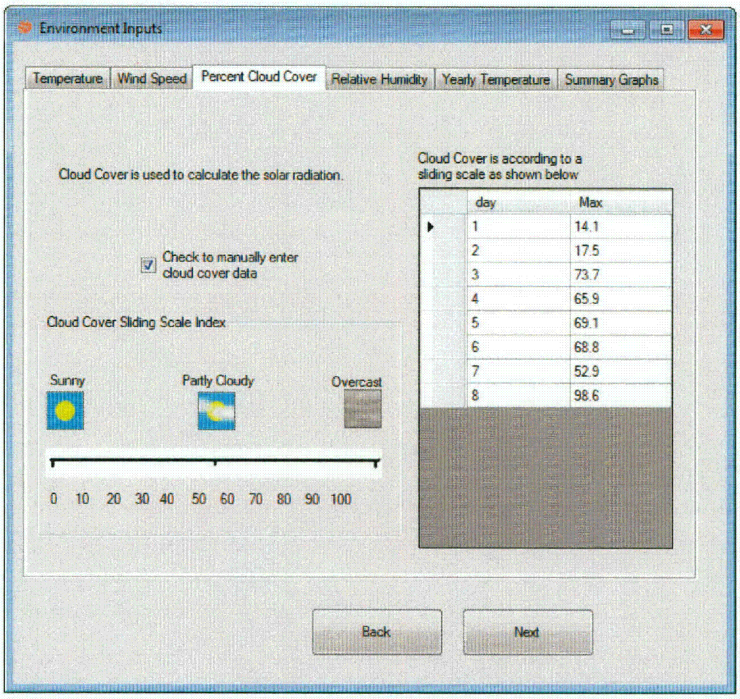

Figure D-15 – WBSB 8 Environment Inputs (Cloud Cover)

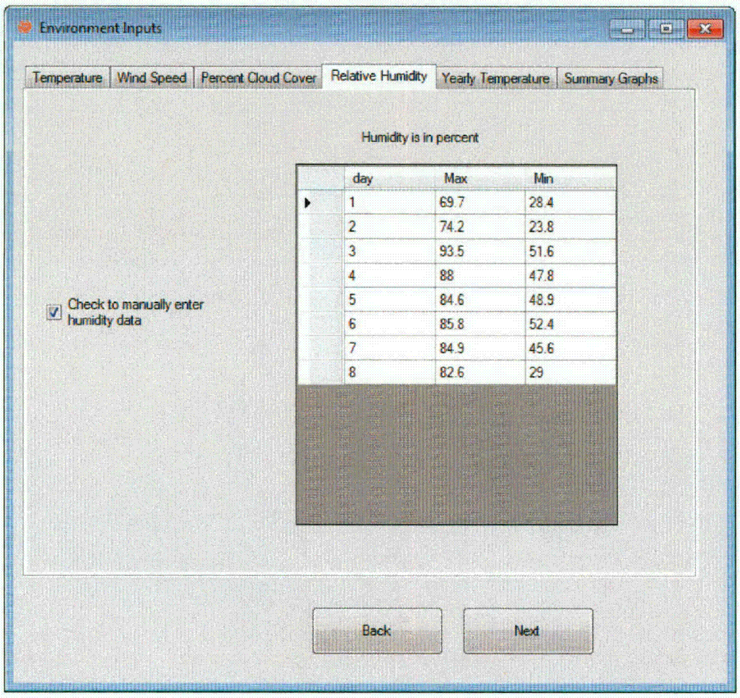

Figure D-16 – WBSB 8 Environment Inputs (Relative Humidity)

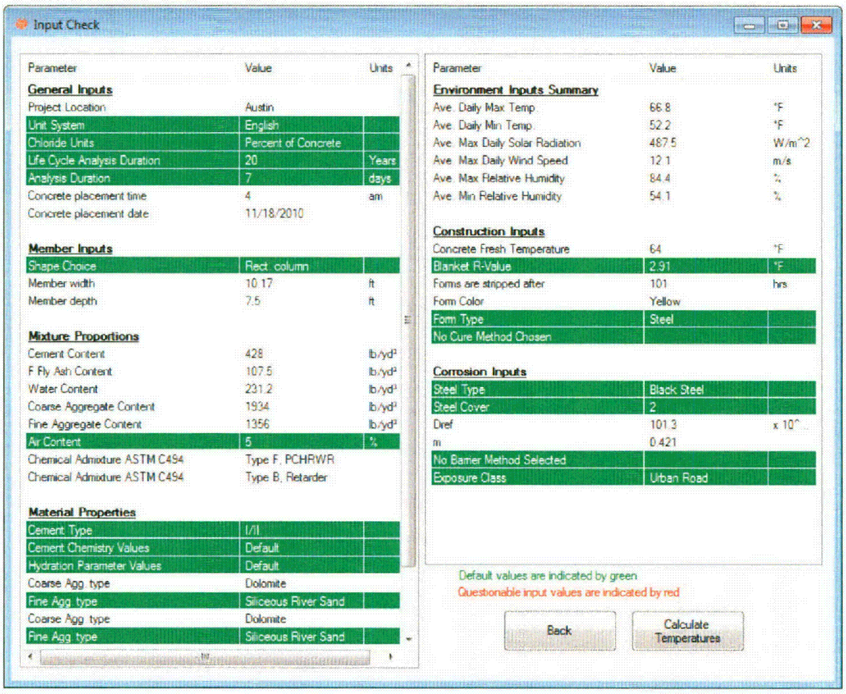

Figure D-17 – WBSB 8 Input Check (LOD 1)

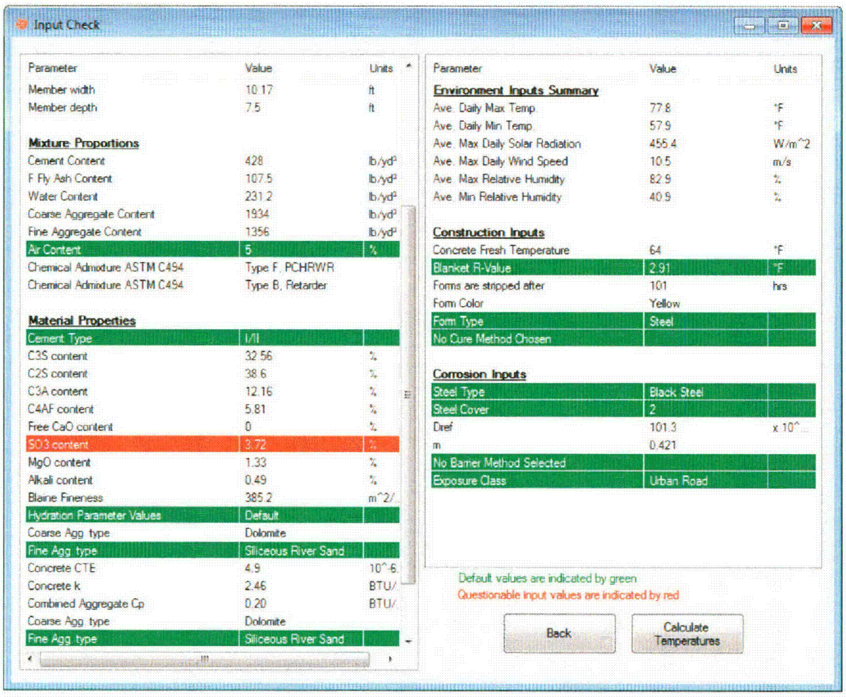

Figure D-18 – WBSB 8 Input Check (LOD 2)

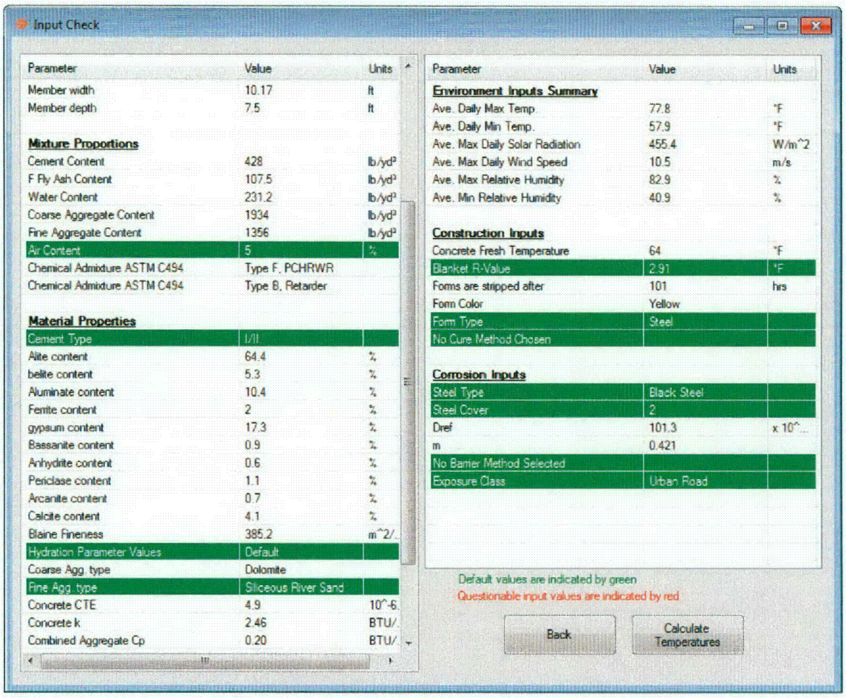

Figure D-19 – WBSB 8 Input Check (LOD 3)

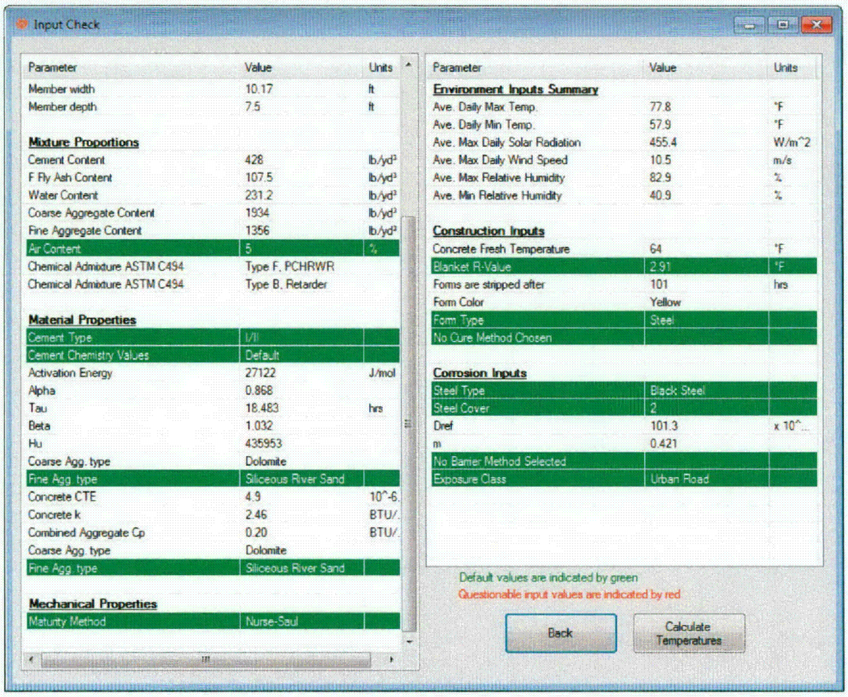

Figure D-20 – WBSB 8 Input Check (LOD 4)

Appendix E: IH35/SH71 WBSB Column 9

Weather Data

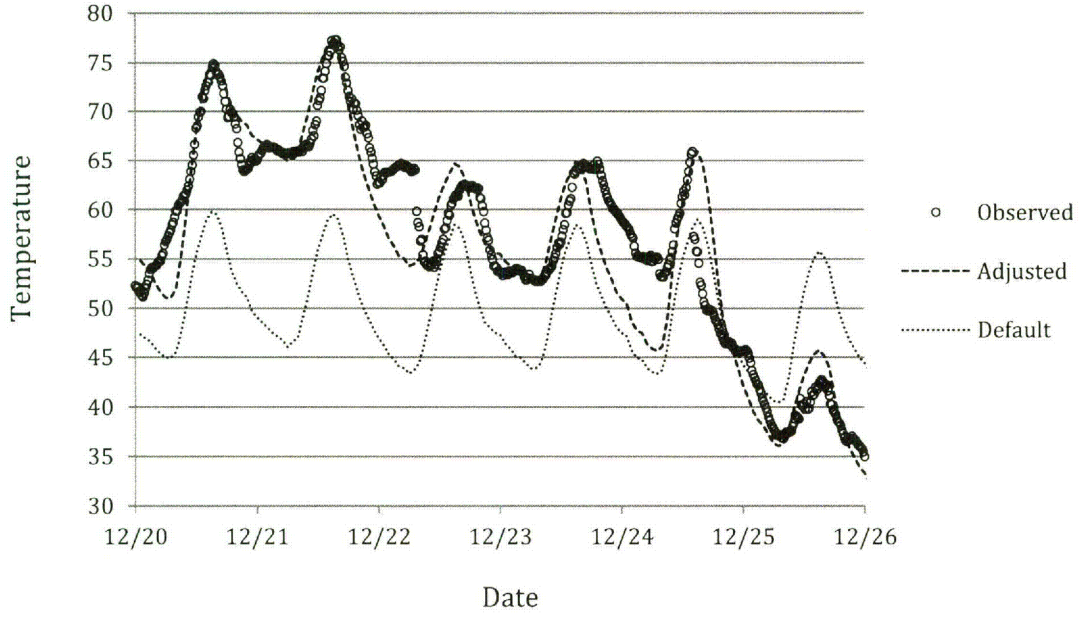

Figure E-1 – WBSB 9 Temperature

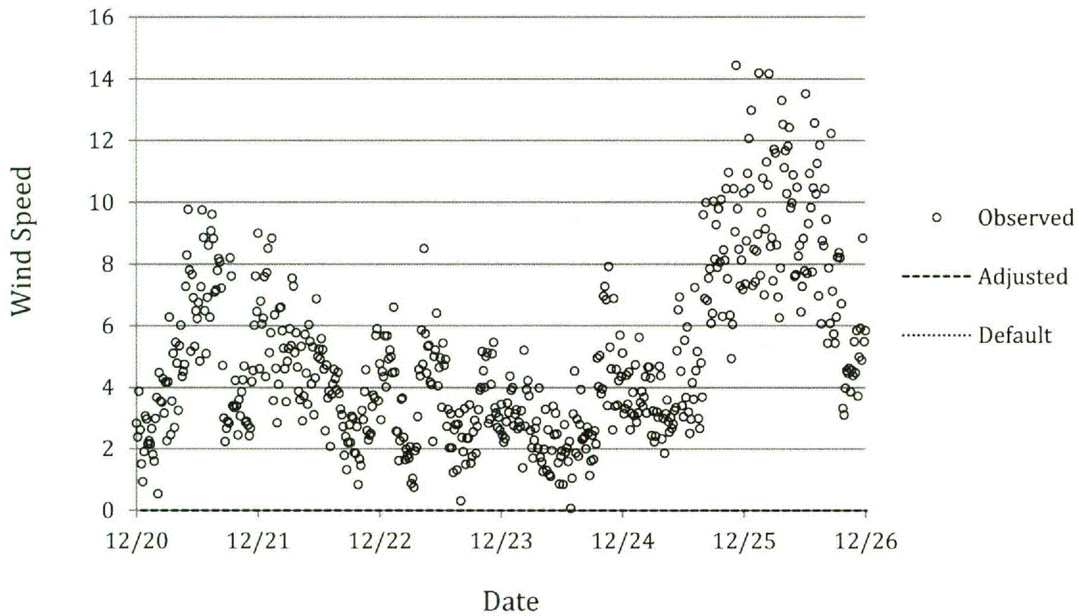

Figure E-2 – WBSB 9 Wind Speed

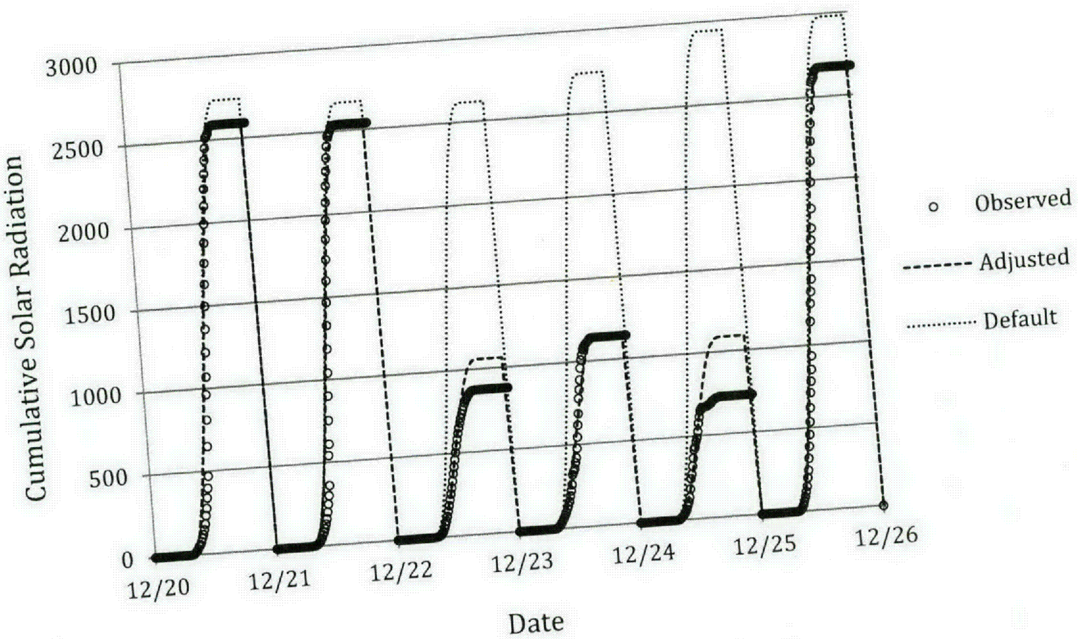

Figure E-3 – WBSB 9 Solar Radiation

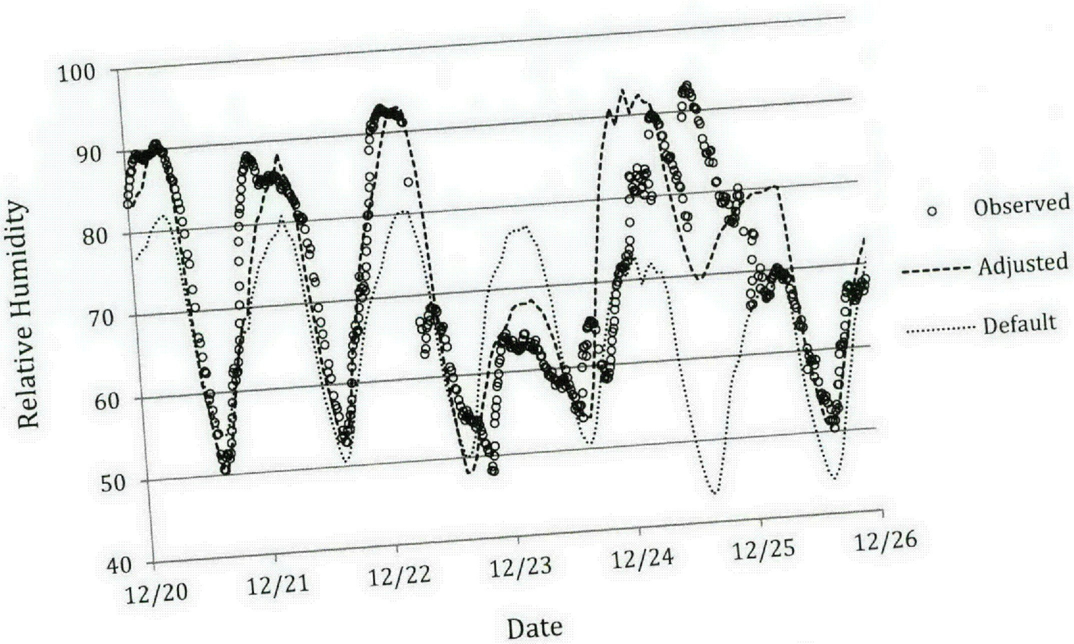

Figure E-4 – WBSB 9 Relative Humidity

ConcreteWorks Screen Prints

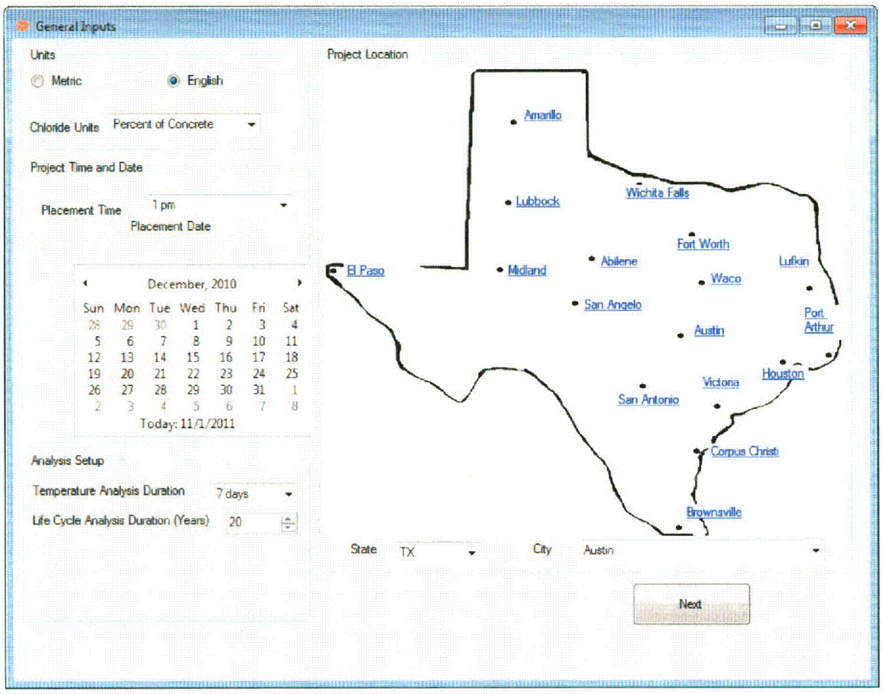

Figure E-5 – WBSB 9 General Inputs

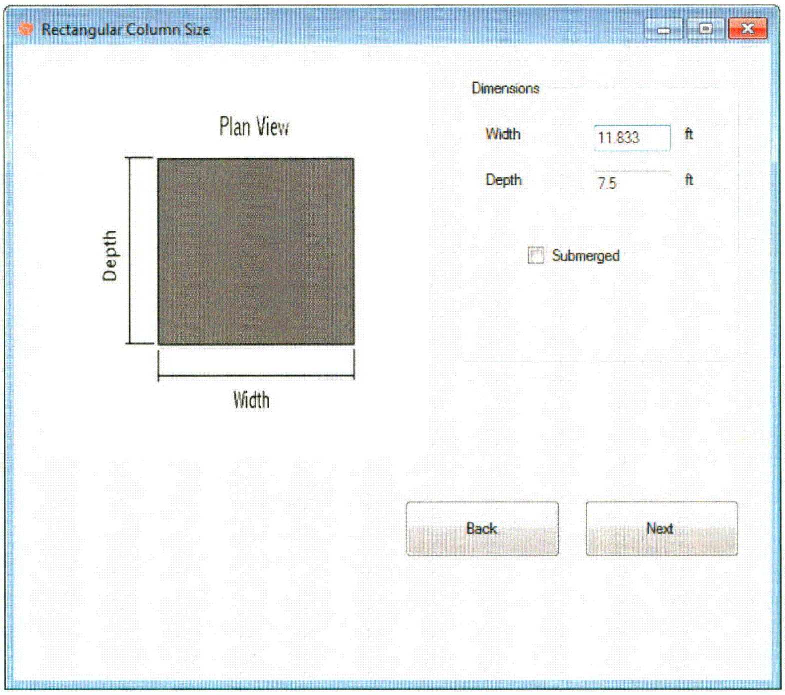

Figure E-6 – WBSB 9 Member Dimensions

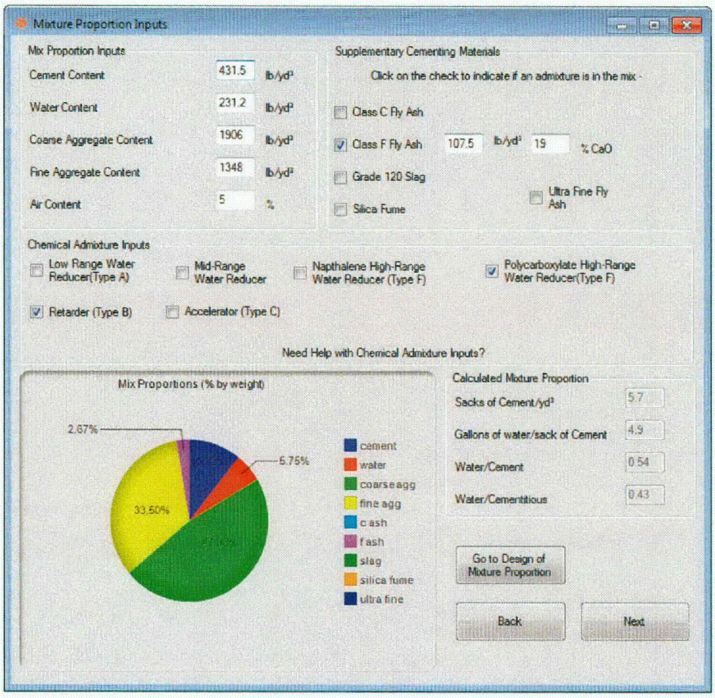

Figure E-7 – WBSB 9 Mixture Proportions

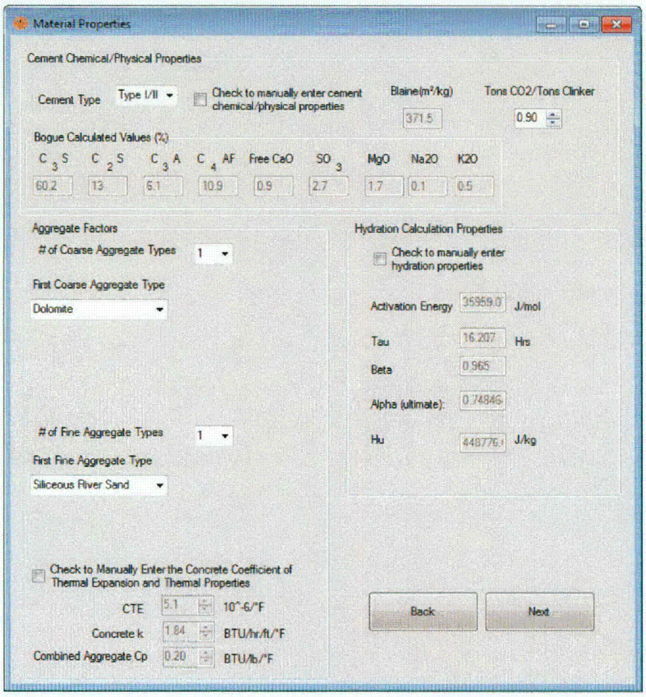

Figure E-8 – WBSB 9 Material Properties (LOD 1)

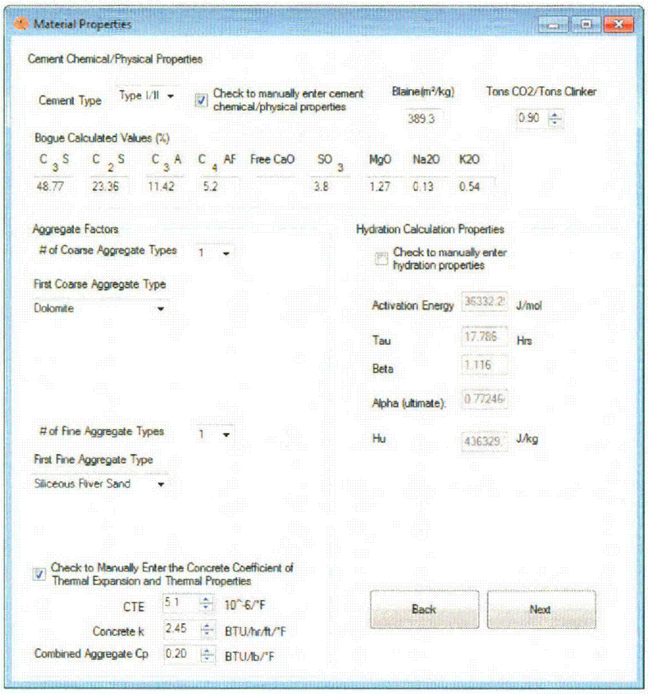

Figure E-9 – WBSB 9 Material Properties (LOD 2)

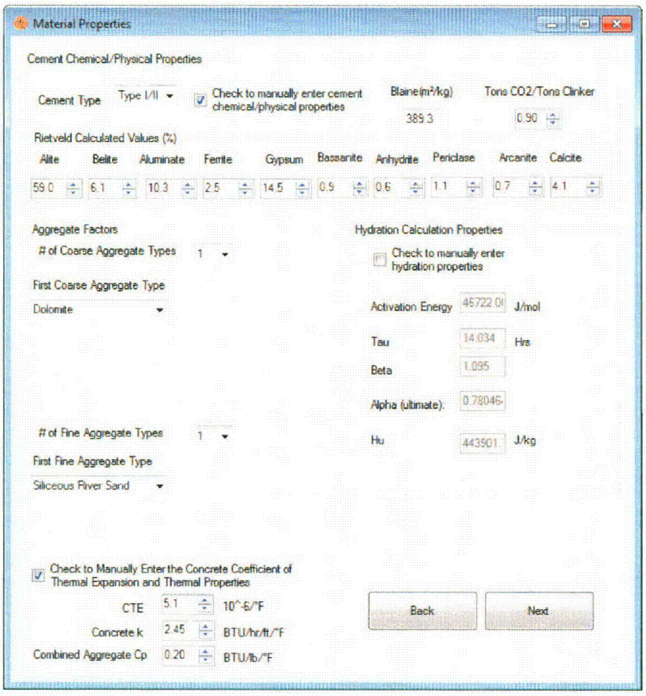

Figure E-10 – WBSB 9 Material Properties (LOD 3)

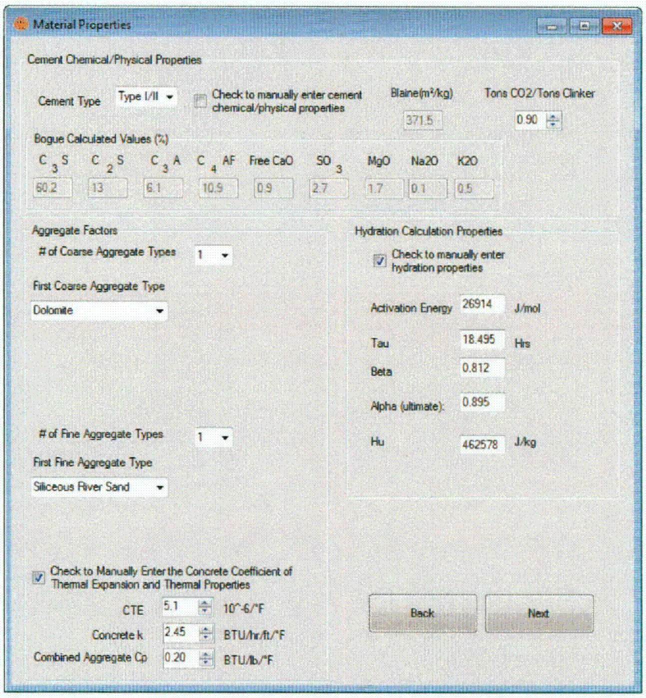

Figure E-11 – WBSB 9 Material Properties (LOD 4)

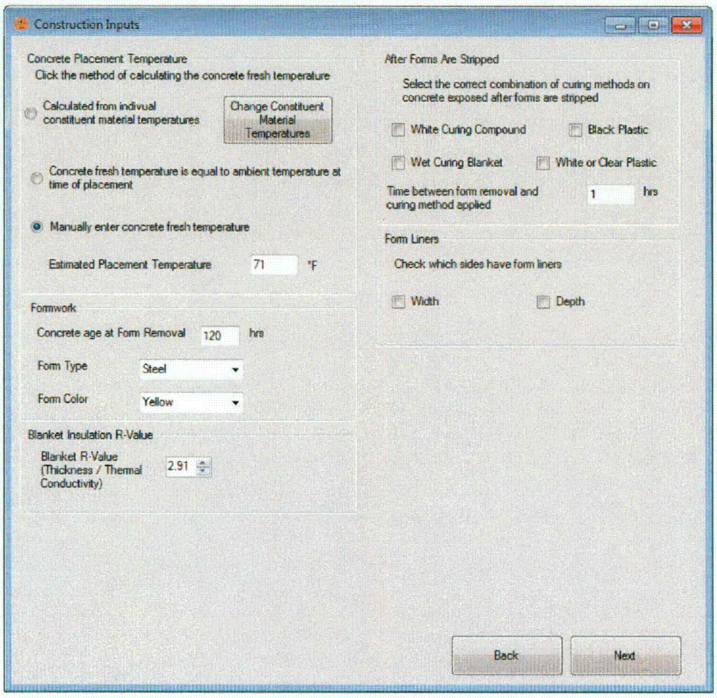

Figure E-12 – WBSB 9 Construction Inputs

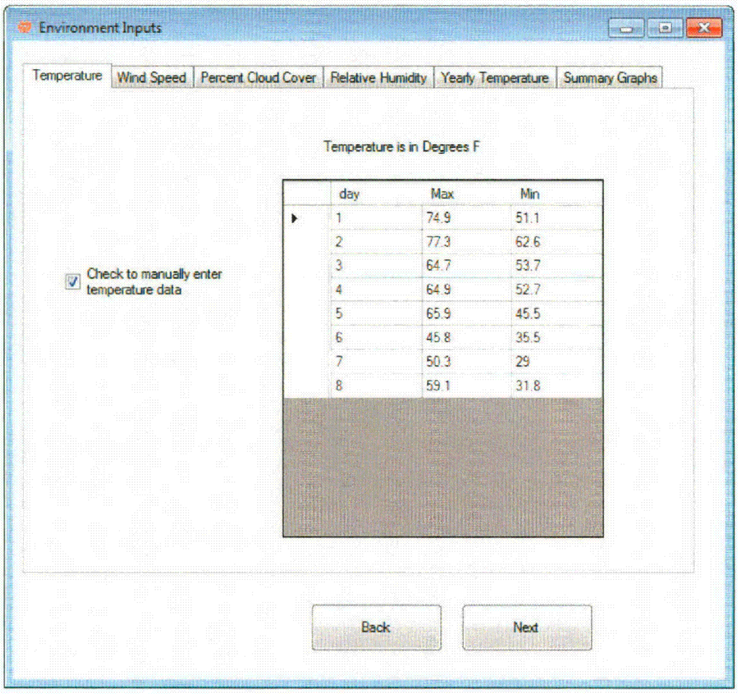

Figure E-13 – WBSB 9 Environment Inputs (Temperature)

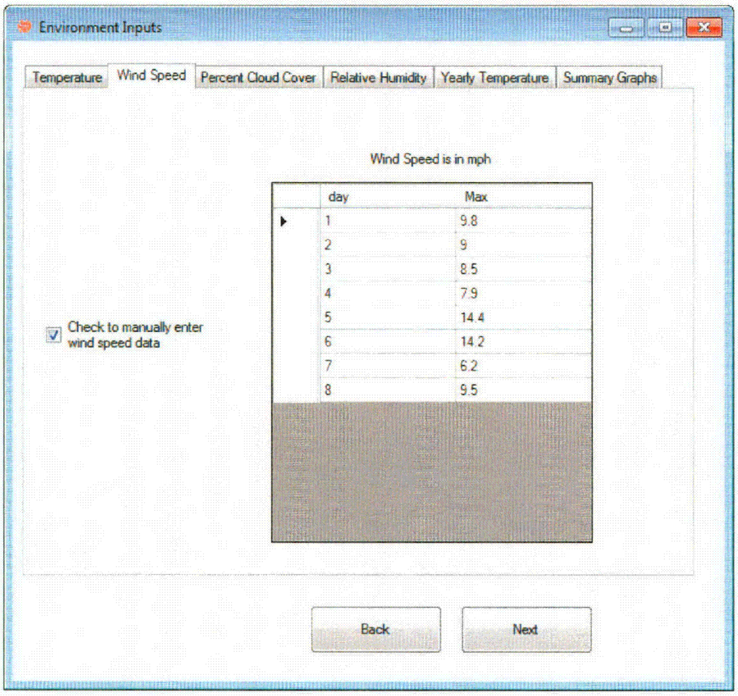

Figure E-14 – WBSB 9 Environment Inputs (Wind Speed)

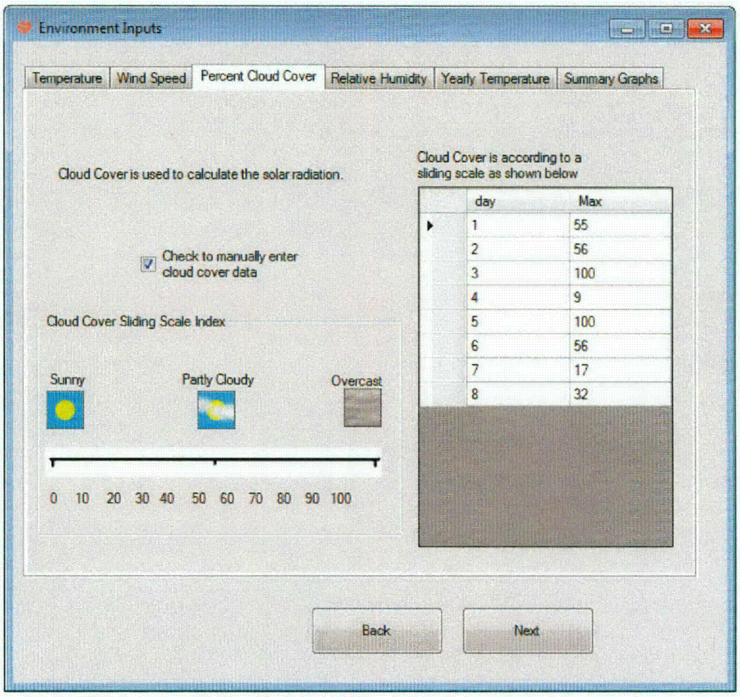

Figure E-15 – WBSB 9 Environment Inputs (Cloud Cover)

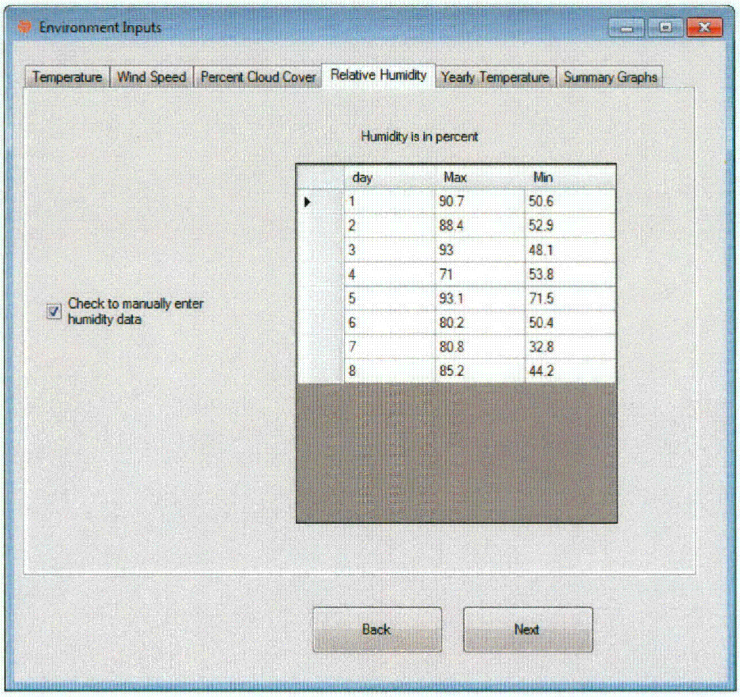

Figure E-16 – WBSB 9 Environment Inputs (Relative Humidity)

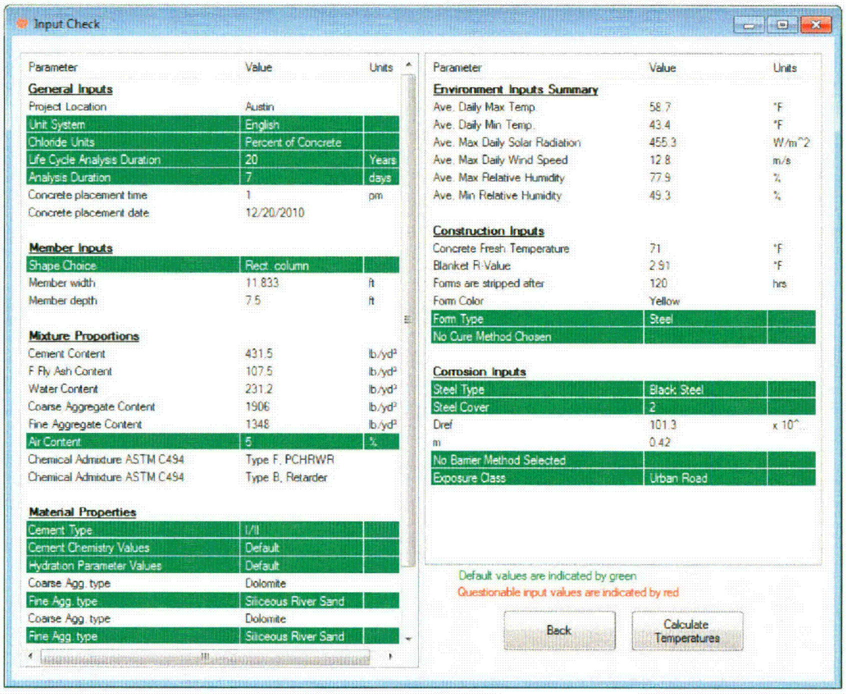

Figure E-17 – WBSB 9 Input Check (LOD 1)

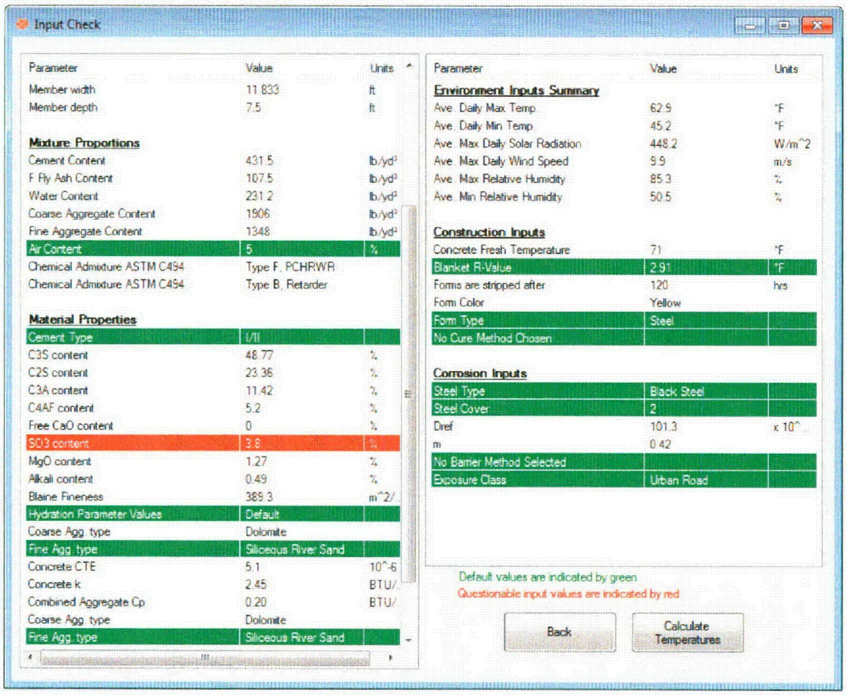

Figure E-18 – WBSB 9 Input Check (LOD 2)

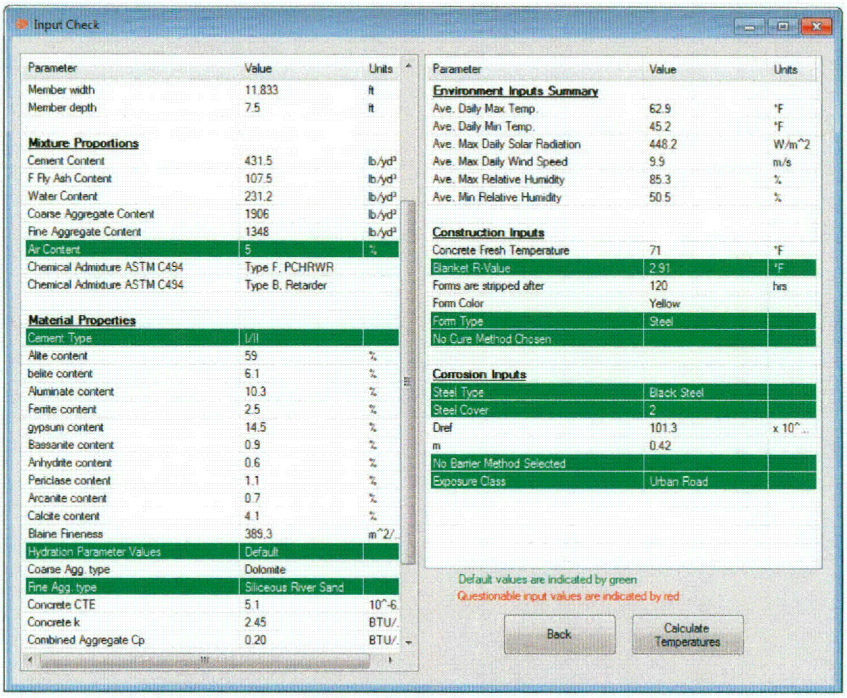

Figure E-19 – WBSB 9 Input Check (LOD 3)

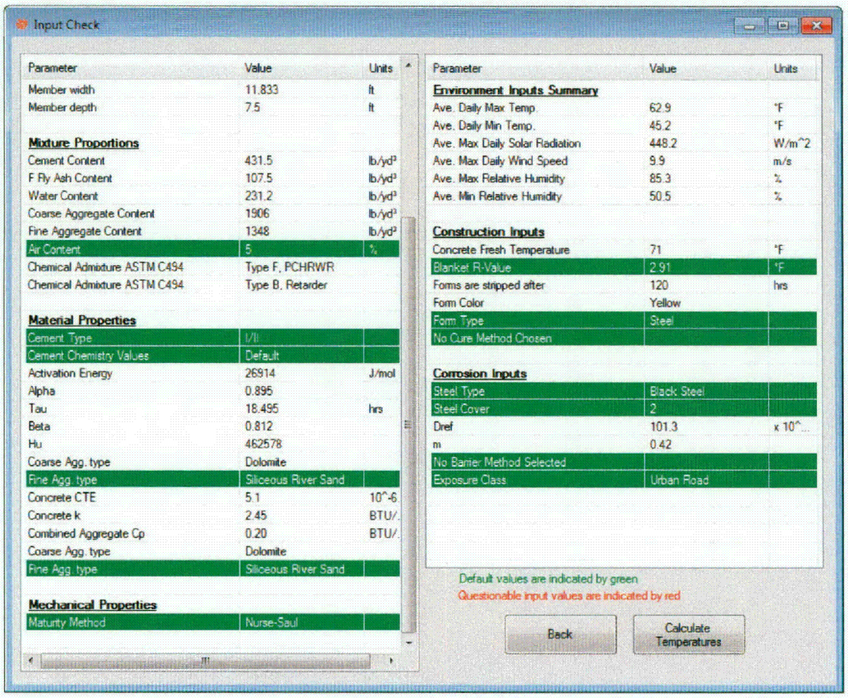

Figure E-20 – WBSB 9 Input Check (LOD 4)

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