CHAPTER 9
PRINCIPLES OF DESIGN FOR PAVEMENT REHABILITATION WITH RIGID OVERLAYS

9.1 M-E Introduction

Overlays are used to remedy structural or functional deficiencies of existing flexible or rigid pavements and extend their useful service life. It is important the designer consider the type of deterioration present when determining whether the pavement has a structural or functional deficiency, so an appropriate overlay type and design can be developed. **Figure 9.1 Rehabilitation Alternative Selection Process** shows the flowchart for the rehabilitation alternative selection process. **Note**: Not all of the steps presented in this figure are performed directly by M-E Design, however designers must consider all of the steps to produce a feasible rehabilitation with rigid overlay design alternatives.

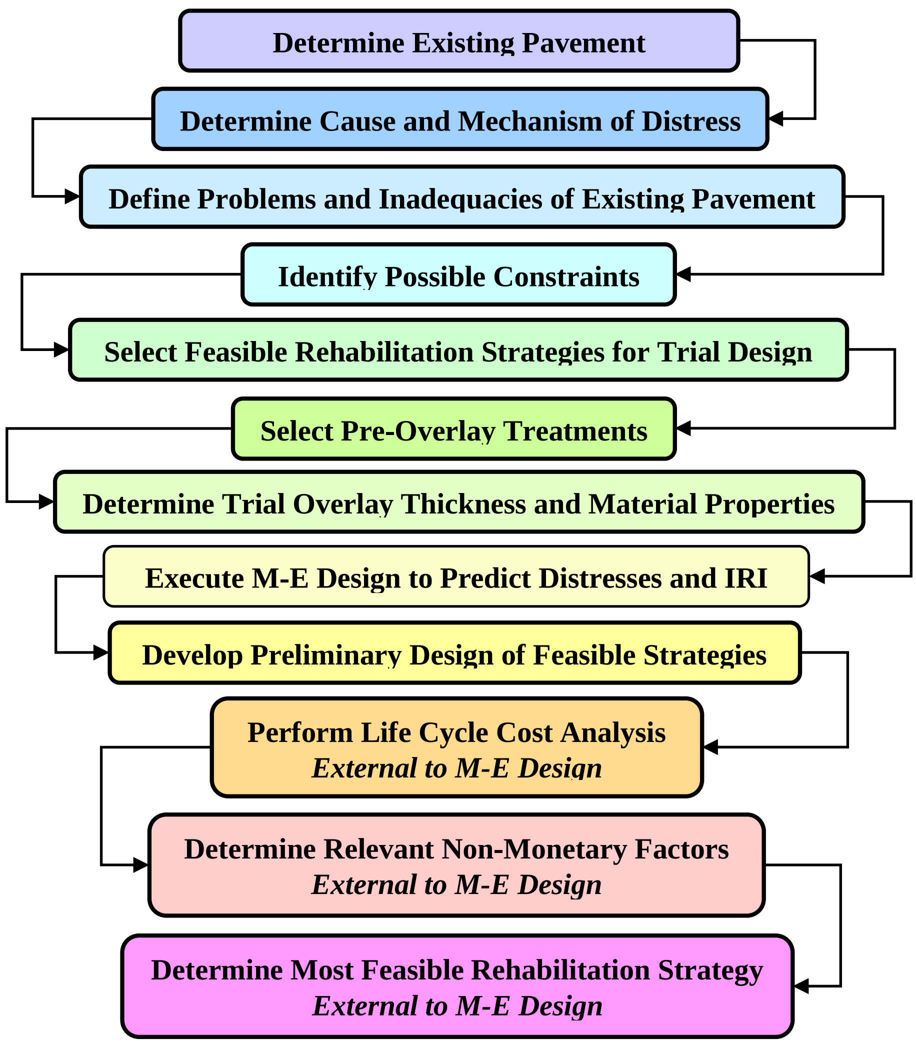

Figure 9.1 Rehabilitation Alternative Selection Process

This chapter describes the information needed to create cost effective rehabilitation strategies with PCC overlays using M-E Design and CDOT Thin Concrete Overlay design. Policy decision making that advocates applying the same standard fixes to every pavement does not always produce a successful pavement rehabilitation. Successful rehabilitation depends on decisions that are based on the specific condition and design of the individual pavement. The rehabilitation design process begins with the collection and detailed evaluation of project information. Once the data is gathered, an evaluation is in order to determine the cause of the pavement distress. Finally, a choice needs to be made to select an engineered rehabilitation technique(s) that will correct the distresses.

9.1.1 CDOT Required Procedure for Rigid Overlays

Concrete overlays are quickly becoming a popular method used nationwide to rehabilitate deteriorated asphalt pavements. Since the flexible asphalt surface is replaced by rigid concrete, the technique offers superior service, long life, low maintenance, low life-cycle cost, improved safety, and environmental benefits. The critical stress and strain prediction equations developed in an initial research report are part of a first generation design procedure and were issued in December 1998 in a document titled *Guidelines for the Thickness Design of Bonded Whitetopping Pavement in the State of Colorado*, CDOT-DTD-R-98-10. An initial MS Excel worksheet was developed along with the report. The equations were verified and/or modified with the collection of additional data and was reported under the August 2004, *Instrumentation and Field Testing of Thin Whitetopping Pavement in Colorado and Revision of the Existing Colorado Thin Whitetopping Procedure*, CDOT-DTD-R-2004-12. A revised MS Excel worksheet accompanies the report.

A concrete overlay is the construction of a new PCCP over an existing HMA pavement. It is considered an advantageous rehabilitation alternative for badly deteriorated HMA pavements, especially those that exhibit such distress as rutting, shoving, and alligator cracking (ACPA 1998). The primary concerns with concrete overlays are as follows:

- The thickness design procedure
- Joint spacing
- The use and spacing of dowels and tie bars

In general, CDOT **does not recommend a thin concrete overlay thickness of less than 5 inches. Conventional concrete overlays use a thickness of 8 inches or greater. Ultra-thin concrete overlay, which uses 4 inches or less of PCCP, should not be used on Colorado's state highways** (see **Table 9.1 Required Concrete Overlay Procedure).**

Table 9.1 Required Concrete Overlay Procedure

Required Thickness	
< 5 inches	Do not use
≥ 5 to < 8 inches	CDOT Thin concrete overlay procedure
≥ 8 inches	AASHTO Overlay design (M-E Design)

9.2 Determining Existing Pavement Condition

9.2.1 Records Review

Obtaining specific project information is the first step in the rehabilitation process. Five basic types of detailed project information are necessary: design, construction, traffic, environmental, and pavement condition. A detailed records review should be conducted before a project evaluation can be made. Refer to **Section 2.3 Project/Files Records Collection and Review** for information concerning a detailed records review.

9.2.2 Field Evaluation

A detailed field evaluation of the existing pavement condition and distresses is necessary for a rehabilitation design. It is important an existing pavement condition evaluation be conducted to identify functional and structural deficiencies so designers may select appropriate combinations of preoverlay repair treatments, reflection crack treatments, and PCC overlay designs to correct the deficiencies present. Designers must, as a minimum, consider the following as part of the pavement evaluation:

- Existing pavement design
- Condition of pavement materials, especially durability problems and subgrade soil
- Distress types present, severities, and quantities
- Future traffic loadings
- Climate
- Existing subdrainage facilities condition

9.2.3 Visual Distress

The types of distress have to be identified and documented prior to the selection of corrective measures. The cause of a distress is not always easily identified and may consist of a combination of problems. **Figure 9.2 Pavement Condition Evaluation Checklist (Rigid)** provides guidance for existing pavement evaluation for rigid pavements. A similar checklist is available in **Figure 8.2 Pavement Condition Evaluation Checklist (Flexible)** for flexible pavement. Refer to **Section A.4 Site Investigation** for information on how to conduct the distress survey.

CDOT has a distress manual documenting pavement distress, description, severity levels, and additional notes. The distress manual is presented in Appendix B - Colorado DOT Distress Manual for HMA and PCC Pavements in the publication *Development of a Pavement Maintenance Program for the Colorado Department of Transportation*, Final Report, CDOT-DTD-R-2004-17, August 2004. The report is in pdf format and may be downloaded from the web page http://www.coloradodot.info/programs/research/pdfs/2004/preventivemaintenance.pdf. A field inspection is mandatory in order to determine the pavement distress and condition. Isolating areas of distress can pinpoint different solutions for various sections along a project.

The condition of drainage structures and systems such as ditches, longitudinal edge drains, transverse drains, joint and crack sealant, culverts, storm drains, inlets, and curb and gutters are all important for diverting water away from the pavement structure. Visual observation will reveal the types and extents of distresses present in the pavement that are either caused by or accelerated by moisture. Drainage assessment can also be benefited by data obtained from coring and material testing. The permeability and effective porosity of base/subbase materials, as determined through laboratory tests or calculated from gradations, can be used to quantify drainability (see **Table 9.2 Distress Levels for Assessing Drainagae Adequacy of JPCP**).

Table 9.2 Distress Levels for Assessing Drainage Adequacy of JPCP

Load-Related Distress	Highway Classification	Current Distress Level		
		Inadequate	Marginal	Adequate
Pumping All Severities (percent joints)	Interstate/freeway	> 25	10 to 25	< 10
	Primary	> 30	15 to 30	< 15
	Secondary	> 40	20 to 40	< 20
Mean Transverse Joint/Crack Faulting (inches)	Interstate/freeway	> 0.15	0.10 to 0.15	< 0.10
	Primary	> 0.20	0.125 to 0.20	< 0.125
	Secondary	> 0.30	0.15 to 0.30	< 0.15
Durability All Severity Levels of D- Cracking and Reactive Aggregate	All	Predominantly medium and high severity	Predominantly low and medium severity	None or predominantly low severity
Corner Breaks All Severities (number/mile)	Interstate/freeway	> 25	10 to 25	< 10
	Primary	> 30	15 to 30	< 15
	Secondary	> 40	20 to 40	< 20

PAVEMENT EVALUATION CHECKLIST (RIGID)

PROJECT NO.: ______________________ LOCATION: ____________________________
PROJECT CODE (SA #): ______________ DIRECTION: ______ MP _____ TO MP ______
DATE: _____________________________ BY: _____________________________________
TITLE: _____________________________

TRAFFIC
Existing ___________________NUMBER OF TRUCKS
Design ___________________NUMBER OF TRUCKS

EXISTING PAVEMENT DATA
Subgrade (AASHTO) ________________
Base (type/thickness) ________________
Pavement Thickness ________________
Soil Strength (R/M_R) ________________
Swelling Soil (yes/no) ________________

Roadway Drainage Condition (good, fair, poor)
Shoulder Condition (good, fair, poor)
Joint Sealant Condition (good, fair, poor)
Lane Shoulder Separation (good, fair, poor)

DISTRESS EVALUATION SURVEY

Type	Distress Severity*	Distress Amount*
Blowup		
Corner Break		
Depression		
Faulting		
Longitudinal Cracking		
Pumping		
Reactive Aggregate		
Rutting		
Spalling		
Transverse and Diagonal Cracks		
OTHER		

* Distress Identification Manual for the Long-Term Pavement Performance Program, U.S. Department of Transportation, Federal Highway Administration, Publication No. FHWA-RD-03-031, June 2003.

Figure 9.2 Pavement Condition Evaluation Checklist (Rigid)
(A Restatement of Figure A.1) Drainage Survey

9.2.4 Non-Destructive Testing

Non-destructive testing may use three methods of testing to determine structural adequacy.

- **Deflection Testing:** Determine high deflections, layer moduli, and joint load transfer efficiencies
- **Profile Testing:** Determine joint/crack faulting
- **Ground Penetrating Radar:** Determine layer thickness

The data obtained from these methods would be project site-specific (i.e. Level 1 inputs). Deflection testing results are used to determine the following:

- Concrete elastic modulus and subgrade modulus of reaction (center of slab)
- Load transfer across joints/cracks (across transverse joints/cracks in wheelpath)
- Void detection (at corners)
- Structural adequacy (at non-distressed locations)

In addition to backcalculation of the pavement layer and subgrade properties, void detection, and deflection testing can also be used to evaluate the load transfer efficiency (LTE) of joints and cracks in rigid pavements. *Evaluation of Joint and Crack Load Transfer*, Final Report, FHWA-RD-02-088 is a study presenting the first systematic analysis of the deflection data under the LTPP program related to LTE.

$$\mathbf{LTE = (\delta_u / \delta_l) \times 100} \qquad \textbf{Eq. 9-1}$$

Where:

LTE = load transfer efficiency, percent

δ_u = deflection on unloaded side of joint or crack measured 6 inches from the joint/crack

δ_l = deflection on loaded side of joint or crack measured beneath the load plate the center of which is placed 6 inches from the joint/crack

Visual distresses present at the joint or crack should be recorded and quantified. Joint and crack distress information is useful in analyzing and filtering the results obtained from the LTE calculation. The load transfer rating as related to the load transfer efficiency is shown in **Table 9.3 Load Transfer Efficiency Quality**.

Crack LTE is a critical measure of pavement condition because it is an indicator of whether the existing cracks will deteriorate further. LTE tests are usually performed in the outer wheelpath of the outside lane. For JPCP, cracks are held together by aggregate interlock; joints designed with load transfer devices have steel and aggregate interlock. In general, cracks with a good load transfer (LTE greater than 75 percent) hold together quite well and do not significantly contribute to pavement deterioration. Cracks with poor load transfer (LTE less than 50 percent) are working cracks and can be expected to deteriorate to medium and high severity levels and will exhibit faulting over time. These cracks are candidates for rehabilitation.

Table 9.3 Load Transfer Efficiency Quality

Load Transfer Rating	Load Transfer Efficiency (percent)
Excellent	90 to 100
Good	75 to 89
Fair	50 to 74
Poor	25 to 49
Very Poor	0 to 24

9.2.5 Coring and Material Testing Program

Experience has shown that non-destructive testing techniques alone may not always provide a reasonable or accurate characterization of the in-situ properties, particularly for those of the top pavement layer. The determination of pavement layer type cannot be made through non-destructive testing. While historic information may be available, the extreme importance and sensitivity calls for a limited amount of coring at randomly selected locations to be used to verify the historic information. Pavement coring, base and subbase thicknesses, and samples are recommended to be collected at an approximate frequency of one sample per one-half mile of roadway. Several major parameters are needed in the data collection process. They are as follows:

- Layer thickness
- Layer material type
- Examination of cores to observe general condition and material durability
- In-situ material properties (i.e. modulus and strength)

Concrete slab durability may have a possible condition of severe D-Cracking and reactive aggregate. Petrographic analysis helps identify the severity of the concrete distresses when the cause is not obvious. Material durability problems are the result of adverse chemical or physical interactions between a paving material and the environment. The field condition survey and examination of cores for material durability reinforce each other.

9.2.6 Lane Condition Uniformity

On many four lane roadways, the outer truck lane deteriorates at a more rapid pace than the inner lane. The actual distribution of truck traffic across lanes varies with the roadway type, roadway location (urban or rural), the number of lanes in each direction, and the traffic volume. Because of these factors, it is suggested the lane distribution be measured for the project under consideration. Obtaining the actual truck lane distributions will determine the actual remaining life of the lane under consideration. Significant savings may result by repairing only the pavement lane that requires treatment.

9.3 Determine Cause and Mechanism of Distress

Knowing the exact cause of a distress a is key input required by designers for assessing the feasibility of rehabilitation design alternatives. Assessment of existing pavement conditions is done using outputs from distress and drainage surveys, usually some coring, and testing of materials. The evaluation of existing pavement conditions is a critical element in M-E Design's rehabilitation design. The observation should begin with a review of all information available regarding the design, construction, and maintenance history of the pavement. This should be followed by a detailed survey to identify the type, amount, severity, and location of surface distresses. Some of the key distress types are indicators of structural deficiencies:

- Deteriorated cracked slabs
- Corner breaks
- Mean transverse joint/crack faulting
- Pumping
- Spalling
- D-Cracking
- Other localized failing areas
- There may be other types of distress that, in the opinion of the engineer, would detract from the performance of an overlay

Depending on the types and amounts of deterioration present, rehabilitation options with or without pre-overlay treatments are considered. **Table 9.4 Common Distress Causes of Rigid Pavements and Associated Problem Types** presents a summary of causes for distresses present on existing rigid pavements.

9.4 Define Problems and Inadequacies of Existing Pavement

Information gathered and presented using the pavement condition evaluation checklist must be reviewed by the designer using guidance presented in **Table 9.4 Common Distress Causes of Righid Pavements and Associated Problem Types** and **Table 8.1 Common Distress Causes of Flexible Pavement and Associated Problem Types** to define possible problems identified with the existing pavement. Accurately identifying existing problems is a key factor to be considered when selecting appropriate rehabilitation design alternatives for the trial design. A review of the extent and severity of distresses present will allow the designer to determine when the existing pavement deficiencies are primarily structural, functional, or materials durability related. It also allows the designer to determine if there is a fundamental drainage problem causing the pavement to deteriorate prematurely.

Once an existing pavement deficiency is characterized, the next step is to select among feasible design alternatives and perform a trial design. A description of common pavement problem types is presented as follows:

Table 9.4 Common Distress Causes of Rigid Pavements and Associated Problem Types

Distress Types	Load	Environment			Materials	Construction
		Moisture	Temperature	Subgrade		
Alkali-Aggregate Reactivity	N	P	C	N	P	N
Blow-Up	N	C	P	N	C	N
Corner Breaks	P	C	C	N	N	N
Depression	N	C	N	P	N	C
"D" Cracking	N	P	P	N	P	N
Transverse Joint Faulting	P	P	C	C	C	N
Joint Failure	N	C	C	N	P	C
Lane/Shoulder Dropoff	C	P	P	C	C	N
Longitudinal Slab Cracking	P	C	P	C	C	P
Spalling (Longitudinal and Transverse Joints)	C	C	P	N	P	C
Polish Aggregate	C	N	N	N	P	N
Popouts	N	C	C	N	P	C
Pumping	P	P	N	C	C	N
Random (map) Cracking, Scaling, and Crazing	N	N	C	N	C	P
Shattered Slab	P	C	N	C	C	N
Swell	N	P	P	C	C	N
Transverse Slab Cracking	P	N	C	C	C	P

Notes: P = Primary Factor; C = Contributing Factor; N = Negligible Factor

- **Functional Deterioration**: Functional deficiency arises from any condition(s) that adversely affect the highway user. These include poor surface friction and texture, faulting, hydroplaning and splash from wheel path rutting, and excess surface distortion. Cracking and faulting affect ride quality but are not classified under functional distress. These conditions reduce load carrying capacity as stated above. The integrity of the base, concrete slab, and joint system is compromised under cracking and faulting. If a pavement has only a functional deficiency, it would not be appropriate to develop an overlay design using a structural deficiency design procedure. Overlay designs, including thickness, preoverlay repairs, and reflection crack treatments must address the causes of functional problems and prevent their reoccurrence. This can only be done through sound engineering, and requires experience in solving the specific problems involved. The overlay design required to correct functional problems should be coordinated with that required to correct any structural deficiencies.

- **Structural Deterioration**: This is defined as any condition that adversely affects the load carrying capability of the pavement structure. Corner breaks, pumping, faulted joints and shattered slabs are some examples of structural related distresses. Evaluating the level of structural capacity requires thorough visual survey and materials testing. Non-destructive testing is important to characterize both pavement stiffness and subgrade support. Restoration is applicable only for pavements with substantial remaining structural capacity. Pavements that have lost much of their structural capacity require either a thick overlay or reconstruction. It should also be noted that several types of distress, (i.e. distresses caused by poor construction techniques) are not initially caused by traffic loads, but do become more severe under traffic to the point they also detract from the load carrying capability of the pavement.

- **Material Durability Deterioration**: This is defined as any condition that negatively impacts the integrity of paving materials leading to disintegration and eventual failure of the materials. Research indicates poor durability performance can often be attributed to the existing pavement material constituents, mix proportions, and climatic factors such as excessive moisture and intense freeze-thaw cycles. Examples of durability problems include spalling, scaling and disintegration of cement-treated materials due to freeze thaw damage, map cracking and joint deterioration resulting from alkali-silica reactivity, stripping in the HMA base, and contamination of unbound aggregate layers with fines from subgrade.

9.5 Identify Possible Constraints

The feasibility of any type of overlay design depends on the following major considerations:

- Construction feasibility of the overlay
- Traffic control and disruptions
- Materials and equipment availability
- Climatic conditions
- Construction problems such as noise, air/water pollution, hazardous materials, waste, subsurface utilities, overhead bridge clearance, shoulder thickness and side slope extensions in the case of limited right-of-way, etc.

Designers must consider all of the factors listed above along with others not mentioned as they determine whether a flexible overlay or reconstruction is the best rehabilitation solution for the given situation.

9.6 Selecting a Feasible Strategy for Rigid Pavement Rehabilitation Trial Designs

9.6.1 Bonded Concrete Overlays

9.6.1.1 PCC Over PCC

Bonded PCC overlays over existing jointed plain concrete pavement (JPCP) involve the placement of a thin concrete layer (typically 3 to 7 inches) atop the prepared existing PCC surface to form a permanent monolithic PCC section. The monolithic section improves load carrying capacity by reducing the critical structural responses which are top and bottom tensile stress in the longitudinal direction for JPCP cracking and slab edge corner deflections at the joint for JPCP faulting. One should consult the Region Materials Engineer for additional information.

For bonded PCC overlays over existing JPCP, achieving long-term bonding is essential. To ensure an adequate bond, the existing surface should be cleaned of all surface contaminants including oil, paint, and unsound concrete. Milling, sand blasting, water blasting, or a combination of the above can accomplish this. Since all cracks in the old surface will reflect through the overlay, all joints and cracks in the original pavement must be reproduced in the overlay. For this reason, thin concrete overlays are restricted to pavements that are not heavily cracked. Thin concrete overlays should be used only when the existing concrete is in good condition or rehabilitated into a good condition.

9.6.1.2 PCC Over HMA

Bonded PCC overlays over existing HMA involve the placement of a thin concrete layer, typically 3 to less than 8 inches, atop the existing HMA surface. These are used to restore the structural capacity and/or correct surface distresses of the existing HMA. The bond between the overlay and underlying HMA assists the horizontal shear transfer at the bond plane between the two types of pavement. Because of this bond, the shear stresses are transferred into the underlying HMA material, thereby reducing the tensile stresses in the PCC. To ensure an adequate bond, the existing HMA surface should be cleaned of surface contaminates such as oil and unsound HMA. Pavement marking material should be removed if more than two layers of marking material have been applied to the pavement. HMA with more than one layer of chip seals or slurry seals should be evaluated for its bond to the existing HMA. Power sweeping, cold milling, water blasting or a combination of the above can accomplish this. It has been determined that older HMA (over a few years old) will provide an adequate macrotexture for bonding without the need to cold plane the existing aged pavement. The Concrete Overlay Task Force has recommended an adequate platform for the PCC to be at least 3 inches of HMA in good condition and have a good bond to one another in the remaining 3 inches. FWD data should be obtained on every project.

9.6.2 Feasibility of Alternatives for Bonded Concrete Overlays

The type of rehabilitation/restoration technique and thickness of the required overlay are based on an evaluation of present pavement conditions and estimates of future traffic. In general, the designer must apply the following rules when considering rehabilitation alternatives involving bonded concrete overlays:

- **An existing JPCP pavement surface evaluation indicates adequate structural strength but the surface needs correction**. Concrete Pavement Restoration (CPR) may be used to remedy the functional problem. CPR is a non-overlay option used to repair isolated areas of distress or to prevent or slow overall deterioration, as well as, to reduce the impact loadings on the concrete pavement without changing its grade. CPR includes diamond grinding, load transfer restoration, partial depth repairs, and full depth repairs.

- **An existing JPCP pavement surface evaluation indicates inadequate structural strength to carry future traffic, but the condition of the surface needs minor correction**. Bonded PCC overlays, in conjunction with surface restoration, may be used. Bonded overlays should be used only when the PCC slab is in good, sound condition to help ensure good bonding and little reflection cracking. Pre-overlay repairs including milling, load transfer restoration, and joint spalling repair may be undertaken as necessary to perform surface corrections of the existing PCC slab.

- **An existing HMA pavement surface evaluation indicates inadequate structural strength to carry future traffic, but the condition of the surface needs minor correction.** Bonded PCC overlays, in conjunction with surface restoration, may be used. The HMA should be evaluated by a combination of visual inspections, non-destructive tests such as FWD testing, and cores. Cores should be taken to determine damage not visible at the surface. Pre-overlay full-depth patching may be undertaken as necessary to repair severe load associated cracking and potholes. Bonded overlays should be used only when at least 3 inches of HMA remains and the HMA layers have good adhesion to each other. Rutting or shoving in the existing HMA exceeding 2 inches will require milling. The milling operation should reduce the affected area to a maximum of 2 inches in depth. When severe load associated cracking and/or severe stripping is found in the underlying layers, it is recommended that FWD testing be used to determine the structural strength of the HMA. Cracks greater than ¾ inch prior to the PCC overlay should be filled with milling material or fine aggregate.

- **When the existing pavement has significant durability problems.** Unbonded PCC or conventional AC overlays over fractured concrete should be used. Unbonded overlays do not require much pre-overlay repair unless there is a spot of significant deterioration. A separator layer using a thin AC layer or paving fabric placed between the overlay and existing pavement should be used. Separating the existing and overlay PCC layers prevents distresses in the existing pavement from reflecting through the overlay. Slabs that move under traffic loads, isolated soft spots, pumping, or faulted areas should be stabilized prior to overlaying. Total reconstruction may also be warranted. CPR is not recommended for rigid pavements that have significant material durability problems or other severe deterioration.

9.6.3 The CDOT Thin Concrete Overlay Thickness Design

The purpose of bonded concrete overlays of asphalt is to add structural capacity and eliminate surface distresses on the existing asphalt pavement. Severe surface defects are corrected to provide an acceptable and relatively smooth surface on which to place the concrete. Cold milling is only required when an asphalt mix has been placed within the last couple of years. The surface needs to be roughened to create a good interlocking bond. Also, by the use of cold milling, grade control can be accomplished at this time. The final operation is to pave the concrete with a conventional concrete paving machine.

Based on the field and theoretical analyses conducted during the research study, the following construction practices should be used:

- A good bond within the concrete/asphalt interface is essential for successful performance.

- For existing asphalt pavement being rehabilitated, the strain (and corresponding stress) in the concrete overlay is reduced by approximately 25 percent when the asphalt is milled prior to concrete placement. The strain (and corresponding stress) in concrete on new asphalt is increased by approximately 50 percent when the asphalt has not aged prior to concrete placement.

A minimum asphalt thickness of 3 inches (after cold planning or other remedial work) is recommended. **Table 9.5 Design Factors for Rigid Pavement** contains the various factors to be used in the concrete overlay design.

For more information, refer to CDOT Research Report No. CDOT-DTD-R-98-10, *Guidelines for the Thickness Design of Bonded Whitetopping Pavement in the State of Colorado, December 1998*, CDOT-DTD-R-2002-3, *Instrumentation and Field Testing of Whitetopping Pavements in Colorado and Revision of the TWT Design Procedure*, March 2002 and CDOT-DTD-R-2004-12, *Instrumentation and Field Testing of Thin Whitetopping Pavement in Colorado and Revision of the Existing Colorado Thin Whitetopping Procedure, August 2004*. The last two research reports can be found on web page http://www.dot.state.co.us/publications/researchreports.htm#White. A revised MS Excel worksheet was developed in conjunction with report CDOT-DTD-R-2004-12. The worksheet may be obtained from CDOT Materials and Geotechnical Branch, Pavement Design Unit 303-398-6561 or CDOT Research Branch 303-757-9506.

The proper selection of candidate projects for CDOT Thin Concrete Overlay is of paramount importance to its continued use as a viable rehabilitation alternative. Listed are guidelines for the pavement designer when considering if a thin concrete overlay will work on the project. The list was compiled from characteristics of good performing concrete overlay projects.

- Determine the modulus of existing asphalt by an analysis using FWD data.
- Cold mill when the rut depth exceeds 2 inches or when new HMA is placed to improve mechanical bond.
- The condition of the asphalt pavement must be in relatively good condition for an overlay.
- An existing roadway having a good aggregate base is preferred.
- Concrete overlays work well with a divided roadway. The median serves as a non-tied longitudinal joint.
- The cross traffic must be added to the mainline traffic at intersection locations for proper pavement design.

Table 9.5 Design Factors for Rigid Pavement

Factor	Source
Primary or Secondary	User input (select primary or secondary)
Joint Spacing	24 to 72 inches (dependent on thickness)
Trial Concrete Thickness	User input
Concrete Modulus of Rupture	650 psi (CDOT default value)
Concrete Elastic Modulus	**Table 7.1 PCC Material Inputs and Recommendations for New JPCP Design** or FWD data
Concrete Poisson's Ratio	0.15 (CDOT default value)
Asphalt Thickness	Soil profile report from laboratory
Asphalt Modulus of Elasticity (When Existing HMA was New)	User input (from FWD data))
Asphalt Poisson's Ratio	0.35 (CDOT default value)
Asphalt Fatigue Life Consumed	$\left[1-\frac{\text{existing asphalt modulus}}{\text{asphalt modulus when new}}\right]*100$ or Estimated by designer
k-value of the Subgrade	Soil profile report from laboratory and correlation equations
Temperature Differential	$\Delta T = 3°$ F/in. throughout the day (CDOT default value)
Design Truck Traffic	DTD Traffic Analysis Unit

A Project Special Provision has been developed and is to be used on thin concrete overlay projects. The Project Special Provision is located on the following web page:

> http://www.coloradodot.info/business/designsupport/construction-specifications/2011-Specs/sample-construction-project-special-provisions/section-300-500-revisions

The specification is titled *Revision of Section 412, Portland Cement Concrete Pavement Thin Concrete Overlay*. Additionally, a thin concrete overlay typical joint layout plan sheet has been developed for the project special provision. It is titled *D-412-2, Thin Concrete Overlay Typical Joint Layout* and is found on web page:

> http://www.coloradodot.info/business/designsupport/standard-plans/2006-m-standards/2006-project-special-details/2006_m_standards_project_special_details_index

9.6.4 Development of Design Equations

Two different modes of distress may exist in pavements overlaid by concrete; corner cracking caused by corner loading and mid-slab cracking caused by joint loading. Both types of failure were considered in developing the original design equations (1998).

9.6.4.1 Corner Loading (1998)

Both a 20-kip Single Axle Load (SAL) and a 40-kip Tandem Axle Load (TAL) were applied to the slab corners of the concrete overlay. The corner loading case was found to produce the maximum concrete stress for relatively few conditions. In general, the corner loading case governed at higher values of the effective radius of relative stiffness. As the stiffness increases, the load-induced stress decreases. All instances when the corner load case governed, relatively lower stresses resulted. The maximum stress, whether edge or corner, was used in the derivation of the concrete stress prediction equations.

9.6.4.2 Mid-Joint Loading (1998)

Load-induced longitudinal joint stresses for a 20-kip single axle load (SAL) and a 40-kip tandem axle load (TAL) were computed. Maximum tensile stresses at the bottom of each layer were calculated for the concrete and asphalt. Maximum asphalt strains used in generating the design equations occurred for the joint loading condition. In most cases, the joint loading condition produced the maximum stress at the bottom of the concrete layer.

9.6.4.3 Determination of Critical Load Location (1998)

The critical load location for the design of concrete pavement was determined during the original 1998 study by comparing the stress and strain data collected for each load position. The critical load location inducing the highest tensile stress in the concrete layer occurred when the load was centered along a longitudinal free edge joint. For concrete pavement, a free edge joint occurs when the asphalt and concrete are formed against a smooth vertical surface such as a formed concrete curb and gutter. It is reasonable that free edge loading produces the highest stress, but it is more likely the joints loaded by traffic will not be free edges. The equation for original data is shown and used in the 2004 procedure but could not be verified.

Original Critical Joint Stresses:

$$\sigma_{FE} = 1.87 \times \sigma_{TE} \qquad \textbf{Eq. 9-2}$$

Where:

σ_{FE} = load induced stress at a longitudinal free joint, psi

σ_{TE} = load induced stress at a longitudinal tied joint, psi

9.6.4.4 Interface Bond on Load-Induced Concrete Stress

The effect of interface bonding was evaluated by comparing measured stresses for zero temperature gradient conditions to the computed stresses for fully bonded pavement systems. Stresses caused by loads at mid-joint and slab corners were computed using the finite element computer program ILLISLAB (ILSL2), assuming a fully bonded concrete-asphalt interface. The program is based on plate bending theory for a medium-thick plate placed on a Winkler or spring foundation. Based on the previous study (1998), all the test sections where existing asphalt was milled prior to concrete placement was determined to be the best approach for promoting bond for existing asphalt substrate conditions.

2004 Interface Bond on Load-Induced Concrete Stresses:

$$\boldsymbol{\sigma_{EX} = 1.51 \times \sigma_{TH}} \qquad \textbf{Eq. 9-2}$$

Where:

σ_{Ex} = measured experimental partially bonded stress, psi

σ_{TH} = calculated fully bonded stress, psi

9.6.4.5 Interface Bond on Load-Induced Asphalt Strain

The effect of interface bond on the load-induced asphalt surface strain was also studied using field-collected data. If slabs were fully bonded, the concrete bottom strain would equal the asphalt surface strain. Due to slippage between the layers, asphalt strains are generally less than the concrete strains. There is approximately a 10 percent loss of strain transfer from the concrete to the asphalt due to the partial bond between the layers.

2004 Interface Bond on Load-Induced Asphalt Strain:

$$\boldsymbol{\varepsilon_{ac} = 0.897 \times \varepsilon_{pcc} - 0.776} \qquad \textbf{Eq. 9-4}$$

Where:

ε_{ac} = measured asphalt surface strain, microstrain

ε_{pc} = measured concrete bottom strain, microstrain

Stresses and strains at the bottom of the asphalt layer decrease with loss of bond. The design procedure assumes the average strain reductions reflecting partial bond at the interface are equally reflected at the bottom of the asphalt layer.

9.6.4.6 Temperature Restraint Stress

Temperature gradients throughout load testing ranged from -2°F/in. to 6°F/in. Measurable stress changes occurred with changing temperature gradient, which indicates the restraint stresses are present and raises concern that there could be loss of support conditions. However, minimizing effects of curling and warping restraint stresses and possible loss of support may be done by minimizing the concrete overlay joint spacing (typically using 6 feet by 6 feet panels).

2004 Temperature Effects on Load-Induced Stresses:

$$\boldsymbol{\sigma_{\%} = 3.85 \times \Delta T} \qquad \textbf{Eq. 9-5}$$

Where:

$\sigma_{\%}$ = percent change in stress from zero gradient
ΔT = temperature gradient, °F/in.

This relationship is applied to the partial bond stresses to account for the effect of temperature induced slab curling and loss of support effects on the load induced concrete stresses. For CDOT projects, a default temperature gradient of 3°F/in. will be used.

9.6.4.7 Development of Prediction Equations for Design Stresses and Strains

Prediction equations were derived for computing design concrete flexural stresses and asphalt flexural strains. The 2004 equations include calibration factors for modeled thin whitetopping concrete stresses and asphalt strains; 151 percent for stresses and approximately 89 percent for stresses and strains would be required to account for the loss of bonding at the 95 percent confidence level. Asphalt strains are decreased by approximately 10 percent to account for the partial bonding condition at the 95 percent confidence level. Effects of temperature-induced slab curling on load-induced stresses were also included in the thickness design procedure, and all of the original 1998 adjustments for these stresses and strains were revised. The revised four equations are as follows:

2004 Concrete Stress for 30-kip SAL

$$(\sigma_{pcc})^{1/2} = 18.879 + 2.918 t_{pcc}/t_{ac} + 425.44/l_e - 6.95 \times 10^{-6} E_{ac} - 9.0366 \log k + 0.0133 L \qquad \textbf{Eq. 9-6}$$

R^2 adj = 0.92

2004 Concrete Stress for 40-kip TAL

$$(\sigma_{pcc})^{1/2} = 17.669 + 2.668 t_{pcc}/t_{ac} + 408.52/l_e - 6.455 \times 10^{-6} E_{ac} - 8.3576 \log k + 0.00622 L \qquad \textbf{Eq. 9-7}$$

R^2 adj = 0.92

2004 Asphalt Strain for 20-kip SAL

$$(\varepsilon_{ac})^{1/4} = 8.224 + 0.2590 t_{pcc}/t_{ac} + 0.044191 l_e - 6.898 \times 10^{-7} E_{ac} - 1.1027 \log k \qquad \textbf{Eq. 9-8}$$

R^2 adj = 0.92

2004 Asphalt Strain for 40-kip TAL

$$(\varepsilon_{ac})^{1/4} = 8.224 + 0.2590 t_{pcc}/t_{ac} + 0.044191 l_e - 6.898 \times 10^{-7} E_{ac} - 1.1027 \log k \qquad \textbf{Eq. 9-8}$$

R^2 adj = 0.92

Where:

σ_{pcc} = maximum stress in the concrete slab, psi
ε_{ac} = maximum strains at bottom of asphalt layer, microstrain
E_{pcc} = concrete modulus of elasticity, assumed 4 million psi
E_{as} = asphalt modulus of elasticity, psi
t_{pcc} = thickness of the concrete layer, in.
t_{ac} = thickness of the asphalt layer, in.
μ_{pcc} = Poisson's ratio for the concrete, assumed 0.15
μ_{ac} = Poisson's ratio for the asphalt, assumed 0.35
k = modulus of subgrade reaction, pci

L = joint spacing, in.
L_e = effective radius of relative stiffness for fully bonded slabs, in
$= \{E_{pcc} \times [t_{pcc}^3 / 12 + t_{pcc} \times (NA\text{-}t_{pcc} / 2)^2] / [k \times (1\text{-}\mu_{pcc}^2)] + E_{ac} \times [t_{ac}^3 / 12 + t_{ac} \times (t_{pcc} - NA + T_{ac} / 2)^2] / [k \times (1\text{-}\mu_{ac}^2)]\}^{1/4}$
NA = neutral axis from topof concrete slab, in.
$= [E_{pcc} \times t_{pcc}^2 / 2 + E_{ac} \times t_{ac} \times (t_{pcc} + t_{ac} / 2)] / [E_{pcc} \times t_{pcc} + E_{ac} \times t_{ac}]$

Each of the equations developed to calculate the critical stresses and strains in a concrete overlay are dependent on the effective radius of relative stiffness of the layered system. The radius of relative stiffness appears in many of the equations dealing with stresses and deflections of concrete pavements. Concrete overlays include an additional structural layer of asphalt concrete. The stiffness contribution of the asphalt layer is incorporated into the effective radius of the relative stiffness equation shown above.

Transverse joint spacing directly affects the magnitude of critical stresses in thin concrete overlays. Depending on the pavement design, climate, season, and time of the day, curling stresses in a concrete overlay can equal or exceed the load stresses. Thus, joint spacing is directly considered as an input in the CDOT design.

CDOT does not use dowels for transverse joints in thin concrete overlay designs; however, it recommends the use of tie bars in longitudinal joints. The 2004 equations are based on using tie bars in the longitudinal joints. The analysis used all wheel loadings next to tied longitudinal joints. CDOT project design drawing D-412-2, Thin Concrete Overlay Typical Joint Layout provides for this requirement.

9.6.4.8 PCCP and HMA Pavement Fatigue

The Portland Cement Association (PCA) developed a fatigue criterion based on Miner's hypothesis stating fatigue resistance not consumed by repetitions of one load is available for repetitions of other loads. In a design, the total fatigue should not exceed 100 percent. The concrete fatigue criterion was incorporated as follows:

For $SR > 0.55$

$$\mathbf{Log10\ (N) = (0.97187 - SR) / 0.0828} \qquad \textbf{Eq. 9-10}$$

For $0.45 \leq SR \leq 0.55$

$$\mathbf{N = [4.2577 / (SR - 0.43248)] \times 3.268} \qquad \textbf{Eq. 9-11}$$

For $SR < 0.45$

$$\mathbf{N = Unlimited} \qquad \textbf{Eq. 9-12}$$

Where:
SR = flexural stress to strength ratio
N = number of allowable load repetitions

Asphalt pavements are generally designed based on two criteria, asphalt concrete fatigue and subgrade compressive strain. Subgrade compressive strain criterion was intended to control pavement rutting for conventional asphalt pavements. For concrete overlay pavements, when the asphalt layer is covered by concrete slabs, pavement rutting will not be the governing distress. The asphalt concrete fatigue equation developed by the Asphalt Institute was employed in the development of the concrete overlay design procedure. The asphalt concrete fatigue equation is as follows:

$$\mathbf{N = C \times 18.4 \times (4.32 \times 10^{-3}) \times [(1 / \varepsilon_{ac}) \times 3.29] \times [(1/E_{ac}) \times 0.854]} \qquad \textbf{Eq. 9-13}$$

Where:

N = number of load repetitions for 20% or greater AC fatigue cracking
ε_{ac} = maximum tensile strain in the asphalt layer
E_{ac} = asphalt modulus of elasticity, psi
C = correction factor, 10M
$M = 4.84 \times [(V_b/V_v + V_b) - 0.69]$
V_b = volume of asphalt, percent
V_v = volume of air voids, percent

For typical asphalt concrete mixtures, M would be equal to zero. The correction factor C, would become one, thus omitted from the equation. However, since a concrete overlay is designed to rehabilitate deteriorated asphalt pavement, the allowable number of load repetitions (N) needs to be modified to account for fatigue life consumed prior to concrete overlay construction. Therefore, the calculated repetitions must be multiplied by the fractional percentage representing the amount of fatigue life remaining in the asphalt concrete. For example, if it is determined that 25 percent of the asphalt fatigue life has been consumed prior to concrete overlay; the calculated allowable repetitions remaining must be multiplied by 0.75.

The concrete overlay pavement thickness design involves the selection of the proper concrete slab dimensions and thickness. Two criteria were used in governing the pavement design asphalt and concrete fatigue under joint or corner loading. Temperature and loss of support effects were also considered in the design procedure. A design example is presented in the next section to illustrate how to use the developed procedure to calculate the required concrete overlay concrete thickness.

9.6.4.9 Converting Estimated ESALs to Concrete Overlay ESALs

CDOT currently designs pavements using the procedure developed by the American Association of State Highway and Transportation Officials (AASHTO). This empirical procedure is based on pavement performance data collected during the AASHO Road Test in Ottawa, in the late 1950's and early 1960's. Traffic (frequency of axle loadings) is represented by the concept of the 18-kip Equivalent Single Axle Load (ESAL). Factors are used to convert the damage caused by repetitions of all axles in the traffic mix (single and tandem) to an equivalent damage due to 18-kip ESALs alone. Because the relative damage caused by ESALs is a function of the pavement thickness, a series of ESAL conversion factors have been developed for a range of concrete thicknesses. However, the minimum concrete thickness included in the AASHTO design manual is 6 inches. Since concrete overlay thicknesses below 6 inches are anticipated, it was necessary to develop correction factors to convert ESAL estimations based on thicker concrete sections. In addition, because the ESAL method of design appears to overestimate the required PCC thickness, it was necessary to develop a conversion factor, which would make the empirical and mechanistic procedures more compatible.

CDOT provided axle distributions for two highway categories (primary and secondary) anticipated as typical concrete overlay traffic loading. The ESAL conversion factors were designed for an 8 inch thick concrete pavement and a terminal serviceability of 2.5. The conversion factors were extrapolated for pavement thicknesses as low as 4 inches and the total ESALs were computed for a range of possible concrete overlay thicknesses. For each highway category, ESAL conversions were developed as a percentage of the total ESALs computed for an 8 inch thick concrete pavement. With these conversions, the designer only needs to obtain the design ESALs based on an assumed concrete thickness of 8 inches. For each trial concrete overlay thickness, the total ESAL estimation is adjusted based on the following conversion equations:

Primary Highway

$$\mathbf{F_{ESAL} = 0.985 + 10.057 \times (t_{pcc})\ {-3.456}} \qquad \textbf{Eq. 9-14}$$

Secondary Highway

$$\mathbf{F_{ESAL} = (1.286 - 2.138 / t_{pcc}){-1}} \qquad \textbf{Eq. 9-15}$$

Where:

F_{ESAL} = conversion factor from ESAL estimation based on assumed, 8 inch thick concrete pavement

T_{pcc} = thickness of concrete layer, inches

For example, in the design of a 4.5 inch thick concrete overlay on a secondary highway, the estimated ESALs based on an assumed 8 inch thick pavement, say 750,000, should be converted to 925,000 using the secondary highway conversion equation.

9.6.5 Example Project CDOT Thin Concrete Overlay Design

Example: A two-lane highway, Colorado State Highway 287 (SH 287) will need the cost for a typical 6 mile project. The cross section has 2 lanes, each 12 feet wide and a 10 foot shoulder on each side. Thus, the pavement is 44 feet wide and the total pavement area is 154,880 square yards. The existing pavement structure is 5.5 inches HMA after cold milling over a 12 inch gravel base from the outside of one shoulder to the other shoulder.

- Highway category (primary or secondary) = secondary
- Joint spacing, L = 72 in.
- Trial concrete thickness = 4.1 in.
- Concrete modulus of rupture, M_R = 650 psi
- Concrete modulus of elasticity, E_{pcc} = 4,000,000 psi
- Concrete Poisson's ratio, μ_{pcc} = 0.15
- Asphalt thickness, t_{ac} = 5.5 in.
- Asphalt modulus of elasticity, E_{ac} = 350,000 psi

- Asphalt Poisson's ratio, $\mu_{ac} = 0.35$
- Existing asphalt fatigue = 25 percent
- Existing modulus of subgrade reaction, k = 200 pci
- Temperature differential, $\Delta T = 3°$ F/in. throughout the day
- Design ESALs = 245,544

The 2004 revised MS Excel worksheet is shown in **Figure 9.4 Input and Required Thickness Form for Thin Concrete Overlay Design** with the required concrete overlay thickness.

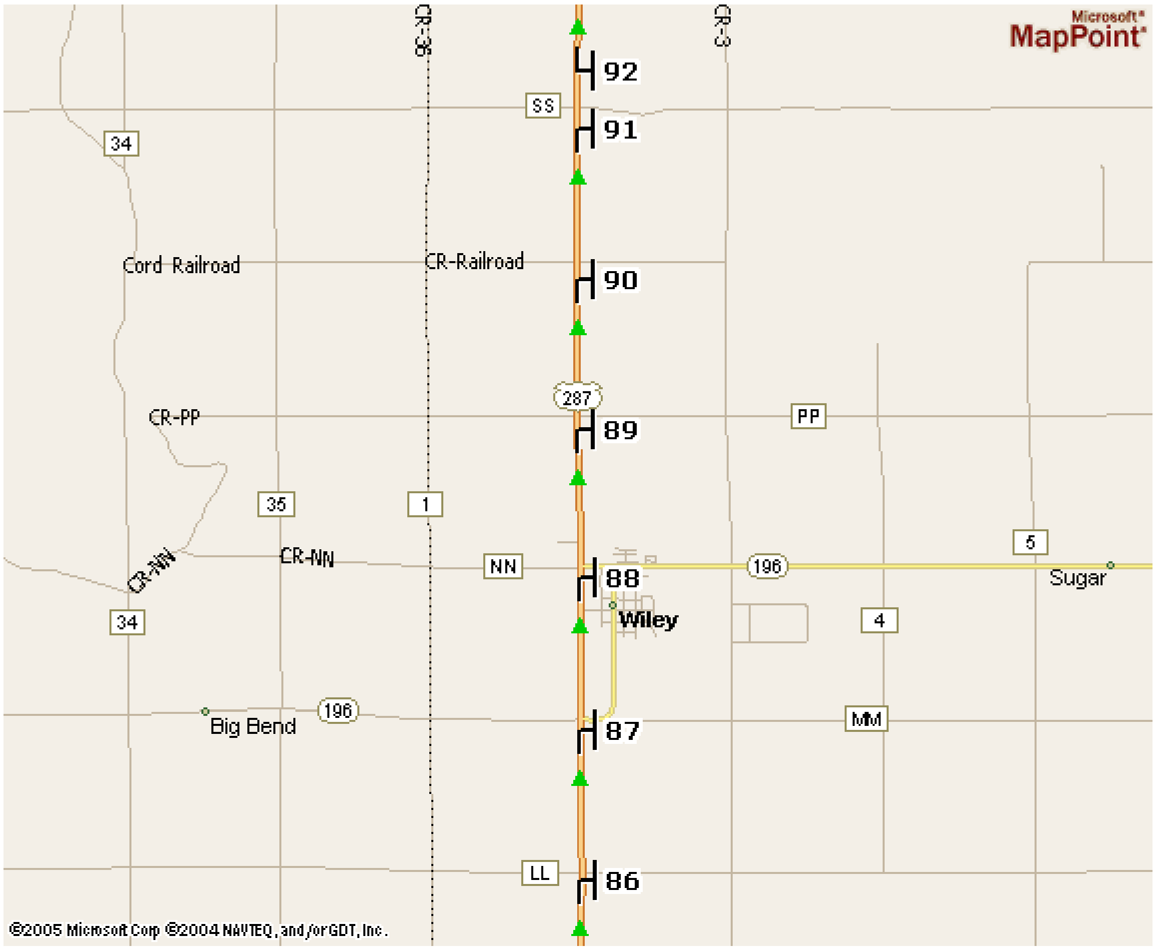

Figure 9.3 Sample TWT Project Location Map

CDOT 2004 Thin Whitetopping Design Procedure

Whitetopping Input Parameters

Highway Category (Primary or Secondary)*	Secondary
Joint Spacing, in.	72
Trial Concrete Thickness, in.	4.1
Concrete Flexural Strength, psi	650
Concrete Elastic Modulus, psi	4,000,000
Concrete Poisson's Ratio	0.15
Asphalt Thickness, in.	5.5
Asphalt Elastic Modulus, psi	350,000
Asphalt Poisson's Ratio	0.35
Asphalt Fatigue Life Previously Consumed, %	25
Subgrade Modulus, pci	200
Temperature Gradient, °F/in.	3
Design ESALs	245,544

Converted Concrete Thickness, in. = 5.24
ESAL Conversion Factor = 1.3072
Neutral Axis = 3.07
le = 27.36
L/le = 2.63

Critical Concrete Stresses and Asphalt Strains					
Load Induced		Bond Adjustment		Support Adjustment	
Stress, psi	μstrain	Stress, psi	μstrain	Stress, psi	μstrain
1	2	3	4	5	6
201	**228**	**303**	**204**	**338**	**204**

ESAL Fatigue Analysis						
No. of 18-kip ESALs	Concrete Fatigue Analysis			Asphalt Fatigue Analysis		
	Stress Ratio	Allowable ESALs	Fatigue, %	Asphalt μstrain	Allowable ESALs	Fatigue, %
7	8	9	10	11	12	13
3.2E+05	**0.520**	**3.2E+05**	**99.9**	**204**	**1.5E+06**	**21.0**

Concrete Fatigue, % = 99.9 **Asphalt Fatigue, % = 46.0**

Required Whitetopping Thickness = 4.25 in.

Figure 9.4 Input and Required Thickness Form for Thin Concrete Overlay Design

References

1. *AASHTO Guide for Design of Pavement Structures*, American Association of State Highway and Transportation Officials, Washington, DC, 1993.

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3. *Whitetopping - State of the Practice*, Publication EB210.02P, American Concrete Pavement Association, 5420 Old Orchard Road, Suite A100, Skokie, IL, 1998.

4. *Guidelines for the Thickness Design of Bonded Whitetopping Pavement in the State of Colorado*, CDOT-DTD-R-98-10, Final Report, Scott M. Tarr, Mathew J. Sheehan, and Paul A. Okamoto, Colorado Department of Transportation, 4201 E. Arkansas Ave., Denver, CO, 80222, December 1998.

5. *Instrumentation and Field Testing of Thin Whitetopping Pavement in Colorado and Revision of the Existing Colorado Thin Whitetopping Procedure*, CDOT-DTD-R-2004-12, Final Report, Matthew J. Sheehan, Scott M. Tarr, and Shiraz Tayabji, Colorado Department of Transportation, 4201 E. Arkansas Ave., Denver, CO, 80222, August 2004.

6. *Distress Identification Manual for the Long-Term Pavement Performance Program*, U.S. Department of Transportation, Federal Highway Administration, Publication No. FHWA-RD-03-031, June 2003.

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