Capital Area Pavement Engineers Council (CAPEC) Initiative

Contract No. PS100298JE
TNR No: 3103-CAPEC0000-07B000A
Phase 1 Interim Report

ADDENDUM

Prepared for:
Ed Poppitt, PE, CAPEC Chairman,
City of Austin
Scott Lambert, PE, CAPEC Secretary and Acting Vice Chairman,
Travis County

Prepared by:
HVJ Associates, Inc.
4201 Freidrich Ln, Ste. 110
Austin, Texas 78744

July 10, 2015

HVJ No: AP-10-17200

Table of Contents

1. Introduction

A task was added to the Phase 2 scope of work to review, summarize and include models for Portland Cement Concrete (PCC) pavement design. As requested by Williamson County and CAPEC, HVJ updated the Phase 1 study to review and provide concrete pavement design procedures. Specifically, HVJ collected information on how rigid Portland cement concrete pavement is designed in other areas of Texas, such as the Dallas/Fort Worth Metroplex and the Houston area, where PCC is more widely used. This task resulted in a review of existing PCC pavement design procedures and a recommended new PCC pavement design procedures for implementation by CAPEC members.

Thus, as an addendum to Phase 1, HVJ completed two subtasks listed below and summarized in this addendum to the Phase 1 report:

1. Review of PCC pavement procedures in the Dallas/Fort Worth and Houston areas.
2. Review CAPEC agency provided examples of historical PCC pavement designs and study sections in Central Texas.

2. Review Pavement Design Methodologies and Policies

Existing pavement design procedures and general standards were reviewed. The current pavement material test procedures and construction inspection requirements will also need to be reviewed and summarized as part of Phase 3. The key question is: How well do the current design procedures, standards, test procedures, and construction inspection requirements insure that the pavement cross section designed is constructed? This activity will identify gaps or disconnects between the pavement design and construction practices. The following entities were included in the reviews: City of Austin, City of Dallas, City of Fort Worth, City of Houston and City of San Antonio.

2.1. City of Austin

City of Austin's current design procedure which will be replaced with the resulting recommendations of the CAPEC study is Municipal Rigid Pavement (MRPS), a customized version of an older TxDOT RPS program (see section 3.2.1). Slab construction on natural soil is not permitted. Subbase must consist of Asphalt Stabilized Base (min. 4" and max. 8"), Cement-Treated Base (min. 6") or Lime-Treated Subgrade (min. 6" and max. 10").

The City requirements for Lime Stabilization include: Mix design shall produce a 28-day Unconfined Compressive Strength of 50 psi for Lime Stabilized Subgrade and 100 psi for Lime Stabilized Base. The City requirements for Cement Stabilization include: 7-day compressive strength between 100 psi for fine-grained and 1,000 psi for coarse-grained soils.

This Loss of Support (LS) factor is included in the design of rigid pavement to account for the potential loss of support arising from subbase erosion and/or differential vertical soil movement. An LS value of 0 is selected for Cement or Asphalt-treated base, 0.5 for Lime treated and 0.5 to 2.0 for Flexible Base.

The minimum slab thickness of six inches to eight inches are typically used for Austin city street designs. The maximum slab thickness is ten inches. The recommended reliability value for all streets is 90%. The Initial Serviceability Index is set at 4.2 and the Terminal Serviceability Index varies by street type: Arterial 2.5; Primary Collector 2.0; Collector 1.5; and Residential 1.0.

2.2. City of Dallas

Subgrade stabilization requirements for the City of Dallas are summarized in Table 2.1 on the following page based on classification and subgrade soil condition. Standard City of Dallas design criteria provides 30-year design life for new concrete streets using mix designs with 4,000 psi (Machine Finish) and 4,500 psi (Hand Finish) 28-day compressive strengths. City of Dallas uses AASHTO design procedure with the computer program '*Pavement Analysis Software (PAS)*' published by the American Concrete Pavement Association. Parameters include a terminal serviceability index of 2.25 with a reliability of 85%.

If lime treatment of subgrade is designed, but deleted at the request of the Owner or Contractor and approved by the City Project Engineer, the pavement thickness shall be increased by at least 1". If cement stabilization of subgrade is designed, but deleted at the request of the Owner or Contractor and approved by the City Project Engineer, the pavement thickness shall be increased by at least 1.5". If cement treated base is designed, but deleted at the request of the Owner or Contractor and approved by the City Project Engineer, the pavement thickness shall be increased by at least 2" for every 4" of CTB deleted. If lime is used in lieu of cement when cement has been designed, the pavement shall be increased by at least 0.5". If the Contractor proposes cement in lieu of lime to expedite construction when lime has been specified, the rate of cement required shall be at least 2% more than the rate of lime required. No pavement thickness reduction is allowed for this substitution.

Minimal steel reinforcement is required for all standard concrete street pavements.

2.3. City of Fort Worth

City of Fort Worth utilized AASHTO Design procedure and requires minimum 6" subgrade modification (2%-6%) or stabilization (4%-12%) for CBR < 3, Arterial/Collector street with CBR < 5, or swell ratio ≥ 1. The design life considered for City of Fort Worth is 25 years for residential and collector streets and 30 years for industrial and arterial streets.

Stabilization can include the following:

- Lime or Portland Cement
- Geosynthetics on compacted subgrade followed by a permeable base material consisting of unbonded crushed stone or crushed stone bonded with cement to form Cement Treated Permeable Base (CTPB)

Modification does not increase the subgrade support value, only reduces plasticity, improve workability, and improve working surface.

Minimum PCC thickness: 6" for Residential, 7" for Collector, and 8" for Industrial or Arterial streets.

Table 2.1 Subgrade Stabilization Required Based on PI and Road Classification - City of Dallas

Subgrade Soil Condition	Classification		Subgrade Treatment							PCC Thickness	k-value, pci
			6” Compacted	8” Compacted	6” Lime/ Cement	8” Lime/ Cement	8” Cement Stab. (4%)	8” Cement Stab. (6%)	8" Cement Stab (8-10%)**		
Subgrade Soils with PI ≤15	Local	Residential	✓							6"	200
		Non-residential		✓						8"	200
	Collector	Normal Residential		✓						8"	200
		Normal Community		✓						9"	200
		Heavy Duty						✓		9"	350
	Minor Arterial	Normal					✓			9"	250
		Heavy Duty						✓		11"	350
	Principal Arterial	Normal					✓			9"	250
		Heavy Duty						✓		11"	350
Subgrade Soils with PI >15	Local	Residential			✓					6"	200
		Non-residential				✓				8"	200
	Collector	Normal Residential				✓				8"	250
		Normal Community				✓				9"	250
		Heavy Duty*							✓	9"	350
	Minor Arterial	Normal				✓				9"	250
		Heavy Duty*							✓	11"	350
	Principal Arterial	Normal				✓				9"	250
		Heavy Duty*							✓	11"	350

* For soils with a PI>45, an 8" cement stabilized subgrade shall be used with a percent cement determined by a testing laboratory

** For soils with PI≤25 but PI >15, 8" cement stabilization shall be used with 8% cement. For soils with PI≤45 but PI>25, 8" cement stabilization shall be used with 10% cement

Drainage coefficients used for design by the City of Fort Worth state that PCC pavements placed without a permeable base layer do not allow for adequate internal drainage. This condition shall be considered “Very Poor” with a Greater than 25% of time that the pavement structure is exposed to moisture levels approaching saturation. Max allowable drainage coefficient shall be 0.70. PCC pavements placed with a 3” minimum permeable base and tied to an edge drain system shall have a maximum drainage coefficient of 1.15. PCC pavements placed with a 5” minimum permeable base and tied to an edge drain system shall have a maximum drainage coefficient of 1.25.

All rigid pavements shall be JRCP or CRCP (CRCP only if approved by Engineer). Steel requirements for JRCP are per AASHTO design guide except for a max spacing #3 at 24”, larger bars shall have max spacing of 36”, Steel requirements for CRCP are per AASHTO design guide except for transverse steel max spacing #3 at 24”, and larger bars shall have a max spacing of 36”

Joints specifications call for the following:

- Transverse Contraction Joints: Max spacing = 5x slab thickness (in.)
- Ratio of Transverse contraction joint spacing to pavement width shall not exceed 1.25.
- Longitudinal Contraction Joints: Used if width from CL to pavement edge is >5x the slab thickness (in.). Typical of turning lanes.
- Dummy Saw Joints: Transverse, placed half way between transverse contraction joints. Longitudinal, placed along CL of pavements with width ≤ 5x the slab thickness.
- Construction Joints: Transverse shall be minimized (only as shown by Engineer or in case of emergency termination). Mandatory along CL of all PCC pavements.
- Expansion Joints: At all intersections, where pavements abut structures, and at a maximum of 600 ft. spacing.

2.4. City of Houston

City of Houston minimum PCC thicknesses are based on pavement widths and street classifications. For concrete pavement widths less than 27 ft., the minimum PCC thickness shall be 6” with a minimum 6” of subgrade stabilization. For concrete pavement widths greater than 27 ft. but not classified as Major Thoroughfares, the minimum PCC thickness shall be 7” with a minimum 6” subgrade stabilization. Lastly, for Major Thoroughfares constructed with PCC, the minimum thickness shall be 8” with a minimum 8” of subgrade stabilization.

The City of Houston requires pavement design to be based on current AASHTO design methodology. All concrete is specified at a 28-day compressive strength of 3,500 and a modulus of rupture of 600 psi.

2.5. City of San Antonio

City of San Antonio requires stabilization of soil with lime whenever the PI is greater than 20. A minimum of 6” of lime stabilized subgrade is needed at the density of 15 lb/ yd^2. If the construction time is limited or sulfate bearing soils (sulfate >3,000 ppm) are encountered, cement stabilization is recommended.

Various techniques for treatment of expansive soils considered by the City of San Antnoio are chemical injection, treatment of soil with lime or cement, placing of geogrid between the base and the subgrade, removal and replacement of the expansive soil or Drains or Barriers to Collect or Inhibit Moisture Infiltration.

Other design inputs are reliability at 70% for Local Type A with/without bus traffic, 90% for Collector and Local Type B streets, and 95% for Primary and Secondary Arterials. The standard deviation for rigid pavements at 0.35, initial serviceability and terminal serviceability at 4.5 and 2, respectively. The drainage coefficient can range from 1.01 to 1.03 for rigid pavements based on average annual rainfall 28 – 31 inches per year.

Joint Spacing recommendations include:

- Construction Joint spacing should not exceed 15 ft. in either direction.
- It is recommended a joint sealant be used.
- It is recommended dowel bars be used and should be #9 smooth spaced 12 in. on center embedded at 8 in.
- Tie bars should be used at longitudinal joints and should be #4 at 36 inches on center with a minimum length of 30 inches.

3. Review PCC Pavement Examples in Central Texas

Specific examples of PCC pavement performance in Central Texas were provided by CAPEC agencies including any documentation available related to the design, construction, and performance of these pavements as summarized in Table 3.1. The City of Austin, Travis County, City of Pflugerville, and Williamson County, have some PCC projects where the performance has been good and others where premature cracking has occurred.

Table 3.1 Summary of PCC Pavement Sections Provided by CAPEC Agencies

Agency	Section Name	Subdivision/Project Name	Current Condition
COA	15th Street	Rio Grande to Guadalupe (intersections only, ~10-15 years old)	Current distress associated with joint details
COA	Anderson Lane	Shoal Creek to Burnet Rd. (Bus Lanes, ~10-15 years old)	Very rough ride due to matching existing curbs and gutters
COA	32nd Street	Duval to Red River (brand new)	Excellent condition < 2 years old
COA	Harris Park Blvd	E 32nd St to E Dean Keeton (at least 40 years old)	Older style long joint spacing, but overall good condition for age
COA	Bellvue Place	Duval to Harris Park Blvd (at least 40 years old)	Older style long joint spacing, but overall good condition for age

Agency	Section Name	Subdivision/Project Name	Current Condition
COA	Cesar Chavez	IH 35 Access to Pleasant Valley (some asphalt mixed with concrete, at least 50 years old)	Very old, replace in some blocks by HMAC. Older style long joint spacing
COA	Congress Ave	Colorado River to Capital (HVJ staff designed, almost 20 years old, CMTA bus lanes)	Excellent condition for > 20 years of CMTA bus traffic
COA	3rd Street	Downtown	Newly constructed
COA	Alexander Ave	Capital Metro Transit Station off MLK Blvd	New, but some distress associated with locked joints
COA	Brazos Street	Downtown	Newly constructed
COA	Comanche Trails Intersection	Comanche Trails	No information
COA	Convention Center Garage	Downtown	No information
COA	Alleys 5I & 5J	Downtown	No information
COA	Lakewood Drive	at Bull Creek low water crossing	New and performing well
COA	Lamar Blvd	5th St to 6th St	No cracking; excellent condition; built in 2005
PFL	Stone Hill Drive	n/a	New designed and installed by mall developer, excellent condition
TNR/COA	Harris Branch Parkway	n/a	No information
WILCO	Hero Way	n/a	Newly constructed in ~2011

3.1. PCC Software Models

The PCC software models reviewed for consideration by CAPEC are summarized in Table 3.2. Available Software User Manuals are listed in the reference listing in Section 6.

Table 3.2 PCC Design Software Models Reviewed

Design Software	*Source*	*Date*	*Rigid Pvt. Design*	*Life Cycle Cost Model*
MRPS-1.0	COA	1986	√	√

Design Software	*Source*	*Date*	*Rigid Pvt. Design*	*Life Cycle Cost Model*
DARWin 3.1.017	AASHTO	2009	√	√
DARWin-ME^{TM}	AASHTO	2011	√	√
PCA-Pave Beta Version	PCA	2009	√	√
StreetPave 12	ACPA	2014	√	√
NTTA	NTTA	2008	√	
WinPRES	TTI	2006	√	
WinPAS	ACPA	1993	√	√
TSLAB	TxDOT	1986	√	

3.1.1. City of Austin MRPS 1.0

The current City of Austin Municipal Rigid Pavement System (MRPS 1.0) model implemented in 1986 was based on the TxDOT Rigid Pavement Design System (RPS 3.0), which was completed in in 1974. The k-value defined the subgrade support along the centerline of the pavement project and was recommended in the City of Austin Transportation Criteria Manual (TCM) to be determined by correlation with the estimated Texas Triaxial Class of the subgrade/roadbed soil (TCM Figure 3-7 of Appendix H).

The MRPS 1.0 model included a life cycle cost model based on future rehabilitation and maintenance events and associated user delay costs based on traffic delays during rehabilitation and maintenance cycles and the expected traffic control model required. The complementary City of Austin Municipal Flexible Pavement System (MFPS 1.0) also has the same life cycle cost model and thus the two model results were directly comparable.

In the interim years, TxDOT replaced RPS 3.0 with the AASHTO DARWin pavement design software, which was produced in conjunction with the 1993 AASHTO Pavement Design Guide. Some TxDOT units also have used the TSlab model. MRPS 1.0 has been used in a limited way over the last 30 years since the City of Austin has traditionally favored hot mix asphalt concrete pavements on a first cost basis. However, as summarized in Table 3.1 the City has several examples of long lasting PCC pavements. As the City expands eastward into poorer subgrade soils it is expected that there will be many locations where PCC pavement will prove to be the most cost effective solution on a life cycle cost basis.

Finally, the MRPS 1 model is not supported in the newer versions of the Microsoft Windows Operating system. The program must be run in Windows XP or earlier.

3.1.2. American Association of State Highway and Transportation Officials (AASHTO) DARWin 3.1.017

Subsequent AASHTO developments produced the Design and Rehabilitation for Windows (DARWin) pavement design software (1991 – 2009), which used the effective modulus of subgrade reaction k –value. This model characterizes the pavement support in terms of an effective modulus of subgrade reaction (k-value), which is calculated was a function of the subgrade roadbed soil resilient modulus, base elastic modulus, and base thickness.

The use of more complex but appropriate laboratory testing procedures such as the Dynamic Resilient Modulus (AASHTO Test T307) and the use of nondestructive deflection testing equipment such as the Falling Weight Deflectometer (FWD) (AASHTO Test D4694) have been incorporated to develop better estimates of insitu pavement material strengths. The material strength values used in design are Elastic Modulus for pavement layers and Resilient Modulus for the insitu subgrade layers. This allows for the proper characterization of the many different materials types that are options for pavement design and construction today.

Now that AASHTO has released a Mechanistic-Empirical Pavement Design software model, DARwin is long longer sold nor is it be supported by AASHTO. Thus this model will not be available to the general geotechnical nor public agencies to purchase or use.

3.1.3. DARWin-ME

AASHTO released the Mechanistic-Empirical Pavement Design Guide Interim Edition, a Manual of Practice in July 2008. Based on refinements made from a 2007 version of mechanistic-empirical (ME) software, AASHTO released a commercial version of ME design software, DARWin-ME^{TM} in 2011. The DARWin-ME^{TM} uses mechanistic-empirical numerical models to analyze input data for traffic, climate, materials, and proposed structure to estimate damage accumulation over the service life. This program can be applied to new, reconstructed, or rehabilitated flexible, or rigid pavements. Performance is based on distresses and smoothness. Distresses analyzed for flexible pavements include longitudinal, transverse, and alligator cracking, and rutting. Distresses analyzed for rigid pavements include faulting, cracking, and punchouts.

3.1.4. PCAPave Beta Version

PCA Pave provides a means to evaluate and design Roller-Compacted Concrete (RCC) for industrial type pavements such as ports, rail terminals, truck terminals, industrial yards, and other pavements subjected to heavy non-highway vehicles and equipment. The program also has the option for conventionally loaded vehicle modeling. For pavement evaluation, the program determines the critical pavement bending stresses due to loading. For pavement design, the program determines the slab thickness required for the anticipated traffic. Sensitivity figures are available to evaluate the effect on thickness design by changing the PCC or subgrade strength values.

3.1.5. American Concrete Pavement Association (ACPA) StreetPave 12

The basis of StreetPave go back to the 1960's Portland Cement Association method. StreetPave is tailored for streets and roads (not highways or interstates) with the failure models being cracking and faulting.

The traffic analysis no longer requires the input of ESALs. StreetPave focuses on a traffic spectrum. Specifically, total trucks in the design lane over the design life calculated from trucks per day, traffic growth rate, design life, directional distribution, and design lane distribution. StreetPave has predetermined traffic spectrums and counts but the user can also enter a custom traffic spectrum if available.

StreetPave looks at the stresses at the edge of the slab generated by the traffic loads. The equation uses equivalent moment which is different for a single, tandem or tridem axles (with and without edge support) which is dependent on concrete modulus, Poisson's ratio, thickness, and k-value.

Included in the equivalent edge stress calculations are adjustment factors for the effect of axle loads and contact area, adjustments for slabs with no concrete shoulder, adjustment for the effect of truck wheel placement at the slab edge, and adjustment to account for an approximate 23.5% increase in concrete strength with age after the 28th day and reduction of one coefficient of variation to account for materials variability.

StreetPave limits the stress ratio to achieve a desired number of design repetitions. StreetPave increases the thickness of the slab to bring the stress ratio low enough to achieve the desired number of traffic repetitions (see Figure 3.1).

$$Stress\ Ratio\ (SR) = \frac{Stress}{Concrete\ Strength}$$

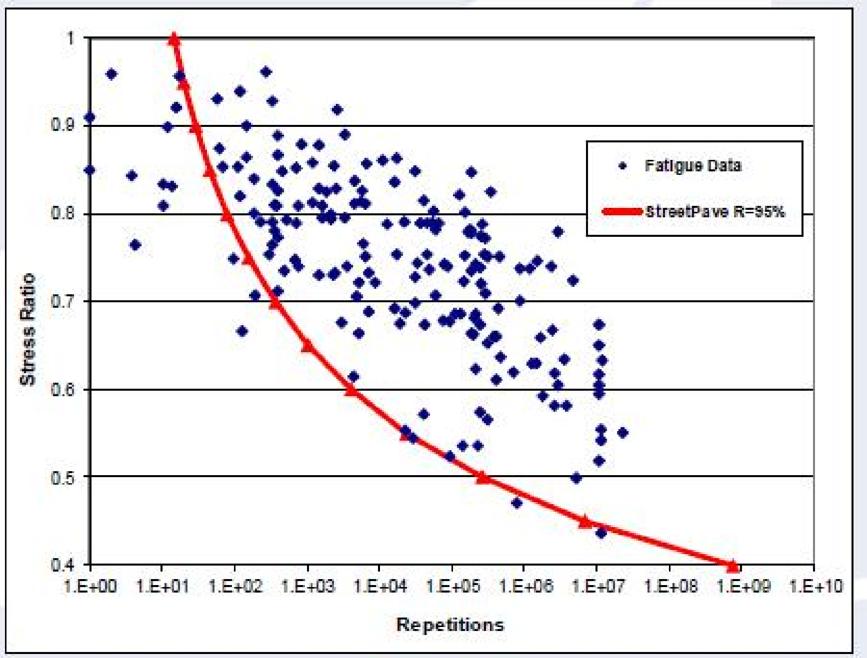

Figure 3.1 Stress Ratio versus Repetitions for StreetPave

Figure courtesy of 2014 TxDOT/CCT Concrete Conference, September 30, 2014, Robert Rodden, P.E.

The other failure model used by StreetPave is faulting. The faulting failure model used by StreetPave increases the concrete thickness until the model predicts that the pavement will not fail by faulting during the design life. Since no faulting data was collected during the AASHO road test, the model was developed in the 1980's using field performance data from Wisconsin, Minnesota, North Dakota, Georgia, and California. This can be characterized as a "weak point" of StreetPave since it is not based on Texas data.

StreetPave has been accepted as the design procedure in Minnesota and "approved" in Virginia. Many other city, state and counties are utilizing StreetPave in the US. StreetPave is used in design tables in ACI 325 and ACI 330. Internationally it is used in Australia, Portugal, Mexico, Uruguay, Argentina, and Chile.

Below is a figure of various design procedures using virtually similar design inputs to demonstrate the thickness comparison.

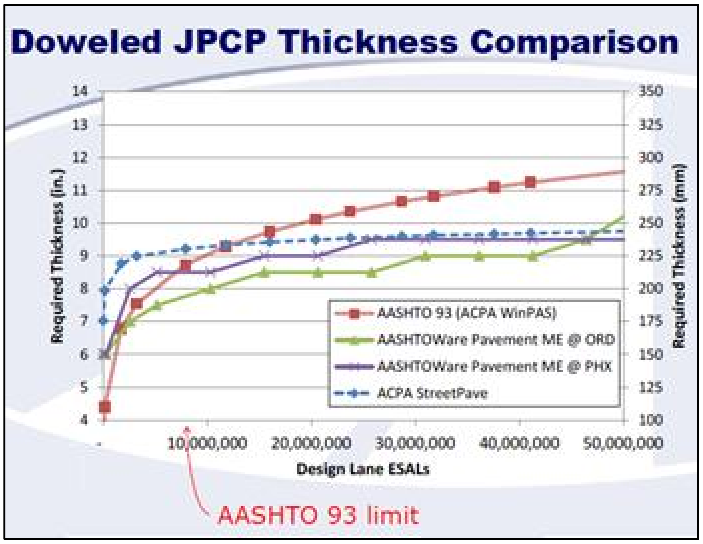

Figure 3.2 Thickness Comparison of Different Software to StreetPave

Figure courtesy of 2014 TxDOT/CCT Concrete Conference, September 30, 2014, Robert Rodden, P.E.

3.1.6. NTTA

The NTTA mechanistic design spreadsheet developed by Dr. Dan Zollinger for CRCP pavements (Ref 5) is trial-and-error method requiring iteration to solve for a specific level of CRCP performance in terms of punchouts per mile.

To simplify the design process of the NTTA mechanistic methodology, the Excel design program has limited the number of user input variables making many of the variables fixed. This resulted in the pavement design having only a few select variables including: CRCP thickness, ADT, lane distribution factor (DL), growth rate, aggregate type, construction season, and k-value.

After all the inputs were entered, the mechanistic analysis was solved for a specific level of performance in terms of punch outs per lane mile, which is a function of the pavement thickness based on an iterative method. The required pavement thickness for SH 161 for the main lane facilities must meet the requirement of less than 3 punch outs per lane mile. The CRCP pavement thickness was gradually increased and reanalyzed until the desired punch out per lane-mile criteria was achieved.

Traditional Jointed Reinforced Concrete Pavement (JRCP) is designed using the 1993 AASHTO Guide and the DARWIN procedure and the Texas DOT Concrete Pavement Contraction Design (CPCD)-94 standard is followed for reinforcement and jointing details. The main contribution of this procedure is the consideration of subgrade moisture treatment for the pavement design.

3.1.7. WinPRES Program

Texas A&M University TTI WinPRES program is not actually a design program; however, it can analyze both flexible and rigid pavement sections. Its significance is that it attempts to quantify the value and benefit of both subgrade stabilization and moisture barrier depth by modeling and estimating the resulting pavement roughness over the design life.

3.1.8. WinPas

WinPas is based on AASHTO 1993 Guide for the Design of Pavement Structures using inputs such as serviceability, traffic (ESALs), load transfer coefficient, concrete properties, subgrade support, coefficient of drainage, and reliability. WinPAS can be used for new concrete pavement design, concrete overlay design, and life-cycle cost analysis (LCCA).

3.1.9. TSLAB

TSLAB was developed by TxDOT using the American Association of State Highway and Transportation Officials (AASHTO) rigid pavement design equation (TxDOT 93). TSLAB generates concrete pavement thicknesses based on AASHTO design inputs. TSLAB, however, simplifies the AASHTO design by omitting loss in serviceability resulting from the environment.

3.2. Comparison of Design Methodologies

After review some of the software design methods were not considered for further analysis, due to the factors provided in Table 3.3.

Table 3.3 Summary of Software Excluded from Further Study

Software	Reason not considered further
ME-PDG V1.1 Beta	New version, complex unavailable inputs, and high cost
PCA-Pave Beta	Beta version no longer in development, only covers RCC
WinPAS	Based on AASHTO (same as DARWin)
NTTA	CRCP pavement
WinPRES	Not design software, but swelling clay analysis model
TSLAB	Based on AASHTO (same as DARWin)

The software considered in the final review are listed in the following table, including the subgrade and pavement layer strength parameters required and the failure criteria considered.

Table 3.4 Summary of Software Considered

Software	Subgrade Strength Parameter	Pavement Layer Strength Parameters	Failure Criteria*
DARWin 3.1.017	Elastic Modulus (FWD Back-calculated and adjusted)	Elastic Modulus to calculated effective k-value	Serviceability Loss; Mechanistic Check; Texas Triaxial Check
MRPS 1.0	k-value	Structural Coefficient	Serviceability Loss
StreetPave 12	CBR or R-Value or k-value or Resilient Modulus	Not Input by user; predefined	Mechanistic (cracking and faulting)

* Serviceability Loss failure criteria is a function of slope variance (ride quality), rut depth, and cracking and patching. Mechanistic failure criteria uses fatigue and rutting equations based on elastic layer theory predicted strains. Texas Triaxial Design method uses triaxial classification of subgrade from lab tests.

3.2.1. Matrix of Design Runs for Comparison

A matrix of design runs was established which included four different traffic levels representing various roadway functional classifications. Additionally, three different subgrade soils conditions were considered. The resulting matrix is summarized as follows.

Table 3.5 Matrix of Design Runs

Classification	***Design 18 Kip ESALs***	***Low Plasticity PI<25***	***Moderate Plasticity PI>26***	***High Plasticity PI>55***
Arterial – High Traffic	6,300,000	√	√	√
Arterial	1,500,000	√	√	√
Collector	290,000	√	√	√
Local	40,000	√	√	√

3.2.2. Input Variables

Input variables selected for the three models are summarized in the table below. Where possible these inputs are exactly the same, however the difference in the models did not always allow input of every variable due to the model not using that variable or that variable being internal to the program and the value not known.

Table 3.6 Software Input Variables

Input *Parameter*	***DARWin Value***	***StreetPave Value***	***MRPS Value***
Design Period	20 years	20 years	20 years
Design Traffic, ESALs			
Local	40,000 psi	40,000 psi	40,000 psi
Collector	290,000 psi	290,000 psi	290,000 psi
Arterial	1,500,000 psi	1,500,000 psi	1,500,000 psi
Arterial - High	6,300,000 psi	6,300,000 psi	6,300,000 psi
Percent of Concrete Slabs Crack at End of Design Life			
Local			
Collector		25%	
Arterial		15%	
		15%	
Lime-treated subgrade Thickness	8”	8”	8”
Lime-treated subgrade Modulus	20,000 psi	20,000 psi	20,000 psi
Hot-Mix Asphalt Base Thickness	4”	4”	4”
Hot-Mix Asphalt Base Modulus	400,000 psi	400,000 psi	400,000 psi
Subgrade Resilient Modulus, M_R	1,000 psi 5,000 psi 10,000 psi	1,000 psi 5,000 psi 10,000 psi	1,000 psi 5,000 psi 10,000 psi

Input *Parameter*	*DARWin Value*	*StreetPave Value*	*MRPS Value*
Compressive Strength of Concrete f'c	4,000 psi	4,000 psi	4,000 psi
Loss of Support Factor, LS	2.0		
Concrete Elastic Modulus, E_c	3.6 x 10^6 psi	3.6 x 10^6 psi	3.6 x 10^6 psi
Mean Concrete Modulus of Rupture, S'_c	620 psi	620 psi	620 psi
Load Transfer Coefficient (JRCP), J	2.9	2.9	2.9
Drainage Coefficient, C_d	1.03	1.03	
Design Serviceability Loss, D psi	2.0	2.0	
Reliability, R			
Local	90%		
Collector	90%		
Arterial	90%		
Arterial High	95%		
Overall Standard Deviation, S_o	0.39	0.39	
Presence of Load Transfer Dowels		No	
Edge Support		Tied Concrete Shoulder, curb and gutter, or widened lane	

3.3. Design Results

The designs were run for three different subgrade strengths, as defined in the table above and the results are summarized by subgrade strength in the following tables.

Table 3.7 PCC Design Thickness for Subgrade Modulus of 1,000 psi

Design Procedure	DARWin	StreetPave	MRPS
Local Thickness, in	4.0"	5.5"	4.0"
Collector Thickness, in	5.5"	6.5"	5.5"
Arterial Thickness, in	7.5"	7.5"	7.5"
Arterial – High traffic Thickness, in	10.0"	9.0"	10.0"

Table 3.8 PCC Design Thickness for Subgrade Modulus of 5,000 psi

Design Procedure	DARWin	StreetPave	MRPS
Local Thickness, in	_	4.5”	4.0”
Collector Thickness, in	4.5”	5.5”	5.0”
Arterial Thickness, in	6.5”	6.5”	7.5”
Arterial – High traffic Thickness, in	9.0”	7.5”	9.5”

Table 3.9 PCC Design Thickness for Subgrade Modulus of 10,000 psi

Design Procedure	DARWin	StreetPave	MRPS
Local Thickness, in	_	4.0”	4.0”
Collector Thickness, in	_	5.0”	4.5”
Arterial Thickness, in	5.5”	6.0”	7.0”
Arterial – High Thickness, in	8.5”	7.0”	9.5”

Comparing the DARWin, Streetpave, MRPS design thicknesses as the subgrade modulus values increase, and as the traffic levels increase by street classification shows the importance which should be placed on the determination of these key input values.

3.3.1. Sensitivity of Subgrade Strength

As sensitivity tests show the subgrade K value typically does not significantly affect the thickness calculations by more than one-half to one inch. However the use of non-erodible supporting layers has been proven to have a large effect on long term PCC pavement performance. Table 3.10 shows the values of typical K-values for various materials.

Table 3.10 Typical Subgrade K-values

Soil Type/Subbase	Strength	K-Value (psi/in)	M_r (psi)	CBR
Silts / Clays	Very Low	50-100	1000-1900	<3
Fine Grained	Low	100-150	1900-2900	3-5.5
Sands	Medium	150-220	2900-4300	5.5-12
Gravely soils	High	220-250	4300-4850	>12
Asphalt Treated Base	High	350-450	100,000+	>12
Cement Treated/Lean Concrete Base	High	400-600	500,000+	>12

Texas DOT requires either HMAC or CTB non erodible base materials beneath PCC pavements based on long term experience that this enhances PCC pavement life and performance. A minimum k-value of 300 psi/in has been specified as a design input for these base layers. The new 2011 TxDOT Pavement Design Guide now allows the design engineer to use a value of up to 800 psi/in if the design value can be proven at all times during construction.

4. Recommended Design Details

The concrete industry has a number of documents providing guidance on laying out concrete joints as well as details for joints. Design of Jointed Concrete (ACI 325-12R-02) and Design of Joints for Concrete Streets (ACPA IS061.01P) are both excellent references by the industry.

4.1. Joint Layout Guidance

It is highly recommended that the designer develop a joint layout (especially important for intersections) that is included in the construction plans. The primary goal of the layout is to ensure that joints pass through fixtures embedded in the concrete, i.e. manholes or inlets. Should the locations of the fixtures change during construction, the joints should be varied therefore a note on the plans to give the field engineer and/or contractor the ability to make these changes should be considered.

An example of a joint layout for an intersection (from the ACPA Intersection Joint Layout pamphlet) is shown below.

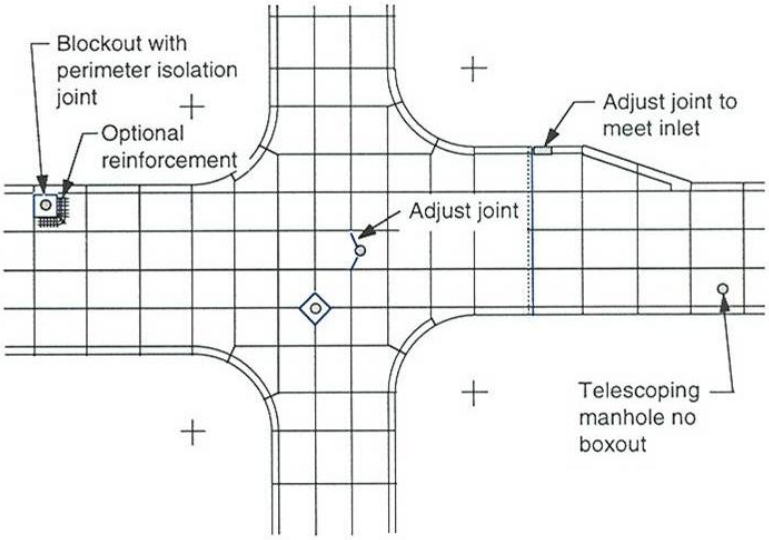

Figure 4.1 Adjusting Joints for Utility Fixtures (ACPA)

The City of Austin recommends targeting a 10’ to 12’ joint spacing with an absolute maximum of 15’ only where necessary. By using short panel lengths intermediate cracking may be minimized sufficiently that distributed reinforcement is not required.

4.2. Joint Details

There are primarily three different types of joints: 1) construction joints, 2) sawed contraction (weakened plane) joints, and 3) isolation or expansion joints. All joints are recommended to be sealed with a joint sealant appropriate for the specific project conditions.

Construction joints are directly related to construction phasing and contractor equipment and practices, as they are located where the paving starts and stops (transverse) and longitudinal based on the width to which the paving machine is set. These joints will be sealed therefore a joint seal reservoir must be sawed along the joint.

Sawed contraction joints are typically transverse and are required to establish the desired panel size. The depth of the initial saw cut is based on the concrete thickness (t), typically $t/4 \pm 1/4$". A joint reservoir is then saw cut over the initial saw cut.

Isolation and expansion joints accommodate anticipated differential movements that occur between a pavement and a structure. The purpose is to allow movement without damaging the adjacent structures. Full depth, full width expansion joints placed at regular intervals (in the past from 50 ft and more) is an old practice that caused joint pumping, spalling and corner breaks. Therefore, only isolation joints are recommended for use at structures adjacent to the concrete pavement. Isolation joints are typically ½ to 1 inch wide and are filled with a pre-formed joint filler material to prevent infiltration of incompressibles.

4.3. Reinforcement

The use of distributed steel reinforcement is only intended to keep cracks that form in the concrete panels closed and will not add load-carrying capacity to the pavement. The use of reinforcing as discussed in sec. 3.8.1, from ACI 330R-08, Guide for the Design and Construction of Concrete Parking Lots, indicates when pavement is jointed to form short panel lengths that will minimize intermediate cracking, distributed steel reinforcement is not needed. This City of Austin is very much opposed to any reinforced pavements except under the most extreme circumstances. A more effective use of that same level of investment would be to add additional thickness to the unreinforced section.

Reinforcement should be considered for irregular panels typically depicted in intersection layouts. Irregular panels would be any panel which has a sharp angle and is neither square nor rectangular or when the length-to-width ratio exceeds 1.7. Distributed steel reinforcement should be calculated based on the drag formula (Portland Cement Association 1955):

$$A\ (\text{in}^2/\text{ft}) = (LC_f wh)/24(f_s)$$

Where:
A = area of distributed steel reinforcement required per unit width of slab, in^2/ft
L = distance between joints, ft
C_f = coefficient of subgrade resistance to slab movement
w = density of concrete (145 pcf)
h = slab thickness, in
f_s = allowable tensile stress in steel, psi (2/3 yield strength commonly used)

Additionally, jointing steel in the form of dowels are recommended to transfer load across the joints. The potential for faulting may thus be reduced. It is critical that the correct alignment and lubrication is utilized for the dowels to function properly. If dowels are misaligned (i.e. either vertical or horizontal), the stresses induced when the joint tries to open with temperature changes will result in cracking in the concrete.

5. Conclusion

Due to the variation of design inputs and failure criteria, the design procedures are difficult to compare in terms of outcome. The various pavement design methodologies, with the proper input variables, should produce an adequate "top down" design. The decision regarding a specific method to consider for a "unified" PCC design procedure will require consideration of additional factors, such as ease of use, cost and support of the software, pavement layer strength input values backed up by field/laboratory tests, etc. Without further input at this time, StreetPave is recommended going forward in Phase 3.

One outcome of the comparison was the need to address the subgrade soils design separately from the pavement thickness design. The Phase 2 efforts are focused on the following: subgrade soil model, soil testing correlations, and soil stabilization strategies. The efforts also include traffic characterizations and parameters, which need to be better defined for whichever model is used.

Of specific interest is the subgrade strength parameter. The design software reviewed use a variety of parameters for subgrade strength including: CBR, R-Value, k-value, stiffness coefficient, elastic modulus and resilient modulus. Resilient modulus may be obtained from laboratory tests (AASHTO T274) as can CBR (ASTM D1557 and D698). Elastic modulus may be back-calculated from nondestructive deflection testing (NDT) collected as per (ASTM D4694), but may require adjustments prior to use in pavement design procedures. Stiffness coefficient is calculated based on empirical data correlating nondestructive deflection testing with specific testing equipment (Dynaflect).

6. References

1. "Appendix B: Computerized Pavement Design Program Municipal Rigid Pavement Design (MRPS-1) Input Guide." *City of Austin, Texas Transportation Criteria Manual.* American Legal Publishing. Web. <Design Guidelines for Streets and Bridges. N.p.: Travis County, 1986. Print.>.

2. Applied Research Associates, Inc. *DARWin Pavement Design System Users Guide.* 3.1 ed. AASHTO, 2009.

3. *Mechanistic-empirical Pavement Design Guide: A Manual of Practice*. Washington, DC: American Association of State Highway and Transportation Officials, 2008.

4. *PCA Pave User's Manual.* Ver. 1.0 Portland Cement Association.

5. *PCA Pave Technical Supplement.* Ver. 1.0 Portland Cement Association.

6. *StreetPave.* Ver. 12 American Concrete Pavement Association, 2012.

7. North Texas Tollway Authority (NTTA). Ver. 1.1, Pavement Design Manual. August 2008.

8. Lytton, Robert, Charles Aubeny, and Gyeong Taek Hong. *WINPRESS User Manual.* Texas Department of Transportation and Federal HighwayAdministration, 2007.

9. *Windows Pavement Analysis Software (WinPAS) Guide.* American Concrete Pavement Association, 2012.

10. TSLAB. American Association of State Highway and Transportation Officials Guide, 1993.

11. NTTA, "Pavement Design Manual – Subgrade Investigation and Design Manual for High Performance Tollway Pavements", and associated NTTA Mechanistic Design Spreadsheet developed by Dr. Dan Zollinger, 2008.

12. "Intersection Joint Layout", Concrete Information, American Concrete Pavement Association, 5420 Old Orchard Road, Suite A100, Stokie, IL 60077-1059, 1996.

13. "Proper Use of Isolation and Expansion Joints in Concrete Pavements", Concrete Information, American Concrete Pavement Association, 5420 Old Orchard Road, Suite A100, Stokie, IL 60077-1059, 1992.