A FOUNDATION FOR HIGH PERFORMANCE BONDED CONCRETE OVERLAY DESIGN AND CONSTRUCTION GUIDELINES

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INTRODUCTION

It has been theorized that early-age behavior due to temperature and moisture changes can significantly affect the performance of a Bonded Concrete Overlay (BCO) over its service life.[1] During the first 72 hours following placement, the bond strength between the BCO and the existing pavement is relatively low in comparison to the strength that it will eventually achieve after this initial period. During this "early-age" period, significant critical stresses at the bond interface can develop. This can lead to premature delamination of the BCO which can subsequently result in a loss of performance of the pavement system.

Very few methods exist to predict bond stress and strength which could serve as tools to prevent delamination from occurring. Those that do exist are generally too simplistic in nature for practical application due to their inherent assumptions. These existing models generally fail to account for the complex interactions between the numerous mechanisms involved, resulting in a significant loss of accuracy. Therefore, an ideal tool for this type of analysis would allow for flexibility in the large number of inputs that determine these phenomena. In addition the ideal tool should be immediately implementable by prompting for inputs which are readily available to the practitioner.

This paper presents the results of an FHWA research project which has focused on modeling early-age behavior of BCOs subjected to stresses from moisture and thermal changes. The end-products of this research effort included the development of a two-part, versatile, comprehensive set of guidelines which provide direction in the proper selection of design and construction variables to minimize early-age delamination in BCO systems. The first part of these guidelines is qualitative in nature, and is based upon the results of the research effort, past experience, and engineering judgment. They are intended to identify design and construction inputs which are most likely to lead to good behavior during the early-age period, thus extending the life of the overlaid structure.

The second part of the guidelines is quantitative in nature. It is comprised of many complex numerical models which have been developed to predict early-age behavior in BCO systems. These models are used to verify good behavior from the selection of inputs made using the qualitative guidelines. These models include a finite-element and finite-difference based Portland cement concrete (PCC) temperature development model which accounts for heat generation from the hydrating paste, solar insolation, surface convection, irradiation, and dynamic specific heat and thermal conductivity values. Several mechanical properties are also modeled including thermal coefficient of expansion, drying shrinkage, and creep relaxation. Bond strength and the PCC modulus of elasticity are predicted using Arrhenius-based maturity methods. Finally, the delamination stresses are predicted using a complex closed-form solution based on engineering mechanics. Additional restraint to free movement due to slab-base friction and curling are also modeled directly.

A comprehensive software package termed HIgh PERformance BONDed concrete overlays (HIPERBOND) has been developed during this research effort. The HIPERBOND software is a user-friendly PC-based application developed with the end-user in mind. It is intended to be used by practicing engineers and qualified technicians in the academic, governmental, and private practice arenas. This package can be used as a stand-alone product to verify specific combinations of design, construction, and environmental inputs in order to determine their overall effect on early-age behavior of a BCO.

GENERAL GUIDELINES FOR BCO DESIGN AND CONSTRUCTION

The purpose of this section is to outline general qualitative guidelines for the design and construction of BCO. Inputs to these guidelines are divided into the following four basic categories: Materials, Environmental, Construction, and Design.

The following sections cite examples of the specific recommendations and guidelines associated with each of the four categories derived from this study.

Materials Inputs

Portland Cement Concrete consists of three basic constituents: aggregate, cement, and water. In addition to these basic components, additional admixtures may be added to enhance or reduce a particular characteristic of PCC. Modification to the three basic PCC components both in type and content can affect the overall PCC performance.

Aggregates

Aggregates are, both volumetrically and by weight, the largest component of a PCC mix. Because of this, it is intuitively determined that the behavior of the aggregate can significantly affect the PCC behavior, and, in the long term, performance. Most aggregates can be divided into two very general categories: calcareous aggregates which include limestones and dolomites, and siliceous aggregates which include granites and quartzes.

It has been observed that, all other factors being equal, PCC pavements constructed with aggregates with a low thermal coefficient of expansion (i.e. many calcareous aggregates) perform better than those built with aggregates with a high thermal coefficient of expansion (i.e. many siliceous aggregates).[2] Siliceous aggregates tend to expand and contract more than limestone for the same change in temperature and thus leads to higher stresses in the pavement. These higher stresses lead to lower performance with all other factors being the same.

Cement

As opposed to aggregates, cement properties change as a function of time. This is particularly true during the early-age period. Because of the complexity of the hydration process, the general guidelines given here should be used with caution. Improper selection of the cement type can lead to a poor performing BCO.

Cement Types I (normal) and III (high early strength) are the most common for fast-track mixes. Cement reacts chemically with water resulting in the generation of heat. Different types of cement release different quantities of heat at different rates. Type III cement is often defined as a key "ingredient" to fast-track mixes. However, serious detrimental effects can occur with its use. Because of the high heat associated with Type III use, the stresses in the pavement at early-ages can be quite significant. Therefore, the use of Type III cement should not be deemed necessary for all fast-track paving purposes. Type I cements have been used successfully for fast-track mixes.

Environmental Inputs

Although the user does not have direct control over the environmental inputs that will occur during construction, they do have some indirect control via selection of the season and time of day of construction. The key parameters which directly influence the performance of a BCO during the early-age period include air temperature, solar radiation, wind speed, and humidity.

Construction Inputs

Some of the critical inputs to proper BCO paving are encompassed in the category of construction parameters. Some of these factors can often be modified on-site as conditions permit. This allows for flexibility in the design of the PCC mixture, and in most cases ensures prevention of early-age damage.

Curing Method

Several curing methods are readily available for BCO construction. The most common curing method is the simple application of a liquid resin or wax-based membrane. Other types of curing methods that have been used successfully in pavements, although more expensive in nature, are polyethylene sheeting, cotton mats, or a combination of any of these. These types of curing methods also influence the heat development in the young BCO, thus affecting the early-age behavior.

Time of Day of Construction

One strategy to counter some of the adverse effects due to the climate is to control the construction time of the BCO. By doing this, the temperature buildup in the PCC can be controlled in order to maximize strength gain and minimize early-age damage. In many cases, by constructing during a time of day such that the maximum PCC temperature during hydration does not coincide with the maximum ambient air temperature, the potential for early-age damage to the BCO can be significantly reduced.

Initial Mix Temperature

Because careful temperature control of the mix is crucial in constructing high performance BCO, the initial mix temperature can be an important variable in the temperature control of the slab during the curing process. Several methods have been used in the past to reduce the concrete temperature. These techniques can be used in conditions where the ambient air temperature is expected to be very high and random cracking or cracking due to excessive thermal expansion can occur. These methods include cooling the mixing water or aggregate prior to mixing.

Design Inputs

The most influential design inputs affecting BCO early-age behavior is the selection of the surface preparation type and bonding agent.

Proper surface preparation is important in minimizing the potential for early-age delamination in BCO. Several surface preparation techniques have been used in the past including no surface preparation, cold milling, sandblasting, air blasting, water blasting, shotblasting, and heavy shotblasting. The final selection of a preparation technique must include many factors. Economics should be considered as a primary variable. The most beneficial surface preparation techniques are typically more expensive than the less beneficial ones. Of those listed here, the best alternative has been found to be heavy shotblasting.[1]

Equally important to the selection of a surface preparation technique is the selection of a bonding agent to be used at the interface of the existing pavement and the BCO. Several types of bonding agents have been used in the past on BCO projects with varying degrees of success. These include no bonding agent, Portland cement grout, latex, and epoxy. Of these, the Portland cement grout or no bonding agent have been found to perform well.[1]

Summary of Qualitative BCO Guidelines

The previous sections have highlighted some guidelines which are specific to the design and construction of bonded concrete overlays. The objective of these qualitative guidelines is to provide the user with a direction in the proper selection of the various properties and values which can affect the overall performance of this type of pavement system. The HIPERBOND system, described in the next section, should be used to verify the selection of the various parameters made in this section. The combination of these qualitative guidelines with the quantitative guidelines in the HIPERBOND system will improve the overall reliability of the design. The potential for early-age damage (delamination) can be identified, and precautions and alternative measures can be taken in order to reduce this possibility.

EARLY-AGE BCO BEHAVIOR MODEL DEVELOPMENT

This section will describe in brief some of the technical background relating to the models used in this study. These models are the key elements to a set of verification guidelines which can be used to "verify" adequacy of performance of a specific subset of design, environmental, construction, and materials inputs. The verification guidelines for early-age BCO have been termed the HIgh PERformance BONDed concrete overlay (HIPERBOND) guidelines. A computer software package of this name has been developed in order to simplify its use.

The HIPERBOND guidelines directly address the following BCO properties during the early-age period:

- PCC Temperature Development including:
  - Heat Generation (i.e. Heat of Hydration - Internal)
  - Solar Insolation
  - Surface Convection
  - Irradiation
  - Age Dependent Specific Heat
  - Age Dependent Thermal Conductivity
- PCC Mechanical Properties including:
  - Age Dependent Thermal Coefficient of Expansion
  - Drying Shrinkage
  - Creep Relaxation
  - Bond Strength Development using Maturity Methods
  - Modulus of Elasticity Development using Maturity Methods
- Restraint to Free Movement including:
  - Restraint of Slab Temperature Gradients (Curling)
  - Axial Restraint due to Slab-Base Friction
  - Overlay Bond Interface Restraint

Models were developed, and described herein, which characterize each of these properties. These models are used by the software to predict the critical bond stresses and strengths in the BCO which will then be compared in order to determine the potential for early-age delamination. The structure of these models can be seen in figure 1.

Early-Age Temperature Prediction Model

Temperature development in concrete due to hydration and ambient temperature conditions can be determined from the general differential equation for heat transfer. The governing model of heat transfer in two dimensions can be expressed below: [3]

$$k_x \bullet \frac{d^2T}{dx^2} + k_y \bullet \frac{d^2T}{dy^2} + Q_h(t,T) = \rho \bullet C_p \bullet \frac{dT}{dt} \qquad (1)$$

where,

k_x, k_y = thermal conductivities of concrete (W/m·°C),
ρ = concrete density (kg/m³),
C_p = specific heat (J/kg·°C),
Q_h = generated heat from heat of hydration of cement and external sources (W/m³),
T = nodal temperature (°C), and
t = time (seconds).

The heat of hydration of the maturing concrete is characterized by the Q_h term in equation 1. The heat of hydration is the amount of heat that is released into the PCC system due to the hydration processes of the cementitious materials. It is mathematically defined as follows: [4]

$$Q_h = H_u C \psi \frac{\lambda_1 \kappa_1}{t_1} \bullet \frac{[\ln(\tau)]^{-(1+\kappa_1)}}{\tau} \bullet e^{\left[-\frac{\Phi}{R}\left(\frac{1}{T+273}-\frac{1}{T_r+273}\right)\right]} \quad (2)$$

where,

H_u = total heat of hydration (J/g),
C = cementitious materials content (g/cm²),
λ_1, κ_1, t_1 = hydration shape and time parameters,

τ = age parameter, defined as: $1 + \left\{ \frac{\sum_{t=0}^{age} \left[e^{\left[-\frac{\Phi}{R}\left(\frac{1}{T+273}-\frac{1}{T_r+273}\right)\right]} \bullet \Delta t \right]}{t_1} \right\}$ (3)

ψ = degree of hydration, defined as: $e^{-\lambda_1 (\ln \tau)^{-\kappa_1}}$ (4)
Φ = activating energy (J/mol),
R = universal gas constant, 8.3144 J/mol/°C,
T = nodal temperature (°C), and
T_r = reference temperature, 20°C.

The heat transfer model is in the form of a finite element model. The concrete substrate and its underlying existing pavement layers are bordered on the bottom by a soil mass. The important parameters for a thermal analysis of a hardening concrete pavement include 1) thermal properties of early-aged concrete, 2) heat of hydration characteristics, 3) pavement geometry, and 4) weather condition data.[5,6,7] These types of parameters serve as input data in the temperature prediction analysis. Table 1 summarizes some of the typical values of the input data for the computer models. Analytical results are given in terms of temperature variation in a concrete pavement at early ages.

Thermal Coefficient of Expansion Prediction Model

One of the keys to characterizing the effects of thermal properties of hardening concrete on a concrete pavement structure is the accounting of thermal movements in relation to the coefficient of thermal expansion (CTE). Accurate values of the CTE are needed to predict potential thermally-induced movements of the concrete pavement. The CTE of early-aged concrete is a function of both the concrete age and relative humidity.

Contrary to the CTE of the cement paste, the CTE for the aggregate is independent of the concrete age. Therefore, the CTE of the cement paste typically governs the overall expansion of the concrete mix during the hardening process. It is also noted that the CTE of concrete in a hardened state is typically larger than the aggregate CTE.

Past research has indicated that the CTE of hardened concrete can be estimated from the volumes of coarse aggregate and mortar.[8] This is the approach used in the development of this model for the guidelines. By using the cement type, aggregate type, and mix design provided by the user, a weighted average can be made and an estimate of the CTE as a function of age is made. In addition, it has been shown that the CTE can vary as a function of the moisture content of the concrete.[9] The following mathematical model is therefore used to assess the CTE, α_{conc}, of the mix:

$$\alpha_{conc} = C_m \left[\sum_{i=1}^{\#\ of\ aggs} \left(\alpha_{agg,i} \frac{V_{agg,i}}{V_{conc}} \right) + \alpha_{paste} \frac{V_{paste}}{V_{conc}} \right] \quad (5)$$

where,

C_m = moisture correction factor,
$\alpha_{agg,i}$ = CTE of i th aggregate (με/°C),
α_{paste} = CTE of cement paste (με/°C),
V_{agg} = volume of aggregate in mix (m³),
V_{paste} = volume of paste in mix (m³), and
V_{conc} = total volume of concrete mix (m³).

Drying Shrinkage Prediction

The drying shrinkage profile can be predicted by combining the predicted ultimate shrinkage with reasonable assumptions concerning the pavement moisture profile. These modeling concepts are discussed herein. The end result is an additional strain gradient in the pavement which can sometimes aggravate stress levels due to curling and axial restraint.

Ultimate Drying Shrinkage

The ultimate drying shrinkage potential of a PCC pavement including a BCO is a function of many parameters. A proposed RILEM model, termed B_3, has been used for this determination.[10] The model is a function of the mix design of the concrete as well as the strength of the mix at 28 days. The general equation for the ultimate drying shrinkage ($\varepsilon_{sh\infty}$) is as follows:

$$\varepsilon_{sh\infty} = \varepsilon_{s\infty} \frac{E(7+600)}{E(t_o + \tau_{sh})} \quad (6)$$

where,

E(t) = elastic modulus (psi) of the concrete at age t (days), estimated using:

$$E(t) = E_{28\text{-days}} \sqrt{\frac{t}{4+0.85t}} \quad (7)$$

t_o = age of the concrete when drying begins (days),
$\varepsilon_{s\infty}$ = $C_1C_2[26w^{2.1}(f'_c)^{-0.28} + 270]$, and (8)
τ_{sh} = shrinkage half-time (days) = $k_t(k_sD)^2$, (9)

where,

$$C_1 = \begin{cases} 1.0 & \text{for type I cement} \\ 0.85 & \text{for type II cement} \\ 1.1 & \text{for type III cement} \end{cases}$$

$$C_2 = \begin{cases} 0.75 & \text{for steam cured specimens} \\ 1.0 & \text{for specimens cured in water or at 100\% relative humidity} \\ 1.2 & \text{for specimens sealed during curing} \end{cases}$$

w = water content of concrete (lb/ft³),
f'_c = 28-day compressive strength of concrete (psi),
k_s = cross-section shape factor (approximately 1.00 for slabs),
D = thickness of the BCO (inches), and
k_t = $190.8 t_o^{-0.08} f'^{-0.25}_c$ (days/in²). (10)

The C_2 values used in the HIPERBOND system are a function of the curing method and range from 0.7 for no curing method to 1.2 for a combination of a polyethylene sheeting and a cotton mat.

Pavement Moisture Profile

Based on previous work, it could be reasonably assumed that the maximum strain due to drying shrinkage occurs at the surface of the overlay.[11] In addition, it is assumed that the shrinkage strains significantly decrease through the depth of the overlay, to near zero at the center of the overlay and below.

BCO Strain Prediction

As figure 1 denotes, a critical junction of the models described is the development of the strain levels present in the BCO. The strain levels are comprised of strains due to thermal movements such as curling and axial movements as well as strains due to moisture loss (drying shrinkage). The bond stress development due to the restraint of these free strains will be discussed later.

Thermal Strain Models

Using the results of the temperature prediction model and the thermal coefficient of expansion model, the free thermal strains (the strain that an unrestrained slab would endure) may be calculated. The general model for this calculation is as follows:

$$\nabla \varepsilon_T = \nabla T \bullet \alpha_{conc}$$

where,

$\nabla \varepsilon_T$ = Thermal Strain Gradient (με/mm)
∇T = Temperature Gradient (°C/mm)
α_{conc} = Thermal Coefficient of Expansion (με/°C)

This general model was divided into two specific models: a curling model and an axial model. These models are discussed in the following subsections.

Curling Strain Model Westergaard developed a model to predict the deflections, strains, and stresses in a rigid pavement due to a uniform (linear) temperature gradient.[12] The resulting model was a closed form solution and was found to be reasonably accurate. Bradbury enhanced Westergaard's original model by accounting for the varying restraint as a function of the pavement geometry and relative stiffnesses.[13] The resulting model is used in the HIPERBOND systems as the curling stress/strain model. The following equations characterize the curling stress prediction using Bradbury's model:

$$\sigma_{curl,critical} = \frac{\alpha_{conc} \bullet \nabla T \bullet E}{2\left(1-\nu^2\right)}\left(C_{\max} + \nu C_{\min}\right) \tag{12}$$

where,

$\sigma_{curl,critical}$ = critical BCO curling stress (Pa),
α_{conc} = thermal coefficient of expansion of the PCC (/°C),
∇T = difference in temperature between the PCCP/BCO surface and bottom (°C),
ν = Poisson's ratio, and
C_{max},C_{min} = maximum and minimum values of C (restraint factor), a function of the slab length (L) in meters, and the following definition for the radius of relative stiffness (l):

$$l = \sqrt[4]{\frac{Eh^3}{12\left(1-\nu^2\right)k}} \tag{13}$$

where,

E = modulus of elasticity of PCC (Pa),
h = thickness of PCCP/BCO (meters), and
k = modulus of reaction of the support layers (Pa/m).

The temperature gradient (∇T) used for this model is based on a datum of the temperature gradient at final set. Therefore, any permanent upward or downward curling of the unloaded slab is directly accounted for by this method. This method is characterized by the following equation:

$$\nabla T\left(from\ Equation\ 12\right) = \nabla T_{current} - \nabla T_{set} = \left(T_{top,current} - T_{bottom,current}\right) - \left(T_{top,final-set} - T_{bottom,final-set}\right) \tag{14}$$

Figure 2 graphically demonstrates the concept of this model. The solid line in figure 2a shows the actual temperature gradient in the BCO at the time of final set (which is defined as the PCC temperature when the degree of hydration is equal to 0.43 times the water-cementitious materials ratio). The dashed line represents the temperature gradient at the time which the curling is currently being analyzed. The horizontal lines represent the difference in temperature at various depths of the BCO between the final set and the current temperature (ΔT). Figure 2b demonstrates the approximations that are sometimes made when determining the actual temperature gradient. If a constant set temperature is assumed (uniform throughout the cross-section), then the differences in temperature for each layer will be different (denoted as ΔT_{iA} instead of ΔT_i, where i is the layer number). In figure 2c, the differences in temperature for each layer are held constant, thus the shape of the gradient is quite different than that in figure 2b. The maximum difference in temperature in the old model is found in the bottom layer (number 19A), while the new model predicts the maximum difference in temperature to occur closer to mid-slab (in layer 14). This difference in the gradient approximation becomes more significant if the gradient at final-set is larger than demonstrated here.

Axial Thermal Strain Model The axial thermal strains are calculated by first deriving the average temperature difference between the current slab temperature and the slab temperature at final set. The following equation is used to perform this operation:

$$\Delta T = \frac{\sum_{z=0}^{h}\left[\left(T_{z,current} - T_{z,final-set}\right)\Delta z\right]}{h} \quad (15)$$

where,

ΔT = temperature difference used by axial thermal strain model (°C),
h = total BCO thickness (mm),
T_z = PCC temperature at depth z (°C), and
Δz = depth increment used in summation (mm).

The unrestrained BCO strains can then be calculated by multiplying the value of ΔT from equation 15 with the thermal coefficient of expansion (α_{conc}).

Shrinkage-Induced Strain Model

The general form of the model to predict free shrinkage strains is as follows:

$$\nabla\varepsilon_{sh} = f(\nabla M, \varepsilon_{sh\infty}) \quad (16)$$

where,

$\nabla\varepsilon_{sh}$ = shrinkage-induced strain gradient (profile),
∇M = moisture gradient, and
$\varepsilon_{sh\infty}$ = ultimate drying shrinkage.

This strain gradient can be superimposed on the strain gradient due to thermal changes, and the resulting gradient can then be used in predicting the bond stress development in the BCO.

The maximum value of shrinkage is assumed to be at the surface of the overlay, linearly decreasing to zero at the center of the BCO, and continuing to be negligible to the interface between the BCO and the existing pavement.

Total Free Strains

Each of the models described in the preceding sections are represented by boxes in the second column of figure 3. The third column represents the two types of free strain calculated by the models. The summation of the strain profiles results in the critical strain values required to calculate the BCO critical bond stresses. The missing elements, namely the modulus of elasticity and the restraint will be discussed in the following sections.

Elastic Modulus Development and Relaxation Creep Effects

The modulus of elasticity of the PCC is a critical factor in determining the overall bond stress level present. In order to simplify the overall modeling process, two early-age characteristics will be combined into a single model. The first is prediction of the actual modulus of elasticity using maturity methods (similar to the prediction of concrete strength). The second characteristic is relaxation creep, or the tendency for PCC under load to demonstrate a decrease in the internal stress level over time.

Predicting Modulus of Elasticity using Maturity Methods

Maturity methods have been used extensively in recent years to predict the in-place strength of PCC.[11] The basis for this method is simple: the strength (and modulus of elasticity) of a PCC specimen are directly related to the quantity of heat developed from the hydrating cement. The practical benefit of this method is that field evaluations of in-place strength can be predicted from simple temperature measurements of the concrete over time. The theoretical benefit is the ability to accurately predict both the strength and modulus of elasticity of a PCC over a wide range of conditions based simply on the temperature development in the modeled pavement.

The Arrhenius method of maturity was selected for this project. The basis of the Arrhenius maturity theory is the prediction of the equivalent age, t_e. The equivalent age can then be used to calculate the degree of hydration of the concrete. The degree of hydration is then used to predict the concrete strength or modulus of elasticity. The equivalent age, t_e, is equal to the numerator of equation 3, or redefined here as:

$$t_e = \sum_{t=0}^{age} \left[e^{\left[-\frac{\Phi}{R}\left(\frac{1}{T+273} - \frac{1}{T_r+273} \right) \right]} \bullet \Delta t \right] \tag{17}$$

where,

t_e = equivalent age (hours),
Φ = activating energy (J/mol) (see typical values in table 1),
t = time (hours),
R = universal gas constant, 8.3144 J/mol/°C,
T = nodal PCC temperature (°C), and
T_r = reference temperature, 20°C,

which can be reduced to:

$$t_e = \sum_{t=0}^{age} \left[e^{\left[-\frac{\Phi}{8.3144}\left(\frac{1}{T+273} - \frac{1}{293} \right) \right]} \bullet \Delta t \right] \tag{18}$$

The degree of hydration, ψ, is then defined as:

$$\psi = e^{-\lambda_1 (\ln \tau)^{-\kappa_1}} \tag{19}$$

where,

τ = age parameter, defined as: $1 + \left(\frac{t_e}{t_1} \right)$, and (20)

λ_1, κ_1, t_1 = hydration shape and time parameters (see typical values in table 1).

The prediction of the modulus of elasticity requires a benchmark value. This value is entered manually by the user as the 28-day design value. In order to calculate the early-age modulus of elasticity, the degree of hydration is used with the following equation:

$$E_{current} = E_{28-day} \left(\frac{\psi_{current} - \psi_{critical}}{\psi_{28-day} - \psi_{critical}} \right)^{2/3} \tag{21}$$

where,

$\psi_{current}$ = degree of hydration at specific time,
$\psi_{critical}$ = degree of hydration at final set of PCC = $0.43 \times {}^{W}/_{CM}$, (22)
$\psi_{28\text{-day}}$ = degree of hydration at 28-days (assuming PCC remains at reference temperature), defined mathematically as:

$$\psi_{28-day} = e^{-\lambda_1 \left[\ln\left(1 + \frac{672.}{t_1} \right) \right]^{-\kappa_1}} \tag{23}$$

${}^{W}/_{CM}$ = water-cementitious materials ratio of the concrete mix.

Relaxation Creep

Creep is a characteristic of many materials, including PCC, which, if not accounted for correctly, can result in erroneous material properties. This has been found to be especially true for PCC during the early-age period.[11] In the HIPERBOND system, creep effects are accounted for by using a creep-adjusted modulus of elasticity. The following subsections describe the basic mechanisms of creep in PCC and demonstrate the rationale behind the adjusted modulus of elasticity model.

The effective or creep-adjusted modulus of elasticity, E_{eff}, is defined by the following general equation: [14]

$$E_{eff} = \frac{E_o}{|1 + J_t E_o|} \tag{24}$$

where,

E_o = elastic modulus at the time of load application (age of set),
J_t = adjusted creep compliance factor (mm²/N), defined as:

$$J_t = J_t \delta_t \xi_t \phi_t \tag{25}$$

where,

J'_t = creep compliance factor (mm²/N), defined as:

$$J'_t = \left[28.74\left(1 - e^{-0.801t}\right) + 8.13\left(1 - e^{-45.38t}\right) + 4.468t\right] \times 10^{-6}, \tag{26}$$

δ_t = stress intensity correction factor, defined as:

$$\delta_t = 0.017\sigma + 0.701, \tag{27}$$

ξ_t = loading time correction factor, defined as:

$$\xi_t = -1.107 \ln(\tau) + 1.538, \text{ and} \tag{28}$$

ϕ_t = temperature correction factor, defined as:

$$\phi_t = 0.0257T + 0.487 \tag{29}$$

where,

t = age of PCC (days),
σ = average PCC stress (N/mm²),
τ = elapsed time since start of loading (days), and
T = average cross-sectional PCC temperature (°C).

Although the formulation of the effective or creep-adjusted modulus is rather complex, the simplicity of the model is maintained by providing the user with a single modulus value for a given age. This value for E can be used in the overall stress calculations.

BCO Bond Restraint and Stress Model

Two mechanisms can lead to delamination, namely, bond shear failure, and bond tensile failure. These failure mechanisms can work independently or simultaneously. The first mechanism, bond shear failure, is caused by a potential for differential lateral movement between the two PCC layers. The second failure mechanism, bond tensile failure, is caused by a potential differential movement in the vertical direction. If the potential differential movement is great enough, the stress at the bond interface can exceed the strength of the bond, leading to delamination. A graphical representation of these failure modes can be seen in figures 4a and 4b.

The model for predicting stresses is represented by a system of laminated beams shown in Figure 4c.[15] Each of the three layers is characterized by a modulus of elasticity (E), thermal coefficient of expansion (α), thickness (h), and Poisson's ratio (ν). The total length of the beam is 2 ℓ.

The model is presented here in a simplified form. A full definition of the model can be found in the original source. The general governing equations for the stress analysis are as follows:

$$\left[C_1\frac{d^4}{d\xi^4}+C_2\frac{d^2}{d\xi^2}+C_3\right]\frac{\sigma_1}{E_1}+\left[C_4\frac{d^4}{d\xi^4}+C_5\frac{d^2}{d\xi^2}+C_6\right]\frac{\sigma_1^*}{E_1}=C_{10} \tag{30}$$

$$\left[C_4\frac{d^4}{d\xi^4}+C_5\frac{d^2}{d\xi^2}+C_6\right]\frac{\sigma_1}{E_1}+\left[C_7\frac{d^4}{d\xi^4}+C_8\frac{d^2}{d\xi^2}+C_9\right]\frac{\sigma_1^*}{E_1}=C_{11} \tag{31}$$

where,

$C_1, C_2, \ldots C_{11}$ = elastic coefficients = $f(E,h,\nu,\alpha,\ell)$ (not defined here due to their complexity),[15]
ξ = normalized x-coordinate of slab ($\xi = -1$ @ $x = -\ell$; $\xi = 1$ @ $x = \ell \rightarrow$ see figure 4c),
σ_1 = primary stress function, and
σ_1^* = secondary stress function.

After solving these differential equations for σ_1 and σ_1^*, the following equations can be used to solve for the tensile and shear stresses at the bond interface:

$$\tau_{xy}=\frac{\partial\sigma_1}{\partial x}\bullet h_1+\frac{\partial\sigma_1^*}{\partial x}\bullet\frac{h_1}{2} \tag{32}$$

$$\sigma_y=\frac{\partial^2\sigma_1}{\partial x^2}\bullet\frac{h_1^2}{2}+\frac{\partial^2\sigma_1^*}{\partial x^2}\bullet\frac{h_1^2}{3} \tag{33}$$

where,

τ_{xy} = shear stress in x-y plane at interface,
σ_y = tensile stress normal to interface surface,
h_1 = overlay thickness (see figure 4c).

BCO Bond Strength Modeling

In order to have the ability to assess the potential for early-age BCO delamination, a model was developed in order to accurately predict the BCO bond strength.

As discussed in the elastic modulus prediction section, maturity is a measure of the thermal history of a PCC specimen. If a concrete is cured in an environment which is insulatory and prevents heat loss to the environment, it will gain strength faster than that of a specimen which is exposed. The detriment of a high heat cure is that the environmentally induced bond stresses in the BCO could ultimately be higher, thus making the BCO more vulnerable to premature delamination.

The bond strengths, therefore, are developed using the same maturity model. The general form of this equation is as follows:

$$\widetilde{S}_{current} = \widetilde{S}_{28-day}\left(\frac{\Psi_{current} - \Psi_{critical}}{\Psi_{28-day} - \Psi_{critical}}\right) \quad (34)$$

where,

$\widetilde{S}_{current}$ = bond strength (tensile or shear) for current time (age) (kPa),
$\widetilde{S}_{28-day}$ = bond strength (tensile or shear) at 28-days (kPa),
$\Psi_{current}$ = degree of hydration at specific time,
$\Psi_{critical}$ = degree of hydration at final set (see equation 33), and
Ψ_{28-day} = degree of hydration at 28-days (see equation 34).

Equation 34 is very similar to equation 21 (calculating the modulus of elasticity). Both equations require a 28-day benchmark value, and both have a correction factor for the age of the PCC. However, note that the exponent on the bond strength equation is 1, while it is 2/3 for the modulus of elasticity.[16]

Early-Age Delamination Model

Delamination in the early-age BCO is the critical distress which is modeled by the HIPERBOND system. The delamination mechanisms were graphically depicted in figures 4a and 4b. Two modes of failure are modeled by the guidelines: shear failure and tensile failure. A violation of the shear or tensile strength of the bond at any time can lead to delamination. The HIPERBOND delamination distress model simply compares the bond stresses with the bond strength.

Figure 5 demonstrates the concepts in this comparison process. The stresses and strengths in this figure represent the conditions at the "critical" bonded location which is defined as the location where the highest concentration of delamination stresses exist. Scenario 1 demonstrates a set of conditions where the strength in shear in tension remain above the stress levels at all times (during the early-age). Scenarios 2 and 3 in figure 5, however, show violations of the bond strength by shear and tension modes, respectively. Note that when delamination occurs, the stress level subsequently decreases in both shear and tension, thus a drop in the curves can be noted at these times. Scenario 4 in figure 5 demonstrates a very poor scenario where delamination occurs first in tension, and then later in shear. This scenario demonstrates the concept of progressive failure if the conditions causing the delamination are not countered.

Each of the latter three scenarios constitutes an early-age failure of the BCO system. A violation of either the shear or tensile strength can lead to delamination. Therefore, during the run-time of the HIPERBOND software, the user should note a violation (or near-violation) of both modes of failure.

CONCLUSIONS

The intent of this study was to develop a comprehensive set of guidelines to be used in predicting the early-age performance of bonded concrete overlays. This objective was accomplished by two means: a qualitative set of guidelines, and a quantitative set of verification guidelines.

A set of qualitative guidelines has been developed which detail the effects on the overall performance of BCO as a function of the mix design, construction, environment, and the overlay design. These guidelines could be used as a stand-alone product offering guidance toward better design and construction of high performance BCO. These inputs consist of a conglomeration of past experiences with the design and construction of high performance BCO.

A computerized verification system termed HIPERBOND was also developed which enables the engineer to investigate the direct impact on the early-age behavior of a BCO. Comprehensive models were developed which predict the critical bond stress levels in young overlays subjected to environmental and internal loading. Parallel models predict the overlay bond strength during the early-age as a function of the heat development from the hydration process. The combination of these properties are then compared and the overall behavior can be predicted. It should be noted that there are many assumptions inherent in the HIPERBOND system. Many of these assumption were required in order to simplify

the procedure to a level which can be more readily implemented by the pavement industry. A compromise between user-friendliness and reliability was made in the current version. Future versions of the system may have flexibility as to the level of input data required by the user.

This project has resulted in a tool which has the potential for use in planning, design, and construction of BCOs. Although the theory behind the models used in the quantitative guidelines is sound, and in most cases, the individual models have been verified, the sum of the models in the form of the HIPERBOND software still requires a verification analysis. This process is currently in progress and will serve to improve the reliability of the final product.

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FIGURE 5 BCO Bond Failure Scenarios

TABLE 1 Inputs for Temperature Prediction Model in HIPERBOND

Data Category	Input Data	Typical Value
Concrete Properties	Thermal conductivity, k_x, k_y, (W/m•°C)	Varies with Age @ t = ∞: 0.612
	Density, ρ, (g/cm³)	2.3325
	Specific heat, C_p, (J/g•°C)	Varies with Age @ t = ∞: 0.91 (LS) 0.71 (Siliceous)
	Emissivity, ε	0.88
	Solar Absorptivity, β_s	0.55
Soil Properties	Thermal conductivity, k_x, k_y, (W/m•°C)	0.30
	Density, ρ, (g/cm³)	1.6000
	Specific heat, C_p, (J/g•°C)	0.80
Heat of Hydration	Cementitious materials content, C, (kg/m³)	User Input
	Total heat of hydration, H_u, (J/g) Activating energy, Φ, (J/mol) Parameter, λ_1 Parameter, t_1 Parameter, κ_1	Type I Cement: H_u = 460.0 Φ = 41750 λ_1 = 2.42 κ_1 = 0.85 t_1 = 2.12 Type II Cement: H_u = 406.0 Φ = 39050 λ_1 = 3.16 κ_1 = 1.07 t_1 = 2.06 Type III Cement: H_u = 468.0 Φ = 44150 λ_1 = 3.52 κ_1 = 1.10 t_1 = 0.97 Addition of Min. Admix: H_u = +15.0 Φ = + 2000
Initial Conditions	Initial PCC mix temperature, (°C)	User Input (Mix Temp)
	Initial base temperature, (°C)	User Input (Avg Air Temp)

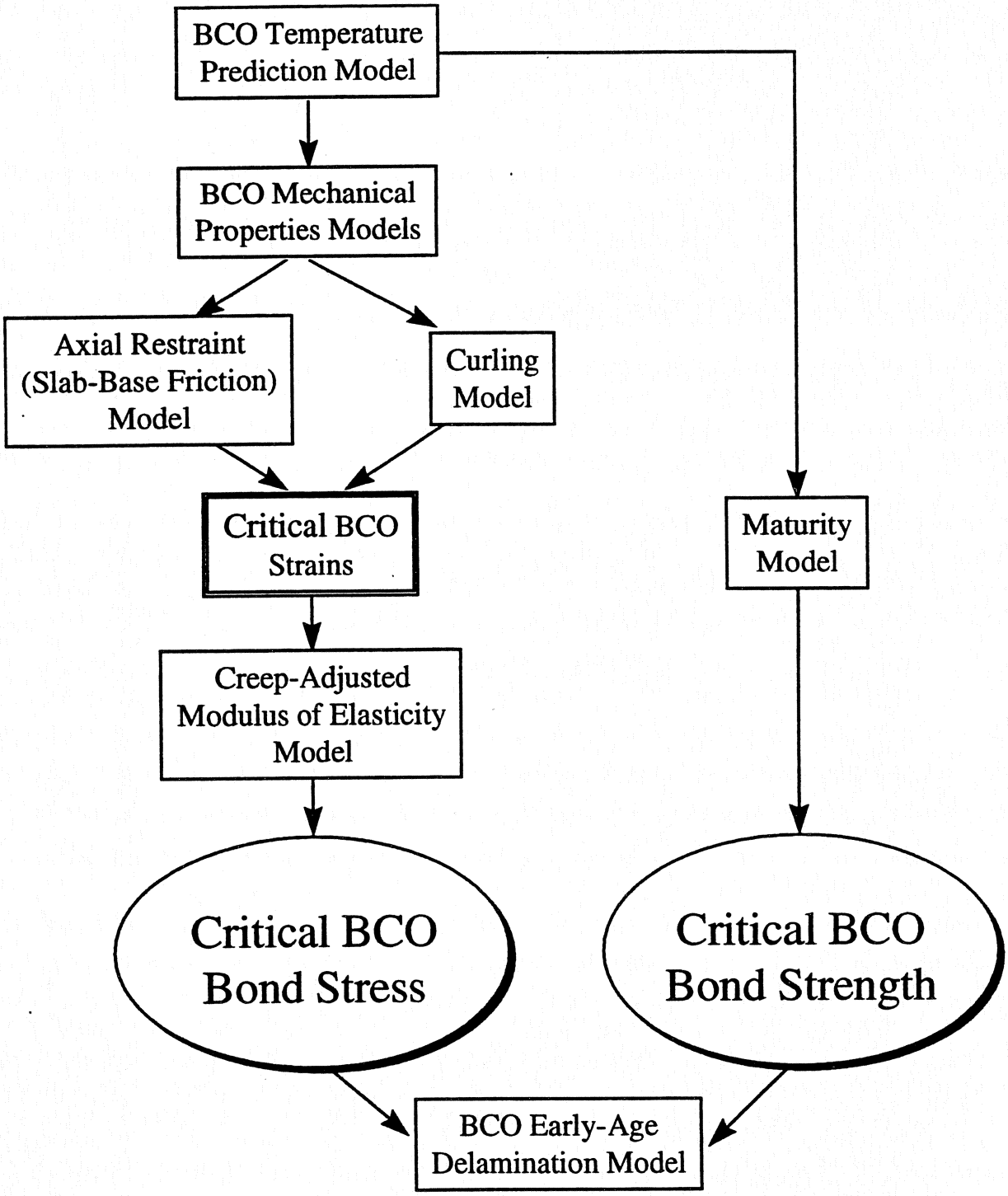


FIGURE 1 Framework for HIPERBOND Guideline Models

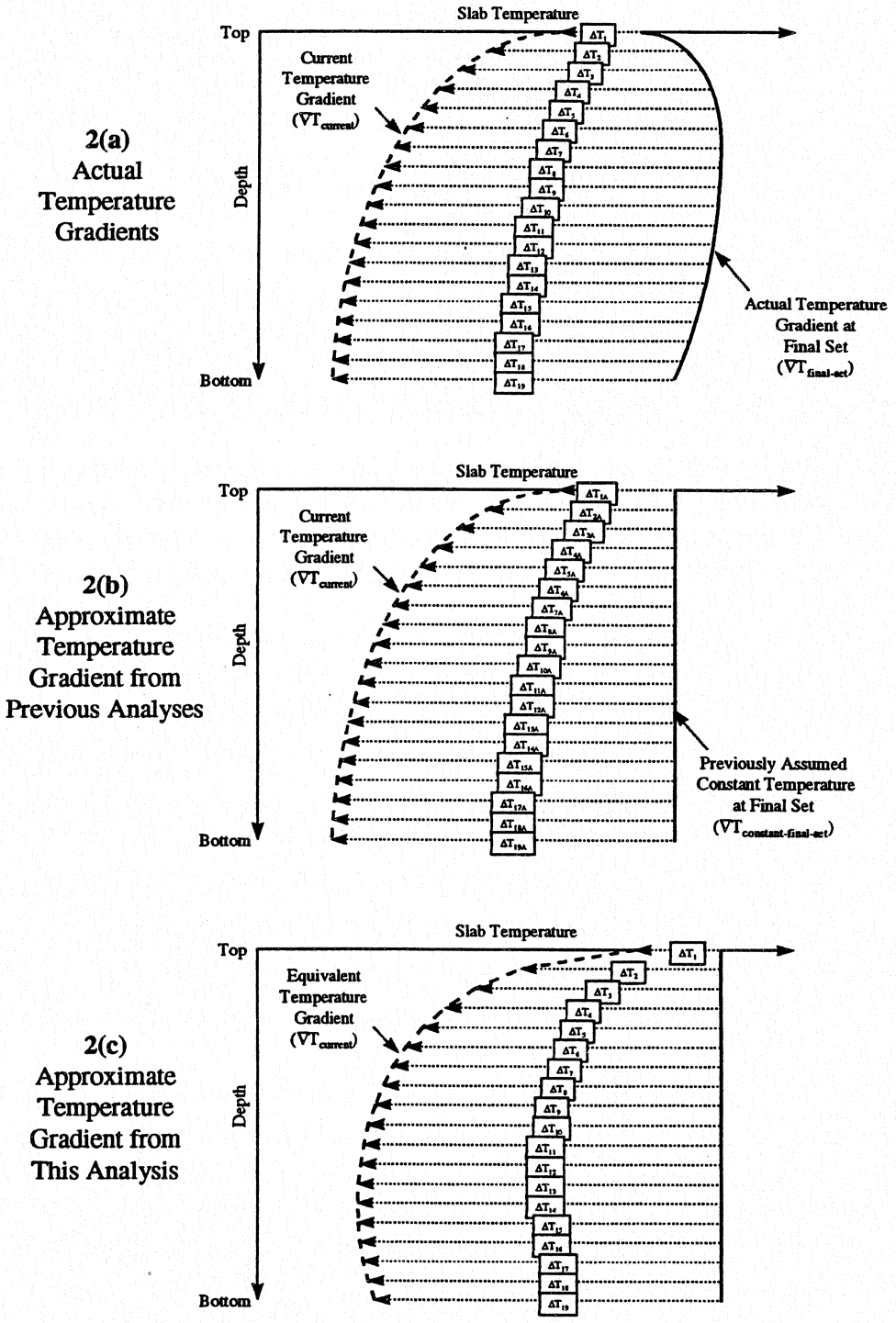
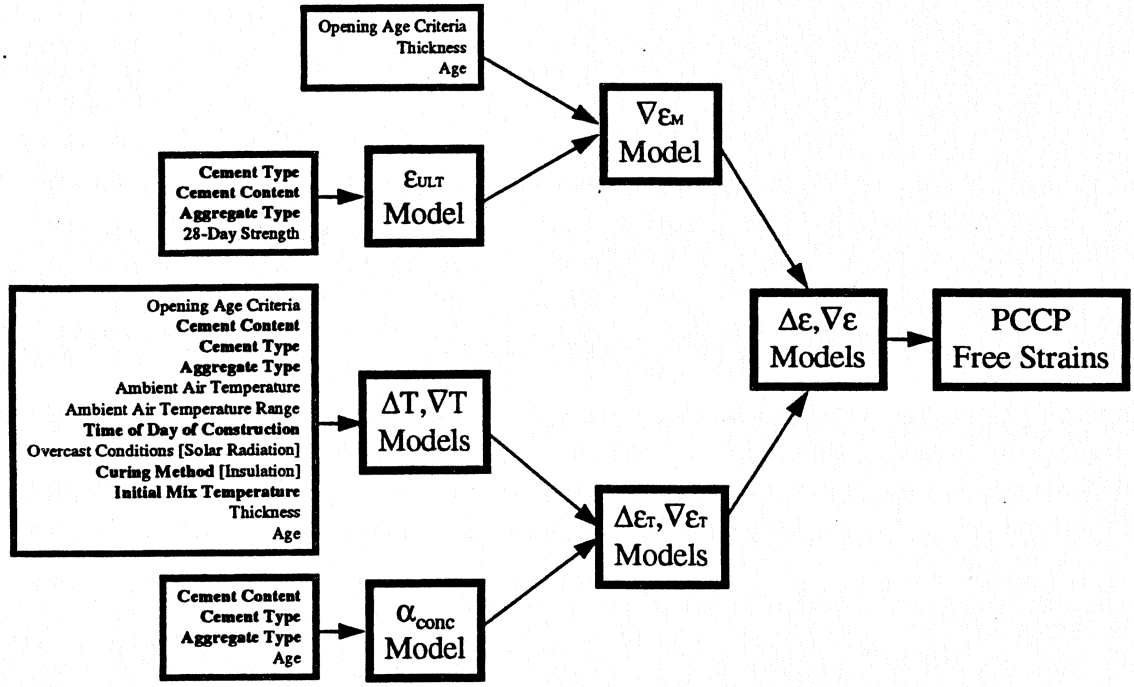


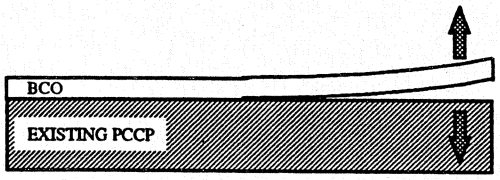
FIGURE 2 Idealization of Equivalent Temperature Gradient



Note:	Items in **BOLD** are variables which can be adjusted by the user for various construction scenarios. Items in [BRACKETS] are model variables derived from the user variables.

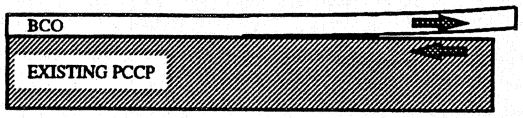
FIGURE 3 Flowchart of Free Strain Model Logic

Figure 4a
Bond Tensile Failure



Bond Tensile Failure

Figure 4b
Bond Shear Failure



Bond Shear Failure

Figure 4c
Bond Stress Model

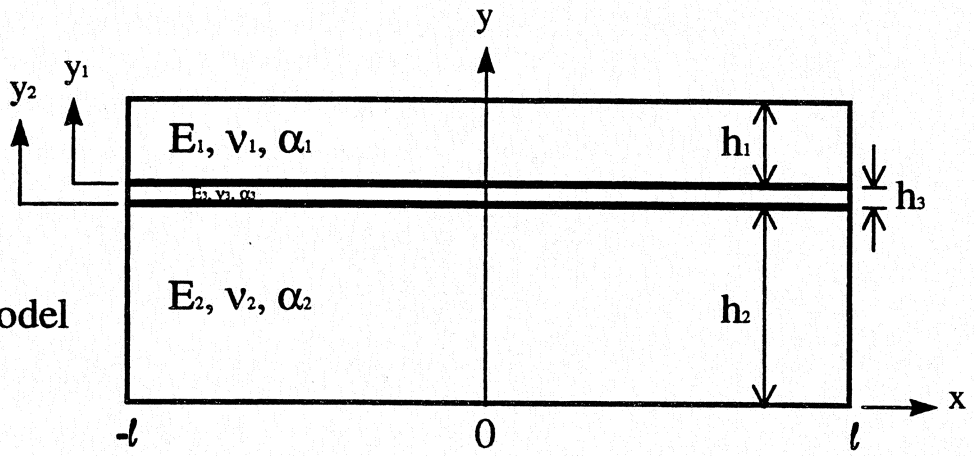


FIGURE 4 BCO Bond Failure Mechanisms and Model Structure

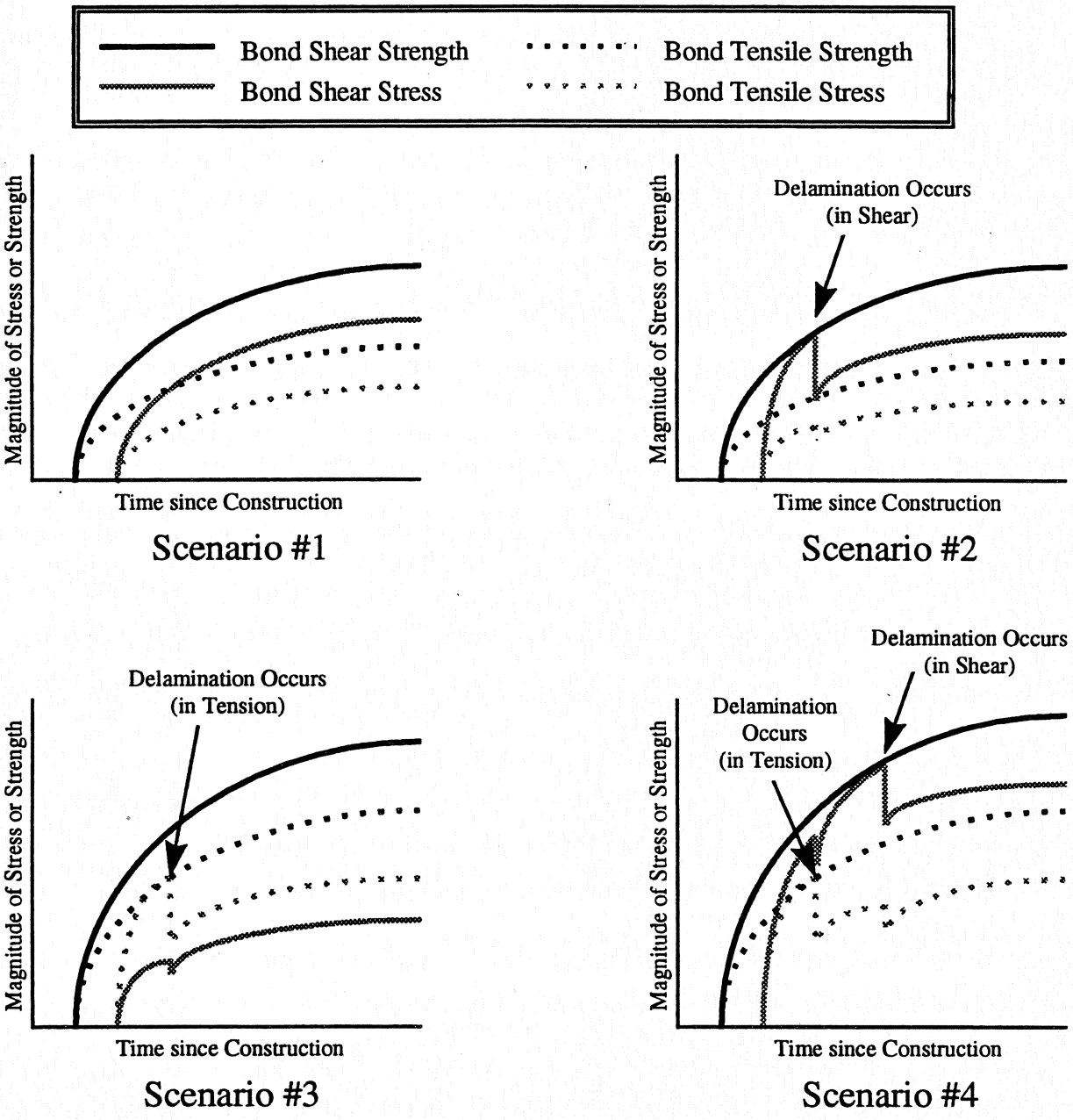


FIGURE 5 BCO Bond Failure Scenarios

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