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16. Abstract
Prestressed concrete pavements have proved to be extremely cost efficient, to require less maintenance compared with other pavement types, and are now being widely used for both highways and airport runways. In prior research relating to prestressed concrete pavements, the various parameters that are significant in the design of these pavements have been isolated and their effects modeled to predict the resulting stresses and displacements in the pavement slab.
This report summarizes an effort to improve the analysis and consequently the design of prestressed concrete pavements. The computer program developed in this study predicts the stresses and displacements in a prestressed pavement slab caused by environmental conditions and wheel loads.
The information obtained from the computer program can be used in design to determine the slab thickness, prestress level, and length of slab, so as to keep the resulting stresses under allowable limits.
A graphical user interface has been provided for the program for ease of use and better organization of the results obtained. This report gives a detailed account of the changes made to the previous version of PSCP computer program and a listing of the new program and the interface.

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Application of PSCP 3.0 Program to Predict Stresses in Prestressed Concrete Pavements

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1. Introduction

1.1 Background

The Highway Research Board defines a prestressed concrete pavement (PCP) as "a pavement in which a permanent and essentially horizontal compressive stress has been introduced prior to the application of live load" [1]. As defined by the ACI Committee 325, "Prestressed concrete pavements are those in which compressive forces have been introduced on the concrete sections during construction, for the purpose of preventing or decreasing tensile stresses in the concrete during service" [2].

Because concrete is weak in tension, prestressing helps to improve its load-carrying capacity by reducing the tensile stresses and preventing cracks. Tensile stresses are introduced into a pavement by wheel loads, shrinkage, and temperature variation in the concrete. These tensile stresses develop along the length of the slab because of the frictional restraint of the subgrade. A broad discussion about the behavior of PCPs and their advantages follows later in this report.

To understand the relevance of analyzing PCP by using models to predict its behavior, research studies in this area are reviewed in Section 1.1.1. Section 1.1.2 presents the advantages of PCPs over conventional reinforced concrete pavements, such as continuously reinforced concrete pavements (CRCP) and jointed concrete pavements (JCP). Sections 1.2 and 1.3 state the objectives of this study and the scope of this report, respectively.

1.1.1 Previous Studies on Prestressed Concrete Pavements

This section discusses the findings of previous research work regarding PCP in Texas. Three research reports are briefly discussed that deal with the development of a design methodology for PCP, models predicting the behavior of PCP under different types of loading, and a computer analysis of this type of pavement.

The Center for Transportation Research, Research Report 401-2 [1]

This report focused on the development of a paving technique that would have the advantages of requiring less material and less maintenance over the design life. The research focused on PCPs and different prestressing methods, advantages of PCPs over conventional pavements, and the various factors affecting PCP design. A comprehensive evaluation of the design, construction, and performance of various pavement projects were also documented. This report also proposed new concepts for the design of PCPs that help overcome problems encountered in previous experiences with the technology. Report 401-2 presented a design procedure for PCP along with construction details and procedures.

The Center for Transportation Research, Research Report 401-3 [3]

This report studied the effect of climatic factors, such as ambient temperature and moisture, on the PCP slab. The effect of climatic variables on the slab was found to be as follows:

1. Changes of concrete temperature and moisture content cause horizontal movement and variation of stress along the length and width of the slab; and
2. Variation of moisture content through the depth of the slab results in warping, and temperature variation across the depth results in curling movements.

The movement of the slab end is caused by the expansion and contraction of the concrete mass. If the slab were to be unrestrained by the self-weight and friction between the slab and the subgrade, there would be no stresses induced. However, the weight of the prestressed slab offers resistance to movement and hence is subject to curling or warping stresses.

A model was developed to simulate the friction between the slab and the subgrade, given the inelastic nature of the frictional forces. This study analyzed both short-term and long-term movements in PCPs. Short-term movements were attributed to daily variations in temperature caused by the restraint on the base's friction. Long-term movements were attributed to concrete swelling, shrinkage, creep, and seasonal temperature changes, caused by unrestrained friction. This model was incorporated in the computer program PSCP-1, along with the models developed for the effect of prestress forces, temperature gradient, and moisture differential. The values predicted by the program were checked for correlation to field data collected at the McLennan County PCP [1].

The Center for Transportation Research, Research Report 556-3 [4]

This report reviewed the existing models for the analysis of PCP and evaluated their performance. Field data collected from the PCP in McLennan County were compared with the values predicted by PSCP-1. Research Report 556-3 developed a new curling model to predict with reasonable accuracy the curling of slabs caused by temperature variations. As a result of the modification and calibration of the models, program PSCP-2 was introduced.

1.1.2 Advantages of Prestressed Concrete Pavements

Constructing PCPs in highways and airfields has some advantages over other pavement types. Some of these advantages are discussed in this section. Further information can be found in the literature [5].

Efficient Use of Construction Materials

The precompression that is applied to PCPs helps reduce the tensile stress that is introduced by wheel loads and aggravated by frictional stresses, warping, and curling. This allows the design of thinner pavements, and hence, less concrete and steel are needed for construction. The amount of steel required is significantly less than that for reinforced concrete pavements. Savings can be achieved in steel transportation costs and corrosion protection.

Better Performance

Inducing precompression in pavement slabs reduces or eliminates the occurrence of cracks, and this allows construction of longer slabs. Longer slabs require fewer joints for a given length of pavement. This reduces construction costs and problems related to maintenance of joints. The distress and failure caused by cracks and joints are also reduced. Owing to the elimination of cracks, PCPs also protect the supporting layers by reducing the infiltration of water from the surface of the road.

Reduced Maintenance

Well−constructed PCPs require less maintenance and have a longer life than conventional reinforced concrete pavements. Resistance to wear and tear is caused by the high strength concrete and steel used in these pavements. However, special attention should be paid to the maintenance of transverse joints, which should be cleaned of debris during maintenance tasks periodically scheduled.

Increased Load−Carrying Capacity

Prestressing of the concrete used in PCPs provides a higher load−carrying capacity. The elimination of cracking helps to maintain the integrity of the pavement over a long period of time. Furthermore, PCPs have been found to be efficient in carrying repetitive and impact loading [6].

1.1.3 Need for This Study

Previous research on PCPs include studying their behavior by developing models, incorporating these models into design procedures, and writing computer programs to help in the design process. This study is a step in providing a better tool for design purposes. The two main objectives of this report are as follows:

1. Introduce a means to analyze the total stresses in PCPs, including the ones caused by wheel loads.
2. Create a graphical user interface (GUI) for the design program, which will make it user friendly.

As a result of this study, the effects of various factors causing stresses in a pavement slab can be easily understood and the design parameters might be varied effectively during design.

1.2 Research Objectives

The main objective of this study is to improve the previous PSCP design program for the analysis of PCP. This is accomplished by achieving the following goals:

1. Incorporate wheel load analysis in the program.
2. Improve the previous program by making it a user-friendly package in the form of a Visual Basic interface to be added between the Fortran source code and the user.
3. Improve the ease of usage and obtain results in a form that can be easily interpreted and processed.
4. Predict the short-term and long-term total stresses and displacements caused by wheel loading, concrete temperature changes, and curling in the prestressed concrete slab.

1.3 Scope

This report contains five chapters. Each chapter deals in detail with the work done to upgrade the program and its results.

Chapter 1 contains a summary of background PCP work conducted in Texas and the work that preceded this study in the area of PCP. Previous research studies help understand the behavior of PCPs and the models used for design.

Chapter 2 discusses the various models used in analysis of PCP and the incorporation of wheel load stress analysis in the current design program.

Chapter 3 presents the organization of the PSCP 3.0 program and shows the typical input and output data of the program in a series of tables.

Chapter 4 provides a sample problem and its execution using PSCP 3.0. There is also a discussion of the results obtained from the program. A description of the use of the program and an interpretation of the results is provided.

Chapter 5 contains a summary of the report, results of this study, achieved improvements, and recommendations for further research.

2. Prestressed Concrete Pavement Program (PSCP 3.0)

Version 2.0 of the PSCP program was developed as a part of Research Project 556. Details of the program can be checked in Research Report 556-3 of the Center for Transportation Research [4]. This program analyzed a prestressed pavement slab for stresses caused by climatic variables and such changes in concrete properties as creep and shrinkage. This version did not consider stresses caused by wheel loads. To understand and predict the behavior of PCPs under service loads, it is necessary that stresses caused by wheel loads are included in the analysis. In the present study, an attempt is made to include these effects on the state-of-stress conditions in the prestressed concrete slab forming the pavement.

2.1 Models Used in the Analysis

This section describes prediction models used in the analysis. There is an emphasis on the assumptions involved in predicting the stresses and displacements in the PCP slab.

2.1.1 Assumptions

The assumptions that are inherent in the models used are listed below:

1. Concrete is homogeneous and linearly elastic.
2. Upward deflections are positive.
3. Tensile stresses are positive.
4. The mid-slab section is considered as the origin.
5. Top-to-bottom temperature and moisture differentials causing downward deflections are positive.
6. The slab behaves elastically under all loading conditions, and total stresses are obtained by superposition of stresses attributed to wheel loading, temperature curling, prestress, frictional restraint stresses, and concrete creep and shrinkage.

2.1.2 Models for Predicting Concrete Properties

Modulus of Elasticity

The modulus of elasticity of concrete changes with time, and it is important to estimate it accurately for the proper determination of stresses in concrete. The modulus of elasticity can be estimated from the age of concrete versus time relation, using Equation 2.1 [2]:

$$E_c = \gamma^{1.5} \times \sqrt[3]{f'c} \qquad (2.1)$$

where,

Ec = Young's modulus of concrete, psi

γ = unit weight of concrete, pcf

f'c = compressive strength of concrete, psi

The modulus of elasticity can also be computed from the twenty-eight-day compressive strength of concrete by assuming a certain gain of strength for periods before twenty-eight days [2].

Concrete Shrinkage Strain

Hansen and Mattock estimated the strain in concrete caused by shrinkage at different time periods by using Equation 2.2 [2]:

$$\frac{Z_t}{Z_t^\infty} = \frac{t}{M + t} \qquad (2.2)$$

where,

Zt = Drying shrinkage strain at time ‘t’

Z_t^{∞} = Ultimate shrinkage strain

t = Time since setting of concrete, days

$$M = 26 \times e^{(0.36 \times D)}$$

D = Thickness of the pavement, inches

2.1.3 Model for Predicting Friction Stresses

As previously mentioned, frictional stresses develop between the slab and its supporting subgrade when the slab expands or contracts, because of changes in its volume caused by temperature variations. These movements cause the development of restraint stresses in the slab. Frictional forces develop as a result of the molecular attraction between the material of the slab and the subgrade when there is relative movement between the two and also because of the irregularities on the surfaces. The slab movement is maximum at the edges and decreases toward the mid-section, as does the friction force. Accumulation of these forces of friction along the length of the slab results in high restraint stresses at the slab mid-length and mid-width.

Restraint stresses are essentially compressive when the slab expands and tensile when it contracts or shrinks [1]. These stresses are dependent on the coefficient of subgrade friction and the dimensions of the pavement slab. The maximum restraint stress in a concrete with unit weight of 144 pcf is given by Equation 2.3:

$$F_r = \frac{\mu \times DL}{2} \qquad (2.3)$$

where,

Fr = Maximum friction restraint stress, psi

μ = Coefficient of subgrade friction

DL = Length of the pavement slab, ft

Other factors that affect the stresses developed due to friction are as follows:

1. Coefficient of thermal expansion (CTE) of concrete;
2. Young's modulus of concrete; and
3. Coefficient of friction versus displacement relationship of the slab

In the design of PCPs, understanding the inelastic nature of frictional forces that develop between the slab and the subbase is very important. Reversal of movements in the slab when it heats from the sun's radiation during the day and when it cools during the night results in stress reversals. When the slab expands due to the surface heating, the friction forces that resist the expansion of the slab are compressive in nature at the bottom fiber of the concrete slab. This compressive stress along with the prestress induced in the slab help in resisting the tensile stress that develops from wheel loading. The contraction of the slab is less favorable in resisting the stresses as it causes tensile friction stresses at the bottom fiber of the slab. To avoid excessive tensile stresses, the friction between the slab and the supporting layer has to be reduced, if necessary, by using a friction-reducing medium.

The use of a friction-reducing medium is highly recommended to minimize subgrade restraint stresses and to allow hygrothermal movements in the slab during its lifetime without inducing high tensile stresses in the slab [1]. Prestressed slabs placed directly over asphalt or a granular subbase have shown a large increase in frictional forces that are undesirable. Some effective friction−reducing materials are polyethylene sheets, sand, and oil.

2.1.4 Model for Predicting Curling

The temperature differential between the top of the concrete slab and the bottom results in the curling of the concrete slab. The temperature gradient across the depth varies when the slab heats during the daytime or when it cools at night. The surface that is hotter (top) tends to expand, whereas the cooler surface (bottom) tends to contract. This results in tensile stresses developing at the cooler surface. As opposed to stresses caused by friction, temperature−curling stresses cause tension at the bottom of the slab during the day and compression at night.

It is important to observe at this point the counteractive effects of friction restraint stresses and temperature curling stresses. During the daytime, the tensile stresses from wheel loading and temperature curling are resisted by the compressive friction stresses. During the night tensile stresses from curling develop at the top of the slab, but usually the compressive stresses from friction at the top are not too high. This upward curling that results in tension at the top is unfavorable and may result in loss of support along the edges, increased edge stresses, and cracking of the pavement surface.

The effects of curling were incorporated in program PSCP-1 using Westergaard's model [7], but were later changed in PSCP-2 because of the drawbacks of the model. The current model used to predict curling stresses involves a series of equations that are presented in this section. The strain in concrete is derived from its thermal coefficient of expansion and the corresponding stress from Hooke's law. The stress caused by an increase in temperature gradient is given by Equation 2.4:

$$\sigma_{TD} = \frac{(E_c \times \alpha \times \Delta T'_D)}{2} \tag{2.4}$$

where,

E_c = Young's modulus of concrete, psi

α = thermal coefficient of concrete, inches/inch-ºF

$\Delta T'_D$ = effective increment of temperature, ºF

$$\Delta T'_D = \frac{1}{(2 \times n)} \times \sum_{0}^{n} \Delta T_{D_i} \tag{2.5}$$

where,

ΔT_{Di} = Sets of increments in temperature differentials, ºF

The vertical curling displacements in inches are obtained from the elasticity theory using Equation 2.6:

$$y = \frac{1}{E_c \times I_D} \times \iint (M_{TD} + M_{TM}) dx^2 \qquad (2.6)$$

where,

I_D = Flexural rigidity of the slab, in^4

$$I_D = \frac{E_c \times D^3}{12 \times (1 - \upsilon^2)} \qquad (2.7)$$

where,

υ = Poisson's ratio of concrete

M_{TD} = Bending moment caused by temperature differential, lb-in:

$$M_{TD} = \frac{\sigma_{TD} \times DW \times D^2}{6} \qquad (2.8)$$

where,

σ_{TD} = Stress due to increase in temperature differential, psi

DW = Slab width, inches

D = Slab thickness, inches

M_{TM} = Bending moment caused by volumetric thermal change and friction, lb-in:

$$M_{TM} = \frac{E_c \times \alpha \times D^2 \times \Delta T'_M}{4} \tag{2.9}$$

where,

$$\Delta T'_M = \Delta T_{M_i} \times \left(\frac{T_{M_i}}{T_{M_0}} \right) \tag{2.10}$$

ΔT_{Mi} = Increment of temperature at time 'i', ºF

T_{Mi} = Temperature at slab mid-depth, ºF

T_{M0} = Curing temperature of slab, ºF

The stresses that develop in the slab from curling are a result of the restraint imposed to the free movement of the slab. Hence, these stresses are maximum at the centerline and gradually decrease to zero at the edges. Equation 2.11 shows how the stress is calculated:

$$\sigma = E_c \times \left[\left(\alpha \times \Delta T'_D \right) + \left(\frac{\upsilon \times \omega \times DL^3}{15 \times E_c{}^2 \times k} \right) \right] \tag{2.11}$$

It is assumed to vary linearly along the depth of the slab, being zero at the mid-depth of the slab.

2.1.5 Models for Predicting Steel Properties and Post-Tensioning Losses

Prestressing steel can be either unbonded or bonded. Unbonded tendons need considerable protection against corrosion and are structurally less desirable than bonded tendons in the case of prestressed pavements. Bonded tendons are more effective and advantageous because they have a greater potential of developing reliable bond resistance, improved resistance to volumetric changes, and improved pavement behavior in case of partially damaged pavements [1]. Pavement repairs are also conducted more easily with bonded tendons.

The prestress that is initially applied to a PCP is usually lost over a period of time either partially or completely, depending upon diverse factors during the prestressing process. In a properly prestressed pavement, these losses should be taken into consideration when designing the pavement for service loads. The final prestress at the end of the slab should be calculated accordingly [5]. The various factors that cause loss of prestress and methods for estimating those are briefly discussed next.

Elastic Shortening

The prestressing steel shortens along with the concrete slab as the slab contracts with the application of the compressive stress. This results in loss of prestress in the strands. The magnitude of loss is given by Equation 2.12, in psi:

$$\Delta f_{ES} = \frac{E_p}{E_c} \times \left(F_c - \frac{F_r}{2} \right) \tag{2.12}$$

where,

E_p = Modulus of elasticity of prestressing steel, psi

E_c = Modulus of elasticity of concrete, psi

F_c = Compressive stress in the concrete, psi

F_r = Maximum subgrade restraint stress, psi

Creep

Creep deformations occur in concrete when it is subjected to continuous loads over a period of time. The stress loss in the prestressing steel from compressive creep in concrete is given by Equation 2.13, in psi:

$$\Delta f_{CR} = \varepsilon_{CR} \times f_{pc} \times E_p \tag{2.13}$$

where,

ε_{CR} = Creep strain

f_{pc} = Prestress in the concrete, psi

E_p = Modulus of elasticity of prestressing steel, psi

Shrinkage

Another cause for the shortening of the slab is the evaporation of water from the concrete. The amount of shrinkage depends on the amount of free water in the concrete, relative humidity, ambient and concrete temperatures, dimensions of the slab, and the type of aggregates used. Shrinkage losses are estimated by using Equation 2.14:

$$\Delta f_{SH} = \varepsilon_{SH} \times E_p \tag{2.14}$$

where,

ε_{SH} = Shrinkage strain

E_p = Modulus of elasticity of prestressing steel, psi

Relaxation of Steel

Loss of prestress occurs in tendons that are maintained at the same length and temperature over a period of time. This loss depends on the grade of steel and the intensity of the initial stress. Steel relaxation values are usually provided by steel manufacturers and suppliers. Owing to creep and shrinkage of concrete, a tendon in a PCP exhibits smaller relaxation, which is given by Equation 2.15:

$$\Delta^{-} f_{pr} = X_r \Delta f_{pr} \qquad (2.15)$$

where,

Δf_{pr} = intrinsic relaxation

X_r = reduction factor (≈ 0.85 for PCPs)

Anchorage Slip

Some amount of prestress is lost when the prestress is transferred to the tendons through the jacks and the tendons are anchored to the ends of the slab. The amount of slip differs for the types of assembly that constitutes the anchorage. For a certain prescribed slip, the amount of prestress loss can be calculated by using Equation 2.16 [2].

$$\Delta f_{AS} = \frac{\Delta L}{L} \times E_p \qquad (2.16)$$

where,

ΔL = slip, inches

L = length of the tendon, inches

E_p = modulus of elasticity of prestressing steel, psi

Friction in the Tendon

This includes losses attributed to both tendon wobble resulting from construction misalignment and curvature friction resulting from the change in grades of the tendon profile. The loss of prestress between the jacking end and any point "L" away from it is given by Equation 2.17:

$$\Delta f_{FR} = e^{(k \times L \times \mu \times \alpha)} \qquad (2.17)$$

where,

k = Wobble coefficient, per feet

L = distance between jacking and given point, ft

μ = Curvature coefficient, per radians

α = Total change in angle of the tendon profile, radians

2.2 Wheel Load Stress Analysis

The present section discusses the models and procedures used to estimate the stresses in PCPs caused by wheel loading.

2.2.1 Review of Models

The stresses induced in a concrete pavement by wheel loading can be modeled using various theories and assumptions. Some of the commonly used models as well as the model used in PSCP 3.0 are discussed herein.

Plate on Winkler Foundation

This method of analyzing the stresses in a pavement slab models the slab as a "plate" resting on a "bed of springs." Winkler first introduced the use of "springs" to represent the interaction between soil and the structure resting on the soil in 1867. The one-dimensional representation of this is called a "beam on an elastic foundation." The analysis of a pavement for wheel load stresses is a two-dimensional application of Winkler's method. This assumption does not account for different material properties in a multi-layered pavement system. It also fails to resolve correctly the stress distributions within each layer beneath the concrete slab. This model does not allow for calculation of edge stresses.

Elastic Layer Theory

This analysis is confined to linearly elastic material properties. Assumptions include a semi-infinite half space domain; hence, it is not possible to consider the behavior of a layered system with a finite boundary. This method also cannot analyze edge stresses and jointed pavements. The elastic layer theory does not account for true wheel footprints, because it is based on axi-symmetric loading. Although this model cannot be used directly for the analysis of the stresses in PCP, it is a very helpful tool in determining the stresses in a pavement that might simulate the PCP [5].

Finite Element Methods

The finite element (FE) methods model the entire soil–pavement system in a three-dimensional way. In many cases, this method is not yet practical because of the following reasons:

1. Requires a large amount of computing power to perform the analyses.
2. Needs expensive computers and trained personnel.
3. Is difficult to determine the concrete and soil properties in such a way as to justify the precision of the analysis, especially when the parameters are highly variable and nonhomogenous.

Modeling using the FE can be very time consuming, especially when pre-processing is required. However, this modeling technique has proved to be quite reliable.

2.2.2 Stress Estimation

The model adopted for this analysis is a plate on Winkler foundation. In this method, the pavement slab is modeled as a two-dimensional plate of infinite length supported by a visco-elastic foundation, the subgrade. Because this method provides reliable results and easily incorporates into the existing PSCP program, it was adapted to the new PSCP 3.0 program. Among the parameters required for this model are the coefficient of subgrade reaction of the foundation soil, wheel–loading characteristics, slab geometry, and concrete properties.

Assumptions

To analyze a PCP as a plate resting on an elastic foundation, certain assumptions have to be made and include the following:

1. The effect of discontinuities in the pavement system at cracks is ignored.
2. Tire–pavement contact area is assumed to be circular, and the change in shape during load variation is neglected.
3. The load variation within the contact area is assumed to be uniform.
4. The material behavior is assumed to be linear elastic.

Loading

A pavement slab experiences compressive and tensile stresses under different types of loading. Because concrete is relatively weak in tension, it is important to analyze the forces causing tensile stresses. Critical tensile stresses are caused by the following types of loading [7]:

1. Stresses caused by environmental conditions
2. Wheel load stresses

3. Combinations of both

According to the theory, in the upper half of the slab the critical tensile stress is caused by environmental loads, because the wheel load causes compression on the top. For the lower half of the slab, the critical tensile stress results from the combined stress caused by environmental loading and wheel loads.

Westergaard's equations can be used to predict the stresses caused by wheel loads on the concrete pavement. However, this method assumes that the pavement system is semi-infinite, and therefore, only the stresses in the interior of the slab can be obtained [13]. According to Westergaard's equation, the maximum interior stress caused by a wheel load is given in Equation 2.18:

$$\sigma = \frac{3 \times (1 + \upsilon) \times P \times \left(\ln\left(\frac{\ell}{b} \right) + 0.6159 \right)}{2 \times \pi \times h^2} \qquad (2.18)$$

where,

h = Thickness of the slab, inches

υ = Poisson's ratio

P = Magnitude of the load, lbs

π = 3.14159

"b" is defined by

$b = a$ when, $a \geq 1.724 \times h$

$b = \sqrt{\left(1.6 \times a^2 + h^2\right)} - (0.675 \times h)$ when, $a \leq 1.724 \times h$

where,

a = Radius of the circular loaded area, inches

ℓ = radius of relative stiffness, given by Equation 2.19

$$\ell = \left[\frac{E \times h^3}{12 \times \left(1 - \upsilon^2\right) \times k} \right]^{0.25} \qquad (2.19)$$

where,

E = Modulus of elasticity of the concrete slab, psi

K = Modulus of subgrade reaction, psi/in

As the wheel loads act on the slab in combination with environmental loads, the maximum stress can occur at the bottom of the slab and can occur when the temperature peaks [7].

Equation 2.18 provides the maximum stress that occurs in an interior point of the slab. To obtain the total stresses in slab, this stress is superimposed onto the stresses caused by temperature changes and prestress. The inherent assumption is that the stresses are low enough that the slab is in the linear-elastic range. This assumption is reasonable because the excessive tensile stresses that would otherwise occur at the bottom of the slab from wheel loading are counteracted by the prestress induced.

2.2.3 Determination of Slab Edge Stresses

In PCP design, it is important to determine the stresses in the slab at the edges. Three-dimensional finite element analysis [14] has shown that edge loadings and edge stresses are significant when concrete bending stresses are considered. Research has shown that the edge stresses—for instance, in the end of the slab length—can be calculated from the edge-interior stress ratio, using Westergaard's equations [3]. The values of edge stresses, calculated using this ratio and from a finite element model used for comparison, match closely. Hence, this ratio is used for calculating slab end stresses in PSCP 3.0 and is described by Equation 2.20:

$$\text{Ratio} = \frac{2}{3+\upsilon} \times \frac{\ln\left(\dfrac{E \times h^3}{100 \times k \times a^4}\right) + 1.84 - \dfrac{4 \times \upsilon}{3} + \dfrac{\ell - \upsilon}{2} + \dfrac{1.18 \times a \times (\ell + 2 \times \upsilon)}{\ell}}{\ln\left(\dfrac{\ell}{b}\right) + 0.6159} \tag{2.20}$$

Once the interior stresses are calculated, the edge stresses can be obtained by simply multiplying the slab interior stress by the stress ratio.

3. Organization of the PSCP 3.0 Program

The PSCP 3.0 program consists of a source code written in Fortran 90 programming language and a user interface developed with Microsoft® Visual Basic 6.0. This setup is thought to be reliable and, most importantly, is user friendly.

3.1 Visual Basic Front End

A graphical user interface was created for PSCP 3.0 using Microsoft Visual Basic 6.0. Using Visual Basic as the front end for this application allows the user to enter values for input at run time. This gives the user the flexibility of going back to any input screen and change input parameters to display and compare different cases. In other words, it serves as a very effective tool for sensitivity analyses.

PSCP 3.0 with the Windows-based interface is dynamic, easy to use, and visually appealing. The main objective of the program is to aid the pavement design engineer in conducting various design attempts until he or she applies judgment and decides which solution is the optimal one.

3.1.1 Input Files and Screens

In PSCP 3.0 the values entered into the input screens are saved to the input file INPUTFILE.TXT, which is read by the Fortran source code. This input file can be checked after execution for verification of data entered.

Organization of Inputs

The input data to PSCP 3.0 can be classified in ten groups, described in the following paragraphs.

1. Geometry

This is the first input screen; it requires basic geometric data regarding the PCP slab, including the dimensions of the slab (length, width, and thickness). The units of length and width are in feet, whereas the unit for thickness is in inches. Figure 3.1 displays a diagram of the dimensions of the slab as required by PSCP 3.0.

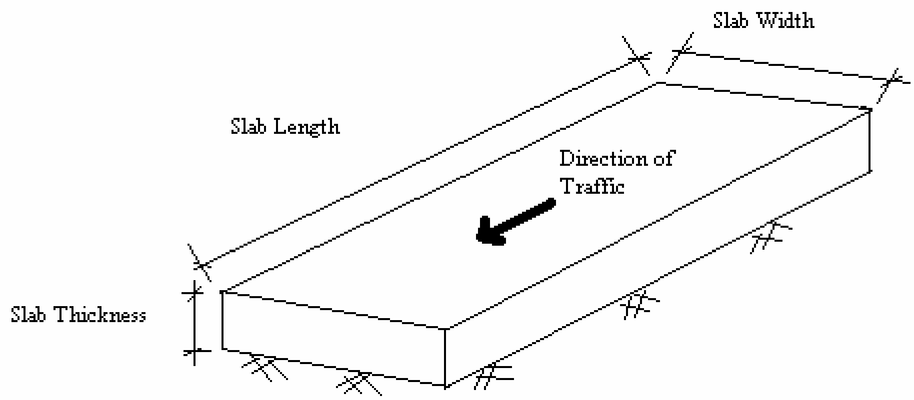


Figure 3.1 Required slab dimensions

2. Concrete Properties

The next input screen asks for various properties of the concrete mix that are used for design of PCPs. The default values provided by the program were adopted from the McLennan County PCP, which is a test section that was constructed in 1985 [1]. Likewise, the values of coefficient of thermal expansion of the concrete, creep of concrete, and so forth correspond to recommendations from previous PCP projects [3]. These values might be varied depending on the concrete mix properties and designer's criterion.

3. Aggregate Type

Aggregates are defining constituents of concrete that significantly affect the properties of the PCP slab. In PSCP 3.0, there are eight different aggregate types for which

Young's modulus has already been defined in the program from previous research studies conducted at the Center for Transportation Research of the University of Texas at Austin. In addition, there is an option to enter an aggregate type different from that defined in the program. If the aggregate type is unknown, this screen can be omitted and the twenty-eight-day compressive strength of the concrete can be entered in the next screen.

4. Concrete Compressive Strength Relationship

When the twenty-eight-day compressive strength of concrete is known from tests, the program generates the age/compressive strength relationship using just this single value. Another option is to provide various age versus strength values, if available. For precast concrete slabs, a compressive strength of 5,000 psi is entered for all ages because, theoretically, the strength of the controlled precast slab does not vary too much over time.

5. Coefficient of Friction−Displacement Relationship

There are three options that might be selected from the program.

1. Linear: The friction is assumed to behave linearly until it reaches the point at which the slab moves freely. In reality, the relationship between slab and subgrade friction is essentially nonlinear [3]; however, this simplification is commonly used for pavements design.
2. Exponential: This type of behavior can be modeled with at least two sets of values of the friction coefficients and their corresponding movements.
3. Multilinear: When data are available for slab movements and corresponding friction coefficients, this option can be selected. Although this is the most difficult model that can be selected because it requires field testing, it is the most reliable of the three.

6. Steel Properties

This input screen is similar to the screen for input of concrete properties. If the prestressing steel is not to be defined then the strand spacing should be assigned a value of zero. Usually, different strand spacings should be analyzed for different pavement thicknesses. Because this is a time-consuming task, PSCP 3.0 helps the designer by doing calculations much more rapidly than hand calculations.

7. Wheel Loading

PSCP 3.0 considers only static wheel−load analysis, and the only data required for the calculation of wheel load stresses are as follows:

1. Magnitude of wheel load that is applied on the slab
2. Radius of the wheel base (6 in. is the default value)
3. Days after concrete setting—that is, when the load is applied on the slab

8. Temperature Data for Initial Period

Temperature history of a recently built PCP (initial period) is one of the most important pieces of information that is needed for the analysis. The mid-depth temperature and the top−to−bottom temperature differential help in monitoring the curling of the slab, the stresses induced through these movements, and the restraints that oppose them. Information needed for the analysis include setting time and setting temperature. Various data points for this initial period can be entered, and as many as five subsequent periods to be analyzed can be input through this screen.

9. Temperature Data for Subsequent Period

The program allows analyzing the behavior of the slab with variations in temperature in the long term. The inputs required are the concrete temperature differentials, mid-depth temperatures, and the number of days after setting when the slab should be analyzed. Up to five subsequent periods can be analyzed, and the results are saved seen in the output file called OUTPUTFILE.TXT.

10. Post-Tensioning Stages

Post-tensioning tasks are crucial for the adequate performance of PCPs. Post-tension can be applied in one or more stages, depending on the structure. Usually, for pavements it is recommended to perform at least two post-tensioning stages [5]. In PSCP 3.0, the prestress applied per strand needs to be input to the program, along with the time after the setting of the concrete when the prestress is applied and the stage in which it is applied.

3.1.2 Output Files and Screens

As mentioned in the previous section, a summary of the performed analysis along with detailed listings of the slab stresses and displacements are saved in the output file OUTPUTFILE.TXT. Additional results can be seen from the Output menu and also from the respective output files. Table 3.1 shows a list of output files generated by PSCP 3.0 and the information they contain. These files are automatically generated every time the program is run. Therefore, if a series of runs are performed, it is wise to rename the files every time the program is executed. This will prevent losing data.

Table 3.1 Output files generated by PSCP 3.0

File	Content
WheelStress.TXT	Mid-slab and slab end stresses
TEXTFILE1.sum	Initial period slab end movements
TEXTFILE2.sum	Initial period slab curling movements
TEXTFILE3.sum	Initial period slab total stresses
TEXTFILE4.sum	Final period slab end movements
TEXTFILE5.sum	Final period slab curling movements
TEXTFILE6.sum	Final period slab total stresses

Organization of PSCP 3.0 Output Files

The output from PSCP 3.0 can be obtained in two forms:

1. Plots
2. Text files

The output is divided in three parts: (1) the results of the analysis for initial period, (2) shortly after setting, and (3) the final period, after a specified time from setting. Likewise, output files include the displacements and stresses in the PCP over a period of time. Displacements include both horizontal end movements at the end of the slab and vertical curling movements. Computed stresses are total stresses from prestress, friction, curling, and wheel loads. Stresses are calculated and displayed for the top and bottom fibers of the slab and for interior and edge–loading conditions. As previously discussed, the stresses at the edge or end of the slab are calculated using a theoretical model [9]. The output screen plots are organized as shown in Table 3.2. The movements and stresses are plotted over a period of time.

Table 3.2 Output screen plots

<table>
<tr><th>Initial Analysis Period</th><th>Final Analysis Period</th><th>Comparisons</th></tr>
<tr><td>End Movements</td><td>End Movements</td><td>Initial versus Final Period</td></tr>
<tr><td>Curling Movements</td><td>Curling Movements</td><td>Mid-Slab versus Slab-End Stresses</td></tr>
<tr><td>Total Stresses</td><td rowspan="2">Total Stresses</td><td rowspan="2">Top versus Bottom Slab Stresses</td></tr>
<tr><td>Stress from prestress, friction, and curling</td></tr>
</table>

3.2 Typical Input and Output

This section provides a summary of all the input data required for PSCP 3.0 to conduct a PCP analysis.

3.2.1 Input

Problem Identification:	Analysis of prestressed pavement slabs	
Problem Definition:	Slab length, ft	240
	Slab width, ft	12
	Slab thickness, in	6
	Number of elements	60
	Maximum No. of iterations	100
	Tolerance, percent	0.5
Concrete Properties:	Thermal coefficient, in/ in/°F	$5x10^{-6}$
	Ultimate shrinkage strain, in/in	$3x10^{-4}$
	Unit weight, pcf	150
	Poisson ratio	0.15
	Creep coefficient	2.10
Age−Compressive Strength Relationship:	Age, days	28
	Compressive strength, psi	4500
Friction Coefficient vs. Displacement Relationship:	Type of relation	Linear
	Displacement, in	0.02
	Friction coefficient	0.2
Stiffness of Slab Support:	K-value, psi/in	1800
Steel Properties: Strand spacing, in	34	
	Strand nominal area, in^2	0.216
	Yield strength, ksi	270
	Elastic modulus, psi	$30x10^6$
	Thermal coefficient, in/in/°F	$7x10^{-6}$
Wheel Loading:	Age of concrete when first loaded, days	28
	Wheel load, lbs	9000
	Wheel base radius, in	6
Temperature Data for Initial Period:	Number of data points for initial period	12
	Curing time (0:00-24:00)	14
	Curing temperature, °F	90

The input values presented above correspond to the default values of the program, which are based on experience and collected data. These provided values might be used with discretion by the designer in case no actual data are available; however, the output values should be carefully interpreted. Temperature data values for the analysis of the initial period should be typed in PSCP 3.0 as shown in Table 3.3.

Table 3.3 Typical initial period temperature data

Mid-Depth Temperature, °F	Top-Bottom Temperature Differential, °F
95	12.5
87	-0.5
78	-6.4
70	-6.4
65	-5.8
62	-5.1
60	-5.3
57	-5.1
57	-2.5
65	1.8
80	17.4
90	20.4

Analogously, temperature data values for subsequent periods (up to five) should be typed in PSCP 3.0 as shown in Table 3.4. The time in days for which the analysis should be conducted should also be entered, as shown next.

Temperature Data for Subsequent Period of Analysis:

Time of analysis since setting, days = 1,207

Table 3.4   Typical subsequent period temperature data

Mid-Depth Temperature, °F	Top-Bottom Temperature Differential, °F	Hour of Day
95	12.5	14
87	-0.5	16
78	-6.4	18
70	-6.4	20
65	-5.8	22
62	-5.1	24
60	-5.3	2
57	-5.1	4
57	-2.5	6
65	1.8	8
80	17.4	10
90	20.4	12

Finally, post-tensioning stages in number and time should be typed as required. Usually, for PCPs post-tensioning is applied in one to three stages. However, for sensitivity analysis purposes, the designer might choose to apply more stages.

Sequence of Post-Tensioning during Initial Period:

Number of stages 1

Time since curing, hours 10

Post-tension per strand, ksi 46.4

3.2.2 Output

As previously mentioned, output data from PSCP 3.0 can be obtained in either text or graphical forms. Because Chapter 4 contains some of the graphics generated by the program, this section presents only the output obtained in text format. The various output files obtained from PSCP 3.0 for the default input values are given next. The output shown is only a partial set of the data that might be obtained.

Initial Period Slab End Movements

The slab end movements estimated at 2-hr intervals starting at placement are displayed in Table 3.5. Note that the time of placement is 14.00 hrs (default input values).

Table 3.5 Initial period end movements over time

Time after Placement, hrs	End Movement, in.
2.00	0.033
4.00	-0.018
6.00	-0.086
8.00	-0.144
10.00	-0.197
12.00	-0.219
14.00	-0.234
16.00	-0.255
18.00	-0.256
20.00	-0.205
22.00	-0.095
24.00	-0.023

Initial Period Slab Curling Movements

The estimated slab curling movements calculated by PSCP 3.0 at 2-hr intervals starting at placement (14.00 hrs) are shown in Table 3.6. These values correspond to the analysis of the initial period only.

Table 3.6 Initial period curling movements over time

Time after Placement, hrs	Curling Movement, in.
2.00	-0.001
4.00	0.033
6.00	0.094
8.00	0.123
10.00	0.136
12.00	0.141
14.00	0.144
16.00	0.148
18.00	0.145
20.00	0.105
22.00	0.060
24.00	0.022

Initial Period Total Stresses

Like those for end and curling movements in the PCP slab, analyses of the total stresses for the initial period are shown in Table 3.7. Again, the output values are displayed for 2-hr intervals starting at placement time (14.00 hrs). Stresses are computed for the mid-slab (center of PCP slab) and at the slab end. For both cases, the stresses are estimated at top and bottom fibers.

Table 3.7   Initial period total stresses over time

Time after Placement, hrs	Mid-Slab Stresses, psi		Slab End Stresses, psi	
	Top	Bottom	Top	Bottom
2.00	-16.773	-16.773	00.000	00.000
4.00	17.663	21.342	-01.839	01.839
6.00	93.003	-47.303	70.153	-70.153
8.00	113.686	-66.610	90.148	-90.148
10.00	71.833	-122.358	47.966	-146.225
12.00	73.246	-123.589	49.288	-147.547
14.00	74.865	-125.087	50.847	-149.638
16.00	75.489	-125.529	51.380	-149.638
18.00	69.280	-119.320	45.170	-143.429
20.00	-44.801	-91.951	-25.554	-72.704
22.00	-66.626	-78.414	-43.236	-55.023
24.00	-71.525	-74.472	-47.656	-50.603

Final Period Slab End Movements

For the final period selected in the design, slab end movements are estimated at 2-hr intervals, as shown in Table 3.8.

Table 3.8 Final period end movements over time

Hour of Day	End Movement, in.
14.00 hrs	-0.379
16.00 hrs	-0.429
18.00 hrs	-0.497
20.00 hrs	-0.555
22.00 hrs	-0.591
24.00 hrs	-0.612
02.00 hrs	-0.627
04.00 hrs	-0.649
06.00 hrs	-0.649
08.00 hrs	-0.598
10.00 hrs	-0.488
12.00 hrs	-0.416

Final Period Slab Curling Movements

As for the initial period analysis, slab curling movements are computed by PSCP 3.0 for the final analysis period, again for 2-hr intervals. The values are shown in Table 3.9.

Table 3.9 Final period curling movements over time

Hour of Day	Curling Movement, in.
14.00 hrs	-0.001
16.00 hrs	0.033
18.00 hrs	0.094
20.00 hrs	0.123
22.00 hrs	0.136
24.00 hrs	0.141
02.00 hrs	0.144
04.00 hrs	0.148
06.00 hrs	0.145
08.00 hrs	0.105
10.00 hrs	0.060
12.00 hrs	0.022

Final Period Total Stresses

Finally, the total stresses for mid-slab and slab end for the final period analysis are shown in 2-hr intervals. These values are shown in Table 3.10.

Table 3.10 Final period total stresses over time

Hour of Day	Mid-Slab Stresses, psi		Slab-End Stresses, psi	
	Top	Bottom	Top	Bottom
14.00 hrs	-248.251	119.882	-371.562	291.234
16.00 hrs	-206.791	165.021	-373.401	293.073
18.00 hrs	-131.278	96.549	-301.409	221.081
20.00 hrs	-110.566	77.270	-281.413	201.086
22.00 hrs	-103.352	70.590	-274.466	194.138
24.00 hrs	-101.939	69.359	-273.144	192.816
02.00 hrs	-100.320	67.860	-271.585	191.257
04.00 hrs	-99.697	67.418	-271.053	190.725
06.00 hrs	-105.906	73.628	-277.262	196.934
08.00 hrs	-219.911	101.072	-347.987	267.659
10.00 hrs	-241.729	114.617	-365.668	285.340
12.00 hrs	-246.627	118.559	-370.088	289.761

4. Execution of PSCP 3.0

Chapter 3 in this report described in detail the organization of the PSCP 3.0 program. It covered a description of the input parameters that are required by the program and explained what the typical output looks like. The explanation in Chapter 3 focused on the input and output data of PSCP 3.0 in text format only, and the input values corresponded to the ones used as default by the program.

Chapter 4 presents the graphics format of the material contained in Chapter 3. Both input and output data windows or screens are shown herein. Figures 4.1 to 4.35 show step by step the way in which the data are input and what the output screens look like.

4.1 Sample Problem

Figure 4.1 displays the main screen of PSCP 3.0. In this window, the user begins to input data as required by the program. This main window has four menus called File, Analysis, Print, and Help.

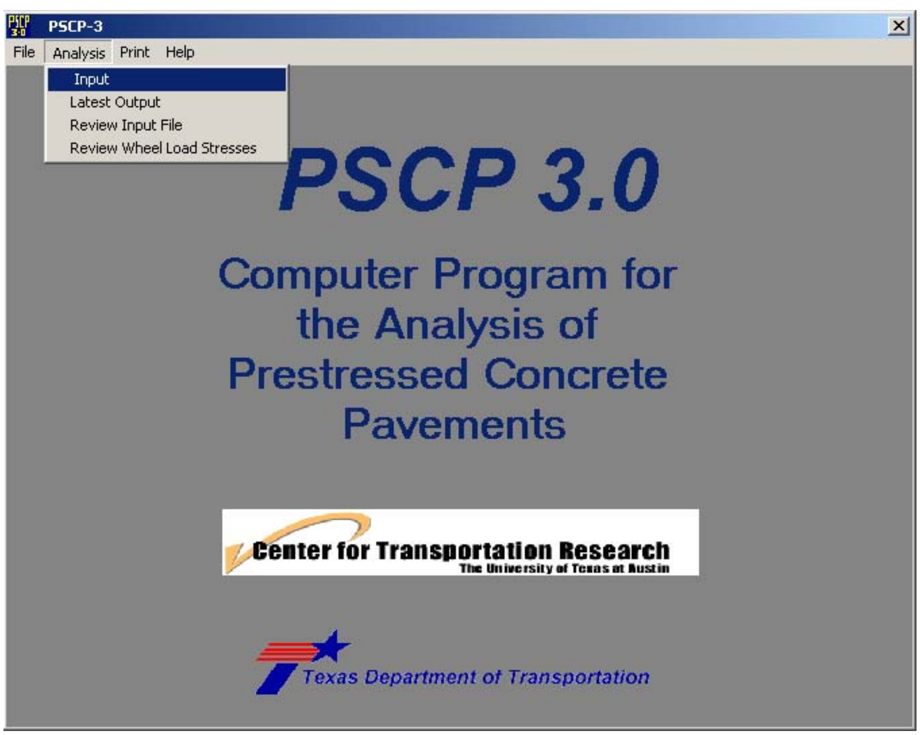


Figure 4.1 Startup screen

4.1.1 Inputs

To begin entering data for a new analysis, the user should select Analysis and then Input. The screen shown in Figure 4.2 will appear, prompting the user for the geometry of the PCP slab and a description of the problem or analysis.

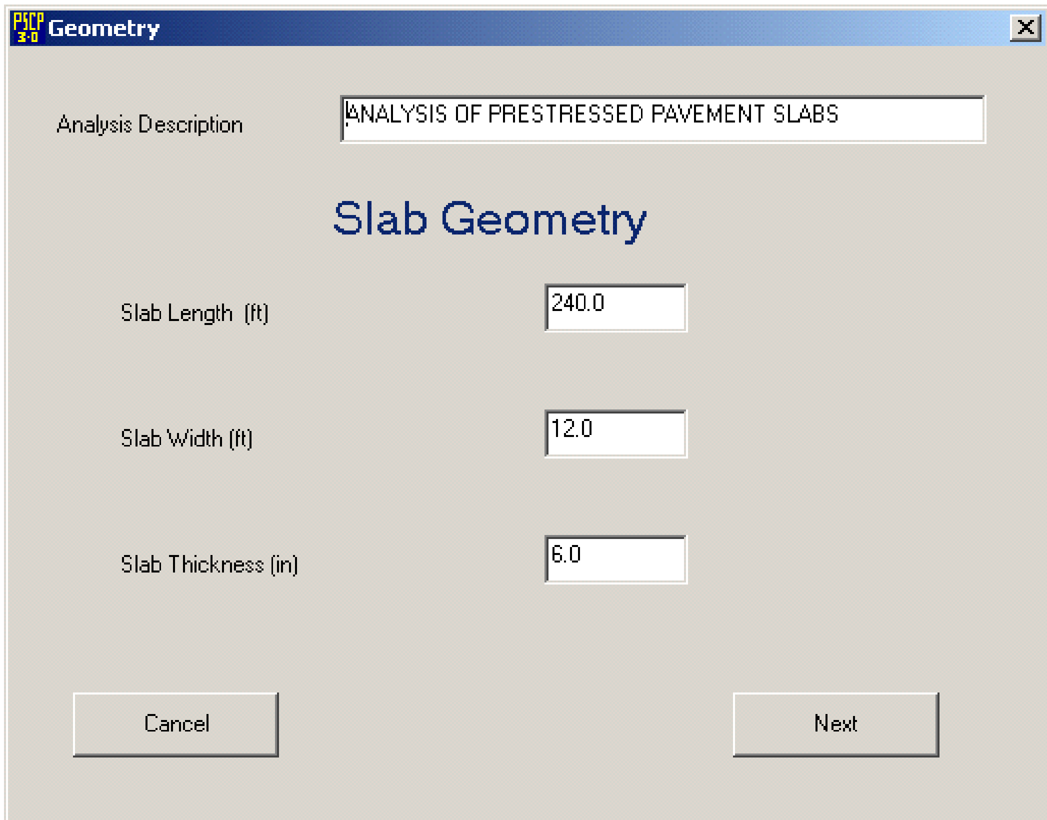


Figure 4.2 Geometry screen

The next input window is shown in Figure 4.3. It requires the properties of the concrete mix including the coefficient of thermal expansion, ultimate shrinkage strain, unit weight, Poisson's ratio, and creep coefficient. The values shown in the figure are the default ones.

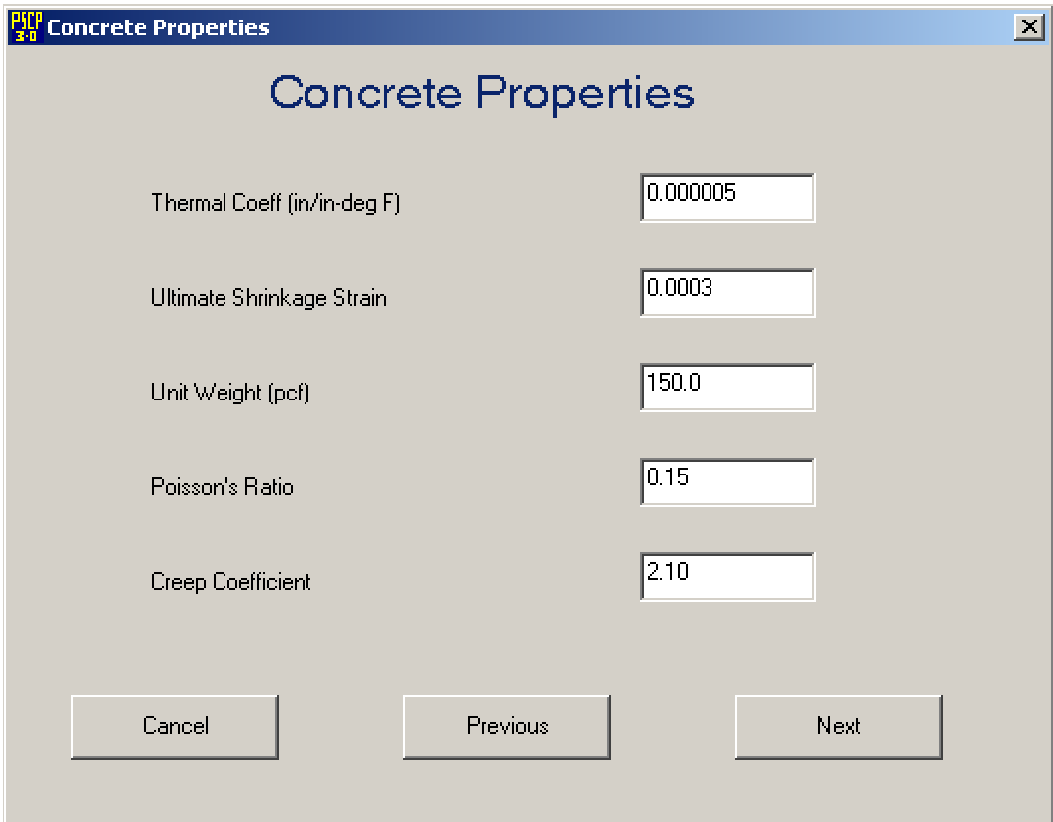


Figure 4.3 Concrete properties screen

Figure 4.4 shows the screen for selecting the type of aggregate to be used in the concrete mix. There are eight aggregate types for which the concrete properties are predefined in the program. These values are used to calculate accurately a strength development curve on the basis of previous research studies [10].

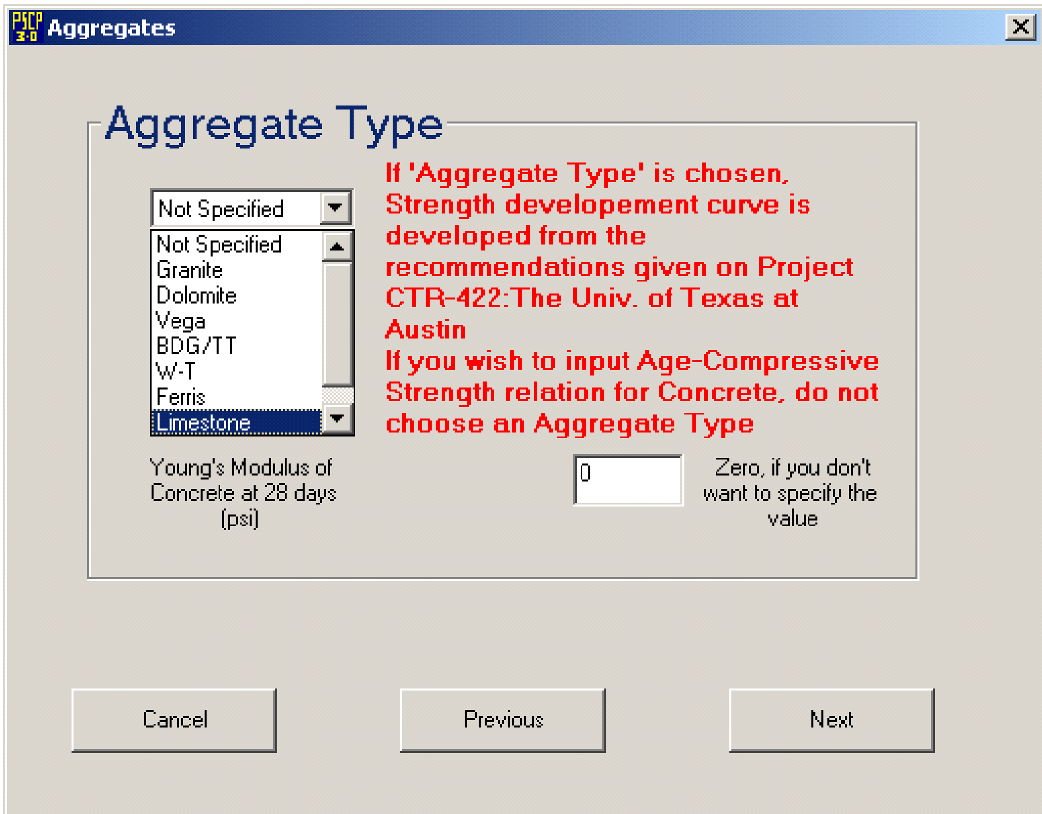


Figure 4.4 Aggregate type screen

The relationship between the age of the concrete and its compressive strength can be input through the screen shown in Figure 4.5. If the twenty-eight-day compressive strength of concrete only is input then the strengths for earlier ages are calculated proportionally to the twenty-eight-day strength. If strength history is known, up to eighteen data points can be entered for this relationship.

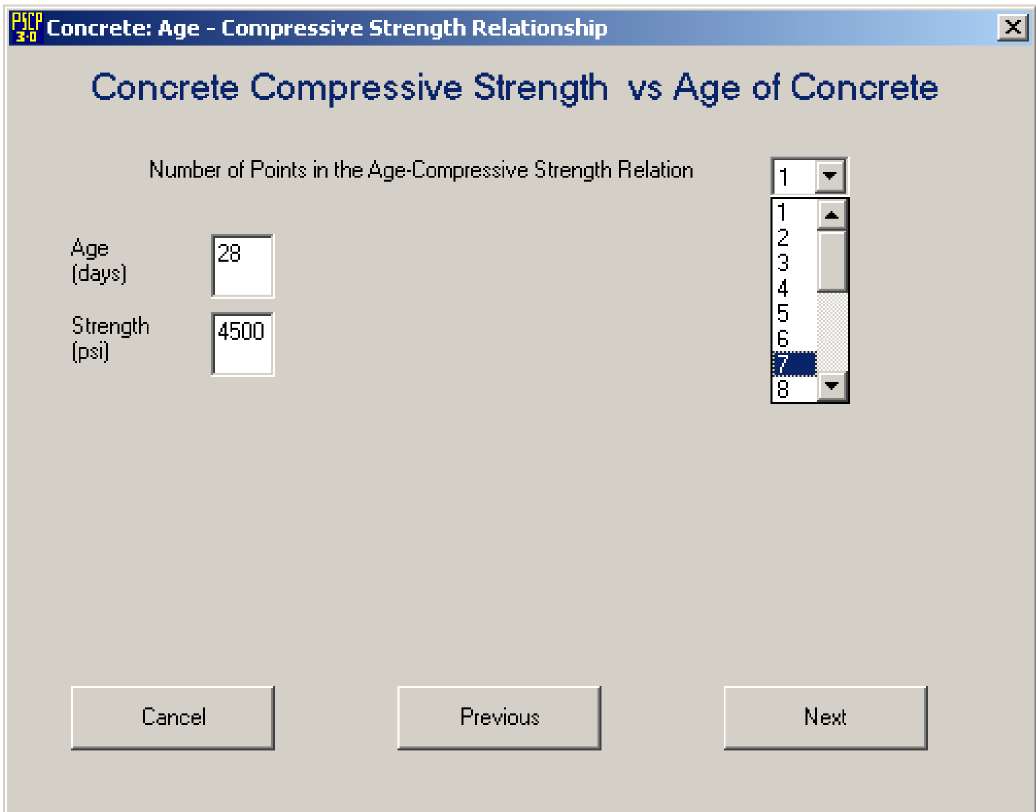


Figure 4.5 Concrete age-compressive strength relationship screen

Figure 4.6 shows the input screen for the relationship between the friction coefficient and displacement of the PCP slab. For a multi-linear relationship, a maximum of eighteen data points can be input for the calculation of the slab's frictional stresses from its movement. One and two data are required for a linear or exponential relationship, respectively.

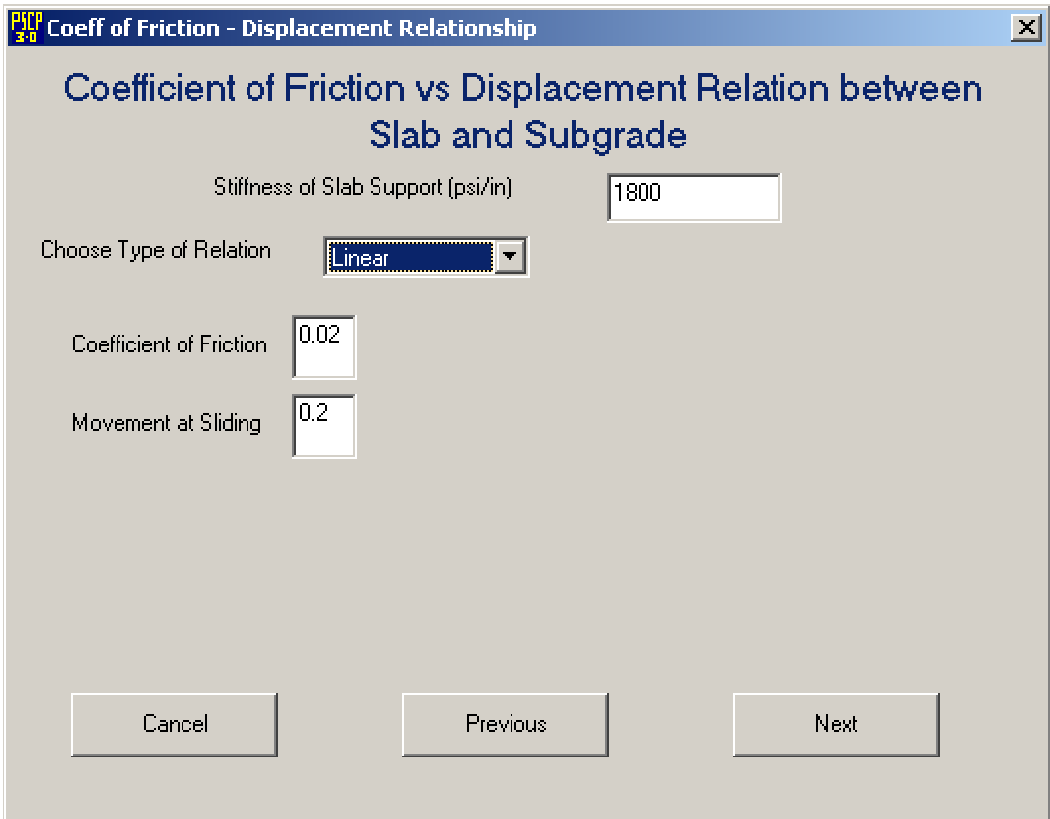


Figure 4.6 Coefficient of friction-displacement relationship screen

The properties of the prestressing steel are entered using the input screen shown in Figure 4.7. Bonded tendons of the high-stress relieved type are recommended for use in PCPs. The steel properties are usually provided by manufacturers.

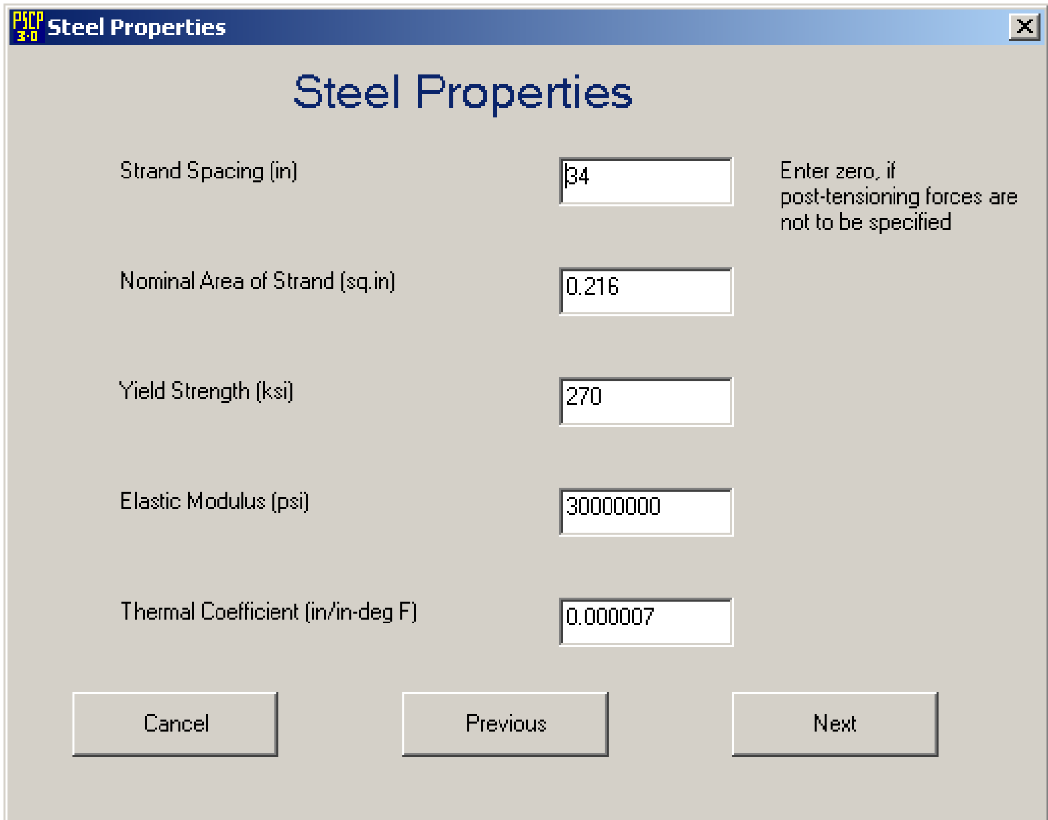


Figure 4.7 Steel properties screen

For the wheel load analysis, it is assumed that the slab is opened to traffic seven days after setting or later. Ideally, twenty-eight days should be allowed for strength gain. PSCP 3.0 analysis calculates only the stresses in the PCP slab caused by a single axle load of a given magnitude. The wheel load input screen is shown in Figure 4.8.

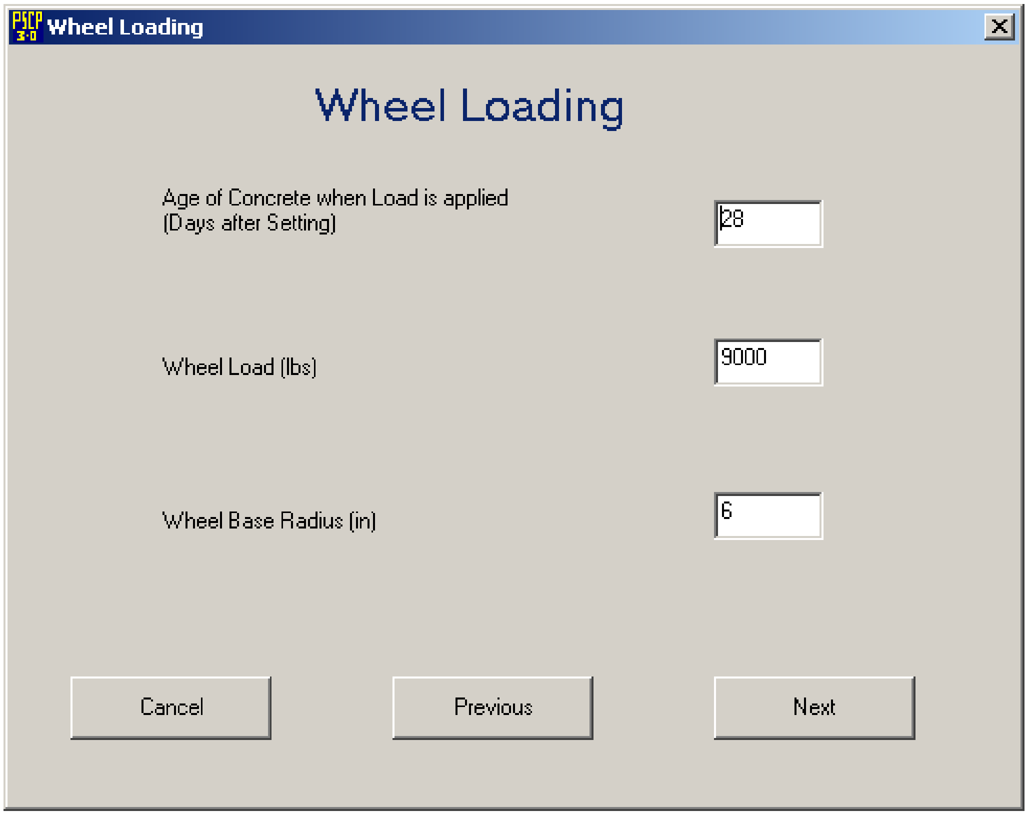


Figure 4.8 Wheel loading screen

The temperature data collected during the first twenty-four hours after setting of concrete help predict the behavior of early age concrete and assist in deciding on the amount and time of prestressing operations. Figure 4.9 shows the screen to input temperature data for the initial period after concrete setting.

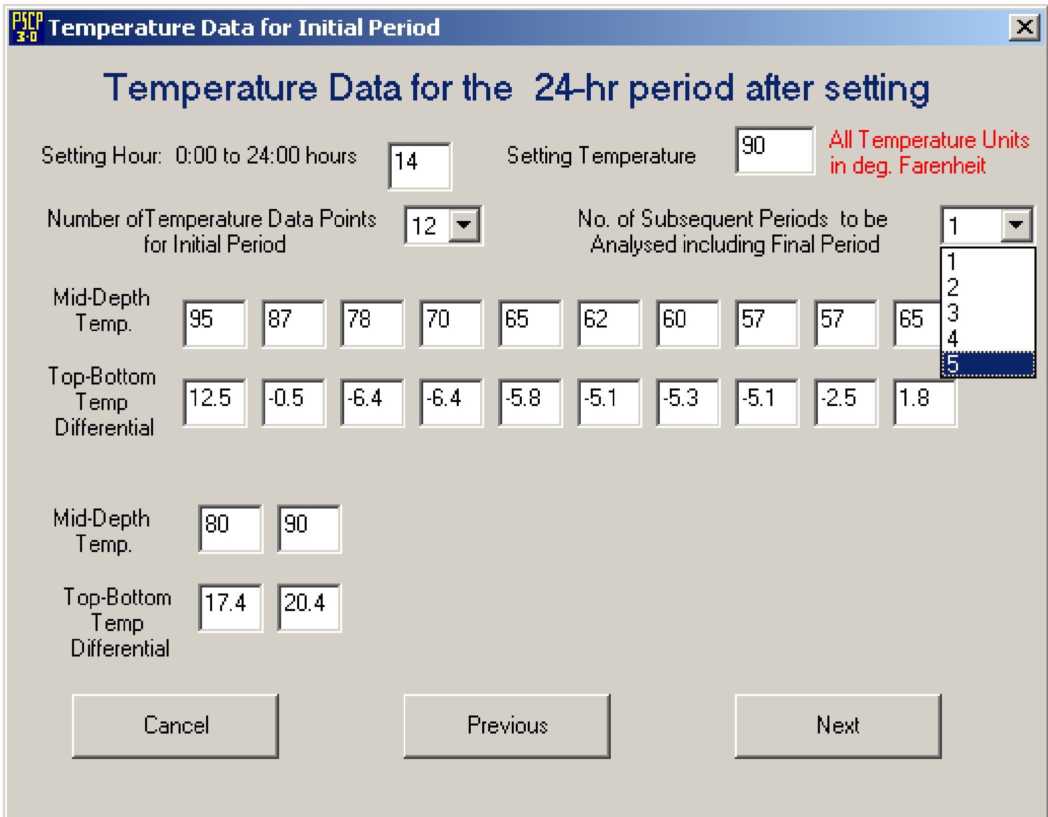


Figure 4.9 Screen for input of temperature data for initial period

With PSCP 3.0 the PCP slab can be analyzed for stresses and displacements months and even years after it was constructed. To analyze the slab in the long term, temperature data are required to be entered at two-hour intervals for a twenty-four-hour time period. In addition, the number of days after setting is required. Up to five subsequent periods can be analyzed in PSCP 3.0. All the subsequent period input screens appear as the screen shown in Figure 4.10.

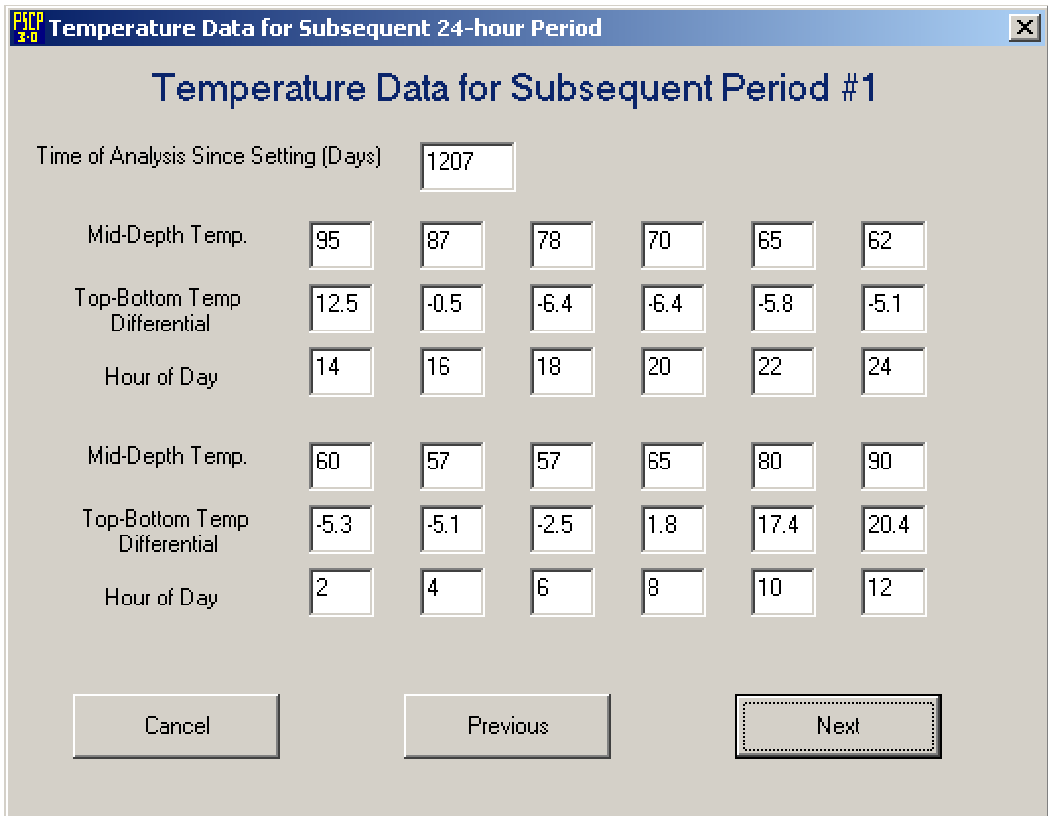


Figure 4.10 Screen for input of temperature data for subsequent period

The last input screen is related to post-tensioning of the PCP. Although post-tension is applied in one to three stages, the program allows entering up to ten stages. The only information required is the amount of prestress applied per strand and the time of application. The program calculates the loss in prestress at any given time. Figure 4.11 shows the corresponding input screen. Finally, when the analysis button is clicked, the program is executed, the analysis is performed, and the output files are generated.

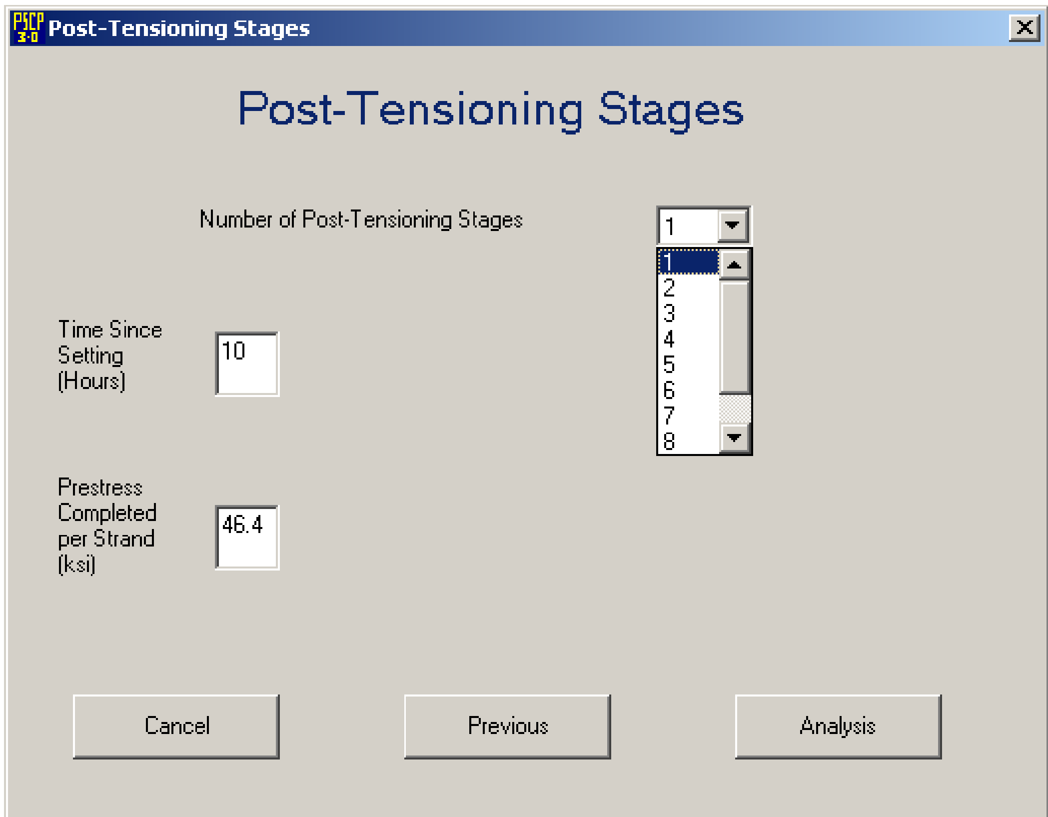


Figure 4.11 Post-tensioning stages screen

4.1.2 Outputs

Once all the input data are entered and the analysis is performed, PSCP 3.0 generates a set of output files. The first screen that is displayed is shown in Figure 4.12. This is the main output screen. Here, the button Click for Results of Current Analysis should be clicked to access all the output files—that is, text and plot files. In the main output screen the two main menus are Plots and Text Files. Under the Plots menu there are submenus to the outputs for the Initial Period, the last subsequent period called Final Period, and comparisons of initial versus final conditions, top versus bottom stresses, and mid-slab versus slab end stresses.

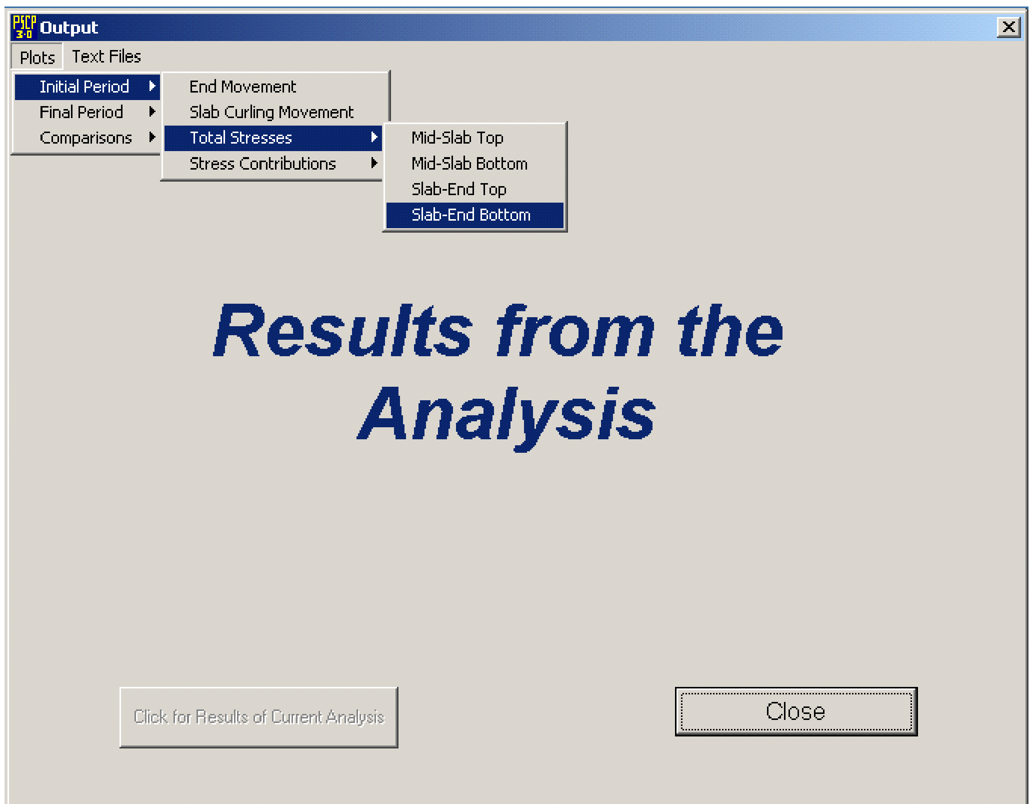


Figure 4.12 Main output screen in PSCP 3.0

Figure 4.13 shows the submenus that can be accessed through the text files menu in the main output screen. The Text Files menu contains the results of the analysis in text format, which can be printed, copied, or saved for further reference. These text files can be accessed only from the main output screen once the analysis of the PCP is performed.

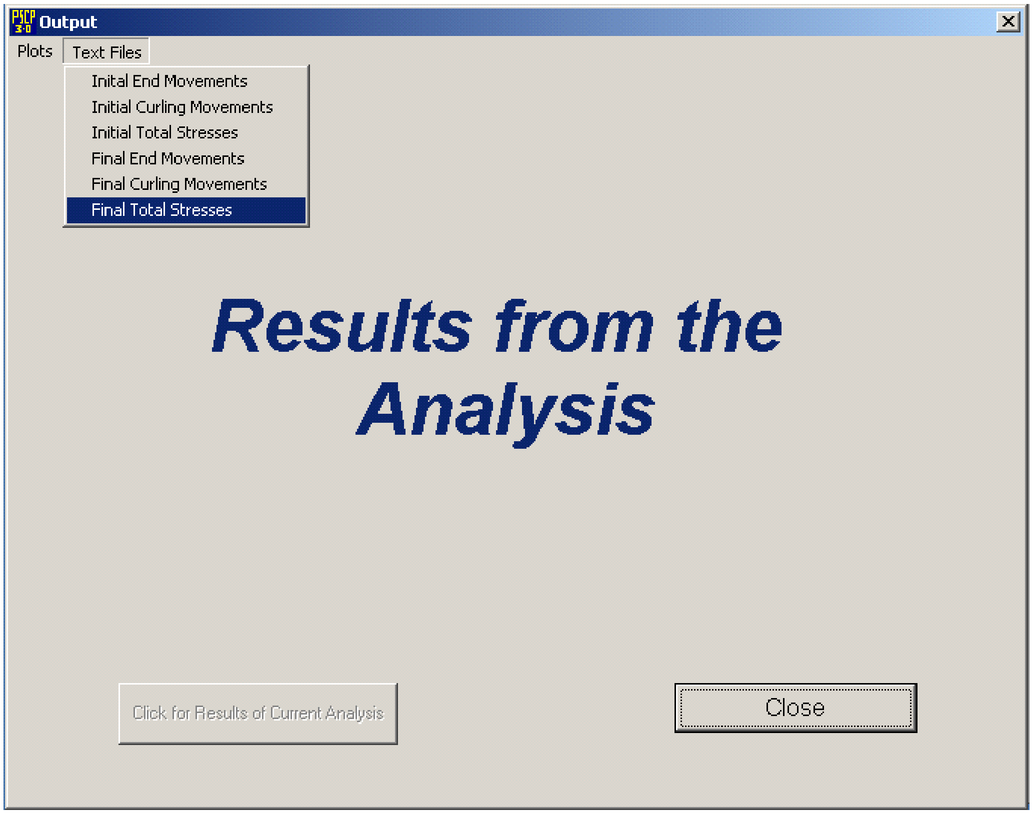


Figure 4.13 Screen showing output text files

4.2 Output Plots and Text Files

Figures 4.14 to 4.35 present the screens showing the results of the analysis that was performed. This output corresponds first to the initial period of analysis and then for the final period. For the example presented here, the temperature data entered for the initial and final periods are identical in order to compare the stresses that occur in the slab over time.

Figure 4.14 shows a plot of the slab end movements during the first twenty-four hours after placement. In this screen, it is possible to access a series of plots by clicking on the appropriate buttons, as shown in the figure.

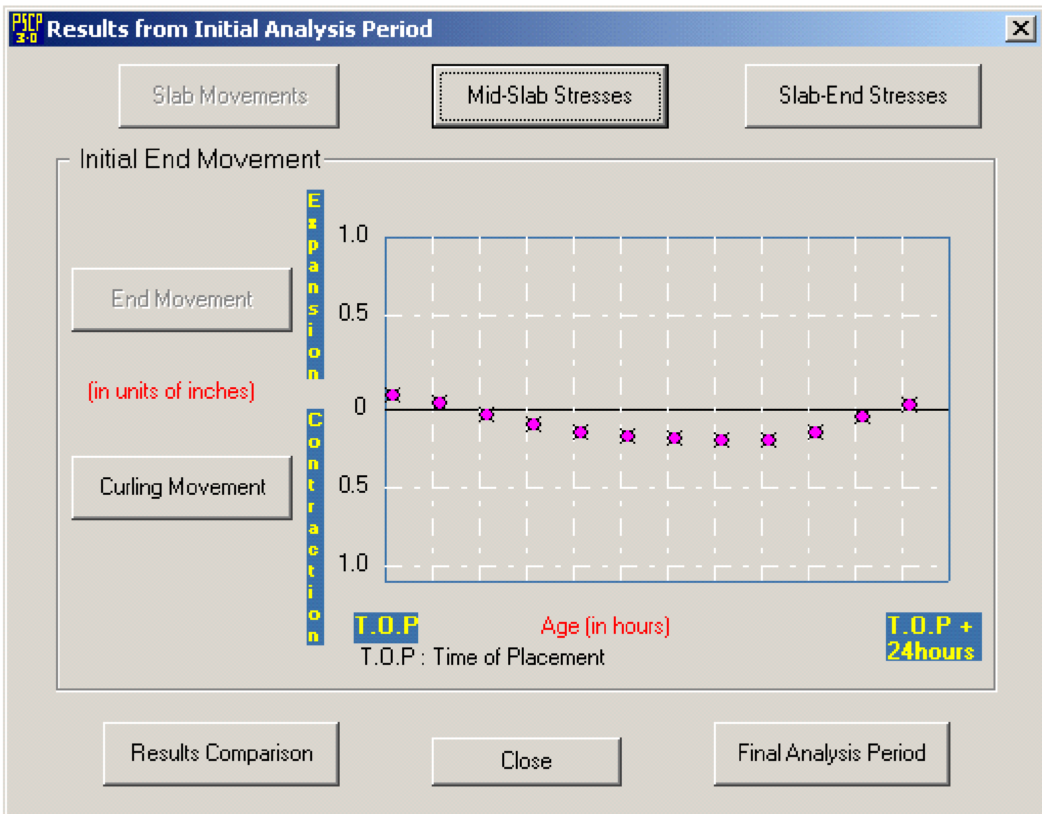


Figure 4.14 Plot of initial period end movements

Figure 4.15 displays the screen that will appear if the Curling Movement button is selected from the screen shown in Figure 4.14. Mid-slab and slab end stresses can also be viewed by clicking on the indicated buttons.

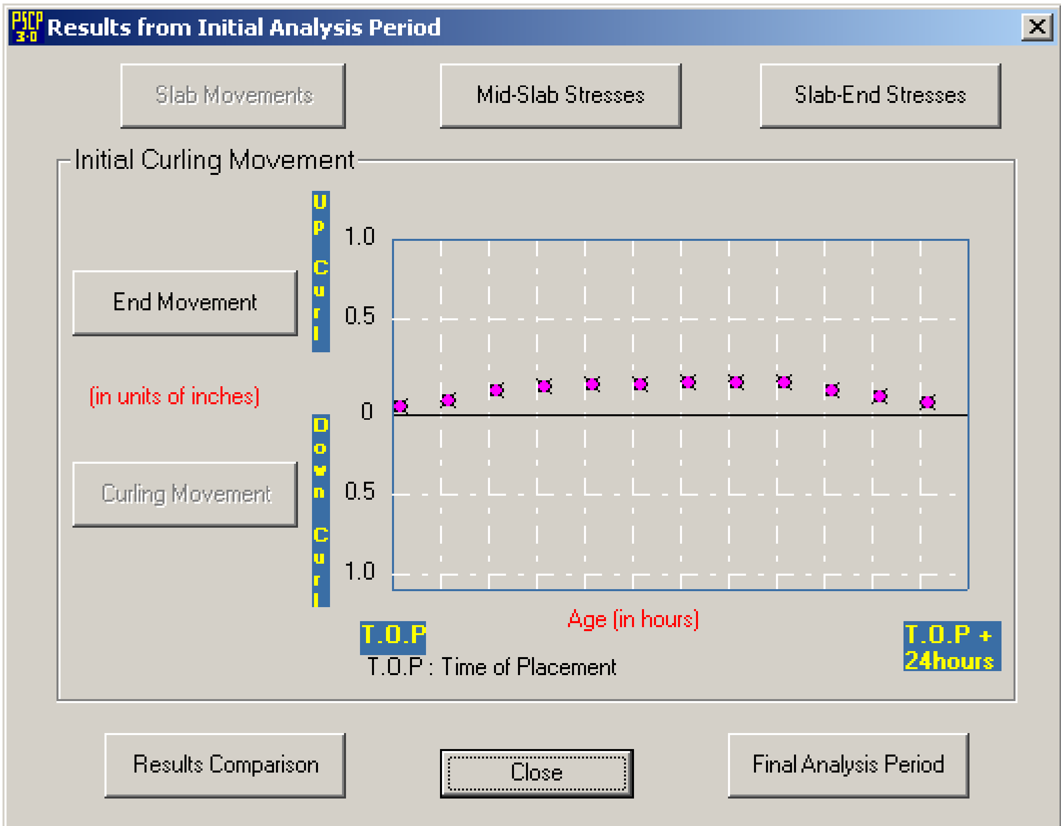


Figure 4.15 Screen showing curling movements for initial period

Figure 4.16 was obtained by selecting Plots, Initial Period, Total Stresses, Mid-Slab Top, from the main output screen. This screen can provide stresses and movements at different locations in the slab, as selected by the user. In this case, the plot displays the stresses calculated for the top fiber at the mid-slab. As can be seen, most of the time the top of the slab is in tension.

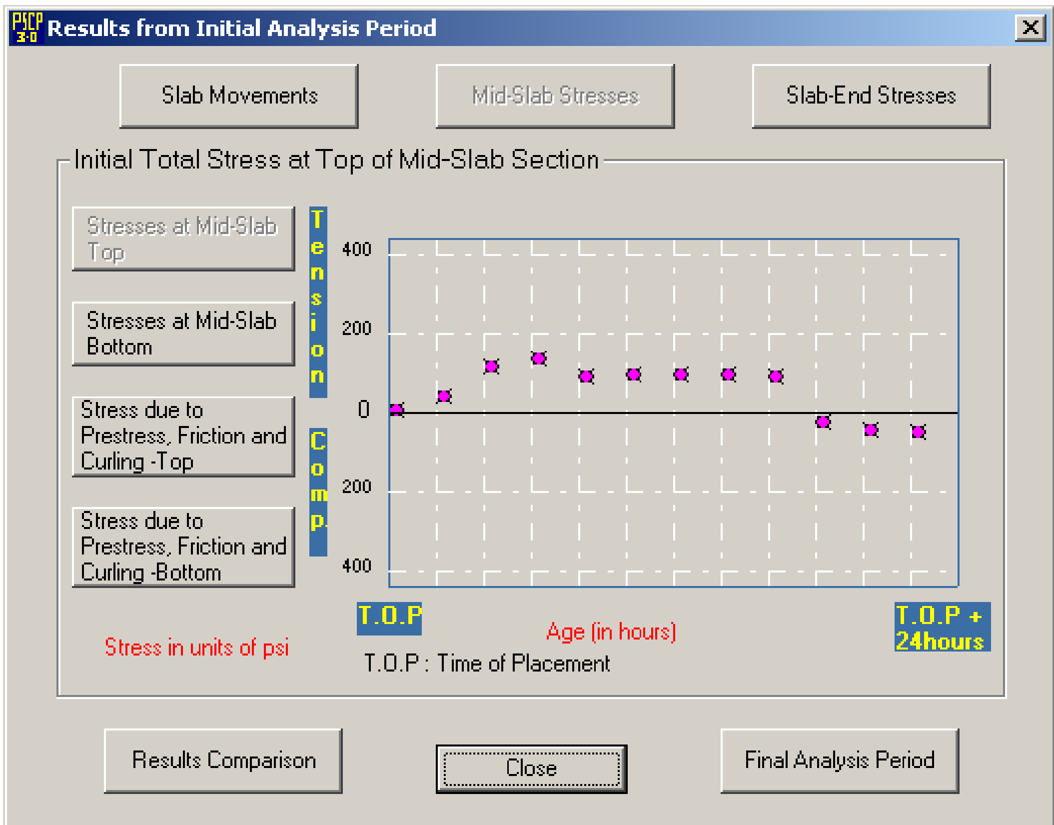


Figure 4.16 Total stresses at top fiber, mid-slab, initial period

Figure 4.17 shows the output screen that displays the total stresses estimated at the bottom fiber of the mid-slab section. As can be seen, the stresses at the bottom of the slab are predominantly compressive in nature.

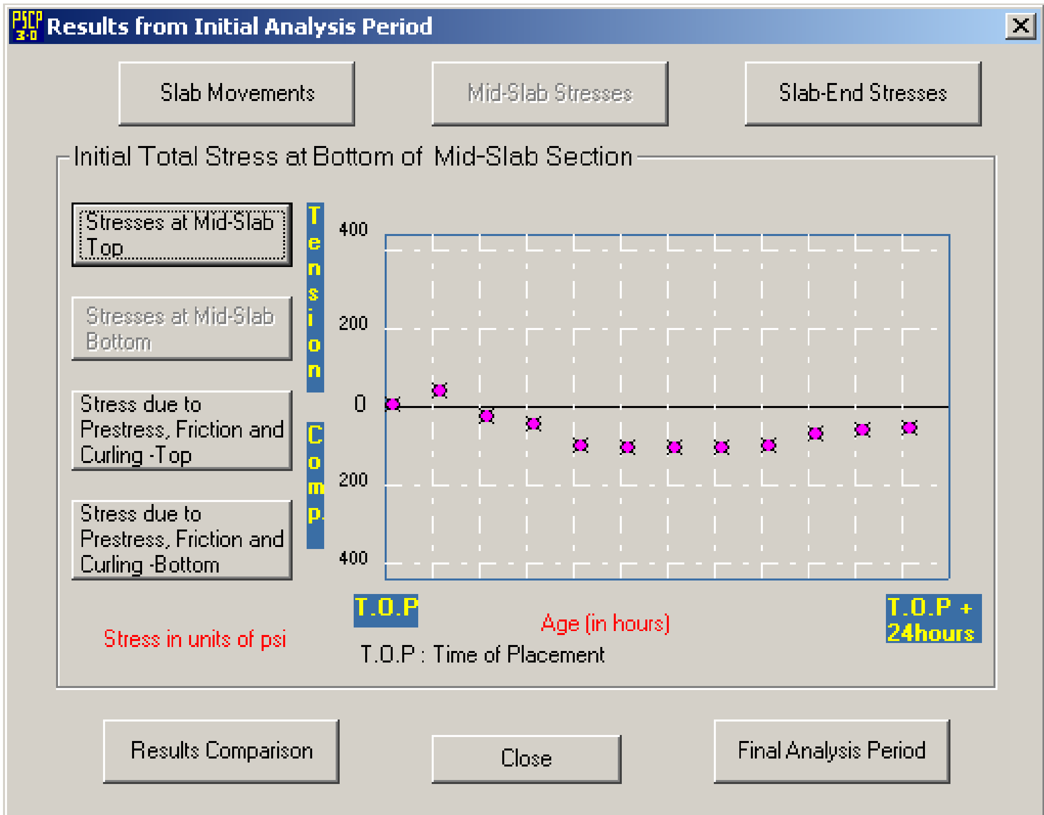


Figure 4.17 Total stresses at bottom fiber, mid-slab, initial period

Figure 4.18 shows the total stress components estimated by PSCP 3.0, including those from prestress, friction, and curling, at the top fiber of the slab. As can be seen, most of the stresses are tensile in nature.

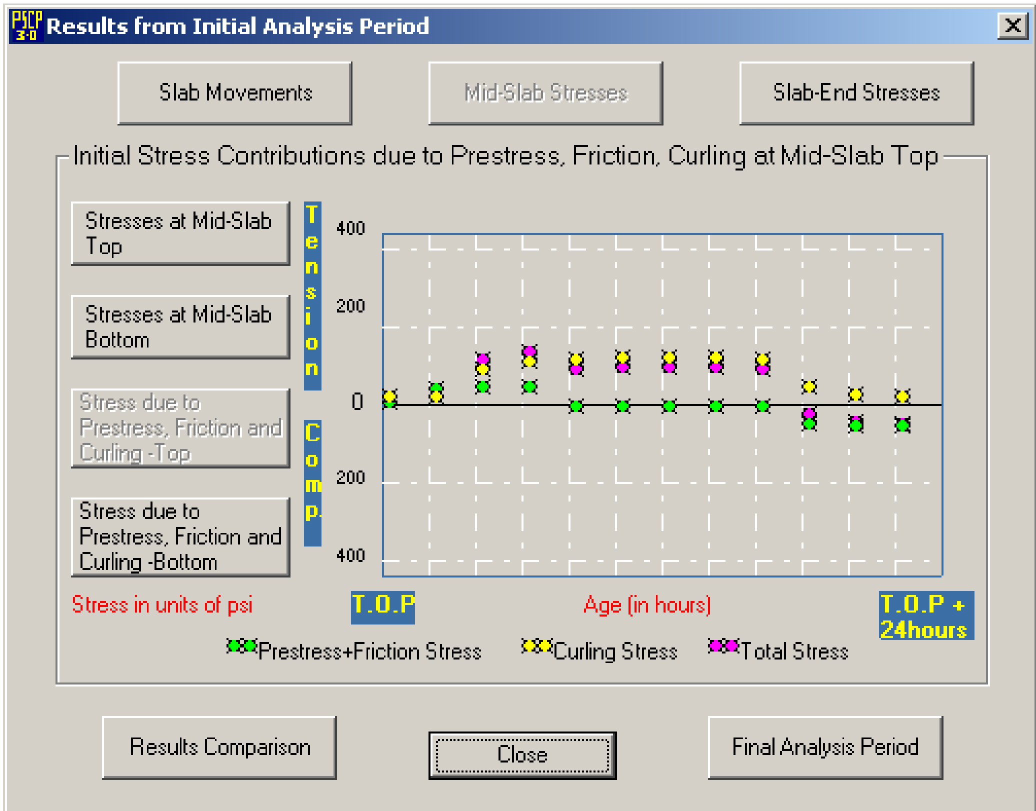


Figure 4.18 Total stress components at the top fiber, mid-slab, initial period

As in Figure 4.18, Figure 4.19 shows the components of the total stress calculated by the program, and including prestress, friction, and curling, for the bottom fiber of the slab.

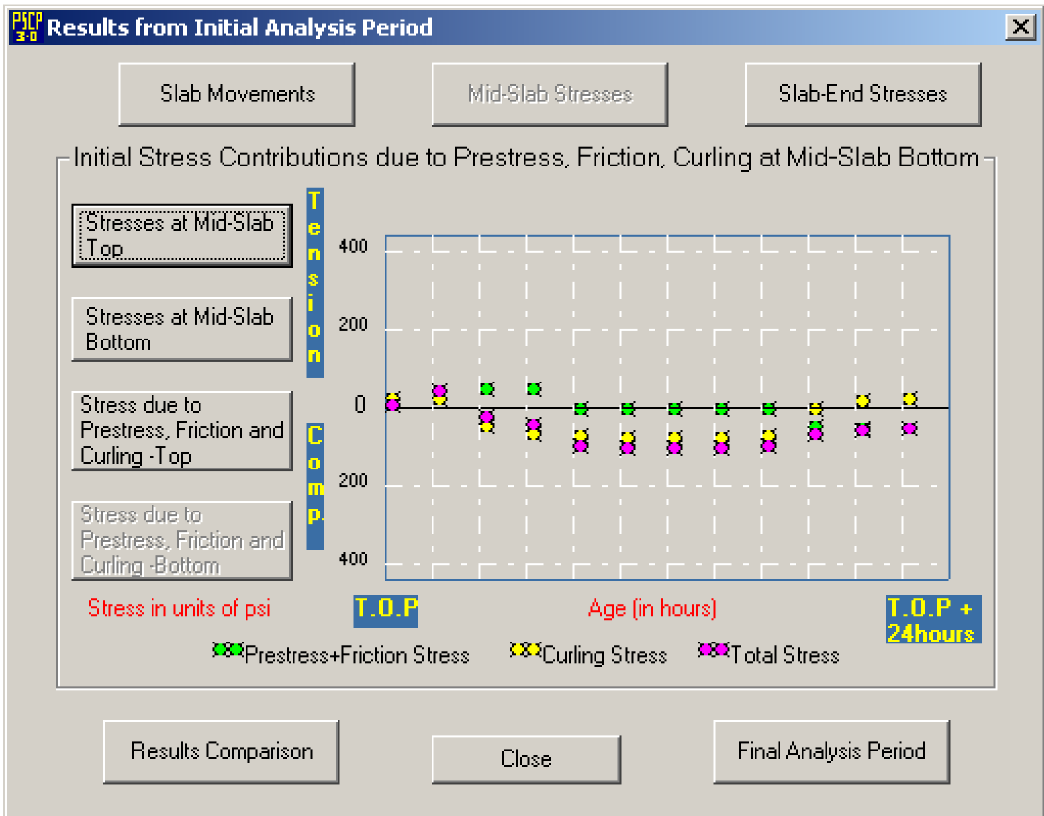


Figure 4.19 Total stress components at the bottom fiber, mid-slab, initial period

Figure 4.20 shows the total stress at the top fiber at the end of the slab for the initial analysis period. As can be seen, the top of the slab is subject to tensile stresses most of the time.

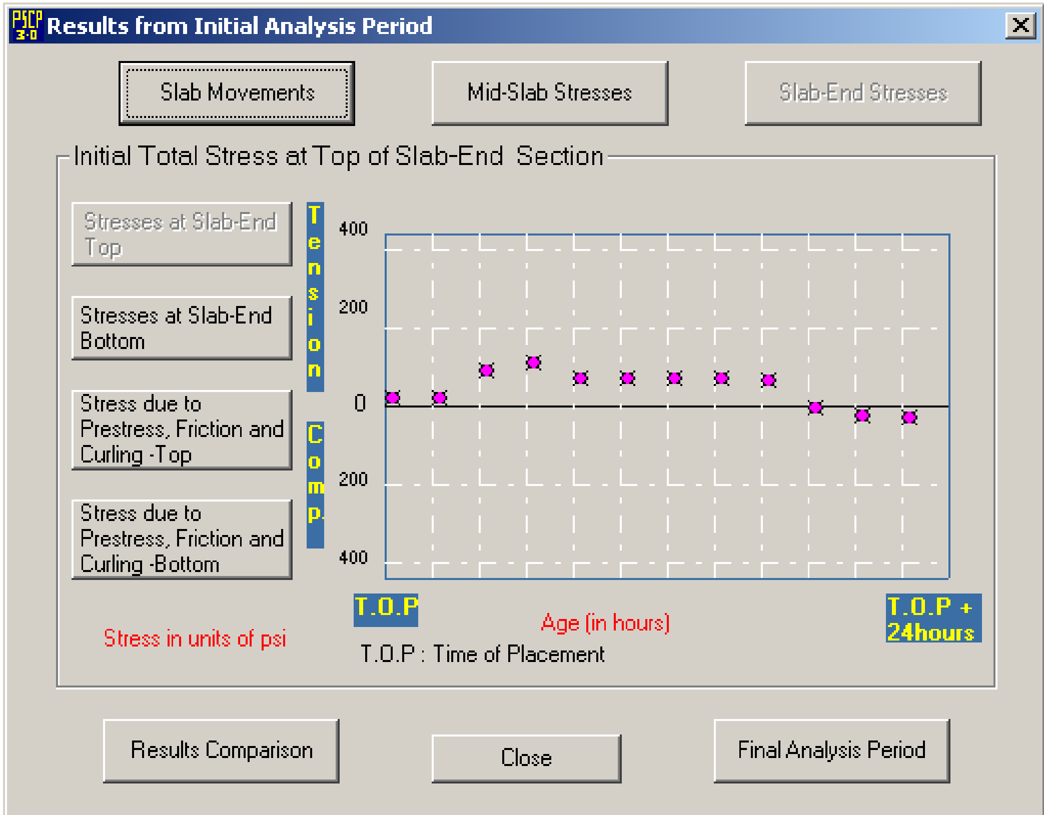


Figure 4.20 Total stress at top fiber, slab-end, initial period

In a similar way, Figure 4.21 shows the estimated total stress at the bottom fiber at the end of the slab for the same analysis period. Opposite to the top of the slab, the bottom fiber experiences compressive stresses most of the time.

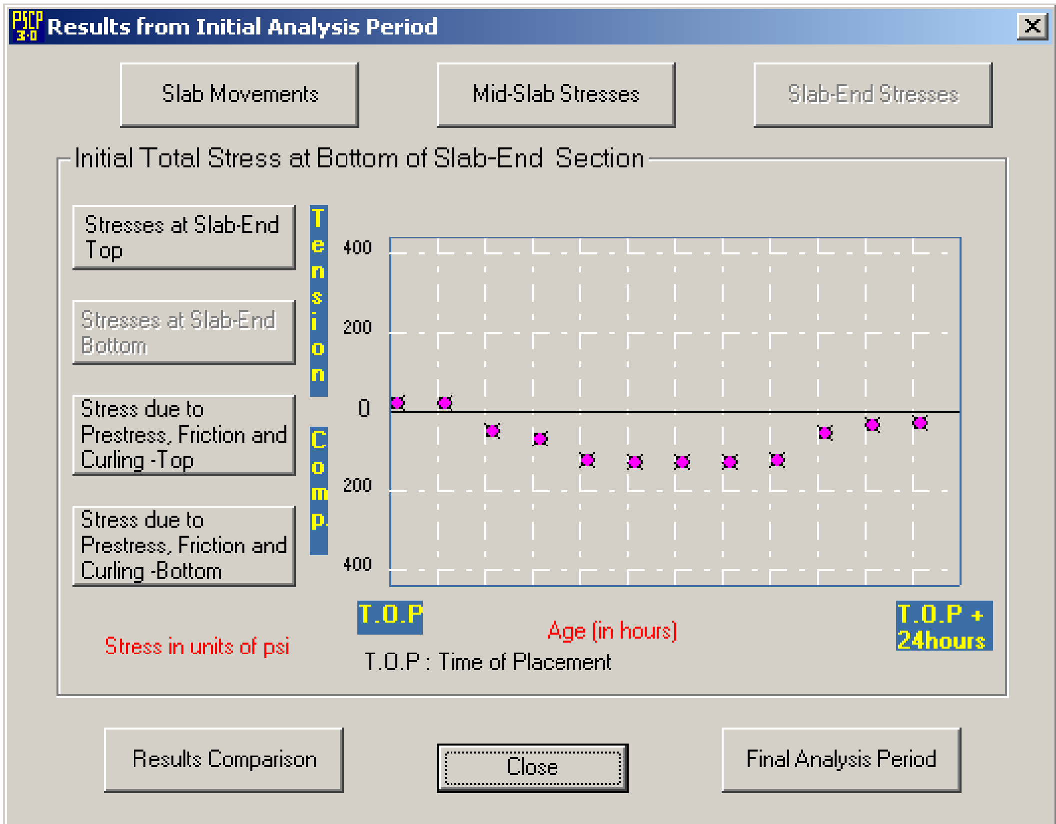


Figure 4.21 Total stress at bottom fiber, slab-end, initial period

Similarly to the stresses in the mid-slab section, slab-end stresses result from a combination of prestress, frictional, and curling stresses. The total stress components at the top of the slab-end section are shown in Figure 4.22.

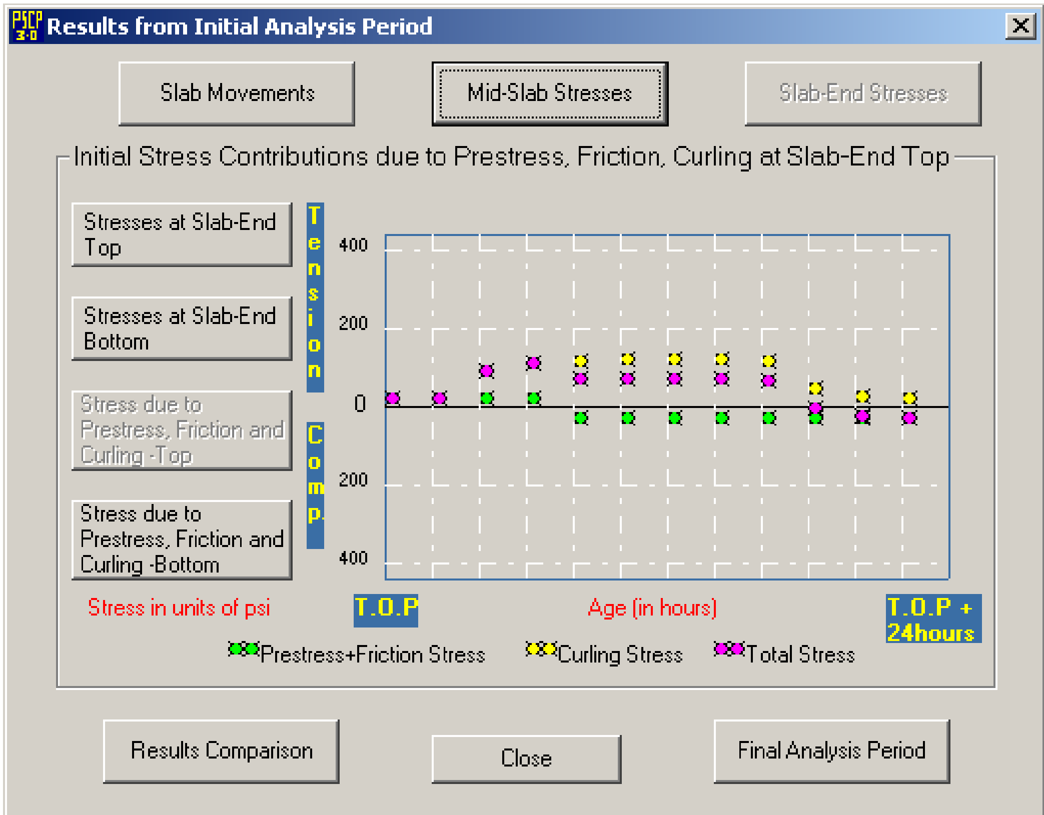


Figure 4.22 Total stress components at the top fiber, slab-end, initial period

Figure 4.23 shows the plot containing the total stress components at the bottom of the slab-end section. This is the last screen of the output of the initial analysis period. The results for the final period of analysis can be viewed by clicking on the button called Final Analysis Period.

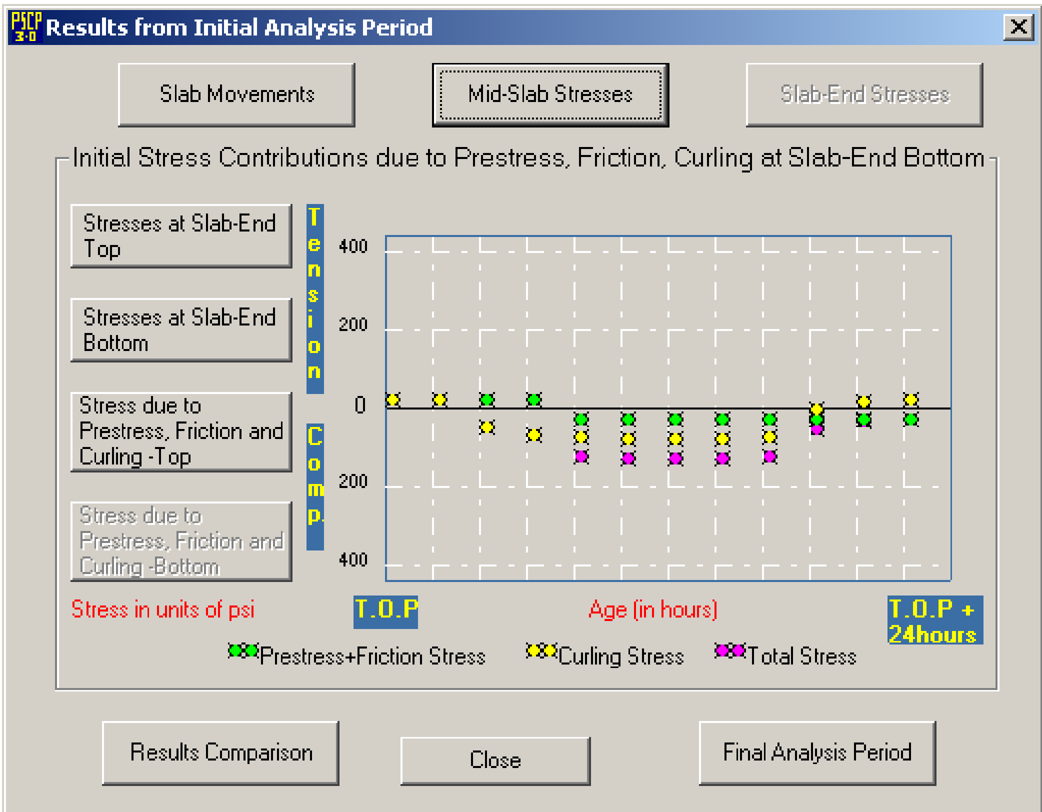


Figure 4.23 Total stress components at the bottom fiber, slab-end, initial period

Figures 4.24 to 4.26 show some plots of end movements, curling movements, and total stresses in the slab during the final period of analysis. To access the outputs for the analysis of the final period, the button called Final Analysis Period has to be clicked.

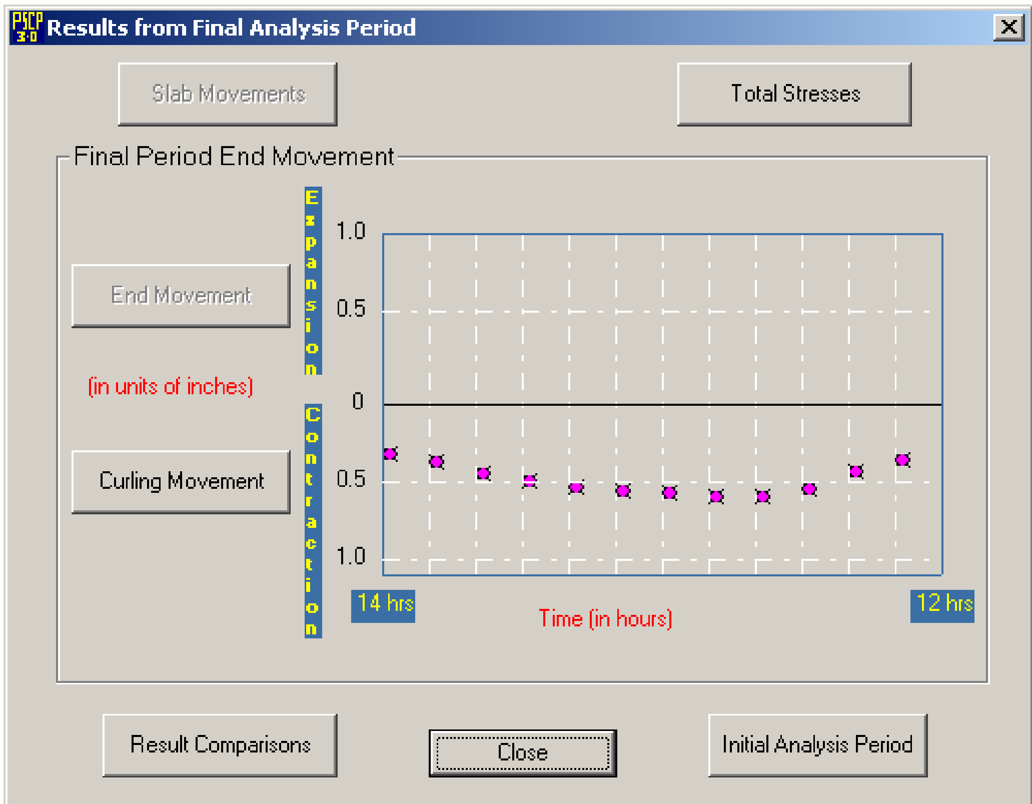


Figure 4.24 Slab-end movement for final analysis period

Figure 4.24 displays the slab-end movement calculated by PSCP 3.0. As can be seen, the PCP slab is always in contraction for the period of time analyzed. The curling movement at the slab end during the final period of analysis is shown in Figure 4.25. For the analysis performed herein, all slab movements are within one inch upward.

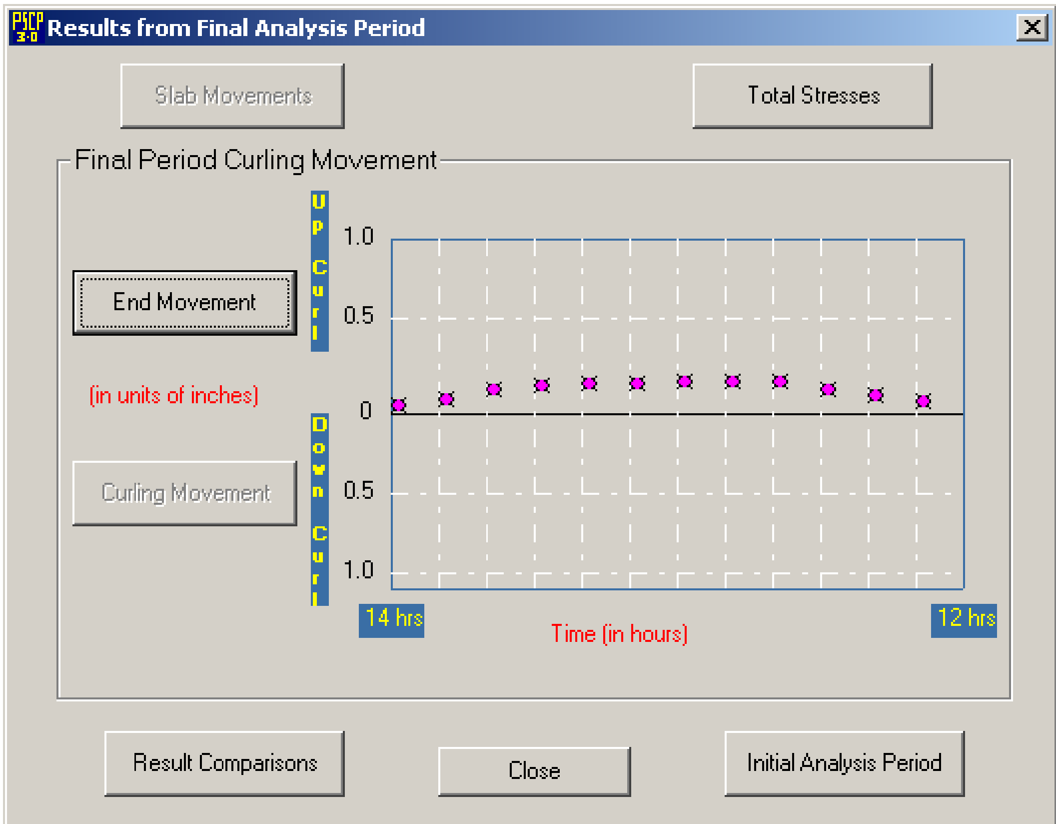


Figure 4.25 Curling movement for final analysis period

The output screen shown in Figure 4.26 displays the variation of stresses over time in the PCP slab. PSCP 3.0 allows comparisons among the stresses that occur at different sections of the slab, as shown in the figure.

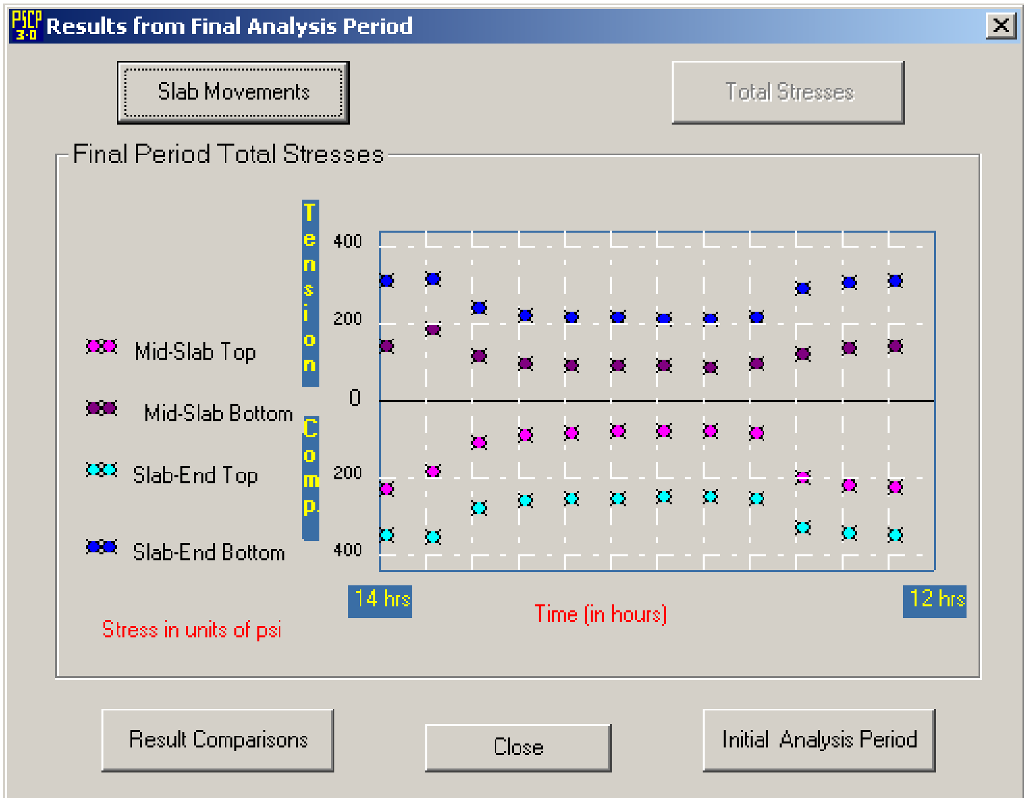


Figure 4.26 Total stresses for final analysis period

The program has the capability to compare the results at the mid-slab or slab end and at the top or bottom of the slab. Likewise, it can compare initial with final analysis period. Figures 4.27 to 4.29 show some of the comparisons that might be performed. For instance, Figure 4.27 shows a comparison of initial with final slab-end movements. The plot demonstrates that the end movement of the slab increases over time. The final end movements are considerably higher than the initial movements, when the slab was newly constructed.

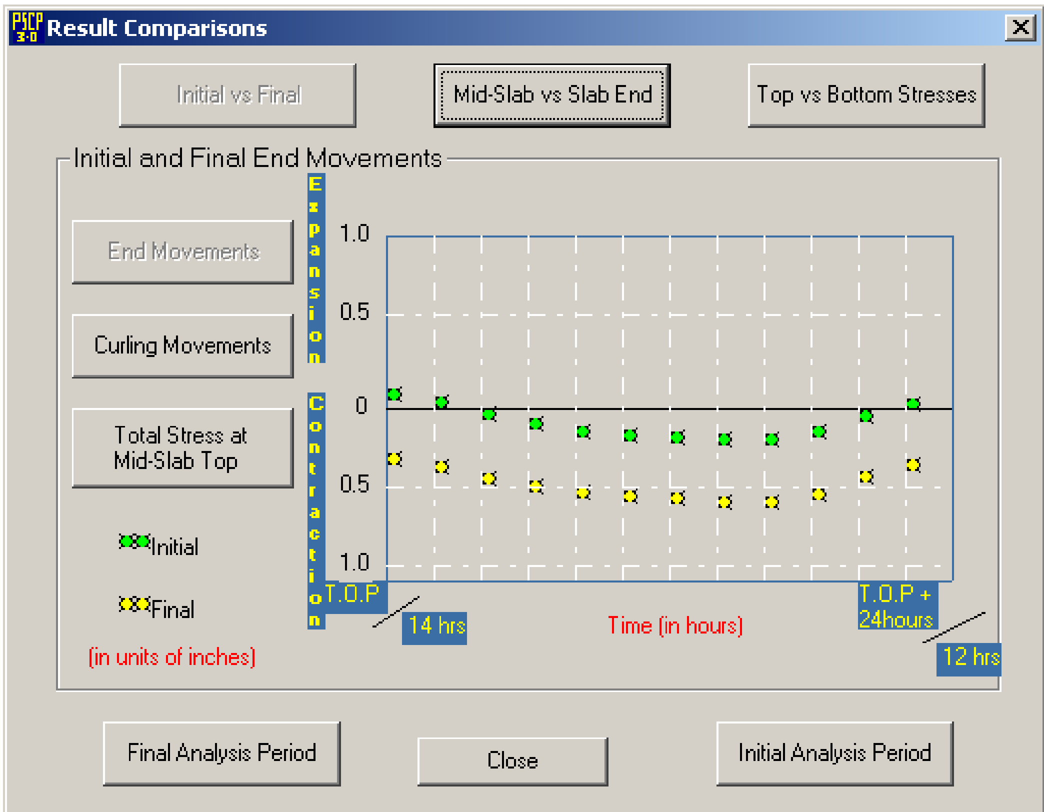


Figure 4.27 Comparison of initial and final end movements

Figure 4.28 compares the stresses at the top of the slab with those at the bottom. In the final analysis period the top of the slab starts to cool down, and hence, it is in compression. Conversely, the bottom fiber experiences tensile stresses.

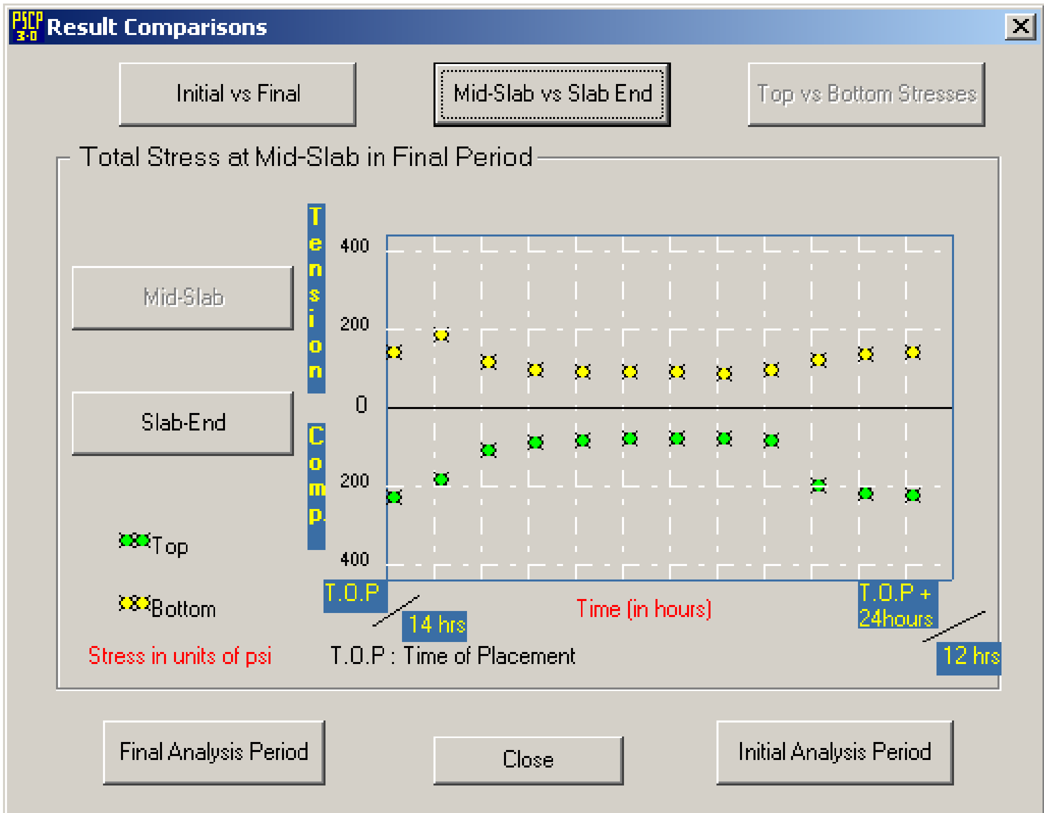


Figure 4.28 Comparison of final analysis period, mid-slab stresses at top and bottom

Figure 4.29 shows a comparison of the total stresses calculated at mid-slab to those estimated at the slab end. These stresses shown correspond to the bottom fiber of the PCP slab.

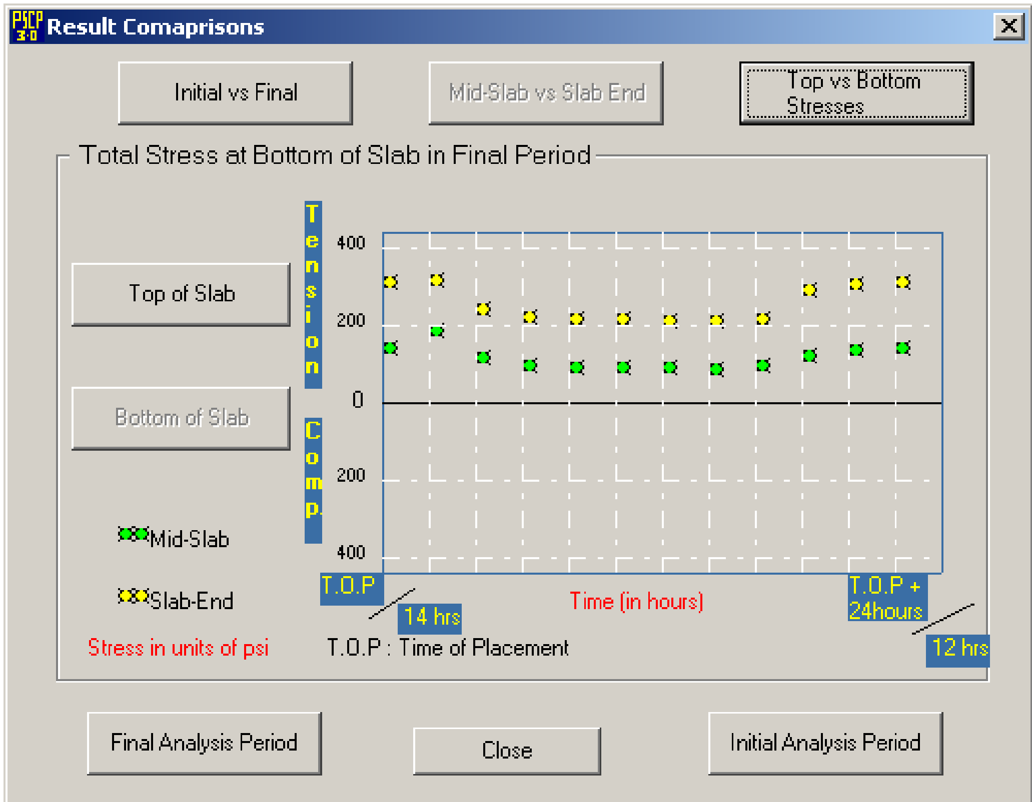
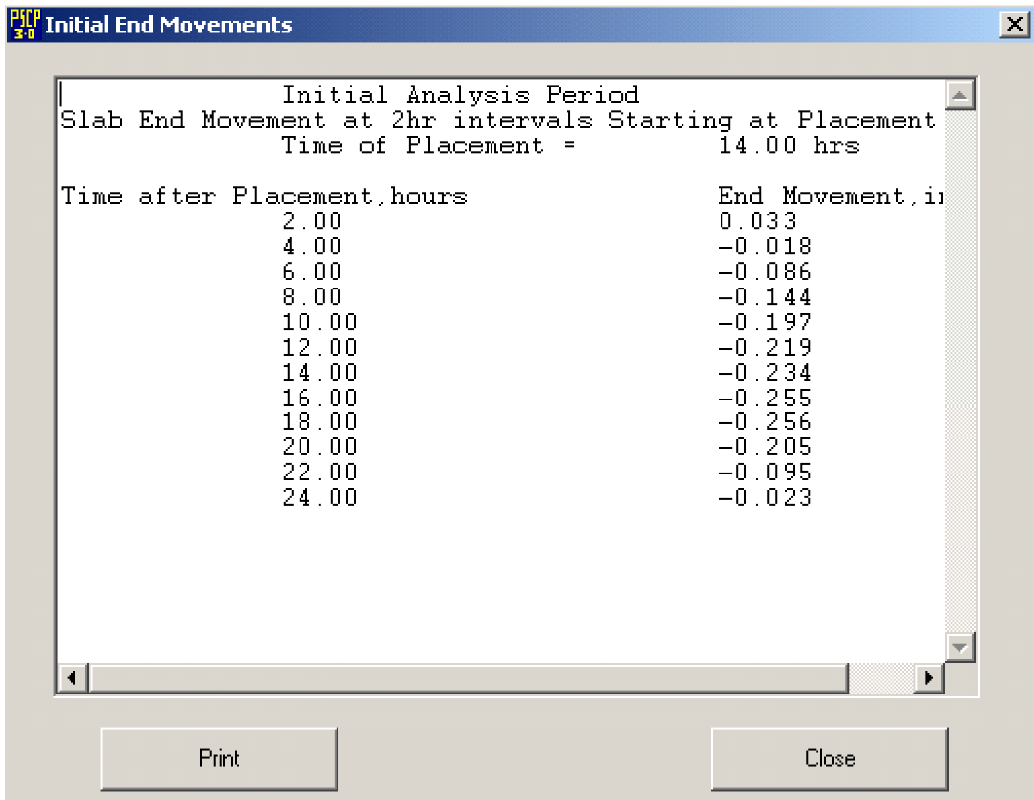


Figure 4.29 Final period mid-slab vs. slab-end stresses at the bottom fiber

Figures 4.30 to 4.35 display the output screens available in text format. The data included in these files correspond to the data plotted in Figures 4.14 to 4.29, previously described. PSCP 3.0 generates six text files that contain the calculated results in tabular forms. In addition to these six text files, the wheel load stresses can be retrieved in PSCP 3.0. To access this file, the user should click on Analysis, Review Wheel Load Stresses, in the main menu screen, after an analysis has been performed. Figure 4.30 displays the results of the slab-end movements for the initial analysis period.


Initial End Movements

Initial Analysis Period
Slab End Movement at 2hr intervals Starting at Placement
Time of Placement = 14.00 hrs

Time after Placement, hours	End Movement, i
2.00	0.033
4.00	-0.018
6.00	-0.086
8.00	-0.144
10.00	-0.197
12.00	-0.219
14.00	-0.234
16.00	-0.255
18.00	-0.256
20.00	-0.205
22.00	-0.095
24.00	-0.023

Print Close

Figure 4.30 Initial slab-end movements text file

Figure 4.31 shows the output text file that displays the curling movements during the initial analysis period. These results, which are in text format as seen in the figure, can be printed and saved to a different file.

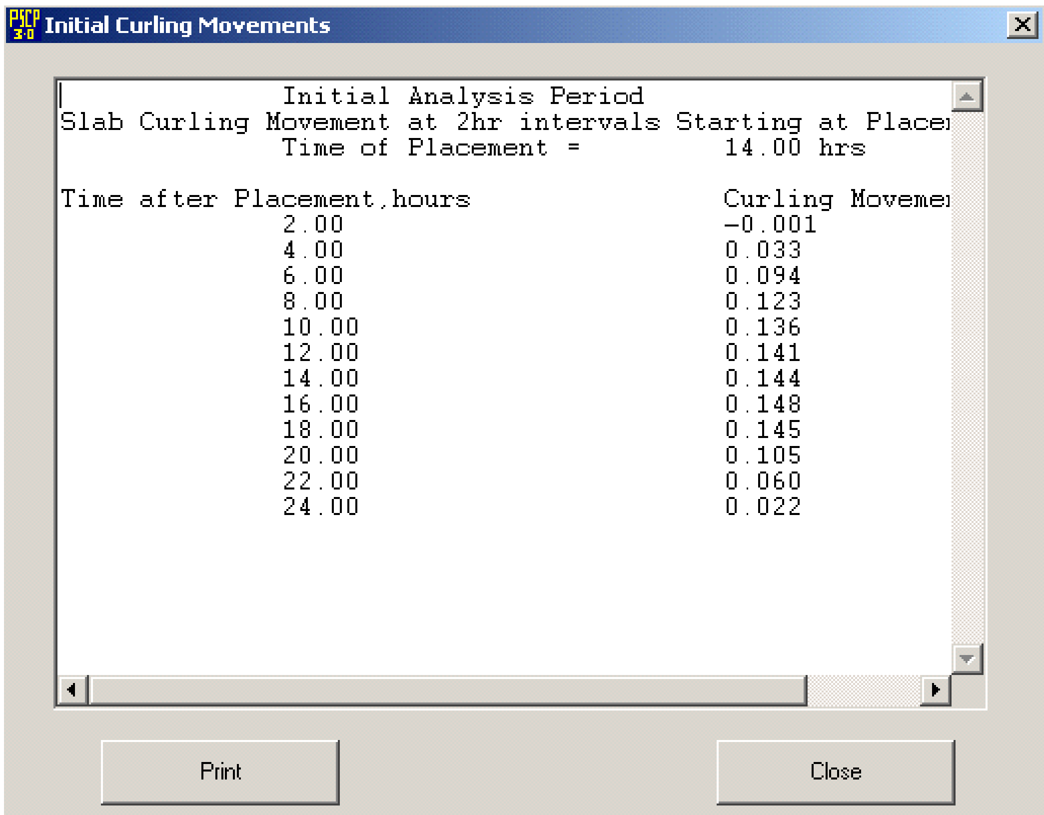


Figure 4.31 Initial curling movements text file

Figure 4.32 displays the output text file showing a summary of the top and bottom total stresses at the mid-slab and slab-end sections during the initial analysis period. The negative stresses are compressive and positive stresses are tensile.

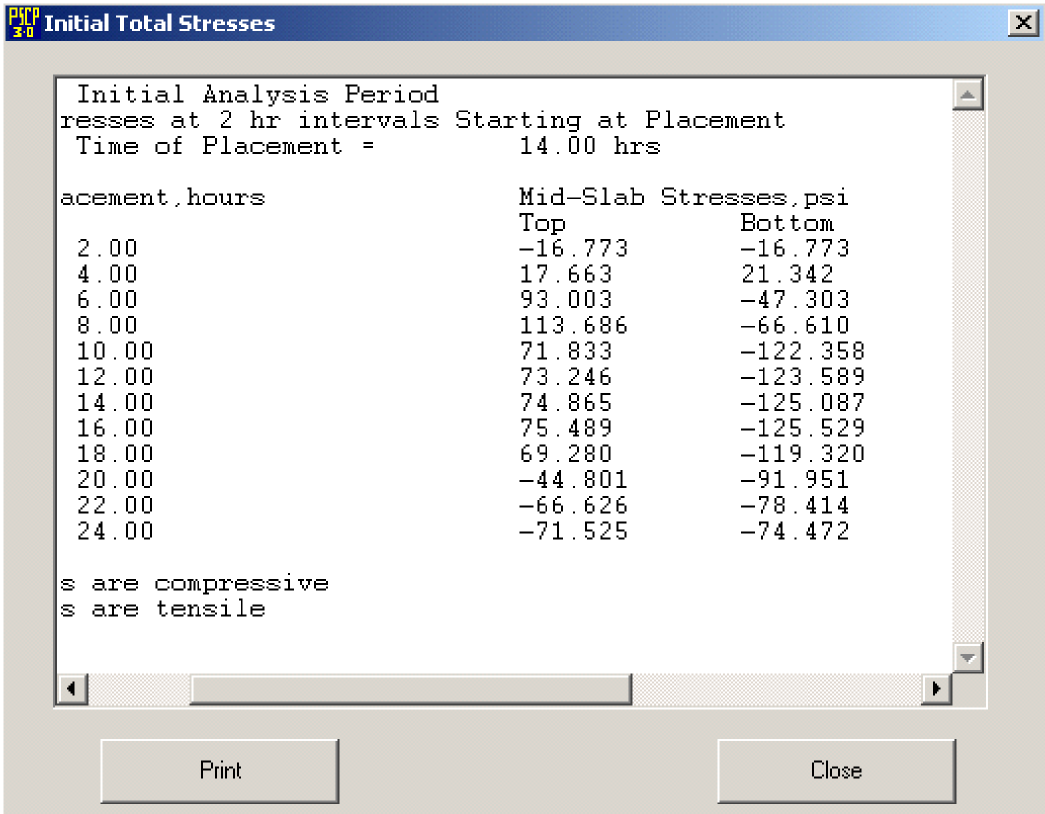


Figure 4.32 Total stresses text file for initial analysis period

Figure 4.33 is analogous to Figure 4.30, because it shows the end movements in the slab, but this time it is for the final analysis period. To access a different output file, this window should be closed and the appropriate menu should be clicked.

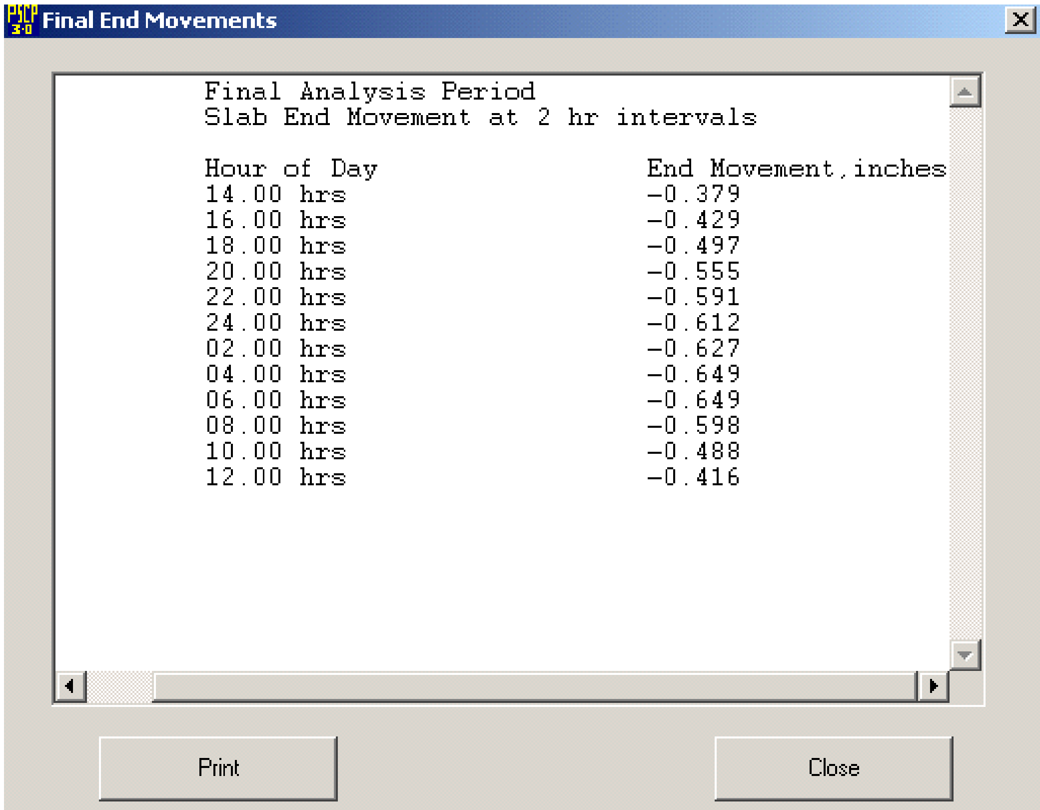


Figure 4.33 End movements text file for final analysis period

Vertical curling movements in the slab for the final analysis period are displayed in the output screen shown in Figure 4.34. According to the input data for the final analysis period, results are calculated at two-hour intervals for a twenty-four-hour period.

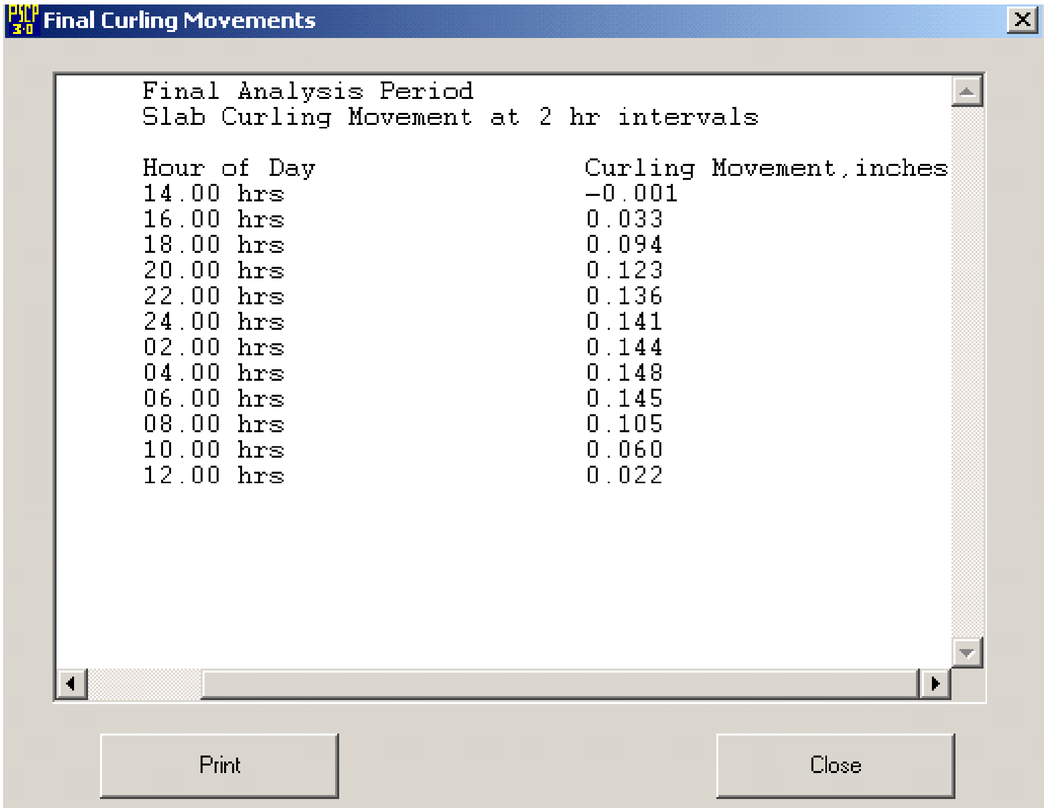
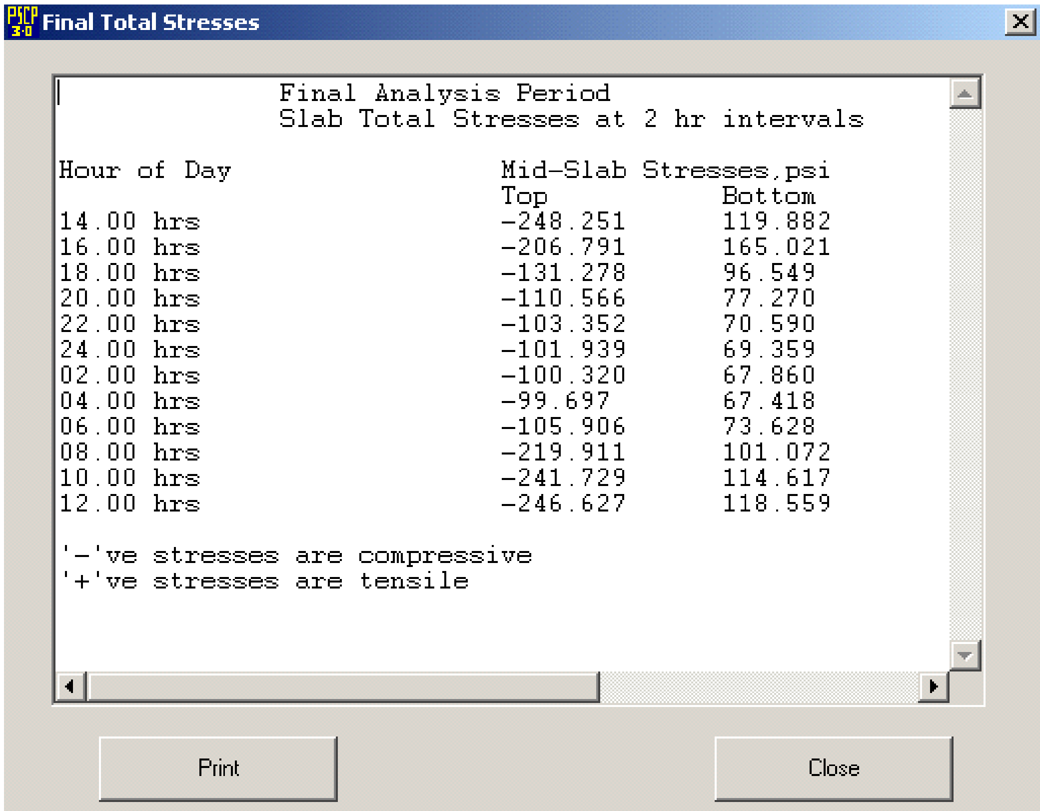


Figure 4.34 Curling movements text file for final analysis period

Finally, Figure 4.35 is the output screen showing the text file for the total stresses for the final analysis period. This is the last output screen available from PSCP 3.0. All the output text files can be printed from the startup screen, after the analysis is completed.



Final Analysis Period
Slab Total Stresses at 2 hr intervals

Hour of Day	Mid-Slab Stresses,psi Top	Bottom
14.00 hrs	-248.251	119.882
16.00 hrs	-206.791	165.021
18.00 hrs	-131.278	96.549
20.00 hrs	-110.566	77.270
22.00 hrs	-103.352	70.590
24.00 hrs	-101.939	69.359
02.00 hrs	-100.320	67.860
04.00 hrs	-99.697	67.418
06.00 hrs	-105.906	73.628
08.00 hrs	-219.911	101.072
10.00 hrs	-241.729	114.617
12.00 hrs	-246.627	118.559

'-'ve stresses are compressive
'+'ve stresses are tensile

Figure 4.35 Total stresses text file for final analysis period

5. Results and Recommendations

This report is the second of a series of reports that will be prepared for TxDOT research project 0-4035. Report 4035-1 [5] contains information about comprehensive material that relates to the design of PCP, construction procedure, materials, and monitoring tasks. This report is intended to complement Report 4035-1 and documents the activities performed to update the auxiliary PCP design program, PSCP 3.0. This final chapter contains the results of the tasks undertaken and the accomplishments of the work. A summary of the report is presented and some recommendations for further improvements are discussed.

5.1 Summary

The two main objectives of this study, as previously stated, were (1) to incorporate stresses from wheel loads in the analysis of PCPs and (2) to add a user-friendly interface to the computer program Prestressed Concrete Pavement, PSCP 3.0. These objectives have been achieved through this study and are documented in this report. The PSCP 3.0 program has been successfully upgraded and can be used to determine the state of stress and displacements in a PCP slab caused by the different loads imposed on it.

In summary, this study focused on the following activities:

- Reviewing previous work on PCPs
- Understanding the models used for their analysis
- Incorporating the effect of wheel load stress in the analysis
- Adding a user-friendly interface to the program
- Organizing the output for easy retrieval and storage, using plot and text files

The following step in the process will be to model PCP slabs using additional theories and assumptions and checking these models against experimental data. It is recommended to collect more information from new and existing PCPs to validate the PSCP 3.0 program.

5.2 Achieved Improvements with PSCP 3.0

The following are some advantages of the new program over the previous version.

1. It is difficult to use program PSCP-2 without a user's manual. The input file that contains all the data required by the program must be typed strictly in the format specified in the Fortran source code. This makes running various cases tedious, because different input files have to be attached for each analysis. In other words, PSCP-2 is not user friendly. This inconvenience has been solved with the new program.
2. PSCP 3.0 is easy to use by anyone who has a basic knowledge of PCPs and understands material properties, temperature effects, and other conventional pavement design variables.
3. In addition to the output files generated by PSCP-2, PSCP 3.0 provides plots of the stresses and displacements along the slab at different time periods, input by the user. The graphic presentation of the state-of-stress and movement of the slab provides a better understanding of the behavior of the slab under different loading conditions.
4. PSCP 3.0 includes wheel load stress analysis along with other sources that cause stress on the pavement slab.

5.3 Recommendations for Further Improvement

PSCP 3.0 includes more features than the previous software version. Some areas where the current program might be improved and where further research is possible are as follows.

1. Analysis of the behavior of the pavement under moving dynamic multiple wheel loads.
2. A model to predict the stresses that occur in the interior of the PCP slab because of wheel loads.

3. Analysis that accounts for the movement and stresses from moisture warping caused by differential moisture contents at the top and bottom fibers of the slab.
4. Consideration of the non-linear variation of temperature across the depth of the slab in the curling analysis.

5.4 Conclusions

As a result of this study, a user-friendly tool is provided to analyze and help design safe and efficient PCPs. The new and improved computer program, PSCP 3.0, helps pavement engineers in the following aspects:

- Understanding the behavior of PCPs under different loading and climatic conditions
- Analyzing PCPs efficiently for specific geometry, materials, and loading conditions
- Checking the viability of a proposed project
- Predicting slab behavior during its early age as well as over a long period of time during its design life.

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