Development and Implementation of a Mechanistic and Empirical Pavement Design Guide (MEPDG) for Rigid Pavements

ANNUAL REPORT FOR FY 2009

ODOT SPR ITEM NUMBER 2208

Submitted to:
Ginger McGovern, P.E.
Planning and Research Division Engineer
Oklahoma Department of Transportation
200 N.E. 21st Street
Oklahoma City, Oklahoma 73105

Submitted by:

Tyler Ley, Shardul Kadam, Robert Frazier and Bret Robertson
Oklahoma State University
Civil and Environmental Engineering
207 Engineering South
Stillwater, Oklahoma 74078

Kyle Riding
Kansas State University
Civil Engineering
2118 Fiedler Hall
Manhattan, Kansas 66506

September 30, 2009

The contents of this report reflect the views of the authors responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the views of the Oklahoma Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. While trade names may be used in this report, it is not intended as an endorsement of any machine, contractor, process or product.

1.0 Overview

This document is an update of the progress of the research on ODOT project 2208 "Development and Implementation of a Mechanistic and Empirical Pavement Design Guide (MEPDG) for Rigid Pavements". This report summarizes the work that was completed at Oklahoma State University between October 1st, 2008 and September 30th, 2009. The focus of this project is on assisting ODOT in implementing the MEPDG into their rigid pavement design practices. It was decided to best accomplish this goal by completing the following tasks:

A. Review of the inputs to the MEPDG and determine the sensitivity on the final design values.
B. Investigate base material practices for concrete pavements through a literature review and survey of experiences from others.
C. Increase the quantity of weather sites in Oklahoma that provide environmental inputs for the MEPDG.
D. Examine different curing methods for rigid pavement construction and their impact on the early age curling and warping of continuous reinforced concrete pavements
E. Provide regional material input parameters that can be used in the MEPDG for the design of rigid pavements

During this period tasks A and C were completed and therefore the bulk of the report is devoted to these subjects. However, progress on tasks B, D and E are also provided.

1.1 Background of the MEPDG

The MEPDG is design software that was developed by Applied Research Associates (ARA) through several funding projects from the National Cooperative Highway Research Program

(NCHRP). The goal of the software is to provide a new design methodology for concrete and asphalt pavements based on the latest failure mechanisms in combination with empirical data from the performance of pavements in the field. Before the release of the MEPDG it was common for designers to use a version of the AASHTO design guide. This design method has seen several different iterations that vary from hand methods that use nomo-graphs to simple software interfaces. The AASHTO design guide is based on empirical performance of several miles of test track in Ottawa, Illinois from 1958 to 1960. This testing is commonly called the AASHO road test. For this testing pavements were continuously loaded with trucks over a period of little more than 2 years.

While the AASHTO design guide has served designers well the following criticisms were made by the MEPDG documentation of the AASHO road test (ARA 2004):

1) Modern traffic levels have increased by 10 to 20 times the levels since the time of the AASHO road test. Because only a limited amount of data could be obtained from the original test, extrapolation of the damage observed in the AASHO road test was needed to determine the long-term performance of the pavements. While some extrapolation was deemed reasonable to determine the performance of pavements in the 1950s; however, this extrapolation would need to be taken to the extreme to meet modern traffic levels.

2) Environmental loading is thought to be an important component in the design of concrete pavements. Since the AASHO road test was only limited to pavements in Ottawa, Illinois and to a short period of little more than 2 years this key component cannot be modeled.

3) A limited number of construction materials were used in the construction of the test track. For example only one type of hot mix asphalt subgrade and only one concrete mixture was used.

4) The vehicle weights used for the test are now out dated.

5) The drainage system for the pavement has not been considered in the test.

6) Pavement rehabilitation procedures were not considered by AASHTO design guide.

The MEPDG has done its best to try and take as many of these variables as possible into account. The creators of the MEPDG feel that these short comings can be overcome if one is able to fundamentally define the performance of a pavement through the use of the latest mathematical models in combination with the measurement of the actual performance of pavements with a significant number of differences in climate, loading, and construction materials. These empirical observations are imperative to help the mathematical expressions to become meaningful and useful.

2.0 Review of the inputs to the MEPDG and determine the sensitivity on the final design - values

2.1 Variables in the MEPDG

The MEPDG software allows the user to change over 150 variables that impact the performance of the pavement. These variables have been grouped by category including: climate, traffic, pavement layers and their material properties.

2.1.1 Significance of Variables

While it is helpful to provide designers with a large number of variables that they are able to control in order to tailor their pavement design, this can also be a challenge for a designer as the number of variables can be overwhelming to try and control. Instead it would be more useful for designers to understand which variables have the largest impact on their designs or are the most significant. Other researchers have realized this and attempted to determine which variables have the biggest impact on the results of the MEPDG (Zaghloul et. al 2006, Kannekanti 2006, Harvey 2006, Mallela et. al 2005, Harrigan and Nov 2002).

While the previous work is useful some common difficulties were found including:

- no information about the MEPDG software version that was used for the analysis
- little information is given about the metrics used to determine if an input was significant
- no constant metric was used across investigations to compare results
- lack of detail of the range of values used in the analysis

Because of these inconsistencies, and the desires for ODOT to implement the MEPDG software it was decided to perform a new sensitivity analysis on the MEPDG. After reviewing the list of possible variables that can be modified and through discussions with ODOT a list of variables was chosen to be investigated that were deemed reasonable to be able to control in the field. A summary of these variables is shown in Table 2. These variables were investigated to quantify if the results of the MEPDG were sensitive to these parameters.

2.2 Sensitivity Analysis

This sensitivity analysis was completed between March and August of 2009 with version 1.0 of the software that was obtained from the MEPDG website, www.trb.org/mepdg/software. Along with this software hourly climatic data files from version 0.910 were also downloaded. It should be noted that the results from the MEPDG may not be the same if a different version of the software or if a different set of climatic data was used in the analysis.

It was decided that all of the comparisons of these previously mentioned variables should be done on a common metric that was easily accessible to a pavement design engineer. One easily recognizable variable to design engineers is the required pavement thickness. Unfortunately the current version of the MEPDG does not provide the user with a satisfactory pavement thickness for the variables presented. Instead it analyzes the pavement design with the variables used and will report if the pavement is adequate.

Therefore, to investigate the sensitivity of these different variables on the required pavement thickness it was decided to start with a pavement design that was representative of an ODOT pavement and find the AADTT that made it just adequate. A variable was then modified and the pavement was analyzed to see if the section was adequate. If the pavement adequacy was decreased then to compensate for this an increase in the overall pavement thickness was made. If the pavement adequacy was increased by the change in the variable then the pavement thickness was decreased to find the thickness that just allowed it to be adequate. By using this technique then it was possible to find how a single variable impacted the thickness design for a pavement.

Both continuously reinforced concrete pavement (CRCP) and jointed plain concrete pavement (JPCP) were considered for analysis. For these pavements the edge support was assumed to be a tied PCC shoulder and PCC-base interface was kept as full friction contact. The material properties of the asphalt, used as a bond breaker, was chosen to meet ODOT standards and not varied. The default parameters from the MEPDG were used unless noted in Table 1.

Table 1 – A summary of the baseline values for Oklahoma pavements.

design life	20 years*
cement	600 lbs of type I
concrete flexural strength	690 psi*
curing	curing compound
shoulder	tied
JCP dowel diameter	1.5"
CRCP reinf. ratio	0.70%
location	Stillwater
pavement openning	Fall
base layers	4" asphalt 8" chemically stabilized base
subgrade	8000 psi resilent modulus

* default values of the MEPDG

In order to find the AADTT for the various thickness of JPCP and CRCP that caused failure of the pavement section a pavement section was created with the previously mentioned baseline parameters and the AADTT values were increased until the pavement was found to just be unsatisfactory.   This allowed the limiting AADTT to be determined for the chosen design variables and thickness. A summary of the results is shown in Figure 1.

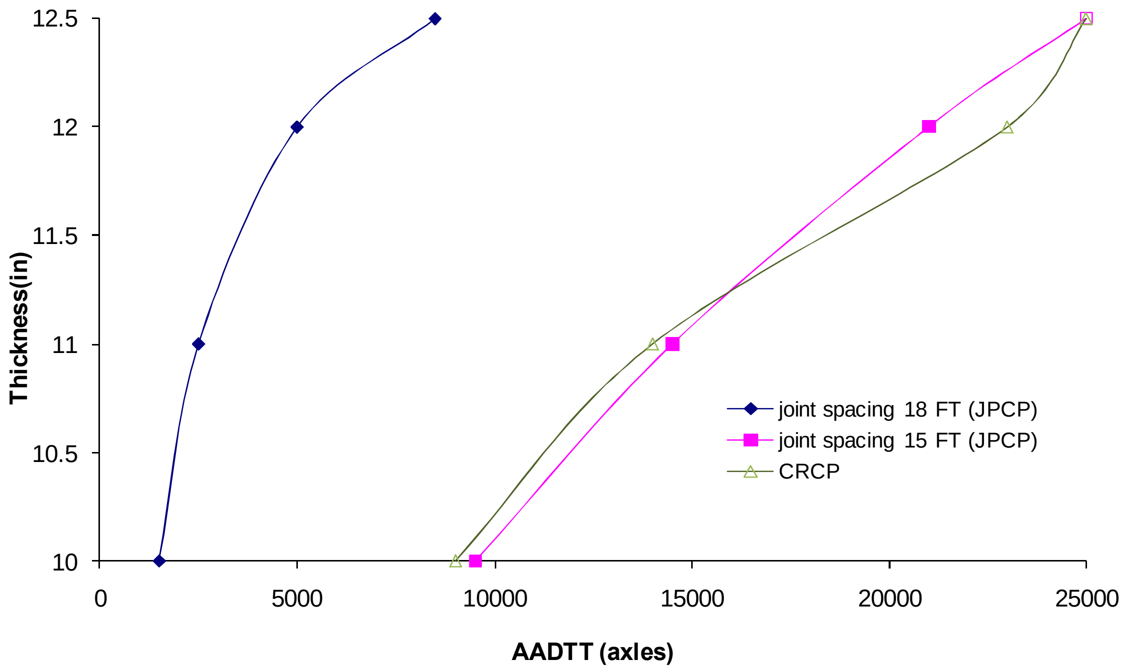


Figure 1 – A plot of the required design thickness for JPCP and CRCP with different AADTTs.

After a baseline AADTT was found for a pavement then the sensitivity analysis could begin. Next a variable from Table 1 was modified in the design and the pavement thickness was also adjusted until the pavement was found to just be acceptable. This allowed the impact on the thickness to be determined for a single variable for a given set of parameters. The range that each variable was varied over is summarized in Table 2.

Table 2 - A summary of the variables and their ranges used in the sensitivity analysis.

CRCP and JPCP parameters are:

parameter	range
pavement opening	fall, spring, or summer
CTE	3.5-8 x 10^{-6} /^{o}F
cement type	type I or II
curing	compound or wet
compressive stress	3000-6000 psi
cementitious material content	400-800 lbs/cy
asphalt layer thickness	0 - 6"
cement fly ash layer thickness	0 - 8"
reinforcement ratio (CRCP)	0.5 – 1%
dowel diameter (in) (JPCP)	1-1.75"
unbound resilient moduls	3000 - 13000 psi
climate	Stillwater, Clinton, Lawton, McAlsester, Oklahoma City, Tulsa, Frederick

2.3 Results

The impact of a change in each variable is reported in terms of the change in the required pavement thickness in the MEPDG to make the section adequate. A summary table is reported in table 4.

For each case the change in the pavement thickness in inches is given. A "+" was used for an increase in thickness and a "-" was used for a decrease in thickness. In some cases there was no impact on the thickness and a "0" is reported. A letter is also reported next to each thickness change that designates the failure mode that governed for that analysis. All default values are indicated by an asterisk, and values that were not expected were shown in bold. The default failure criteria established by the MEPDG was used in each analysis. These are summarized in Table 3.

Table 3 – A summary of the failure criteria used in the sensitivity analysis.

CRCP failure criteria	limit	reliability
terminal IRI (in/mi)	172	90
CRCP Punchouts (per mi)	10	90
maximum CRCP crack width (in)	0.02	
minimum crack load transfer efficiency (LTE %)	75	
JPCP failure criteria		
terminal IRI (in/mi)	172	90
transverse cracking (% slabs cracked)	15	90
mean joint faulting (in)	0.12	90

The following example is used to illustrate the use of the table. If we have a 12" CRCP pavement that is adequate and we change the CTE value of the aggregate from 5.5×10^{-6} to 6.5×10^{-6} then the design thickness will have to be increased by 1.5" to 13.5" to make the pavement adequate for the same AADTT. The controlling failure mechanism will be cracking and inefficient load transfer. This technique is able to quantify the impact of a change in a given variable on the design thickness of the pavement, for different pavement thicknesses.

Table 4 - Results from MEPDG sensitivity analysis.

material parameters

	CRCP				JPCP (spacing 18 FT)				JPCP (spacing 15 FT)			
parameters	12.5"	12"	11"	10"	12.5"	12"	11"	10"	12.5"	12"	11"	10"
cement type												
I*	0"L	0"P,L	0"P,L	0"P,L	0"T	0"T	0"T	0"T	0"J	0"J	0"J	0"T,J
II	-0.5"L	-0.5"P,L	- 0.5"P,L	0"L	0"T	0"T	0"T	0"T	0"J	0"J	-0.5"J	0"T,J
curing												
curing compound*	0"L	0"P,L	0"P,L	0"P,L	0"T	0"T	0"T	0"T	0"J	0"J	0"J	0"T,J
wet cure	-1" P,L	-0.5" L	-0.5"L	-0.5"P,L	0"T	0"T	0"T	0"T	0"J	0"J	-0.5"J	0"T,J
cement content (lbs/cy)												
500	-1"L	-0.5"L	-0.5"L	-0.5"P,L	0"T	0"T	0"T	0"T	0"J	0"J	-0.5"J	0"T,J
600*	0"L	0"C,L	0"P,L	0"P,L	0"T	0"T	0"T	0"T	0"J	0"J	0"J	0"J
700	**>+3"C,L**	**>+3"P,C,L**	**>+3"P,C,L**	**>+3"P,C,L**	+0.5"T	0"T	0"T	0"T	+1"J	+1"J	+0.5"J	+0.5"J
compressive strength (psi)												
3000	**0"P,L**	**0"P,C,L**	**0"I,P,L**	+0.5"P,L	+3.5"I,T	+3"I,T	+3"T	+3.5"T	+1.5"T	+1.5"T	+2"T	+1.5"I,T
4200	+0.5"L	+1"P,C,L	+0.5"P,C,L	+0.5"P,C,L	+1.5"I,T'	+1.5T	+1"T	+1.5"T	+0.5"J	0"J	0"T,J	+1"I,T
5000	0"C,P,L	+0.5"L	+0.5"C,L	+0.5"C,L	+0.5"T	+0.5"T	0"T	0"T	0"J	0"J	0"J	+0.5"T
6000	0"L	+0.5"L	0"P,L	+0.5"L	-0.5"T,J	-0.5"T	-1"T	-1"T	0"J	0"J	0"J	0"J
CTE (1x10^{-6}/^{o}F)												
4.5	-0.5"L	0"L	0"L	0"L	**-3"T**	**-2"T**	**-2.5"T**	**-2"T**	**>+3.5"J**	**-1.5"J**	**-3"J**	-1"I,T
5.5*	0"L	0"C,L	0"P,L	0"P,L	0"T	0"T	0"T	0"T	0"	0"J	0"J	0"J
6.5	**+2"C,L**	**+1.5"C,L**	**+1.5"C,L**	+1"C,L	**+3.5"T**	**+2.5"I,T,J**	**+2"T**	**+2.5"T**	**+3"I,J,T**	**+1.5"I,T,J**	**+2"J**	**+2.5"I,T,J**
resilient modulus (psi)												
3000	-0.5"L	0"L	0"L	0"L	0"J	**-1.5T**	**-1.5T**	**-0.5T**	+2J	+2J	+1"J	+1"J
5500	0"L	0"L	0"L	0"P,L	0"T	**-0.5"T**	**-0.5"T**	0"T	+0.5"J	+0.5"J	+0.5"J	+0.5"J
8000*	0"L	0"P,L	0"P,L	0"P,L	0"T	0"T	0"T	0"T	0"J	0"J	0"J	0"J
10500	0"L	+0.5"L	0" P,L	+0.5"L	**+0.5"T**	**+0.5"T**	0"T	0"T	0"J	0"J	-0.5"J	0"J
13000	0"L	+0.5"L	+0.5"L	+0.5"L	**+1T**	**+0.5"T**	**+0.5"T**	0"T	0"J	0"J	-0.5"J	+0.5"T

The required change in pavement thickness to insure comparable performance for the change in the variable. Positive values suggest an increase in thickness negative a decrease.
* - values used to represent typical ODOT pavements, therefore they have no impact on the pavement thickness
Bold values correspond to a result that was unexpected.
The controlling failure mode is given by the letters.
L - load transfer efficiency
P - punchouts
J - joint faulting
T - transverse cracking
I - IRI
C- cracking

design parameters

	CRCP				JPCP (spacing 18 FT)				JPCP (spacing 15 FT)			
parameters	12.5"	12"	11"	10"	12.5"	12"	11"	10"	12.5"	12"	11"	10"
pavement opening												
Summer	-0.5" L	0" L	0" L	0" L	+0.5" T	0"T	0"T	0"T	0"J	0"J	-0.5"J	0"I,T,J
Spring	**-2"L**	**-2"P,L**	**-1.5"PL**	**-1"P,L**	+0.5"T	0"T	0"T	0"T	-0.5"J	-0.5"J	**-1"J**	0"I,T,J
Fall*	0" L	0" P,L	0" P,L	0" P,L	0"T	0"T	0"T	0"T	0"J	0"J	0"J	0"I,T,J
reinforcement steel (%)												
0.6	**>+3.5"P,C,L**	**+2P,C,L**	**>+3.5"P,C,L**	**>+3.5"P,C,L**	-	-	-	-	-	-	-	-
0.7	0" L	0" P,L	0" P,L	0" P,L	-	-	-	-	-	-	-	-
0.8	-1.5"L	-1"L	-0.5"L	-0.5"L	-	-	-	-	-	-	-	-
dowel diameter (in)												
1	-	-	-	-	**>+3.5"I,J**	**+3.5"I,J**	**+3"I,J**	**+2.5"I,J**	**>+3.5"I,J**	**>+3.5"I,J**	**>+3.5"I,J**	**>+3.5"I,J**
1.25	-	-	-	-	**>+3.5"I,J**	**+3.5"I,J**	**+2.5J**	0"T	**>+3.5"I,J**	**>+3.5"I,J**	**>+3.5"I,J**	**>+3.5"I,J**
1.5*	-	-	-	-	0"T	0"T	0"T	0"T	0"J	0"J	0"J	0"T,J
1.75	-	-	-	-	0"T	0"T	0"T	0"T	-0.5"J	-0.5"J	-1"J	0"J
asphalt layer thickness(in)												
0	0"L	+0.5"L	+0.5"L	0"L	**>-3.5"T**	**-2.5"T**	**>-3.5"T**	**>-3.5"T**	**-1"J**	**-2"J**	**-3"T**	**-1.5"T**
2	0"L	0"L	0"P,L	0"P,L	+1"T	+0.5"T	+0.5"T	+0.5"T	+1"J	+0.5J	0"J	+1"T
4*	0"L	0"P,L	0"P,L	0"P,L	0"T	0"T	0"T	0"T	0"J	0"J	0"J	0"I,T,J
lime cement fly ash stabilized layer (in)												
0	0"J	+0.5"P,L	0"P,L	+0.5"L	0"J	**-0.5"T**	**-0.5"T**	**-0.5"T**	+1.5J	+1"J	+0.5"J	+0.5"J
3	0"T	0"L	0"L	0"P,L	0"T	**-0.5"T**	**-0.5"T**	**-0.5"T**	+0.5"J	+0.5"J	**-0.5"J**	0"T
5	0"T	0"P,L	0"P,L	0"P,L	0"T	**-0.5"T**	**-0.5"T**	0"T	+1"J	+0.5"J	0"J	0"T,J
8*	0"T	0"P,L	0"P,L	0"P,L	0"T	0"T	0"T	0"T	0"J	0"J	0"J	0"T,J
Climate												
Clinton	**>+3.5"C,L**	**>+3.5"C,L**	**+3"C,L**	+1.5C,L	0"T	-0.5"T	0"T	-0.5"T	-0.5"J	-0.5"J	-1.5"T	0"T
Fedrick	+0.5"L	+0.5"L	+0.5"L	+0.5"L	+0.5"T	+0.5"T	+0.5"T	+0.5"T	-0.5"J	-1"J	-1"T	+0.5"T
Lawton	0"L	+0.5"L	+0.5"L	+0.5"L	+1"T	0"T	0"T	0"T	-1"J	-1"J	-1"T	+0.5"T
Tulsa	-0.5"L	0"L	0"L	0"L	-0.5"T	0"T	-0.5"T	0"T	-0.5"J	0"J	0"J	0"T,J
Stillwater*	0"L	0"L	0"L	0"L	0"T	0"T	0"T	0"T	0"T	0"T	0"T	0"T
McAlester	-0.5"L	0"L	0"L	0"L	-0.5"T	0"T	-0.5"T	0"T	0"J	-1"J	-1"T	0"T

The required change in pavement thickness to insure comparable performance for the change in the variable. Positive values suggest an increase in thickness negative a decrease.

* - values used to represent typical ODOT pavements, therefore they have no impact on the pavement thickness

Bold values correspond to a result that was unexpected.

The controlling failure mode is given by the letters.

L - load transfer efficiency
P - punchouts
J - joint faulting
T - transverse cracking
I - IRI
C- cracking

2.4 Discussion -

From the results it is clear that some variables had a more significant impact than others. Furthermore, these variables often had different impacts on the different pavement types and thicknesses investigated. A discussion for each one of the variables is provided along with a summary in Table 5.

The season that the pavement was opened to traffic had little impact on the JPCP. However the CRCP pavements that were opened to traffic in the Spring were able to be reduced in design thickness between 1” and 2”. More work is needed to determine why this is and if it is rational.

The curing type had little impact on JPCP design thickness. However, it consistently impacted the design of CRCP by allowing for a decrease in design thickness of up to 1”. This size of impact makes this parameter significant for thicker CRCP.

The CTE was a variable that consistently had the biggest impact on the design thickness of both CRCP and JPCP. When CTE values of 6.5 was used instead of 5.5 there was a significant increase in pavement design thickness. The lower CTE value of 4.5 has very little impact on the design thickness of CRCP. However, this same change had a significant impact on JPCP. This lead to changes of over 3” in some cases and was the most significant variable investigated. At this time it is unclear if this result is reasonable. What can be said is that the change in CTE value investigated is believed to be reasonable for concrete pavements constructed in Oklahoma. More work should be done to investigate the long term performance of Oklahoma pavements and their corresponding CTE and see if these results match the suggested results of the MEPDG.

The cement type used allowed a 0.5” reduction of the design thickness with CRCP but has no impact on JPCP.

Compressive stress has more impact on JPCP compared to CRCP. Lower compressive stress of 3000 psi caused significantly higher pavement thicknesses to be required for JPCP. Higher compressive strengths allowed for a reduction in thickness. A small impact was made on the design thickness for CRCP whether the compressive strength was higher or low. There appears to be some error in the analysis of CRCP with 3000 psi compressive strength. These pavements actually showed less of an impact then the same sections with 4200 psi. This is unexpected.

When the cementitious material content was increased this resulted in higher shrinkage strains in the pavement. Typical values for these parameters will be determined for the state of Oklahoma in this research project and compared to those predicted by the MEPDG. However, until then the MEPDG suggests that this variable has a higher impact on CRCP pavements than JPCP. Higher cementitious content caused substantial increases in the design thickness for CRCP. This increase was much more substantial than in JPCP. For the CRCP pavements investigated a lower cementitious content allowed a reduction in thickness.

As the thickness of the asphalt layer was reduced for the JPCP from the 4” default value the required thickness for the pavement increased. However, when this layer was removed from the analysis results show that a decrease in the required pavement thickness is allowed. This behavior is not expected. The asphalt layer thickness showed very little impact on the CRCP design thickness. This suggests that the base material has little impact on the required design thickness for CRCP.

As the lime cement fly ash layer thickness was decreased in the design it showed a reduction in the pavement thickness for JPCP with 18’ spacing but for JPCP with 15’ spacing it shows an increase in the thickness required. Again the reason for this behavior is not intuitive. There was not a significant impact of the lime cement fly ash layer thickness on the CRCP design thickness. This again suggests that the base material has little impact on the required design thickness for CRCP.

Changes in the stiffness of the unbound resilient modulus for JPCP with 18’ spacing and 15’ joint spacing showed an exact opposite response. The pavements with 18’ joints suggested that as the stiffness of the unbound resilient modulus decreased that the pavement thickness could also decrease. Furthermore, when the unbound resilient modulus was increased the pavement thickness was required to be increased. While it is reasonable to assume that the stiffness of the base should have an impact on the design thickness of a pavement, the research team expected that the performance of the JPCP with a 18’ joint spacing would behave similarly to one with a 15’ joint spacing. More work is needed to investigate this work. In the CRCP investigations the resilient modulus had almost no impact on the required design thickness of the pavement.

Increase in the dowel diameter from 1.5” to 1.75” showed no effect on the thickness design for either JPCP sections investigated. However, a change in the dowel diameter from 1.5” to 1.25” lead to pavement thickness designs of over 3.5”. It is unclear to the research team why such a small change in a variable can lead to such a significant change in thickness.

The reinforcement ratio for CRCP was another variable that showed significant changes in the required design thickness for small changes in the value. For example a change from 0.7% to 0.6% required a thickness change in several cases of over 3.5”. This is a drastic change in the design thickness for a very small reduction in the amount of reinforcement. In turn an increase in the amount of reinforcement led to a small decrease in the required design thickness.

Several different cities within Oklahoma were chosen to evaluate how the different environments in the state impact the pavement design thickness. The majority of these cities had very little impact on the design thickness of the pavements investigated. However, for some reason the city of Clinton has a significant impact on the design thickness for thicker CRCP. It is not clear why this is happening and more work is needed to verify these results. This behavior was only for CRCP as the JCPC were not significantly impacted by the environment in Clinton.

Table 5 – A summary of the impact on the thickness design requirement for each of the investigated variables.

	intensity of impact		
parameter	CRCP	JPCP 18' joints	JPCP 15' joints
cement type	low	none	low
curing compound	high	none	low
cement content	high	low	high
compressive strength	high	high	high
CTE	high	high	high
resilient modulus	low	high	high
pavement opening	high	low	high
reinforcment percentage	high	-	-
dowel diameter	-	high	high
asphalt thickness	low	high	high
thickness of stabilized layer	low	low	high
climate	high	high	high

none = no impact
low = 0.5" or less
high = greater than 0.5"

2.5 Conclusion

In this study a sensitivity analysis was completed that allows the user to quantitatively compare the impact of different variables on the design thickness in the MEPDG for CRCP and JPCP. The ability to quantify the impact of these different variables in this manner was not found in any previous publication or journal paper. While completing this sensitivity analysis several variables were found to make a much more significant impact then was expected. Also, several variables behaved in ways that were unexpected by the research team. More work will be completed to better understand why this is occurring. It should be said that no combinations of variables were investigated beyond what is presented here and so care should be taken in extrapolating the data to other combinations.

3.0 Investigate base material practices for concrete pavements through a literature review and survey - of experiences from others

3.1 Introduction

The use of sub-grade drainage systems, in the form of permeable bases and/or the incorporation of edge drains, has over the last few decades been considered an option for improving the long term performance of concrete pavements. The effectiveness of these features as a means of draining seepage water and consequently extending the life of a roadway is still unclear. A major problem with this subject is that past investigations have not been able to monitor the performance of these drainage systems from their installation throughout the lifetime of the pavement to monitor their performance. Also, most projects have focused on only the effectiveness of subsurface drainage systems without monitoring the structural effect of these systems over the life of the pavement surface. These studies will be initially covered in this document. The most comprehensive research over this topic was performed in the National Cooperative Highway Research Program's (NCHRP) Project 1-34, "Performance of Pavement Subsurface Drainage". Project 1-34 represents the cumulative effort of four research projects, each following up on the shortcomings of the previous. Because of the thorough investigations completed by this report it will be thoroughly reviewed in this literature review. Furthermore, through conversations with the FHWA it was realized that a new document has been issued over sub surface drainage. This document was not received in time to thoroughly cover in this document. Future work on this task will focus on adding this reports information to the literature review.

3.2 Past Research on Subsurface Drainage

3.2.1 "An Evaluation of IDOT's Current Underdrain Systems"; Illinois Department of Transportation, 1995

Illinois as a state has been using underdrain systems since the 1970's. In 1995 IDOT evaluated the effectiveness of pipe and mat underdrains. Both have been heavily used in the state and it was unclear if one performed better than the other. The experiment consisted of unearthing a section of shoulder at 52 locations which had underdrain systems. The removed sections were then examined for damage and later tested in a lab for flow rates. The results of which provide valuable recommendations for agencies considering either. The recommendations include:

- Discontinuing the use of polypropylene products because they tend to collect fines and lose functionality
- Discontinuing the use of two manufacturers drainage mats as they are prone to structural damage and loss of functionality; drainage mats are typically plastic with circular openings that are placed below the pavement surface and act as a highly permeable layer
- Revised maintenance procedures to ensure screens are in place at all drain outlets and that mowing occurs as close to the outlets as possible

3.2.2 "Evaluation and Analysis of Highway Pavement Drainage"; Kentucky Transportation Center, 2003

The Kentucky Transportations Center conducted an analysis of drainage system performance by utilizing finite element models to investigate various pavement designs incorporating subsurface drainage components. The models assumed a steady state saturated flow. In these models the drainage system components and pavement materials and conditions were varied. The project was interested in not only determining the effectiveness of drainage systems but what factors affect the inflow of water into the pavement layers. The results of this modeling led to the following conclusions:

- Pavement geometry affects surface drainage but not subsurface drainage

- Cracks in the pavement increase the inflow of water into subsurface layers and thus the need for subsurface drainage features
- For widening projects, longitudinal drains should be placed at the interface of new and old layers to shorten the drainage path
- A surface drainage layer with low permeability should have underlying layers with increasing permeability to ease the movement of subsurface water while still maintaining structural integrity

3.2.3 "Comparison of Pavement Drainage Systems"; MnROAD, 1995

This project detailed the effectiveness of drainage in four test sections. These sections were designed with varying subsurface drainage features including one control section without subsurface drainage designs. The remaining three sections utilized longitudinal drains and/or permeable asphalt treated layers. Reflectometers were placed in the constructed layers of the sections so that saturation and flow could be measured at the time of construction and after rain events. The conclusions for this experiment include:

- Although all sections demonstrated the ability to drain subsurface water, sections with a permeable asphalt treated layer drained the most volume of water, typically within two hours
- About 40% of all rainfall penetrates the pavement surface
- Sealing longitudinal and transverse joints provided protection from inflow for roughly two weeks before typical inflow resumed
- The project recommended that measurements continue to be made and that structural performance of the surface pavement be monitored.

3.2.4 NCHRP Project 1-34

In this section a summary of the methodology, results, and recommendations of all four phases is provided. Project 1-34, phase A was the first attempt for the NCHRP at characterizing the performance of subsurface drainage systems. This project was completed in 1998. Once complete, the NCHRP financed phase B to critically review the original project as well as establish a blue print for long-term evaluation. This plan was enacted upon in phase C of the project through the Special Pavement Study-2 (SPS-2). Phase C ran from 1998 until 2002. The final installment, phase D, continued analyses of the SPS-2 sections in addition to focusing on testing the long term functionality of the drainage systems. This phase included data through 2005.

3.2.4.1 Project 1-34 A and B

NCHRP Project 1-34A and B provided an initial look at the performance of subgrade drainage systems in use at that time. The bulk of observations made were from databases provided by the Federal Highway Administration (FHWA) and from visual distress surveys performed on rigid pavements found throughout the country. Data collected through these methods was then used to create mechanistic-empirical models. Visual surveys were completed for each section in which a verbal description was provided on the condition of the roadway. Rutting, fatigue cracking, and the condition of the drain outlets were the predominant comments for the surveys. Additionally, information was collected on the age, repair history, and traffic volume seen at each location. Table 6 provides a summary of the test sections surveyed. States represented in this phase include: Kansas, Minnesota, North Carolina, Pennsylvania, Wisconsin, Illinois, Oklahoma and Ontario. For JPCP sections, three of the nine locations investigated had drained and undrained sections at the same location; for JRCP and CRCP sections each had one location with both a drained and undrained sections.

Table 6 – Summary of pavement sections investigated in NCHRP 1-34A and B.

Pavement Type	JPCP	JRCP	CRCP
sections with permeable base	11	4	10
sections with edge drains	19	5	12
Number of Locations	9	3	4

The findings for this project were reported by identifying the pavement type and then summarizing visual distress surveys. Ideally, direct comparisons between undrained sections and drained sections were made and the performance could be evaluated. However this was rarely possible. Most observations revealed that small, if any, statistical differences existed between drained and undrained sections if the undrained sections "were properly designed". Of the observations where statistical evidence existed, conclusions made by the research team include:

The number of deteriorated cracks in JRCP was lower for permeable bases

- Cement-treated permeable bases (CTB) should not be used in conjunction with CRCP due to excessive bonding
- Concrete sections with permeable bases averaged less than half the amount of deteriorated joints than that of sections with dense-graded bases
- Permeable bases are easily penetrated by fines
- Edge drain outlets must be well maintained to function properly due to vegetation overgrowth and other means of clogging such as rodent nests

Upon completion of this phase, the research team added note that any conclusions presented were with the limited amount of data available and should be investigated with a larger sample group along with more numerical methods as opposed to subjective visual reports. It was with this knowledge that Project 1-34B was able to create a plan that would eliminate many of the shortcomings of Project 1-34A. Among their suggestions for future research were longer analysis of sections, direct comparisons between drained and undrained sections at the same location to eliminate doubt about climactic and geological variables, and more advanced analytical techniques (coring, deflection data, roughness measurements, video inspection of edge drains).

3.2.4.2 Project 1-34 C

With the recommendations of Project 1-34B and the inclusion of SPS-2 sections, Project 1-34C undertook a long term evaluation of rigid pavements with subsurface drainage features. The SPS-2 experiment was designed to assess the influence of concrete width and thickness, flexural strength, base type, sub drainage, climate and traffic level.

Some specifics of the investigation is given below:

- Fourteen locations were investigated to represent varied climactic variables (rain and temperature)
- Each location has 12 sections of varying width, flexural strength and thickness – 4 drained and 8 undrained
- Every drained section (asphalt treated permeable base) has two control sections – 1 dense graded aggregate and 1 lean concrete base

The focus of this project was on the structural performance of the trial sections, thus parameters reflecting the structural integrity were measured throughout the project. Parameters of interest include transverse and longitudinal cracking, faulting, rutting and the International Roughness Index (IRI). IRI calculations were made by averaging the IRI value of each wheel path at the time of construction and periodically throughout the phase. The conclusions for this project were framed around the statistical differences in these parameters by comparing numerical values of undrained sections versus drained sections.

The team found that for transverse and longitudinal cracking as well as faulting, the control sections tended to deteriorate first, although in most cases the differences were statistically insignificant. In the case of IRI, they determined that the quality of drainage was not a factor.

Recommendations from the 1-34C team include:

- Adding deflection data to the list of structural integrity parameters used above (cracking, faulting, rutting and IRI)
- Testing the capabilities of the drainage systems in place by measuring flow rates
- Determining the effect of filter fabrics on flow rates
- Adding the data from the SPS-2 to the most recently completed database

The team found that the largest shortcoming of their findings was differentiating what effects were due to base type and which were due to drainage capabilities.

3.2.4.3 Project 1-34 D

With the recommendations of Project 1-34C, the methodology of Project 1-34D would continue to collect structural data such as cracking, faulting, rutting and IRI values in addition to the collection of deflection data, the measurement of flow rates through the drainage systems and the use of video equipment to survey the condition of drainage pipes below the ground surface. Flow rates through the sections were tested by coring and removing a hole in the pavement surface, then running water through the hole. The outlets were then monitored to measure flow through them. The sections analyzed in this project include not only the SPS-2 sites but also related data from the Minnesota Road Research Project and the Wisconsin Department of Transportation. At the time of this project's conclusion. This allowed for analysis to be done for the sections of 10 years or more.

Highlights from the findings of this project are found below:

- Edge drains may never function fully or at all due to the nature of some subgrade soils. Water may be more conducive to flowing downwards through the soil as opposed to laterally through the edge drains
- Deflection data suggests that deformation in a section is related to the stiffness of the base material rather than the quality of drainage.
- Load transfer values for undrained sections are no worse than drained, permeable base sections
- IRI values, initial and final, are predominantly due to base stiffness
- In terms of faulting, sections with undrained lean concrete bases or permeable asphalt-treated base are slightly better than sections with dense graded aggregate bases
- In terms of cracking, lean concrete bases (LCB) performed the worst, followed by dense aggregate bases and then permeable asphalt treated bases; more than 60% of the LCB sections had some cracking while only 30% of the aggregate-base and PATB sections had only nominal cracking
- Edge drain pipes were sometimes crushed during construction
- Outlets that received little maintenance would become overgrown and lose functionality

Overall, the research team concluded that performance of the test sections was related more with the stiffness of the base material rather than the drainage capabilities of the base. This however should not deter agencies from considering subgrade drainages systems. Project 1-34D makes these final recommendations to agencies:

- Consider climate and soil taxonomy as to identify sites that are at risk for excessive moisture and poor natural drainage
- Review visual distress surveys from local roads for signs of poor drainage (pumping, potholes, etc.)

Due to the conclusion that stiffness of the base layers contribute more to structural performance than drainage, it is recommended that designers consider a stiffer base layer, although a base layer that is too stiff such as LCB showed increased cracking in a significant number of sections investigated.

3.3 Conclusions

The majority of the reports reviewed suggested that roadways with subgrade drainage systems tend to perform closely with that of their undrained counterparts in terms of structural integrity. Furthermore, with subgrade drainage systems proper construction procedures and periodic maintenance of drainage outlets must be taken into consideration to ensure the effectiveness of these systems. Areas with high annual precipitation or soils with low permeability appear to be good candidates for these drainage features.

The accumulation of the research performed in Project 1-34 was incorporated into the Pavement Subsurface Drainage Design Reference Manual published by FHWA in 2008 and has only recently been obtained by the OSU research team. This manual is designed to provide a complete guide to drainage design. The highlights of which include:

- A proposed system which includes a permeable base layer day lighted or with longitudinal drains, a dense graded aggregate separator layer, and ditches to transport water which are to have a grade greater than 0.5%
- Drainage considerations including factors that affect infiltration, such as climate, water table levels, roadway geometry and freeze/thaw levels; and factors that increase moisture damage such as traffic levels and subgrade properties
- Guidelines for assessing drainage needs which are quantified by the Moisture Accelerated Damage Index
- Drainage type selection guidelines which describe how to decide which drainage components are needed
- Hydraulic design criteria for designing for certain volumes and drainage times
- Sections on designing individual subsurface drainage components including permeable bases, separator layers, and edge drains
- Maintenance recommendations

This guide appears to be the authority on subsurface drainage design as it is the accumulation of numerous research findings. During phase II of the project further investigation will be made by the research team.

3.4 Future Work

One future step on this task is to contact engineers in other states to determine if they have similar or different experiences then the NCHRP I-34 report. During these conversations best practices for construction details, specifications, and maintenance will be requested. This information would be very helpful to assist ODOT if they were to attempt to construct new pavements with drainable bases. Based on previous publications and talks with Jeff Dean of ODOT contact will be made with Iowa DOT and other states that have reported research results.

Further steps will also be taken to evaluate the FHWA Pavement Subsurface Drainage Design Reference Manual. This guide was not acquired until late in the task and questions about the research which supports the recommendations have yet to be addressed. Although research from Project 1-34 is included, there exist numerous other references. These have not been included as these were viewed to be the seminal papers.

This task is on budget and on schedule and should be completed as outlined in the original proposal by March 2010.

4.0 Increase the quantity of weather sites in Oklahoma that provide environmental inputs for the MEPDG

4.1 Introduction

Reliable climatic inputs are critical to produce high quality results with the AASHTO MEPDG. The temperature and moisture gradients in the pavement and subsurface and consequently the pavement stresses are directly dependent on the weather inputs. In the current version of the MEPDG, the user may select several weather stations that can be interpolated based on the project location to produce a virtual weather station (ARA 2004). At least 2 years of data is required for a station to be used in the MEPDG, however more data is recommended. Having more weather stations over a longer period of time will greatly improve the reliability of the designs made using the MEPDG.

This project involved the updating or creation of 39 weather files in Oklahoma, along with 14 in neighboring states. This is an increase from only 15 weather files previously available for Oklahoma. A map and data file compatible with Google Earth of depths to groundwater in Oklahoma have been made for guidance in selecting the average annual depth of water table for input in the MEPDG.

4.2 Weather Files Creation and Validation

The weather data used for the MEPDG climate file upgrading and creation was supplied by the National Climatic Data Center (NCDC), which is part of the National Oceanic and Atmospheric Administration of the U.S. Department of Commerce. The Global Integrated Hourly Surface dataset is available via free online access for unrestricted use inside the U.S.. This data can be accessed using the NCDC Climatic Data Online system at http://cdo.ncdc.noaa.gov/. After obtaining this data it was imported into a spreadsheet for filtering and editing. The data was first filtered to ensure that only one data point per hour was included, as some weather stations collected data at more frequent intervals. Next, the hourly relative humidity was calculated from the dry and wet bulb temperatures contained in the weather files. The sky cover was converted to a numeric value according to the following scale: clear skies was assigned to be 100, scattered clouds was assigned to be 67, broken sky cover was assigned to be 33, and overcast was assigned to be 0. Missing weather values, which are inevitable for any weather station because of maintenance, malfunction, or extreme weather, were corrected to supply the software with a continuous set of data. Missing values of less than 3 hours in a row were filled in from the average of the weather data from the hours immediately before and after the missing data points. This method was chosen for continuity of data, and barring an unusually short and extreme event is believed to be the most probable values for the missing data. When less than two days in a row of data was missing, the missing data was calculated as the average of the value from the same hour on the days before and after the missing data points. When more than two days of data in a row was missing, the missing data was calculated from the average of the weather values from the same date and time from the data from other available years of that weather station. When these longer periods of data were missing, it was considered necessary to use the average of the values from the remaining year's data so as to not bias the weather data towards any particular year's data. It was also considered unlikely that the data from surrounding days would be representative for these missing days.

Fifteen weather files that were created by ARA, Inc. and included as part of the original data available with the MEPDG were updated to include available data from 2006 to the present. Weather files were created from weather station data available from 24 additional cities in Oklahoma. The weather files are comma separated text files with the extension .hcd. Each line of data contains one hour of weather information for the city of interest in the following format: "YYYYMMDDHH,Temperature,Wind Speed,%Clouds,Precipitation,RelativeHumidity". The file number needs to match that found in the station.dat file used by the MEPDG, and is the Weather-Bureau-Army-Navy (WBAN) ID number assigned to the weather station. The station.dat file contains the file number, the city name, the weather station description, the Latitude and Longitude, the elevation, the first date found in the climatic data file, and if the data file is clean "C" or has a missing month "M1". It is the station.dat file that is used during the weather station selection process in the MEPDG, so it is important that the information in the station.dat file match that found in the climatic data file. The existing data files were updated by simply appending the new weather information in the correct format to the end of the existing files. Fourteen additional weather files were created from weather stations available in neighboring states that are close to the Oklahoma border. These climatic data files will be useful when using the MEPDG to create a virtual weather station by interpolation. Table 6 shows the cities now available, the dates previously available in the climatic data files, and the date ranges now available.

Table 6 – Dates contained in previous and new climatic data files

		Previous File		New File	
Weather Station Location	Weather Station Description	Date Started	Dated Ended	Date Started	Date Ended
ADA, OK	ADA MUNICIPAL AIRPORT	-	-	4/1/2004	3/31/2009
ARDMORE, OK	ARDMORE DOWNTOWN AIRPORT	-	-	6/1/2005	4/30/2009
BARTLESVILLE, OK	BARTLESVILLE FP FIELD	-	-	6/1/2003	5/31/2009
CHANDLER, OK	CHANDLER MUNICIPAL AIRPORT	-	-	7/13/2004	4/30/2008
CHICKASHA, OK	CHICKASHA MUNICIPAL AIRPORT	-	-	12/29/2004	3/31/2009
CLAREMORE, OK	CLAREMORE REGIONAL AIRPORT	-	-	8/1/2004	3/31/2009
CLINTON, OK	CLINTON-SHERMAN AIRPORT	11/1/1996	2/28/2006	11/1/1996	3/31/2009
CUSHING, OK	CUSHING MUNICIPAL AIRPORT	-	-	7/1/2005	3/31/2009
DUNCAN, OK	HALLIBURTON FIELD AIRPORT	-	-	7/14/2004	3/31/2009
DURANT, OK	DURANT EAKER FIELD AIRPORT	-	-	5/1/2004	3/31/2009
EL RENO, OK	EL RENO MUNICIPAL AIRPORT	-	-	9/1/2005	3/31/2009
ENID WOODRING, OK	ENID WOODRING MUNICIPAL AIRPORT	-	-	4/1/2005	4/30/2009
ENID VANCE, OK	ENID VANCE AFB	-	-	11/2/2006	4/30/2009
FREDERICK, OK	FREDERICK MUNICIPAL AIRPT	2/1/1998	2/28/2006	2/1/1998	3/31/2009
GAGE, OK	GAGE AIRPORT	11/1/1996	2/28/2006	11/1/1996	3/31/2009
GROVE, OK	GROVE MUNICIPAL AIRPORT	-	-	8/1/2004	3/31/2009

GUTHRIE, OK	GUTHRIE MUNICIPAL AIRPORT	4/1/1998	2/28/2006	4/1/1998	3/31/2009
GUYMON, OK	GUYMON MUNICIPAL AIRPORT	12/1/1998	2/28/2006	12/1/1998	3/31/2007
HOBART, OK	HOBART MUNICIPAL AIRPORT	8/1/1996	2/28/2006	8/1/1996	3/31/2009
IDABEL, OK	IDABEL RGNL AIRPORT	-	-	8/1/2005	3/31/2009
LAWTON, OK	LAWTON-FORT SILL RGNL ARPT	10/1/1996	2/28/2006	10/1/1996	3/31/2009
MC ALESTER, OK	MC ALESTER REGIONAL ARPT	8/1/1996	2/28/2006	8/1/1996	3/31/2009
MUSKOGEE, OK	DAVIS FIELD AIRPORT	8/1/1996	2/28/2006	8/1/1996	3/31/2009
NORMAN, OK	NORMAN WESTHEIMER AIRPORT	-	-	2/1/2005	3/31/2009
OKLAHOMA CITY, OK	WILEY POST AIRPORT	8/1/1996	2/28/2006	8/1/1996	3/31/2009
OKLAHOMA CITY, OK	WILL ROGERS WORLD AIRPORT	7/1/1996	2/28/2006	7/1/1996	7/31/2008
OKMULGEE, OK	OKMULGEE MUNICPAL AIRPORT	-	-	5/26/2004	3/31/2009
PAULS VALLEY	PAULS VALLEY MUNICIPAL AIRPORT	-	-	11/1/2004	3/31/2009
PONCA CITY, OK	PONCA CITY REGIONAL ARPT	11/1/2000	2/28/2006	11/1/2000	3/31/2009
POTEAU, OK	POTEAU ROBERT KERR AIRPORT	-	-	6/1/2004	3/31/2009
SALLISAW, OK	SALLISAW MUNICIPAL AIRPORT	-	-	6/1/2004	3/31/2009
SEMINOLE, OK	SEMINOLE MUNICIPAL AIRPORT	-	-	2/1/2006	4/30/2009
SHAWNEE, OK	SHAWNEE NAS	-	-	6/1/2004	3/31/2009
STILLWATER, OK	STILLWATER REGIONAL ARPT	12/1/1996	2/28/2006	12/1/1996	3/31/2009
TAHLEQUAH, OK	TAHLEQUAH MUNICIPAL AIRPORT	-	-	6/1/2004	3/31/2009
TULSA, OK	TULSA INTERNATIONAL ARPT	7/1/1996	2/28/2006	7/1/1996	9/30/2008
TULSA, OK	RICHARD LLOYD JONES JR APT	8/1/1998	2/28/2006	1/1/1998	3/31/2009
WATONGA, OK	WATONGA AIRPORT	-	-	12/1/2004	1/31/2009
WEST WOODWARD, OK	WEST WOODWARD AIRPORT	-	-	6/1/2004	3/31/2009
Coffeyville, KS	Coffeyville Municipal Airport	7/1/1996	2/28/2006	7/1/1996	7/31/2009
Elkhart, KS	Elkhart, KS	-	-	11/1/2003	7/31/2009
Liberal, KS	Liberal Municipal Airport	-	-	5/1/2004	7/31/2009
Parsons, KS	Tri-City Airport	7/1/1996	2/28/2006	7/1/1996	7/31/2009
Winfield, KS	Strotner Field Airport	7/1/1996	2/28/2006	7/1/1996	7/31/2009
Canadian-Hemphill, TX	Canadian, TX	-	-	8/1/2003	7/31/2009

Clarksville, TX	Clarksville Red River Airport	-	-	6/1/2004	05/31/2009
Gainesville, TX	Gainesville, TX	-	-	6/1/2004	05/31/2009
Mt. Pleasant, TX	Mount Pleasant Airport	7/1/1996	2/28/2006	7/1/1996	5/31/2009
Perryton, TX	Perrytown Ochiltree Airport	-	-	6/1/2004	5/31/2009
Randolph, TX	Randolph Air Force Base	-	-	1/1/2004	5/31/2009
Sherman, TX	Grayson Co Airport	-	-	6/1/2004	5/31/2009
Vernon, TX	Vernon Wilbarger Co Airport	-	-	6/1/2004	5/31/2009
Wichita Falls, TX	Shephard AFB	7/1/1996	2/28/2006	7/1/1996	5/31/2009

The MEPDG currently does not consider any data in the climatic files after February of 2006, which is the most relevant data and also the majority of the new data included from this project. After conversations with Mike Darter, one of the lead researchers on the development of the MEPDG, it was determined that the best course of action for the weather files would be to backdate the years of the weather data created in this project from anywhere between one and three years. Any data from February 29 was then moved to the nearest leap year to prevent any program errors. This would allow for the maximum amount of weather data to be used in the MEPDG calculations, and would not affect the values calculated since the years of the climatic data are not used in the calculations. A copy of the original weather files before backdating is also included with this report for archival purposes and for when this problem with the MEPDG is corrected. Figure 2 shows a map of the location of the MEPDG climate files upgraded or created as part of this project.

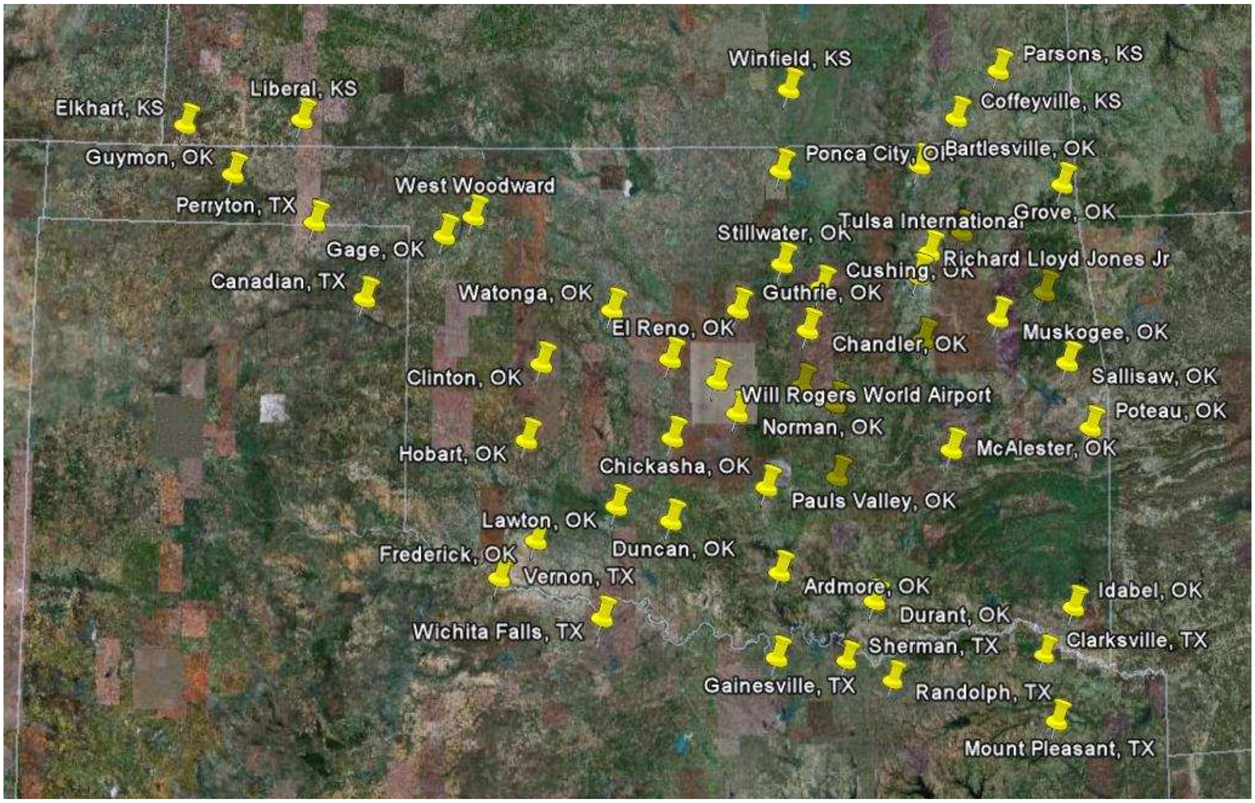


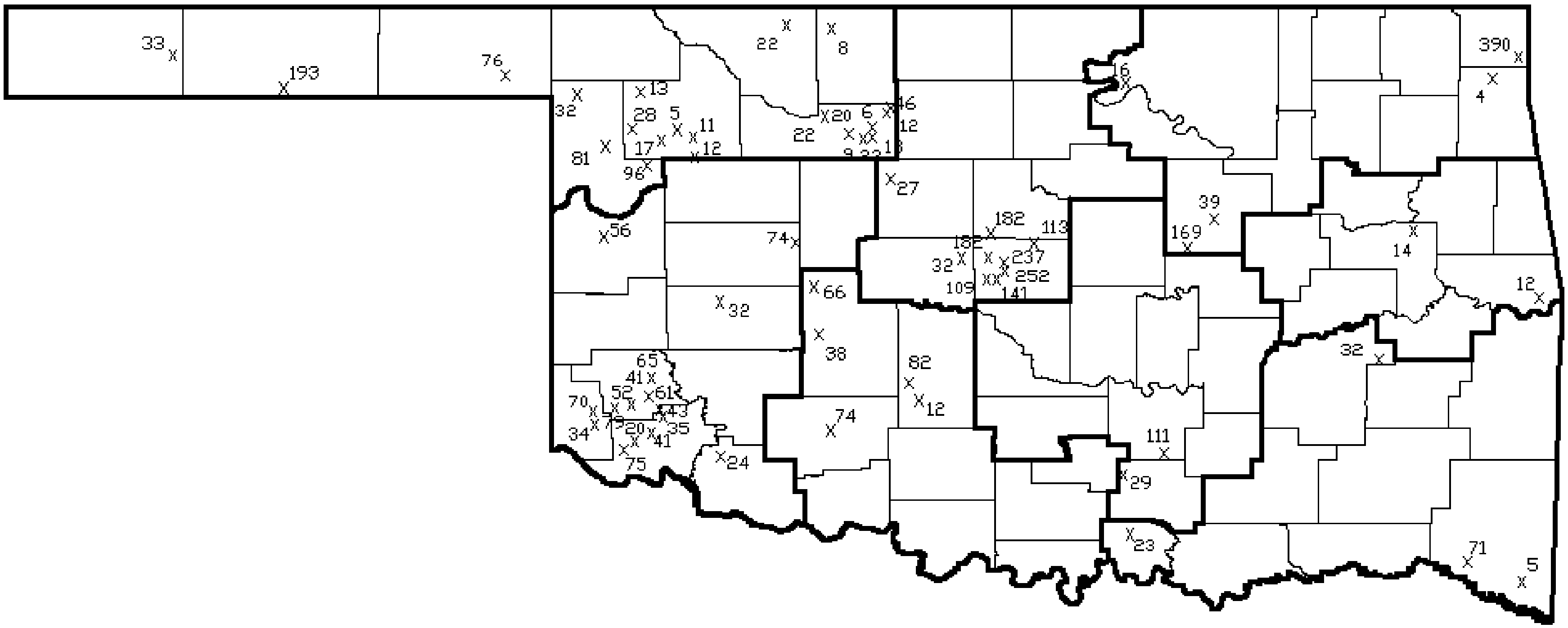
Figure 2 - Location of weather stations used to update and create new MEPDG climate files.

A program has been created to install the MEPDG climate files in the proper folders on the user's computer. The file installer begins by double clicking on the setup.exe file, and is installed by following the on-screen directions. The program when launched will ask for the root folder containing the MEPDG and all of its subfolders and files, which is usually "C:\DG2002". Once the folder is selected and the user clicks the OK button, the program will automatically install the new climate files and station master list file to the correct locations for use by the MEPDG. To install the climate files manually, simply copy the climate files and paste them in the "HCD" subfolder of the MEPDG program folder. Then, the station.dat file must be copied to the "HCD" subfolder and the "Defaults" subfolder.

4.3 Depth of Water Table Map and Data File Creation

Average values for the depth to groundwater for 84 locations throughout the state of Oklahoma were compiled from data available from the U.S. Geological Survey National Water Information Survey at http://nwis.waterdata.usgs.gov/ok/nwis/gwlevels. The well locations were selected from those that contained at least 100 observations. The data was first averaged for each month, and then averaged from the average monthly well depth values. This averaging method was used to prevent bias in the average value resulting from a large number of observations being recorded in a particular month. Figure 3 shows the average yearly depth below the ground surface to water in feet for the well locations used in Oklahoma. The depth below the surface to the groundwater was also entered into a .kml file that is compatible with the Google Earth program, which can be used to better view the depth to groundwater for places where there are several average values available. In order to use this file one must first download the free Google Earth software from www.earth.google.com and then use it to open the provided .kml file. Caution should be exercise in using the values presented in Figure 3 and the .kml file, as the local geological conditions may vary significantly over short distances.

Figure 3 - Map of water table depths for Oklahoma. Values given are in feet.



4.4 Conclusion

Climatic data files have been updated and created for use in designing rigid and flexible pavements in the state of Oklahoma. Average yearly depth to groundwater values have also been compiled for a wide range of geographical locations in Oklahoma. This is expected to result in better pavement designs which should translate into an overall reduced life-cycle cost.

5.0 Examine different curing methods for rigid pavement construction and their impact on the early - age curling and warping of continuous reinforced concrete pavements

Currently, the MEPDG requires that the user input the curing methodology to be used in the construction of a pavement. From analysis completed in this report it can be shown that this input variable is significant in determining the design thickness of CRCP. The MEPDG only allows the user two choices between curing type. They are either wet mat or spray on cure. Although the wet mat cure has been indicated to be the most effective curing technique, it is the least economical to be implemented in the field. The goal of this task is to find if the properties of a concrete pavement receiving a wet mat cure can be provided by a method that is more economical.

After further investigation of the MEPDG it has been determined that for design purposes of CRCP that the assumed difference between a wet mat and spray cure is the amount of initial curling and warping of the pavement due to differentials in shrinkage, moisture, and zero stress temperature. This initial deformation of the pavement is detrimental as it causes the pavement to lose its initial support from the sub base and therefore increase the stresses in the pavement from subsequent external loads.

5.1 Progress on this Task

Through conversations with several Oklahoma paving contractors it has been determined that there would be significant interest in either reducing the design thickness of a pavement or extending the pavements life through the use of a curing method that is more efficient than a spray on cure. During these conversations several different possibilities were mentioned including using burlap, watering the pavement at regular intervals, or the use of a more robust or multiple application of a curing compound.

In this project the research team’s aim is to determine a baseline for the curling and warping of these different curing methods and then determine their effectiveness with small laboratory paste specimens stored at 73^{o} F and 40% relative humidity. Next these curing techniques will be investigated in specimens that are 1' x 1' x 8' with reinforcing. This size is chosen to examine the performance of a strip of concrete pavement. Again these specimens will be stored at 73^{o} and 40% RH to compare the early age warping of the different curing methods. It is then planned to take this research to a much larger scale on either the OSU campus or at an actual job site to construct a full scale pavement and monitor the early age curling and warping of the pavement.

At this point the tests are being designed by the research team and the paste laboratory mixtures are about to begin.

6.0 Provide regional material input parameters that can be used in the MEPDG for the design of rigid - pavements

The MEPDG user manuals have suggested that more accurate pavement designs can be determined if accurate material input values can be obtained for local materials. Through the sensitivity analysis contained in this report and through discussions with ODOT it has been determined that the following parameters should be further investigated for Oklahoma paving concrete mixtures:

1. Concrete Shrinkage
2. Coefficient of thermal expansion (CTE)
3. Strength testing

6.1 Progress on this Task

6.1.1 Concrete Shrinkage

There are a significant number of concrete mixture shrinkage parameters that must be characterized for the MEPDG. These include: maximum shrinkage, reversible shrinkage, and time to develop 50% of the maximum shrinkage. These parameters will be investigated with the AASHTO T160 "Standard Method of Test for Length Change of Hardened Hydraulic Cement Mortar and Concrete" with the only modification being that a relative humidity of 40% is used instead of 50% as suggested in the MEPDG design manual (ARA 2004).

It is well documented that the shrinkage of a concrete mixture depends largely on the percentage of the mixture that is paste, the water content of the mixture, and the types of cementitious materials in the mixture. A standard paving mixture for the state of Oklahoma has been determined through discussions with ODOT and review of typical Oklahoma concrete paving mixtures. These mixtures consist of 0.42

water to cementitious ratio (w/cm) with total cementitious content of 564 lbs and a 20% replacement with fly ash. The aggregate is proportioned to have approximately 60% coarse aggregate and 40% fine aggregate. Approximately five percent air is entrained in each mixture. This mixture produces a paste content of 25% in the mixture. This mixture will be systematically altered by substituting different mixture components including four different cements, four different fly ashes, and three different paste contents to examine their impact on the shrinkage parameters measured by the MEPDG.

This testing is underway.

6.1.2 CTE Testing

In the sensitivity analysis completed for this research project it was determined that the design of CRCP is very sensitive to the CTE value of the concrete. In order to get a better understanding of these values for typical Oklahoma concrete paving mixtures the research team plans on evaluating how different components of a mixture impact the CTE. This will be done by measuring the CTE of a standard concrete mixture to find a baseline for the mixture for the raw materials. Next different parameters of the mixture are proposed to be varied and the resulting impact on the CTE to be measured. By combining the influence from the different aggregate sources and the impact of the paste on the CTE then one should be able to create a tool that is able to estimate the CTE for a mixture based on the mixture ingredients and proportions for typical ODOT mixtures. It is anticipated that the following variables will be investigated: cement content, cement replacement with supplementary cementitious materials (SCMs), water to cement ratio, and aggregate gradation.

From discussions with ODOT the following seven coarse aggregate and 3 fine aggregate pits will be investigated in this project. These pits were chosen as they cover a significant geographic area and mineralogy of the state. A summary of the pits is provided in Table 7.

Table 7-Summary of the aggregates to be investigated for this project.

	Owner	Town	Rock Type	Absorption (%)	SG (SSD)	Unit Weight (lb/ft^3)
Coarse Ag.	Dolese	Davis	Limestone	0.89	2.67	168.1
	Hanson	Davis	Rhyolite	0.64	2.71	165.6
	Dolese	Coleman	Dolomitic Limestone	0.55	2.77	173.1
	Martin Marietta	Sawyer	Sandstone	2.02	2.52	156.1
	Dolese	Hartshorne	Limestone	1.13	2.62	169.2
	Pryor Stone	Pryor	Sandy Limestone	1.61	2.63	162
	Quapaw	Drumwright	Dolomitic Limestone	0.92	2.81	147
Fine Ag.	Dolese	Dover	River Sand		2.6	110
	Southwester State Sand	Snyder	Manufactured Sand		2.7	108

* Aggregate properties from ODOT Materials Division

6.1.3 Strength Testing

The strength of a mixture depends on the cementing materials in the mixture, the water to cement ratio, and the bond between the aggregates and the paste. To evaluate these parameters 4” x 8” compression cylinders (AASHTO T 22 “Standard Method of Test for Compressive Strength of Cylindrical Concrete Specimens”) and flexural beams (AASHTO T 97 “Standard Method of Test for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)”) will be prepared for a number of the mixtures prepared for the CTE and shrinkage testing and tested for strength at 7, 14 and 28 days of hydration. This testing will not only provide ODOT with a range of results for the common mixtures used in the state but will also provide a correlation between the two measurements.

7.0 Conclusion -

This report has provided a summary of the work completed to date on ODOT project 2208 "Development and Implementation of a Mechanistic and Empirical Pavement Design Guide (MEPDG) for Rigid Pavements". This document contains completed work for Task A and C and provides updates on the others. This project is currently on time, within budget, and has met the promised milestones for the first year. Work will commence on phase 2 of the project once funding is received from ODOT.

8.0 References

ARA Inc., "Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures", NCHRP Project 1-37A, Mar. 2004.

ERES Consultants, "Performance of Pavement Subsurface Drainage"; NCHRP Results Research Digest – 268, November 2002.

Duboe, J.B., "An Evaluation of IDOT's Current Underdrain Systems", Illinois Dept. of Transportation – Physical Research Report No. 120, December 1995.

FHWA, Pavement Subsurface Drainage Design Reference Manual, FHWA/USDOT – FHWA-NHI-08-030, February 2008.

Hagen, M.G., Cochran, G.R., "Comparison of Pavement Drainage Systems", Minnesota Department of Transportation- Report Number 95-28, 1997.

Hall, K.T., Correa, C.E., "Effect of Subsurface Drainage on Performance of Asphalt and Concrete Pavements", NCHRP Report 499, 2003.

Hall, K.T., Crovetti, J.A., "Effect of Subsurface Drainage on Performance of Asphalt and Concrete Pavements – Analysis of the SPS-1 and SSPS-2 Field Sections", NCHRP Report 583, 2007.

Harvey, "Analysis of 2002 Design Guide Distress Prediction Models for Jointed Plain Concrete Pavement", Transportation research record , Volume issue-1947, 2006. Harrigan and Nov, "Performance of Subsurface Drainage", NCHRP, Research Result Digest, 2002.

Kannekanti, Venkata, "Sensitivity analysis of 2002 Design guide distresses prediction models for jointed plain concrete pavement", Transportation Research Record , Volume issue-1947, 2006.

Mahboub, K.C., Liu, D.L., Allen, D.L., "Evaluation and Analysis of Highway Pavement Drainage", Kentucky Transportation Center – Research Report KTC-03-32/SPR-207-00-1F, October, 2003.

Mallela, Jagannath, "Measurement and Significance of Co-efficient of Thermal expansion in Concrete Rigid pavement", Transportation Research Record , Volume issue-1919, 2005.

Zaghloul, Sameh, "Investigation of Environmental and Traffic inputs on Mechanistic- Empirical pavement design guide prediction", Transportation Research Record , Volume issue-1967, 2006.