Analytical Technique to Mitigate Early-Age Longitudinal Cracking in Jointed Concrete Pavements

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Abstract

This paper reviews the fundamental issues that may create conditions ripe for early-age random cracking in jointed concrete pavement (JCP) construction, specifically in longitudinal direction, and also provides an analytical approach to predict cracking potential. The finite element analysis technique was used to investigate the level of restrained stresses in the transverse direction of JCP slab resulting from different combinations of variables influencing the stress development. Influencing factors considered for the analysis include slab (paving) width, slab length, slab thickness, interface friction, modulus of subgrade reaction, temperature gradient (due to temperature drop), and concrete modulus of elasticity. Graphical charts for stress level versus concrete modulus of elasticity were produced for different combinations of other variables. These charts can be used to estimate the potential for early-age longitudinal cracking in JCP construction, provided the characteristics of early-age strength development of the concrete are known. Application examples are presented to demonstrate the analysis techniques.

Introduction

Although early age longitudinal random cracking is not a very common occurrence, this type of cracking can occur in newly placed jointed concrete pavements (JCP) when a unique set of circumstance develops that creates conditions ripe for the development of excessive restrained stresses in the Portland cement concrete (PCC) slab. This undesirable condition is caused by complex interactions of many factors related to the climatic conditions, construction practices, structural constraints, and the properties of concrete. Pavement engineers need to properly take account the influencing factors into the procedures of design and construction of JCP to prevent or minimize the development of uncontrolled early-age random cracking. Practices to determine the longitudinal joint spacing, as well as depth and timing of joint sawing operations, should correspond to the potential of cracking. It should be noted that the presence of reinforcing steels can also influence the development of the restrained stress and cracking in jointed reinforced concrete pavements (JRCP).

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However, JRCP is not considered in this paper, and therefore, JCP herein refers only to jointed plain concrete pavement (JPCP).

Over the years, based on experience and some theoretical formulations, procedures and best practices have been proposed to minimize the development of uncontrolled early-age cracking (*1*-*3*). Other studies provided computerized analysis tools, which can be used for determining the early-age cracking potential in JCP construction (*4*). Although the theoretical basis would be the same for the developments of both transverse and longitudinal cracks, most of the past studies have focused on the development of early-age transverse cracking. One recent paper presented a discussion of analytical investigation for understanding the conditions that may contribute to the development of early-age longitudinal cracking (*5*). The investigation has since been expanded to develop data to identify the potential for early-age longitudinal cracking for more general cases of JCP construction. The results of the expanded investigations are presented in this paper.

Factors Affecting Early Age Longitudinal Cracking

Figure 1 shows a typical longitudinal random cracking occurred in a JCP at early-ages. The early-age random cracking results from complex interactions of many factors. Newly placed concrete pavements experience linear volume changes as well as curling/warping deformations due to the changes of temperature or moisture conditions. Uniform temperature drop or drying shrinkage causes axial contraction of concrete pavement slab.

Figure 2 shows the developments of axial tensile stresses in the slab due to the frictional restraint between the slab and the underlying layer. Figure 3 shows the mechanism of curling or warping stress developments in a concrete pavement slab due to the effects of non-uniform temperature or moisture distribution in the slab combined with the slab's self weight. Note that the critical condition for early-age cracking is likely to happen during the first night after the placement of PCC. The nighttime low ambient temperature forces the top of the PCC slab cooler, while the bottom of the slab is still at high temperature due to the heat of hydration. Therefore, the temperature gradient in the concrete is likely to be the highest during this period, yet the concrete strength is still low. Considering this fact, the upward curling was the only condition of interest for the curling/warping stress analysis conducted in this study.

Cracking initiates when the level of stress in concrete pavement slab reaches to the strength of the concrete as schematically depicted in Figure 4. Therefore, the potential of early age longitudinal cracking can be determined by investigating both the state of stress and strength development in the concrete in early ages. The level of restrained stress at any time is dependent upon many factors and their interactions. These factors may be categorized into weather condition, construction practice, structural constraints, and properties of concrete, as follows:

Figure 1. Early Age Longitudinal Cracking

- Weather condition – Rate and magnitude of the changes, particularly decrease, of temperature and moisture conditions in and outside of concrete slab. Night-time temperature drop or sudden passing of cold or rain front would induce critical condition for higher restrained stress development and early-age random cracking.
- Construction practice – Inadequate curing can result in slab warping due to excessive concrete surface moisture loss. Dimensioning and timing of joint sawing practice is one of the most critical factors for the development of early-age random cracking. The construction practice must be properly adjusted in accordance with the other construction conditions.
- Structural constraints – Restrained stress can be developed in a JCP slab due to the structural constraints provided from underlying base or subbase layer. Interface friction between concrete slab and underlying layer induces axial restrained stress in the slab. Other structural conditions, including the slab dimension, affect the degree of constraints.
- Properties of concrete – Many concrete properties, including coefficient of thermal expansion, shrinkage coefficient, strength, and modulus of elasticity, affect the level of restraints and corresponding stress development in the concrete slab.

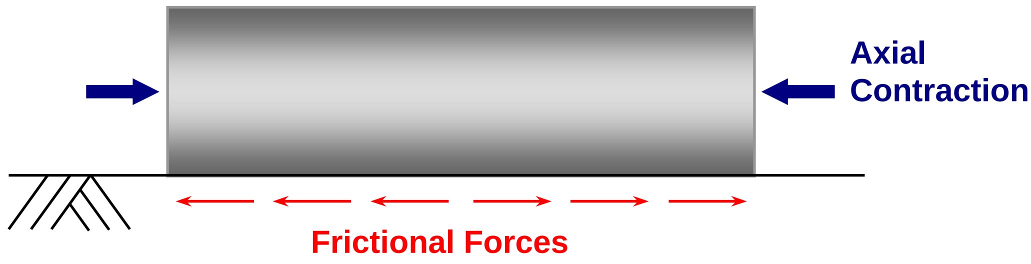
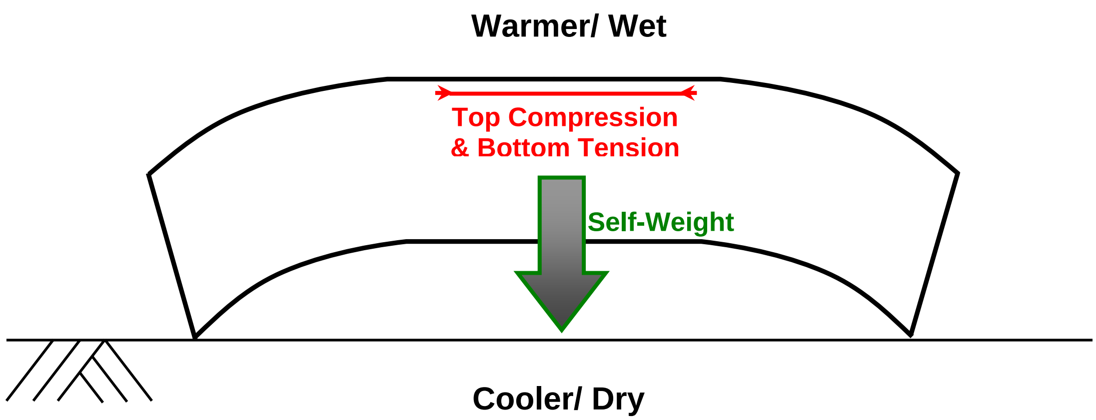
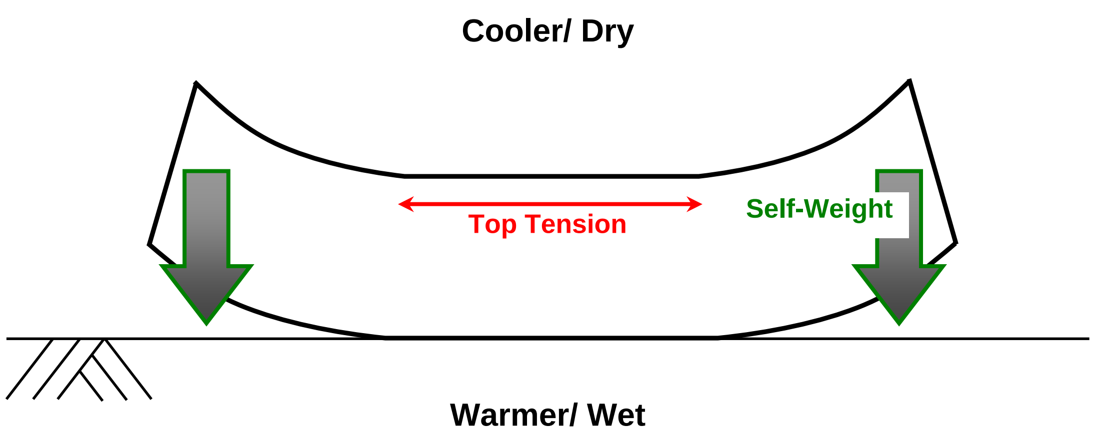


Figure 2. Development of Axial Stress due to Frictional Restraint



(a) Tension in the bottom of slab during downward curling



(b) Tension in the top of the slab during upward curling

Figure 3. Curling/Warping and Restrained Stress Development in a Jointed Concrete Pavement Slab

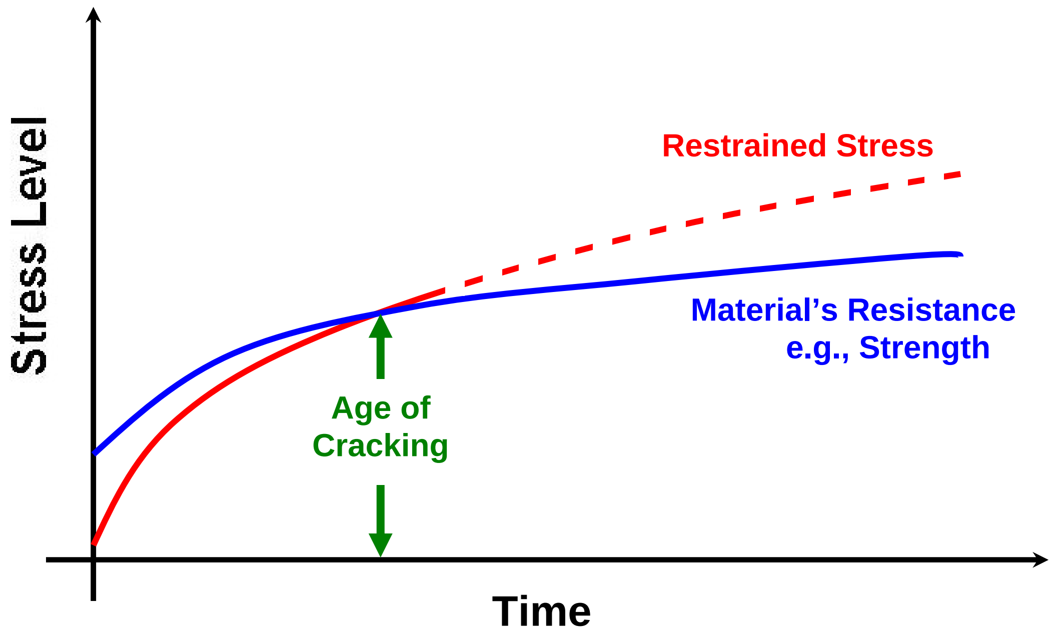


Figure 4. Developments of Concrete Strength, Restrained Stress, and Early Age Cracking

Note that there are other factors or construction conditions that may affect the degrees of impact of the above-listed factors. For instance, time of paving in a day may greatly affect the rate and magnitude of temperature drop in PCC slab. High curling stress can occur when concrete is placed during the early part of the day in warm days. Therefore, any possible conditions or factors should be carefully examined for their impacts on the level of stress developments in the concrete slab.

Factors that determine early age concrete strength development may include the following:

- Concrete mixture characteristics,
- Ambient temperature and humidity, and
- Curing environment.

The rate of strength development in concrete during the first few days is of significant interest with respect to determining the potential for early-age cracking. If the strength development is retarded due to any number of reasons, such as poor curing conditions, low ambient temperature, incompatible concrete constituents, etc., the critical conditions may develop that may lead to longitudinal cracking during the first or second night's temperature drop.

Restrained Stress Analysis

As noted, two types of restraint stresses, bending and axial, in transverse direction are of concern with respect to the development of early-age longitudinal cracking. The occurrence of early age cracking is considered to be a result of the combined effect of the restrained axial and bending stresses. Axial or frictional tensile stress increases almost linearly as the distance from the slab free edge increases. Bending stresses develop as a result of restrained slab curling due to temperature gradient effect as well as warping due to moisture gradient effect. In this study, however, the effect of moisture gradient is implicitly incorporated into the curling stress analysis by using equivalent temperature gradient. Discussions on the modeling and analysis of the combined restraint stresses are presented in the following sections.

Curling/Warping

The restrained curling stresses in transverse direction were determined using the finite element structural analysis program JSLAB. As previously mentioned, only the upward curling/warping was of interest in this stress analysis. The description of JSLAB is given elsewhere (*6*). JSLAB can analyze a jointed concrete slab system resting on a Winkler (liquid) foundation. Loading can be in terms of wheel loading as well as linear temperature gradient. JSLAB allows incorporation of loss of support due to slab curling/warping by using an iterative analysis process that checks for loss of support. Detailed theoretical discussion on this subject is beyond the scope of this study.

JSLAB performs curling/warping analysis using a two-step process. In the first step, the natural slab curvature is determined for a weightless slab resting at the center point of the slab. This gives the deformation and apparent stress responses for unrestrained condition. In the second step, the slab curvature is determined with the slab weight considered and the slab resting on the Winkler foundation. An iterative process is used to incorporated appropriate loss of support due to the upward curvature of the slab. The restrained stress is the difference between the apparent stress of the unrestrained condition and the stress obtained for the condition with the slab weight incorporated.

The focus of the analysis was to determine if a concrete pavement slab subjected to certain environmental conditions exhibits the potential for early-age longitudinal cracking. Two different analysis cases were considered as follows:

- Case 1 – Transverse joints are sawed in a timely manner and are working joints soon after saw cutting. For this case, a transverse joint spacing of 15 ft was used.
- Case 2 – Transverse joints are not sawed in a timely manner or are not working properly within the first couple of days after concrete placement. For this case a longer slab length of 48 ft was used instead of the use of infinite element.

Other analysis parameters include the following:

- Slab thickness: 8, 10, 12, and 14 in.
- Slab width, as paved: 12, 14, 24, and 26 ft
- Modulus of subgrade reaction, k: 100 and 500 pci
- Concrete modulus of elasticity: 0.5, 1.5, and 3.0 million psi, representing hardening of normal concrete at the early ages of interest.
- Concrete Poisson's ratio: 0.20
- Coefficient of thermal expansion: 5×10^{-6} in/F
- Temperature gradient: -1, -2, -3, and -4 °F/in. A composite temperature gradient of -4 °F/in. would represent the condition of slab surface cool down by about 25 to 40 °F (depending on slab thickness) from the maximum concrete temperature due to hydration and some surface drying shrinkage.

Friction

A newly place concrete shrinks uniformly as it hydrates. Also, a uniform temperature or moisture decrease in a concrete slab causes a uniform volume change of the slab. However, the underlying layer prevents the slab from free moving and thus, frictional tensile stresses are developed in the concrete. The frictional stresses in the transverse direction can be determined using the classical slab drag equation (*7*), as shown in Equation 1.

$$\sigma_f = (\gamma_c \times f \times W)/2 \qquad (1)$$

where, σ_f = axial restrained stress, psi

γ_c = the unit weight of concrete, lb/in^3

f = average coefficient of friction at the slab and subbase interface

W = slab width as paved, in

Values of the coefficient of friction vary widely from 1.0 to 15.0 depending the subbase materials used. In general, as the stiffness of the subbase layer increases, the coefficient of friction between slab and subbase increases. For design purpose, different agencies recommend different values of coefficient of friction of various subbase materials. AASHTO Design Guide (*8*) applies friction factor, which is equivalent to the coefficient of friction, and its value ranges from 0.9 for natural subgrade to 2.2 for treated surface. On the other hand, FAA recommends higher values of coefficient of friction ranging from 1.0 for natural subgrade to 15.0 for rough and stiff materials, such as lean concrete, asphalt stabilized, and asphalt or cement treated open grade layers (*9*). In this study, four different values of coefficient of friction (f= 0, 1, 2, and 3) were considered for the analysis.

It should be noted that the slab edges, depending on the magnitude of the composite temperature gradient, might not be in contact with the base. However, it is assumed that the weight of the portion of the slab that is not in contact is distributed uniformly along the portion of the slab that is in contact with the base. As such, it is assumed that the effect of the loss of support condition would be negligible on the axial restraint stress development. The magnitude of the coefficient of slab/base friction is greatly influenced by the type of base, smoothness of the base surface, bonding between the base and the slab, the penetration of the concrete into the base (if permeable), and use of a debonding treatment such as geo-textile or plastic membrane.

Total Restrained Stresses

Four different frictional coefficients (f= 0, 1, 2, 3) were considered for the calculation of total restrained stresses. As previously noted, total restrained stress is determined by direct summation of the frictional axial stress and the curling restraint stress. With the combinations of variables considered in curling stress analysis, a total of 3,072 cases of stress analysis were performed. These combinations are expected to cover wide ranges of field construction conditions including the critical conditions that may cause the early-age longitudinal cracking in JCP construction.

Figures 5 and 6 show typical results of the stress analysis for different sets of slab thickness and width. Only the cases for the long slab length (L = 48 ft.) with highest frictional coefficient (f =3.0 psi/in) are shown here. The stress curves with lower frictional coefficients would shift linearly to the left side of the charts due to the lower frictional stresses of the respective cases.

Obviously, the restrained stress level increases as concrete gets more stiffness for a given set of the other conditions. Note that non-linear relationships exist between the stresses and concrete modulus of elasticity. For wide slabs (W = 26 ft.), the non-linearity becomes more significant at thicker slabs with softer bases, while the opposite seems to be the case for the slabs having shorter width (W = 12 ft.).

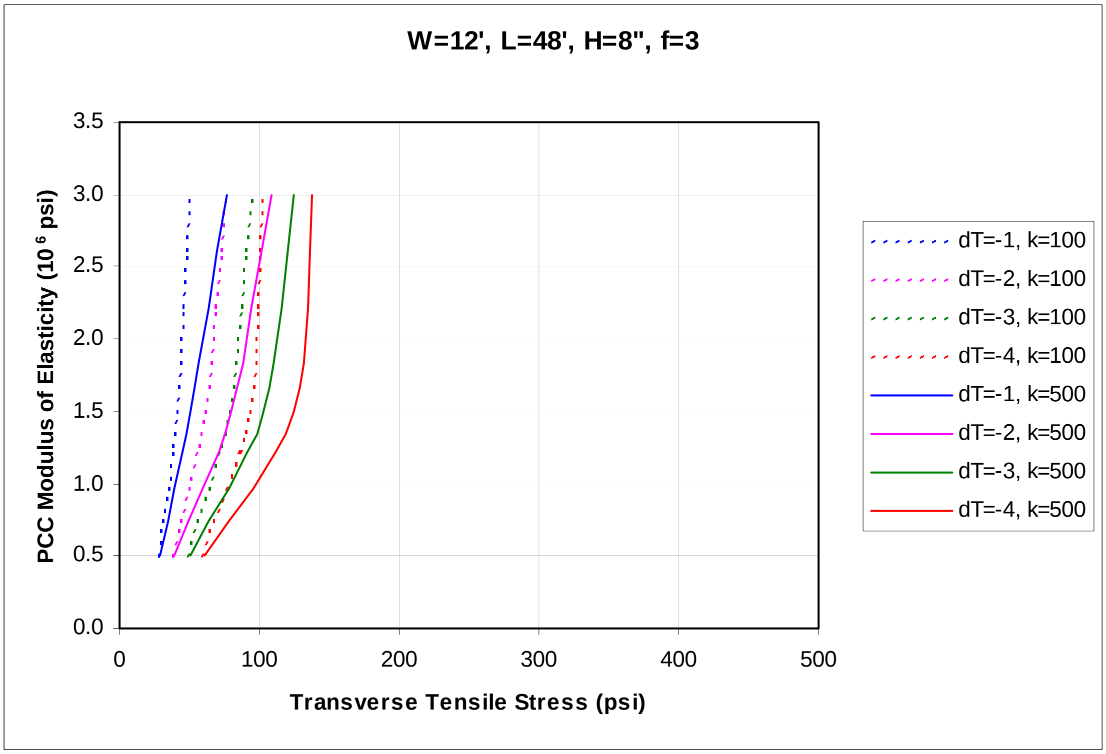
As seen in Figure 5, stress level stays low for all cases of the 12 ft. wide slab. This indicates that, if the pavement slab is effectively maintained at this width by means of proper and timely joint sawing even in case of wide lane construction, longitudinal early-age cracking is not likely to occur within the slab.

Figure 6 shows stress level stays safe even for the cases of 26 ft. wide slab as long as the temperature gradient stays low, e.g., dT= -1 °F/in.. Under such conditions, use of wider lanes or some delay in longitudinal joint sawing may be acceptable with regard to the early-age cracking potential. In general, however, the restrained stress level in 26 ft. wide slab is very likely to be critically high with respect to the cracking potential if the concrete experiences higher temperature gradient in early ages.

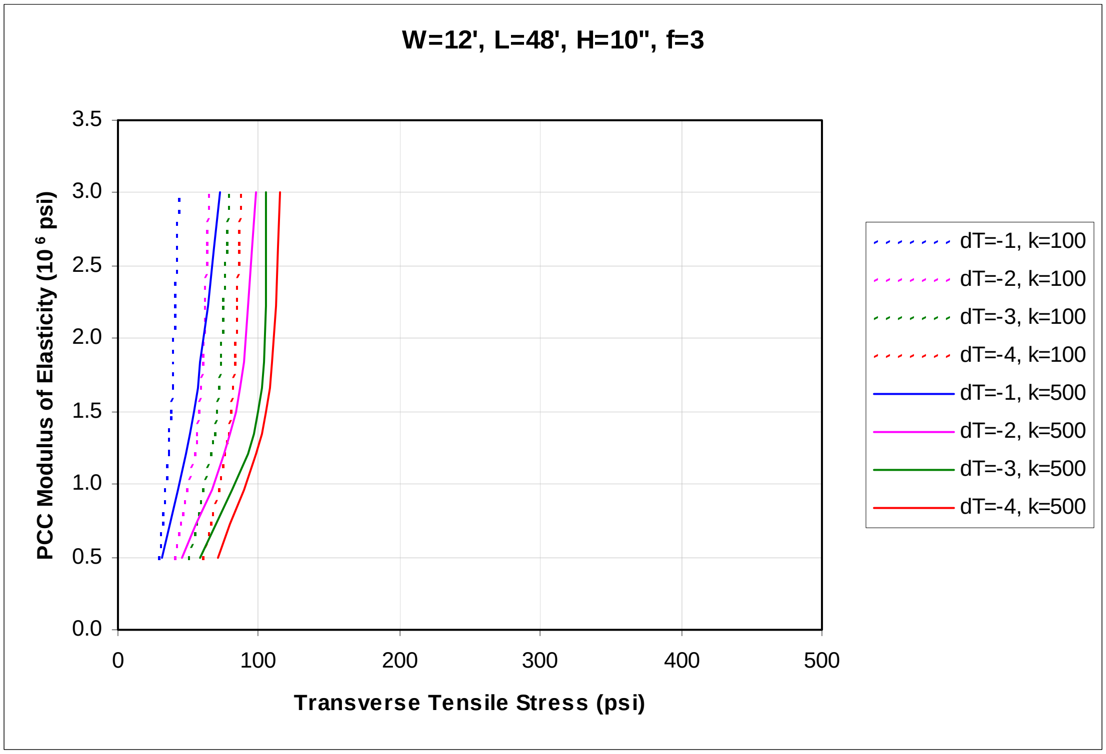
As previously stated, these charts can be used to estimate the potential of early-age longitudinal cracking in JCP construction, provided concrete strength is known at any time of interest. When a critical condition for excessive restrained stress development is expected, appropriate efforts should be placed to effectively mitigate the stress level and early-age cracking in the pavement.

Concrete Strength Development

Proper estimation of early-age strength development in newly placed concrete is required to achieve a good prediction of the potential of early-age cracking. It was noted that early-age concrete strength development is influenced by many factors, such as concrete mixture characteristics, environmental conditions, and curing practice. The combined effect of these factors on concrete strength gain is complex.

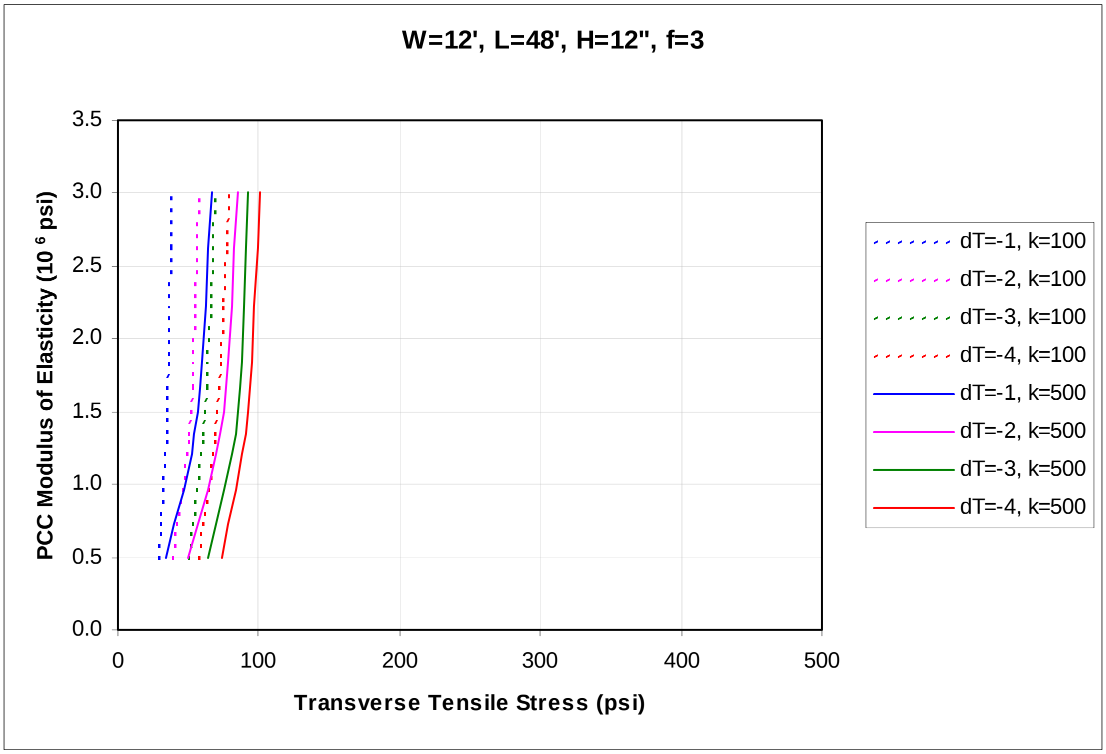


(a) Slab thickness, H = 8 in.

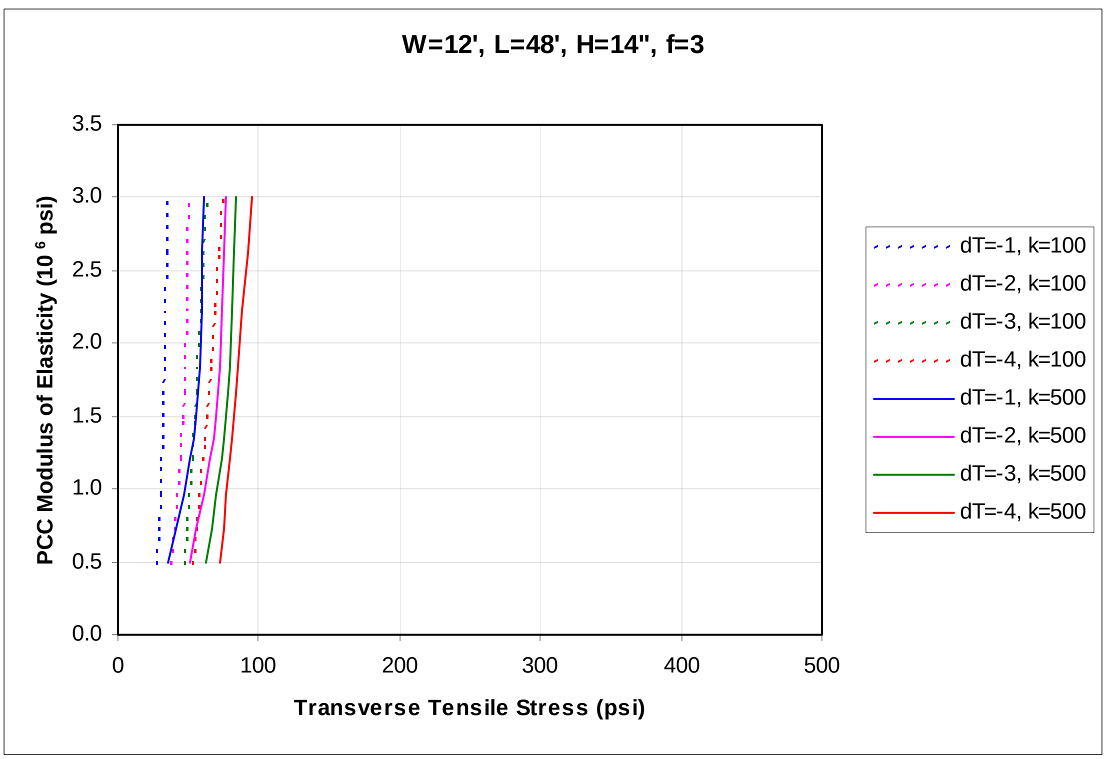


(b) Slab thickness, H = 10 in.

Figure 5. Total Transverse Restrained Stresses (Slab Width=12 ft)

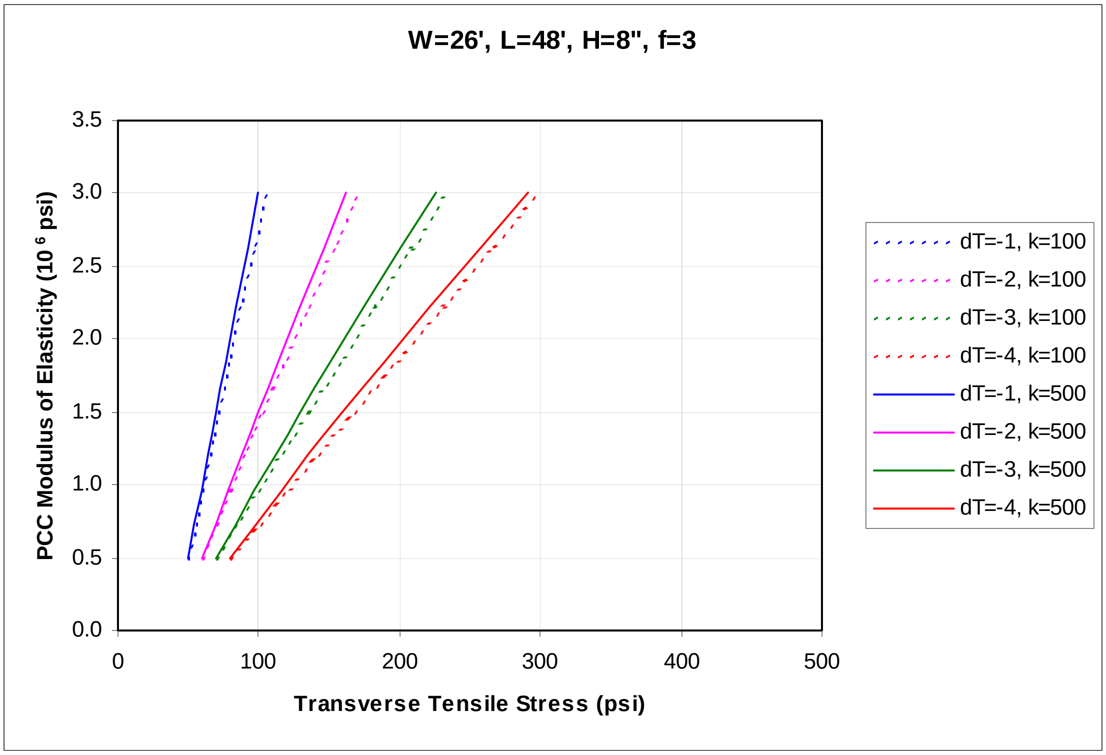


(c) Slab thickness, H = 12 in.

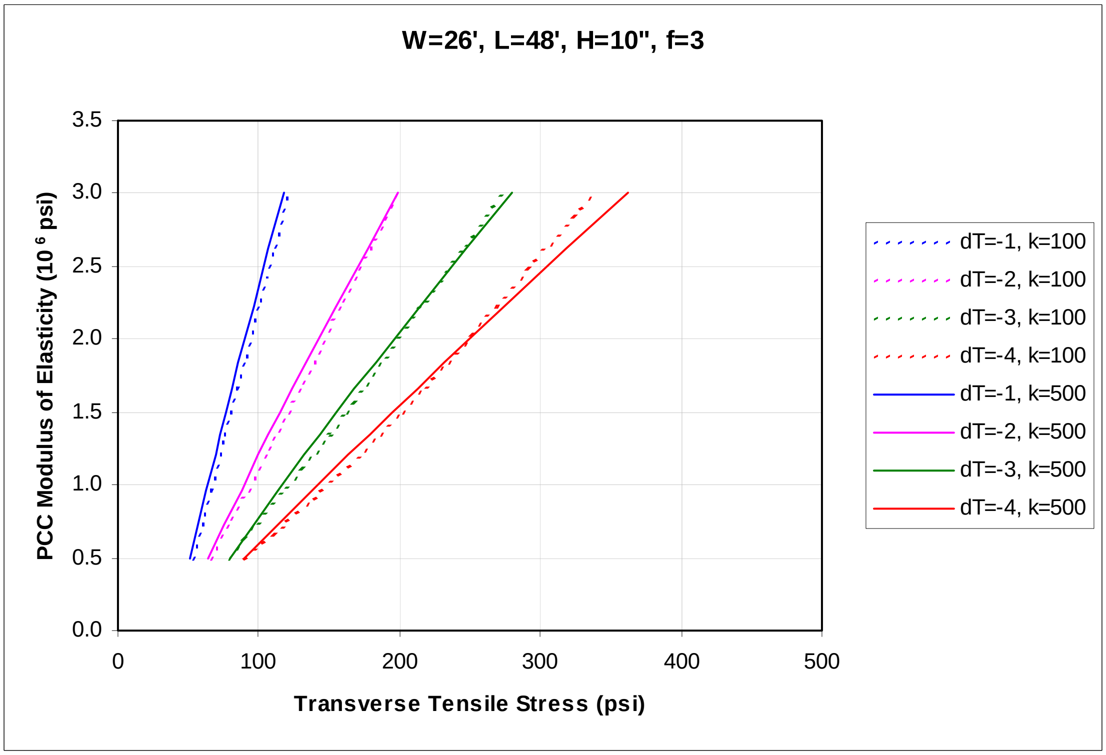


(d) Slab thickness, H = 14 in.

Figure 5. Total Transverse Restrained Stresses (Slab Width=12 ft) (Cont'd)

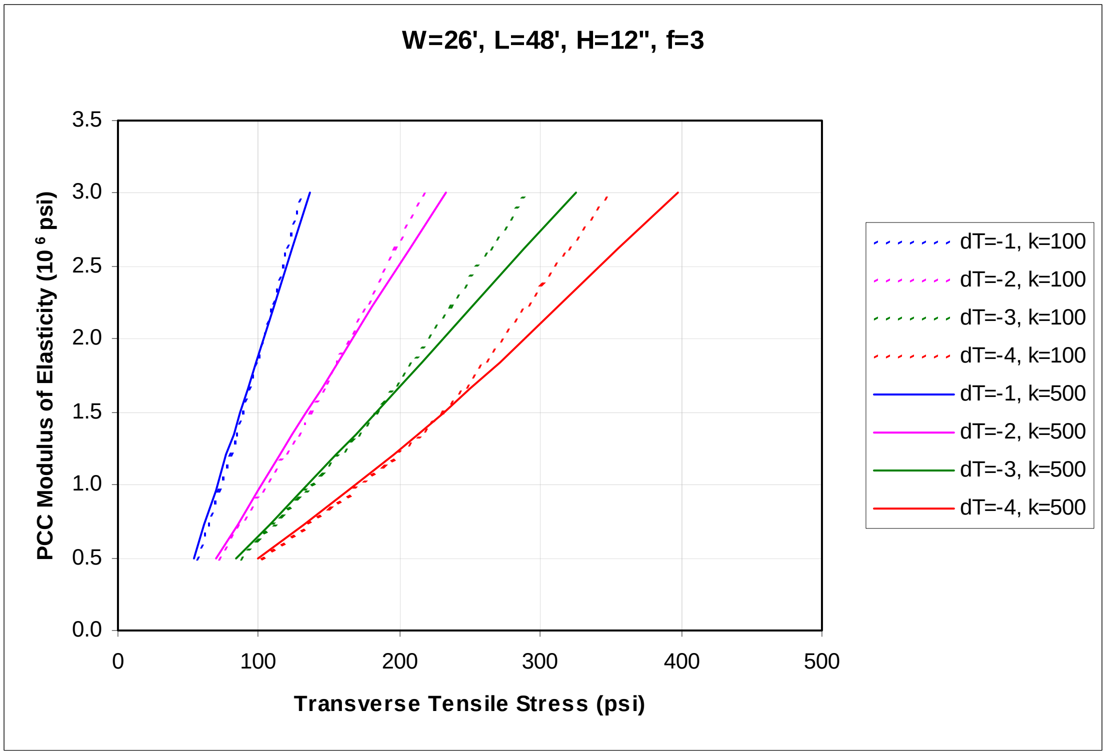


(a) Slab thickness, H = 8 in.

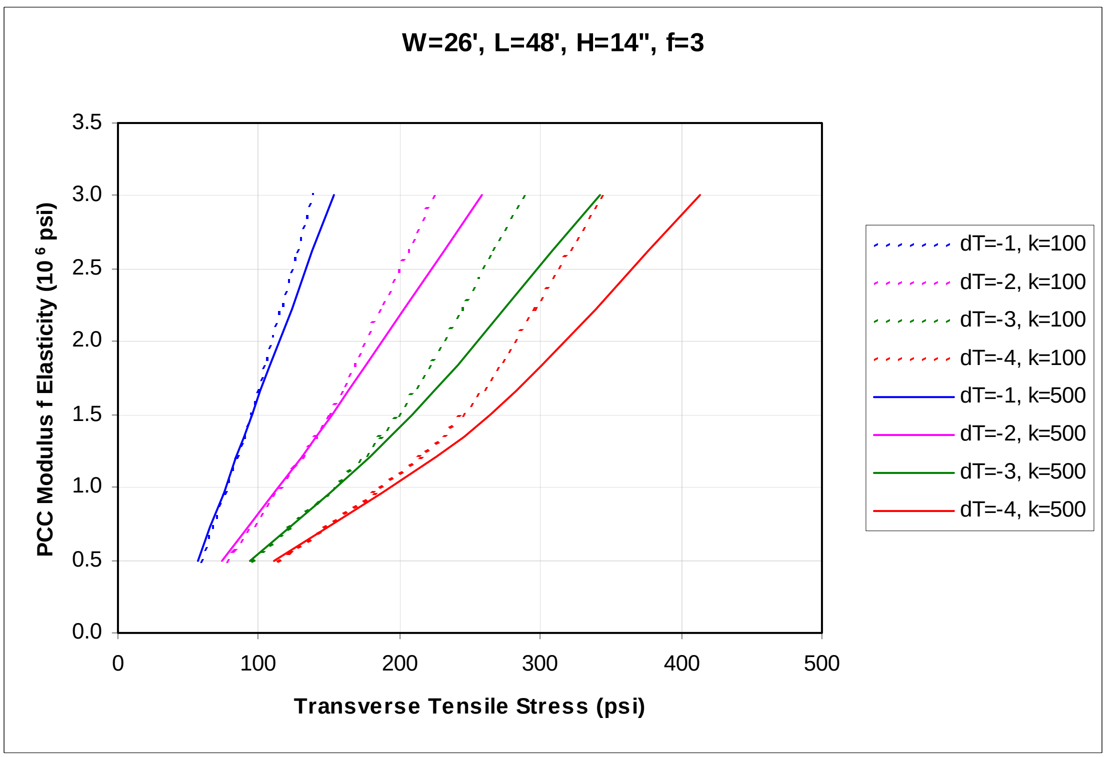


(b) Slab thickness, H = 10 in.

Figure 6. Total Transverse Restrained Stresses (Slab Width=26 ft)



(c) Slab thickness, H = 12 in.



(d) Slab thickness, H = 12 in.

Figure 6. Total Transverse Restrained Stresses (Slab Width=26 ft) (Cont'd)

The maturity method is a useful technique for estimating concrete strength development in early-ages. The theory and application of the maturity method has been covered extensively elsewhere (*1, 10, 11*). Maturity can be represented by two different parameters: equivalent time (t_e) or time temperature factor (TTF). The TTF method, as illustrated in Equation 2, was used in this study.

$$M(t) = \Sigma(T_a - T_0)\Delta t \qquad (2)$$

where, M(t) = Maturity in time-temperature factor (TTF) at time *t*, C-hrs or F-hrs
Δt = time interval, hrs
T_a = average concrete temperature during time interval, °C or °F
T_0 = datum temperature at which it is assumed that concrete ceases to gain strength with time, °C or °F

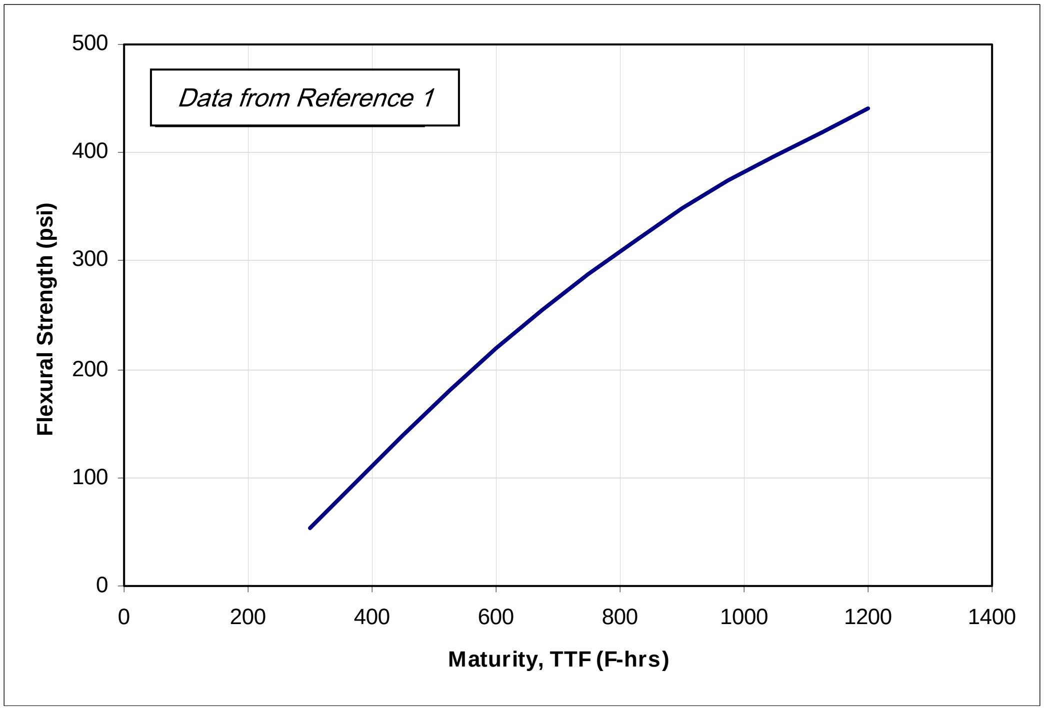
Figure 7 represents examples of early age flexural strength developments estimated by the maturity method. Figure 7 (a) shows the maturity-strength curve for a high strength concrete mixture, while Figure 7 (b) is for a low strength concrete mixture (from References 1 and 10). Concrete mixture proportions of the examples are presented in Table 1. Datum temperatures (T_0) used in those studies are 0 °C (32 °F) and –10 °C (14 °F), respectively. Using the information from the maturity curve and temperature history, concrete strength at any time can be simply estimated. For instance, assuming that the concrete was cured under constant temperature at 25 °C (78 °F), maturity of the high strength concrete at 24 hours is, by Equation 2, to be 1,080 F-hrs and the strength at that time is, from Figure 7 (a), 420 psi. Table 2 presents the maturity and strength at 12, 24, and 48 hours for the both the low and high strength concrete examples. Estimation of modulus of elasticity is discussed in the following section.

Cracking Prediction Charts

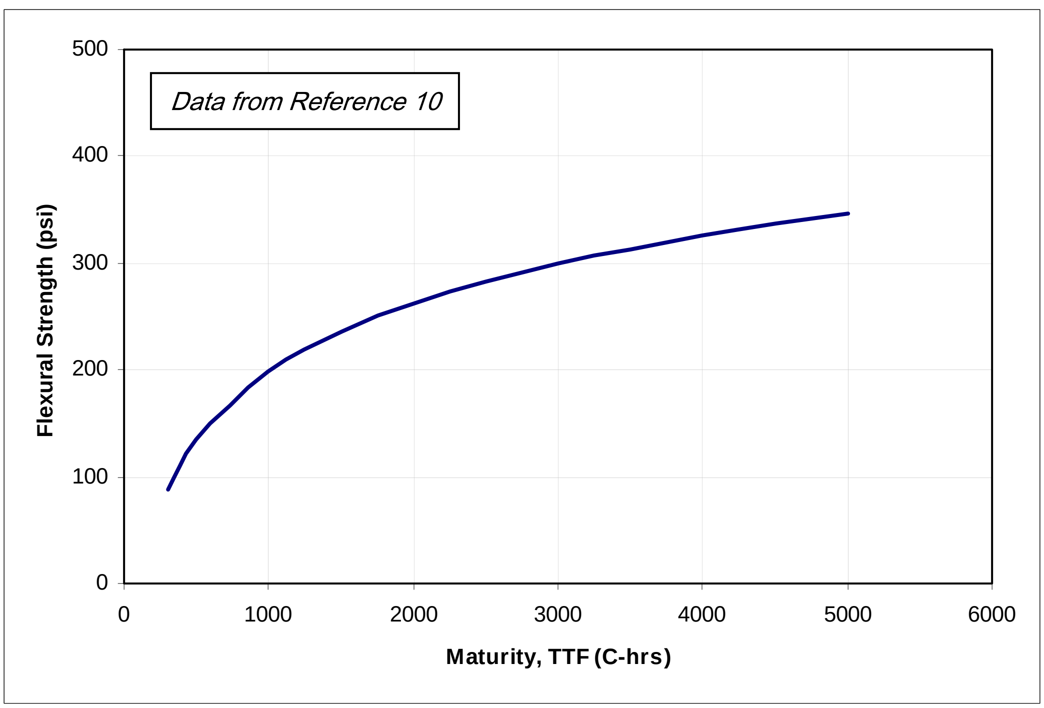
Previous sections discussed on the developments of the transverse restrained stresses (Figures 5 and 6) and the strength (Figure 7) in the PCC slab in its early-ages. Comparison of these stress and strength information can identify the potential of early age longitudinal cracking at any time of interest. This section presents application examples of the cracking prediction using the charts discussed earlier.

Note that time or age of concrete is represented in different terms, i.e., concrete modulus of elasticity in the stress charts and maturity in the strength charts. To compare the restrained stress and concrete strength, therefore, a relationship between concrete maturity and modulus of elasticity is needed. This relationship can be developed by testing or by identifying the relationship between concrete strength and modulus of elasticity. Figure 8 presents the maturity-modulus of elasticity relationship established for the example concrete mixtures. Modulus of elasticity in this example was estimated based on the flexural strength by using the American

Concrete Institute (ACI) equations (*12*) that relate concrete strength and the modulus



(a) Normal to high strength concrete



(b) Low to normal strength concrete

Figure 7. Estimated Strength of Early Age Concrete

Table 1. Mixture Proportions of the High and Low Strength Concrete Examples

	High Strength Concrete (from Reference 1)	Low Strength Concrete (from Reference 10)
Cement (lb/yd^3)	640 (Type I)	450 (Type II/V)
Fly Ash (lb/yd^3)	100 (Class F)	150 (Class F)
Fine Aggregate (lb/yd^3)	1210	1210
Coarse Aggregate (lb/yd^3)	1750	1815
Water (lb/yd^3)	270	285
AE Agent (oz/yd^3)	50	7

Table 2. Properties Estimated at Early Ages for the Example Concrete Mixtures

		Example A High Strength Concrete [Figure 7 (a) & Figure 8 (a)]	Example B Low Strength Concrete [Figure 7 (b) & Figure 8 (b)]
Maturity	12 hours	540 F-hrs	425 C-hrs
	24 hours	1,080 F-hrs	850 C-hrs
	48 Hours	2,160 F-hrs	1,700 C-hrs
Flexural Strength (psi)	12 hours	170	100
	24 hours	420	180
	48 Hours	(600)	250
Modulus of Elasticity (psi)	12 hours	1.5×10^6	0.7×10^6
	24 hours	2.3×10^6	1.3×10^6
	48 Hours	(2.7×10^6)	1.8×10^6

* Values in parenthesis are approximate extrapolation from the curve.

of elasticity. The estimated values of concrete modulus of elasticity at selected ages are also listed in Table 2.

Figure 9 illustrates example applications of the stress charts for investigating the potential of early age longitudinal cracking in JCP construction with either high or low strength concrete mixtures. As indicated in the figures, construction conditions that would create excessive restrained stress (full width paving (paving width = 26 ft.) and high slab/base interface friction (f= 3)) were selected for the illustration of the examples. As seen in Figures 9 (a) and (b), the strength and modulus of elasticity at different ages of the high and low strength concrete examples are lined on the stress chart. The procedure to investigate the cracking potential using the charts is as follows:

1. Find stress chart for the appropriate set of construction conditions (e.g., from Figures 5 and 6),
2. Develop the strength development curve (using the maturity method) on the stress chart (this will provide a chart similar to Figure 4),
3. Compare the stress and strength at any time of interest to find the potential of cracking.

For the example illustrated in Figure 9, the following can be established:

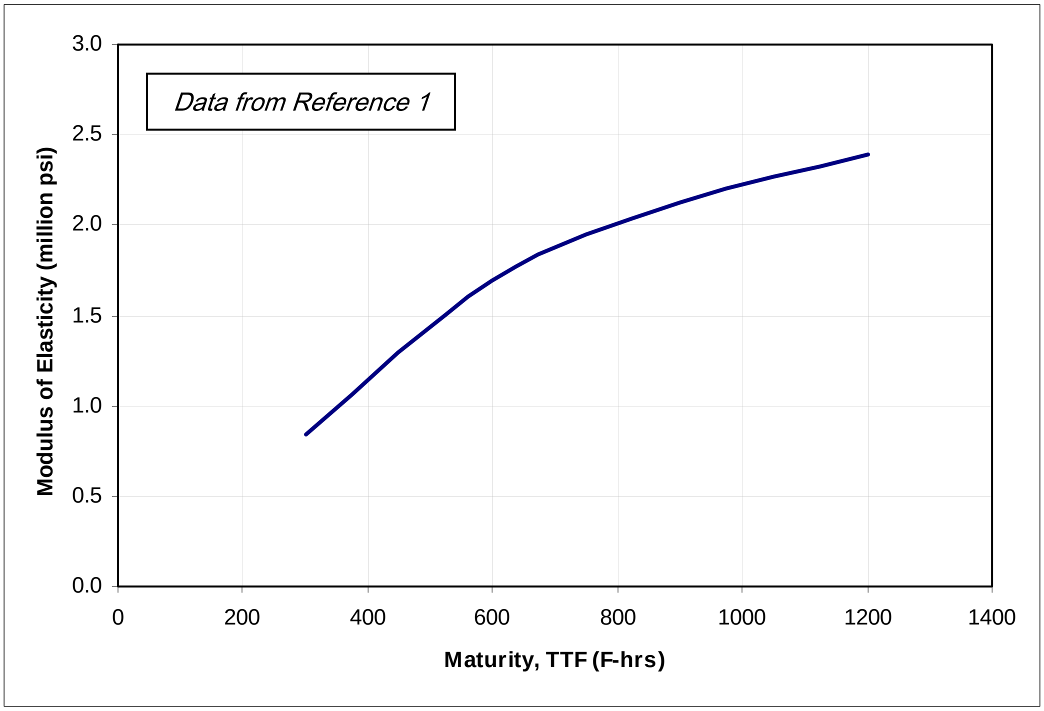
1. For Figure 9(a) – high strength concrete mixture, the strength data in Table 2 indicates the flexural strength of the concrete reaches at 170 psi during the first night that is about 12 hours after placement. Estimation of concrete modulus of elasticity from the strength is about 1.5 million psi. The chart shown in the figure indicates, at this level of concrete stiffness, a significant potential for cracking exists if the temperature gradient becomes higher than about 2.5 °F/in. The total restrained stress becomes higher than the strength of the concrete (170 psi) at a higher temperature gradient.

   The cracking potential decreases as the concrete gains more strength with time. At 24 hours after placement, the concrete strength reaches to about 420 psi, which seems to have some safety margin against the cracking potential being higher than the maximum restrained stress estimated with the marginal conditions considered in this study.

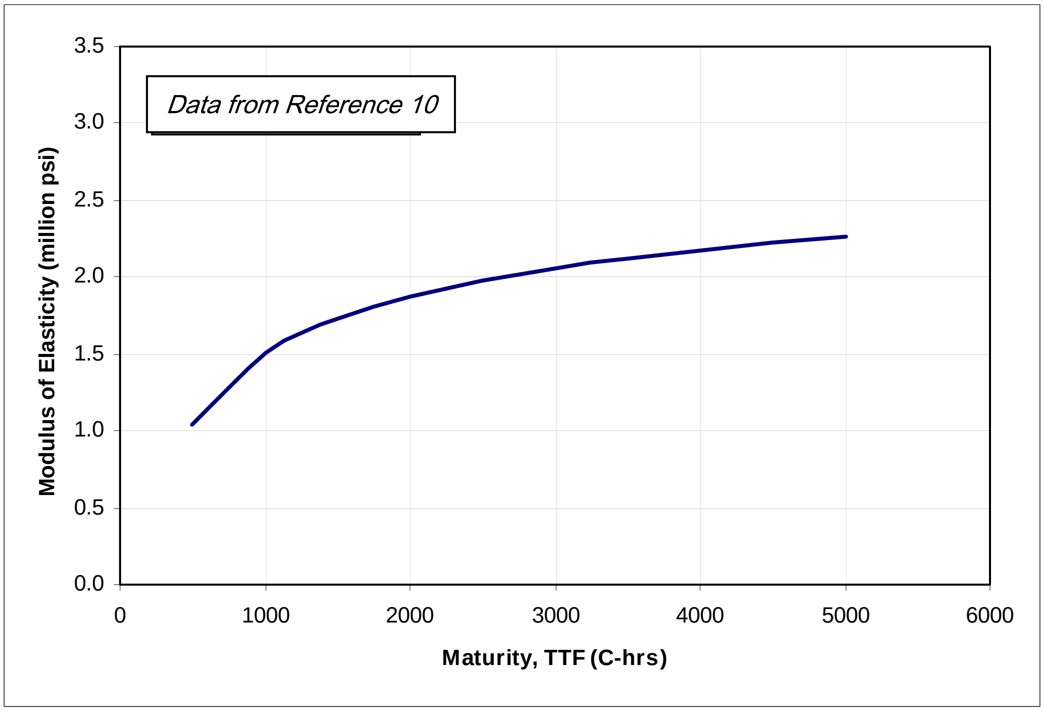
2. For Figure 9(b) – low strength concrete mixture, the estimated flexural strength and the modulus of elasticity of the concrete during the first night about 12 hours after placement are 100 psi and 0.7 million psi, respectively (Table 2). The chart indicates the total restrained stress becomes higher than the strength of concrete at about 12 hours (100 psi) if the temperature gradient exceeds about 2.5 °F/in, creating a significant potential for cracking if the temperature gradient is to be higher.

   The chart also indicates that, although the cracking potential diminishes slightly as the concrete ages, the chance of cracking still exists even after the concrete ages more than 24 or 48 hours for this low strength concrete mixture. It is shown that a temperature gradient higher than about 3.0 °F/in creates the critical condition for cracking at the later ages.

3. Other analysis results indicated that the critical stress conditions do not develop for paving widths that are less than 24 ft and for slab/base friction coefficient values less than 2.

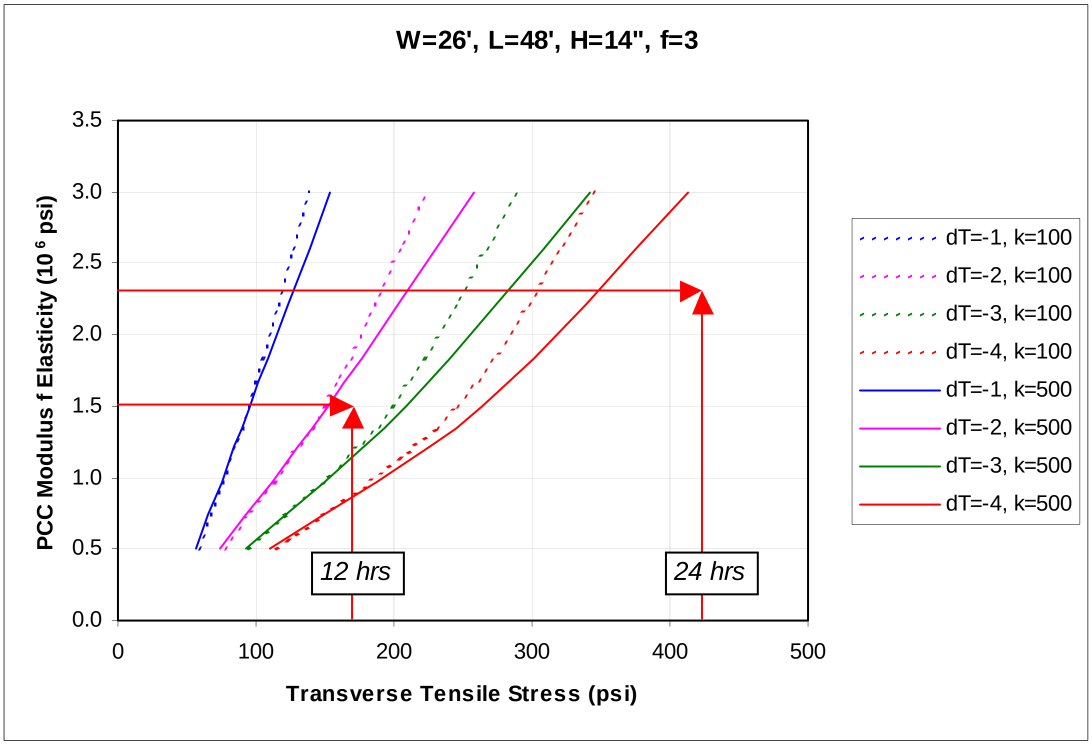


(a) Normal to high strength concrete

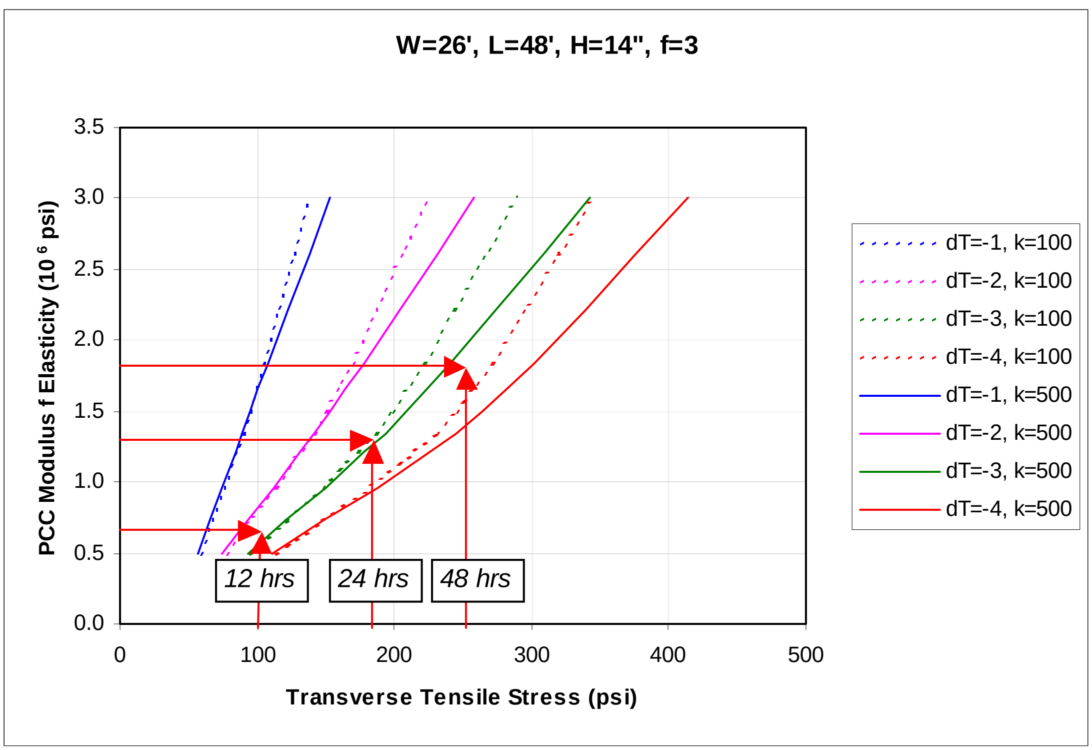


(b) Low to normal strength concrete

Figure 8. Estimated Modulus of Elasticity of Early Age Concrete



(a) Example A: High Strength Concrete



(b) Example B: Low Strength Concrete

Figure 9. Determination of the Potential of Early Age Longitudinal Cracking

It should be emphasized that the potential of cracking becomes higher as the restrained stress level reaches to the strength of concrete. As illustrated in the charts and the examples discussed above, the stress levels can rise up to the level of strength developed during the early age in the event of high temperature gradient, i.e., dT = -3 or -4 °F/in, combined with large paving width and high PCC slab and base interface friction. Given this critical situation, any further increase in the rate of stress development and/or decrease in the rate of strength development can, with a high probability, create conditions that lead to early-age longitudinal cracking.

Summary and Conclusion

The above analysis results illustrate that critical conditions can develop rapidly in JCP construction with widened lanes or for situations where there is delay in sawing centerline longitudinal joints. The factors contributing to development of the critical conditions include the following:

- High temperature gradient, especially the high temperature drop during the first night with poor curing environment
- Rough, bonded or locked slab and base interface
- Delay in joint sawing in multiple lane construction
- High coefficient of thermal expansion, e.g., concrete using gravel aggregates
- Slower rate of strength development

The analysis technique demonstrated in this paper can be used to estimate the potential of early-age longitudinal cracking and finally to mitigate them. It is necessary to identify proper causes of early-age cracking to ensure appropriate corrective measures are taken to eliminate conditions that create the potential for early-age cracking.

It must be emphasized that for routine pavement construction with well prepared and protected base surfaces and normal ambient temperature conditions, the potential for early-age longitudinal cracking is not considerable, even if for full width (e.g., 26 ft) paving. However, if the exceptional temperature condition is expected, it may be prudent to delay paving, considering night-time paving or partial width (lane at a time) paving.

Acknowledgements

The findings presented in this paper is are based on the work performed by the Construction Technology Laboratories, Inc. (CTL) under the research project, "Premature Cracking on Concrete Pavements: Causes and Impact on Performance," sponsored by the American Concrete Pavement Association (ACPA). Mr. Jerry Voight served as the Project Manager for ACPA. The views and opinions expressed in this paper are those of the authors and not necessarily those of ACPA.

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