THE UNIVERSITY OF TEXAS AT AUSTIN
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ConcreteWorks V3 Training/User Manual (P1)

ConcreteWorks Software (P2)

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THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

0-6332-P1

CONCRETEWORKS V3 TRAINING/USER MANUAL

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Project 0-6332: Development of Predictive Model for Bridge Deck Cracking and Strength Development

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1. Introduction

ConcreteWorks is designed to be a user-friendly software package that can help concrete professionals optimize concrete mixture proportioning, perform a concrete thermal analysis, and increase the chloride diffusion service life. The software package contains design modules for several structural concrete applications, including mass concrete shapes, bridge decks types, precast concrete beams, and concrete pavements. Table 1 shows the ConcreteWorks analysis modules available for each member type.

Table 1 - Software features available for each concrete member type

Member Type		Initial Chloride Profile Input for Existing Structures	Chloride Service Life	Thermal Cracking Risk	Temperature Prediction
Mass Concrete	Rectangular Column		X	X	X
	Rectangular Footing		X	X	X
	Partially Submerged Rectangular Footing		X	X	X
	Rectangular Bent Cap		X	X	X
	T-Shaped Bent Cap		X		X
	Circular Column		X		X
	Drilled Shaft		X		X
Precast Concrete Members	Box Beam (Type 5B40)				X
	Type IV I-Beam				X
	U40 Beam				X
	U54 Beam				X
Bridge Deck Types	Pre-cast 1/2 Depth Panels	X	X		X
	Permanent Metal Decking	X	X		X
	Removable Forms	X	X		X
	User-Defined	X	X		X
Pavements	User-Selected Layers				X

In order to obtain accurate temperature, thermal stress, and corrosion risk calculations, the user be familiar with the fundamental principles and mechanics of concrete proportioning, temperature concerns in concrete members, concrete maturity, and diffusion theory for concrete employed in the software inputs and calculations explained in this user manual. It is assumed that users will have a good knowledge of fundamental concrete materials principles and practices. The purpose of this manual is not to give an exhaustive compilation on all concrete thermal, durability, and corrosion research in the literature. Instead, this manual is designed assist the user with the specific knowledge of concrete behavior needed to successfully use ConcreteWorks, built upon an already existing knowledge of fundamental concrete behavior. It is recommended that users carefully read this user manual as well as cited references as needed before using the software.

This manual is divided into an informational section followed by an operator's manual. Chapter 2 presents the information on the ConcreteWorks mixture proportioning guide. Chapter 3 describes how the heat transfer calculations in the program are performed. Chapter 4 explains how the program's thermal stress analysis and consequent cracking risk assessment is done. Chapter 5 discusses the chloride service life model built into ConcreteWorks. Finally, a ConcreteWorks operator's manual is provided in Chapter 6.

2. Concrete Mixture Proportioning Guide

2.1. Basic Mixture Proportioning

The backbone for the mixture proportioning guide found in ConcreteWorks is the procedure outlined in the ACI 211 document "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete" (ACI 211, 1991). For a detailed explanation of this mixture proportioning method, users are encouraged to read the ACI 211.1-91 document.

The basic steps of the concrete mixture proportioning procedure can be summarized as the following:

1. Determine the amount of water needed to achieve a given slump for the selected maximum aggregate size. Adjust the required water amount based on material conditions, chemical admixtures, air entrainment, etc. (covered in Section 2.2 of this document).
2. Determine the water-to-cementitious-materials ratio (w/cm) needed for a given air content to achieve selected target strength. The use of supplementary materials is assumed to not affect the w/cm needed to achieve the target strength (which may or may not be true depending on the reactivity of the material and the replacement rate). Supplementary cementing materials replacement percentages are only used in calculating the volume of cementitious materials.
3. Adjust the w/cm to account for maximum w/cm allowed for given exposure conditions (chloride and sulfate exposure levels).
4. Calculate the coarse aggregate fraction based on the maximum size aggregate, the sand fineness modulus, and the coarse aggregate dry-rodded unit weight.
5. Calculate the amount of sand needed to fill the remaining concrete volume (that volume not already accounted for by the cementitious materials, water, coarse aggregate, or air). The sand weight is then calculated for this volume using the sand specific gravity.

The required water amount is calculated using Equation 1 and the coefficients found in Table 1 based on the ACI 211.1-91 Table 6.3.3. The required water amount is then reduced by the percentages specified using the water adjustment factors discussed in Section 2.2 and calculated using Equation 1:

$$W = (a_w \cdot \ln(sl) + b_w) \cdot (1 - WA)$$ **Equation 1**

where W is the required water (lb/yd³), a_w and b_w are constants determined from Table 2 (lb/yd³), *sl* is the desired concrete slump (in), and *WA* is the water reduction factor. The amount of water needed to obtain the required slump increases as the maximum aggregate size decreases and consequently the total aggregate surface area increases.

Table 2 - Concrete water requirement and coarse aggregate volume fit parameters based on the maximum size aggregate

Maximum Aggregate Size (in.)	a_w (lb/yd³)	b_w (lb/yd³)	a_{ca}
2	27.411	249.41	0.78
1.5	27.411	264.41	0.75
1	27.411	289.41	0.71
0.75	30.618	302.31	0.66
0.5	34.176	321.45	0.59
0.375	40.941	333.49	0.5

The connection between compressive strength and w/cm was first published in 1918 by Duff Abrams. W/cm is one of the major factors in determining the concrete porosity and consequently compressive strength (Mindess, Young, and Darwin, 2003). Air entrainment will increase the amount of voids in concrete, and consequently reduce the strength. The required w/cm ratio is calculated using Equation 2 through Equation 4:

$$w/cm = (a_a \cdot \ln(f_{ct}^{'}) + b_a) \qquad \textbf{Equation 2}$$

$$a_a = 0.00065 * air - 0.3762 \qquad \textbf{Equation 3}$$

$$b_a = -0.0263 * air - 3.7275 \qquad \textbf{Equation 4}$$

where *air* is the target percent air in the concrete, and f_{ct}' is the concrete target strength. Equations 3 and 4 were calculated using a regression analysis from the data found in ACI 211.1-91 table 6.3.4, assuming the quoted values of 2% entrapped air for the non-air entrained concrete and 6% for the air entrained concrete.

The coarse aggregate weight is calculated using Equation 5:

$$CAW = (a_{ca} + \frac{(2.4 - FM)}{10}) \cdot DRUW \qquad \textbf{Equation 5}$$

where *CAW* is the coarse aggregate weight (lb/yd³), a_{ca} is a fit parameter found in Table 2, *FM* is the fineness modulus, and *DRUW* is the coarse aggregate dry rodded unit weight (lb/yd³). The coefficient a_{ca} was derived by fitting the data found in ACI 211.1-91 Table 6.3.6.

2.2. Water Adjustments

The required water adjustments procedures and magnitudes are based on the National Highway Institute (NHI) Course 15123 Participant Workbook (Hover, 2003). The amount of water adjustment needed for each material used is highly material dependent. Concrete mixture proportioning knowledge and experience with the local materials used is critical to accurately estimate the influence of each material on the concrete mixture. A trial batch is normally required to confirm the validity of the concrete mixture designed, and to make any necessary adjustments to the concrete workability.

The range of water adjustment permitted for different materials in ConcreteWorks is that suggested by the NHI course 15123 Participant Workbook (2003) and shown in Table 3. Water-reducing chemical admixtures will reduce the required water content in the concrete mixture by different amounts depending on the chemical admixture chemistry and dose used. Values selected for water reducers should be based on experience or recommendations from the chemical admixture supplier. Air entrainment will also increase the concrete workability by both chemical and physical means (Mindess, Darwin, and Young, 2003). The effect of supplementary cementing materials will depend on the particle size and shape. Silica fume will greatly increase the water demand and should not be used without a high range water reducer that will aid in the dispersion. Fly ash can, however, increase the workability, although the amount is very material dependent. Aggregates will also have a large effect on the concrete workability. Poorly shaped and graded aggregates will have a very high water demand. Round, smooth, and well-graded aggregates will, however, decrease the concrete water demand. Experience with the use of local aggregates is especially important when gauging the amount of water adjustment needed in the mixture proportioning.

Table 3 - Range of water adjustment factors used in ConcreteWorks (Hover, 2003)

Factor	**Water Adjustment Range (a negative value is a water reduction)**	
ASTM Type A Low Range Water Reducer	0	-10
Mid-Range Water Reducer	-8	-15
ASTM Type F High Range Water Reducer	-12	-30
Air Entrainment	0	-10
Aggregate Shape & Texture	5	-5
Aggregate Gradation	-10	10
Supplementary Cementing Materials	-10	15

2.3. Aggregate Gradations

Three simple methods of optimizing aggregate gradations are commonly used to decrease the amount of water needed in the concrete. Two of the methods, the 0.45 power curve method and the percent retained method, are based on the combined aggregate gradation. The third method, the Shilstone Coarseness Factor-Workability Factor method (Shilstone, 2002) uses an empirical relationship between the percent retained on the No. 8 sieve, the percent retained on the 3/8” sieve, and the cementitious content to determine if a mixture is acceptable.

The 0.45 power curve method is commonly used in asphalt aggregate gradations. The aggregate percent passing is plotted versus the sieve size to the 0.45 power on a log scale. The aggregate maximum density line is plotted on the same graph, with the percent passing (PP) calculated using Equation 6:

$$PP = \left(\frac{d}{D}\right)^{0.45}$$ **Equation 6**

where d is the sieve size (in.), and D is the maximum aggregate size (in.).

The Shilstone Coarseness Factor-Workability Factor method uses an empirically derived, graphical relationship between aggregate gradation and cementitious content to classify a mixture as acceptable or not. The coarseness factor is plotted on the x axis while the workability factor is plotted on the y axis. The coarseness factor is the cumulative percent retained on the 3/8" sieve divided by the cumulative percent retained on the No. 8 sieve times 100 (%). The workability factor is the "percent of the combined aggregate that passes the No. 8 sieve (Shilstone, 2002)." The workability factor is then adjusted for the cementitious content by Equation 7:

$$WF = CA8 \cdot \frac{cm - 564}{94} * 2.5$$ **Equation 7**

where WF is the workability factor, $CA8$ is the combined aggregate that passes the No. 8 sieve (%), and cm is the concrete cementitious material content (lb/yd^3). If the coarseness factor and workability factor for the mixture plots inside of an empirically derived box, defined below, then the mixture is deemed acceptable (Shilstone, 2002). The concrete mixture proportions acceptability box whose corners are shown in Table 4:

Table 4 - Corners of box of acceptable mixtures for Shilstone Coarseness Factor-Workability Factor aggregate gradation method (TxDOT Special Provision 421)

Corner #	Coarseness Factor	Workability Factor
1	68	36
2	68	32
3	52	38
4	52	34

The percent retained method involves plotting the percent retained on each sieve, and eliminating large valleys and peaks in the gradation. This method is very subjective, but may help avoid having a very gap-graded mixture.

3. Temperature Prediction

3.1. Heat Transfer Modeling

3.1.1. Fundamentals and Numerical Scheme

Heat transfer is governed by the second order differential equation known as the *heat diffusion equation*, as shown in Equation 8:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + q' = \rho c_p \frac{\partial T}{\partial t}$$ **Equation 8**

where k is the material thermal conductivity (W/m/K), $T(x,y,z)$ is the scalar temperature field (°C), q' is the heat generation term (W), ρ is the material density (kg/m^3), c_p is the material specific heat (kJ/kg/°K), and t is the time (s) (Incropera and Dewitt, 2002).

Closed form solutions for the heat diffusion equation are only available for very simple geometries and conditions. The heat transfer in real concrete members is much too complex for direct solutions. Numerical approximations can, however, be used to estimate the concrete temperature development. One such method is the finite difference method. An energy balance on an assumed differential control volume can be used to account for all thermal energy changes inside the control volume, as shown in Equation 9:

$$E_{in} - E_{out} + E_{gen} = \Delta E_{st} \qquad \textbf{Equation 9}$$

where E_{in} is the thermal energy entering the control volume (W), E_{out} is the thermal energy leaving the control volume (W), E_{gen} is the thermal energy being generated in the control volume (in the case of concrete, the heat generated by hydration) (W), and ΔE_{st} is the change in thermal energy stored in the control volume (W). The energy entering and leaving the control volume by conduction is equivalent to the first three terms in the heat diffusion equation. The heat generation term is the chemical energy being released in the control volume. The change in heat energy being stored in the control volume is equal to the change in temperature in the control volume times the specific heat and density. The temperature and material properties are assumed to be constant for each control volume. Sufficiently small control volumes must then be used to adequately approximate the heat transfer for each volume.

Figure 1 shows three neighboring control volumes with insulated sides. An explicit time discretization has been used in formulating these equations, which is explained in Section 3.1.2. The change in energy entering and leaving the control volume 2 can be calculated using Equation 10 and Equation 11.

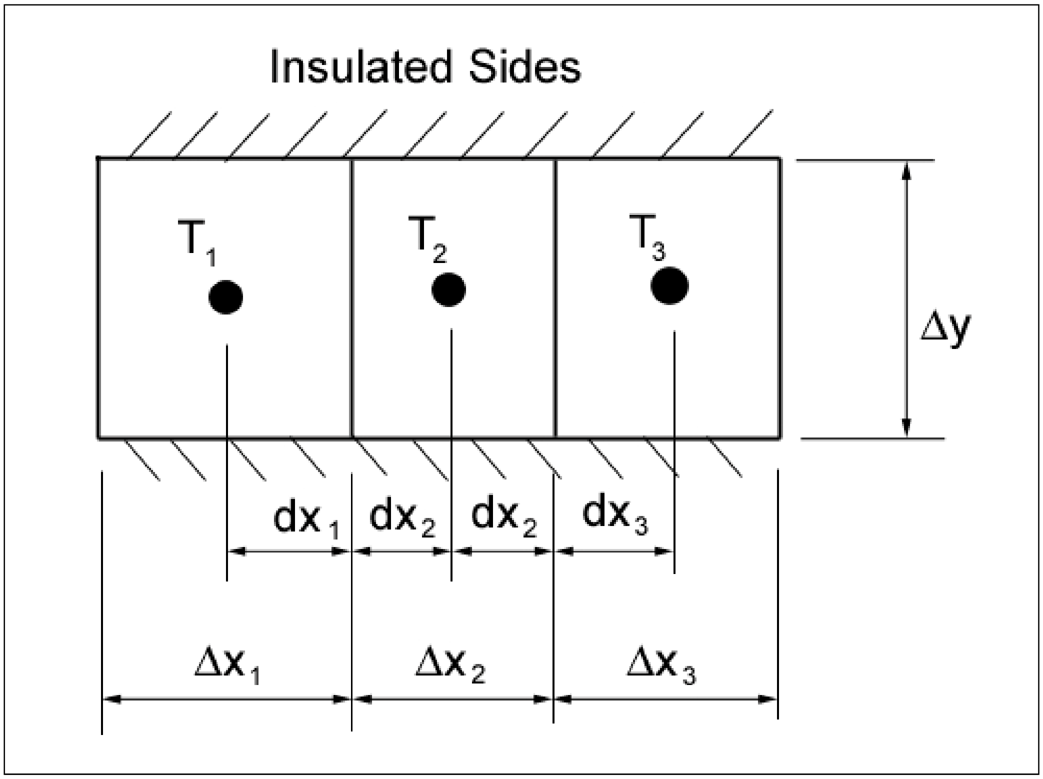


Figure 1 - Control volume example - three neighboring nodes

$$E_{in} = T_1 \cdot a_{1-2} + T_3 \cdot a_{2-3}$$ **Equation 10**

$$E_{out} = T_2 \cdot a_{1-2} + T_2 \cdot a_{2-3}$$ **Equation 11**

where T_1, T_2, and T_3 are the temperatures at the respective nodes shown in Figure 1 for the current time step (°C), a_{1-2} and a_{2-3} are heat transfer coefficients between control volumes 1 – 2 and 3 – 4 and are defined by Equation 12 and Equation 13 (Patankar, 1980).

$$a_{1-2} = \left[\frac{dx_1}{k_1} + \frac{dx_2}{k_2}\right]^{-1} \cdot \Delta y$$ **Equation 12**

$$a_{2-3} = \left[\frac{dx_2}{k_2} + \frac{dx_3}{k3}\right]^{-1} \cdot \Delta y$$ **Equation 13**

where dx_1, dx_2, dx_3, and Δy are as shown in Figure 1 (m); k_1, k_2, and k_3 are the thermal conductivity for the material in the respective control volume (W/m/K). The energy generated in control volume 2 is equal to the heat generated by hydration per unit mass of cementitious materials times the mass of cementitious materials in the control volume as shown in Equation 14.

$$E_{gen} = Q \cdot \Delta x_2 \cdot \Delta y$$ **Equation 14**

where Q is the heat generated per unit mass of cementitious materials (W); Δx_2 and Δy are as shown in Figure 1 (m). For control volume 2, Q may be calculated based on the Arrhenius equation as shown in Equation 15 (Schindler, 2004):

$$Q(t_e) = H_u \cdot C_c \cdot \left(\frac{\tau}{t_e}\right)^{\beta} \cdot \left(\frac{\beta}{t_e}\right) * \alpha_u \cdot \exp\left(-\left[\frac{\tau}{t_e}\right]^{\beta}\right) \cdot \exp\left(\frac{E_a}{R}\left(\frac{1}{273+T_r} - \frac{1}{273+T_2}\right)\right) \cdot \left(\frac{1}{3600}\right) \qquad \textbf{Equation 15}$$

where t_e is the concrete equivalent age at the reference temperature as shown in Equation 16 (hrs), H_u is the total amount of heat generated at 100% hydration (J/kg), C_c is the total amount of cementitious materials (kg/m^3), τ is the hydration time parameter (hrs), β is the hydration slope parameter, α_u is the ultimate degree of hydration, E_a is the activation energy (J/mol), R is the universal gas constant (J/mol/K), and T_r is the reference temperature (°C). The degree of hydration is calculated as shown in Equation 17.

$$t_e(T_2) = \int_0^t \exp\left(\frac{AE}{R} \cdot \left(\frac{1}{273+T_r} - \frac{1}{273+T_2}\right)\right) \cdot dt \qquad \textbf{Equation 16}$$

$$\alpha(t_e) = \alpha_u \cdot \exp\left(-\left[\frac{\tau}{t_e}\right]^{\beta}\right) \qquad \textbf{Equation 17}$$

The change in energy stored in the control volume is shown in Equation 18.

$$\Delta E_{st} = \frac{\rho_2 \cdot c_{p2} \cdot \Delta x_2 \cdot \Delta y \ \cdot (T_2^{+1} - T_2)}{\Delta t} \qquad \textbf{Equation 18}$$

where ρ_2 is the material density in control volume 2 (kg/m^3), c_{p2} is the material specific heat in control volume 2 (J/kg/K), T_2^{+1} is the temperature at node 2 for the next time step (°C), T_2 is the temperature at node 2 for the current time step (°C), and Δt is the time step (seconds).

Boundary conditions are easily handled using the energy balance approach. A control volume with a side exposed to convection is shown in Figure 2.

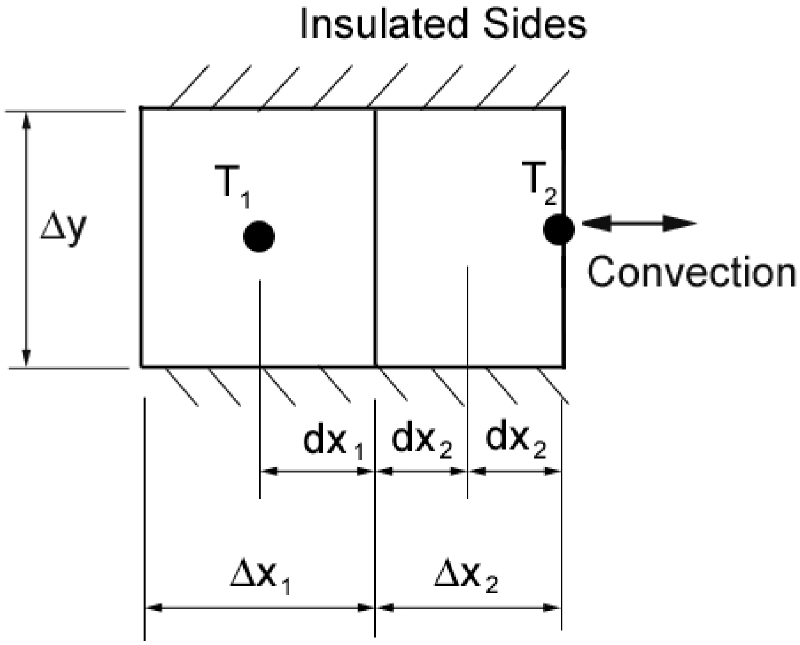


Figure 2 - Example of control volume with a convection boundary condition

A "half control volume" is used for control volumes located on an external boundary (Patankar, 1980). The conduction energy entering or leaving that side of the control volume can be replaced with the convection energy entering or leaving the control volume, as shown in Equation 19 and Equation 20:

$$E_{in} = T_1 \cdot a_{1-2} + T_\infty \cdot h \cdot \Delta y$$ **Equation 19**

$$E_{out} = T_2 \cdot a_{1-2} + T_2 \cdot h \cdot \Delta y$$ **Equation 20**

where h is the convection heat transfer coefficient (W/m^2/K). Radiation and irradiation terms may be similarly added to E_{in} and E_{out}. Constant temperatures, such as those found at the concrete exterior of a submerged concrete member, may be enforced by setting the next time step for the control volume equal to the prescribed temperature.

3.1.2. Time Discretization

To calculate the temperature in a node, the temperature variation with time needs to be assumed. A common assumption is to assume that the integral with respect to time and temperature is a linear combination of the temperature at the beginning and end of the time step as shown in Equation 21 (Patankar, 1980).

$$\int_t^{t+\Delta t} T_p dt = \left[f \cdot T_2^{+1} + (1-f) \cdot T_2 \right] \cdot \Delta t$$ **Equation 21**

where t is the beginning of the time step being evaluated (s), $t + \Delta t$ is the end of the time step in question (s), f is a constant between 0 and 1, T_2^{+1} is the temperature at node 2 at the end of the time step (°C), and T_2 is the temperature at node 2 at the beginning of the time step (°C). When f is chosen to be 0, the time discretization is said to be fully explicit and the temperature during the time step is assumed to be equal to the beginning temperature during the time step. If f is greater than 0, the method is called implicit. If f is assumed to be 1, the method is called fully implicit. The temperature during the time step is then assumed to be equal to the ending temperature during the time step. Explicit methods allow for temperature calculations directly from previous time step temperatures. Implicit methods however, are dependent on unknown temperatures. A system of unknown temperatures must be solved for simultaneously (Patankar, 1980). When the explicit method is used, the temperature at a node for the next time step is completely dependent on the current time step. This means that the unknown temperatures for the next time step do not have to be solved simultaneously.

If care is not taken when fully explicit methods are used, unstable results may be calculated. The stability criterion is shown in Equation 22:

$$E_{out} < \frac{\rho_2 \cdot c_{p2} \cdot \Delta x_2 \cdot \Delta y \cdot T_2}{\Delta t}$$ **Equation 22**

where E_{out}, ρ_2, c_{p2}, Δx_2, Δy, T_2, and Δt are as defined above. Equation 9 means that the amount of energy leaving the control volume has to be less than the amount of the energy stored in the control volume to give physically possible results. As seen in Equation 22, as the control volume decreases, the time step must also decrease. As a result, explicit finite difference methods can be computationally expensive.

3.1.3. Symmetry

The use of symmetry can significantly decrease the amount of computations needed. At a line of symmetry, the derivative of the temperature profile is zero. This implies that no heat is exchanged across the line of symmetry. The energy leaving and entering the face of the control volume on the line of symmetry is set equal to zero. The assumption of symmetry may lead to some inaccuracies when modeling boundary conditions, such as when one side of a concrete member is shaded and the other is not. If symmetry where not assumed, longer run times would occur and more complex program inputs (including inputs that may not be available to the engineer) would be required.

3.1.4. Concrete Thermal Properties

Because of the constantly changing early age properties of concrete, the concrete thermal properties must be updated at every time step. The thermal conductivity is known to be a function of "the moisture content, content and type of aggregate, porosity, density and temperature (Van Breugel, 1998)." The concrete thermal conductivity increases with increasing moisture content. There is conflict in the literature about the change in thermal conductivity with increasing hydration. Some suggest that the thermal conductivity increases with the degree of hydration, while others report that it decreases up to 30% (Van Breugel, 1998; Schindler, 2002). Based on the recommendation of Schindler (2002), ConcreteWorks assumes a linear decrease of the thermal conductivity with the degree of hydration from 1.33 times the ultimate thermal conductivity to the ultimate thermal conductivity as shown in Equation 23:

$$k_c(\alpha) = k_{uc} \cdot (1.33 - 0.33 \cdot \alpha)$$ **Equation 23**

where k_c is the concrete thermal conductivity (W/m/K), α is the degree of hydration, and k_{uc} is the ultimate hardened concrete thermal conductivity. The thermal conductivity of the concrete is not adjusted for moisture content in ConcreteWorks because the moisture content in mass concrete does not change significantly during early ages. The thermal conductivity is also not adjusted for temperature because of the differing responses of different aggregates.

The specific heat of concrete is also dependent on the mixture proportions, degree of hydration, temperature, and moisture level (Van Breugel, 1998; Schindler, 2002). A model proposed by Van Breugel accounts for changes in the specific heat based on degree of hydration, mixture proportions, and temperature as shown in Equation 24:

$$c_{pconc} = \frac{1}{\rho_{conc}} \cdot (W_c \cdot \alpha \cdot c_{cef} + W_c \cdot (1-\alpha) \cdot c_c + W_a \cdot c_a + W_w \cdot c_w) \qquad \textbf{Equation 24}$$

where c_{pconc} is the specific heat of the concrete (J/kg/K), ρ_{conc} is the concrete density (kg/m^3), W_c is the weight of cement (kg/m^3), W_a is the weight of aggregate (kg/m^3), W_w is the weight of water (kg/m^3), C_c is the cement specific heat (J/kg/K), C_a is the aggregate specific heat (J/kg/K), C_w is the water specific heat (J/kg/k), and C_{cef} is a fictitious specific heat of the hydrating cement as shown in Equation 25:

$$c_{ref} = 8.4 \cdot T_c + 339 \qquad \textbf{Equation 25}$$

where T_c is the concrete temperature (°C).

3.1.5. Concrete Heat of Hydration

The concrete heat of hydration parameters H_u, τ, β, α_u, and E_a can be calculated based on the concrete mixture proportions and constituent material properties. The τ, β, α_u parameters are calculated from a statistical analysis developed based on over 300 semi-adiabatic calorimetry tests performed according to recommendations from the RILEM technical committee 119 (1998) and validated by 18 tests conducted on concrete sampled from concrete construction sites and 44 tests conducted independently by Schindler and Folliard (2005) and Ge (2006). The dataset used includes concrete containing various chemical admixtures, cement fineness and chemical composition, and supplementary cementing materials on the heat of hydration. The apparent activation energy E_a can also be calculated based on the cementing material properties and the chemical admixtures used. A statistical analysis of 117 apparent activation energies calculated from isothermal calorimetry was developed by Poole (2007). The H_u parameter can also be calculated from the cement chemical composition using a model developed by Schindler and later altered to better characterize the influence of grade 120 ground granulated blast furnace slag by Poole (2007). The cement composition can be defined in ConcreteWorks using either the Rietveld method (Rietveld, 1969) determined from quantitative x-ray diffraction or the Bogue method calculated according to ASTM C 150 (2005). When the Rietveld method is used to determine the cement chemical composition, Equation 26–31 are used in ConcreteWorks to calculate the concrete heat of hydration parameters:

$$\alpha_u = \frac{1.031 \cdot w/cm}{0.194 + w/cm} + \exp\begin{pmatrix} -0.297 - 9.73 \cdot p_{Ferrite} \cdot p_{cem} \\ -325 \cdot p_{Na_2Oeq} \cdot p_{cem} \\ -8.90 \cdot p_{FA} \cdot p_{FA-CaO} \\ -331 \cdot WRRET - 93.8 \cdot PCHRWR \end{pmatrix} \qquad \textbf{Equation 26}$$

$$\tau = \exp\begin{pmatrix} 2.95 - 0.972 \cdot p_{Alite} \cdot p_{cem} + 152 \cdot p_{Na_2O} \cdot p_{cem} + 1.75 \cdot p_{GGBF} \\ -4.00 \cdot p_{FA} \cdot p_{FA-CaO} - 11.8 \cdot ACCL + 95.1 \cdot WRRET \end{pmatrix} \quad \textbf{Equation 27}$$

$$\beta = \exp\begin{pmatrix} -0.418 - 2.66 \cdot p_{Aluminate} \cdot p_{cem} - 0.864 \cdot p_{GGBF} \\ +108 \cdot WRRET + 32.0 \cdot LRWR + 13.3 \cdot MRWR \\ +42.5 \cdot PCHRWR + 11.0 \cdot NHRWR \end{pmatrix} \quad \textbf{Equation 28}$$

$$\begin{aligned} H_u &= H_{cem} \cdot p_{cem} + 461 \cdot p_{GGBF-100} + 550 \cdot p_{GGBF-120} \\ &+ 1800 \cdot p_{FA-CaO} \cdot p_{FA} + 330 \cdot p_{S.F.} \end{aligned} \quad \textbf{Equation 29}$$

$$\begin{aligned} H_{cem} &= 500 \cdot p_{Alite} + 260 \cdot p_{Belite} + 866 \cdot p_{Aluminate} + 420 \cdot p_{Ferrite} \\ &+ 624 \cdot p_{sulfate} + 1186 \cdot p_{Lime} + 850 \cdot p_{Periclase} \end{aligned} \quad \textbf{Equation 30}$$

$$\begin{aligned} E_a &= 39{,}200 + 107 \cdot \left[(P_{Aluminate}) \cdot p_{Cement} \cdot (P_{CaSO_4 \cdot xH_2O} + p_{Arcanite}) \cdot p_{Cement} \right] \\ &- 12.2 \cdot Blaine + 1.24 \cdot p_{FlyAsh} \cdot p_{CaO-FlyAsh} + 120 \cdot p_{GGBFS} - 533 \cdot p_{SF} \\ &- 30{,}100 \cdot WRRET - 1{,}440 \cdot ACCL \end{aligned} \quad \textbf{Equation 31}$$

where p_{alite} is the percent alite content in the Portland cement, p_{cem} is the percent portland cement of total cementing materials, p_{Na2Oeq} is the percent sodium equivalent alkalis in the portland cement, p_{Na2O} is the percent Na_2O in the Portland cement, $p_{Aluminate}$ is the percent aluminate in the Portland cement, p_{Belite} is the percent belite in the Portland cement, $p_{Ferrite}$ is the percent ferrite in the Portland cement, $p_{sulfate}$ is the percent total sulfate in the Portland cement, p_{Lime} is the percent Lime in Portland cement, $p_{Periclase}$ is the percent periclase in the Portland cement, $p_{CaSO4*xH2O}$ is the percent total Gypsum in the Portland cement, p_{FA} is the percent fly ash of the total cementing materials, $p_{FA\text{-}CaO}$ is the percent CaO content of the portland cement, p_{GGBFS} is the percent ground granulated blast furnace slag of the total cementing materials, p_{SF} is the percent silica fume of the total cementing materials, *WRRET* is the ASTM Type B & D water reducer/ retarder dose, *PCHRWR* is an ASTM Type F polycarboxylate based high range water reducer dose, *LRWR* is the ASTM Type A water reducer dose, MRWR is the mid-range water reducer dose, *NHRWR* is the Type F naphthalene high range water reducer dose, and *ACCL* is the ASTM type C accelerator. The chemical admixture dosages are in percent solids by weight of cementing materials.

When the Bogue method is used, however, ConcreteWorks uses Equation 32–37 to calculate the concrete heat of hydration parameters:

$$\alpha_u = \frac{1.031 \cdot w/cm}{0.194 + w/cm} + \exp\begin{pmatrix} -0.885 - 13.7 \cdot p_{C_4AF} \cdot p_{cem} \\ -283 \cdot p_{Na_2Oeq} \cdot p_{cem} \\ -9.90 \cdot p_{FA} \cdot p_{FA-CaO} \\ -339 \cdot WRRET - 95.4 \cdot PCHRWR \end{pmatrix} \quad \textbf{Equation 32}$$

$$\tau = \exp\begin{pmatrix} 2.68 - 0.386 \cdot p_{C_3S} \cdot p_{cem} + 105 \cdot p_{Na_2O} \cdot p_{cem} + 1.75 \cdot p_{GGBF} \\ -5.33 \cdot p_{FA} \cdot p_{FA-CaO} - 12.6 \cdot ACCL + 97.3 \cdot WRRET \end{pmatrix} \quad \textbf{Equation 33}$$

$$\beta = \exp\begin{pmatrix} -0.494 - 3.80 \cdot p_{C_3A} \cdot p_{cem} - 0.594 \cdot p_{GGBF} \\ +96.8 \cdot WRRET + 39.4 \cdot LRWR + 23.2 \cdot MRWR \\ +38.3 \cdot PCHRWR + 9.07 \cdot NHRWR \end{pmatrix}$$ **Equation 34**

$$H_u = H_{cem} \cdot p_{cem} + 461 \cdot p_{GGBF-100} + 550 \cdot p_{GGBF-120}$$
$$+1800 \cdot p_{FA-CaO} \cdot p_{FA} + 330 \cdot p_{S.F.}$$ **Equation 35**

$$H_{cem} = 500 \cdot p_{C_3S} + 260 \cdot p_{C_2S} + 866 \cdot p_{C_3A} + 420 \cdot p_{C_4AF}$$
$$+ 624 \cdot p_{SO_3} + 1186 \cdot p_{FreeCa} + 850 \cdot p_{MgO}$$ **Equation 36**

$$E_a = 41{,}230 + 8{,}330 \cdot \left[(C_3A + C_4AF) \cdot p_{Cement} \cdot Gypsum \cdot p_{Cement}\right]$$
$$- 3{,}470 \cdot Na_2O_{eq} - 19.8 \cdot Blaine$$
$$+ 2.96 \cdot p_{FlyAsh} \cdot p_{CaO-FlyAsh} + 162 \cdot p_{GGBFS} - 516 \cdot p_{SF}$$
$$- 30{,}900 \cdot WRRET - 1{,}450 \cdot ACCL$$ **Equation 37**

where p_{C3S} is the percent alite content in the Portland cement, p_{C3A} is the percent aluminate in the Portland cement, p_{C2S} is the percent belite in the Portland cement, p_{C4AF} is the percent ferrite in the Portland cement, p_{SO3} is the percent total sulfate in the Portland cement, p_{MgO} is the percent MgO in the Portland cement and p_{freeCa} is the percent CaO in the portland cement. To simplify the inputs needed, ConcreteWorks uses average assumed chemical admixture dosages as shown in Table 5:

Table 5 - Chemical admixture dosages assumed in ConcreteWorks

Chemical Admixture	Dose by Mass of Cementing Materials (%)
LRWR	0.0029
WRRET	0.0035
MRWR	0.0032
NHRWR	0.0078
PCHRWR	0.0068
ACCL	0.013

3.1.6. Boundary Conditions

In calculating the heat transfer of concrete members, the boundary conditions are usually the most difficult parameters to quantify. ConcreteWorks makes numerous assumptions about the heat sources and sinks that are external to the concrete, depending on the member type chosen. The heat sources and sinks modeled in ConcreteWorks may include irradiation from the member, radiation from the ground, radiation from the air, solar radiation, radiation from the formwork, convection to/from the member, evaporative cooling, conduction to the soil/subgrade, and exposure to water. The amount of each heat source or sink that is included in ConcreteWorks depends on the member type, shading effects, and other user inputs. More details on the assumptions made for each member type are discussed in Section 3.2.

Modeling each type of heat source or sink in ConcreteWorks requires numerous equations. Details about many of the boundary conditions equations used in ConcreteWorks, especially for vertical members may be found in the paper "Temperature Boundary Condition Models for Concrete Bridge Members" (Riding et al., 2007). The evaporative cooling model is from Schindler (2002). It combines models from the ASHRAE handbook (1993) and Al-Fadhala and Hover (2001) to predict the evaporation and consequently the cooling rate for concrete surfaces. The model is based on the work of Menzel that applied water evaporation rate equations developed by Koehler to concrete. The evaporation rate follows Dalton's law, which relates the water-vapor pressure of the air, at the water surface, and the wind speed (which helps speed up evaporation) to the evaporation rate (Hover, 2006). Menzel's equation is shown as Equation 38 (Al-Fadhala and Hover, 2001):

$$E_w = 0.315(e_0 - RH \cdot e_a)(0.253 + 0.060w) \qquad \textbf{Equation 38}$$

where E_w is the water evaporation rate (kg/m^2/hr), e_0 is the water surface saturated water vapor pressure (mmHg), e_a is the air water vapor pressure (mmHg), RH is the relative humidity (as a decimal), and w is the wind speed (m/s). The terms e_0 and e_a are dependent on the water surface and air temperatures. Concrete follows Dalton's law pretty well when bleed water is on the surface, and decreases rapidly during setting. The amount of evaporation from concrete may be related to the amount of evaporation from a water surface by Equation 39 (Al-Fadhala and Hover, 2001):

$$\frac{E_c}{E_w} = \exp\left[-\left[\frac{t}{a_{evap}}\right]^{1.5}\right] \qquad \textbf{Equation 39}$$

where Ec is the evaporation rate from concrete (kg/m^2/hr), t is the time from mixing (hrs), and a_{evap} is mixture dependent time constant (hrs). ConcreteWorks assumes that a_{evap} is equal to 3.75 hours. The evaporative cooling model is applied until either a cure method is applied or 24 hours after placing.

3.2. Concrete Member Models

Each type of concrete member modeled in ConcreteWorks has different formwork, boundary conditions, geometry, and opportunities to use symmetry. Different nodal arrangements are also required to keep nodes in a regular pattern and in line.

3.2.1. Rectangular Column

ConcreteWorks models a two-dimensional horizontal cross section for rectangular columns, as shown in Figure 3. The column heat transfer in the vertical direction is assumed to be zero, which is a reasonable assumption except near the top and bottom ends of the column. Rectangular columns are modeled using symmetry in both directions as shown in Figure 4. The formwork is handled by using half control volumes around the concrete, as shown in Figure 5. ConcreteWorks allows the user to select up to three construction stages to model for rectangular columns by selecting different formwork removal times and curing techniques.

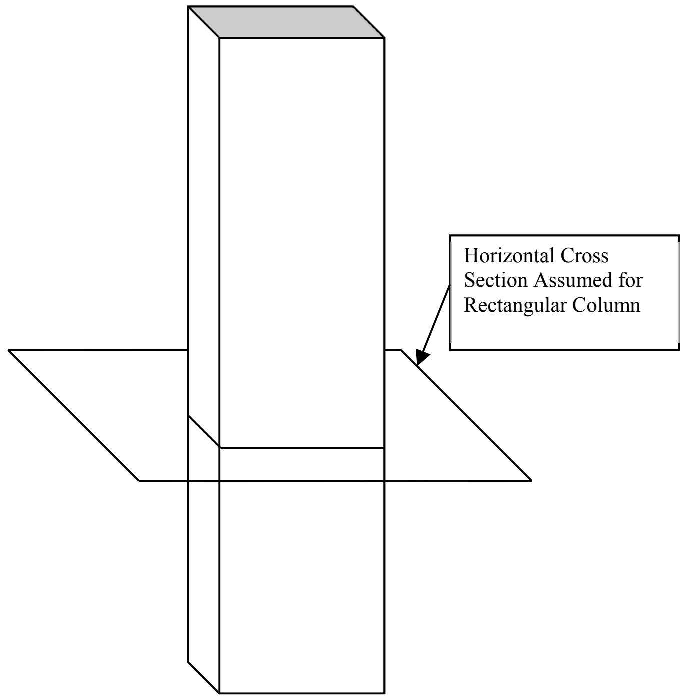


Figure 3 - Horizontal cross section of rectangular column assumed in ConcreteWorks

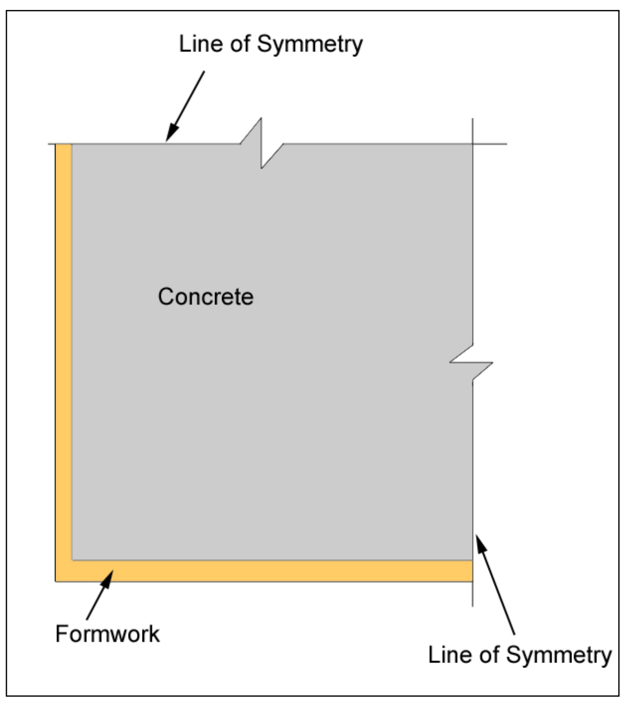


Figure 4 - Simplified rectangular column model used in ConcreteWorks

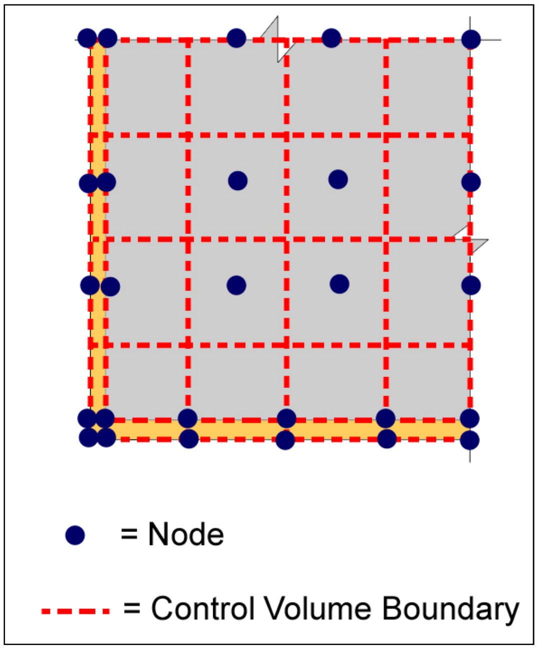


Figure 5 - Example rectangular column node and control volumes

The first construction stage is during concrete placement and curing before form removal. When steel formwork is selected and form-liners are not selected, ConcreteWorks assumes that the steel provides no insulation because of the "little resistance to heat dissipation from the concrete" (ACI 207.2, 1995). The steel emissivity, absorptivity, and shading values are then assigned to the concrete surface node, so that the surface of the column will still see the same heating from the environment. Eliminating the form control volumes for steel formwork greatly increases the runtime because of the small time step needed to maintain stability with such a thin control volume needed to model a steel form. When form-liners are used, ConcreteWorks calculates an equivalent form thermal conductivity, density, and specific heat for the selected combination of form and form-liner. The thermal conductivity, density, and specific heat of the equivalent form are calculated using Equation 40–42:

$$k_{ef} = \left[\frac{w_f}{k_f} + \frac{w_{fl}}{k_{fl}} \right]^{-1}$$ **Equation 40**

$$\rho_{ef} = \frac{\rho_f \cdot w_f + \rho_{fl} \cdot w_{fl}}{w_f + w_{fl}}$$ **Equation 41**

$$cp_{ef} = \frac{cp_f \cdot w_f + cp_{fl} \cdot w_{fl}}{cp_f + cp_{fl}}$$ **Equation 42**

where k_{ef} is the effective form thermal conductivity (W/m/K), w_f is the width of the form (m), w_{fl} is the width of the form-liner (m), k_f is the form thermal conductivity (W/m/K), k_{fl} is the form-liner thermal conductivity (W/m/K), ρ_{ef} is the effective form density (kg/m^3), ρ_f is the form density (kg/m^3), ρ_{fl} is the form-liner density (kg/m^3), cp_{ef} is the effective form specific heat (J/kg/K), cp_f is the form specific heat (J/kg/K), and cp_{ef} is the form-liner specific heat (J/kg/K). In ConcreteWorks, form-liners are assumed to have a thickness of 0.036 m (1.4 in), a thermal conductivity of 0.7437 W/m/°C, a specific heat of 1549.1 J/kg/K, and a density of 1121 kg/m^3.

The second construction stage modeled is after form-removal and before curing techniques such as plastic, cure blankets, or cure compounds are applied. An example of a structure during the beginning of the second construction stage is shown in Figure 6. The formwork is virtually removed in ConcreteWorks by eliminating the formwork control volume, and applying boundary conditions such as convection and radiation directly to the surface concrete control volumes. Concrete emissivity, absorptivity and surface roughness values are assigned at this point to the surface concrete control volumes.

Figure 6 - Rectangular column during form removal and the beginning of construction stage two

Construction stage three is during the time period of concrete curing using blankets, curing compounds, or plastic. When only curing compounds or only plastic are used, ConcreteWorks assigns the curing compound or plastic emissivity, absorptivity, and roughness values to the concrete surface control volumes. When curing compounds are used in conjunction with plastic or blankets, the effect of curing compounds is assumed to be negligible. When blankets are used but no plastic is used for curing, half control volumes (similar to those used for modeling the formwork) are applied to the exterior of the concrete control volumes. Blanket thermal and roughness properties are assigned to the exterior half control volumes. When plastic and blankets are used to cure the concrete, blanket insulation properties (thermal conductivity, specific heat, density, and thickness) are assigned to the exterior half control volumes while the plastic emissivity, absorptivity, and roughness values are used.

Blanket insulation properties are calculated from the blanket R-value entered by the user. The R-value is equivalent to the thickness divided by the thermal conductivity. ConcreteWorks assumes a blanket thickness of 0.02 m and then solves for the blanket thermal conductivity k_{bl} (W/m/K) as shown in Equation 43:

$$k_{bl} = \frac{0.02}{R_{bl}} \quad \textbf{Equation 43}$$

where R_{bl} is the blanket R-value (m^2K/W). The specific heat of the wet blanket is assumed to be 320 kg/m^3 while the specific heat is assumed to be 2000 J/kg/K.

3.2.2. Rectangular Footing

Footings have some unique features that require special cases for modeling. When footings are modeled in two dimensions, ConcreteWorks assumes a vertical cross section of the footing as shown in Figure 7 with no heat transfer perpendicular to the cross section. The heat exchange between the footing and the environment is dependent on the formwork, cure blankets and plastic used, soil conditions, weather, orientation of the footing, shading from scaffolding and embankments, and heat conduction from the concrete interior. Figure 8 summarizes the footing surface boundary conditions.

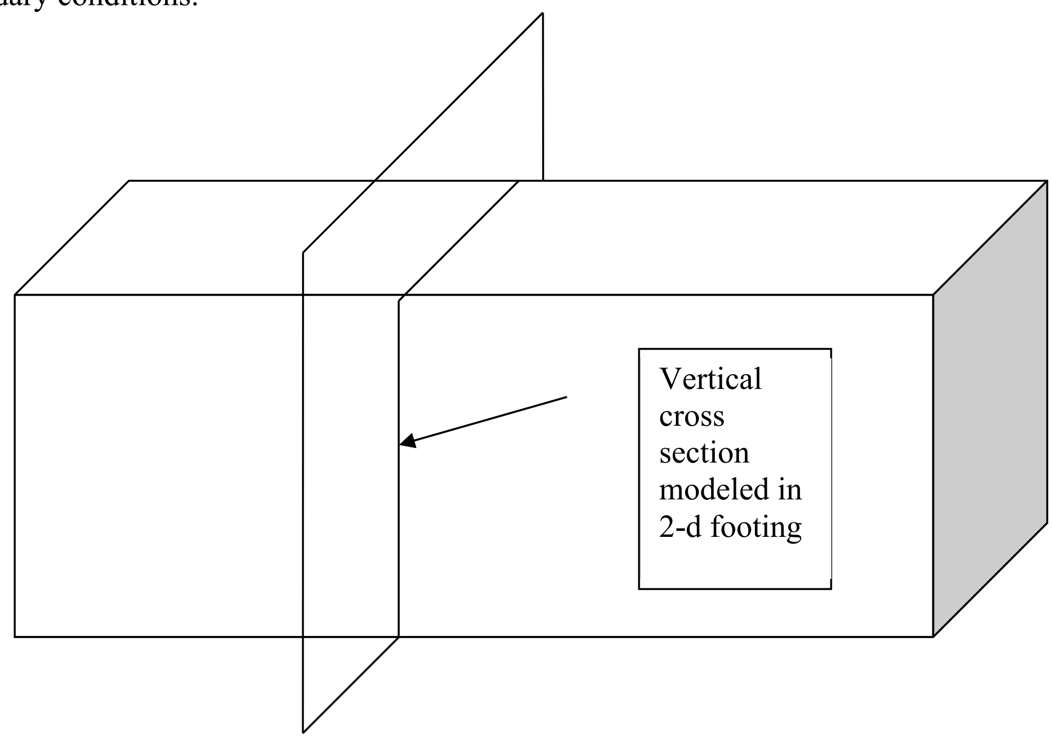


Figure 7 - Diagram of the vertical cross section assumed in modeling a two-dimensional footing

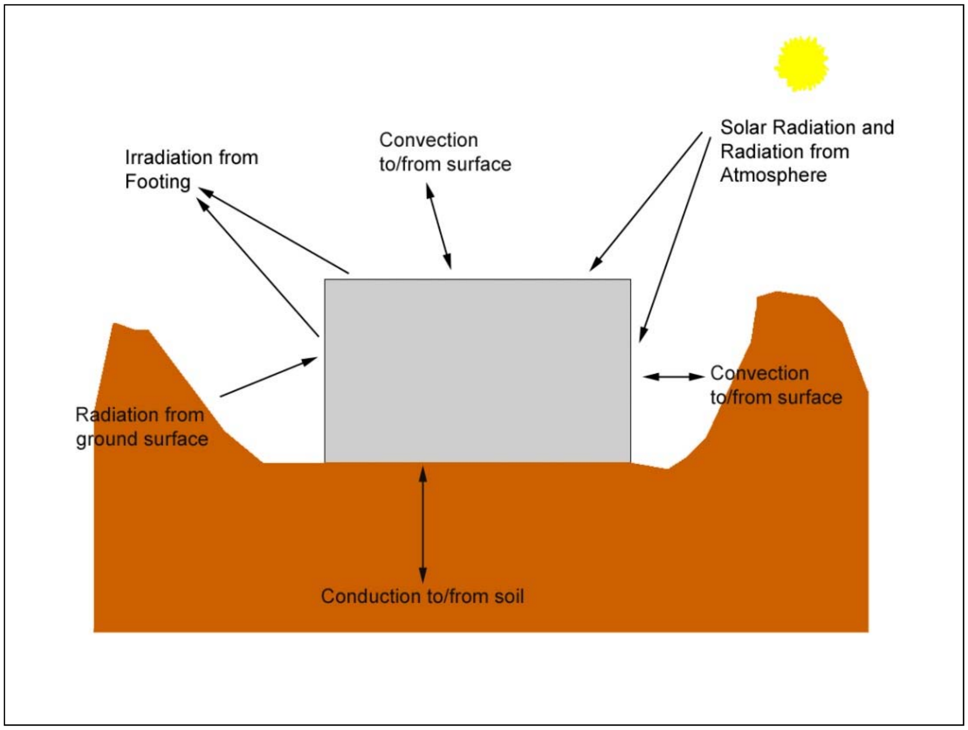


Figure 8 - Summary of rectangular footing boundary conditions

Radiation

Solar Radiation, atmospheric radiation, irradiation from the footing, and the radiation exchange between the vertical surface and form horizontal cross bracing models are used in the side and top boundary condition calculations. Radiation emitted by the ground surface is assumed to be incident on the side surface only. If the user chooses to shade the sides of the footing because of scaffolding or the embankment, then the solar radiation is set to zero.

Conduction to/from Soil

Conduction to/from the soil underneath the footing is modeled by assuming a constant depth of soil. The initial temperature of the soil is set to the user defined average soil temperature. The temperature at the bottom of the modeled soil is set also set to the user defined average soil temperature. Table 6 lists the thermal properties of the different soil and rock types modeled by ConcreteWorks. Figure 9 shows how the rectangular footing is modeled, and Figure 10 illustrates the node and control volume boundaries assumed. Symmetry is assumed in the model in the width and length (when calculated in three dimensions) direction as shown in the figure.

Table 6 - Footing subbase material thermal properties

Subbase Material	Density (kg/m3)	Thermal Conductivity (W/m/K)	Specific Heat (J/kg/K)	Reference
Clay	1460	1.3	880	Incropera and Dewitt, 2002
Granite	2630	2.79	775	
Limestone	2320	2.15	810	
Marble	2680	2.8	830	
Quartzite	2640	5.38	1105	
Sandstone	2150	2.9	745	
Sand	1515	0.27	800	
Top Soil	2050	0.52	1840	
Concrete	-	-	-	

Note: Concrete is assumed to have the same thermal properties of the concrete used on the footing, with a degree of hydration equal to 0.6. This option is only available with rectangular footings without soil on the sides.

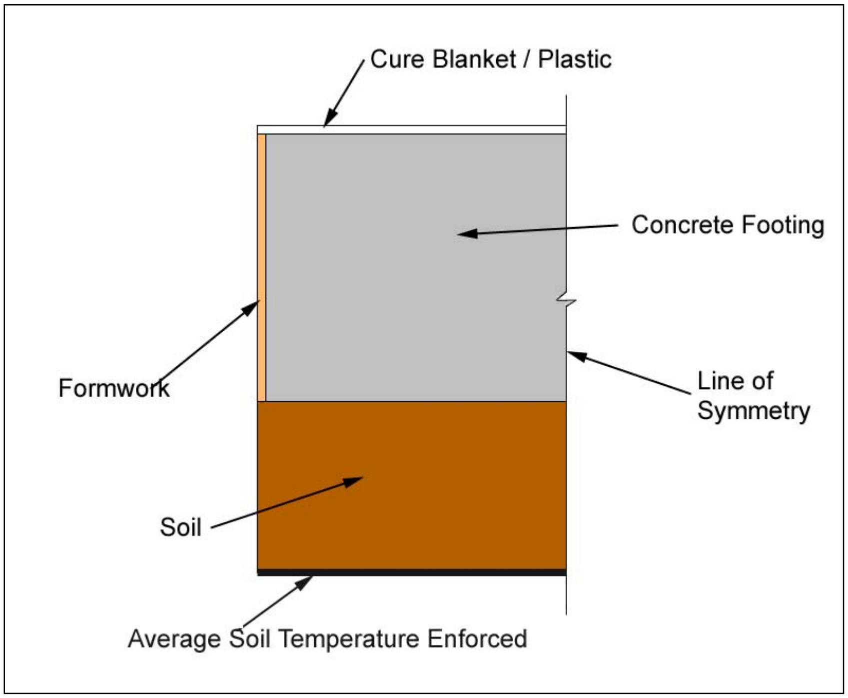


Figure 9 - Rectangular footing model

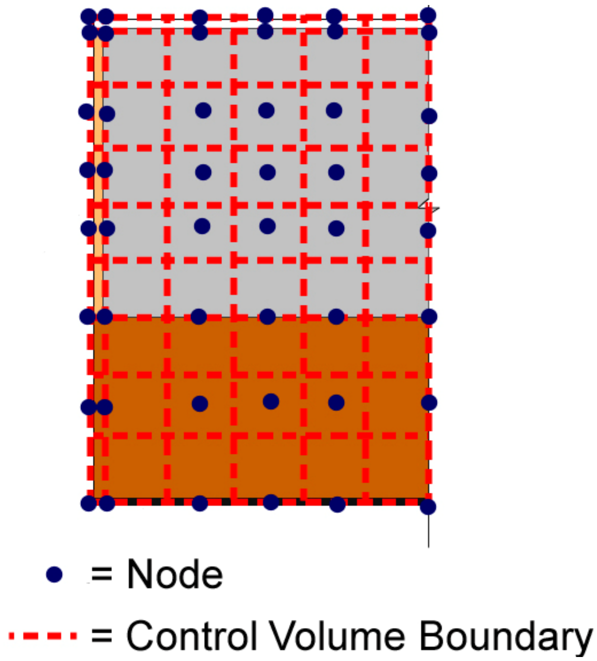


Figure 10 - Node layout for rectangular footing

Construction Stages

Rectangular footings can modeled with up to four potential construction stages. The first stage is before the blanket or any cure method is applied to the top surface. The second stage is when the cure method is applied to the top surface. ConcreteWorks assumes that a cure blanket is placed on the top surface when the cure method is applied. Any other cure methods such as plastic will also be placed and will affect the absorptivity and emissivity of the top cure surface. The third stage is after form and cure method removal. The fourth construction stage represents the time period when a cure method on the top and sides is used after the forms and initial top surface curing methods are removed. If a cure blanket is selected for this stage, it is applied uniformly over the top and side surfaces.

3.2.3. Rectangular Footing with Soil on the Sides

ConcreteWorks contains an option for soil to be used as the formwork, as shown in Figure 11. Symmetry is assumed in the middle of the member as shown. Conduction to/from the soil on the sides is treated in a similar manner to the soil underneath the footing. A constant thickness of soil is modeled on the sides of the footing. The average soil temperature is enforced on the sides at the edge of the soil, as shown in Figure 12. The node and control volume layout for the rectangular footing with soil on the sides is shown in Figure 13.

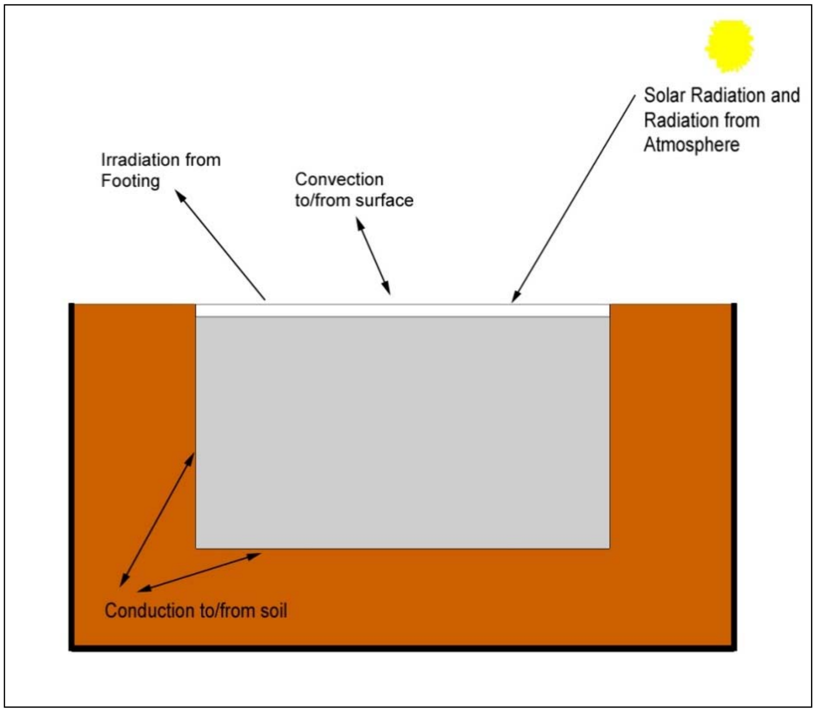


Figure 11 - Summary of rectangular footing with soil on the sides

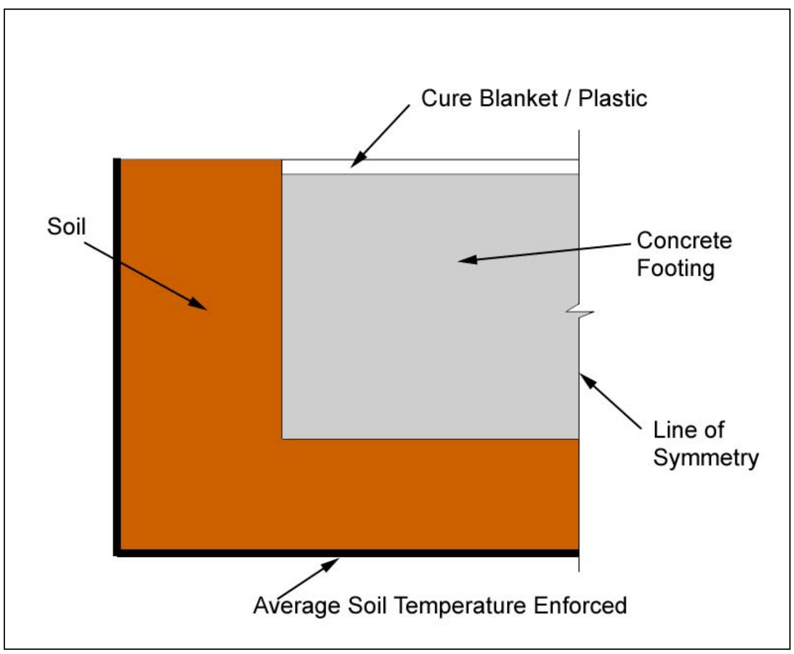


Figure 12 - Rectangular footing with "soil on sides" model

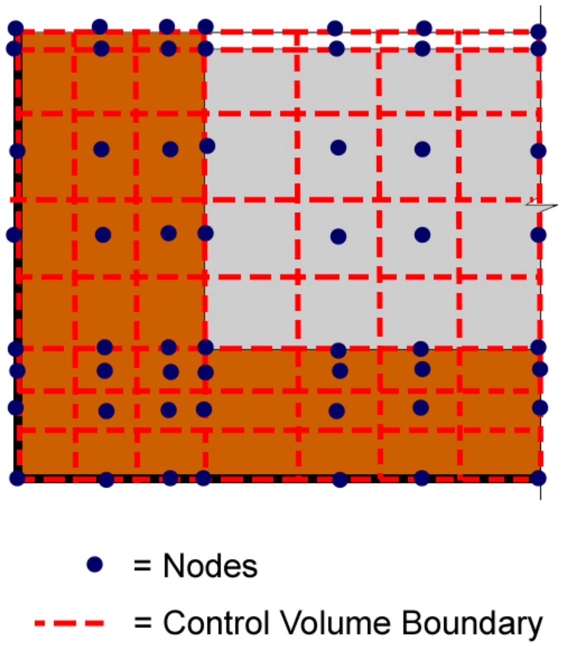


Figure 13 - Node and control volume layout for rectangular footing with soil on the sides

Construction Stages

Rectangular footings surrounded by soil can contain up to two construction stages. The first is before any cure methods are placed on the top surface. The second is after cure methods are placed on the top surface. It is assumed that a cure blanket is used in addition to any other cure methods applied.

3.2.4. Bent Caps

The heat transfer at the exterior of the bent caps is handled using many of the same equations as that of the other concrete members. There are a few types of bent caps, each with unique boundary conditions. Symmetry is assumed in all bent cap members.

Rectangular Bent Cap

Figure 14 shows the vertical cross section assumed in the two-dimensional heat transfer analysis performed for rectangular bent caps. Figure 15 summarizes how ConcreteWorks models radiation for a rectangular bent cap. Solar radiation is assumed to be incident on the top and side surfaces only. Radiation from the ground surface is assumed to be incident on the bottom and side surfaces only. Radiation from the atmosphere is assumed to be incident on all surfaces of the rectangular bent cap. ConcreteWorks assumes that the rectangular bent cap emits radiation from all surfaces. ConcreteWorks assumes that the wind creates convection on all of the rectangular bent cap surfaces, as shown in Figure 16. ConcreteWorks allows the user to select different types of bottom and side formwork, as shown in Figure 17. A summary of the node and control volume layout for rectangular bent caps is shown in Figure 18.

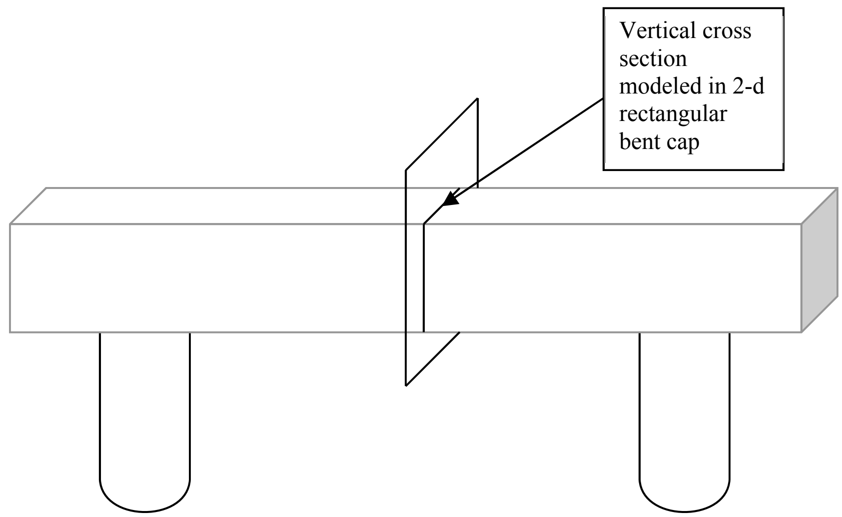


Figure 14 - Diagram of the vertical cross section modeled in a rectangular bent cap

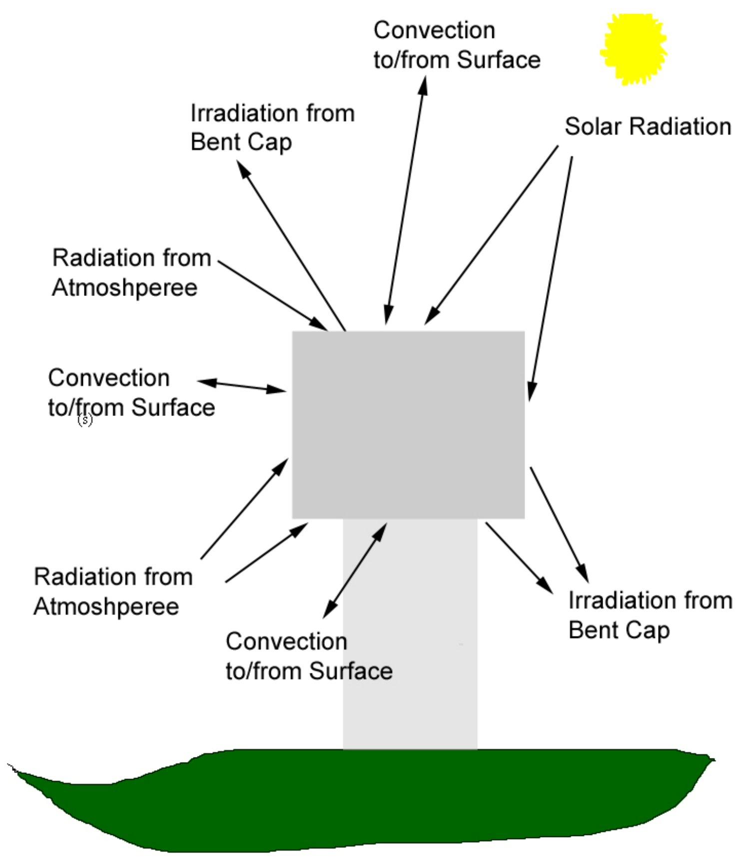


Figure 15 - Rectangular bent cap radiation summary

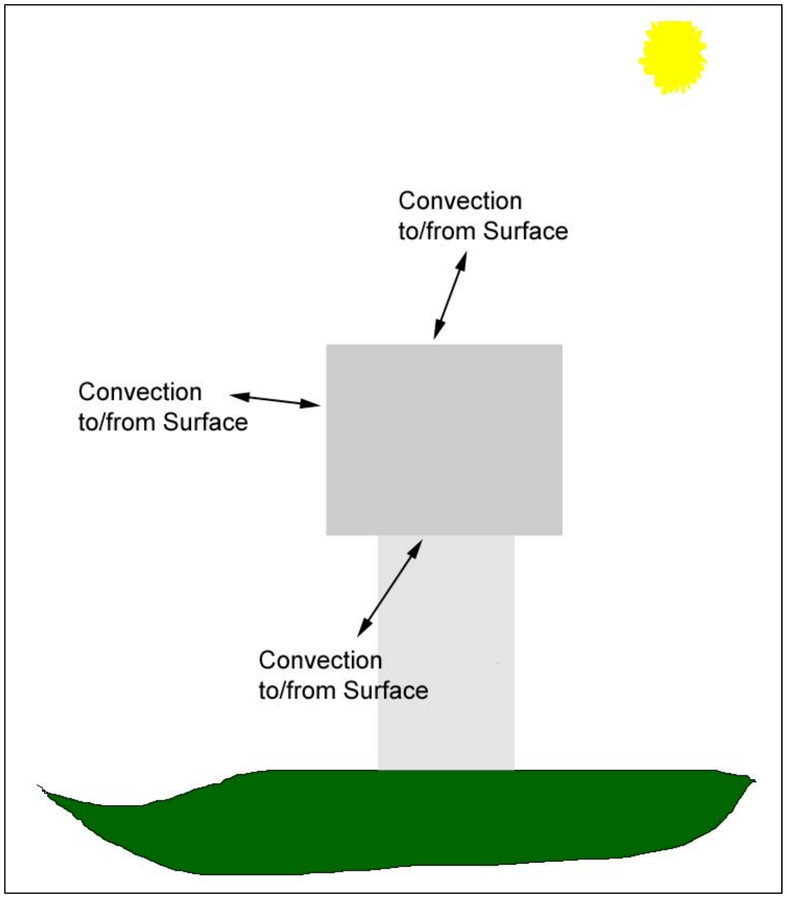


Figure 16 - Rectangular bent cap convection summary

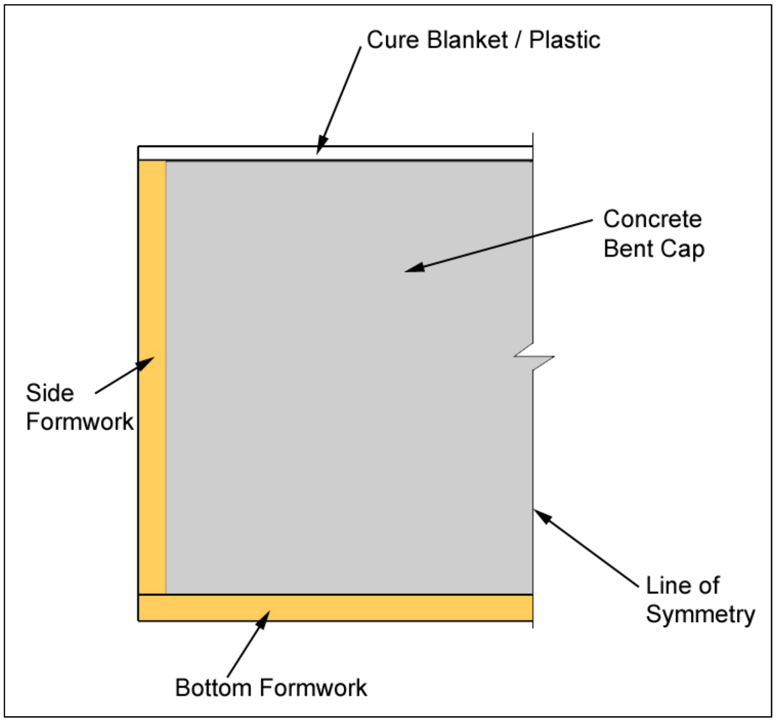


Figure 17 - Summary of rectangular bent cap

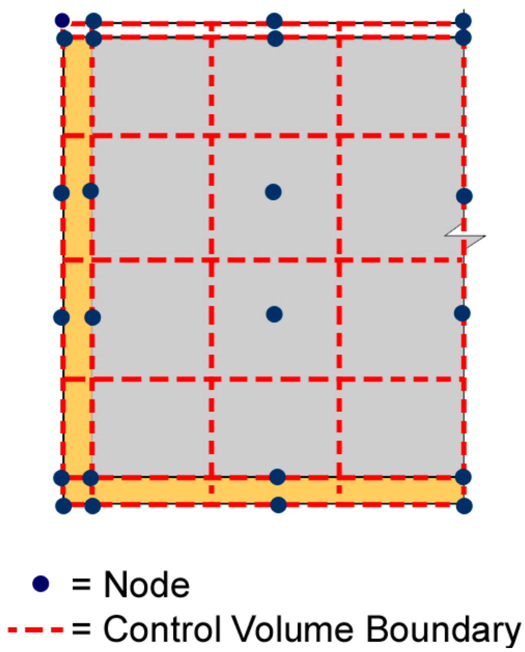


Figure 18 - Node and control volume layout of rectangular bent cap

Construction Stages

Rectangular bent caps have a total of four possible construction stages. The first stage is before a curing blanket is placed on the bent cap top surface. The second stage is after the curing blanket is placed on the top surface and before the formwork is removed. The third possible construction stage is after the formwork and curing blanket is removed. The last possible construction stage is after a curing blanket is wrapped around the bent cap.

Dolphin

ConcreteWorks allows the user to select pre-cast concrete as the bottom formwork material. Pre-cast concrete is assumed to have the same material thermal properties as the concrete mixture used for the bent cap with a degree of hydration equal to 0.6. When the user inputs that the bent cap is a dolphin, the temperature of the bottom of the bent cap is set equal to the average water temperature. Figure 19 shows a summary of a dolphin with a pre-cast concrete bottom.

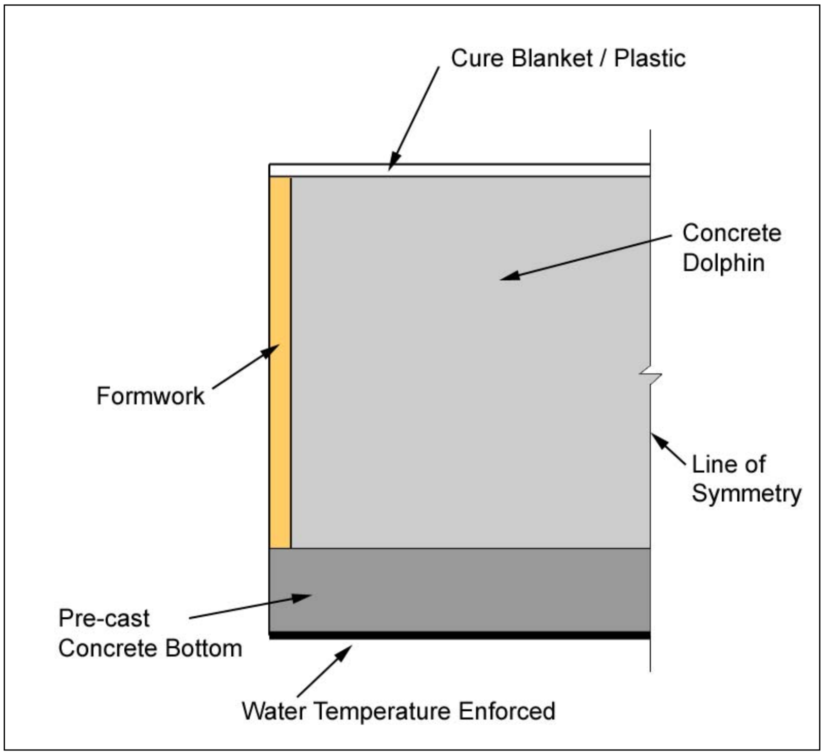


Figure 19 - Summary of dolphin with pre-cast concrete bottom

3.2.5. T-Shaped Bent Cap

The T-shaped bent cap modeled in ConcreteWorks assumes the same type of vertical cross section as the rectangular bent cap. Figure 20 shows a summary of how ConcreteWorks models radiation boundary conditions in T-shaped bent caps. Radiation from the ground surface is assumed to be incident on the cap bottom and sides. Solar Radiation is assumed to be incident on all the top of the cap, the top of the corbel, and the sides. Radiation from the atmosphere is assumed to be incident on all sides. The cap is assumed to emit radiation from all surfaces. ConcreteWorks assumes that the wind creates convection on all of the T-shaped bent cap surfaces, as shown in Figure 21. ConcreteWorks allows the user to select different types of bottom and side formwork, as shown in Figure 22. The node and control volume layout for the T-shaped bent cap is shown in Figure 23.

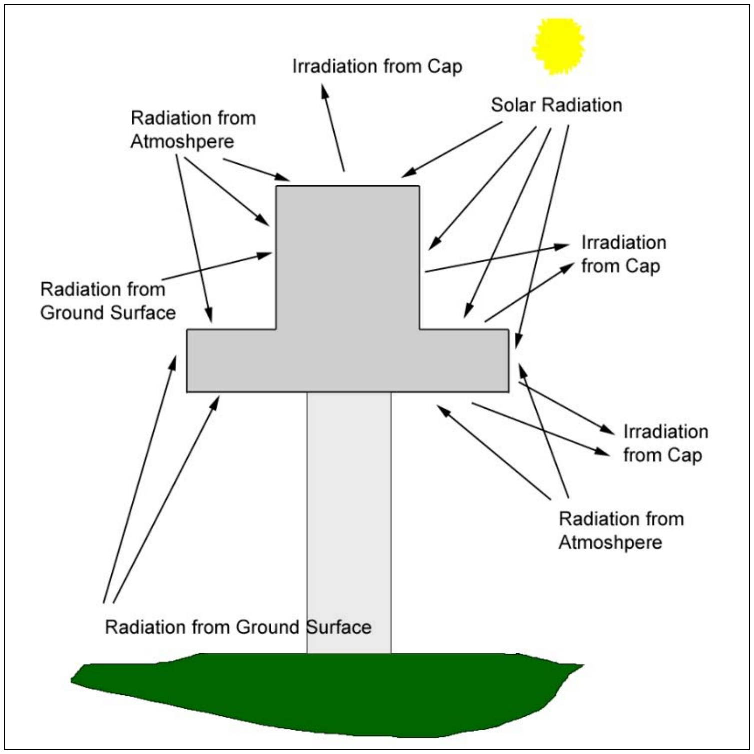


Figure 20 - Summary of radiation boundary conditions for T-shaped bent caps

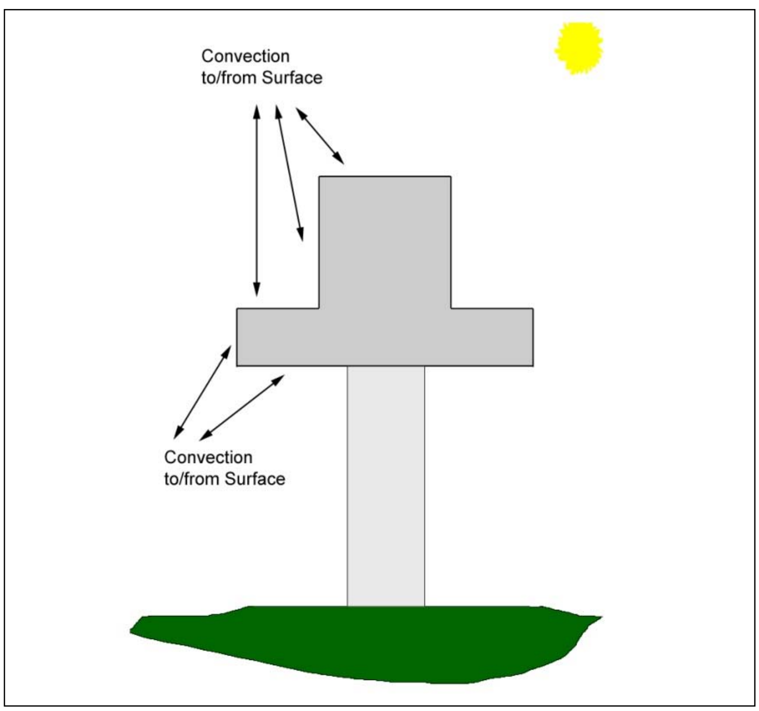


Figure 21 - Summary of convection boundary conditions on T-shaped bent cap

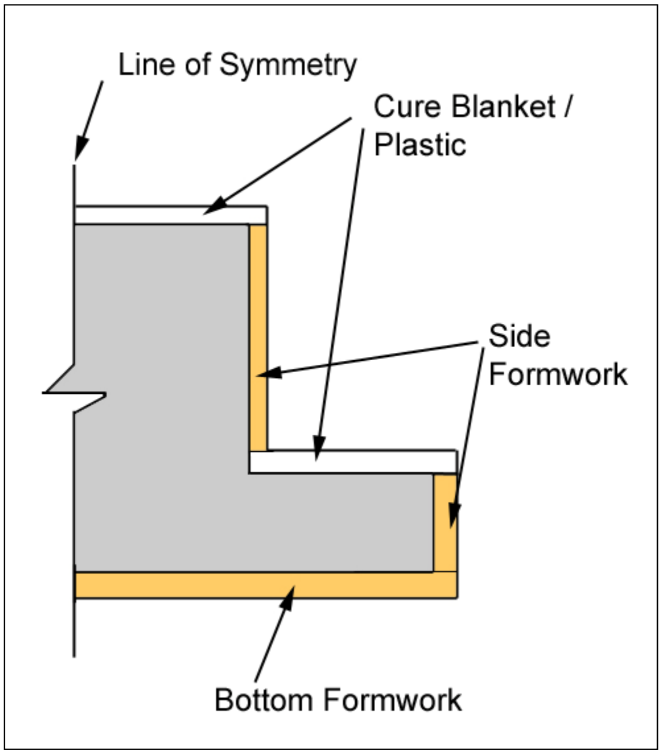


Figure 22 - Construction summary form T-shaped bent cap

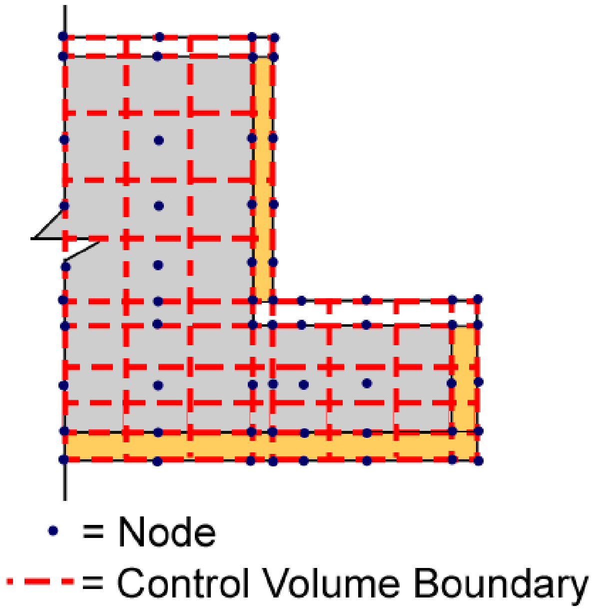


Figure 23 - Node and control volume layout for T-shaped bent caps

Construction Stages

T-shaped bent caps use the same construction stages as rectangular bent caps.

3.2.6. Circular Columns

ConcreteWorks models a horizontal cross section of the circular column, just like that of a rectangular column. The boundary conditions for both rectangular and circular columns are handled in a similar manner. Circular columns are modeled in ConcreteWorks using the same radiation and convection boundary conditions as rectangular columns. Figure 24 shows a summary of the construction model used for a circular column in ConcreteWorks. Symmetry is assumed in the circumferential direction. Figure 25 shows the node and control volume layout for a circular column. Figure 26 shows the boundary conditions modeled for circular columns. ConcreteWorks applies convection on the outer surface of the model of the circular column. Radiation from ground surfaces, atmospheric radiation, solar radiation, and irradiation are also modeled on the outer surface of the column.

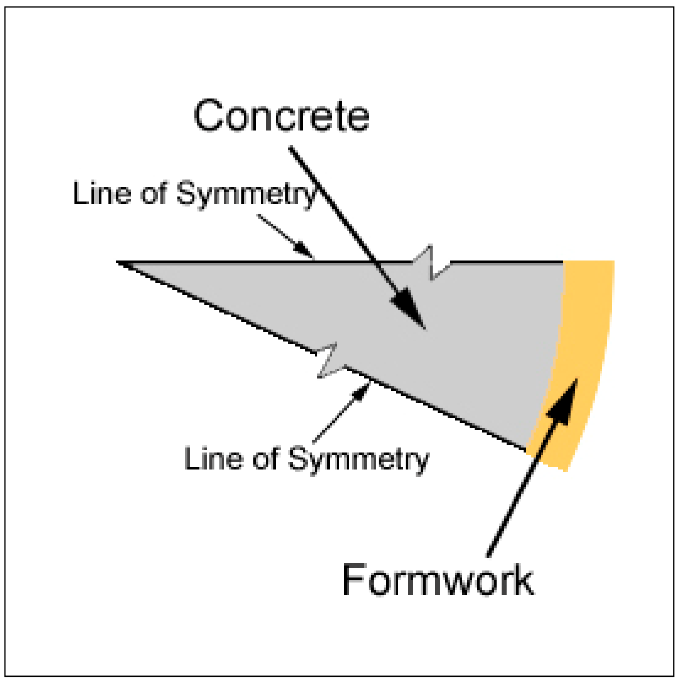


Figure 24 - Circular column model

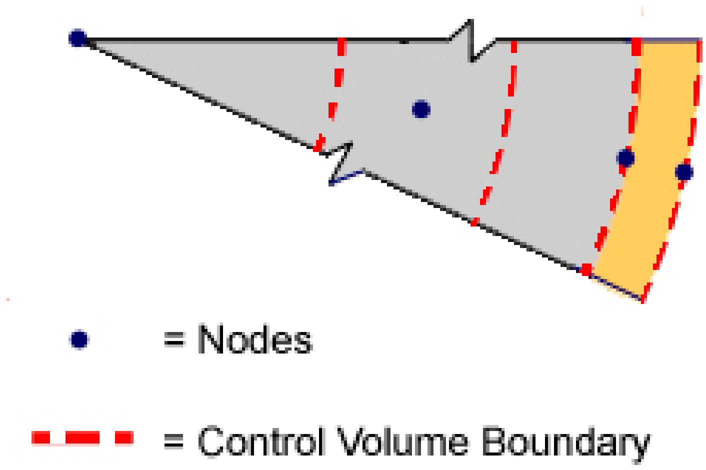


Figure 25 - Node and control volume layout for circular columns

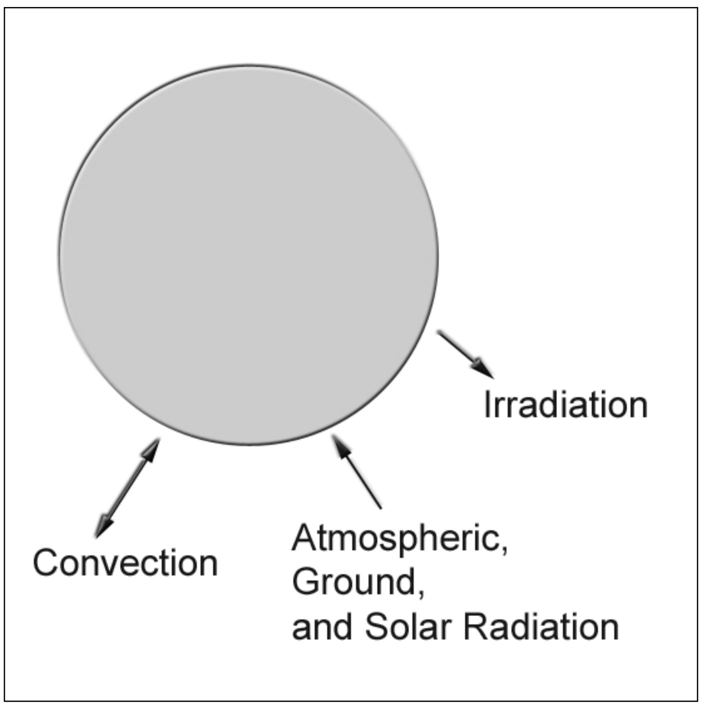


Figure 26 - Circular column boundary conditions

Construction Stages

Circular columns use the same construction stages as rectangular columns.

3.2.7. Bridge Decks

The fundamental heat transfer calculations performed for all four types of bridge decks modeled in ConcreteWorks are the same. Figure 27 shows the basic layout of the bridge deck modeled. In the case of a bridge deck with a precast panel, no bottom form is modeled. The precast panel thermal conductivity and specific heat properties are calculated using Equation 23 and Equation 24, with a degree of hydration equal to 0.6. The precast panel is assumed to generate no heat. The bottom formwork is also not modeled when a galvanized panel is used. The calculations are performed assuming one-dimensional heat transfer, and control volumes as shown in Figure 28. The portion modeled is assumed to be open underneath the bottom form (i.e. not directly over a beam). Figure 29 shows the bridge deck temperature boundary conditions modeled in ConcreteWorks.

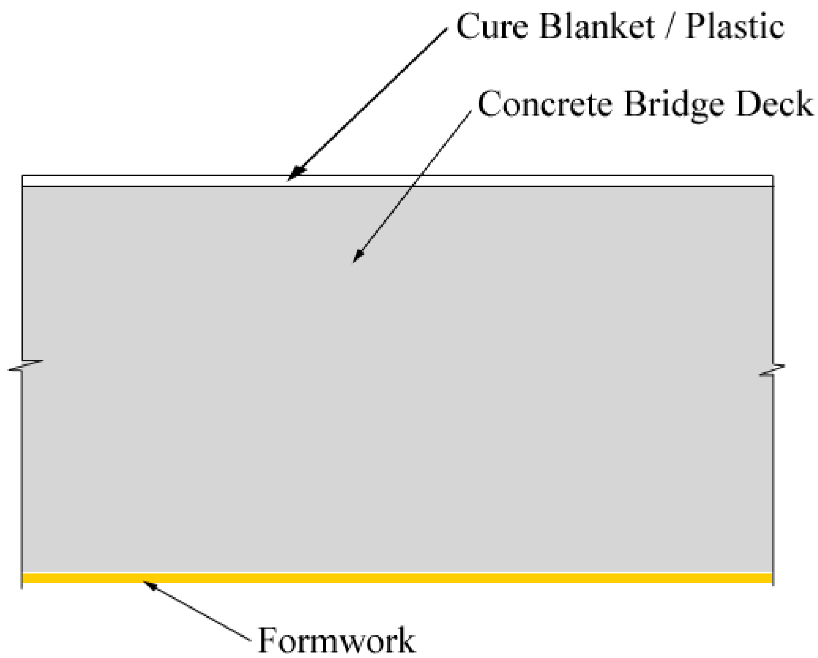


Figure 27 - Bridge deck layout

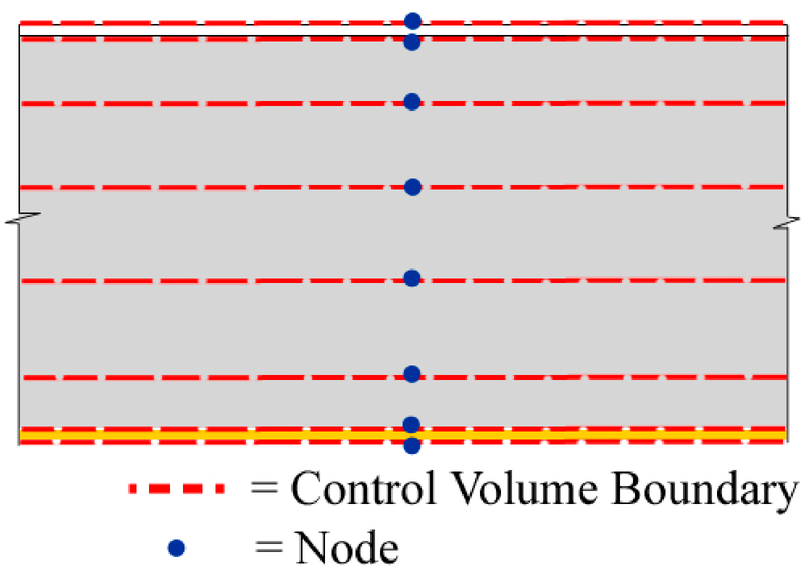


Figure 28 - Bridge deck node and control volume layout

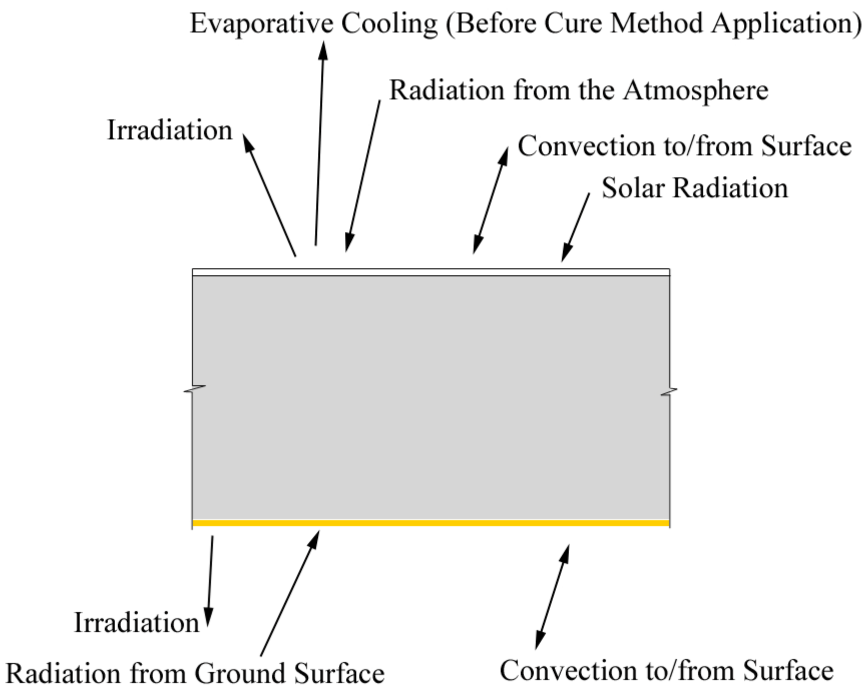


Figure 29 - Bridge deck temperature boundary conditions

Construction Stages

Bridge decks have up to four possible construction stages. The first is before the cure method is applied to the top surface. A cure blanket is assumed to be used along with any additional curing methods selected by the user. The second stage is after the cure blanket is placed on the top surface, but before form removal and cure method removal. There are two possible final construction stages. An optional third construction stage is when the formwork remains on, but the cure method is removed from the top surface. The fourth construction stage in this option is when the form has been removed following the blanket removal. In the second option, the third construction stage is when the formwork is removed before the cure method is removed from top. Option two's fourth construction stage is when the cure method is removed after the bottom formwork removal.

3.2.8. Precast Rectangular and U-Shaped Beams

Precast rectangular and U-shaped beams are handled in the same way in ConcreteWorks. Only the dimensions and number of nodes are changed, depending on which member is selected. ConcreteWorks only models a vertical cross section of the solid beam end block, as shown in Figure 30. Only the end block is modeled to greatly simplify the analysis, and to capture the maximum temperature in the beam, which occurs in the solid end region. Figure 31 shows how the end region concrete, formwork, and soil underneath are modeled in ConcreteWorks. Figure 32 shows the node and control volume layout for the rectangular and U-shaped precast beams.

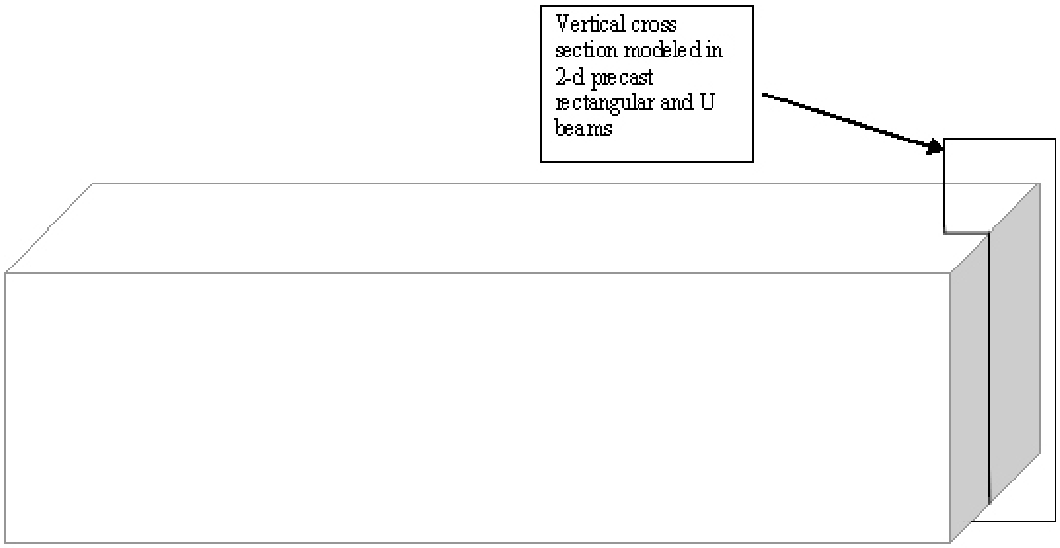


Figure 30 - Modeled region of rectangular and U-shaped beams

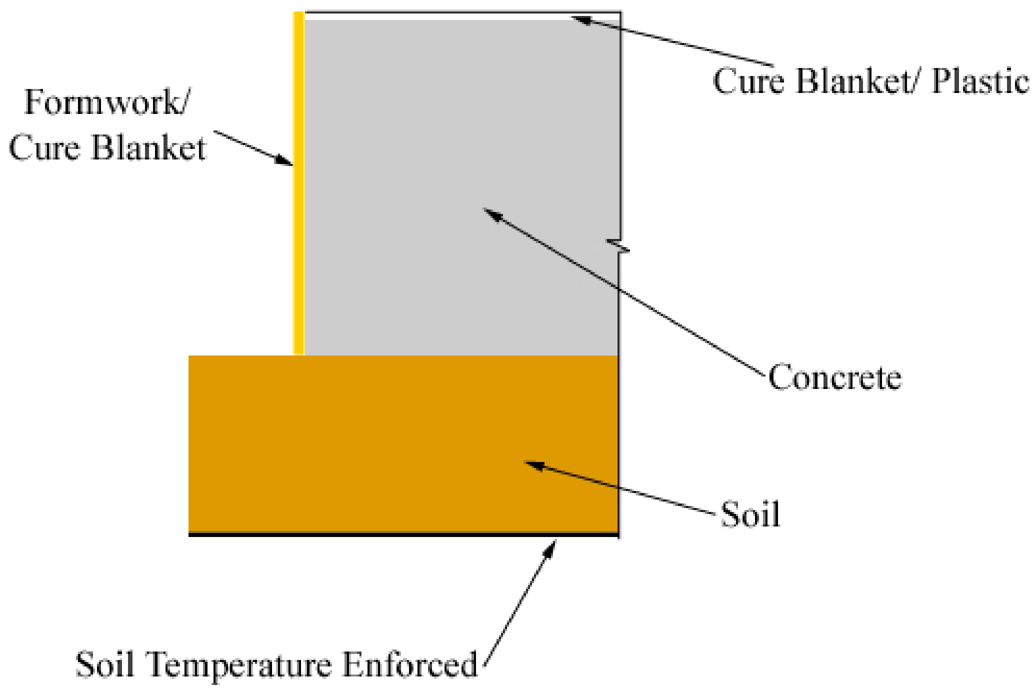


Figure 31 - ConcreteWorks *simplified model for rectangular and U-shaped beams*

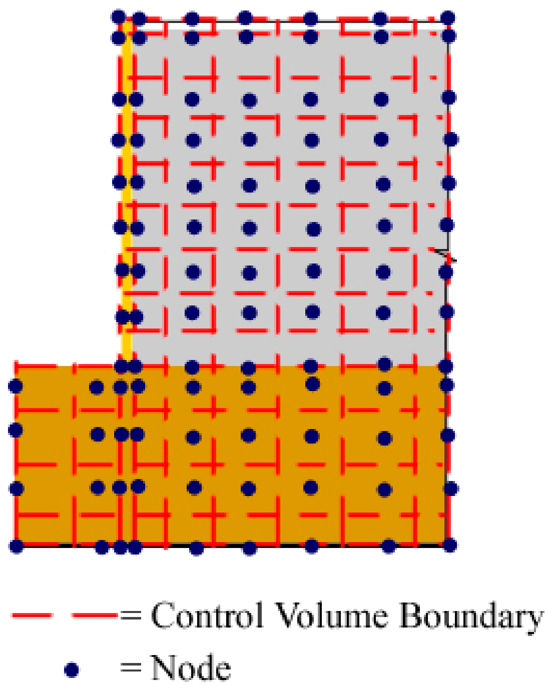


Figure 32 - Rectangular and U-shaped beam node and control volume layout

Boundary Conditions

The rectangular and U-shaped beam model uses the same boundary conditions as the rectangular footing, except that a portion of the soil to the side of the beam is modeled. The soil surface to the side of the beam is modeled using irradiation, solar radiation, and convection.

Construction Stages

The rectangular and U-shaped beam model can have up to four construction stages. The first is before the cure methods are applied. The second is after the cure methods are applied. It is assumed that a cure blanket is placed on top of the precast beam at this stage along with any other selected cure methods. The third stage occurs after the cure method and formwork is removed. The fourth possible stage accounts for any further cure method application.

3.2.9. Precast Type IV Beams

The precast type IV beam model in ConcreteWorks models a vertical cross section through the middle of the beam. The model assumptions are shown in Figure 33. The type IV beam node and control volume boundaries assumed in the model are shown in Figure 34.

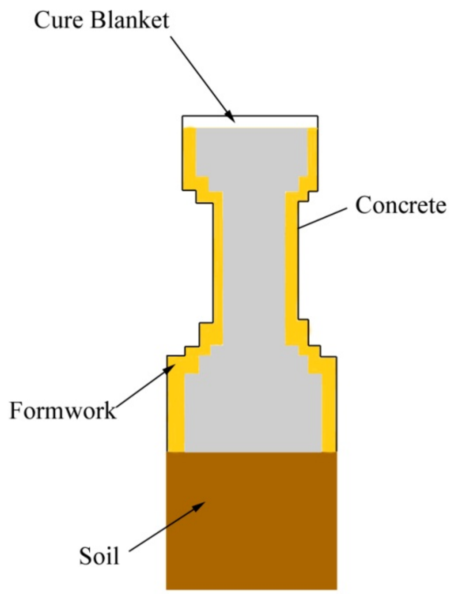


Figure 33 - Precast type IV beam model assumed in ConcreteWorks

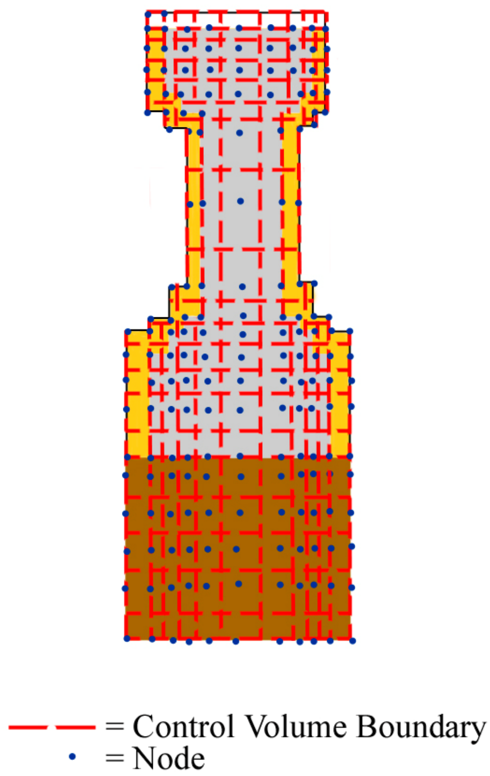


Figure 34 - Precast type IV beam node and control volume boundary layout

Boundary Conditions

The precast type IV beam top and side boundary conditions include solar radiation, irradiation, radiation from the air, and convection. In addition to conduction from the bottom of the member to the soil, convection is also allowed to occur because of a small gap of air that exists between the member bottom form and the ground underneath. Because the gap is not sealed, convection may occur resulting in cooling.

Construction Stages

The precast type IV beam utilizes the same construction stages as the rectangular precast beam.

3.2.10. Pavements

Pavements are modeled assuming one-dimensional heat transfer in the vertical direction. Figure 35 shows the pavement layers modeled in ConcreteWorks. The thermal conductivities, specific heat, and density values used for the pavement subgrade depends on the user inputs, according to Table 6.

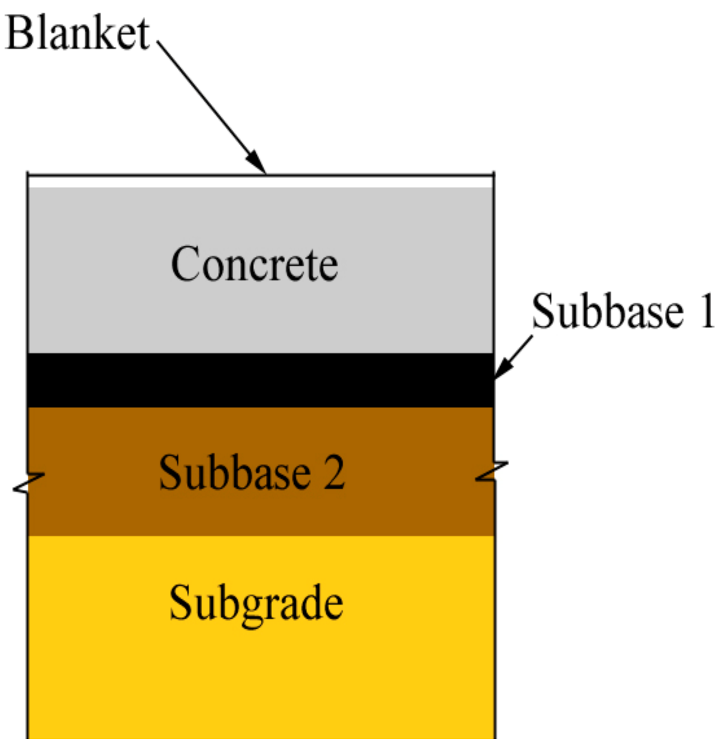


Figure 35 - Pavement layers modeled

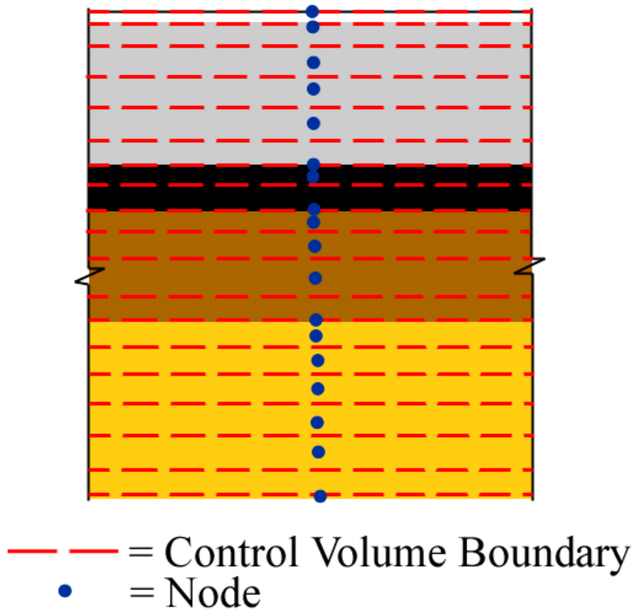


Figure 36 - Pavement node and control volume boundary layout

Boundary Conditions

The top surface of the pavement is exposed to the same boundary conditions as the bridge deck top surface. The pavement may be cured with a monomolecular compound, a single coat of curing compound, a double coat of curing compound, a clear or black plastic sheet, or a cure blanket. If a monomolecular compound or a curing compound is used, then the user may enter the concrete color after the cure method application. The cure method color will change the concrete surface emissivity and absorptivity. Darker colors (like black and dark gray) have higher solar absorptivity and emissivity values than lighter colors (like white or light gray).

The pavement layered system provides conduction to the supporting subbase layers and to the subgrade. ConcreteWorks models 49.2 ft (15 meter) of subbase. The temperature of the bottom of the subbase is modeled using the deep ground water temperature calculated using Equation 44 (Yoshitake, Nagai, Tanimoto, and Hamada 2002):

$$T_{gw} = 0.83 \cdot T_{aat} + 3.7$$ **Equation 44**

where T_{gw} is the deep ground water temperature (°C), and T_{aat} is the average annual temperature (°C). The average annual temperature in ConcreteWorks is calculated from the weather data entered for the city selected. The soil about 0.6 m below the ground surface remains at a fairly constant temperature throughout the year (Yoshitake, Nagai, Tanimoto, and Hamada 2002).

The initial subbgrade and subbase temperature profile used in the analysis is then calculated using the Barber model. The Barber model can estimate the subbase and subgrade temperature profile based on the weather data selected in ConcreteWorks, as shown in Equation 45–51 (Barber 1957, Schindler 2002):

$$T(z) = T_M + T_V \cdot \left(\frac{H \cdot \exp(-z \cdot C)}{\sqrt{(H+C)^2 + C^2}} \right) \cdot \sin\left(0.262 \cdot t - z \cdot C - \arctan\frac{C}{H+C} \right)$$ **Equation 45**

$$T_M = 0.5 \cdot T_A + (0.0498 \cdot \mathrm{L}) \text{ for } T \geq T_A$$ **Equation 46**

$$T_m = 0.5 \cdot T_A + 0.278 \cdot (0.0498 \cdot \mathrm{L}) \text{ for } T < T_A$$

$$T_V = 0.5 \cdot T_R + 1.67 \cdot (0.0498 \cdot \mathrm{L}) \text{ for } T \geq T_A$$ **Equation 47**

$$T_V = 0.5 \cdot T_R \quad \text{for } T < T_A$$

$$H = \left(\frac{4.1 + 1.13 \cdot w^{0.75}}{k} \right)$$ **Equation 48**

$$C = \left(\frac{k}{c_p \cdot \rho} \right)$$ **Equation 49**

where $T(z)$ is the soil temperature (°C) at depth z (m), T_M is the mean effective air temperature (°C) as calculated in Equation 46, T_A is the mean air temperature (°C), L is the solar radiation (W/m^2), T_V is the maximum variation in temperature from the mean (°C) calculated using Equation 47, T_R is the maximum daily temperature minus the minimum daily temperature (°C), H is calculated using Equation 48, w is the wind speed (m/s), k is the soil thermal conductivity (W/m^2), C is the soil thermal diffusivity calculated using Equation 49 (m^2/s), c_p is the soil specific heat (J/kg/°C), ρ is the soil density (kg/m^3), and t is the time from the beginning of the temperature cycle (hours). The finite difference model excluding the concrete is then run from midnight of the placement date to the placement time to further improve the initial soil temperature profile. The thermal conductivity, specific heat, density, solar absorptivity, and emissivity values assumed for different subbase materials is shown in Table 7:

Table 7 - Pavement subbase material properties

Material	Thermal Conductivity (W/m^2)	Specific Heat (J/kg/°C)	Density (kg/m^3)	Solar Absorptivity	Emissivity
Asphalt Concrete	1.38	1047	2302	0.93	0.93
Cement Stabilized Base	0.985	985	2101	0.65	0.9
Asphalt Stabilized Base	0.865	1025	2002	0.9	0.9
Granular Base	1.59	1214	2066	0.8	0.9
Existing Concrete	2.7	921	2403	0.55	0.92

Construction Stages

The pavement temperature analysis module contains three possible construction stages: before the cure method is applied, after the cure method is applied, and after the cure method is removed. If a monomolecular compound or a curing compound is chosen, then it is assumed to stay on during the length of the analysis.

4. Thermal Stress Analysis

4.1. Overview

Thermal stress modeling in concrete members is non-linear because of changing early age material properties (E modulus, strength, Poisson's ratio, and coefficient of thermal expansion), differential temperature development, and creep. Figure 37 shows how the non-linear concrete property and restrained stress development is calculated in ConcreteWorks.

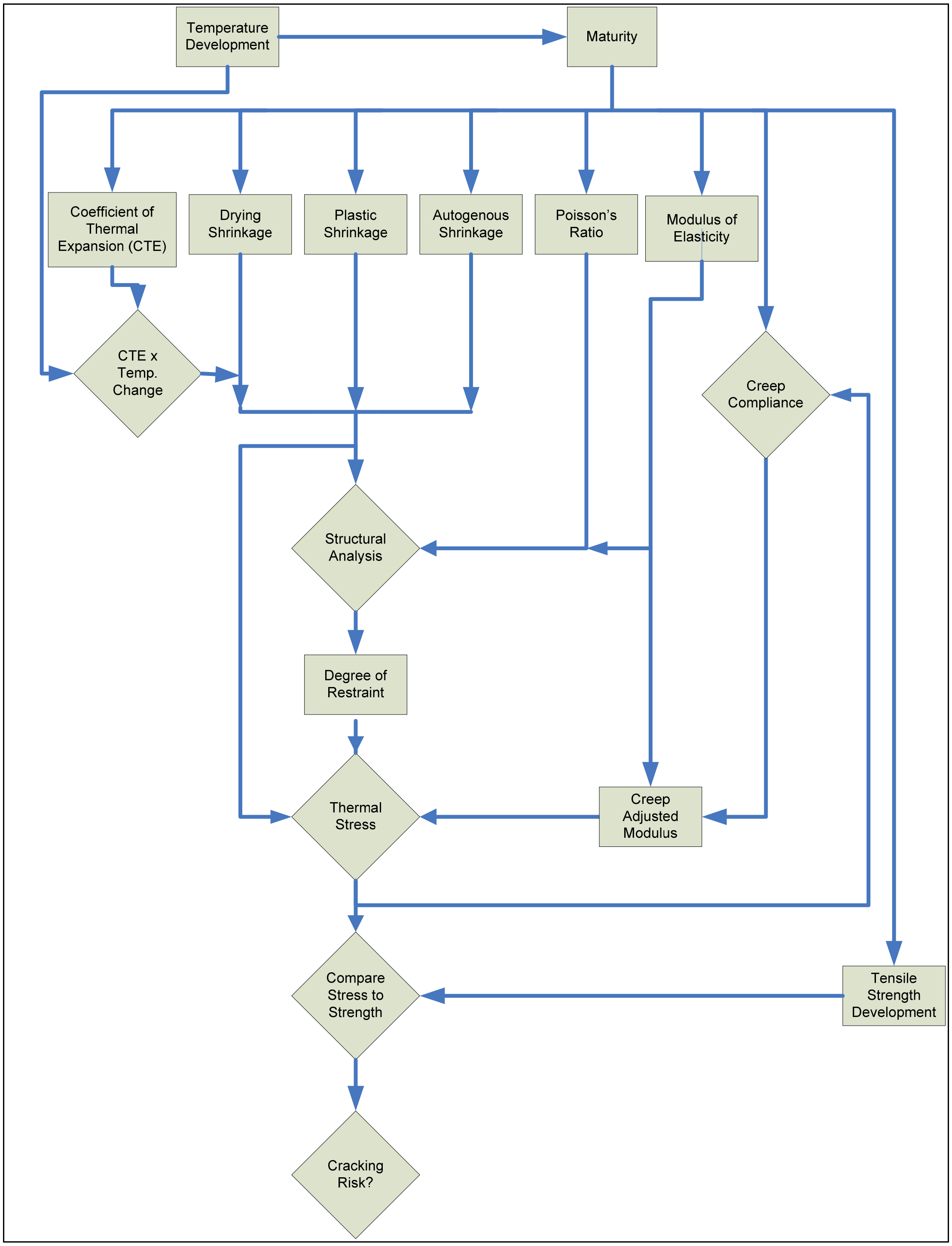


Figure 37 - Flow chart describing the relationship between different parameters in thermal stress modeling of concrete structures

In order to calculate the thermal stresses, the concrete member degree of hydration and temperature development must first be calculated as described in Chapter 3. Next, the degree of hydration and temperature development is used to calculate the the strains the concrete would undergo if there were restraint, including the elastic modulus development, Poisson's ratio, the tensile strength development, the coefficient of thermal expansion, and autogenous and drying shrinkage. Next, the concrete elastic stress must be calculated from the free shrinkage strains and mechanical properties by performing a structural analysis. Stress relaxation may then be applied to the concrete elastic stress. Finally, a failure criterion such as the stress to tensile strength ratio may be used to determine the cracking risk.

4.2. Plastic Shrinkage

Plastic shrinkage cracking is very difficult to predict. Our knowledge of the tensile strength development at very young ages is lacking. Stresses are known to develop once the protective bleed water covering the structure and the pore water near the surface evaporates. There are currently no known models available for assessing the bleeding rate of different concrete mixtures at differing temperatures to know how much protective bleed is available at a given time. The evaporation rate is calculated using the model described in Section 3.1.6. The plastic shrinkage probability classification is described as low if the evaporation rate is kept below 0.1 lb/ft^2/hr. Evaporation between 0.1 and 0.2 is classified as high. Evaporation above 0.2 lb/ft^2/hr is classified as very high. For concrete containing silica fume, the evaporation rate limits used in the classification are reduced by 75% for 5% or more silica fume used in the mixture. The evaporation rate limit is reduced linearly between 0 and 5% silica fume to the 75% reduction at 5% silica fume content.

4.3. Free Shrinkage and Mechanical Properties

Both the concrete the mechanical property development and the early-age free shrinkage strains are dependent on the concrete degree of hydration and temperature development. The mechanical property development is calculated using the equivalent age maturity (ASTM C 1074, 2004). Several different equations have been developed to relate the maturity to strength development and are discussed in Section 4.2.1. Section 4.2.2 discusses the development of Poisson's ratio. The free shrinkage strain is composed of the concrete thermal strains, the autogenous strains, the drying shrinkage strains, and the plastic shrinkage strains. In mass concrete, the drying shrinkage may be assumed equal to zero for early-age analysis because of the small surface to volume ratio. Free thermal deformation calculation methods are discussed in Section 4.2.3 and autogenous shrinkage calculation methods are discussed in Section 4.2.4.

4.3.1. Concrete Maturity and Strength Development

The rate of cement hydration is dependent on the temperature and the time since mixing (Mindess, Young, and Darwin, 2003). Maturity is a method of comparing the cement hydration progress made at different temperatures. Two maturity methods are commonly used, both of which are described in ASTM C 1074 (2004). They are the Nurse-Saul method and the Equivalent Age method. The Nurse-Saul method concept was developed first in the 1950s and uses a temperature-time factor to define maturity. The temperature-time factor may be defined as the integral of the temperature history and may be calculated using Equation 50 (ASTM C 1074, 2004):

$$M(t) = \sum (T_a - T_0) \cdot \Delta t \qquad \textbf{Equation 50}$$

where $M(t)$ is the maturity (°C-hrs) at time t (hrs), T_a is the average temperature (°C) during time interval Δt (hrs), and T_0 is the datum temperature (°C). The equivalent age maturity is the age a concrete sample would have to be cured isothermally at some reference temperature T_r (°C) to have the same degree of reaction or properties as the sample cured at a different temperature. The equivalent age maturity may be calculated using Equation 51 (ASTM C 1074, 2004):

$$t_e = \sum e^{-Q\left(\frac{1}{(T_a+273)}-\frac{1}{(T_r+273)}\right)} \Delta t \qquad \textbf{Equation 51}$$

where t_e is the equivalent age maturity (hrs), and Q is the activation energy divided by the gas constant (°K). ConcreteWorks uses the equivalent age maturity method because it does a better job of predicting the concrete strength development than the Nurse-Saul method (Emborg 1998a, Mindess, Young, and Darwin 2003). One of the problems with the maturity method, termed the *cross-over effect*, is that curing at higher temperatures can result in lower long-term concrete strengths than concrete cured at lower temperatures (Emborg 1998a). This effect does not usually occur until later ages, meaning that the maturity method may still be used at early-ages with little expected loss of accuracy. For this reason, ConcreteWorks does not consider the cross-over effect in calculating the strength from the maturity.

Compressive Strength Development

A good model that describes the compressive strength development is essential in ConcreteWorks because it is used to calculate the elastic modulus development and the splitting tensile strength development. The compressive strength is the most widely used strength quality control test. Many engineers and contractors have already gained experience in developing compressive strength-maturity relationships, making it a much easier parameter for ConcreteWorks users to input than the modulus or splitting tensile strength to maturity relationship.

Many equations of different forms have been developed to relate the compressive strength to the maturity development. Two very common equations used are shown in Equation 52 and Equation 53 (Viviani, 2005):

$$f_c(t) = a + b \cdot \log\left(\log(M(t))\right), f_c \geq 0 \qquad \textbf{Equation 52}$$

$$f_c(t_e) = f_{cult} \cdot \exp\left(-\left(\frac{\tau_s}{t_e}\right)^{\beta_s}\right) \qquad \textbf{Equation 53}$$

where f_c is the compressive strength development (MPa), a is a fit parameter which is usually negative (MPa), b is a fit parameter (MPa/°C/hr), f_{cult} is the ultimate compressive strength parameter fit from the compressive strength tests (MPa), τ_s is a fit parameter (hrs), and β_s is a fit parameter. Equation 52 is not very good for use in thermal stress analysis, because before setting, the compressive strength is zero. Any modulus value calculated from the compressive strength which is equal to zero will result a singular matrix in the structural analysis. Equation 53 is only allowed to be used in ConcreteWorks when the Nurse-Saul maturity method is used.

Elastic Modulus Development

The elastic modulus provides the link between restrained strains and stresses. The elastic modulus is known to be dependent on the mixture proportions, unit weight, maturity, aggregate modulus, strength, and moisture condition. The elastic modulus is known to develop faster than the tensile and compressive strength. Several models for the elastic modulus development with time are based on a form of Equation 54:

$$E(t) = E_{ref} * \beta(t) \qquad \textbf{Equation 54}$$

where E_{ref} is the reference modulus (MPa), E is the elastic modulus at time t, and β is a modification factor that accounts for the modulus development with time. Equation 55–57 for β are compared to experimental data (Larson, 2003):

$$\beta(t) = \begin{cases} 0 & for \quad t < t_s \\ b_1 * \log(t/t_s) & for \quad t_s \le t_0 < t_B \\ b_1 * \log(t_B/t_s) + b_1 * \log(t/t_s) & for \; t_B \le t < 28day \\ 1 & for \quad t \ge 28day \end{cases} \qquad \textbf{Equation 55}$$

$$\beta(t) = \left(\exp\left(s \cdot \left(1 - 1 / \sqrt{\frac{t - t_s}{28 - t_s}} \right) \right) \right)^{0.5} \qquad \textbf{Equation 56}$$

$$\beta(t) = \frac{E_\infty}{E_{ref}} \cdot \exp\left(-\left(\frac{\tau}{t} \right)^{\alpha} \right) \qquad \textbf{Equation 57}$$

where t_s is the apparent setting time (hours); b_1, b_2, α, τ, and s are model parameters; t_B is a constant that represents the time of change in slope of the elastic modulus (hours); and E_∞ is the ultimate elastic modulus (MPa). Larson (2003) found that all three models gave satisfactory results when elastic modulus data from concrete less than one day old was used in the model parameter regression analysis.

Rostasy, Gutsch, and Laube (1993) have proposed a model for the normalized modulus development based on degree of hydration as shown in Equation 58:

$$\hat{E} = \left[\frac{\alpha - \alpha_0}{1 - \alpha_0} \right]^{\frac{2}{3}} \qquad \textbf{Equation 58}$$

where $\hat{E}$ is the normalized elastic modulus, α is the degree of hydration, and α_0 is the degree of hydration at time of initial setting. Bernard, Ulm, and Lemarchand (2003) found that the elastic modulus of cement paste increases almost linearly with the degree of hydration. This result arises the modulus development is highly dependent on the porosity of the cement paste. They found that when aggregates are added the relationship between elastic modulus and degree of hydration stops being linear.

The elastic modulus is also commonly calculated from the compressive strength of the concrete. Most models of this type follow a form of Equation 59:

$$E = k \cdot (f_c)^n \qquad \textbf{Equation 59}$$

where f_c is the compressive strength (MPa), and k and n are model parameters. ACI 318 (2005) uses a form of this equation where n is equal to 0.5 and k is as shown in Equation 60:

$$k = 0.043 \cdot w_c^{1.5} \quad \textbf{Equation 60}$$

where w_c is the unit weight of the concrete (kg/m^3). ConcreteWorks uses Equation 59 and Equation 60 in calculating the elastic modulus from the compressive strength development. The default values set in ConcreteWorks are equal to those used in the ACI 318 building code. This equation was chosen because most engineers are familiar with this equation from prior experience in structural design, and readily accept its use. Most ConcreteWorks users will also not have test data available to model the elastic modulus development, making the use of readily accepted default equations necessary.

Tensile Strength Development

Concrete failure in early age concrete stress models is usually considered to occur when the stress exceeds the concrete strength. An accurate knowledge of the tensile strength development of concrete is just as crucial in determining concrete cracking risks as knowing the stress. The tensile strength development of concrete is known to be effected by aggregate strength, smoothness, and size, saturation level, and cementitious materials.

Tensile strength develops in a similar manner to the elastic modulus. The tensile strength has been found to develop faster than compressive strength, but slower than the elastic modulus. The elastic modulus is often related to the compressive strength by Equation 61 (Raphael, 1984):

$$f_t = l \cdot (f_c)^m \quad \textbf{Equation 61}$$

where f_t is the tensile strength (MPa), and l and m are fit parameters.

The tensile strength of concrete can be determined by uniaxial tensile tests, the splitting tensile test, or the flexural tensile test. The uniaxial tensile test is difficult to perform especially at early ages. The uniaxial tensile strength, splitting tensile strength, and flexural tensile strength of concrete have been found to develop at the same rate, allowing conversion from the splitting tensile and flexural tensile strength to the uniaxial tensile strength (De Schutter and Taerwe, 1996). Rostasy, Gutsch, and Laube (1993) have shown that the tensile strength development is independent of the load history, allowing for independent calculation of the strength and stress. ConcreteWorks assumes that the splitting tensile strength is used, and uses the parameters developed by Raphael (1984) of l equal to 1.7 and m equal to 2/3 for the default values.

4.3.2. Poisson Ratio

Stress modeling in two- or three-dimensional elements requires the knowledge of Poisson's ratio. Poisson's ratio is a measure of the deformation in one direction due to a load in the transverse direction. There is debate as to whether Poisson's ratio is constant or changing in young concrete. Oluokun, Burdette, and Deatherage (1991) have concluded that Poisson's ratio is independent of the age of the concrete. This conclusion is not supported by their data, which shows the Poisson ratio at 6 hour to be less than that at later ages. To illustrate why the Poisson ratio of concrete must not be a constant value, consider the concrete fresh plastic state. The Poisson ratio of concrete while the concrete is in its liquid state must be equal or close to that of water, 0.5. After setting, the cementitious system stiffens and transforms from a suspended liquid to a rigid skeleton. The long-term Poisson ratio of concrete varies between 0.15 and 0.2 (Mindess, Young, and Darwin, 2003). A transition from a Poisson ratio of 0.5 to around 0.2 must occur during hardening.

Three models describe how Poisson's ratio changes with time. The first model assumes a linear decrease in Poisson's ratio with time. Experimental data has shown that with concrete the Poisson ratio decreases to a minimum value before rising slightly to its final long-term value (De Schutter and Taerwe, 1996). This is the second model. Byfors suggests that the Poisson ratio changes from 0.48 during the plastic state to 0.13 at a strength 1 to 2 MPa, to a final long-term value of around 0.28 (De Schutter and Taerwe, 1996; Byfors, 1980). Bernard, Ulm, and Lemarchand (1994) suggest that during the plastic state, the continuous water structure dominates the Poisson ratio. As the concrete begins to set, the water structure becomes discontinuous, decreasing the component of Poisson's ratio supplied by the water structure. During setting, the concrete microstructure begins to form, increasing the component of the Poisson ratio supplied by the solid skeleton. The sum of the components of the Poisson ratio results in a minimum value during setting which increases to a stable long-term value as shown in Figure 38 (Bernard, Ulm, and Lemarchand, 2003). De Schutter and Taerwe (1996) proposed a model for the Poisson ratio υ based on the degree of hydration, as shown in Equation 62:

$$\upsilon(r) = 0.18 \sin \frac{\pi \cdot r}{2} + 0.5 e^{-10r} \qquad \textbf{Equation 62}$$

where *r* is the degree of hydration. ConcreteWorks uses this model because the model captures the shape of Poisson's ratio development and because of the model's simplicity.

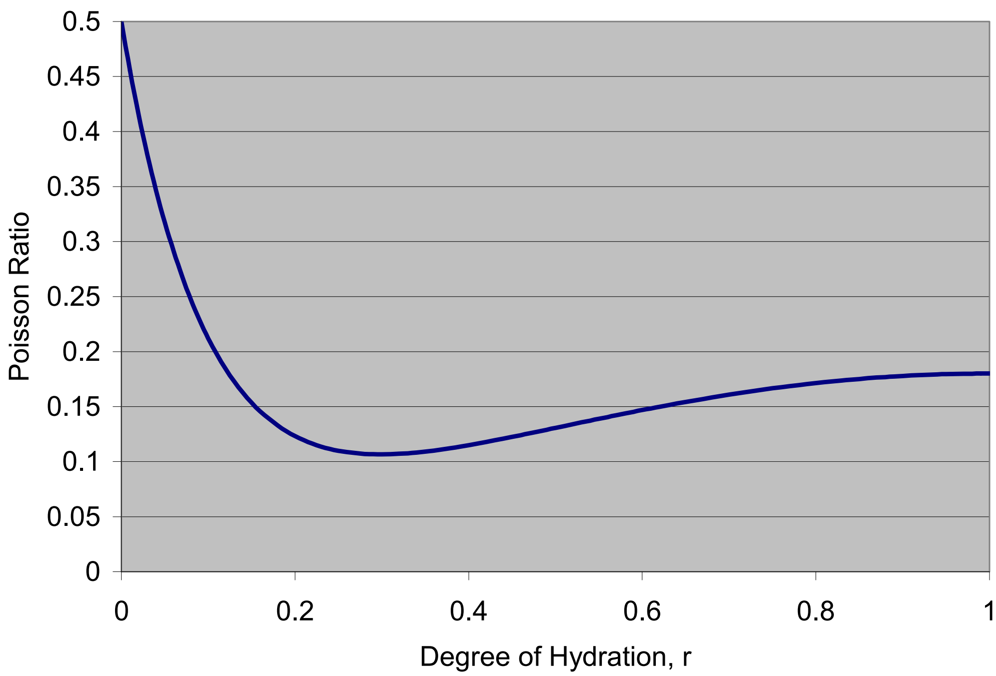


Figure 38 - Poisson ratio development during hydration

The third model is based on the composite sphere model. Poisson's ratio is calculated form the bulk modulus *K* (GPa) and the shear modulus *G* (GPa) of the concrete as shown in Equation 63. Paulini and Gratl (1994) conclude from this model that Poisson's ratio does not reach a minimum value and then increase, but steadily decreases to an asymptotic value. Bernard, Ulm, and Lemarchand (2003) on the other hand, use Equation 63 to support the second model by suggesting that the bulk modulus and shear modulus change at different rates. The ratio of the shear modulus to bulk modulus increases to a maximum value and then declines.

$$\upsilon = \frac{3K - 2G}{6K + 2G}$$ **Equation 63**

Poisson's ratio has been found to be equivalent in tension and compression (Lydon and Balendran, 1986)—a very important point for use in computer models of thermal stresses. ConcreteWorks assumes that the Poisson's ratio is equal in compression and tension.

The dynamic Poisson ratio is about 25–40% higher than the static Poisson ratio (Byfors, 1980). The dynamic Poisson ratio is thought to be more representative of the actual elastic behavior of concrete (Mindess, Young, and Darwin, 2003). The static Poisson's ratio has been found to be principally a function of the percent volume of aggregates in the mixture, while the dynamic Poisson's ratio has been found to be a function of the age, w/cm, and percent volume of aggregates.

Poisson's ratio has been shown to be constant up to a stress of 50–60% of the compressive strength. Micro-cracking at higher stress levels can change the Poisson's ratio. Poisson's ratio may also be different under biaxial or triaxial states of stress (Anson and Newman, 1966). ConcreteWorks assumes that the Poisson's ratio is independent of the stress level and the state of stress.

4.3.3. Coefficient of Thermal Expansion

The coefficient of thermal expansion (CTE) of concrete is an indicator of the concrete member length change due to temperature changes in the concrete. It is one of the most important parameters in predicting stress distributions in concrete members. Knowledge of the CTE allows researchers to separate the effects of temperature induced deformations from autogenous shrinkage in laboratory tests. Separate models for thermal and autogenous deformations can then be made, allowing for their superposition in computer based stress models. Several factors can affect the CTE, including mixture proportions, aggregate type, degree of saturation, and age.

The hardened concrete CTE is primarily a function of the CTE of the concrete mixture's constituent materials (Mitchell, 1953; Emanuel and Hulsey, 1977). Because of the volume of aggregates in concrete mixtures, the hardened concrete CTE is dominated by the CTE of the aggregate. Some common values of the CTE for concrete containing different types of aggregates are shown in Table 8. A change in the cementitious material properties such as fineness, type, and composition will also affect the CTE (Mitchell, 1953).

Table 8 - CTE for concretes made with different aggregates (Bamforth and Price, 1995)

Aggregate Type of Concrete	CTE (m/m/°C)	CTE (in/in/°F)
Siliceous River Gravel	12.0	6.7
Granite	10.0	5.6
Limestone	8.0	4.4
Lightweight	7.0	3.9

Materials change volume as the temperature changes because the temperature changes the attractive forces in molecular and atomic structures, as well as capillary stresses. It has been observed that concrete has a higher CTE when partially saturated than at oven dry or saturated. The CTE reaches a maximum value between 60% and 80% relative humidity (Meyers, 1950; Mitchell, 1953; Emanuel and Hulsey, 1977; Walker, Bloem, and Mullen, 1952). As the water in capillary pores expands with temperature, the surface curvature and hence surface tension and capillary under pressure in the pores decreases. This surface-tension-induced volume change does not occur at oven dry conditions or at saturated conditions because the pore has no air-water meniscus in these states (Bjøntegaard, 1999). When autogenous shrinkage occurs in concrete, the relative humidity will drop in the capillary pores to a limiting value of about 75% (Jensen and Hansen, 2001). The CTE will then rise because of the change in relative humidity (Hedlund, 2000), further increasing the development of thermal stresses.

Some researchers have found different coefficients for thermal expansion and contraction (Byfors, 1980; Emborg, 1989). The difference in measured coefficients may be explained by the changing mechanical properties of concrete during young ages, so that the concrete that is measured during the heat phase is different mechanically than that measured during cooling a short time later (Emborg, 1989). Differences between measured coefficients of thermal expansion and contraction may also be due to non-linear effects from differences in the CTE between the concrete and embedded strain gauges (Yamakawa, Nakauchi, Kita, and Onuma, 1986).

As the concrete hydrates, the CTE will change. The fresh concrete CTE is estimated to be 8–10 times greater than the hardened CTE (Schöppel and Springenschmid, 1994). There is debate about how the CTE changes during hydration. Kada, et. al. (2002) measured a decrease in the CTE for a low w/cm mixture (0.30) during the first few hours after setting. The CTE then increased to a stable long-term value. Mixtures with a w/cm of .35 and .4 both showed the CTE decreasing to assume a stable value at around 10 hours. The drop in the CTE and subsequent rise can be attributed to the reduction of relative humidity in the sample because of self desiccation, which increases the CTE. Other researchers have found that the CTE decreases to an asymptotic long-term value (Byfors, 1980; Glisic, 2000). Hashida and Yamaziki (2002) have developed an equation to relate the time of final set to the CTE, as shown in Equation 64:

$$\alpha_{cte}(t) = a_1 \cdot \ln\left(\frac{t}{t_{fs}}\right) + b$$ **Equation 64**

where α_{cte} is the concrete CTE (με/°C), a_1 and b are fit parameters (με/°C), t is the time, and t_{fs} is the time of final set. The parameters a_1 and b are dependent on the w/cm, supplementary cementitious materials, cement type, and aggregates used.

ConcreteWorks uses a constant CTE, because of the lack of a data to model how the mixture proportions relate to CTE development. Because the CTE decreases very rapidly before the time of set, little loss in accuracy is expected from using a constant value except in the case of low w/cm where the CTE may increase after set and during curing. The constant CTE used in ConcreteWorks is calculated from the mixture proportions and the aggregate type using the method proposed by Emanual and Hulsey (1977) shown in Equation 65.

$$\alpha_{cteh} = \frac{\alpha_{ca} \cdot V_{ca} + \alpha_{fa} \cdot V_{fa} + \alpha_p \cdot V_p}{V_{ca} + V_{fa} + V_p}$$ **Equation 65**

where α_{cteh} is the hardened concrete CTE, α_{ca} is the coarse aggregate CTE (με/°C), V_{ca} is the coarse aggregate volume (kg/m^3), α_{fa} is the fine aggregate CTE (με/°C), V_{fa} is the fine aggregate volume (kg/m^3), α_p is the paste CTE (με/°C), and V_p is the paste volume (kg/m^3). In order to simplify the inputs, ConcreteWorks uses the assumed material specific gravity values for constituent materials shown in Table 9 in calculating the hardened concrete CTE. The assumed constituent material CTE values are shown in Table 10. Material CTE and specific gravity values can vary substantially, and may affect the calculated CTE value substantially. The values selected for use in ConcreteWorks were selected to represent typical, commonly used Texas materials. For more accurate results, it is suggested that the user test and input into ConcreteWorks the hardened concrete CTE of the specific materials used.

Table 9 - Concrete constituent materials assumed specific gravity values

Material	Specific Gravity
Water	1
Cement	3.14
Class F Fly Ash	2.4
Class C Fly Ash	2.7
Slag	2.87
UFFA	2.57
Silica Fume	2.2
Coarse Aggregate	2.65
Fine Aggregate	2.65

Table 10 - Concrete constituent materials assumed CTE

Material	CTE values used in ConcreteWorks (με/°C)	CTE from Emanuel and Hulsey, 1977 (με/°C)
Hardened Cement Paste	10.8	10.8
Limestone Aggregate	3.5	3.5–6
Siliceous River Gravel and Sand	11	11–12.5
Granite Aggregate	7.5	6.5–8.5
Dolomitic Limestone Aggregate	7	7–10

4.3.4. Autogenous Shrinkage Model

The volume of the cement hydration products is less than the volume of the cement before hydration. In low w/cm concrete, all of the water will be used to react with the cement. The unhydrated cement will then react with the water in the concrete pores, drying the pores and causing shrinkage. ConcreteWorks uses a modified version of the autogenous shrinkage model developed by Hedlund (2000). Hedlund developed a model based on his testing and that found in the literature for autogenous shrinkage starting at 24 equivalent age hours. The model is based on an ultimate autogenous shrinkage calculated from the w/cm which is altered to account for temperature effects. Equation 66-69 show the equations proposed by Hedlund for calculating the autogenous shrinkage with the concrete equivalent age:

$$\varepsilon_{SH} = \varepsilon_{su} \cdot \beta_{s0}(t_e) \cdot \beta_{ST}(T) \qquad \textbf{Equation 66}$$

$$\varepsilon_{su} = (-0.65 + 1.3 \cdot \frac{w}{cm}) \cdot 10^{-3}$$ **Equation 67**

$$\beta_{s0}(t_e) = \exp\left(-\left[\frac{t_{s1}}{t - t_{s0}}\right]^{\eta_{SH}}\right)$$ **Equation 68**

$$\beta_{ST}(T) = a_0 + a_1 \cdot \left[1 - \exp\left(-\left(\frac{T}{T_1}\right)^{b_1}\right)\right] + a_2 \cdot \left[1 - \exp\left(-\left(\frac{T}{T_2}\right)^{b_2}\right)\right]$$ **Equation 69**

where t_{s0} (days), t_{s1} (days), η_{SH}, a_0, *a1*, *a2*, *b1*, *b2*, *T1* (°C), and *T2* (°C) are fit parameters. Hedlund recommends setting the parameters t_{s1}, η_{SH}, a_0, *a1*, *b1*, *b2*, *T1* (°C), and *T2* (°C) may be set equal to 5 days, 0.3, 0.4, 0.6, 9 °C, 2.9, 55 °C, and 7, respectively. Additionally, he recommends setting the parameter a_2 may be set equal to 1.3 for normal strength concrete and 0.1 for high performance concrete. The parameter t_{s0} is the time at which the concrete shrinkage begins. Before this time, the concrete autogenous shrinkage is set equal to zero (Hedlund, 2000).

The autogenous shrinkage model used in ConcreteWorks modifies the model developed by Hedlund to reduce the w/cm at which autogenous shrinkage develops, the time at which autogenous shrinkage begins, and does not include the temperature modification term. The ultimate concrete shrinkage value used in ConcreteWorks is calculated using Equation 70:

$$\varepsilon_{ault} = (-0.94 + 2.238 \cdot w/cm) \cdot 10^{-3}$$ **Equation 70**

The w/cm ratio at which autogenous shrinkage develops in ConcreteWorks is 0.42, which corresponds to the theoretical w/cm at which complete hydration is possible (Mindess, Young, and Darwin, 2003). Additionally, autogenous shrinkage begins at the virtual time of set, not at 24 equivalent age hours as in the Hedlund model. The autogenous shrinkage model will be improved in future versions of ConcreteWorks as more data and models become available.

4.4. Elastic Stress and Degree of Restraint

The restraint is needed at each point in the concrete member at each time step to be able to accurately model the stresses in the concrete. The restraint can be obtained by performing a structural analysis of the concrete member with non-uniform material properties across the cross section. ConcreteWorks uses a plane strain finite-difference scheme to calculate the elastic stress in the member. The software considers the non-homogenous material development of the member by assuming a constant modulus and Poisson ratio for each control volume. The elastic modulus and Poisson ratio for each control volume is different, and is based on the maturity for the case of the elastic modulus and the degree of hydration for the Poisson ratio. The restraint case modeled for the rectangular column is the same as that shown in Figure 4, a two-dimensional horizontal cross section of the column. The restraint case modeled for the rectangular bent cap is the same as that shown in Figure 14, a two-dimensional vertical cross section of the cap. Footings are modeled assuming a two-dimensional cross section as shown in Figure 7, assuming a fixed base condition. The state of stress in the rectangular column and bent cap can be adequately represented using the two-dimensional models assumed because the stress in the third direction should be relatively small compared to the other two dimensions. The footing model, however, may deviate from the actual member stresses because the stress in the third dimension may not be small relative to the other two dimensions. Care should be taken in interpreting results from the footing model in ConcreteWorks. Improvements in the footing elastic stress calculation module are being considered for future versions of ConcreteWorks.

After the elastic stress is calculated, the elastic strain is then calculated using Hooke's law, as shown in Equation 71–73.

$$\varepsilon_x = \frac{\lfloor \sigma_x - \upsilon \cdot \sigma_y \rfloor}{E}$$ **Equation 71**

$$\varepsilon_y = \frac{\lfloor \sigma_y - \upsilon \cdot \sigma_x \rfloor}{E}$$ **Equation 72**

$$\varepsilon_{xy} = \frac{\sigma_{xy} \cdot 2 \cdot (1 + \upsilon)}{E}$$ **Equation 73**

where ε_x is the strain in the x direction, σ_x is the stress in the x direction (MPa), ν is the Poisson ratio, σ_y is the stress in the y direction (MPa), ε_y is the strain in the y direction, ε_{xy} is the shear strain in the xy direction, σ_{xy} is the shear stress in the xy direction, and E is the elastic modulus (MPa).

4.5. Early-Age Concrete Creep Model

Creep may be defined as a time-dependent deformation during a constant stress. Stress relaxation may be defined as a time dependent decrease in stress during a constant strain. Creep is applied to the stresses in the x, y and xy directions independently. The uniaxial constitutive equation for concrete creep is shown in Equation 74.

$$\varepsilon(t) = \int_0^t J(t, t_0) \cdot d\sigma(t_0) + \varepsilon_0(t)$$ **Equation 74**

where ε is the total strain, t is the time, t_0 is the time of the load application, $J(t,t_0)$ is the creep compliance, $d\sigma(t_0)$ is the stress imposed at time t_0, and ε_0 is the instantaneous or elastic response to the stress application.

Creep is applied to the elastic strains using the principle of superposition. The principle of superposition assumes that a step stress function is applied, with a corresponding strain response. The strain responses are then superimposed using the assumption of linearity as shown in Figure 39. The assumption of linearity is probably a valid assumption up to stress levels of about 40% (Emborg, 1998b). The two obvious problems with the approach used in ConcreteWorks are 1) the thermal stresses calculated in the model can exceed 40% of the tensile strength and 2) the model assumes linearity. The second assumption is a simplification necessary for simplicity and to reduce the runtime of the analysis. This assumption is definitely not true. Because the stresses in the member are relieved non-linearly by stress relaxation, the thermal stresses would redistribute in the member. These assumptions, however, do not preclude ConcreteWorks from being used in design. High tensile stresses should be avoided during the design stage to prevent damage from micro-cracking and potential through cracks.

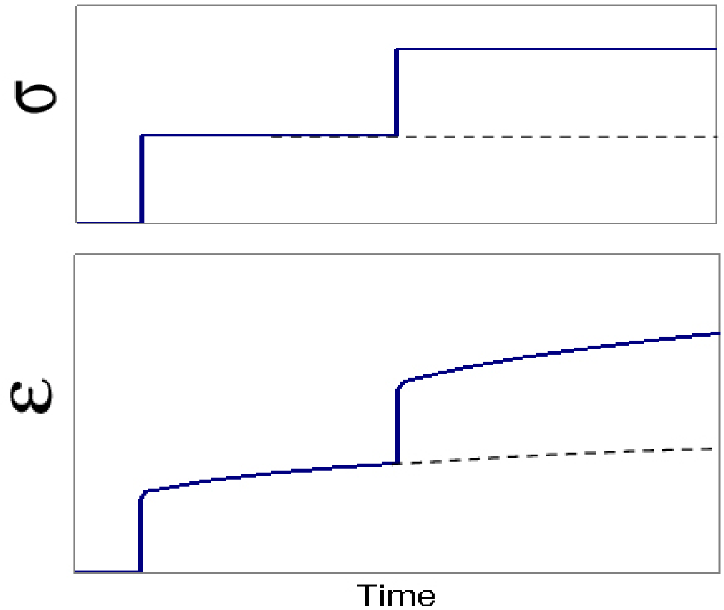


Figure 39 - Illustration of the principle of superposition

ConcreteWorks uses a modified version of the Linear Logarithmic Model for calculating the early-age concrete stress relaxation for mass concrete members. The Linear Logarithmic Model was developed in Sweden by Larson (2003) to model early-age concrete creep. The method models the early-age concrete creep compliance function as a series or lines in log scale, as shown in Figure 40. The slope of the lines can be calculated using Equation 75–78.

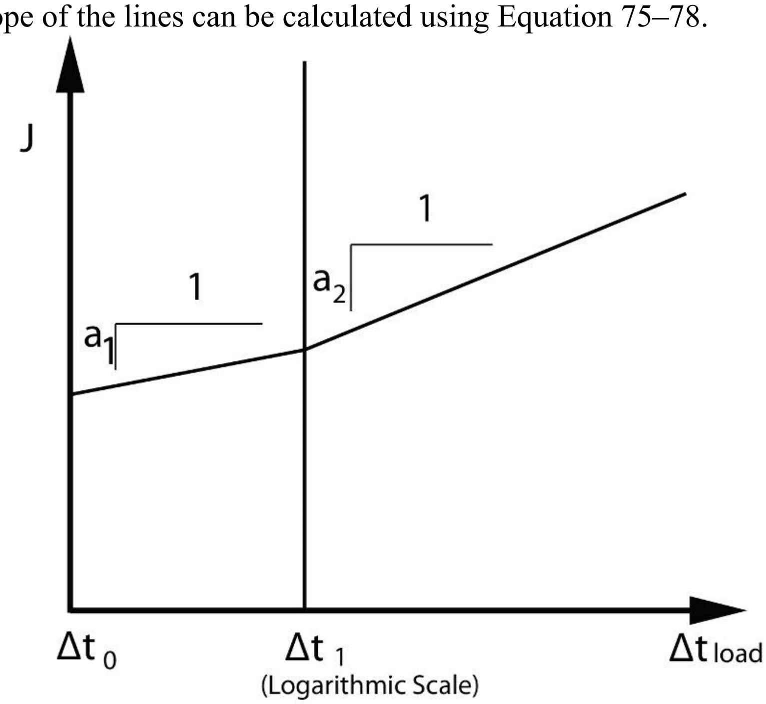


Figure 40 - Creep compliance modeled using the Linear Logarithmic Model (Larson, 2003)

$$J(\Delta t_{load}, t_0) = \frac{1}{E(t_0)} + \Delta J(\Delta t_{load}, t_0)$$ **Equation 75**

$$\Delta J(\Delta t_{load}, t_0) = a_1 \cdot \log\left(\frac{\Delta t_{load}}{\Delta t_0}\right)$$ **Equation 76**

For $\Delta t_0 \le \Delta t_{load} < \Delta t_1$

$$\Delta J(\Delta t_{load}, t_0) = a_1 \cdot \log\left(\frac{\Delta t_{load}}{\Delta t_0}\right) + a_2 \cdot \log\left(\frac{\Delta t_{load}}{\Delta t_0}\right)$$ **Equation 77**

For $\Delta t_{load} \ge \Delta t_1$

$$a_i(t_0) = a_i^{min} + (a_i^{max} - a_i^{min}) \cdot \exp\left(-\left(\frac{t_0 - t_s}{t_{ai}}\right)^{n_{ai}}\right)$$ **Equation 78**

For i=1,2

where $J(\Delta t_{load}, t_0)$ is the creep compliance (1/Pa), $E(t_0)$ is the concrete elastic modulus at the time of load application, $\Delta J(\Delta t_{load}, t_0)$ is the change in creep compliance (1/Pa), Δt_{load} is the time since load application (days), t_0 is the time of load application (days), Δt_1 is the time of the change in creep compliance slope (days), t_s is the concrete time of set, a_i^{min}, a_i^{max}, t_{ai}, and n_{ai} are fit parameters. ConcreteWorks assumes that the time of set occurs when the concrete reaches a compressive strength of 80 psi (Tuthill and Cordon, 1955).

The Linear Logarithmic Model contains no creep compliance adjustment for changes in temperature. It is well known that the creep rate increases at elevated temperatures (Emborg, 1998a). The creep compliance can be modified by a temperature modification factor, as shown in Equation 79 (Emborg, 1998a):

$$J(t, t_0, T) = \Phi_c(T) \cdot J(t, t_0)$$ **Equation 79**

where $J(t,t_0,T)$ is the temperature adjusted creep (1/Pa), T is the absolute temperature (K), and $\Phi_c(T)$ is the creep modification adjustment factor. ConcreteWorks uses a temperature modification factor based on the empirical temperature adjustment parameter suggested by Bažant and Panula (1978) as shown in Equation 80–84, where Equation 81–84 come from Bažant and Panula:

$$\Phi_c(T) = 1 + \frac{C_T}{C_{TMF}}$$ **Equation 80**

$$C_T = c_T \cdot \tau_T \cdot c_0$$ **Equation 81**

$$c_T = \frac{19.4}{1 + \left(\frac{100}{T - 253.2}\right)^{3.5}} - 1$$ **Equation 82**

$$\tau_T = \frac{1}{1+\left(\frac{60}{(t_T)^{0.69}}\right)} + 0.78$$ **Equation 83**

$$c_0 = \left(\frac{1}{8}\right)\cdot\left(\frac{w}{cm}\right)^2\cdot\left(\frac{a}{cm}\right)\cdot a_1$$ **Equation 84**

where C_{TMF} is a fit parameter equal to 2.5, t_T is the concrete age at the time the temperature is applied, w is the water content (kg/m^3), cm is the cementing materials content (kg/m^3), a is the aggregate content (kg/m^3), a_1 is a constant that accounts for the type of cement used.

4.5.1. LLM Creep Parameter Estimates

The creep parameters used in ConcreteWorks for the LLM model are based on a statistical model developed from early-age rigid cracking frame tests on 36 different concrete mixtures. A few of these mixtures were tested under several different temperature histories, in order to quantify the effects of temperature on concrete early-age creep. The creep parameters t_{a1}, t_{a2}, and n_{a2} are calculated from the concrete mixture proportions and constituent material properties according to Equation 85-87 when the Rietveld method (Rietveld, 1969) of determining the cement composition is used (Riding, 2007):

$$t_{a1} = 0.680 + 0.0064\cdot FA + 0.429\cdot\ln(w/cm) - 0.00965\cdot Ferrite$$ **Equation 85**

$$t_{a2} = \exp(3.671 - 0.0192\cdot(FA+GGBFS) - 3.7169\cdot w/cm - 0.10078\cdot(Gypsum + Hemihydrate + Anhydrite + Arcanite) - 0.0556\cdot Ferrite)$$ **Equation 86**

$$n_{a2} = \exp(-26.735 + 0.0705\cdot FA + 0.072\cdot GGBFS + 6.586\cdot\ln(Alite) - 0.177\cdot Ferrite - 0.253\cdot Alum + 5.194\cdot w/cm)$$ **Equation 87**

where *FA* is the percent fly ash replacement of cement by mass, *w/cm* is the water-to-cementing-materials ratio, *Ferrite* is the percent ferrite of the cement, as determined by Rietveld analysis, *GGBFS* is the percent grade 120 ground granulated blast furnace slag replacement of cement by mass, *Gypsum* is the percent gypsum of the cement, as determined by Rietveld analysis, *Hemihydrate* is the percent hemihydrate in the cement, as determined by Rietveld analysis, *Anhydrite* is the percent anhydrite in the cement, as determined by Rietveld analysis, *Alite* is the percent alite in the cement, as determined by Rietveld analysis, and *Alum* in the percent aluminate in the cement as determined by Rietveld analysis. When a supplementary cementing material is used, the percent values used of the cement chemistry are the percent of the material in the cement times the percent cement of the total cementing materials.

When the Bogue method (ASTM C 150) of determining the cement composition is used, Equation 88-90 are used to relate the mixture proportions and constituent material properties to the early age MLLM creep parameters t_{a1}, t_{a2}, n_{a2} (Riding, 2007):

$$t_{a1} = 0.728 + 0.0061\cdot FA + 0.448\cdot\ln(wcm) - 0.0111\cdot C_4AF$$ **Equation 88**

$$t_{a2} = \exp(3.436 - 0.0179 \cdot (FA + GGBFS) - 3.404 \cdot wcm - 0.0186 \cdot C_2S - 0.0566 \cdot C_4AF) \quad \textbf{Equation 89}$$

$$n_{a2} = \exp(6.165 - 0.0541 \cdot FA - 0.0619 \cdot GGBFS - 0.00869 \cdot cement - 0.425 \cdot C_3A - 0.572 \cdot C_4AF + 0.0107 \cdot CemBlaine) \quad \textbf{Equation 90}$$

where C_4AF is the percent C_4AF of the cement, as calculated using the Bogue method, C_2S is the percent C_2S of the cement, as calculated using the Bogue method, C_3A is the percent C_3A of the cement, as calculated using the Bogue method, *cement* is the total amount of cementing materials used in lb/yd^3, and *CemBlaine* is the cement Blaine fineness (m^2/kg). When a supplementary cementing material is used, the percent values used of the cement chemistry are the percent of the material in the cement times the percent cement of the total cementing materials. The remainders of the MLLM creep parameters are kept constant, according to Table 11:

Table 11 - Modified linear logarithmic model parameters assumed to remain constant in ConcreteWorks

Modified Linear Logarithmic Model Parameter	Value	Units
Δt_0	0.001	days
Δt_1	0.1	days
a_1^{min} (*10^-12)	0.1	1/Pa
a_1^{max} (*10^-12)	60	1/Pa
n_{a1}	1.19	
a_2^{min} (*10^-12)	5	1/Pa
a_2^{max} (*10^-12)	30	1/Pa

4.6. Cracking Potential

In ConcreteWorks, the cracking potential classification of a mass concrete member is based on the calculated tensile stress-to-tensile strength ratio. The concrete tensile-stress-to-tensile-strength ratio calculated in the software is assigned a cracking probability classification using the probability density shown in Figure 41. The cracking probability density was obtained from the distribution of the tensile stress-to-splitting tensile strength at cracking in the rigid cracking frame tests performed.

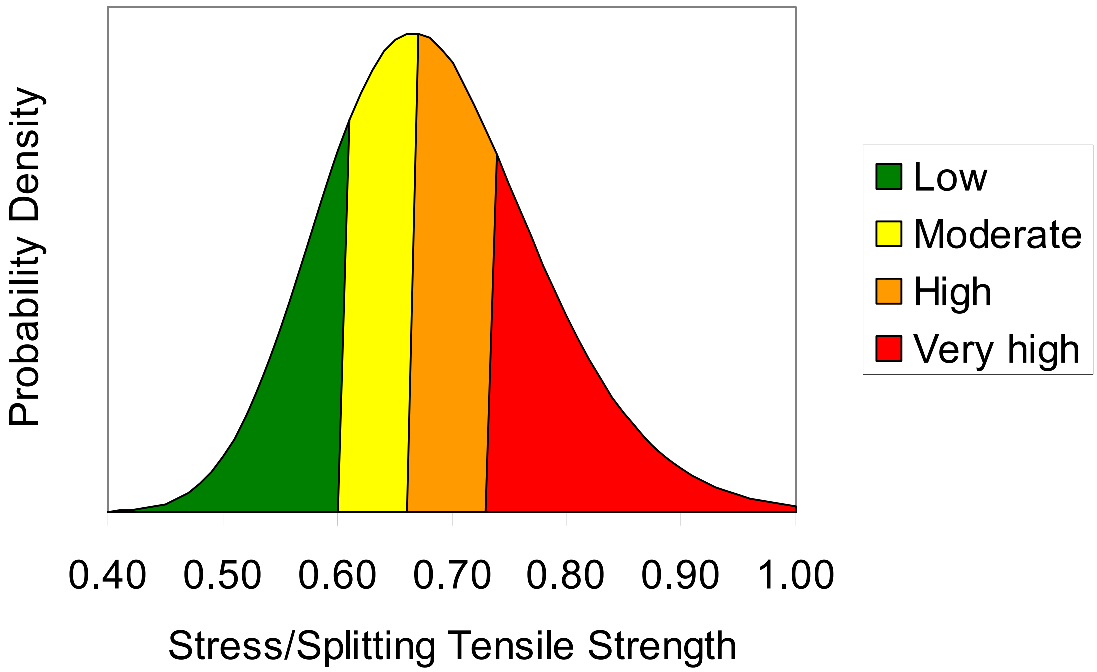


Figure 41 - Probability density for cracking based on the stress/splitting tensile strength

A lognormal distribution is assumed to model the relationship between the stress to strength ratio and the probability of cracking. A 25% or lower cracking probability is assumed to be low, a 25 to 50% cracking probability is assumed to be moderate, a 50 to 75% is assumed to be high, and higher than a 75% cracking probability is assumed to be a very high cracking probability. A lognormal distribution is used instead of a normal distribution because the tensile stress and splitting tensile strength are both positive quantities.

4.7. Bridge Deck Stresses

Bridge deck stresses are calculated in ConcreteWorks for the first year of service life. The analysis is performed in two stages. First, the concrete stresses are calculated for the time period before the curing methods are removed. During this initial period, the stresses are calculated every half hour. The free concrete strain used to calculate the elastic stress and ultimately creep adjusted stress include thermal and autogenous shrinkage effects as described in Section 4.2.4. The modeled bridge deck temperature is used in the thermal strain calculations. The degree of restraint and elastic modulus is then used to calculate the elastic stress from the free strain. A degree of restraint of 1.0 is used for the concrete bridge decks made with concrete panels as a conservative measure of the larger restraint provided by the panels. A degree of restraint of 0.6 is used for the remaining bridge deck types to simulate the resistance to curvature and movement provided by composite action between the deck and girders (Krauss and Rogalla, 1996). The modified B3 creep model used to relax the elastic stresses calculated is described in detail by Byard (2011).

The free concrete strain after curing methods are removed is calculated using 24-hour time steps. The average daily environmental temperatures are used to calculate the thermal strains. The autogenous strains used in the free strain analysis are those described in Section 4.2.4. Drying shrinkage free strains are calculated using the B3 model (ACI 209.2, 2008). The relative humidity measurements used in the drying shrinkage strain calculations are assumed to decrease linearly during the first 60 days from 100% relative humidity to the average daily environment relative humidity. Additionally, to be conservative the relative humidity is also assumed no to increase after decreasing below 100%. The free strains are then multiplied by the elastic modulus and degree of restraint to calculate the elastic stress. Stress relaxation is then applied to the elastic stress using the modified B3 model. The stress calculated at the end of the curing period is added after relaxation to the relaxed long-term stress to give the total stress from the two periods. The results are plotted against the modeled concrete tensile strength development for the user to see the potential for deck cracking.

5. Chloride Service-Life Modeling

ConcreteWorks contains a chloride diffusion service life model for mass concrete and bridge decks. The model is based on Fick's second law of diffusion, as shown in Equation 91 (Incropera and Dewitt, 2002):

$$\frac{\partial}{\partial x}\left(D_c \frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_c \frac{\partial c}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_c \frac{\partial c}{\partial z}\right)=\frac{\partial c}{\partial t}$$ **Equation 91**

where D_c is the concrete diffusion coefficient (m^2/s), and c is the chloride concentration (%). Equation 91 assumes that the concrete is uncracked and saturated, the density is constant, and that diffusion is the only mass transport mechanism (the mass transport from any temperature gradient or pressure gradient is negligible). A comparison of Equation 8 and Equation 91 show that the mechanisms for heat transport and mass transport are similar and may be calculated using the same numerical scheme.

The concrete service life can be modeled using a simplified corrosion damage model proposed by Tuutti (1982), as shown in Figure 42. The concrete is assumed to be undamaged during a corrosion initiation period. The corrosion initiation period ends when a threshold chloride concentration is reached, indicating that the protective steel passive layer has been broken down and corrosion has initiated. After the corrosion has initiated, damage in reinforcing bars is assumed to occur linearly with time. The propagation period for reinforcing bars is assumed to occur over a period of 6 years. Prestressed strand service life is assumed to end when the chloride threshold is reached because of the increased consequences of strand failure and higher rates of corrosion in the highly stressed strands.

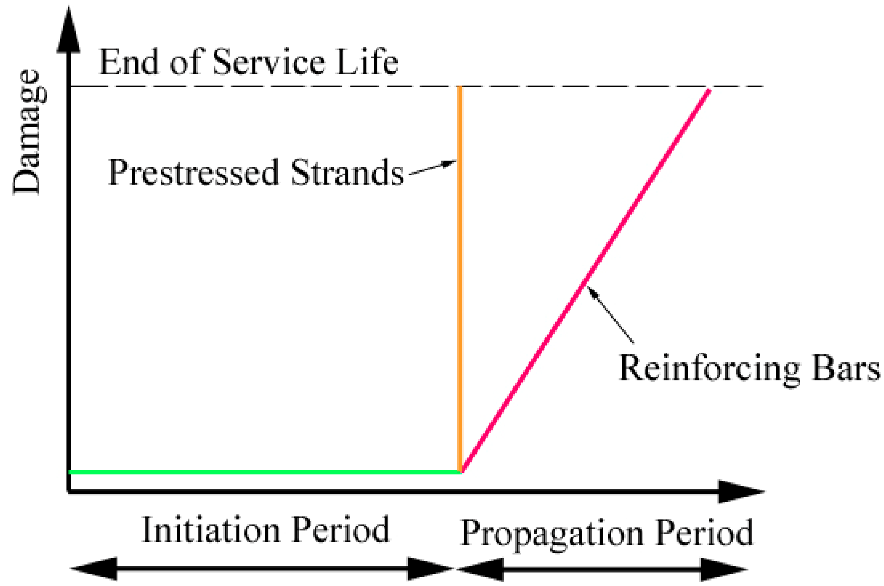


Figure 42 - Damage model used in ConcreteWorks *based on the Tuutti Model (1982)*

The service life model used in ConcreteWorks assumes that the concrete is uncracked, and that the chloride ingress occurs only through diffusion. The concrete structure service life will be lower than that predicted if joints are not properly sealed, cracks occur and are not sealed properly, if the service conditions or materials used differ significantly from those used in the software inputs, or if the concrete is not cured properly. Significant engineering judgment is needed in ensuring that the software results, including the software limitations are applied properly.

5.1. Diffusion Coefficient

The diffusion coefficient for concrete changes as the concrete hydration progresses and the porosity decreases. Both the total amount of porosity and the interconnectedness of the porosity play a significant role in concrete mass transport. Concrete diffusivity will decrease as hydration progresses and the pore size distribution changes and the network of pores becomes more discontinuous. This decrease in porosity and consequent diffusivity should decrease indefinitely; there is a limit to how much the concrete diffusivity can decrease. ConcreteWorks assumes that the concrete diffusion coefficient decays asymptotically to an ultimate value as shown in Equation 92–94 (Thomas, 2007 personal communication). The ultimate diffusion coefficient value is shown in Equation 93. Elevated temperatures will increase the chloride diffusion, and may be approximated using an Arrhenius type relationship. The concrete diffusion coefficient is multiplied by an Arrhenius temperature adjustment term as shown in Equation 94 (Bentz and Thomas, 2001).

$$D_t(t) = D_{28} \cdot \left(\frac{28}{t}\right)^m + D_{ult} \cdot \left(1 - \left(\frac{28}{t}\right)^m\right) \qquad \textbf{Equation 92}$$

$$D_{ult} = D_{28} \cdot \left(\frac{28}{36500} \right)^m$$ **Equation 93**

$$D_{tT}(t,T) = D_t(t) \cdot \exp\left[\frac{U}{R} \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right]$$ **Equation 94**

where $D_t(t)$ is the concrete diffusion coefficient (m^2/s) at time t (days), D_{28} is the 28-day concrete diffusion coefficient (m^2/s), m is the concrete diffusion decay constant, U is the diffusion process activation energy, which can be assumed to 35000 J/mol, R is the universal gas constant (8.314 J/K/mol), T_{ref} is the concrete diffusion coefficient reference temperature (293 K), and T is the temperature of the concrete (K). Figure 43 and Figure 44 show the effect of a change in the 28-day concrete diffusion coefficient D_{28} and the decay constant m on the concrete apparent diffusion coefficient.

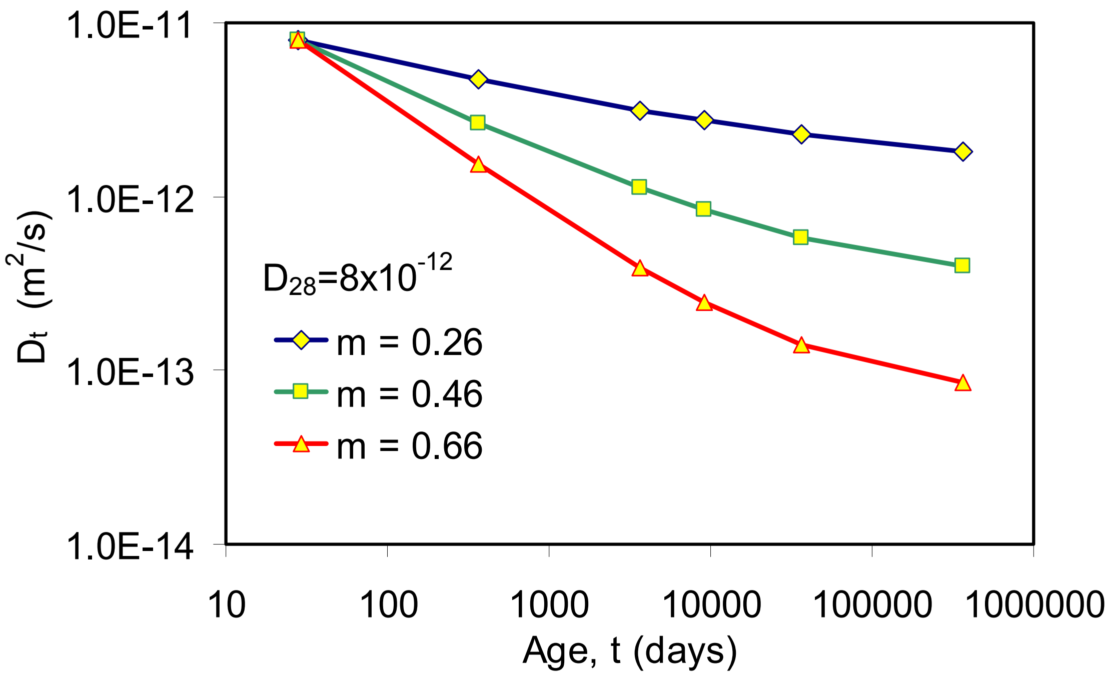


Figure 43 - Effect of a change in the decay constant m on the concrete apparent diffusion coefficient D_t

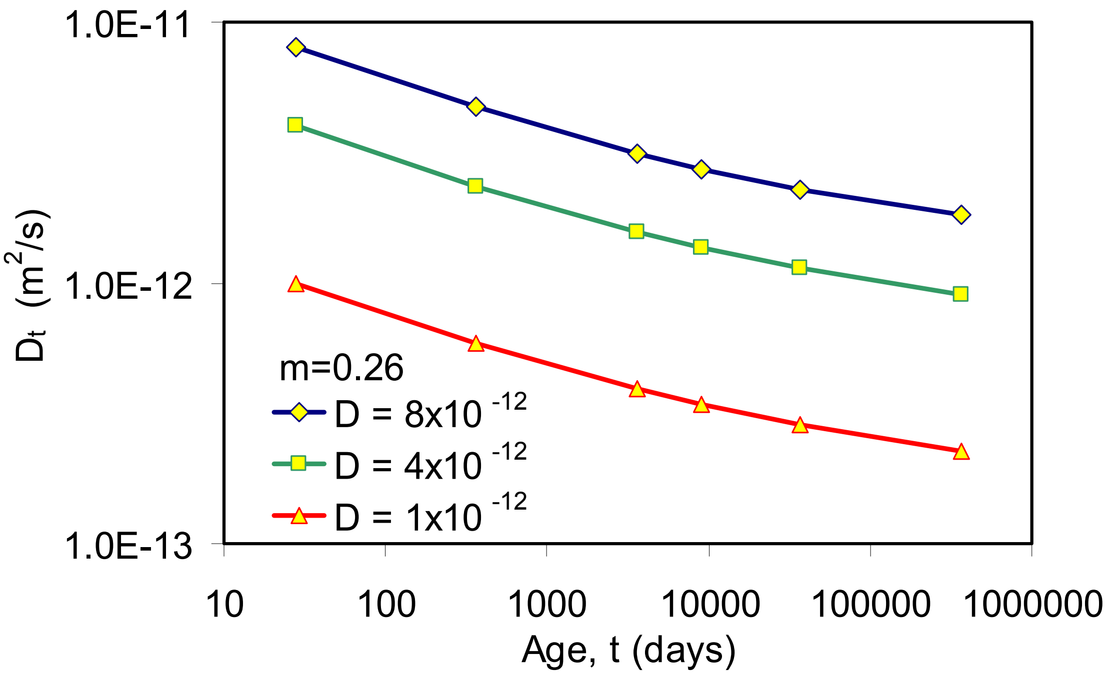


Figure 44 - Effect of a change in the 28-day apparent diffusion coefficient on the concrete apparent diffusion coefficient D_t with time

ConcreteWorks uses the yearly temperature profile calculated from the weather data files for the city selected in Equation 94. The value for each temperature point used in the yearly temperature profile is calculated as the average of the 24 hourly temperature points for the day selected. When the user selects 12 temperature points per year, the 12 temperature data points are calculated using the first day of each month. When the user selects 24 points per year, the 24 temperature data points are calculated using the first and fifteenth days of each month. When the user selects 52 temperature points per year, a temperature point is calculated for every 7 days.

All concrete bulk diffusion material models used in ConcreteWorks were developed by Mike Thomas at the University of New Brunswick (UNB) based on tests performed according to ASTM C 1556. The literature reports many differences in reported chloride diffusion values because of differences in material, testing conditions, and analysis method. Because the materials used were well characterized, the testing and analysis methods are known, and for consistency, only data collected at the University of Toronto (UT) and UNB was used in developing the concrete diffusion coefficient material models used in ConcreteWorks (Mike Thomas, 2007 Personal Communication).

5.2. Water-to-Cementitious-Materials Ratio

The water-to-cementitious-materials ratio (w/cm) is a major factor in the chloride diffusion coefficient. It is well known that the concrete porosity and consequently permeability decreases as the w/cm decreases (Mindess, Young, and Darwin, 2003). The base 28-day diffusion coefficient D_{28} used in ConcreteWorks is calculated using the w/cm as shown in Equation 95:

$$D_{28} = 2.17 \cdot 10^{-12} \cdot e^{\frac{w/cm}{0.279}}$$ **Equation 95**

Figure 45 shows the test results from a study performed at UNB and UT used to model the effect of w/cm ratio on the concrete 28-day bulk diffusion value. All of the tests shown in Figure 45 were cast with a type I cement with 12% C3A, with w/cm ratio varying between 0.2 and 0.8, and cement contents varying between 225 and 725 kg/m^3 (Mike Thomas, 2007 Personal Communication).

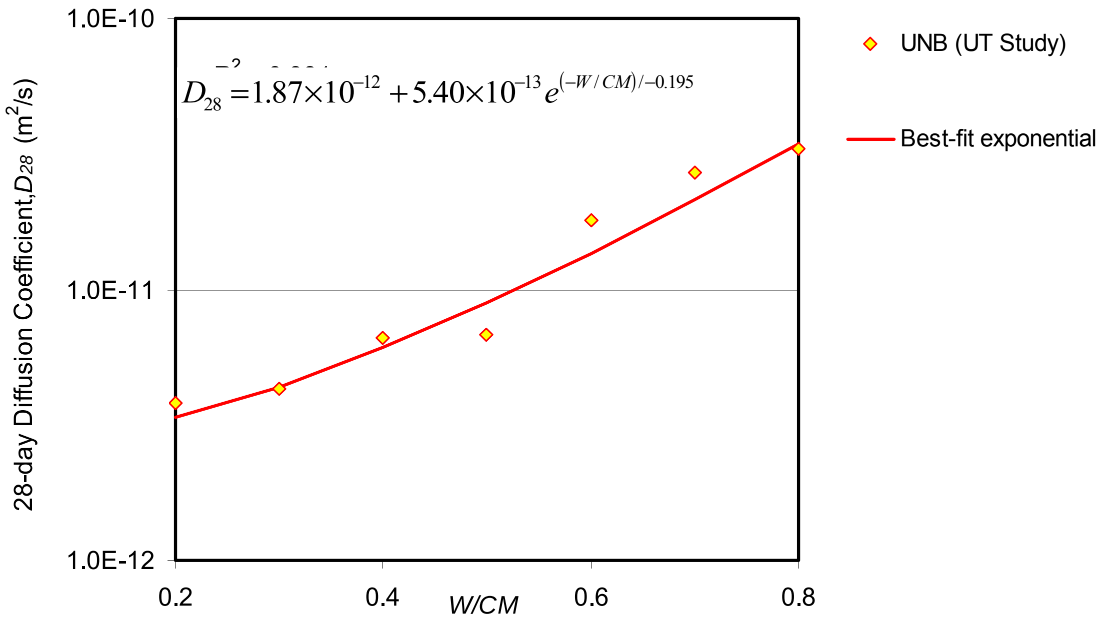


Figure 45 - Relationship between 28-day concrete apparent diffusion coefficient and w/cm

5.2.1. Supplementary Cementing Materials

Supplementary cementing materials can reduce the diffusivity of concrete by reducing the porosity and pore size distribution of concrete (Mindess, Young, and Darwin, 2003). Ultra-fine fly ash and silica fume will reduce the 28-day diffusivity by particle packing and the pozzolanic reaction that will occur at a faster rate because of the high surface area. The effect of ultra-fine fly ash and silica fume on concrete 28-day diffusivity is calculated in ConcreteWorks using Equation 96 and Equation 97:

$$\frac{D_{UFFA}}{D_{PC}} = 0.170 + 0.829 e^{(-UFFA/6.07)}$$ **Equation 96**

$$\frac{D_{SF}}{D_{PC}} = 0.206 + 0.794 e^{(-SF/2.51)}$$ **Equation 97**

where D_{UFFA} is 28-day diffusivity of concrete containing ultra-fine fly ash (m^2/s), D_{PC} is the 28-day diffusivity of concrete containing no supplementary cementing materials (m^2/s), *UFFA* is the percent replacement of cement with ultra-fine fly ash, D_{SF} is the 28-day diffusivity of concrete containing silica fume (m^2/s), and *SF* is the percent replacement of cement with silica fume. The concrete diffusivity adjustments used for silica fume replacement are based on bulk concrete diffusivity tests performed using ASTM C 1556 and an immersion period of 35 days. The concrete diffusivity adjustments used for ultra-fine fly ash are based on bulk diffusivity tests using ASTM C 1556 using an immersion period of 40 days. Both silica fume and ultra-fine fly ash testing were performed at UNB and UT (Mike Thomas, 2007, personal communication).

Fly ash will reduce the later age concrete diffusivity due to the pozzolanic reaction although there is no clear trend on the effect of fly ash on the young concrete (28 day) diffusivity. No model has yet been developed that can explain why some fly ashes will increase the 28-day concrete diffusivity while other will decrease it. Because of this inconsistency, fly ash is assumed to have no effect on the 28-day concrete apparent diffusivity. Fly ash will, however, increase the reduction in the concrete bulk diffusivity with time, as modeled using the concrete diffusivity m parameter. Ground granulated blast furnace slag will also increase the reduction in the concrete bulk diffusivity. A linear increase in the m parameter (which consequently reduces the concrete diffusivity with time) is used in ConcreteWorks as shown in Equation 98:

$$m = 0.26 + 0.4\left(\frac{FA}{50} + \frac{SG}{70}\right) \qquad \textbf{Equation 98}$$

where *FA* is the percent cement replacement with fly ash, and *SG* is the replacement with ground granulated blast furnace slag (Mike Thomas, 2007, personal communication).

5.3. Chloride Surface Concentration

The chloride surface concentration is a major parameter in calculating the chloride concentration profile with time. For relatively constant boundary conditions, such as marine exposure conditions, the surface concentration can be accurately modeled. For structures such as bridge decks and parking garages, the surface concentration will vary dramatically even in the same structure. The local conditions in the member may vary because of local differences in slope, proximity to drains, location relative to wheel paths and deicer salt application, and local variability in materials. Chloride service life analysis can still be used as a design tool to compare the relative performance of different materials.

5.3.1. Chloride Surface Concentration Buildup

The concrete surface concentration will also change with time. The concrete surface level will be higher during the winter when deicer salts are applied to the road, and lower in the summer and after rain storms wash away some of the salt. A smooth curve may, however, be used as a good approximation of the seasonal surface chloride concentration build-up, as shown in the hypothetical surface chloride buildup and approximation in Figure 46.

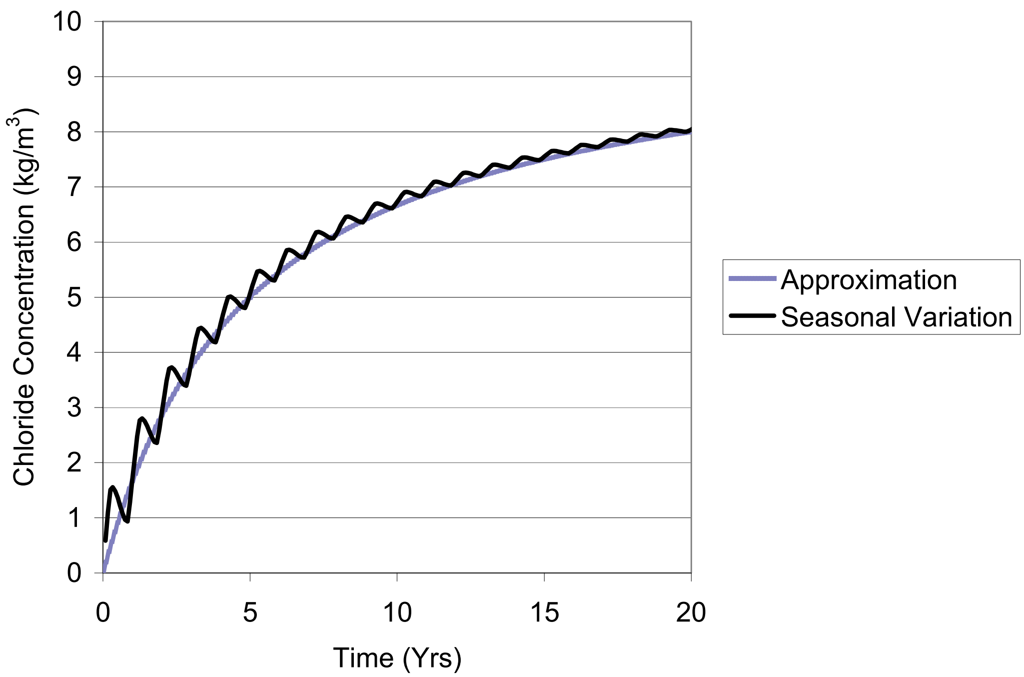


Figure 46 - Chloride surface concentration versus time with and without accounting for seasonal variations

ConcreteWorks uses a smooth curve to approximate the surface chloride according to Equation 99:

$$C_s(t) = C_{s\max} \cdot \frac{b \cdot t}{1 + b \cdot t}$$ **Equation 99**

where $C_s(t)$ is the chloride surface concentration with time t (years), C_{smax} is the maximum chloride surface concentration, and b is the chloride surface concentration build-up rate constant. The time t is not equal to zero at the time the concrete is placed, but at the age of the concrete when it is exposed to chlorides.

The maximum chloride surface concentration and build-up rate constant for each city used in ConcreteWorks are stored in a data file in the application's root directory. Three possible structural classifications are used in determining the maximum chloride surface concentration: Urban Bridge, Rural Bridge, and Parking Garage, similar to those used in the software Life365 (Bentz and Thomas, 2001). If the city selected is near the ocean, the user will also have the option of siting the structure in a marine splash zone, spray zone, within 0.5 miles of the ocean, and within 1 mile of the ocean. The maximum chloride surface concentration and build-up rate constants used in ConcreteWorks for marine exposure are shown in Table 12. ConcreteWorks uses the same maximum surface concentration values as found in the software package Life365, except for Florida. The build-up rate constants used in ConcreteWorks were determined by fitting the initial slope of the smooth curve used in ConcreteWorks to the initial slope of the bilinear surface concentration build-up used in Life-365. The build-up rate constant for a few of the cities available for selection in Texas were increased, while the build-up rate constants for the Florida cities were decreased to better reflect the amount of deicer salt actually used. Figure 47 shows the build-up rate constants used in ConcreteWorks. In order to determine the build-up rate constant for cities in

ConcreteWorks that were not available in Life365, the annual snowfall for each city was compared to that of other cities in the same state for which values were available in Life365. This approach is expected to give a reasonable approximation for these cities, because states usually have uniform deicer salting policies. The maximum surface concentrations used for different exposure conditions corresponding to the build-up rate constant are shown in Table 13.

Table 12 - Chloride surface concentration constants used in ConcreteWorks for marine exposure

Exposure condition	Maximum surface concentration (%)	Build-up rate constant
Splash zone	0.8	Instantaneous
Spray zone	1	0.15
Within 0.5 miles of ocean	0.6	0.06
Within 1 mile of ocean	0.6	0.03

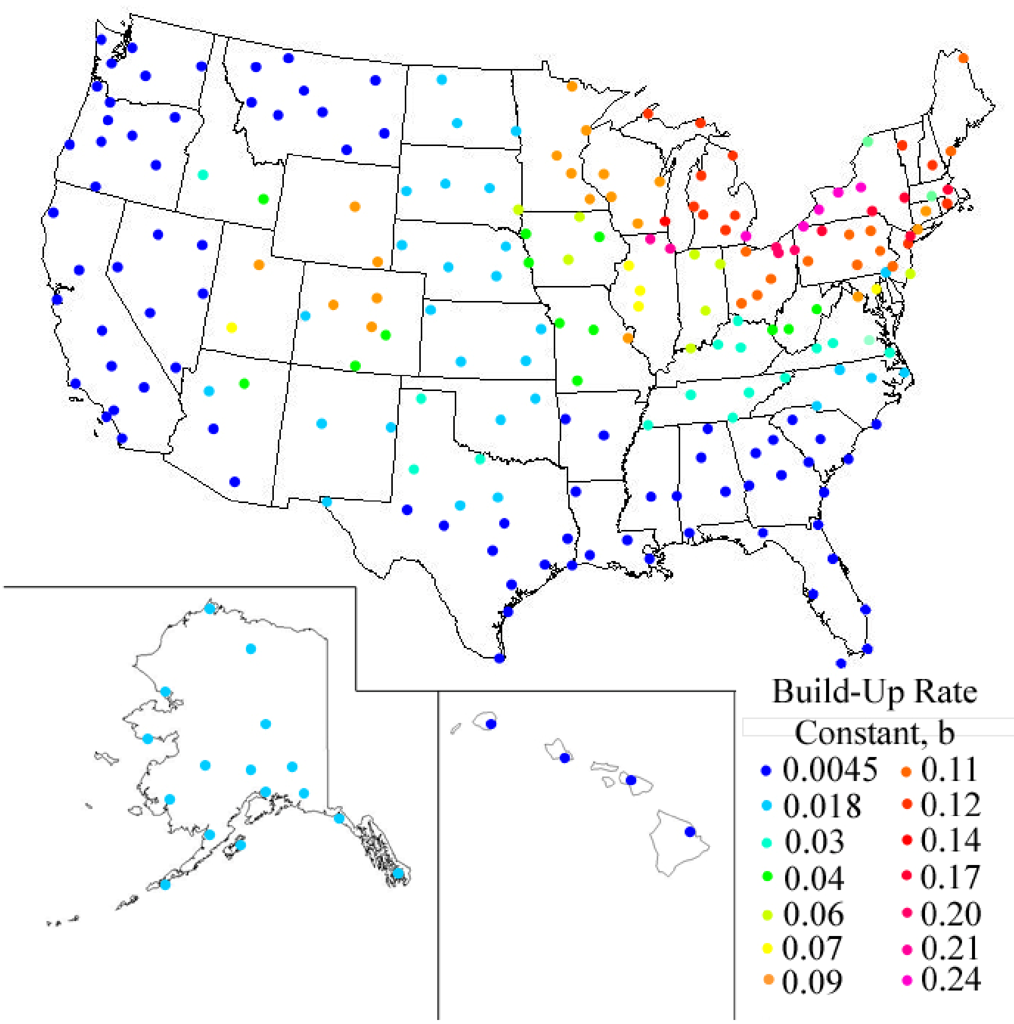


Figure 47 - Build-up rate constants used in ConcreteWorks

Table 13 - Build-up rate constants with their corresponding maximum surface concentration values used in ConcreteWorks

Build-up Rate Constant	Parking Garage Maximum Surface Concentration, C_{smax}	Urban Road Maximum Surface Concentration, C_{smax}	Rural Road Maximum Surface Concentration, C_{smax}
0.0045	0.8	0.68	0.56
0.018	0.8	0.68	0.56
0.03	0.8	0.68	0.56
0.04	0.8	0.68	0.56
0.06	0.8	0.68	0.56
0.07	0.8	0.68	0.56
0.09	0.8	0.68	0.56
0.11	0.8	0.68	0.56
0.12	0.8	0.68	0.56
0.14	0.8	0.68	0.56
0.17	0.8	0.68	0.56
0.20	1.0	0.85	0.7
0.21	1.0	0.85	0.7
0.24	1.0	0.85	0.7

5.3.2. Membranes and Sealers

Membranes are modeled in ConcreteWorks by using an equivalent time approach. The equivalent age used in calculating the chloride surface concentration in Equation 99 is considered zero during the warranty period. After the warranty period ends, the membrane is assumed to degrade linearly. The change in the surface chloride build-up equivalent age for a time step during the membrane degradation period is assumed to follow Equation 100:

$$t_{esc} = \sum_{t_{ewp}}^{t_{edp}} \frac{(t - t_{ewp}) \cdot \Delta t}{t_{edp} - t_{ewp}} \qquad \textbf{Equation 100}$$

where t_{esc} is the equivalent time for calculating the surface concentration (years), t_{ewp} is the time when the warranty period ends (years), t_{edp} is the time when the degradation period ends, which is equal to the warranty period plus the degradation period (years), t is the real time, and Δt is the time step used. After the degradation period ends, the change in equivalent time for calculating the surface concentration is equal to the change in real time.

Sealers are also modeled using an equivalent time approach. Sealers are also assumed to degrade linearly, from being 100% effective at the time of application to 0% effective at the end of the degradation period. Sealers are assumed to be 100% effective again when reapplied. Figure 48 shows a comparison of the chloride surface concentration build-up without a membrane or sealer, with a membrane, and with a sealer used. In this case, the membrane is assumed to have a 10-year warranty period and a 10-year degradation period. The sealer is assumed to have a 5-year degradation period and be reapplied every 5 years.

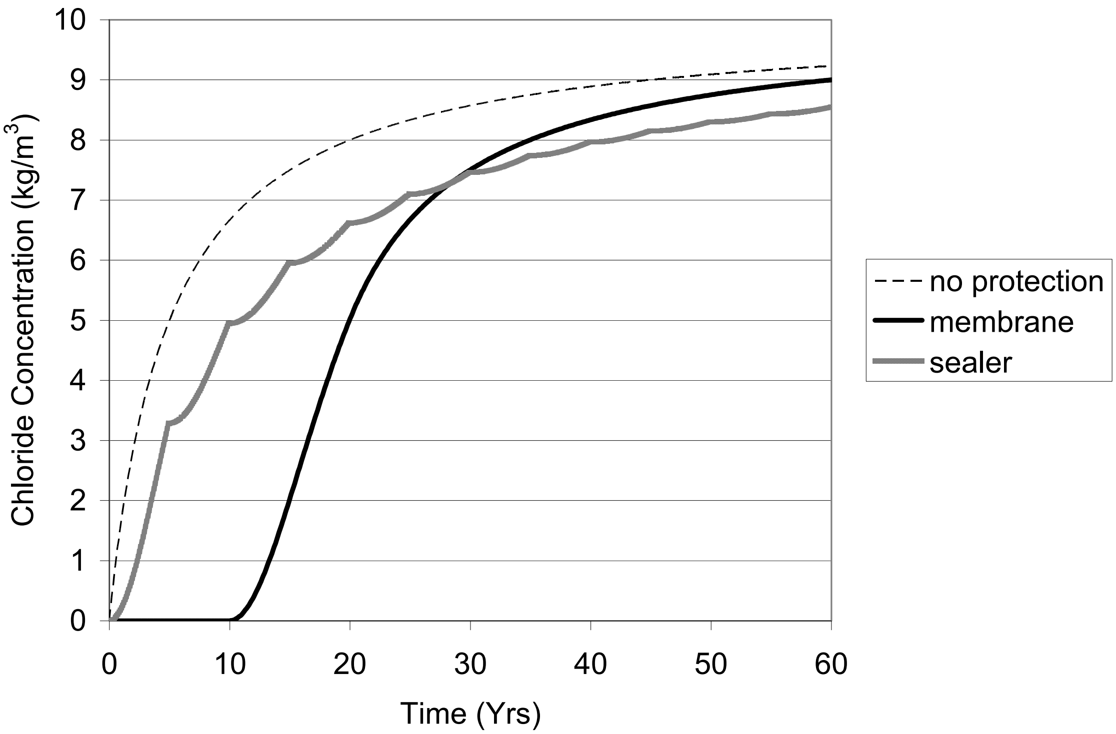


Figure 48 - Chloride surface concentration for cases where no barrier protection method is used, a membrane is used, and a sealer is used

5.4. Chloride Threshold

In ConcreteWorks, corrosion is assumed to initiate after the chloride concentration at the steel reaches a threshold value. A one-size fits all corrosion threshold value is certainly not valid. Many different chloride threshold values are published in literature. However, a comprehensive model for determining the chloride threshold value from the temperature, relative humidity, mixture proportions, and steel type used does not currently exist. A single chloride threshold value that is dependent on the type of steel chosen is a reasonable assumption for design. A chloride threshold value of 0.07% chloride by mass of concrete is used for black steel and epoxy coated steel (need references). A chloride threshold value of 0.7% chloride by mass of concrete is used for grade 316 Stainless steel.

ConcreteWorks contains inputs for two types of corrosion inhibitors, calcium-nitrite-based corrosion inhibitors or amines and esters. ConcreteWorks uses the same chloride threshold values as Life365 when a corrosion inhibitor is used, as shown in Table 14. Corrosion inhibitors in ConcreteWorks are only used in the cast-in-place concrete. This means that if the user selects a precast panel to be used with a bridge deck, the chloride threshold value of the steel in the precast panel does not change when a corrosion inhibitor is used in cast-in-place concrete above it. In addition, like Life365, the diffusion coefficient is reduced by 10% and the chloride surface concentration build-up rate constant is also reduced by 50% when amines and esters are selected.

Table 14 - Chloride threshold values assumed for black steel based on corrosion inhibitor dose

Corrosion Inhibitor and Dosage	Chloride Threshold Value (% of Concrete)
Calcium Nitrite at 10 L/m^3	0.15
Calcium Nitrite at 15 L/m^3	0.24
Calcium Nitrite at 20 L/m^3	0.32
Calcium Nitrite at 25 L/m^3	0.37
Calcium Nitrite at 30 L/m^3	0.40
Amines and Esters at 5 L/m^3	0.12

5.5. Initial Chloride Profile

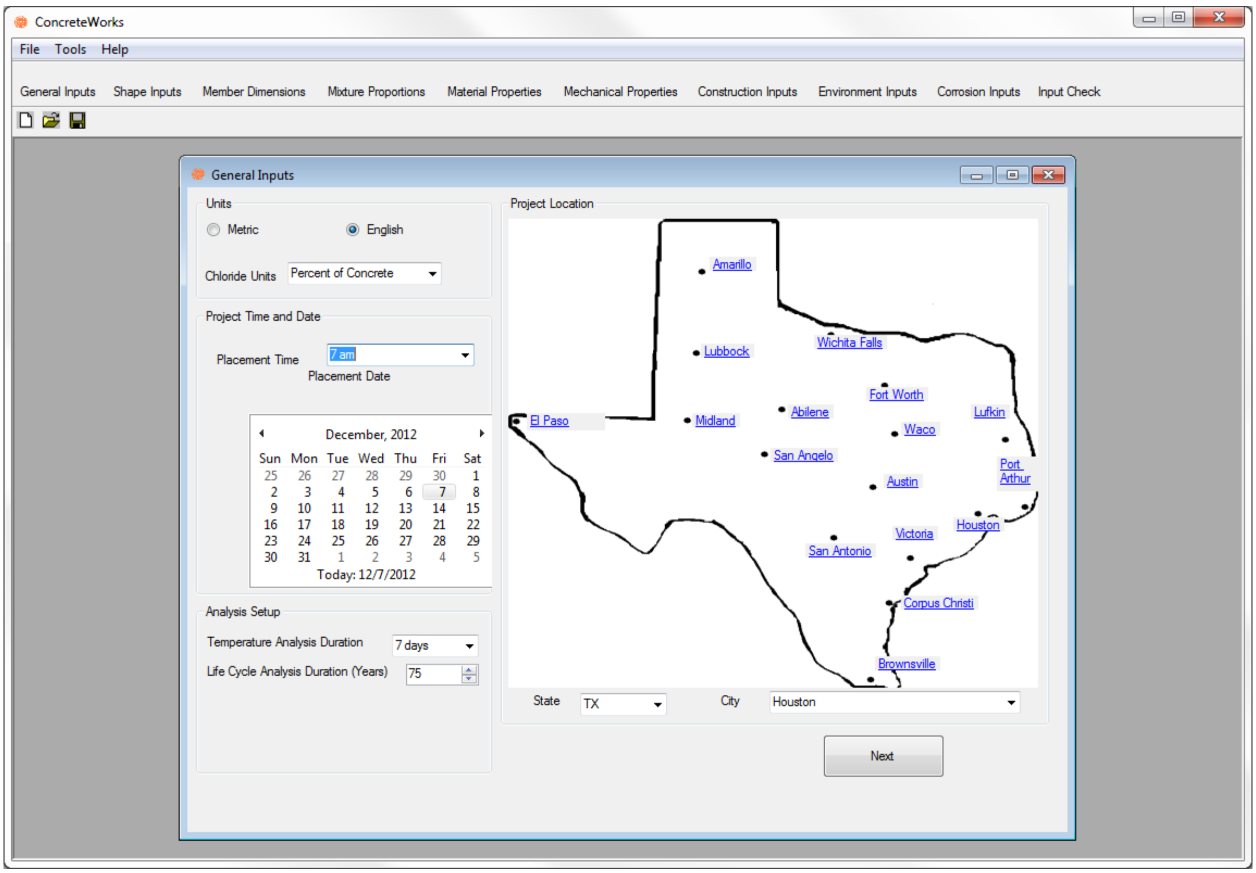
ConcreteWorks contains an option to model the chloride diffusion considering an initial chloride profile. This initial chloride concentration profile may be used because of the addition of a significant amount of chlorides in the concrete mixture (such as the ill-advised use of sea water instead of fresh water or the use of a calcium-chloride based admixture in reinforced concrete). Additionally, the initial chloride profile may be used to enter the chloride profile obtained from performing chloride profile grinding of the actual structure. Considerable engineering judgment should be used in performing this type of test and the subsequent service life analysis. Chloride profile tests can be highly variable depending on the location in the structure because of local water runoff conditions and local variability in the concrete cover quality. When an existing structure is modeled, the age of the structure is added to the time used in determining the chloride surface concentration and the concrete diffusion coefficients. The default chloride surface concentration constants should be altered to account for the actual concrete chloride surface concentration and the expected future concentrations. This type of analysis should only be performed by those intimately familiar with the service life calculation methods used in ConcreteWorks and those with considerable experience in corrosion investigations. Additionally, if corrosion has already initiated, the use ConcreteWorks to estimate the remaining concrete service life is not recommended.

ConcreteWorks

Version 3.0[1]

Operator's Manual

This program is made possible through funding by the Texas Department of Transportation under TxDOT Project 4563 and 6332 (Project Director: Ralph Browne).



6. Operator's Manual

6.1. Getting Started

6.1.1. Introduction to Using ConcreteWorks

ConcreteWorks is a suite of Windows®-based concrete technology programs intended for use by engineers, researchers, inspectors, contractors, and precasters already familiar with concrete materials and construction practices. The first program in the series is the self-titled ConcreteWorks program. ConcreteWorks is a concrete durability design tool that may be used to predict temperature development, thermal stress cracking probability, or the concrete chloride service life for various concrete members, as explained in the software introduction. ConcreteWorks is meant to be used by operators described above that have a working knowledge of concrete behavior. It is recommended that ConcreteWorks users thoroughly read the background information on the software to understand some of the limitations and the assumptions made in the software.

Mix Proportions is a program that assists the user in concrete mixture design and proportioning. *Mix Proportions* is based on the procedures outlined in ACI 211 (1991) and National Highway Institute (NHI) Course 15123 (Hover, 2003). This user manual provides help with using the program ConcreteWorks. No warranty of the accuracy of results calculated by any of the ConcreteWorks programs is given or implied.

6.1.2. Installation

To install ConcreteWorks, the target computer must be running the Microsoft .NET Framework v3.5. The .NET Framework should be updated through automatic updates.

Once the target computer is running the .NET Framework, you may install ConcreteWorks. ConcreteWorks may be downloaded from www.texasconcreteworks.com. Once downloaded, the user should unzip the downloaded file and double-click on the setup.exe file to begin installation. The program should then start the Installation Wizard.

The installation wizard will guide you through all of the necessary steps to install ConcreteWorks. The first screen is the installation welcome screen. Click the *Next* button to continue with the installation. The second screen contains the End-User License Agreement (EULA). Click the *I Agree* button if you agree with the terms of the EULA, and then click *Next*. If you do not agree with the terms of the EULA, click *I Do Not Agree* and then *Cancel*, ending the installation process. The software will not install unless you signify that you agree to the terms of the EULA by clicking *I Agree*. Internet Explorer must be on the computer to access the official ConcreteWorks website from ConcreteWorks as described in Section 6.4.7. Lack of access to Internet Explorer could result in an error and/or the program crashing.

Adobe Reader® is also required to be installed on the computer to access the ConcreteWorks *User Manual* as described in Section 6.4.7. Failure to have Adobe Reader® installed on the computer could result in an error and/or the program crashing.

6.1.3. Navigating the Program

There are two methods of opening a new or saved file in ConcreteWorks. The first method is to click on the *New File* or *Open Existing File* toolbar button. The second method is to click *New* or *Open* under the *File* Menu. Figure 49 shows a zoomed in view of the upper left side of ConcreteWorks. The red arrows point to the different menus and toolbars available in

ConcreteWorks. If a file is already open, the program will prompt to save the current file. If the *Yes* button is clicked, the program follows the save procedure outlined in Section 6.4.4. If a file is not already open, the program will prompt the user for a filename and location, as described in Section 6.4.3.

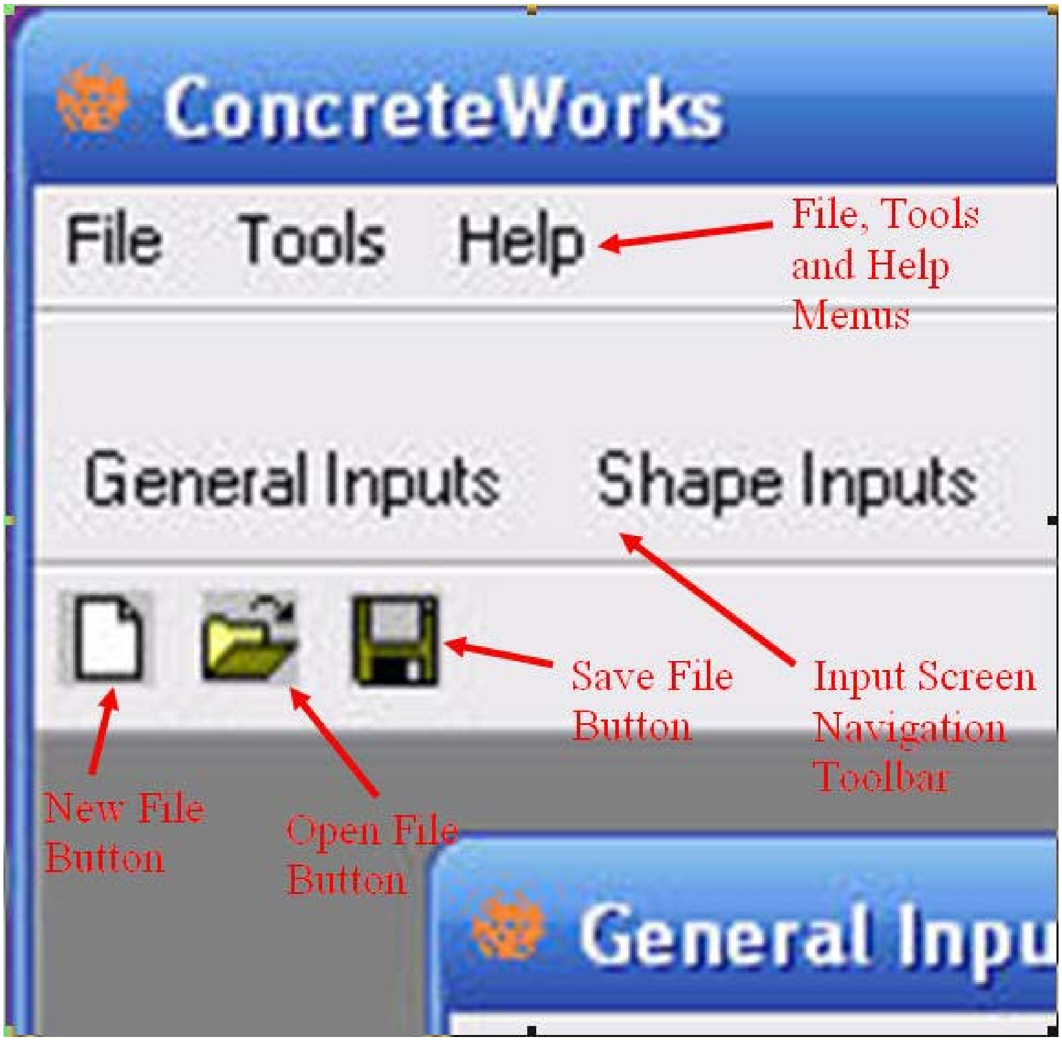


Figure 49 - Close-up view of toolbars and menus

There are also two methods of changing the current input/results screen in ConcreteWorks. The navigation toolbar found at the top of the program allows the user to quickly navigate between input/results screens. Each button, when clicked, displays the corresponding input/results screen. Clicking on the *Next* button displays the next chronological input screen. Clicking the *Back* button displays the previous screen shown. The navigation toolbar shows the order the screens are displayed.

For more information on the printing features found in the *File* menu, see Section 6.4.1. See Section 6.4.6 for more information on the *Tools* menu and Section 6.4.7 for more information on the *Help* menu.

6.2. Inputs

6.2.1. Member Type

When a new file is selected, the user is prompted to select the type of member to analyze. In ConcreteWorks v2.0, the user may select from four basic types of concrete members: mass concrete, bridge decks, pavements, or precast beams. The analysis options available for each type of concrete member are shown in Table 1 of Chapter 1. The input screens available will depend on the type of member selected, and will only be shown if needed. For example, the *Corrosion Inputs* screen is not available when the user selects the *Precast Concrete* member type because ConcreteWorks does not contain a chloride service life module for precast beams. This manual will explain the inputs for all member types; note that if the input is not applicable for a particular member type, it will simply not be shown in the software. Additionally, the *next* and *back* buttons will show the next input screen available in the same order as the order of inputs shown in the input screen navigation toolbar shown in Figure 49.

6.2.2. General Inputs

The basic model settings and project inputs are all done in the *General Inputs* screen, as seen in Figure 50. The *General Inputs* screen is the first screen shown after opening a new or saved file, which is why there's not a *Back* button shown. Changing the inputs in the *General Inputs* screen will fundamentally change other data entered later in the program. Changing the *placement date*, *analysis duration*, or *project location* will cause the weather data to change, even if maximum or minimum values have been entered earlier.

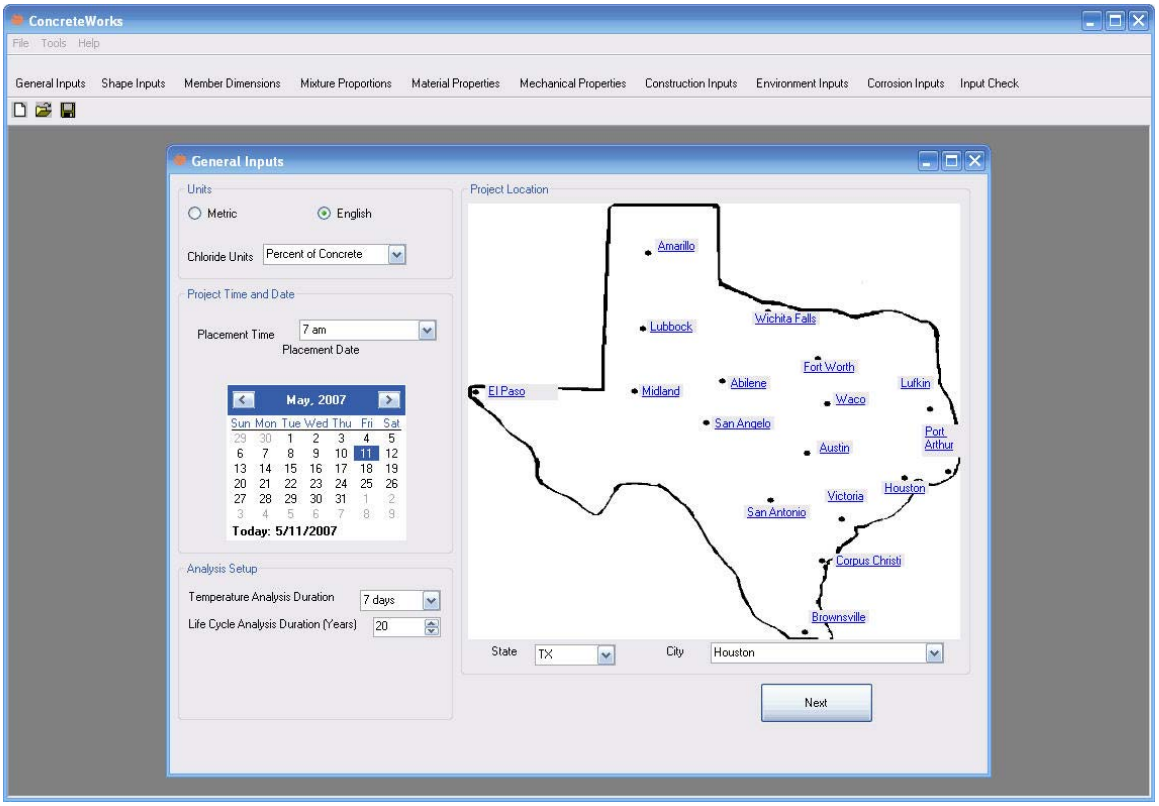


Figure 50 - General Inputs screen

Units

Many inputs in ConcreteWorks can be entered in either English units or Metric (S.I.) units. The English units system is the default units system in ConcreteWorks. When the system of units is changed, the program will prompt the user to change all values or cancel to stay in the current unit system. If the user chooses to change the values entered, the program assumes that the user entered the correct values for the old unit system, and will then multiply the entered values by the appropriate conversion factor for the new unit system. The *Chloride Units* input allows the user to select to perform the chloride service life calculations by % Chlorides by mass of concrete, or by mass per unit volume. The chloride surface concentration inputs in the *Corrosion Inputs* will be in the units chosen, as will the steel chloride threshold at corrosion initiation values, and the initial chloride concentration values.

Project Time and Date

The *Placement Time* box allows the user to enter the time concrete placement is started on the element being analyzed. If the cross section being analyzed is a horizontal cross section (such as a column), then the user should input the time concrete is placed at the particular cross section being analyzed. The default time is 7:00 a.m.

The *Placement Date* is entered by clicking on the number corresponding to the date of concrete placement. The month or year of placement can be changed by either clicking on the appropriate arrow or by clicking on the month or year. The default date is the current date.

Accurate results in ConcreteWorks depend on the user entering the correct time and date. Even if the minimum and maximum weather data is entered later in the program, the correct date and time must still be entered. The shape of the weather data plots are extracted from 30-year average data. Because of the changing sunrise and sunset times, every day has fundamentally different shape of the weather data plot. Entering the correct maximum and minimum weather data later in the program will give the correct overall magnitude for the weather data plots, but will not change the weather data's fundamental shape.

Analysis Setup

ConcreteWorks predicts the temperature development of a concrete cross section for the number of days selected under the *Analysis Duration* option. The default number of days is 7. The *Chloride Service Life Analysis Duration* input allows the user to select the number of years that are used to calculate the chloride ingress into the concrete. If the steel chloride threshold has not been exceeded during the time period selected for the *Chloride Service Life Analysis Duration*, then the results will show that the time to corrosion initiation will be greater than the *Chloride Service Life Analysis Duration*.

Project Location

Under the *Project Location* option, the user should select the closest city to the construction site that has a similar climate. Besides using the drop-down list of cities to select the project location, cities in the currently selected state can be selected by clicking on the city name in the city map. When installed, ConcreteWorks automatically installs weather data files for seventeen Texas cities (as shown on the map on the *General Inputs* screen). The files are located in the same folder as the ConcreteWorks application. Weather files for states other than Texas may be installed during the installation process. This is done by checking on the box corresponding to the state desired found on installation screen 3, as described in Section 6.1.2. Weather files for other cities will also be detected automatically and added to the available cities list by placing a copy of the weather file in the same folder as ConcreteWorks. ConcreteWorks automatically detects all weather files located in the same folder as ConcreteWorks, and adds them to the drop-down list of available cities. Caution: only genuine ConcreteWorks weather files can be recognized by ConcreteWorks. Other weather files may cause an error in the program.

6.2.3. Shape Inputs

ConcreteWorks can predict the temperature distribution for several types of mass concrete elements. All available concrete shapes available according to the type of concrete member selected are listed in the *Shape Inputs* screen.

Available Shapes

ConcreteWorks has the capability of predicting temperature development in six unique mass concrete member types, four types of bridge decks, and four precast beam shapes. ConcreteWorks also has a pavement temperature prediction built in, but because only one concrete pavement type is allowed, the *Shape Inputs* screen is not shown when pavement member types are selected. The shapes available were selected in cooperation with TxDOT engineers to reflect the most common types used in Texas. Figure 51 shows the mass concrete shapes available in the *Available Shapes* frame. Figure 52 shows the four types of bridge deck types available in the *Shape Inputs* screen, while Figure 53 shows the precast beam types available. When a shape is checked, a picture of the shape is shown to the right for confirmation. Once the desired shape is selected, proceed to the next screen.

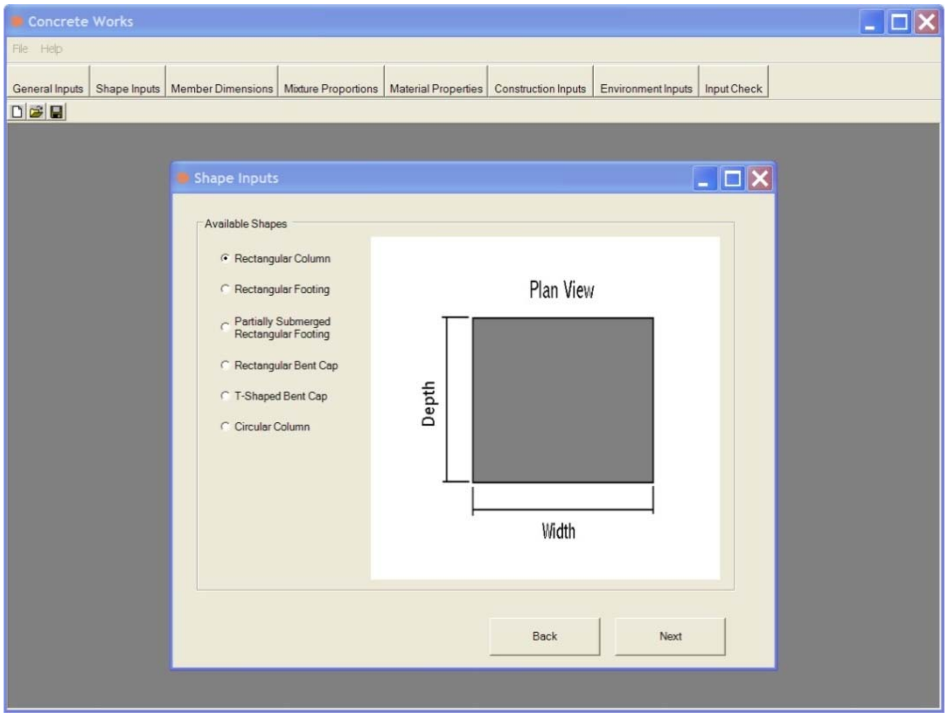


Figure 51 - Shape Inputs screen for mass concrete member types

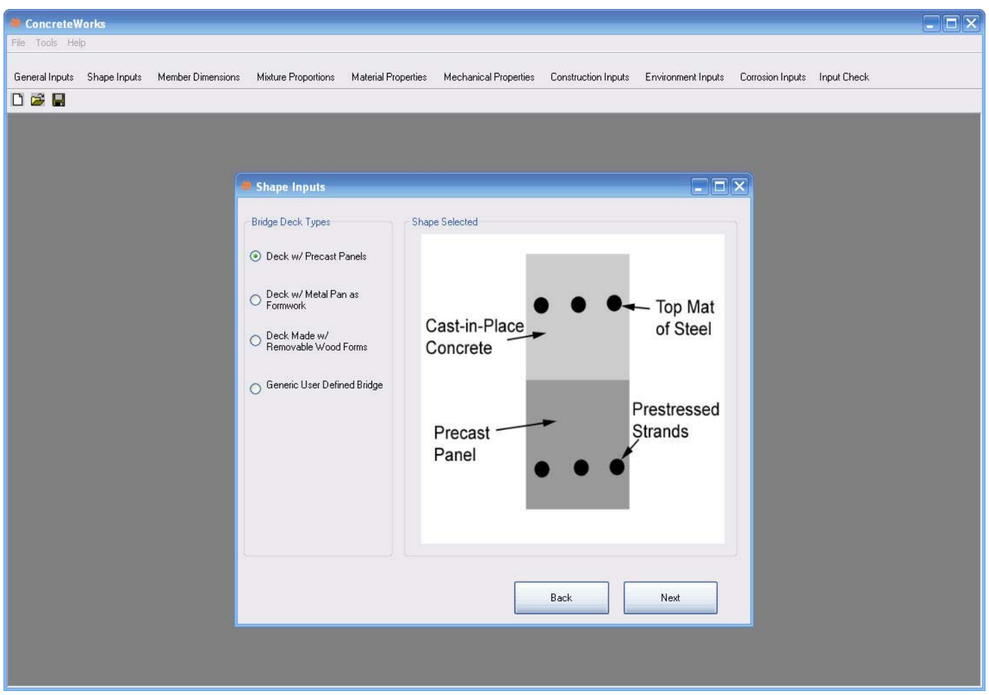


Figure 52 - Shape Inputs screen for bridge deck member types

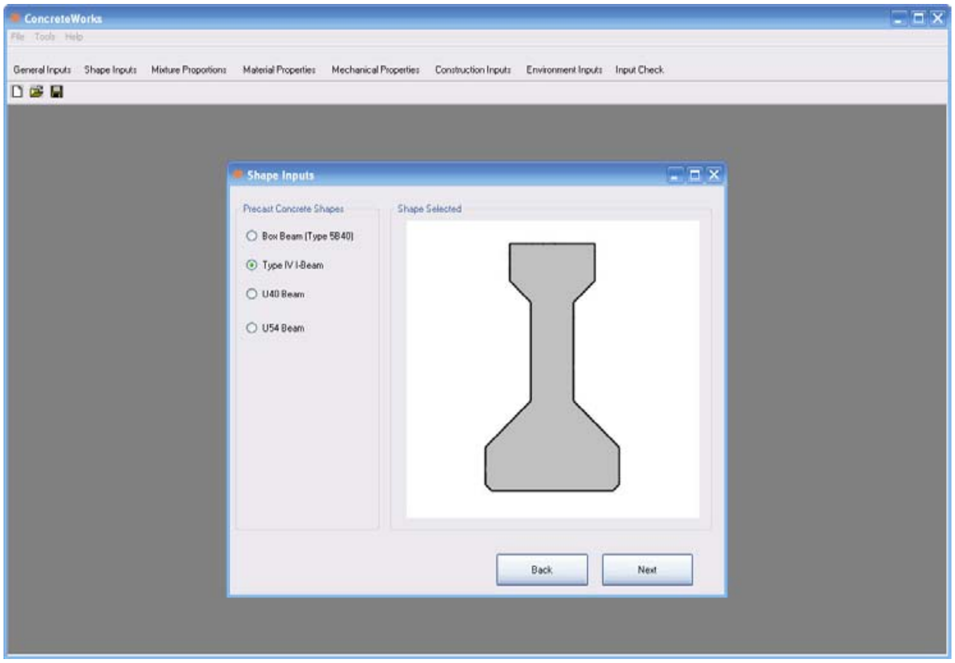


Figure 53 - Shape Inputs screen for precast beam member types

6.2.4. Member Dimensions

Each unique concrete cross section type will display a different picture and inputs on the *Member Dimensions* screen. All shapes, however, use the same basic format. Figure 54 shows the *Member Dimensions* screen for the Rectangular Column member.

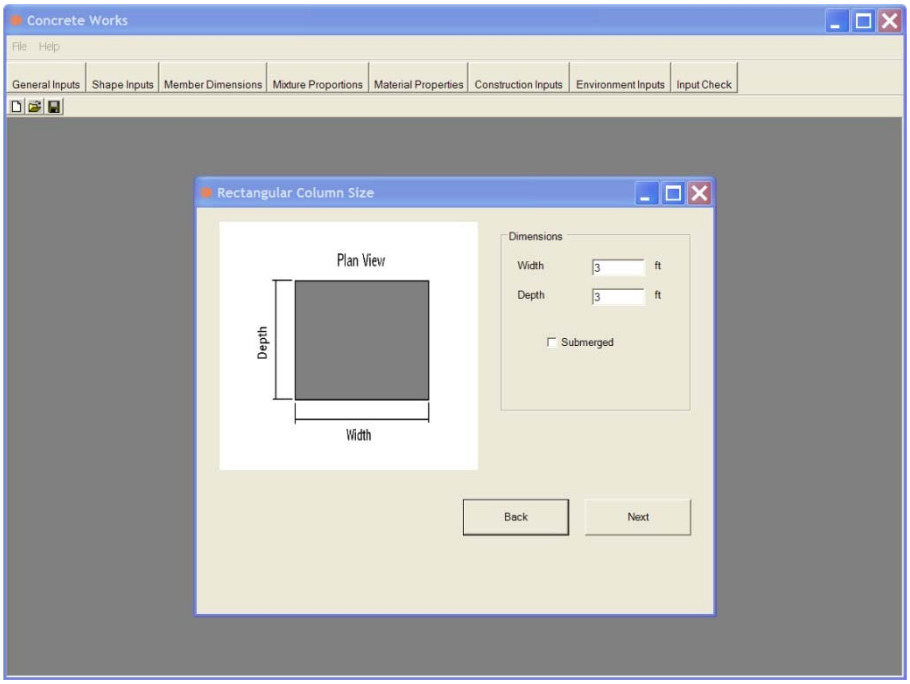


Figure 54 - Member Dimensions screen for the Rectangular Column element

Dimensions

Each shape will require the user to enter the member cross-sectional dimensions. All dimensions input will correspond to the same dimensions on the picture on the left side. Because the program's focus is on transportation-related concrete (bridges and pavements), ConcreteWorks limits the size of some member dimensions. The Rectangular Column, Rectangular Footing, Partially Submerged Rectangular Footing, and Rectangular Bent Cap have minimum dimensions of three feet each. The Circular Column has a minimum diameter of three feet. The T-Shaped Bent Cap has a minimum seat height of 9 in. and a minimum top width of 1.5 feet. The overall cap height must also be 1.5 feet taller than the seat, and the overall cap width must be 1.5 feet greater than the top width. If an invalid dimension is entered, an error will appear when the user attempts to calculate the member temperature development using the *Calculate Temperatures* button on the *Input Check* screen. Member dimension limits for decks and pavements are enforced by the numeric-up-down control used to input the dimension. The *Overall Deck Thickness* is limited to 14 in., while the *Precast Panel Thickness* is limited to 8 in. The *Pavement Thickness, Subbase 1 Thickness*, and *Subbase 2 Thickness* are all limited to 24 in.

Pavement analysis is broken up into different layers with different material properties, as shown in Figure 55. Users may select up to two types of subbase materials, in addition to the pavement and subgrade. The subgrade material is assumed to extend infinitely beneath the subbase layer(s). Pavement layer dimensions and types are not changed in ConcreteWorks until the user clicks on the *Re-Draw Pavement System* button. The figure to the right of the pavement dimensions inputs will then update, allowing the user to check the currently selected inputs.

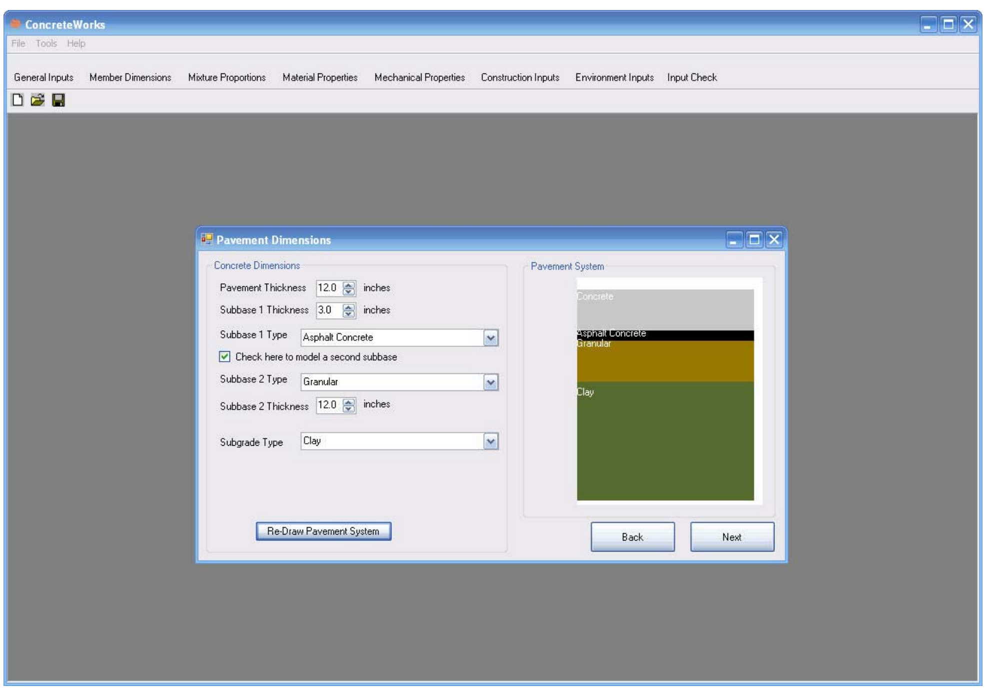


Figure 55 - Pavement Dimensions Input screen

Submerged

Some of the available member types have the option of being submerged in water. This means that the cross section being modeled is completely immersed in water. One example of when the submerged option would be selected is when a column is placed in a lake or ocean.

Soil on the Sides

Some member types have the option of modeling soil on the sides of the member. This option is selected when earthwork is used instead of formwork. Figure 56 shows an example of the type of member that would use soil on the sides instead of formwork.

Figure 56 - Example of a footing that would use the "soil on the sides" option

Cross Sections Analyzed

Temperature predictions are in some cases based on one- or two-dimensional cross sections of the member. When ConcreteWorks does not calculate the temperature distribution for a direction in a concrete member, the program assumes that there is no heat loss in that direction (i.e., perfectly insulated). For example, with the rectangular column, ConcreteWorks calculates the temperature profile of a horizontal cross section of the column. The program assumes that there is no heat loss from the top of the column to the air or from the bottom of the column to the footing. This assumption is a valid assumption for the vertical middle of the column, and becomes less accurate towards the ends in the column.

When the user decides to analyze a rectangular footing or partially submerged rectangular footing in three dimensions, the temperature distribution in the footing is calculated for all three directions. Calculating the temperature in three dimensions can give slightly better results in some cases, but significantly increases the calculation run time. The user only has the option of calculating the footing temperature in three dimensions when the user does not select soil on the sides of the footing. When the user selects to calculate a two-dimensional cross section of the footing temperatures, as seen in Figure 57, the width side is used in calculations. The length dimension entered is then ignored. The user should enter the smaller dimension of the two horizontal footing dimensions in the width text box.

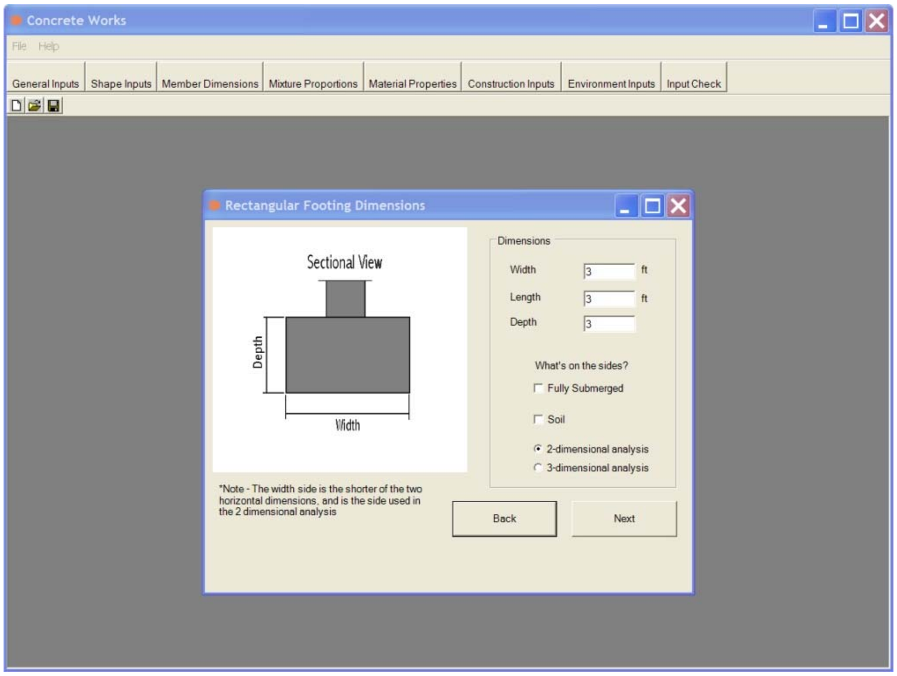


Figure 57 - Rectangular Footing screen with Two-Dimensional Analysis selected

Precast Panel Inputs

When the user selects a *Generic User Defined Bridge* on the *Shape Inputs* screen, then the user has the option of selecting to use a precast panel and the number of mats of steel. Figure 58 shows the *Bridge Deck Dimensions Inputs* screen when the *Generic User Defined Bridge* deck type is selected. When the user selects two mats of steel and a precast panel, the bottom mat of steel is assumed to be made of prestressed strands.

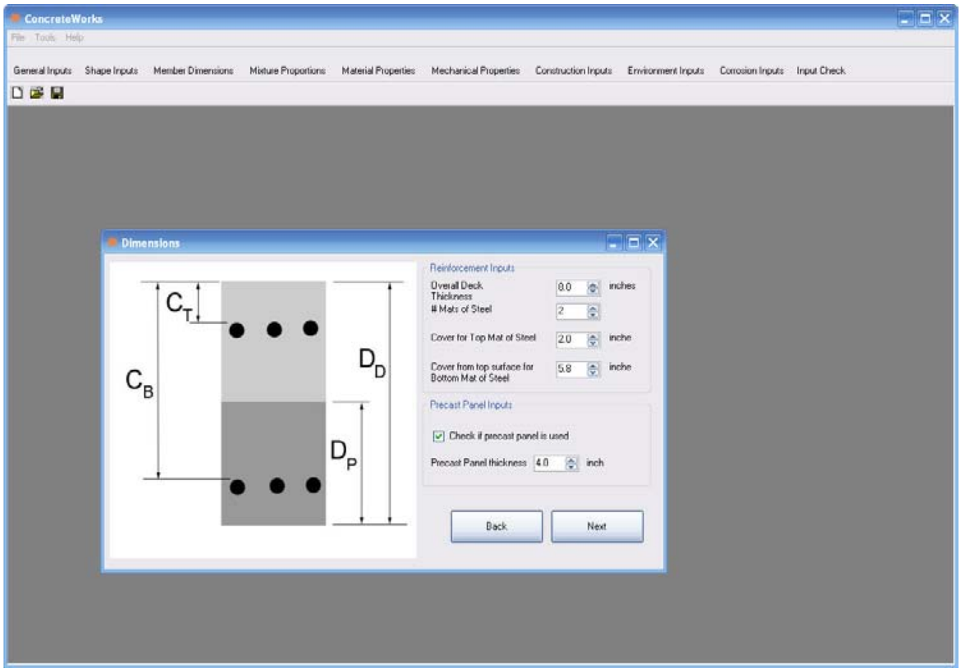


Figure 58 - Bridge Deck Dimensions Input screen when the Generic User Defined Bridge Deck Type is selected

6.2.5. Mixture Proportions

The *Mixture Proportions* screen is where the user inputs the concrete batch information, as seen in Figure 59. If blended cement is used, the user should enter the fly ash and cement quantities separately, as if they were added to the concrete completely separate.

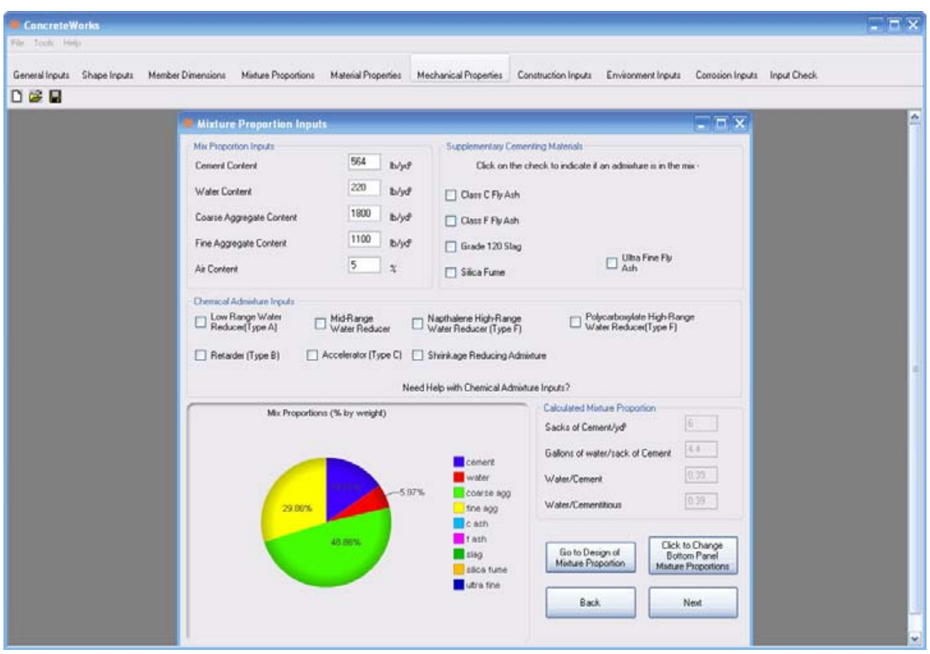


Figure 59 - Mixture Proportion Inputs screen when a bridge deck member type is selected with precast panels

Mix Proportion Inputs

All information found in the *Mix Proportion Inputs* area must be inputted correctly for the program to generate a heat signature curve for the concrete. Mixture information is entered by the amount of weight of a particular material for every unit volume (pounds per cubic yard for English units, kilograms per cubic meter for SI units). The aggregate contents are entered assuming the aggregate is saturated surface dry (SSD). The water is entered based on total amount of free water available for hydration (aggregate moisture not absorbed + water/ice added).

Supplementary Cementing Materials

The *Supplementary Cementing Materials* (SCM) frame is where SCMs are input. To include an SCM in the batch, check the box corresponding to the particular SCM. Enter in the amount of SCM used in the batch. The program defaults the free lime content of the ASTM Class C fly ash to 29% and the ASTM Class F fly ash to 19%. These values can be changed if the free lime content of the fly ash used is known. To remove the SCM from the batch, simply uncheck the corresponding box or set the amount used to zero.

Calculated Mixture Proportions

The *Calculated Mixture Proportions* frame displays calculated mixture ratios based on the current values entered. The *Sacks of Cement*/volume quantity is based on the total number of 94 pound sacks of cementitious materials used in the batch (cement + SCMs) per cubic yard/meter. The number of *Gallons of water per sack/liters per sack* figure is the amount of water per sack of cementitious materials. The density of the water is assumed to be $1 g/cm^3$ ($62.43 lb/ft^3$). The *Water/Cement Ratio* is equal to the water content entered divided by the cement content. The *Water/Cementitious Ratio* is equal to the water content entered divided by cementitious materials content.

Chemical Admixture Inputs

Chemical admixtures are entered by checking on the admixture. To simplify mixture proportion inputs, typical values of chemical admixture doses are assumed as shown in Table 5.

Bottom Panel Mixture Proportions

When a bridge deck member type with precast panels is selected, the user may change the bottom panel mixture proportions by clicking the button *Click to Change Bottom Panel Mixture Proportions*. When this button is clicked, an input screen similar to the *Mixture Proportion Inputs* screen is shown. Figure 60 shows the *Precast Panel Mixture Proportions Inputs* screen that is displayed. Here, the user may enter the mixture proportions used in the precast panel concrete. There are two visible differences between the *Mixture Proportion Inputs* screen and the *Precast Panel Mixture Proportions Inputs* screen. The first is the title shown on the blue form bar. The second is that the button on the lower right hand corner is the *Next* button on the *Mixture Proportion Inputs* screen, while on the *Precast Panel Mixture Proportions Inputs* screen is the *OK* button. The *OK* button, when clicked, will return the user to the *Mixture Proportion Inputs* screen. Although the precast panel is assumed to not generate any heat, the concrete diffusion coefficients used in the chloride service life analysis is determined from the concrete panel mixture proportions.

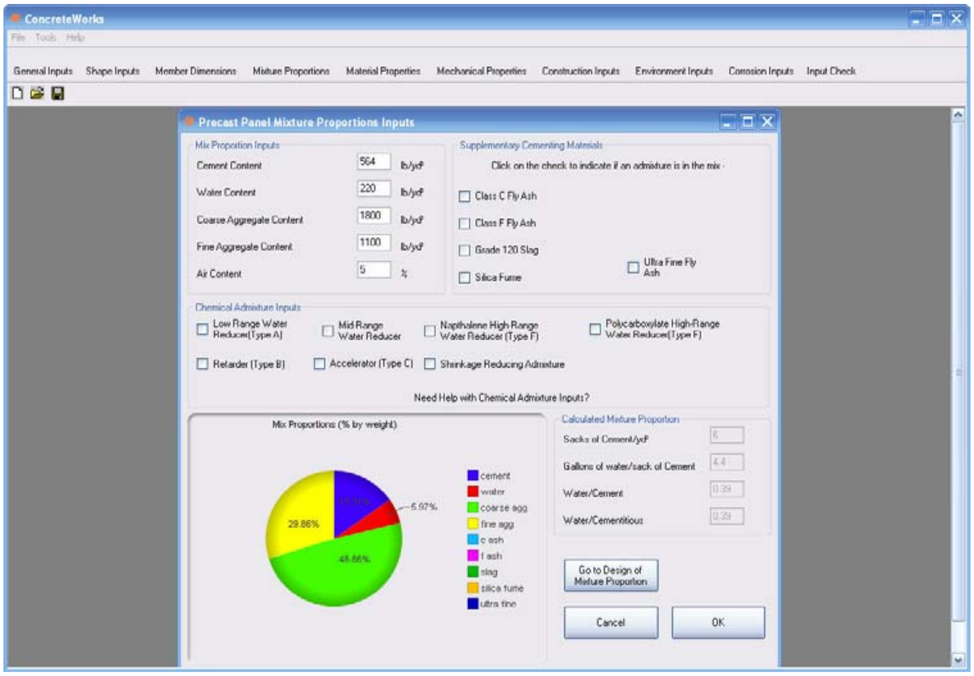


Figure 60 - Precast Panel Mixture Proportions Inputs screen

6.2.6. Concrete Mixture Proportioning

If the user needs help with the concrete mixture design and proportioning, the user may click on the *Go to Design of Mixture* Proportion button on the lower right corner of the *Mixture Proportions* screen, as seen in Figure 59. The *Design of Mixture Proportion* screen will appear, as seen in Figure 61. The *Design of Mixture Proportion* screen guides the user through the mixture proportioning steps as found in ACI 211 (1991) and NHI Course 15123 (Hover, 2003). For a more detailed presentation of the mixture proportioning procedure and limitations, please refer to ACI 211 (1991) and Chapter 2 of this document. The most important thing to remember about the mixture proportion calculations is that they are only designed to create the proportions for making and testing a trial batch. The calculations in the *Design of Mixture Proportions* screen can never be used as a substitute for local knowledge of material properties or for trial batches. This is designed to be a user-friendly tool as the first step in designing mixtures for field applications.

The *Cancel* button on the *Design of Mixture Proportion* screen sends the user back to the *Mix Proportions Inputs* screen without any changes being made to the material weights. The *OK* button sends the user back to the *Mixture Proportions Inputs* screen, changing the material weights to those shown in the *Final Volume Calculations*. When a chemical admixture is checked in the *Water Adjustment* tab, the admixture is then checked on the *Mix Proportions Inputs* screen. When the *High-Range Water Reducer (Type F)* box is checked in the *Design of Mixture Proportion* screen, ConcreteWorks assumes that a Napthalene-based admixture is used.

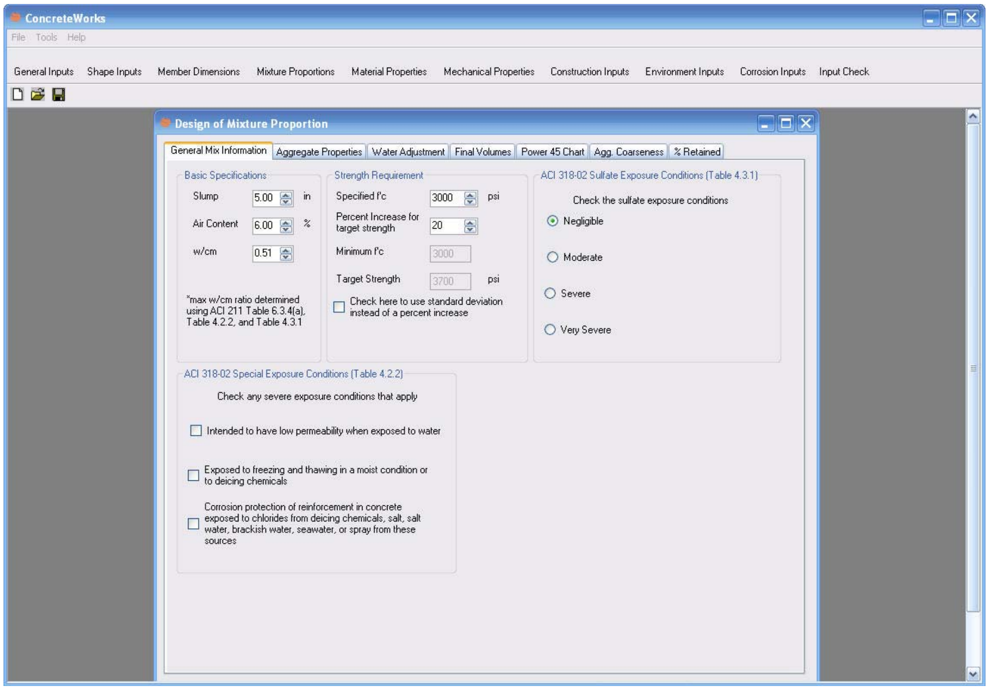


Figure 61 - Design of Mixture Proportion screen—General Mix Information inputs

General Mix Information

The *General Mix Information* tab of the *Design of Mixture Proportion* screen displays all of the general material specifications. If not entered manually, the *w/cm ratio* is calculated from the *Target Strength* shown in the *Strength Requirement* frame, the air content, and any minimum w/cm ratios imposed by selecting a severe exposure condition from ACI 318-05 Tables 4.2.2 or 4.3.1.

The target strength is calculated by default on the specified f'_c increased by the percent increase in target strength value. Alternatively, the user may calculate the concrete target strength by checking the box for using the concrete standard deviation, and then entering the standard deviation.

Aggregate Properties

The *Aggregate Properties* tab allows the user to either input the aggregate properties or calculated some of the inputs needed from an aggregate sieve analysis. Figure 62 shows the *Aggregate Properties* tab. *Sieve Analysis Data* for each aggregate type used should be entered as percent passing. Additionally, the percent of each aggregate used should be input as percent of the coarse or fine aggregate used, not the total amount of aggregates used. When the *Update Agg. Properties* button is clicked, the combined *Coarse Aggregate Specific Gravity*, combined *Fine Aggregate Specific Gravity*, and *Maximum Size Aggregate* inputs are updated. Additionally, the aggregate gradation charts are updated when the *Update Agg. Properties* button is clicked. An error is generated when the user enters a percent passing value that is larger than that from a larger size sieve, when the sum of coarse aggregate percent used values does not equal 100 percent, or when the sum of fine aggregate percent used values does not equal 100 percent. When the user checks the button that states *Instead of ACI 211, optimize aggregate weights by:*, the software will calculate the aggregate amounts to use by optimizing the selected aggregate gradation index selected instead of the ACI 211 methods.

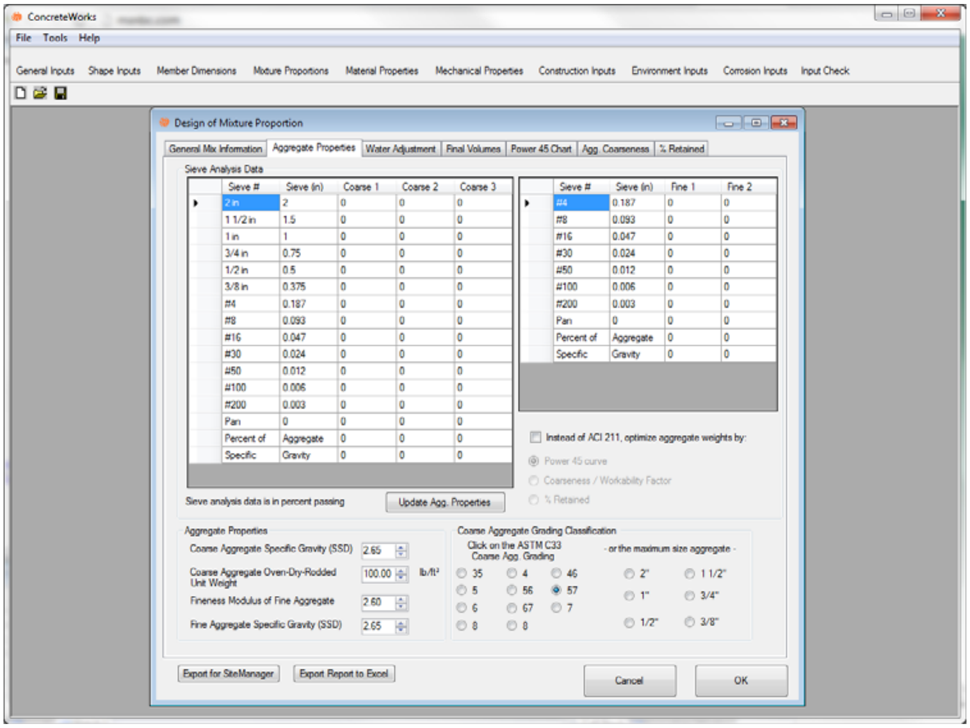


Figure 62 - Aggregate Properties tab on the Design of Mixture Proportions Inputs screen

Water Adjustment

The *Water Adjustment* tab contains tracking bars that let the user adjust the water requirements for the concrete by moving the tracking bar values, as seen in Figure 63. To use a water reducer, check the corresponding box on the *Water Adjustment* tab. Then move the track bar value to correspond to the water reduction gained from that particular admixture. The values used for maximum and minimum water reduction for all factors come from the NHI Course 15123 (Hover, 2003). A local knowledge of the water reduction properties for all the materials is extremely important. The quality of the concrete mixture designed will depend greatly on the accuracy of the inputs. Trial batches should always be made to verify the slump and strength properties of the concrete.

The *Adjusted Water Content* shown in the *Paste Content* frame is calculated based on the desired slump, the percent air, the aggregate gradation, and any water requirement adjustments made in the *Water Adjustment* tab (as described in Section 6.2.6). The cementitious material content is calculated by dividing the *Adjusted Water Content* by the *w/cm ratio*.

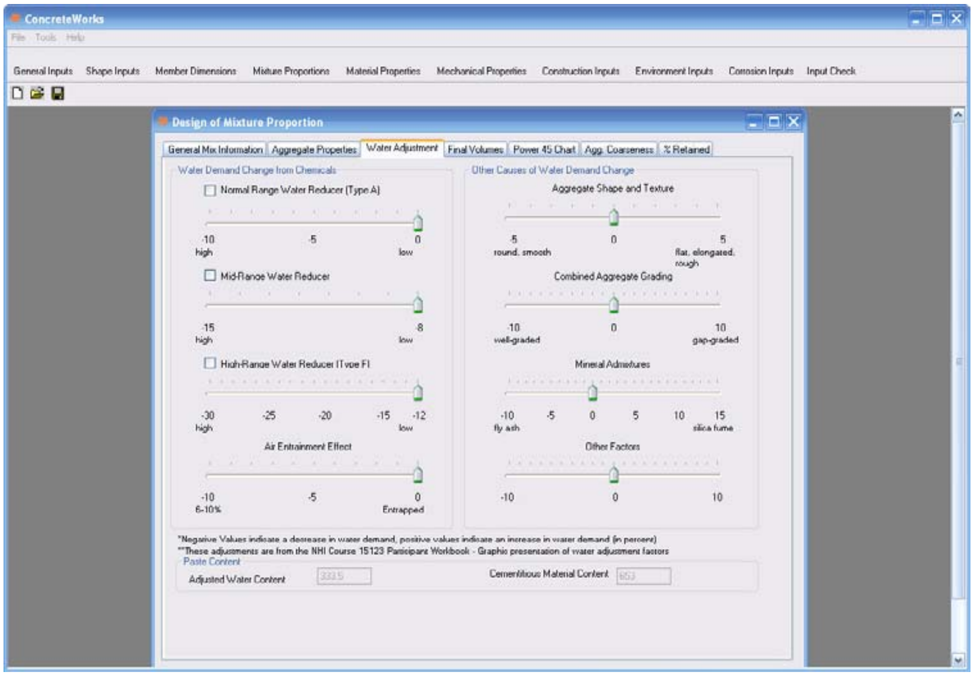


Figure 63 - Water Adjustment tab on the Design of Mixture Proportion screen

Final Volume Calculations

The final volume calculations for the concrete mixture are calculated based on the aggregate properties, cement content, adjusted water content, mineral admixture replacement, and air content. The batch weights per yard of concrete are shown in the *Final Weights* frame. The pie graph shows the percent of each material in the concrete mixture by volume. Figure 64 shows the *Final Volume Calculations* tab. When the total calculated paste content exceeds 30% by volume a warning appears to warn the user that the concrete mixture may be more susceptible to drying shrinkage. This does not preclude the use of the concrete mixture, but caution should be used for concrete members with a high surface area-to-volume ratio when exposed to low relative humidity.

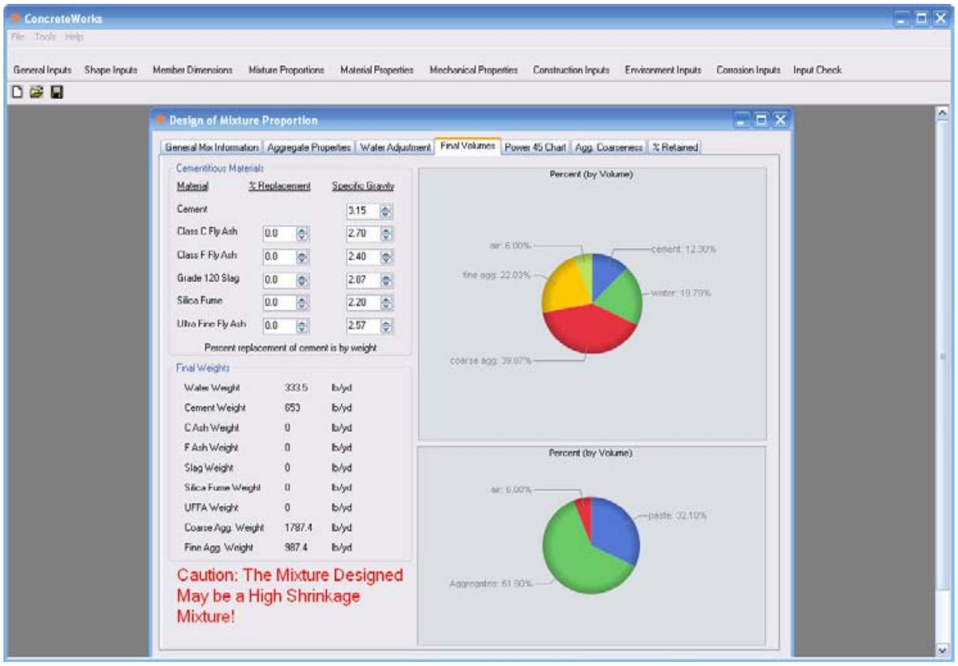


Figure 64 - Final Volume tab of the Design of Mixture Proportion screen

6.2.7. Material Properties

The material characteristics are entered in the *Material Properties* screen. Figure 65 shows the *Material Properties* screen. To manually override the default cement chemistry and hydration parameters, check the corresponding boxes and enter in the desired values, as seen in Figure 66.

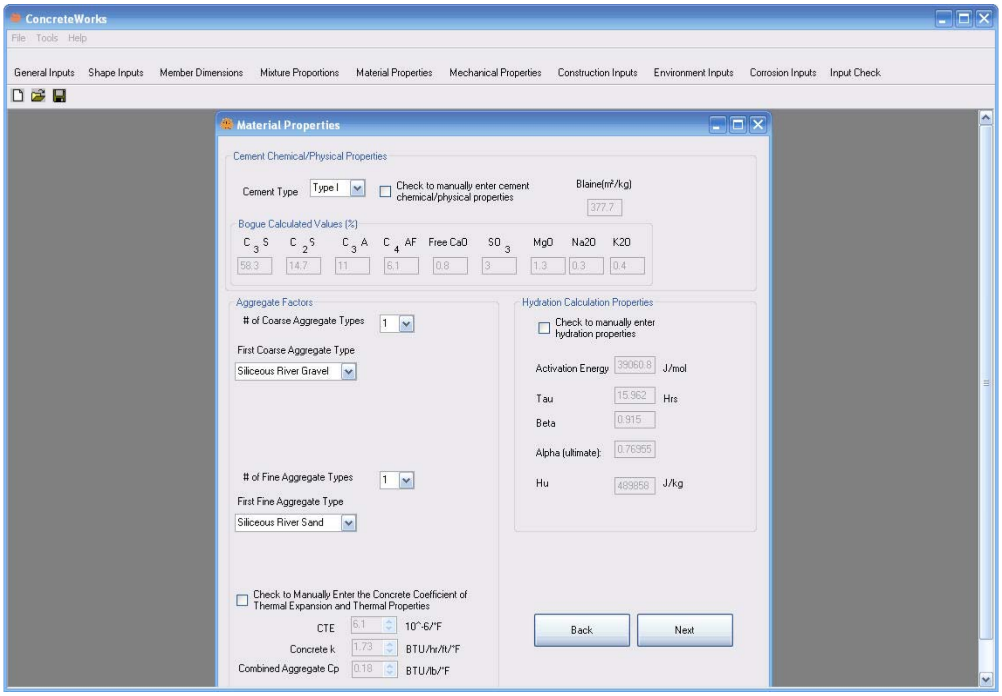


Figure 65 - Material Properties screen

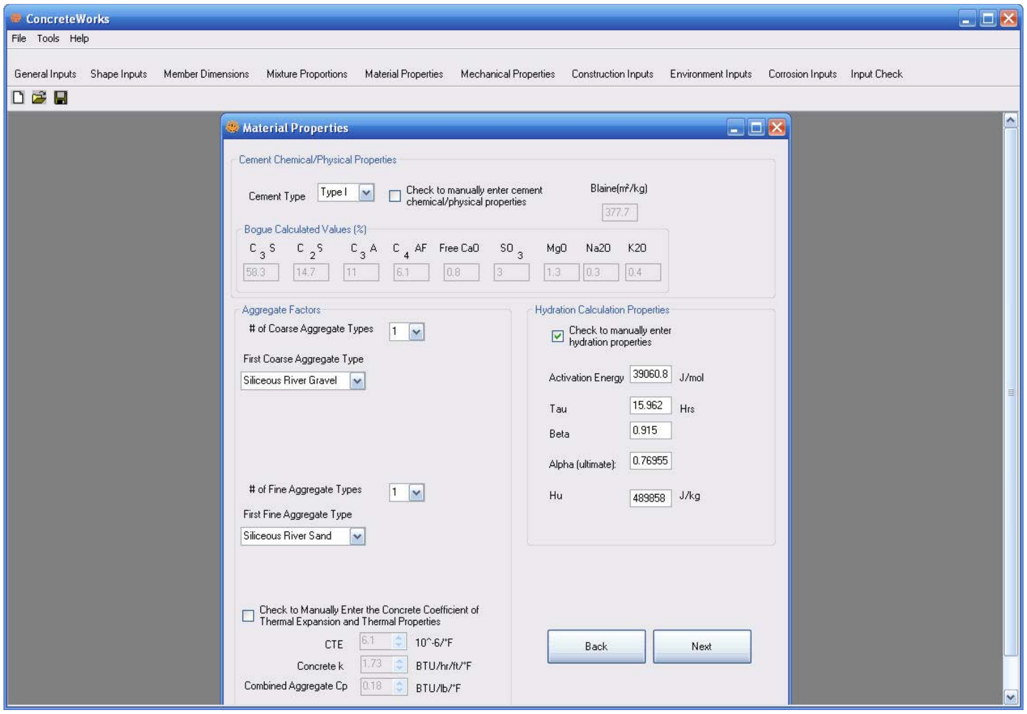


Figure 66 - Material Inputs screen with manual adjustment checkboxes checked

Cement Chemical/Physical Properties

The *Cement Chemical/Physical Properties* frame is where the cement type, composition, and physical properties are entered. To change the cement properties to those for the cement used, check the *Check to manually enter cement chemical/physical properties* box. If the user unchecks the *Check to manually enter cement chemical/physical properties box*, the cement properties revert back to the default values for the cement type selected. When the Bogue method is selected under the *Cement Analysis Method* found in the *Tools* menu, the Bogue values and oxide contents for the cement properties are displayed. If the Rietveld method is selected instead of the Bogue method, then the cement composition phases corresponding to that method is displayed. Actual cement properties estimated using the Bogue method can be found on mill sheets shipped with the cement.

Hydration Calculation Properties

Hydration Calculation Properties are based on equations developed as part of TxDOT research project 0-4563, and are described in Section 3.1.5. Different models that describe the Hydration Calculation Properties are used depending on whether the Bogue method of the Rietveld method is used to define the cement properties. If the user has performed a semi-adiabatic calorimetry test on the concrete mixture used, then the calculated hydration properties can be changed by checking the *Check to manually enter hydration properties* box. When the *Check to manually enter hydration properties* box is checked, the hydration parameters do not change when the mixture proportions is changed or the cement type changes. The semi-adiabatic calorimetry test performed to determine hydration parameter equations for ConcreteWorks Version 2.0 came from mixes that used Texas materials. Low alkali cements were used in a majority of tests, and thus the hydration parameters for any mix containing a large amount of alkalis may not be as accurate. If the concrete material properties deviate substantially from those used in Texas, a semi-adiabatic calorimetry test should be performed to determine the hydration parameters.

Aggregate Factors

Choose the type of coarse and fine aggregates used in the concrete batch. Up to three coarse aggregates types can be blended, while up to two fine aggregate types may be used. The user may change the number of coarse aggregates blended by changing the number in the *# of Coarse Aggregate Types* drop-down menu, and the number of fine aggregates blended by changing the number in the *# of Fine Aggregate Types* drop-down menu. When more than one type of aggregate type is selected to be blended, additional corresponding drop-down menus will appear that prompt the user for the type of additional aggregate used. The coefficient of thermal expansion (CTE) and material thermal properties are calculated based on the mixture proportions and the coarse aggregate types. The CTE and material thermal properties may be input by the user if a hardened concrete CTE test, hardened concrete thermal conductivity test, or aggregate specific heat test is performed. The combined aggregate c_p value shown in Figure 65 is the C_a parameter shown in Equation 24. It is highly recommended that the user perform a hardened concrete CTE test on the concrete mixture to be used, as the thermal stresses calculated are very sensitive to the concrete CTE. When the checkbox *Check to Manually Enter the Concrete Coefficient of Thermal Expansion and Thermal Properties* is unchecked, the concrete CTE and thermal properties revert to default values as calculated according to the chosen aggregate types.

6.2.8. Mechanical Properties Inputs

The *Mechanical Properties Inputs* screen allows the user to input the type of maturity method used, the maturity-strength relationships, and the early age creep parameters as shown in Figure 67.

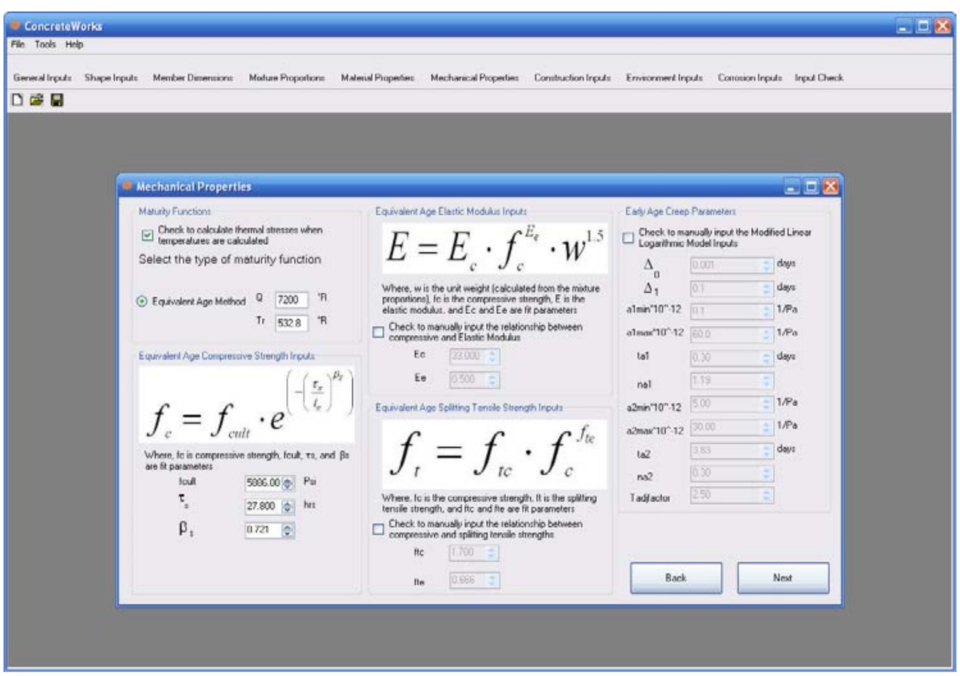


Figure 67 - Mechanical Properties inputs

Maturity Functions

The *Maturity Functions* frame allows the user to select between the Nurse-Saul method of maturity and the Equivalent Age method, both as described in ASTM C 1074 (2004). For the Nurse-Saul method, a reference temperature of 0°C is used when metric units are selected and 0°F is used as the reference temperature when English units are selected. If the user has a maturity curve already calculated for the given concrete mixture, the user may enter the *a* and *b* strength parameters according to the equation shown on the *Materials Inputs* screen. The *Check to calculate thermal stresses when temperatures are calculated* checkbox must be checked for the software to calculate the concrete member cracking probability failure classification. When thermal stresses are to be calculated, the equivalent age maturity method must be used. The elastic modulus and splitting tensile strength equations are calculated from the concrete compressive strength fit parameters entered. At a minimum, the compressive strength/maturity relationship must be entered for the concrete mixture proportions and materials used. The accuracy of the thermal cracking probability analysis increases when the elastic modulus and splitting tensile strength are measured and input in the software.

Early Age Creep Parameters

The concrete early age creep is calculated using the Modified Linear Logarithmic Model (MMLM) described in Section 4.5. The early age creep parameters for the MLLM are calculated from the mixture proportions and material properties entered. Different equations are used, depending on whether the Bogue method or the Rietveld method is selected as described in Section 4.5.1.

6.2.9. Construction Inputs

The *Construction Inputs* screen is where the construction-related options are entered. Each type of concrete member will have different construction options to choose from. ConcreteWorks will automatically display the needed inputs based on the other options selected by the user, such as member type or whether the member is submerged. Do not be alarmed if a particular set of inputs does not appear with the particular choices made. If you change the member shape or submerged status, the available construction inputs will change. Even small mistakes, such as the form type, or blanket insulation, can yield dramatically different results. Figure 68 shows the *Construction Inputs* screen for a rectangular column.

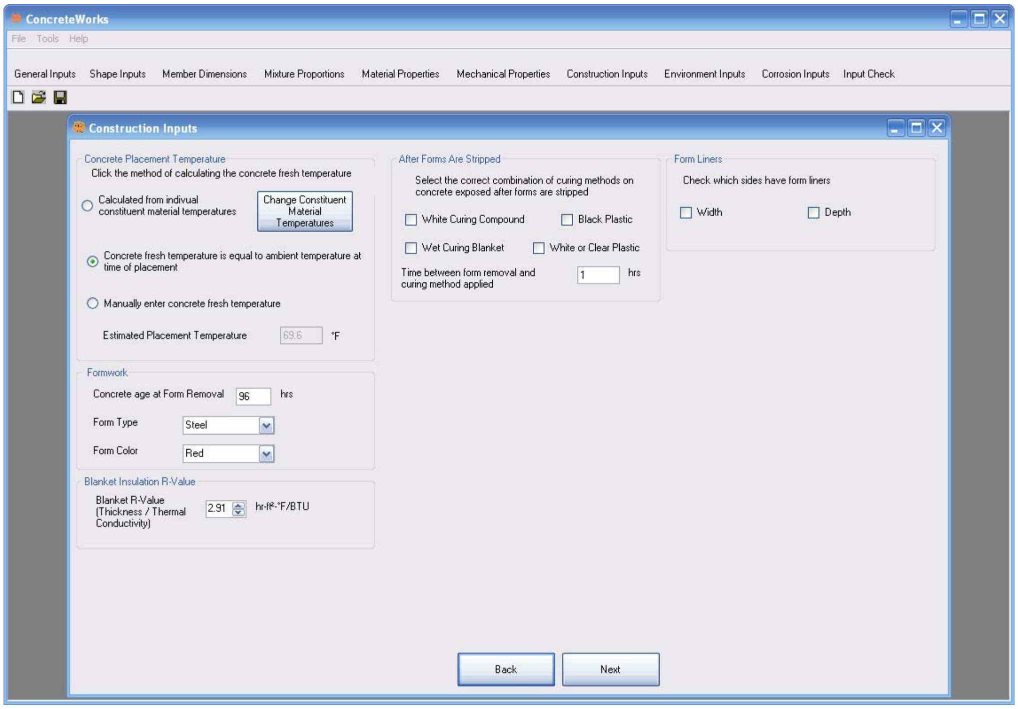


Figure 68 - Construction Inputs screen for a rectangular column

Concrete Placement Temperature

The *Estimated Placement Temperature* is the temperature of the concrete when it arrives on the jobsite. The concrete placement temperature can be calculated three ways.

The first way is to click on the *Calculate* button. After it is clicked, the *Raw Material Temperature Inputs* screen will pop up. The temperature of the cementitious materials, aggregates, and water must be entered. Aggregate moisture contents and absorptions must also be entered. Optionally, ice may be entered if it is used in the batch. The *OK* button will not work until all of the required information is entered. After all of the required information is entered and the *OK* button is clicked, the calculated placement temperature will be displayed in the *Estimated Placement Temperature* box. ConcreteWorks uses the ACI 305 model for predicting the fresh concrete temperature (ACI 305R, 1991). When the *Mixture Proportion* inputs are changed, the predicted fresh concrete temperature will also change, if all of the required inputs are entered in the *Raw Material Temperature Inputs* screen. Note: if all of the required inputs in the *Mixture Proportion Inputs* screen are not entered, ConcreteWorks will not be able to calculate the fresh concrete temperature.

The second way is to calculate the concrete placement temperature from the ambient temperature. In this method, the concrete fresh temperature is estimated as the ambient temperature at the time of placement.

The third way to enter the concrete placement temperature is to check the *Check here to manually enter Fresh Concrete Placement Temperature* box. After the box has been checked, the user may enter the concrete placement temperature in the *Estimated Placement Temperature* box. If the *Check here to manually enter Fresh Concrete Placement Temperature* box is checked, the value in the *Estimated Placement Temperature* box will only change when manually entered by the user.

Formwork

The *Concrete age at Form Removal* input requires the user to input the concrete age when formwork is removed (at the cross section being analyzed), starting from the time the concrete was first mixed. The form type and form color must also be input in their corresponding boxes.

Surrounding Temperature

If the element selected is a footing or the element is submerged, the *Construction Inputs* screen will have inputs for the soil temperature and water temperature. The soil temperature refers to the average soil temperature for the time being modeled. A good estimate of the soil temperature for most footings is the average of the maximum and minimum ambient temperatures during the time period in question. The water temperature refers to the temperature of the water surrounding a concrete element. For example, if a column was being placed in a lake, the user would enter the average lake water temperature for that time period.

Curing Methods Applied after Forms Are Stripped

The *After Forms Are Stripped* area asks the user to input what kind of curing methods are applied to the member after the forms are removed. ConcreteWorks requires the user to enter a time in the box *Time between form removal and curing method applied* if a cure method is checked. If the user enters a delay time, but does not check a cure method box, ConcreteWorks assumes that no cure methods are used. The user cannot check both the *Black Plastic* option and the *White or Clear Plastic* option at the same time. If for some reason, both types of plastic are used in construction, the user should check the type of plastic used as the outside layer. All curing methods applied after forms are stripped are assumed to remain on the concrete member until the end of the analysis duration. The default time between removing forms and applying the cure method is one hour.

Footing Inputs

When a footing is selected as the member type, the *Footing Inputs* frame becomes visible on the *Construction Inputs* screen, as seen in Figure 69. The input *Type of footing subbase* asks the user to select the type of soil or rock on which the footing is built. If a plastic sheet is also used in curing, the user should select which color plastic is used. If both types of plastic are used, the user should select the color of the plastic placed on top. The input *Concrete age when cure blanket is placed* is the number of hours between concrete placement time and when cure methods are applied (the cure methods applied to the top before form removal). This input allows the concrete to set before placing the cure blankets on top of the footing.

If the sides of the footing are shaded from the sun because of scaffolding or the ground, the user should check the input *Footing Sides Shaded*.

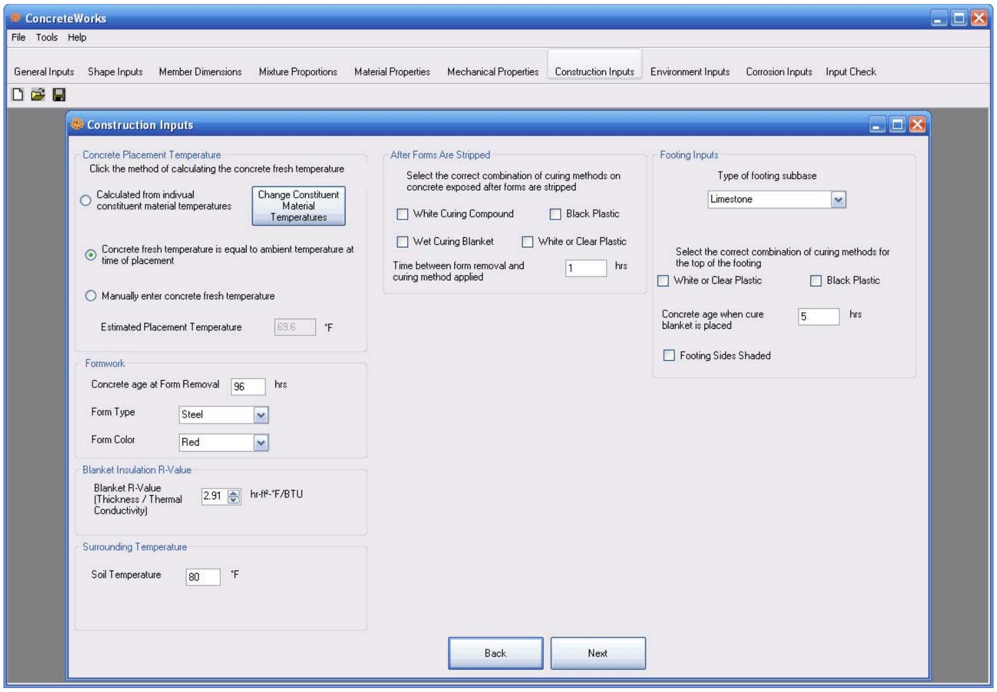


Figure 69 - Construction Inputs screen shown when the rectangular footing member shape is chosen

Bent Cap Inputs

The user must select which type of form is used for the bottom of the bent cap. This allows the user to use different forms for the sides and bottom of a bent cap. For example, the user could select steel forms for the sides of the bent cap, and wood for the bottom. If the user selects *Precast Concrete* for the bottom form of the cap, the *Precast Concrete Section Thickness* input box appears, as seen in Figure 70. The default cap bottom form type is steel. The default precast concrete thickness is two feet. The *Concrete age when cure blanket is placed* is the number of hours between concrete placement time and when cure methods are applied (the cure methods applied to the top before form removal). This input allows the concrete to set before placing the cure blankets on top of the bent cap. If a plastic is used on top of the cure blanket before form removal, the user should select which color plastic is used. If more than one color of plastic is used, the user should select the plastic placed on top.

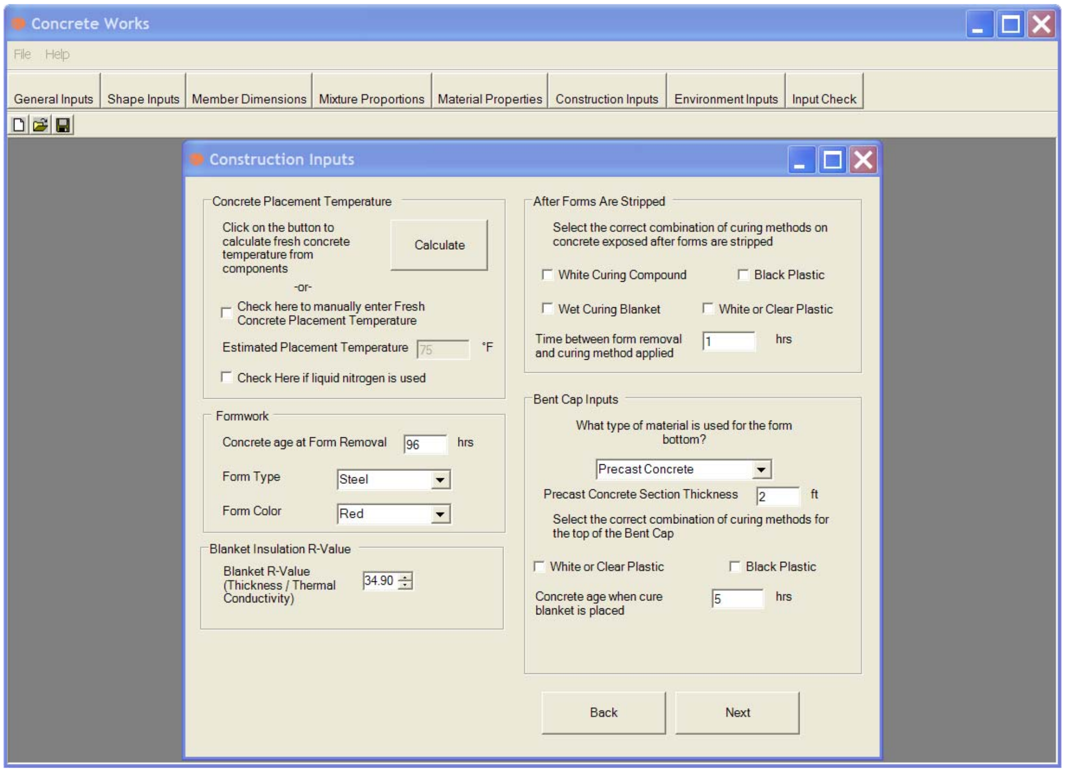


Figure 70 - Construction Inputs screen for a rectangular bent cap with pre-cast concrete selected as the bottom form

Bridge Deck Inputs

ConcreteWorks assumes that a cure blanket is used on top of bridge decks. The user may additionally select to use a layer of plastic on top of blanket, the time the blanket is placed, and the concrete age when the cure blanket is removed. If wood forms are selected for the bridge deck, the user may additionally specify the concrete age at the wood form removal, as shown in Figure 71.

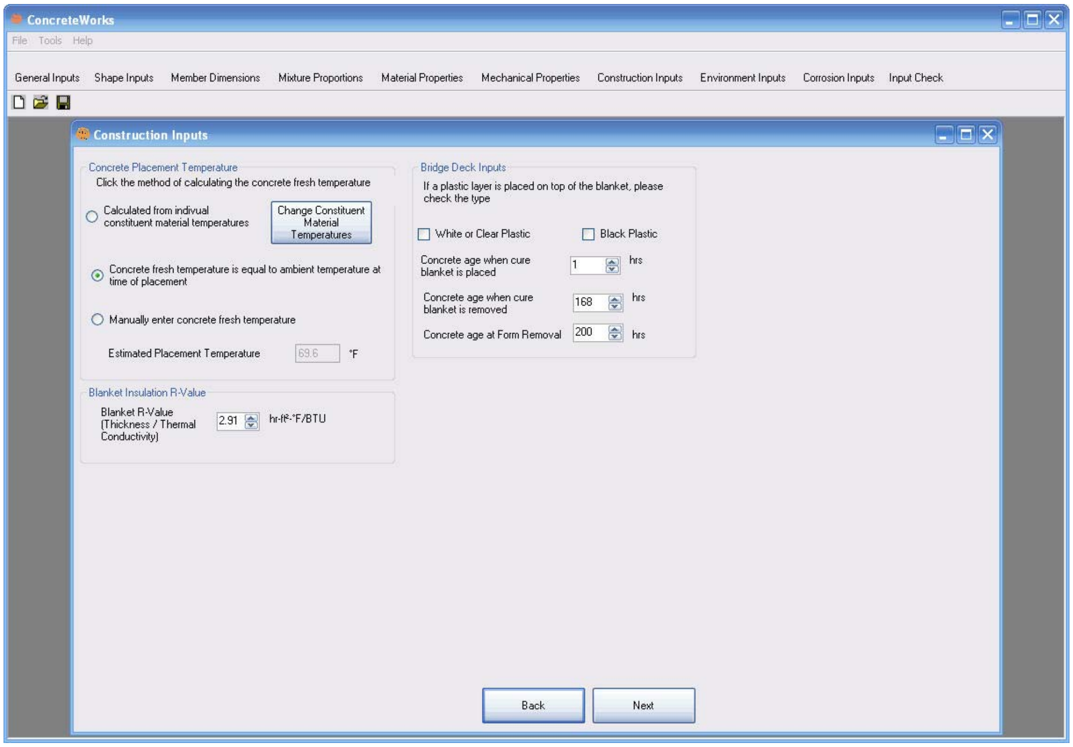


Figure 71 - Bridge Deck inputs when wood forms are selected

Precast Concrete Construction Inputs

Precast concrete members allow the user to specify a tarp or blanket to be used on the member sides. When a tarp or blanket is used on the sides of the precast beam, the same R-value is used for the blanket on the top and sides of the beam. The software also allows the user to select the subbase underneath the precast member, and the age when the cure method is started. The cure method is assumed to end when the forms are removed.

Pavement Construction Inputs

ConcreteWorks asks the user to input the type of cure method used as shown in Figure 72. The other pavement curing options depends on the curing method selected, and may ask the user for the application rate, the time of cure method application and removal, and the cure method color.

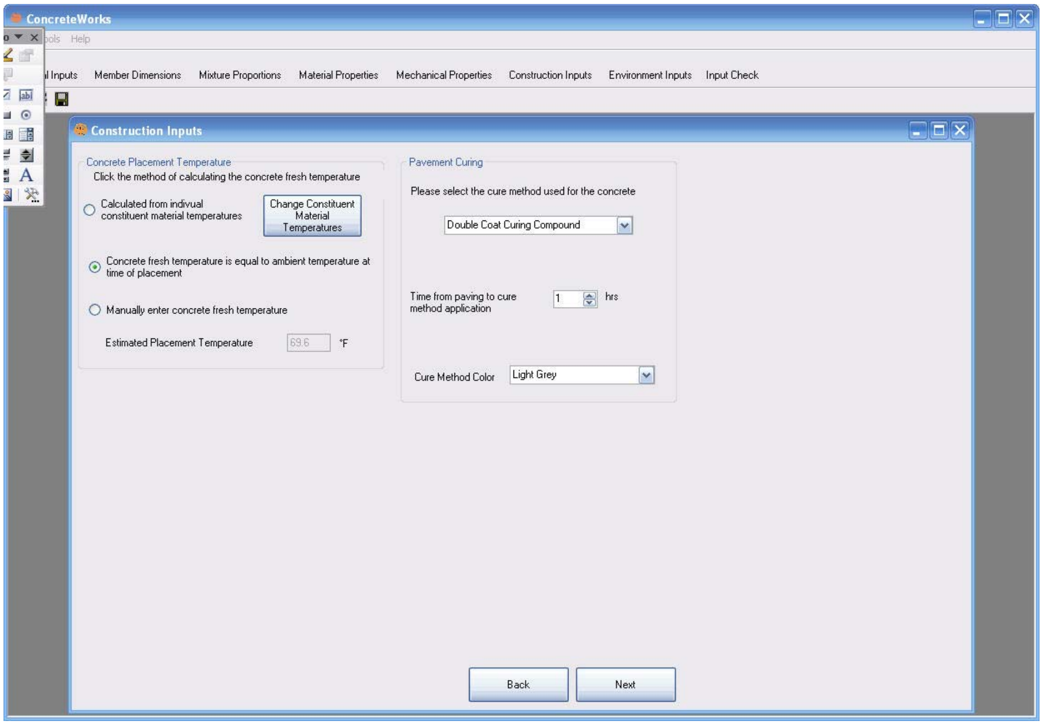


Figure 72 - Pavement Construction inputs

Blanket Insulation R-Value

The *Blanket Insulation R-Value* frame allows the user to select the R-Value of all cure blankets used during the concrete member construction. The R-Value is a measure of the blanket's thermal insulation. A high R-Value indicates a good insulator. Recommended R-values are 3 in.^{2}-hr-F/BTU for a thick, good quality cure blanket and 1 in.^{2}-hr-F/BTU for burlap or worn cure blankets.

Form Liners

The *Form Liners* frame asks the user to input which sides of the member use form liners. The width and depth sides correspond to the width and depth sides input in the *Member Dimensions* screen. ConcreteWorks assumes that the form liners are solid rubber reusable form liners (such as the Symons brand Elasto-Tex™[2] form liner).

6.2.10. Environment Inputs

The *Environment Inputs* screen is where all weather inputs are entered. All weather inputs are entered in tables that function similar to cells in a spreadsheet. ConcreteWorks requires that the user enter one more day than the number of days selected for analysis. The first day entered is the day selected as for the project date. Default values are the average 30-year weather data for the days selected for each individual city. When the user changes the *Placement Date*, *Temperature Analysis Duration*, or project location on the *General Inputs* screen, the environment inputs are automatically updated to the 30-year average values. The environmental inputs will always be updated, even if the user checks the boxes to input maximum and minimum weather values

[2] The Elasto-Tex™ trademark belongs to the Symons Co.

manually. Care should be taken to manually input environment values last. Clicking on the table headings will sort the table by the values of the column clicked on. The overall data will not be affected by sorting the data.

Temperature

The maximum and minimum temperature for each day is shown in the table on the *Temperature* tab. Default values can be overridden by checking the *Check to manually enter temperature data* input. Next, click on the table cell desired, and change the maximum or minimum value. Figure 73 shows the *Environment Inputs* screen with the *Temperature* tab selected.

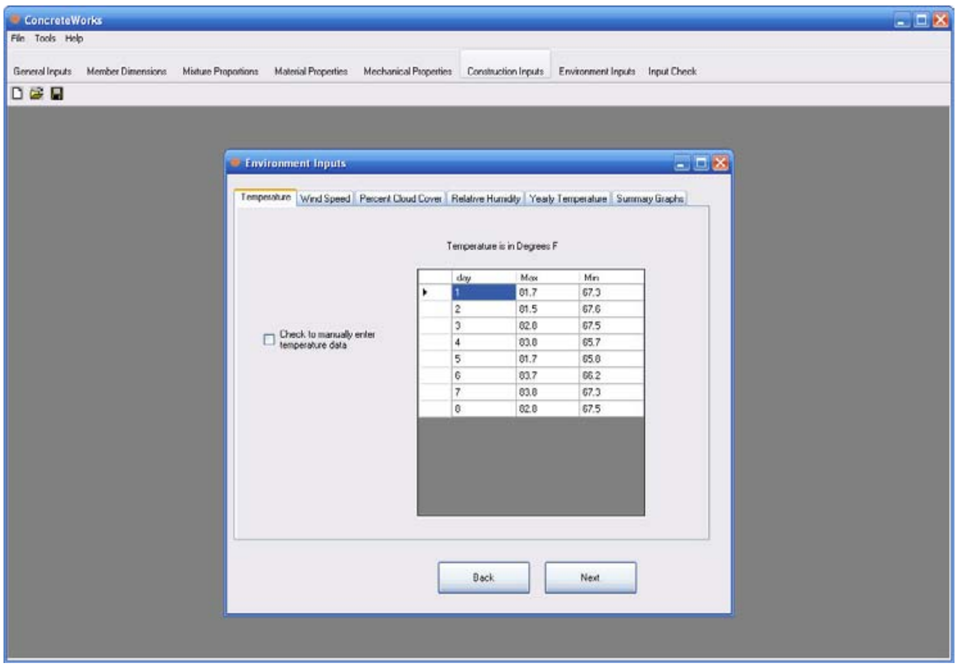


Figure 73 - Temperature tab on the Environment Inputs screen

Relative Humidity

The maximum and minimum relative humidity for each day are shown in the table on the *Relative Humidity* tab. Default values can be overridden by checking the *Check to manually* enter humidity data box. Next, click on the table cell desired, and change the maximum or minimum value.

Percent Cloud Cover

Average daily cloud cover value for each day is shown in the table on the *Percent Cloud Cover* tab. Default values can be overridden by checking the *Check to manually enter cloud cover data* box. Next, click on the table cell desired, and change the average cloud cover value. Enter cloud cover according to the scale shown. A zero cloud cover value is entered for sunny conditions, 50 for partly cloudy, and 100 for overcast. Figure 74 shows the *Environment Inputs* screen with the *Percent Cloud Cover* tab selected.

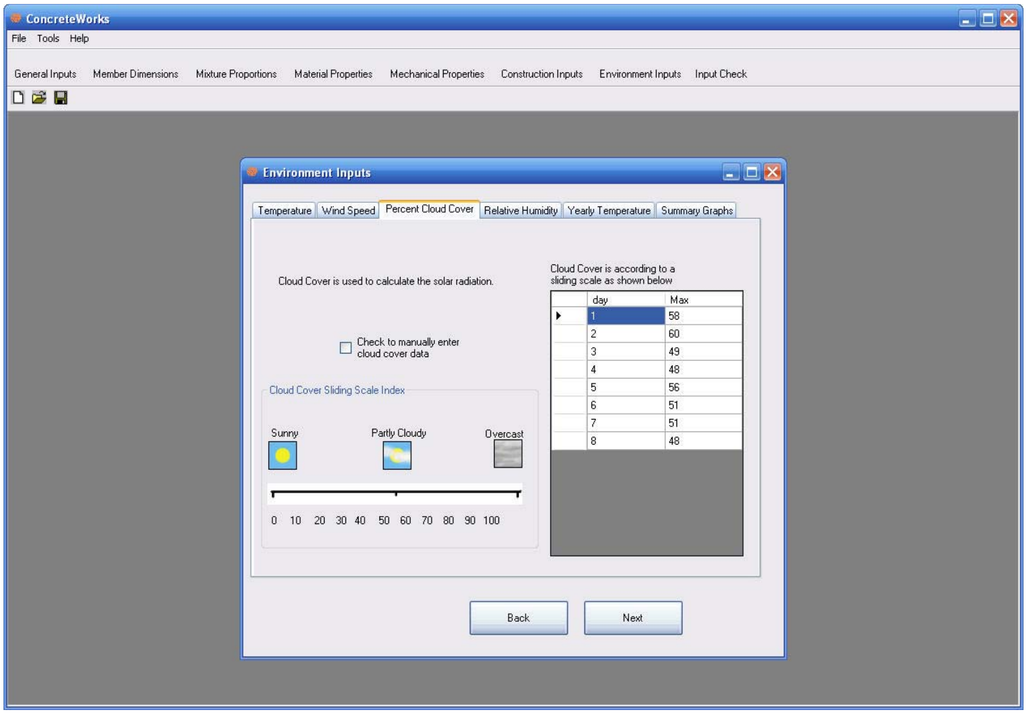


Figure 74 - Percent Cloud Cover tab on the Environment Inputs screen

Wind Speed

Maximum wind speed value for each day is shown in the table on the *Wind Speed* tab. Default values can be overridden by checking the *Check to manually enter wind speed data* box. Next, simply click on the table cell desired, and change the maximum wind speed value.

Yearly Temperature

The yearly temperature profile is calculated based on the number of temperature points per year selected as shown in Figure 75. Additionally, under the input *Temperature Value to Use*, users can select to use the average temperature values, the average temperature plus one standard deviation, or the average plus two standard deviations. The yearly temperature profile is used in calculating the chloride service life. The estimated chloride service life is not very sensitive to the number of data point per year selected, but is moderately affected by using the average temperature plus one or two standard deviations.

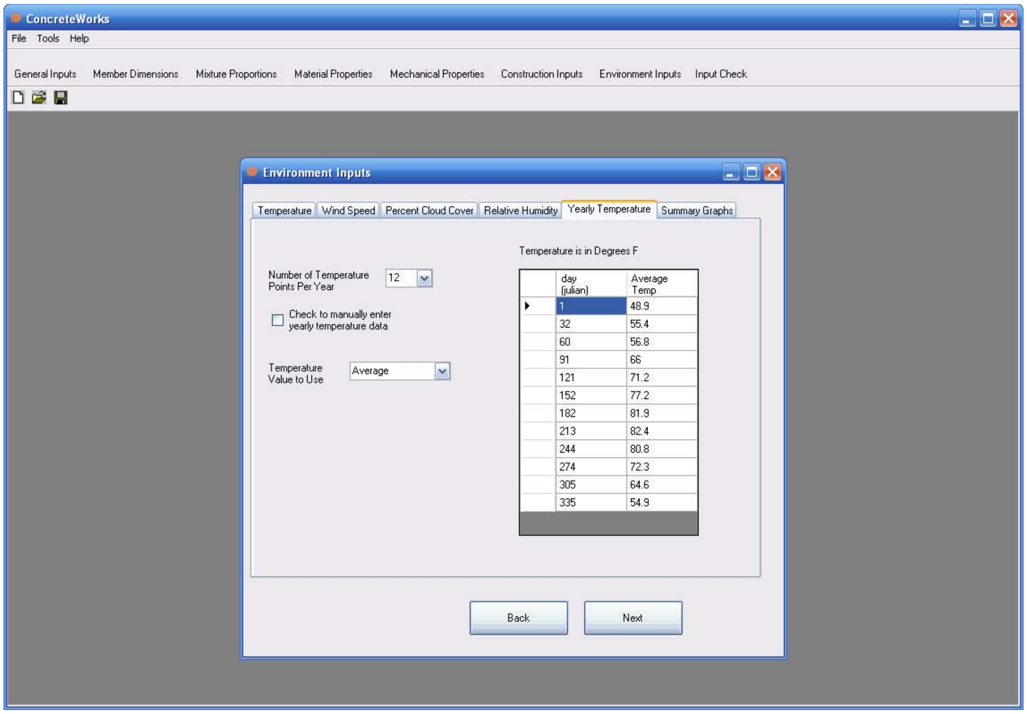


Figure 75 - Yearly Temperature inputs

Summary Graphs

The *Summary Graphs* tab can display the updated weather data on a graph. All plots start at 1:00 a.m. on the project date selected. The *Temperature* button shows a plot of temperature data with time. The *Humidity* button displays the relative humidity data with time. The *Wind Speed* tab shows a plot of wind speed with time. The *Solar Radiation* tab shows a plot of solar radiation with time. The solar radiation values are calculated based on the cloud cover data and relative humidity data. Figure 76 shows the *Environment Inputs* screen with the *Summary Graphs* tab selected. The graph shown in Figure 76 is a plot of the temperature.

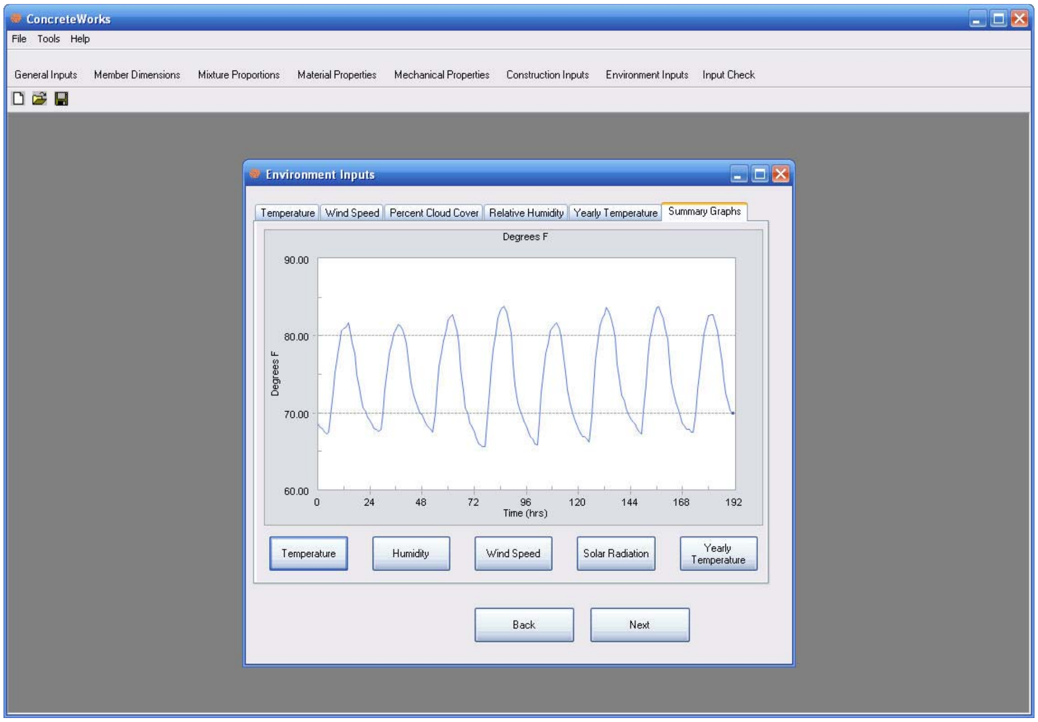


Figure 76 - Summary Graphs tab on the Environment Inputs screen (the temperature graph is currently displayed)

6.2.11. Input Check

The *Input Check* screen shows the values that have been entered, providing the user an opportunity to catch any mistakes made in the inputs section of ConcreteWorks. Anytime a user enters a character not allowed, ConcreteWorks assumes the value of the input to be zero. For example, if the user types "78u" on the *Cement Content* input in the *Mixture Proportion Inputs* screen, the *Input Check* screen would show that the cement content is "0". Figure 77 shows the *Input Check* screen. Notice the default values are highlighted green, and the questionable values are highlighted red.

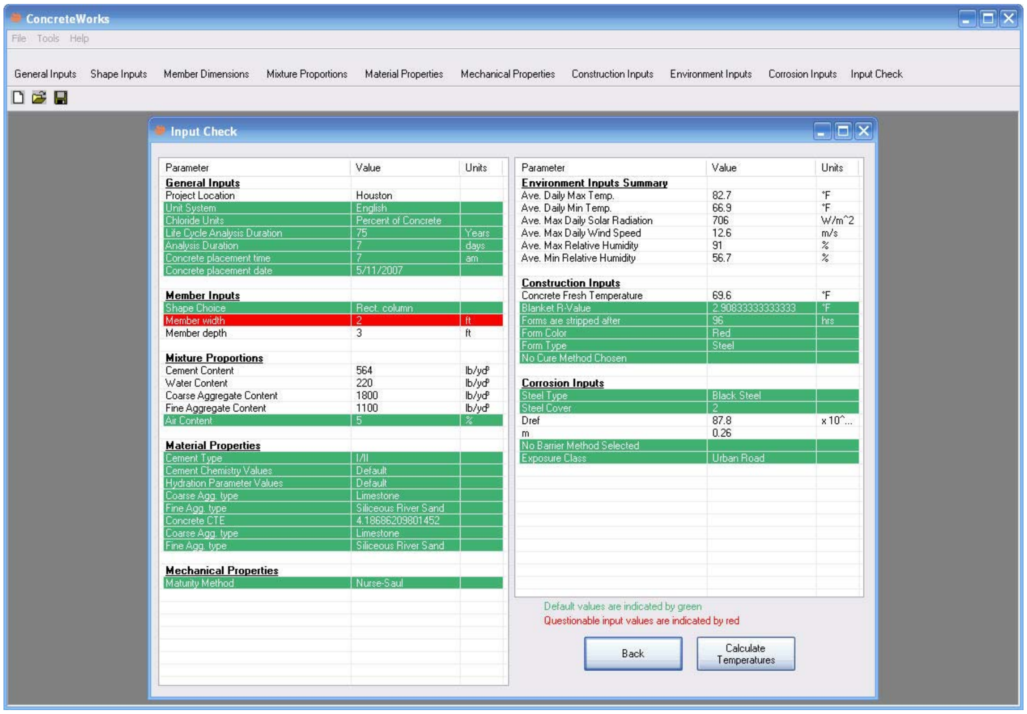


Figure 77 - Input Check screen

Default Check

Anytime the user chooses to use the default program value for an input, the *Input Check* screen will highlight that value in green. This feature makes it easy for the user to see how many entries the user actually made.

Questionable Values

Anytime the user enters a value that the program deems questionable, ConcreteWorks highlights that value red. Just because ConcreteWorks deemed the value questionable does not always mean that the program will not calculate temperature profiles for the element. A red value simply means that the user should check to make sure that the value is indeed what the user wanted. Caution: questionable values can (but not always) cause instability in ConcreteWorks or give unrealistic results. This feature makes it easy for the user to quickly scan the *Input Check* screen for common mistakes in entering data.

Table 15 shows which values are considered questionable by ConcreteWorks.

Table 15 - Values deemed questionable by ConcreteWorks

Input	If the input is less than this value	If the input is greater than this value
Rectangular Column Width or Depth	3'	30'
Rectangular Footing Width, Length	3'	80'
Rectangular Footing Depth	3’	30’
Rectangular Bent Cap Width or Depth	3'	30'
T-Shaped Bent Cap Width	3'	15'
T-Shaped Bent Cap Height	3'	15'
Circular Column Diameter	3'	15'
Cement Content	100#	1200#
Water Content	100#	1200#
Coarse Aggregate Content	100#	4000#
Fine Aggregate Content	100#	4000#
Air Content	0%	10%
Class C Fly Ash Content	0#	1200#
Class C Fly Ash CaO	20%	30%
Class F Fly Ash Content	0#	1200#
Class F Fly Ash CaO	0%	20%
Slag Content	0#	1200#
Silica Fume Content	0#	1200#
Ultra-Fine Fly Ash	0#	1200#
Any Bogue Compound Content	0%	100%
Any Bogue Compound that does not meet ASTM C 150		
C_3A	1%	
Blaine Fineness	280(m^2/kg)	1000(m^2/kg)
Alkali Content	0%	100%
Fresh Concrete Placement Temperature	32°F	212°F
PCC age at form removal	0 hrs	
Delay between removing forms and cure method application	0	
Hydration Parameter alpha	0	1

6.3. Results

6.3.1. Results Summary

After clicking the *Calculate Temperatures* button on the *Input Check* screen, ConcreteWorks will begin performing model calculations for the member type selected. A progress bar will appear in the lower left corner of the *Results* screen, showing the calculations' progress. If a serious error was made in entering an input, a message box will appear describing the error. The *Results* screen has a different heading, depending on the type of member shape chosen.

Mixture Checks

The *Mix Checks* tab shows a summary table of the calculated results, as seen in Figure 78. The first section in the *Mix Checks* table states the set of specifications used to check the calculated results (for example, the TxDOT 2004 specifications), the maximum temperature in the concrete member during the analysis period, the maximum temperature difference at time *t* anywhere in the concrete member, and whether the concrete mixture meets the specifications selected for alkali silica reactivity. The second section in the *Mix Checks* table tells the user the time to corrosion initiation and damage estimated in the concrete member. The last section gives the cracking risk classification. The cracking risk classification criteria are explained in Section 4.6. A low or moderate cracking risk classification does not guarantee that the structural member will be free of cracks. A low cracking risk classification only indicates that the probability of cracking is lower than if the concrete cracking risk classification were moderate, high, or very high. Any classification, including the low cracking risk classification, includes some chance that cracking will occur. When the TxDOT 2004 specification is selected, the maximum temperature difference line in the *Mix Checks* table will be highlighted red if the value exceeds 35°F, the maximum temperature in the member line will be highlighted if the value exceeds 158°F, and the alkali-aggregate reactivity line will be highlighted red if the concrete does not meet TxDOT specification 420 (Texas Department of Transportation, 2004).

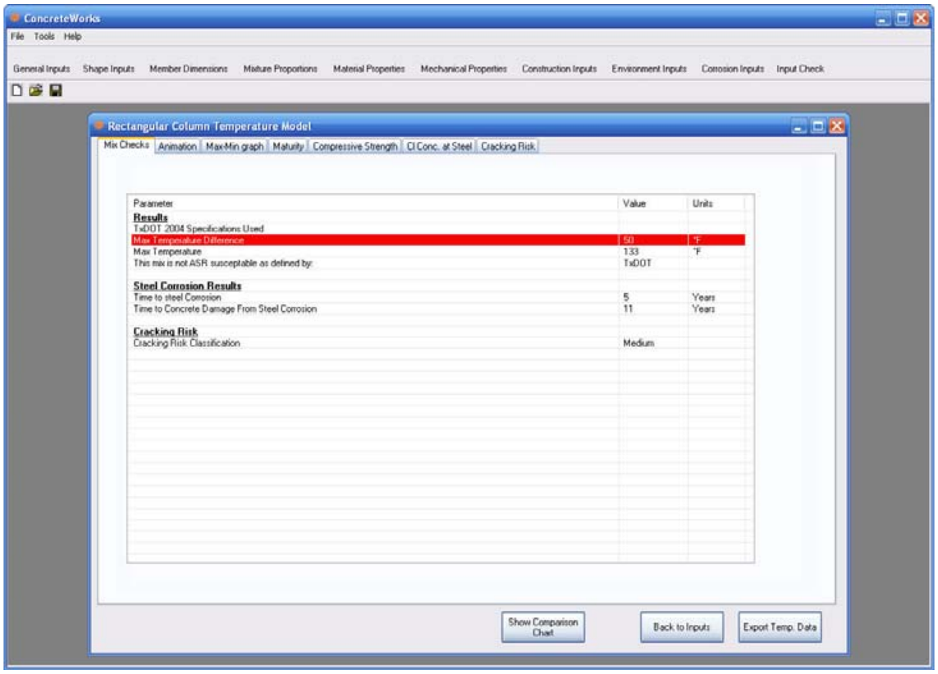


Figure 78 - Mix Checks tab shown on the Rectangular Column Temperature Model screen

Max-Min Graph

The *Max-Min Graph* tab shows the user a graph of the important calculated values with time, as seen in Figure 79. The values shown are the maximum temperature anywhere in the concrete member at each point in time, the minimum temperature anywhere in the concrete member at each point in time, the maximum temperature difference in the concrete member at each point in time, and the ambient temperature.

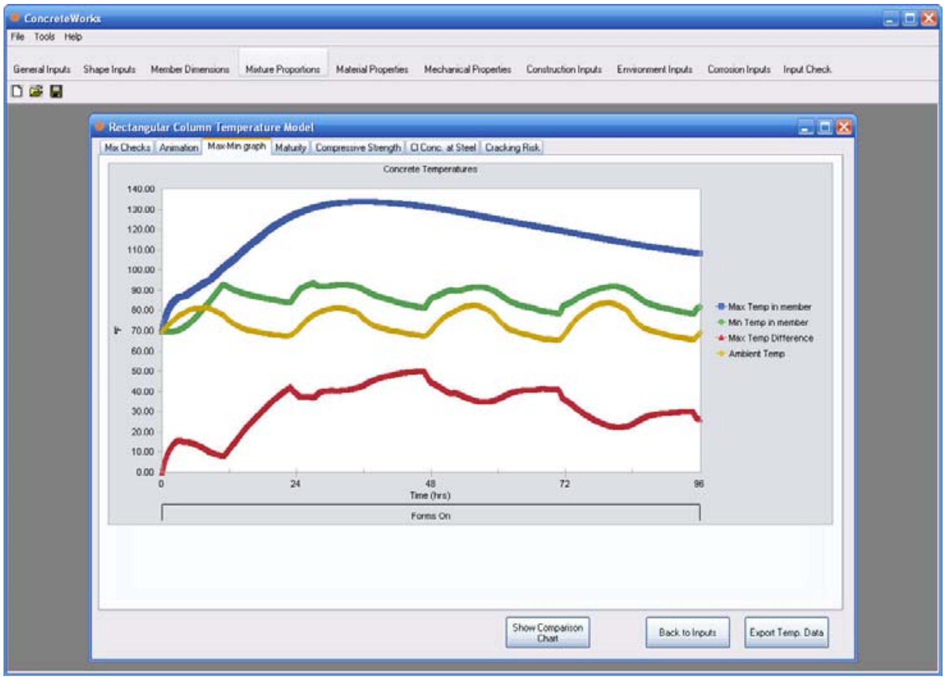


Figure 79 - Max-Min Graph tab as shown on the Rectangular Column Temperature Model screen

Animation

The *Animation* tab allows the user to view an animated chart of the concrete member, as seen in Figure 80. The *Animate* button shows the charts and starts the animation from the start of concrete placement. The *Stop Animation* button stops the animation. ConcreteWorks animates the calculated property checked in the *What to animate?* frame. If no compressive strength parameters are entered in the *Material Properties* screen (see Section 6.2.8), then the *Comp. Strength* button will be disabled. The *CircularColumnfinite* screen does not show a three-dimensional animation of the concrete temperature. Instead, the *CircularColumnfinite* screen will show a two-dimensional animated graph of the temperature on the column diameter cross section. When the cracking failure classification is calculated, the animation will also display a bar at the bottom of the animation that will show the cracking classification at that point in time that is being animated.

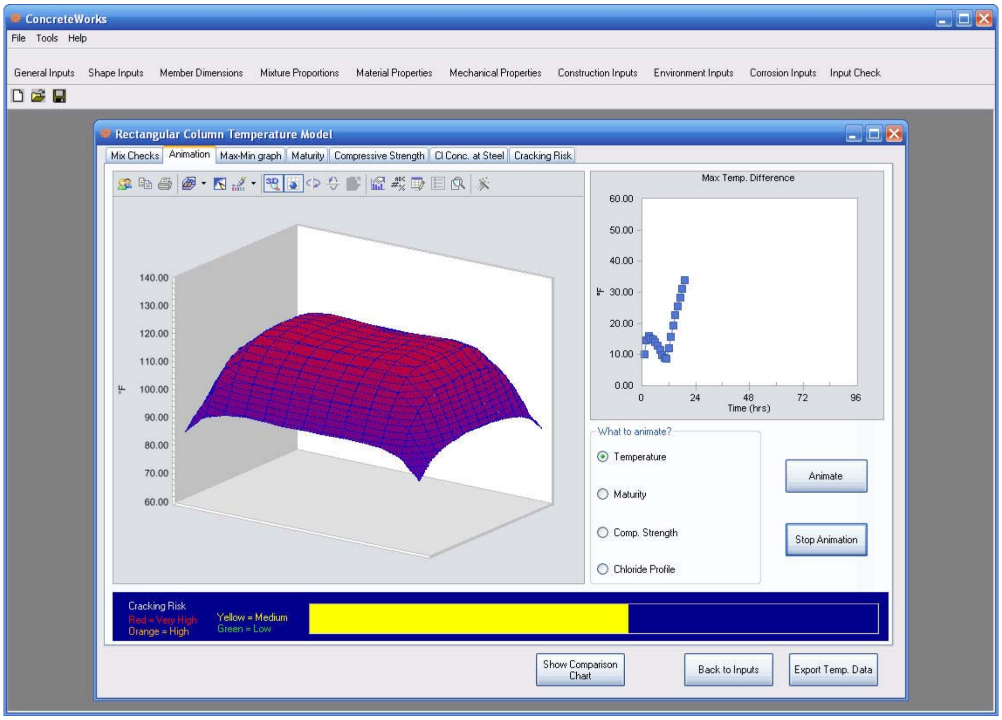


Figure 80 - Animation tab as shown on the Rectangular Column Temperature Model screen

Maturity

The *Maturity* tab contains a graph that shows the calculated maximum, minimum, and maximum maturity difference for the concrete member, as seen in Figure 81. The maturity is calculated from the strength parameters chosen on the *Material Inputs* screen (see Section 6.2.8). The calculated maturity is only an estimate, and only applies when the maturity parameters entered are from same concrete mixture as the one entered.

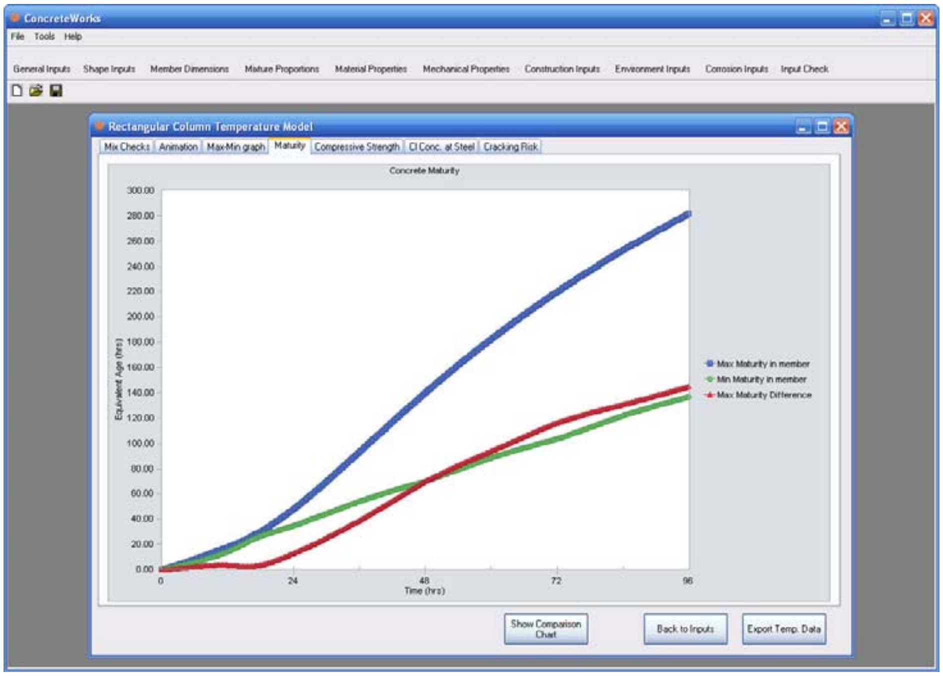


Figure 81 - Maturity tab as shown on the Rectangular Column Temperature Model screen

Compressive Strength

The *Compressive Strength* tab shows the maximum compressive strength, minimum concrete strength, and the average compressive strength of the concrete member, as seen in Figure 82. The average compressive strength is a weighted average of the compressive strength in the member. This means that the compressive strength of the concrete member is integrated, and then divided by the total area. The compressive strength is calculated using the calculated concrete temperature, the calculated concrete maturity (see Section 0), and the compressive strength parameters entered on the *Mechanical Properties Input* screen (see Section 0). If the user does not enter the compressive strength parameters in the *Mechanical Properties Input* screen, the concrete compressive strength is not calculated. The compressive strength graph on the *Compressive Strength* tab is then not visible.

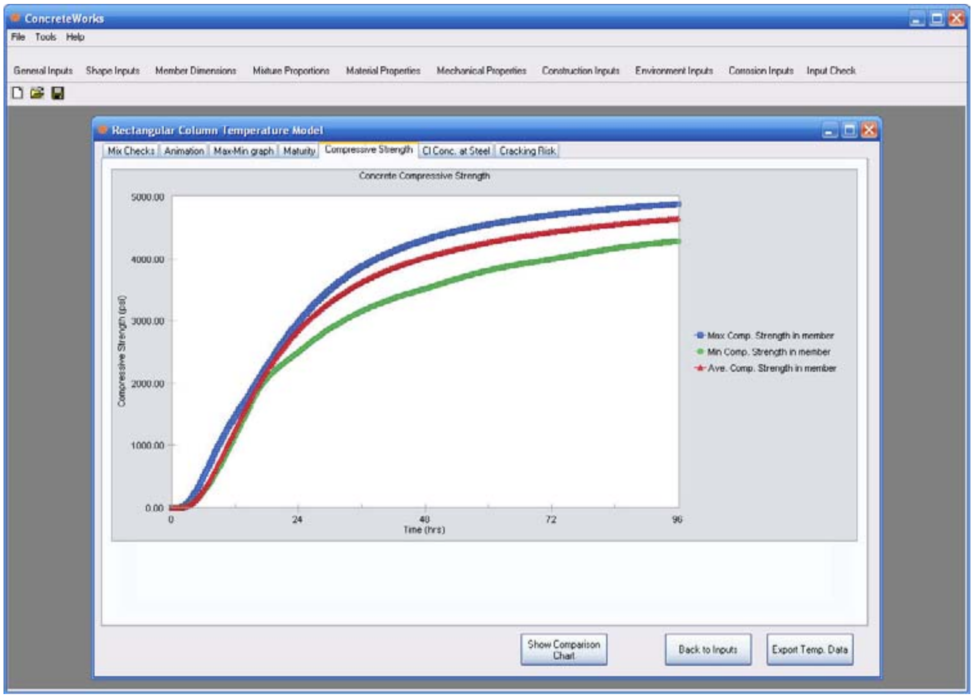


Figure 82 - Compressive Strength tab with compressive strength calculated as shown on the Rectangular Column Temperature Model screen

Chloride Concentration at the Steel

As part of the chloride service life analysis, ConcreteWorks calculates the chloride concentration at the steel. When the chloride concentration reaches the chloride threshold level, corrosion is considered to have initiated. The chloride concentration at the steel level value will turn orange once corrosion exceeds the chloride threshold level, as shown in Figure 83.

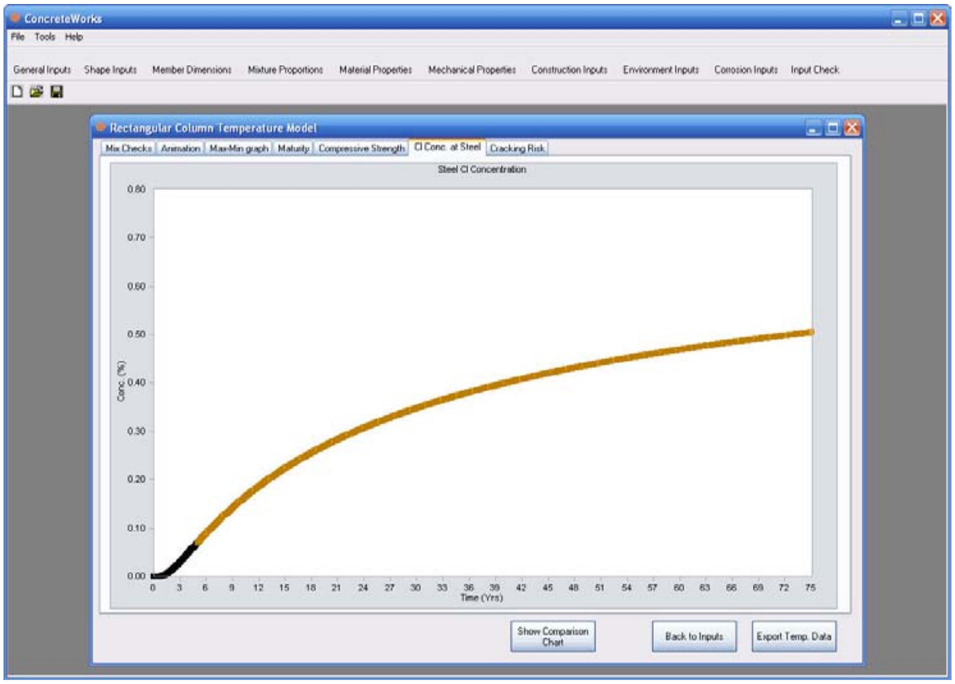


Figure 83 - Graph of chloride concentration at steel

Cracking Risk Classification

The cracking risk classification at different times is plotted as a bar chart, with the maximum temperature difference plotted as a blue line on the same graph to show how the temperature gradient in the concrete affects the cracking risk classification. Figure 84 shows the graph used to show the cracking risk classification and maximum temperature difference. The bar color shown for the cracking risk classification corresponds to the classification shown at the bottom of the chart. The methodology used to determine the cracking risk classification is discussed in Section 4.6. A green color corresponds to a low cracking risk classification, yellow to moderate, orange to high, and red to a very high cracking risk classification.

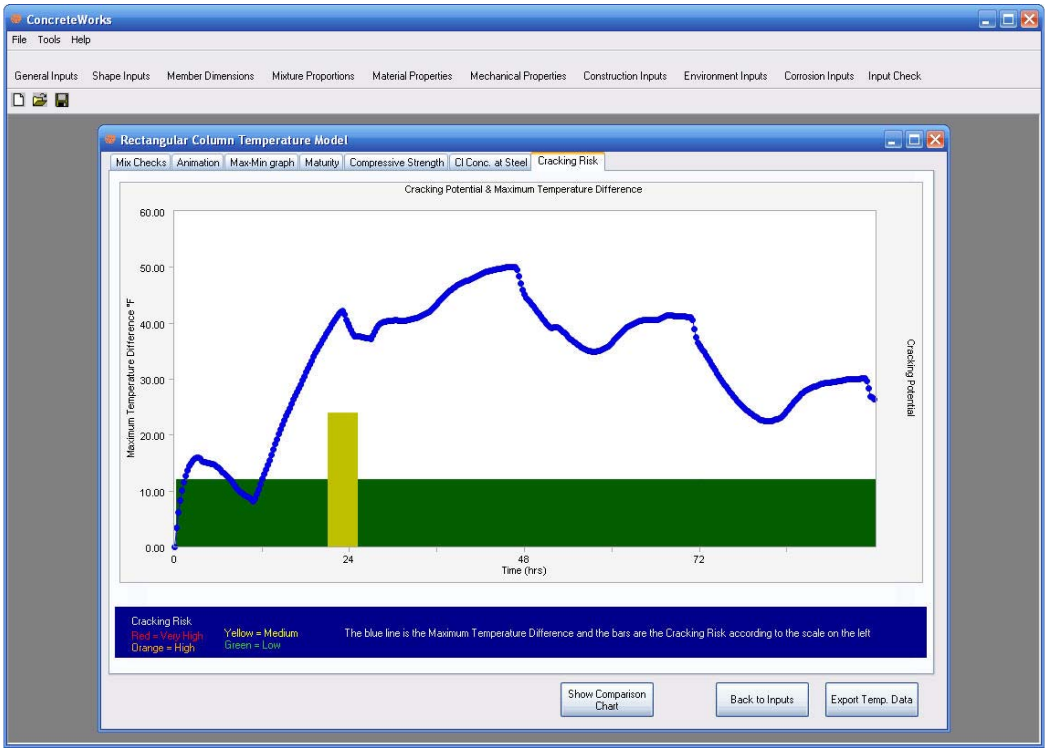


Figure 84 - Cracking risk classification chart

6.3.2. Results Screen Buttons

The buttons found on the *Results* screen give the user choices on how to view and manipulate the calculated temperature data.

Show Comparison Chart

The *Show Comparison Chart* button displays a form that allows users to compare the results from different analysis runs as seen in Figure 85. The *Show Comparison Chart* screen allows the user to compare calculated maximum temperatures, maximum temperature differences, cracking probability classifications, and chloride concentration levels at the steel from one model calculation run to another. Graphs comparing the results will also be displayed. The *Print Chart* button on the *Comparison Chart* screen will print the comparison chart results and charts on the *Comparison Chart*. A PDF report of the printout will be created when the user clicks on the *PDF Comparisons* button, and will prompt the user for a location to the save the PDF file. The user may name an analysis run by typing in a name under the *Series Name* textbox, selecting the number of the analysis run in the *Selected Analysis Number* input, and clicking on the *Update Series Name* button. When a user selects the *Delete Series* button, the analysis run number selected under the *Selected Analysis Number* will be deleted.

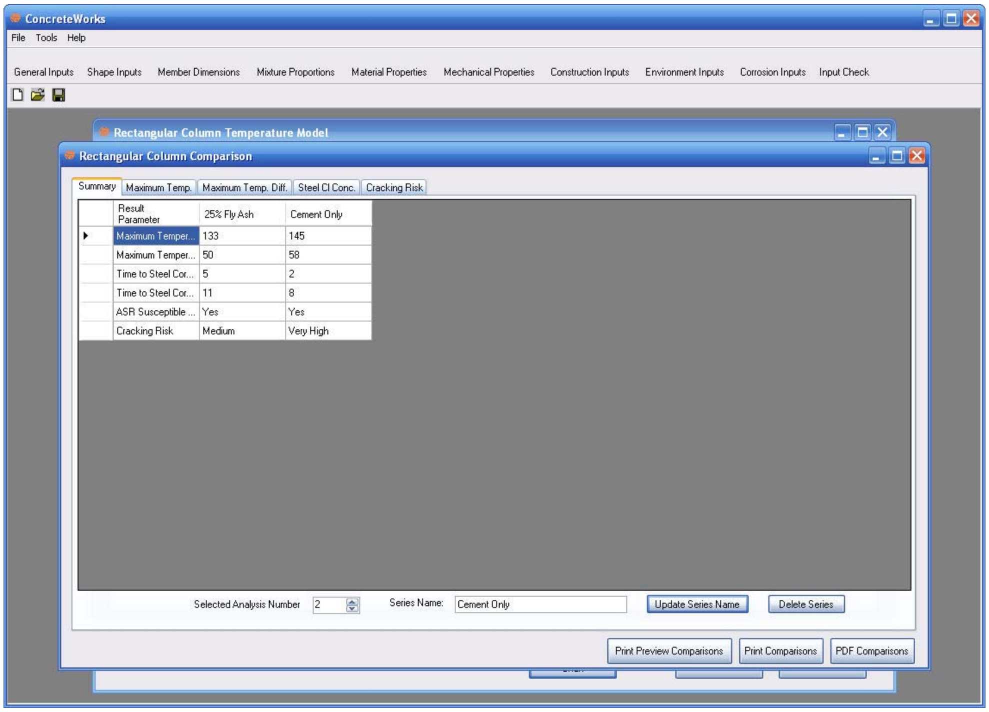


Figure 85 - Comparison chart screen

Export Temperature Data

To export the temperature data calculated, click on the *Export Temperature Data* button on the *Results* screen. ConcreteWorks saves the data in an ASCII text file when the extension .txt is used. ConcreteWorks will also save the data as an excel spreadsheet when the extension .xls is used. Data will be shown for discrete points in the member with time. The default file extension for data exported is ".xls".

Cross Section to Be Displayed

ConcreteWorks only displays data in the graphs from two-dimensional cross sections. When a footing temperature distribution is calculated in three dimensions, the user may change which cross section is shown in the graphs by changing the *Cross-Section Number to be Displayed* value, and then clicking on the *Display new cross-section* button, as seen in Figure 86. The *Mix Checks* values are calculated for the full three-dimensional temperature distributions, however, and will not change when the *Display new cross-section* button is clicked. The temperature data exported when the *Export Temperature Data* button is clicked (as explained in Section 6.3.2) only exports the temperature data from the two-dimensional cross section currently selected.

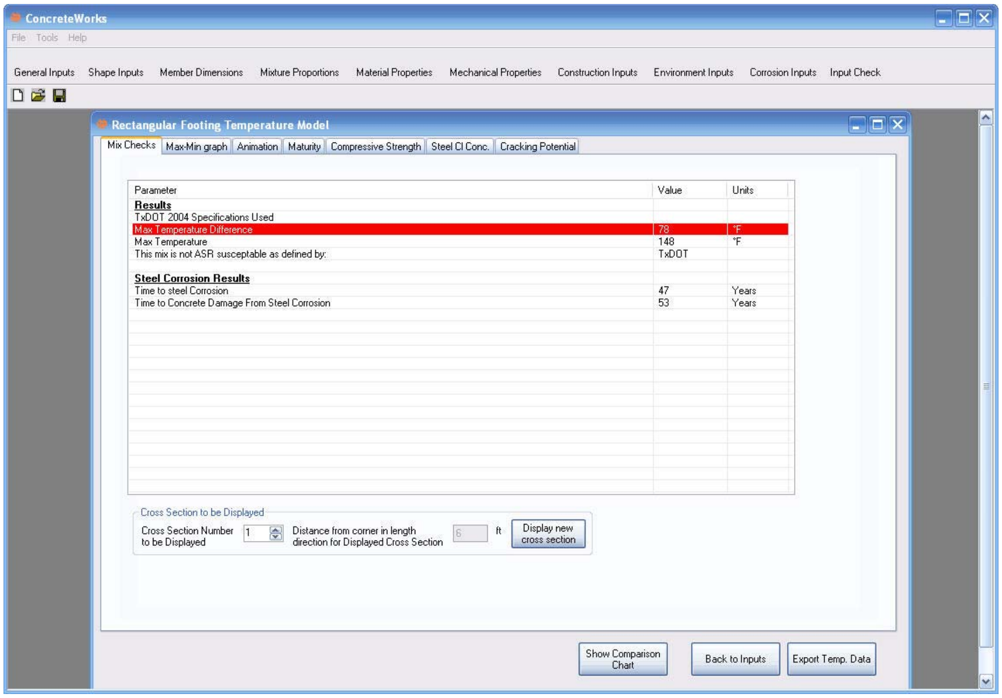


Figure 86 - Rectangular Footing Results screen with the Cross-Section to be Displayed frame showing

6.4. Program Features

6.4.1. Printing

While the *Results* screen is displayed, the user can print out the results and inputs entered in a report format.

Print

To print the report, click *Print* under the *File* menu.

Print Preview

To see of preview of the printed report, click *Print Preview* under the *File* menu, as seen in Figure 87. The report may be printed from the *Print Preview* window by clicking on the *Print* button in the *Print Preview* window.

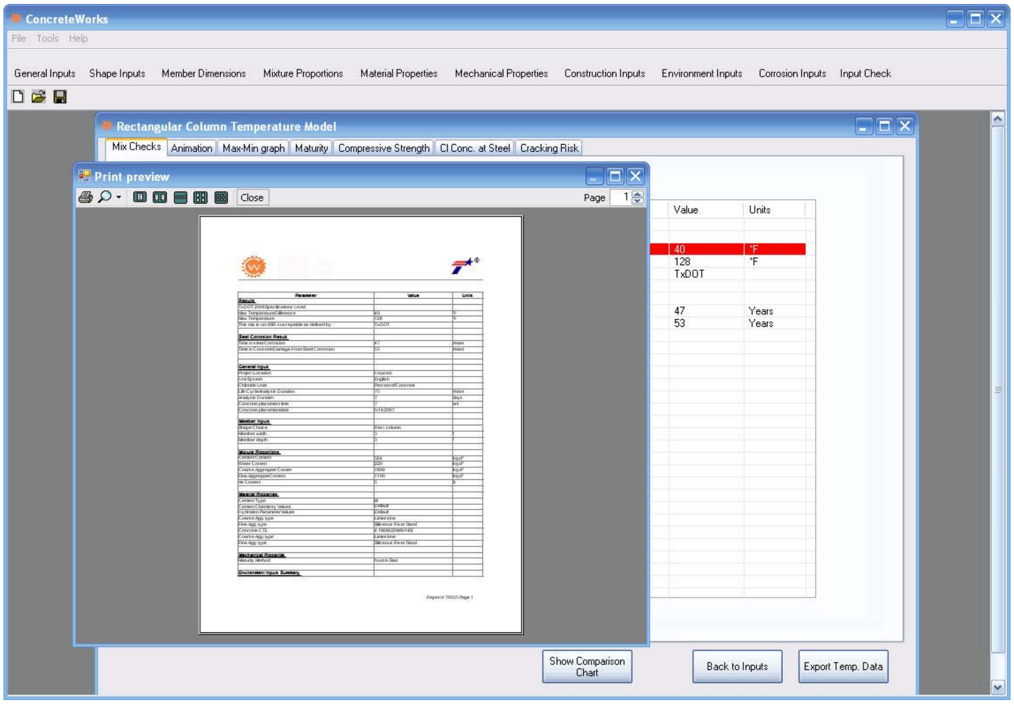


Figure 87 - Print Preview screen

Page Setup

The *Page Setup* screen allows the user to select which graphs to print in the report. The *Page Setup* dialog can be opened by clicking on *Page Setup* under the *File* menu. If compressive strength parameters are not entered in the *Mechanical Properties* screen, then the *Compressive Strength* graph will not print, even if the user selects to print it on the *Page Setup* dialog. The *Page Setup* dialog can be seen in Figure 88.

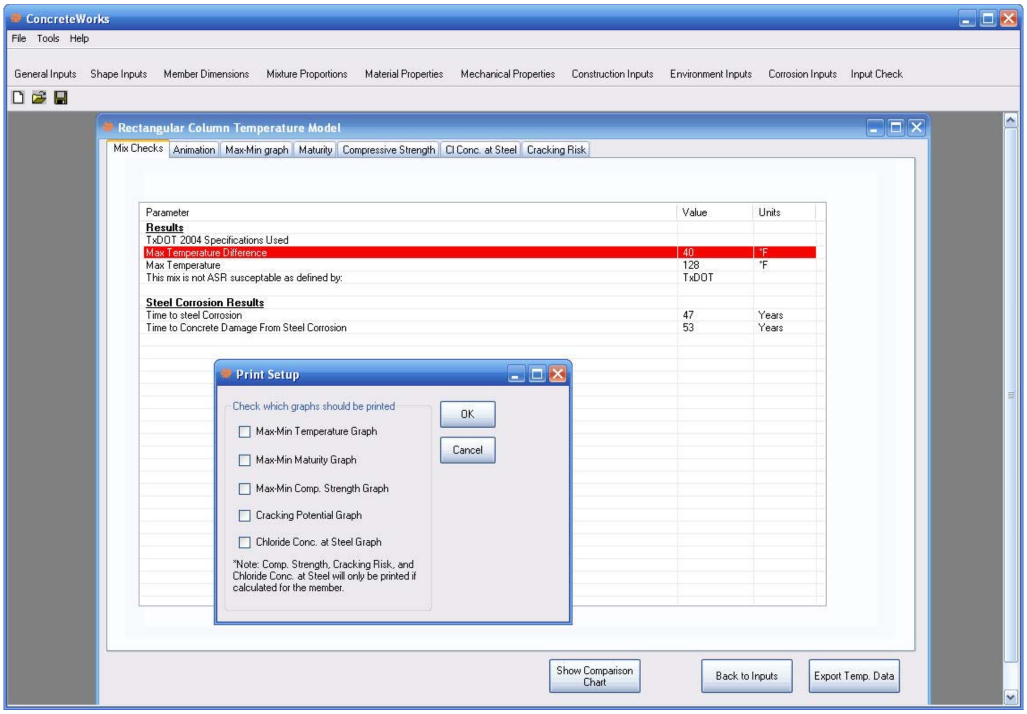


Figure 88 - Page Setup dialog

6.4.2. Export

The ConcreteWorks inputs and results can be exported to a PDF file. The PDF file exported is similar to the printed reports. To make the PDF report, select “PDF” from the “Export to” option under the *File* menu. The software will then prompt the user for a location to save the PDF file. It may take a few minutes for the software to generate the PDF file. After the file has been generated and saved, ConcreteWorks will display a message that the PDF file was generated.

ConcreteWorks also contains an option to export the inputs to SiteManager™. SiteManager™ is an AASHTOWare® product used by several state departments of transportation. The export to SiteManager™ function in ConcreteWorks will create an XML file that can be used to import ConcreteWorks inputs into SiteManager™.

6.4.3. Save As

To save the inputs entered in a new file, click *Save As* under the *File* menu. The default file extension for an inputs file is “.dat”.

6.4.4. Save File

To save a currently opened file, click the *Save* button, or click *Save* under the *File* menu. If the *Save* button is clicked and the file has not previously been saved, the program will prompt for a name and location.

6.4.5. Change Defaults

Click the *Change Defaults* item under the *File* menu to change the default values used for inputs to custom values. All values entered in the *Change Defaults* screen are input in English units, but are displayed in the correct units in the inputs section of ConcreteWorks the next time a new file is opened. All units stay the same in the *Change Defaults* screen, except for the *a* and *b* strength parameters under the *Mechanical Properties* tab. The *a* and *b* parameters change units depending on the type of maturity function chosen under the same tab. The *Material Inputs* tab on the *Change Defaults* screen is seen on Figure 89.

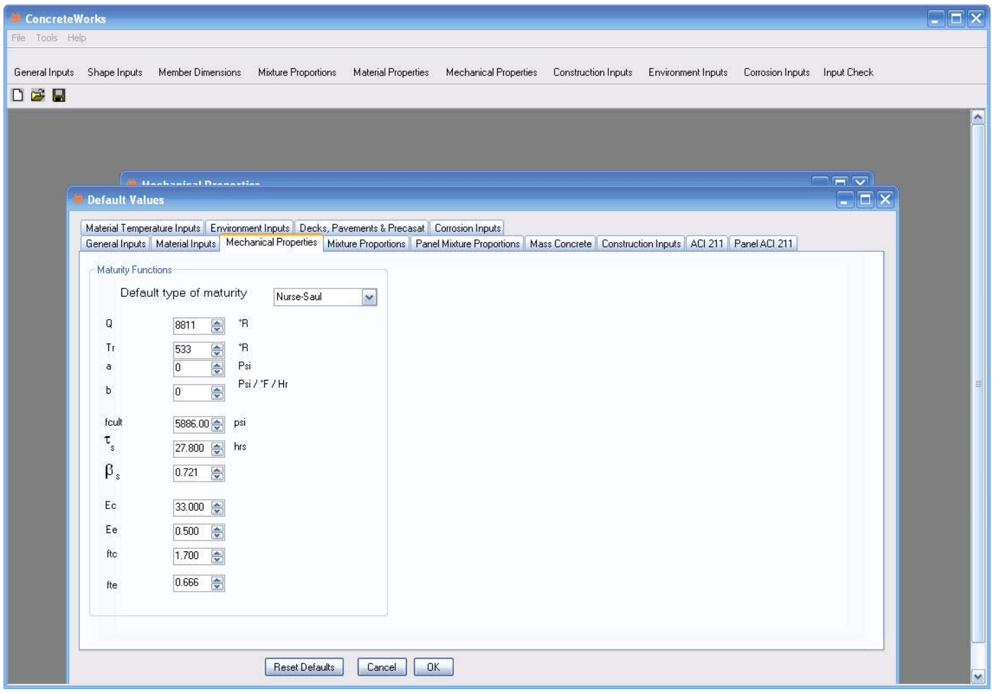


Figure 89 - Material Inputs tab on the Change Defaults screen

6.4.6. Tools Menu

The *Tools* menu contains a few options that increase the power and versatility of ConcreteWorks. The first is the analysis method used to calculate the cement chemical properties. To select the Bogue method of determining the cement composition, select *Bogue (ASTM C 150 2005)* under the *Cement Analysis Method* under the *Tools* menu. To select the Rietveld method of determining the cement chemistry, select *Rietveld* under the *Cement Analysis Method* under the *Tools* menu. Different equations are used to determine the concrete heat of hydration and early age concrete creep properties based on the cement analysis method selected, as explained in Sections 3.1.5 and 4.5.1.

The specification used in the results check section can be changed by selecting the desired specification from the *Specifications Used* option under the *Tools* menu. ConcreteWorks currently only contains the 2004 specifications for the Texas Department of Transportation. If the *Basic ASR and DEF* specification is selected, ConcreteWorks will check to see if the predicted maximum temperature exceeds 160°F, and if the minimum amounts of SCMs prescribed by TxDOT in the 2004 specification are used. If the minimum amounts of SCMs are not used, then a warning that more investigations should be done is shown. Caution should be used in interpreting this check for alkali-silica reaction (ASR). Specifications that require the use of minimum amounts of supplementary cementing materials or maximum cement alkali levels to reduce the likelihood of ASR do not guarantee that this deleterious reaction will be prevented. Alkali silica reaction is highly dependent on the aggregate type, type, and quantity of supplementary cementing materials, alkali loading, and exposure environment.

6.4.7. Help Menu

The *Help* menu provides the user with useful information about the ConcreteWorks program.

About ConcreteWorks

When the user clicks on the *About* ConcreteWorks item under the *Help* menu, a splash screen appears with information on the ConcreteWorks version being used, a link to the official ConcreteWorks website, www.texasconcreteworks.com, and a button that shows the End-User License Agreement. When the link to the official ConcreteWorks website is clicked, ConcreteWorks uses Internet Explorer® to navigate to the website—which is why Internet Explorer is required for using ConcreteWorks (as described in Section 6.1.2).

View User Manual

When the user clicks on the *View User Manual* item under the *Help* menu, the ConcreteWorks User Manual is opened as a new Adobe Reader® process (which is why Adobe Reader® is required for using ConcreteWorks*,* as described in Section 6.1.2).

6.5. Input Sensitivities

ConcreteWorks asks the user to input a great deal of data. To receive a correct answer, the user must enter correct data. Some of the data needed may be hard to obtain. Other data have less of an effect on the calculated results and performance of the model. This section contains some comments on these input sensitivities.

6.5.1. Environment Inputs Sensitivity

All of the *Environment Inputs* directly affect the way heat is transferred to or from the concrete member to the surrounding environment. Of the four types of environmental inputs, the temperature inputs have the greatest impact on the resulting temperature distribution in the element. The relative humidity and cloud cover inputs have a moderate effect on the data. A percent cloud cover value within 30% is generally acceptable. The wind data can also have a moderate effect on the calculated temperatures.

6.5.2. Run Speed

The run speed of the program is one of the biggest concerns to many designers. Following are the six factors that most influence the run speed of the program:

1. The computer speed and computer RAM
2. Analysis duration—A 14-day duration takes longer to run than a 5-day duration. When a thermal stress analysis is performed, the analysis duration has a very large impact on the run time. Because of the numerical methods used, an analysis duration of 4 days may have a run time several times that of a 3 day analysis, instead of the expected 33% longer runtime.
3. Member size—the larger the element, the longer the run-time.

4. Concrete age at form removal–the greater the time before form removal, the greater the run-time.
5. Cure method after form removal–if a cure blanket is used after form removal, the run-time is longer.
6. Three-dimensional analysis greatly increases the run-time compared to a two-dimensional analysis.

6.6. Troubleshooting

6.6.1. Installation Problems

If more than one version of the .NET Framework is installed, errors may occur during installation or when the ConcreteWorks is started. To resolve the issue, try deleting the folder containing the old version of the .NET Framework, usually found in the directory C:\WINDOWS\Microsoft.NET\Framework. Before installing or deleting any files or folders, make sure that the owner of the computer or appropriate network administrator is contacted to obtain permission and/or assistance.

6.6.2. Screen Settings

The screen settings on the computer running ConcreteWorks may adjust the program's appearance. Some of the buttons may be cut off or not visible. The problem may be corrected by either manually resizing the program windows or adjusting the screen settings on the computer. To adjust the screen settings on the computer, open up the display settings window by right-clicking on the desktop. Then click on the *Settings* tab. Then adjust the screen resolution for optimal software viewing.

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