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Sensitivity analysis of pavement thickness design software for local roads in Iowa

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SENSITIVITY ANALYSIS OF PAVEMENT THICKNESS DESIGN SOFTWARE

FOR LOCAL ROADS IN IOWA

by

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A thesis submitted in partial fulfillment
of the requirements for the Master of
Science degree in Civil and Environmental Engineering
in the Graduate College of
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CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

Jeremy Purvis

has been approved by the Examining Committee
for the thesis requirement for the Master of Science
degree in Civil and Environmental Engineering at the May 2013 graduation.

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INTRODUCTION

To minimize the life-cycle cost of building and maintaining pavements, it is critical to determine the most appropriate pavement thickness for given traffic level, subgrade condition and environmental factor. In Iowa, the statewide urban design and specifications (SUDAS) currently utilize a simplified version of the AASHTO 1993 pavement design guide, which can be considered conservative based on placement of the pavement on natural subgrade, distribution of truck classifications and other design parameters. Therefore, there is a need for a modified pavement design methodology to be used for determining the most appropriate pavement thickness for local roads in Iowa.

PAVEMENT DESIGN PROCEDURES ADOPTED BY SIX STATE DEPARTMENT OF TRANSPORTATION ADJACENT TO IOWA

Most states have developed their own pavement design procedures for low-volume roads. As shown in Figure 1, forty state DOT's currently use the AASHTO 1993 guide for designing low-volume road pavements (Hall and Bettis 2000). The main features of asphalt pavement design procedures adopted by some state DOT's for low-volume roads are summarized in Table 1.

Figure 1. Survey of low-volume pavement design procedure

Table 1. Summary of low-volume road pavement design procedures in select state departments of transportation

State	Main Features of Pavement Design Procedure
Illinois	▪ Road with less than 400 ADT. ▪ Required inputs: traffic (% heavy vehicles) and subgrade modulus. ▪ Design period of 15 or 20 years. ▪ Estimated using the ADT for the year representing one-half of the design period.
Kentucky	▪ Road with less than 500 ADT ▪ Required inputs: ADT and aggregate thickness. ▪ Aggregate thickness is estimated by a design chart relating to total pavement structure thickness.
Minnesota	▪ Two procedures: 1) Gravel Equivalency method and 2) R-value method. ▪ Required inputs: soil strength and traffic load structural requirements were considerably influenced by R-value ▪ GE method was less conservative than R-value method
Mississippi	▪ Required inputs: Soil strength (Soil support value found from using CBR), design life (5-8 years), traffic loads (ADT and ADL) ▪ Soil support value = 30289 log base 10 * (CBR) + 1.421 ▪ 4-inch minimum subbase required for all full depth asphalt construction.
Pennsylvania	▪ Required inputs: traffic (18-kip ESALs), the soil strength (CBR), and the effects of freeze-thaw action (Design Freezing Index, DFI). ▪ No traffic data necessary for each type of truck.
Texas	▪ Required inputs: traffic (18-kip ESALs) and soil strength. ▪ Designed for a design period of 20 years. ▪ Layer moduli values are back-calculated from FWD data

Questionnaire about Local Road Pavement Thickness

Design

As shown in Figure 2, six adjoining state departments of transportation (Minnesota, Wisconsin, Illinois, Missouri, Nebraska and South Dakota) were surveyed with respect to their pavement design procedures for low-volume roads. A survey form was sent out to each of six departments of transportation and all but Nebraska have returned the survey. A follow-up interview was also performed with contact persons listed in Figure 2.

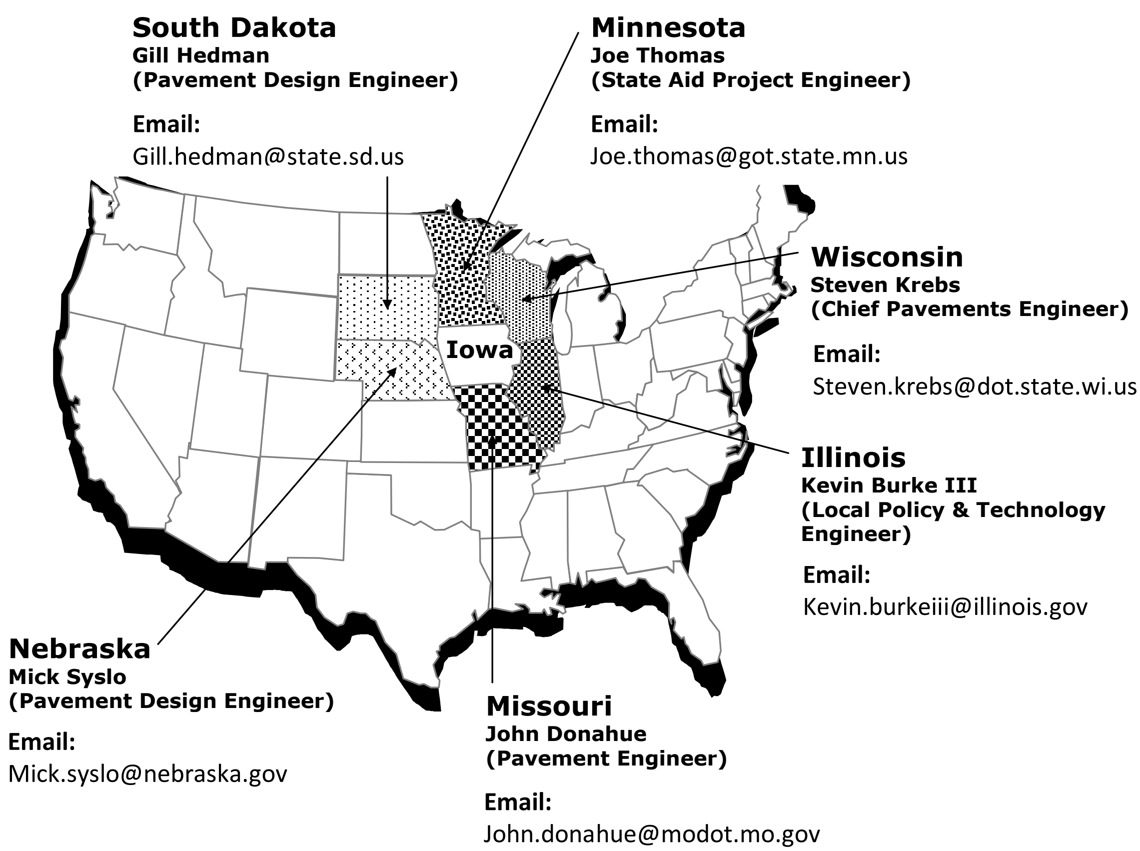


Figure 2. Contact information at adjoining state DOT’s

As shown in Table 2, a questionnaire was prepared to identify pavement thickness design methods and their common input parameters for local roads adopted by adjoining state DOT's. It should be noted that the state departments of transportation have jurisdiction over a limited amount of streets and local roads. This study's TAC and researchers recognize that local agency engineers and technicians would need to be surveyed as to the best methods for pavement design. The survey of state DOT's is used herein as a means to identify general design procedures that might be employed.

Table 2. Questionnaire about local road pavement design procedures

No.	Question
1.	What kind of pavement design methodology do you use for local road?
2.	What kind of pavement thickness design software do you use for local road?
3.	How does your state agency classify road as local road?
4.	Has your state agency developed a pavement thickness design procedure for local road?
5.	What are the layer types and thicknesses of a typical local road (asphalt pavement) in your states?
6.	What are the layer types and thicknesses of a typical local road (concrete pavement) in your state?
7.	What are the most important factors for designing local road?
8.	What type of soil is most common in your state?
9.	How do you estimate subgrade strength for local road design?
10.	What kind of soil parameter does your state agency typically use for local road design?
11.	What type of paving materials and properties does your state agency use for local road design?
12.	What type of traffic input do you use for local road design?
13.	What type of drainage features does your agency commonly use for local road design?
14.	Does your state agency use a serviceability index to local road?
15.	What level of the design reliability does your state agency use for local road?
16.	What are the important characteristics of asphalt pavement for local road design?
17.	What are the important characteristics of concrete pavement for local road design?

Survey Results

Five state departments of transportation adjacent to Iowa (Nebraska was the only exclusion) returned the survey. Survey results are summarized for each question below in Table 3.

Table 3. Responses about local road pavement design procedures

Question 1: What kind of pavement design methodology do you use for local road?

Answer:

- Illinois DOT: Other (mechanistic empirical design developed by U of I and IL DOT)
- Missouri DOT: AASHTO
- Minnesota DOT: Other (charts and tables for soil factor and R-value)
- South Dakota DOT: AASHTO
- Wisconsin DOT: Other (WisPave based on AASHTO 72)

Question 2: What kind of pavement design software do you use for local road?

Answer:

- Illinois DOT: None
- Missouri DOT: Mechanistic-empirical pavement design guide
- Minnesota DOT: http://www.dot.state.mn.us/materials/pvmtdesign/software.html
- South Dakota DOT: 1993 AASHTO design guide and the DARWIN software
- Wisconsin DOT: Other (WisPave based on AASHTO 72)

Question 3: How does your state agency classify road as local road?

Answer:

- Illinois DOT: less than 400 ADT and less than 0.25 traffic factor
- Missouri DOT: less than 1000 AADT and less than a 100 trucks a day
- Minnesota DOT: less than 1000 ADT
- South Dakota DOT: None
- Wisconsin DOT: less than 400 AADT

Question 4: Has your agency developed a pavement design procedure for local road?

Answer:

- Illinois DOT: Yes (http://www.dot.il.gov/blr/manuals/Chapter%2037.pdf)
- Missouri DOT: No
- Minnesota DOT: Yes (http://www.dot.state.mn.us/materials/pvmtdesign/docs/RValueChart.pdf)
- South Dakota DOT: No
- Wisconsin DOT: No

Table 3. Continued

Question 5: What are the layer types and thicknesses of a typical local road (asphalt pavement) in your state?

Answer:

- Illinois DOT: Surface (HMA: 3”), Base (Class A aggregate: 8”), Subbase (Modified soil: 8”)
- Missouri DOT: Surface (HMA: 7-8”), Base (crushed stone: 4”), Subbase (N/A)
- Minnesota DOT: Surface (HMA: minimum 3”), Base (Class 5 or 6: 6-8”), Subbase (Existing soils: N/A)
- South Dakota DOT: Surface (HMA: 3-4”), Base (N/A: 10-12”), Subbase (8”)
- Wisconsin DOT: Surface (HMA: 3”), Base (Dense graded aggregate: 8”), Subbase (None)

Question 6: What are the layer types and thicknesses of a typical local road (concrete pavement) in your state?

Answer:

- Illinois DOT: Not used
- Missouri DOT: Surface (JPCP: 6-7”), Base (crushed stone: 4”), Subbase (N/A)
- Minnesota DOT: Surface (Concrete: 7-9”), Base (Class 5 or 6: 0-6”), Subbase (Existing soils: N/A)
- South Dakota DOT: Not used
- Wisconsin DOT: Not used

Question 7: What are the most important factors for designing local road?

Answer:

- Illinois DOT: Traffic and paving materials
- Missouri DOT: Subgrade and load
- Minnesota DOT: Traffic and subgrade
- South Dakota DOT: Traffic, subgrade and load
- Wisconsin DOT: Traffic, load, and pavement performance criteria

Question 8: What type of soil is most common in your state?

Answer:

- Illinois DOT: A-1 to A-7
- Missouri DOT: A-4, A-7-5, and A-7-6
- Minnesota DOT: A-1 through A-6 and A-7-5 and A-7-6
- South Dakota DOT: A-6 to A-7
- Wisconsin DOT: A-2. A-2-4, A-4, A-6 and A-7-6

Question 9: How do you estimate subgrade strength for local road design?

Answer:

- Illinois DOT: No response
- Missouri DOT: Assume resilient modulus value from AASHTO class
- Minnesota DOT: R-value derived from soil tests
- South Dakota DOT: typical liquid limit value and convert to a resilient modulus value
- Wisconsin DOT: No response

Table 3. Continued

Question 10: What kind of soil parameter does your state agency typically use for local road design?

Answer:

- Illinois DOT: No response
- Missouri DOT: Resilient modulus (Mr)
- Minnesota DOT: Soil factor and/or R-value
- South Dakota DOT: Resilient modulus (Mr)
- Wisconsin DOT: k-value, soil support value (SSV), and design group index (DGI) base on pedology is primary. DGI ranges from 0 (best) to 20 with 10-14 being most common

Question 11: What type of paving materials and properties does your state agency use for local road design?

Answer:

- Illinois DOT: HMA (E; elastic modulus)
- Missouri DOT: Granular (CBR or Mr), HMA (E; elastic modulus) and PCC (E; elastic modulus, f'c; compressive strength, S'c ; flexible strength)
- Minnesota DOT: HMA (E; elastic modulus)
- South Dakota DOT: Granular (CBR or Mr), HMA (E; elastic modulus)
- Wisconsin DOT: Granular (CBR or Mr) and HMA (E; elastic modulus)

Question 12: What type of traffic input do you use for local road design?

Answer:

- Illinois DOT: ESAL (< 10,000; 10,000-50,000; 50,000-100,000)
- Missouri DOT: Load spectra in the MEPDG
- Minnesota DOT: ADT and ESAL (100,000-250,000)
- South Dakota DOT: ESAL (50,000-100,000)
- Wisconsin DOT: ADT and ESAL (10,000-50,000; 50,000-100,000)

Question 13: What type of drainage features does your agency commonly use for local road design?

Answer:

- Illinois DOT: Ditches
- Missouri DOT: Ditches
- Minnesota DOT: Ditches
- South Dakota DOT: Ditches
- Wisconsin DOT: Ditches

Question 14: Does your state agency use a serviceability index for local road pavement design?

Answer:

- Illinois DOT: No response
- Missouri DOT: PASER rating system (IRI and visual distress data)
- Minnesota DOT: QI – Ride quality Index, ranges from 0 -5 (best).
- South Dakota DOT: 4.5 to 2.5
- Wisconsin DOT: IRI, ranges from 0 -5 (worst)and PDI, ranges 0-100

Table 3. Continued

Question 15: What level of the design reliability does your state agency use for local road?

Answer:
- Illinois DOT: No response
- Missouri DOT: 50%
- Minnesota DOT: 80%
- South Dakota DOT: 90%
- Wisconsin DOT: 50%

Question 16: What are the important characteristics of asphalt pavement for local road design?

Answer:
- Illinois DOT: No response
- Missouri DOT: Adequate structure and proper compaction of lower layers
- Minnesota DOT: Subgrade and ADT/HCADT
- South Dakota DOT: No response
- Wisconsin DOT: thickness, PG grade, gradation, asphalt content

Question 17: What are the important characteristics of concrete pavement for local road design?

Answer:
- Illinois DOT: No response
- Missouri DOT: Short joint spacing and proper compaction of lower layer
- Minnesota DOT: Subgrade and ADT/HCADT
- South Dakota DOT: traffic, subgrade, and loads
- Wisconsin DOT: N/A

Summary of Survey Results

The survey responses from five state departments of transportation are summarized in Table 4. South Dakota DOT uses the 1993 AASHTO design guide and the DARWIN Software to design low-volume road pavements. Illinois DOT developed a local agency pavement design procedure described in Ch. 37 of the BLRS Manual. Missouri DOT does not have a separate pavement design procedure for low-volume roads but uses the AASHTO 93 design guide and mechanistic-empirical pavement design guide (M-EPDG) software to design low-volume roads.

Table 4. Summary of survey results on local road pavement thickness design procedures from five state DOT's

Q	Illinois DOT	Missouri DOT	Minnesota DOT	South Dakota DOT	Wisconsin DOT
1	Mechanistic Empirical Design developed by U of I and IL DOT	Mechanistic-Empirical Pavement Design Guide	Charts and tables for soil factor and R-value	1993 AASHTO	1972 AASHTO
2	None	Mechanistic-Empirical Pavement Design Guide	MnDOT Flexible MnDOT Rigid	DARWIN software	WisPave
3	400 ADT (Traffic Factor < 0.25)	less than 1000 AADT and less than a 100 trucks a day	ADT less than 1000	Don't have a low volume road classification	< 400 ADT
4	Conventional Flexible Design (Chapter 37-3 of the BLRS Manual)	No	Yes	No	No
5	Surface: HMA 3" Base: Class A Agg 8" Subgrade: Modified Soil 8"	Surface: HMA 7"-8" Base: crushed stone 4" Subgrade: N/A	Surface: HMA min 3" Base: Class 5 or 6, 6" Subgrade: Existing Soil	Surface: 3"-4" Base: 10"-12" Subgrade: 8" (if needed)	Surface: SuperPave E-0.3 12.5mm-3" Base: dense graded aggregate 8" Subgrade: N/A
6	No Response	Surface: JPCP 6"-7" Base: crushed stone 4" Subgrade: N/A	Surface: Concrete 7-9" Base: Class 5 or 6, 0-6" Subgrade: Existing Soil	Surface: 3"-4" Base: 10"-12" Subgrade 8" (if needed)	N/A
7	Traffic Paving Materials	Subgrade, Loads	Traffic, Subgrade	Traffic, Subgrade, Loads,	Traffic, Load, Pavement Performance Criteria
8	No Response	A-4, A-7-5, and A-7-6	A-1 thru A-6, A-7-5, and A-7-6	A-6 to A-7	A-3, A-2-4, A-4, A-6, A-7-6

Table 4. Continued

Q	Illinois DOT	Missouri DOT	Minnesota DOT	South Dakota DOT	Wisconsin DOT
9	No Response	Assume resilient modulus value from AASHTO class	R-Value derived from soil tests	Use the typical liquid limit value for the family of soils and convert that number to a resilient modulus value	No Response
10	No Response	Resilient Modulus (Mr)	Soil Factor and/or R-Value	Resilient Modulus (Mr)	k-value and SSV
11	HMA (E: elastic modulus)	Granular (CBR or Mr) HMA (E: elastic modulus) PCC(E: elastic modulus), f'c (compressive strength), S'c (flexural strength)	HMA (E: elastic modulus)	Granular (CBR or Mr) HMA (E: elastic modulus)	Granular (CBR or Mr) HMA (E: elastic modulus)
12	ESAL <10,000 10,000-50,000 50,000-100,000 100,000-250,000	Load spectra in the MEPDG	ADT ESAL 100,000 – 250,000	ESAL 50,000-100,000	ADT ESAL 10,000-50,000 50,000-100,000
13	Ditches	Ditches	Ditches	Ditches	Ditches
14	No Response	Use IRI and visible distress data	RQI – Ride quality Index, ranges from 0 -5 (best)	2.5 – 4.5	Use IRI and PDI
15	No Response	50%	80%	90%	50%
16	No Response	Adequate structure and proper compaction of lower layers	Subgrade and ADT/HCADT	Traffic Subgrade Loads	Thickness, PG grade Gradation, % AC
17	No Response	Short joint spacing and proper compaction of lower layers	Subgrade and ADT/HCADT	Not typically pave a low-volume road with PCCP	N/A

PAVEMENT DESIGN PROCEDURES BY COUNTIES AND CITIES IN IOWA

A survey was sent out to every county and the top 10 cities in Iowa by population to find out the design procedure each county or city uses. Of the 109 surveys sent out, 39 were sent back (35 county, 4 city). The survey sought after the very same details of the previous state DOT surveys outlined in Table 5. Of the 35 returned county surveys, 8 of the surveys had county responses where very few to no new roads were being designed because of budget constraints, and the county is only maintaining their existing infrastructure (in some cases turning roads back to gravel).

Table 5. Questionnaire about pavement design procedures for counties and cities

No.	Question
1.	What kind of pavement thickness design software do you use for low volume road?
2.	What type of traffic input do you use for low-volume road design
3.	What design reliability and design life do you use for low volume load?
4.	What soil type do you use when designing? (Select/Good, Suitable/Fair, Unsuitable/Poor)
5.	Is any soil testing to find the resilient modulus done before designing? If so, what are typical ranges?
6.	What is your minimum design thickness for rigid pavement (assume JRCP)?
6a.	Is any stone base material typically required for your minimum design? If so, how much (in inches)?
6b.	Is any soil stabilization typically required for your minimum design? If so, how much (in inches)?
7.	What is your minimum design thickness for flexible pavement?
7a.	Is any stone base material typically required for your minimum design? If so, how much (in inches)?
7b.	Is any soil stabilization typically required for your minimum design? If so, how much (in inches)?

Summary of Survey Results

63% of the results from the counties used experience alone to design their road while every city used SUDAS design manual. Low volume pavement designs typically had a traffic load from 100,000-500,000 ESALs with design life of typically 20-30 years in Poor to Fair soil conditions. Almost exclusively, cities design with soil stabilization. The design thickness for each respective pavement is shown in Figure 3 and Figure 4. A typical minimum flexible pavement is 7-8 inches in depth and 4-6 inches of stone subbase. A typical minimum rigid pavement section is 8 inches in depth and 4-6 inches of stone subbase.

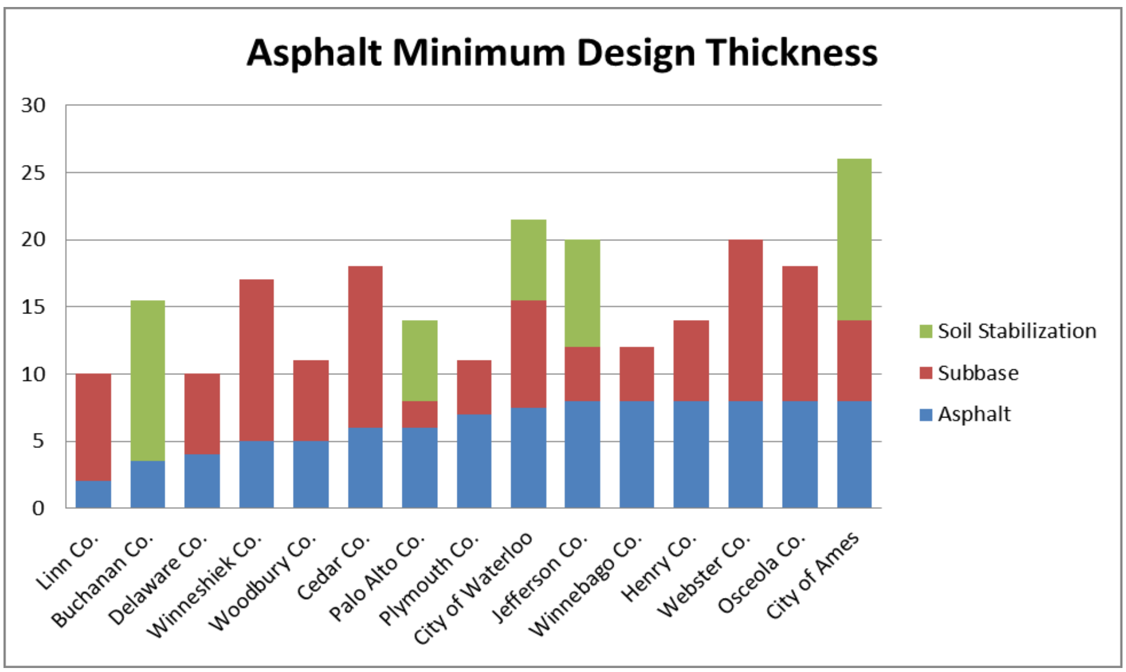


Figure 3. Flexible design thickness for surveyed counties and cities in Iowa

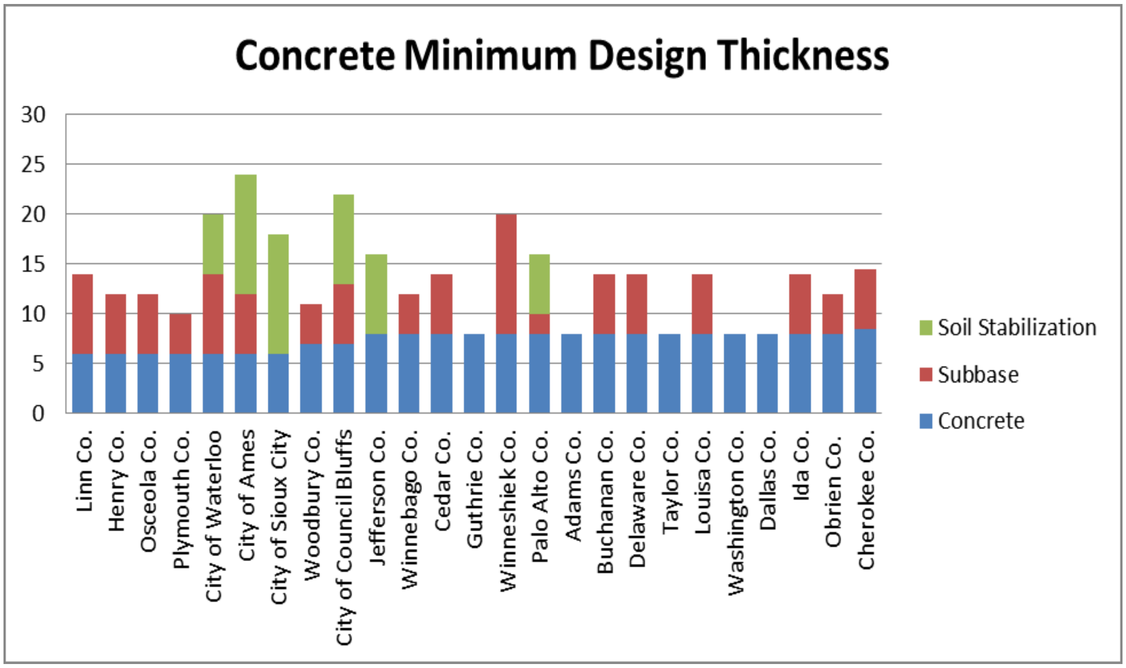


Figure 4. Rigid design thickness for surveyed counties and cities in Iowa

PAVEMENT THICKNESS DESIGN SOFTWARE PACKAGES USED IN IOWA

To minimize the life-cycle cost of maintaining pavements, it is critical to determine the most appropriate pavement thickness for a given traffic level, subgrade condition and environmental factor. There are several pavement software packages available which would give different pavement thicknesses for the similar soil and traffic conditions. In addition, the impacts of design parameters on the pavement thickness are not transparent to a user. Therefore, there is a critical need for comparing these software packages and identifying the critical design input parameters through the sensitivity analysis.

In the past, Bergeson and Barber (1998) developed a pavement design method for low-volume roads in Iowa by utilizing the reclaimed hydrated Class C fly ash as an aggregate for base and Sharma et al. (2005) developed a guide to improve the quality of subgrade and subbase. The following three pavement design software packages were evaluated on how they are different in determining design input parameters and their influences on the pavement thickness: 1) StreetPave software based on the ACPA thickness design for concrete highway and street pavements and PCA method (PCA 1984; ACPA 2006), 2) WinPAS software based on AASHTO 1993 pavement design guide (ACPA 2006), 3) I-Pave software based on AASHTO 1993 design guide.

StreetPave Software

StreetPave is a concrete pavement thickness design software package tailored for local road pavements (PCA 1984; ACPA 2006). This software package generates the optimum concrete pavement thickness for city, municipal, county, and state roadways. ACPA claims that it incorporates an asphalt pavement design process based on the Asphalt Institute method and creates an equivalent asphalt design for the given load carrying capacity requirement. A life cycle cost analysis module allows a user to perform a detailed cost/benefits analysis. The input values include project information, traffic information, pavement design parameters and pavement maintenance schedule. As shown in Figure 5, the StreetPave software displays the optimum concrete thickness, the equivalent asphalt thickness and the life cycle cost analysis. It also provides the sensitivity analysis module with regards to k-value, concrete strength, design life, reliability and percentage of cracked slabs.

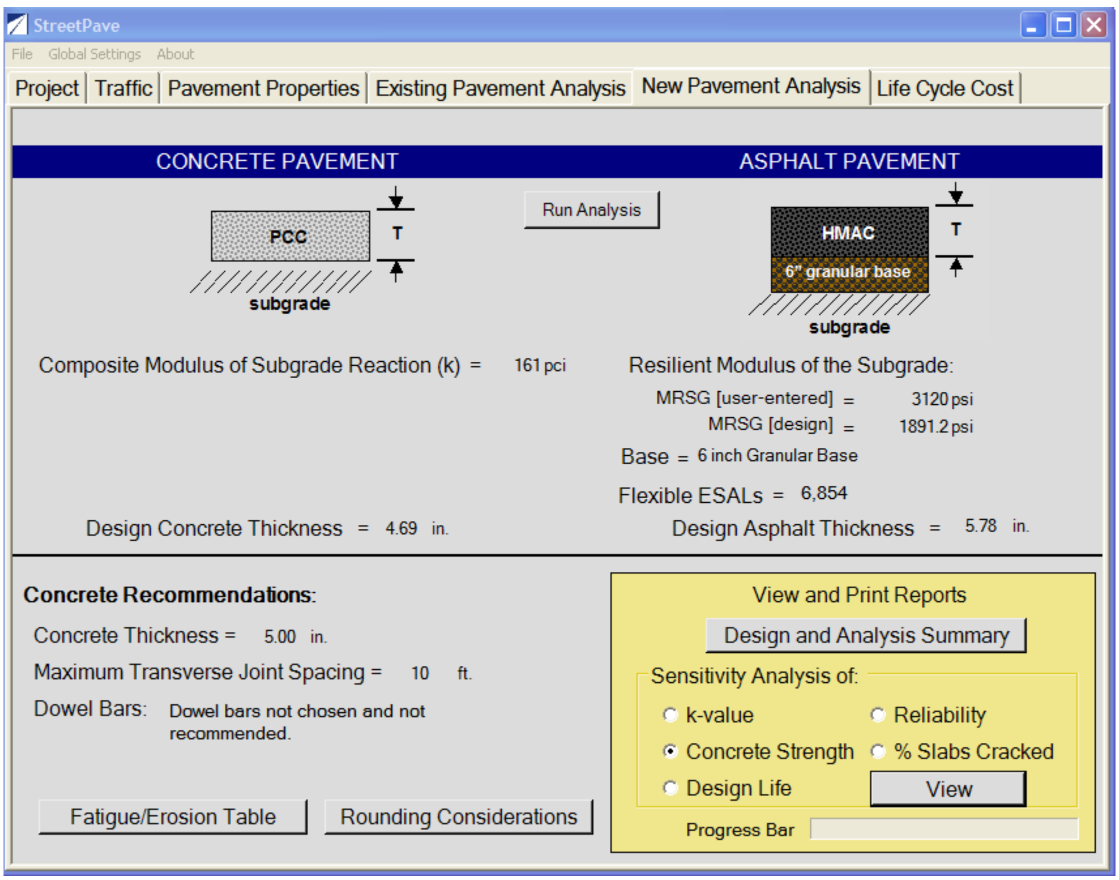


Figure 5. Screenshot of StreetPave pavement design software

According to the PCA design manual (1984), weights, frequencies, and type of truck axle loads are needed. But, if specific axle load data is not available, as shown in Table 6, a simple design table by PCA can be used that represents different categories of road and street type.

Table 6. Axle load categories used in StreetPave software

Axle Load Category	Description	Traffic			Maximum Axle Loads, kips	
		ADT	AADT			
			%	Per Day	Single Axles	Tandem Axles
1	Residential Streets Rural and secondary roads (low to medium)	200-800	1-3	Up to 25	22	36
2	Collector Streets Rural and secondary roads (high) Arterial streets and primary roads (low)	700-5,000	5-18	40-1,000	26	44
3	Arterial streets and primary roads (medium) Expressways and urban and rural interstate (low to medium)	3,000-12,000 (2 lane) 3,000-50,000 (4 lane or more)	8-30	500-5,000+	30	52
4	Arterial streets, primary roads , expressways (high) Urban and rural interstate (medium to high)	3,000-150,000 (4 lane or more)	8-30	1,500-8,000+	34	60

**High, medium, and low refer to the weights of axle loads for the type of street or road*

WinPAS Software

The WinPAS software package performs roadway pavement thickness design and evaluation following the AASHTO 1993 design guide for pavement structures (ACPA 2006). This software package also provides a life-cycle cost module to allow a user to compare alternative pavement designs. As shown in Figure 6, the input values include project information, traffic information and pavement design parameters. The report module prints out optimized concrete thickness design and the results of life cycle cost analysis in a predefined report format. This software package provides a simple user interface and an effective help module.

Table 7 shows a comparison between rigid and flexible ESAL's with the same traffic stream (ACPA 2006). As can be seen from Table 7, there is a significant difference between asphalt and concrete ESAL's where asphalt ESAL's are about 1/3 less than concrete.

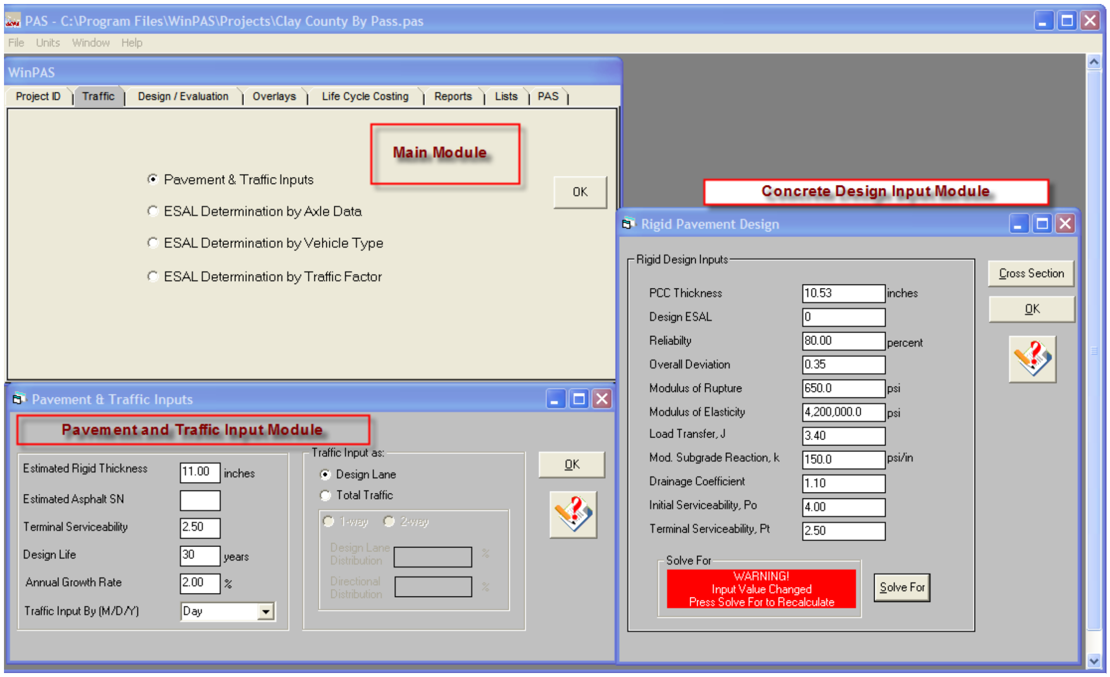


Figure 6. WinPAS pavement design software

Table 7. Concrete and asphalt ESAL's generated by a mixed traffic stream

Vehicle	Number	ESAL	
		Concrete	Asphalt
Busses	5	13.55	8.73
Panel Trucks	10	10.89	11.11
Single Unit, 2 axle trucks	20	6.38	6.11
Semi-Tractor Trailer, 3 axles	10	20.06	13.41
Semi-Tractor Trailer, 4 axles	15	39.43	29.88
Semi-Tractor Trailer, 5 axles	15	57.33	36.87
Automobile, Pick-up, Van	425	1.88	2.25
Total	500	149.52	108.36

I-Pave Low Volume Road Design Guide

The I-Pave software package is new software recently released by the Asphalt Paving Association of Iowa that uses AASHTO 1993 design guide to determine pavement thicknesses for flexible and rigid pavement while also comparing life-cycle costs of each pavement with current prices being updated from the Iowa DOT Bid Tab Analysis for the previous 12-months. The intended purpose of the I-Pave software is designing low volume roads under 3,000,000 ESALs. The life-cycle cost analysis compares a 12ft wide lane mile for each flexible and rigid pavement. As shown in Figure 7, the input values include project information, traffic information, and design parameters. The software runs the analysis for these factors and then allows to be printed out in a predefined report format. This software package provides a simple user interface.

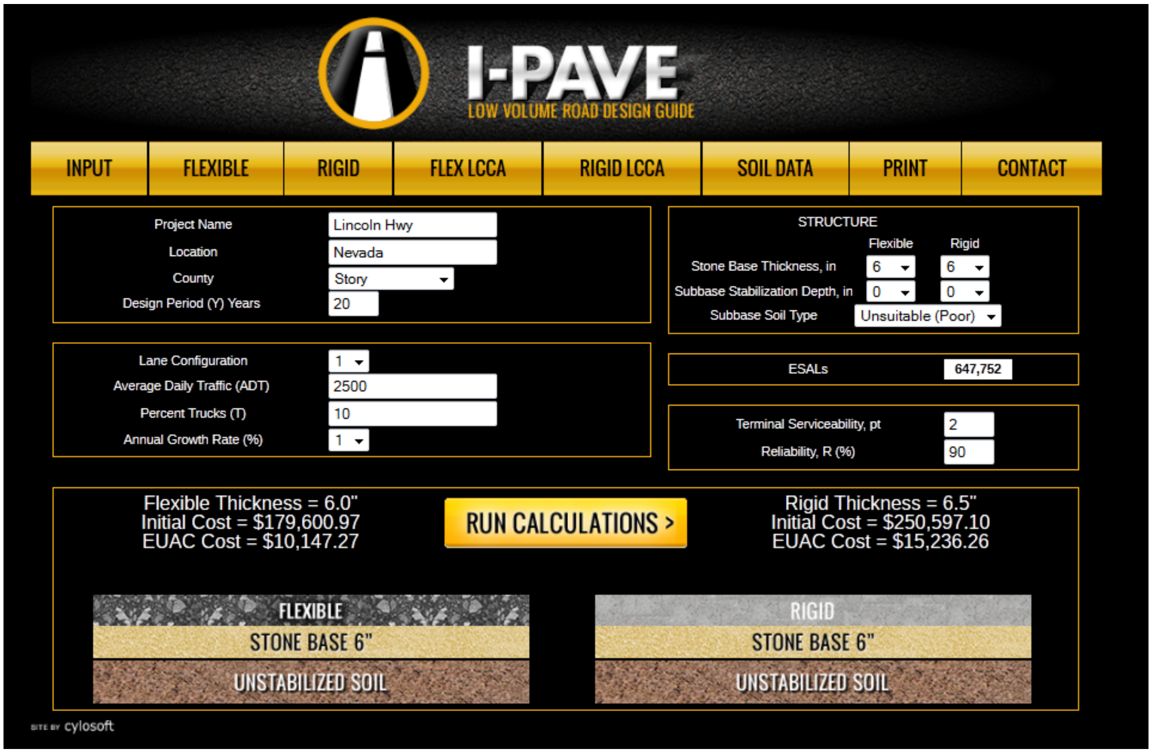


Figure 7. Screenshot of I-Pave Low Volume Road Design Guide

The I-Pave software classifies three different soil types with a CBR value and equivalent k-value for each as shown in Figure 8. Since the AASHTO design method does not use CBR, the k-value is converted to resilient modulus by equation k= $M_r/30$. One neat features of the design program is it will display the typical AASHTO soil type for each county when inputting the location of the project.

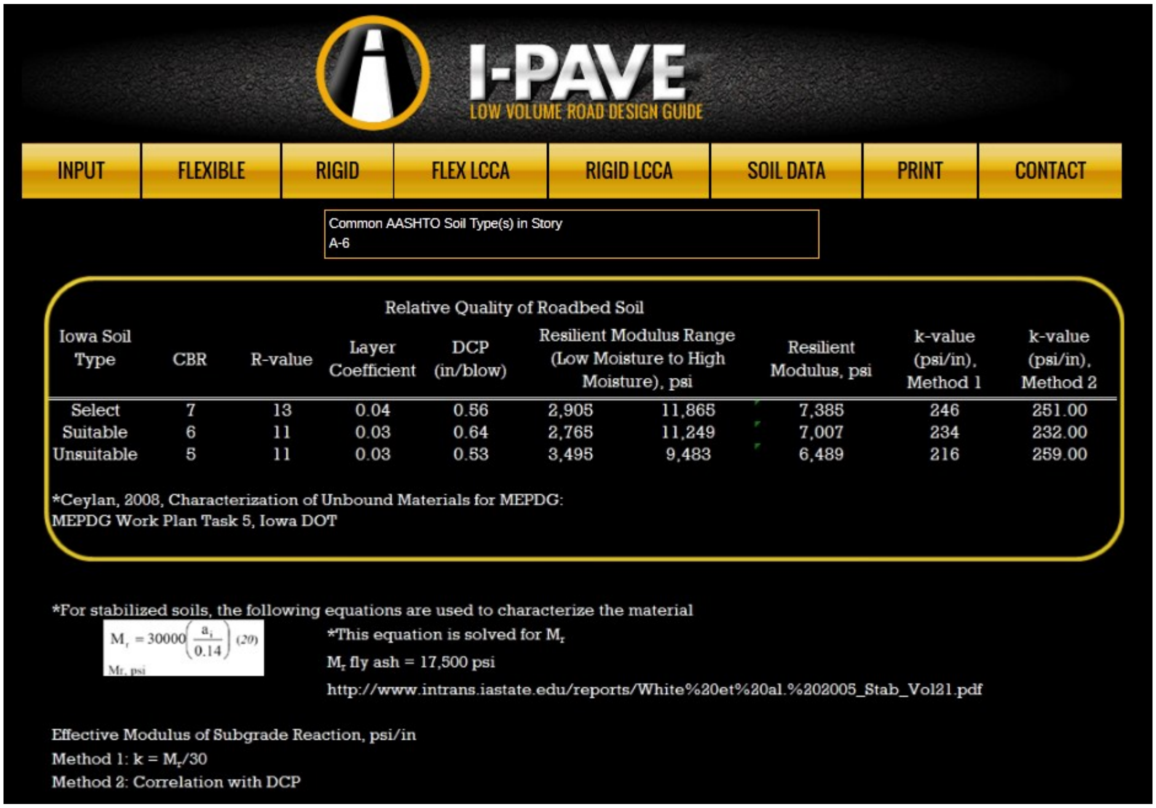


Figure 8. I-Pave Soil Data

SENSITIVITY ANALYSIS OF DESIGN INPUT PARAMETERS USING THREE PAVEMENT DESIGN SOFTWARE PACKAGES

The sensitivity analysis examined the design input parameters for each of three current pavement design software packages discussed earlier: StreetPave, WinPAS, and I-Pave. As shown in Figure 9, four critical design input parameters were identified and the sensitivity analysis of each parameter was performed using each of three pavement design software packages.

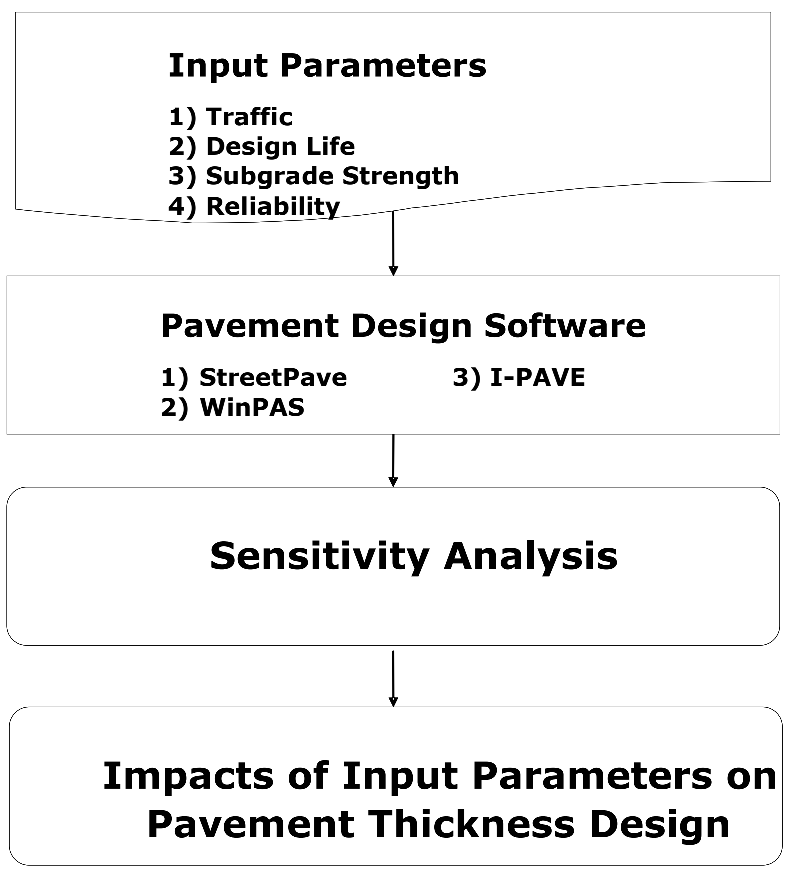


Figure 9. Sensitivity analysis flow chart of input parameters for pavement thickness design

Input Parameters

To identify the input parameters that affect the pavement thickness the most, the sensitivity analysis was performed. Table 8 and Table 9 show the common input parameters and traffic information, respectively, which were used in the sensitivity analysis. Average daily truck traffic (ADTT) was used as a traffic input parameter for all three software packages.

Table 8. Common design input parameters used for sensitivity analysis

Parameter	Input Values Used
Number of Lanes	2
Directional Distribution	50%
Design Lane Distribution	100%
Traffic Growth	2%
Terminal Serviceability (P_t)	2.0
Subbase Thickness	6.0

Table 9. Traffic input parameters used for sensitivity analysis

Parameter	Input Values Used		
Road Classification	ADT	% Trucks	ADTT
Residential	100	5	20
Collector	1,000	10	100
Minor Arterial	1,665	15	250
Major Arterial 1	2,500	20	500
Major Arterial 2	4,000	20	1,000

The reliability is used in the AASHTO design equation in the form of Z_R S_0 where Z_R represents the normal deviate for a given reliability and S_0 is the standard deviation in the design equation. The standard deviation is the amount of statistical error present in the pavement design equation which represents the amount of scatter between predicted performance and actual performance and different values are often used for asphalt (typically 0.45) and concrete pavements (typically 0.35). WinPAS and I-Pave software packages use this reliability concept. However, StreetPave software applies the reliability to the flexural fatigue equation for concrete pavements and to the resilient modulus of the subgrade for asphalt pavements. All three pavement design software packages were run using two design lives of 20 and 40 years and three levels of reliability of 50%, 80%, and 90%. However, the I-Pave software could not be run for the 50% reliability because the lowest level allowed was 80%.

The ESAL factor of 1.0 was also applied to the WinPAS software but not for StreetPave software because it automatically generates ESAL from the ADTT. As can be seen from Table 10, the WinPAS software requires the most amount of input parameters in order to complete the design procedure.

Table 10. Additional input parameters required for WinPAS software

Parameter	Input Value Used
Overall Deviation	0.35 (Concrete), 0.45 (Asphalt)
Modulus of Rupture	650 psi
Modulus of Elasticity	4,200,000 psi
Load Transfer (J)	3.20
Drainage Coefficient	1.0
Initial Serviceability (P_0)	4.5

Each software package uses different terms in determining the subgrade strength; resilient modulus for StreetPave software and k-value for WinPAS and I-Pave software. Following the StreetPave software manual, the equivalent resilient modulus values of 4350psi, 7950psi, 8735psi, 10020psi, and 11820psi were used for StreetPave software. The conversion from CBR to resilient modulus was based on 1500 *CBR (for CBR values of 2.9 and 5.3) and 1941.488* $CBR^{0.06844709}$ (for CBR values of 9.0, 11.0 and 14.0).

To design concrete pavement using, WinPAS converts the resilient modulus values to k-value using the relationship k = M_R/19.4 based on an analysis of a 30-inch plate bearing test. However, due to the small size of the plate used to develop this relationship, this conversion equation results in too large k-values. Therefore, using the conversion chart from CBR to k-value developed by Packard (1973), the following equivalent k-values were used for the WinPAS software: 97psi/in, 146psi/in, 190psi/in, 206psi/in and 222psi/in. The I-Pave software converts the k-value to resilient modulus by equation k= M_r/30. The k-values for the concrete design are 246psi/in, 234psi/in, and 216psi/in. The three soil inputs for the asphalt design have resilient modules of 7,385 psi, 7,007 psi, and 6,489 psi.

Analysis Results Using StreePave Software - Concrete

StreetPave software package recommends the concrete pavement a minimum thickness of 3.5 inches for 25 ADT with 1% truck traffic, 50% reliability, and the best subgrade strength whereas the AASTHO 1993 design guide recommends 5.0 inches as a minimum design thickness. Table 11 and Table 12 show the sensitivity analysis results of concrete pavement thickness and the diameter of the dowel bar for the design life of 20 years and 40 years, respectively. StreetPave software assume the edge support and recommend the dowel bar with a diameter of 1.5 inches for the pavement thickness greater than 10 inches; 1.25 inches for the pavement thickness between 8 and 10 inches; 1.0 inch for the pavement thickness less than 8 inches only when the erosion is a cause of failure. The ESAL values generated by StreetPave software reported as flexible ESAL's for the concrete pavement design which indicates the ESAL's are based on conversion factor for flexible pavements.

Figure 10 shows concrete pavement thickness against traffic level at low and high subgrade strengths for three different levels of reliability and the design life of 20 years. As can be seen from Figure 10, the pavement thickness is more sensitive to traffic at a lower traffic level up to 1.17 million (increase in thickness by 1.5 inches) than the higher traffic level from 1.17 million to 5.42 million ESAL (increase in thickness by 1.0 inch). Reliability had a limited impact on the thickness, increasing the thickness by up to 0.5 inch, when the reliability increased from 50% to 90%.

Table 11. Sensitivity analysis results of concrete pavement thickness for design life of 20 years using StreetPave Software

50% Reliability

Road Classification	ADTT	ESAL Factor	Resilient Modulus, M_r (psi)									
			M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
			Thickness (in)/ Dowel (in)	ESALs	Thickness (in)/ Dowel (in)	ESALs	Thickness (in)/ Dowel(in)	ESALs	Thickness (in)/ Dowel (in)	ESALs	Thickness (in)/ Dowel (in)	ESALs
Residential	20	1.0	4.51	45,504	4.12	45,039	4.06	44,962	3.97	44,843	3.88	44,723
Collector	100	1.0	5.20	242,016	4.78	240,964	4.71	240,749	4.62	240,458	4.51	240,082
Minor Arterial	250	1.0	6.08	1,170,882	5.61	1,172,185	5.54	1,172,229	5.44	1,172,220	5.32	1,172,101
Major Arterial	500	1.0	6.67	2,711,829	6.17	2,721,003	6.10	2,722,254	5.99	2,724,185	5.87	2,726,231
Major Arterial 2	1000	1.0	6.86	5,416,756	6.47	5,431,032	6.43	5,423,509	6.37	5,434,719	6.28	5,438,018

80% Reliability

Road Classification	ADTT	ESAL Factor	Resilient Modulus, M_r (psi)									
			M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
			Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	4.84	45,829	4.44	45,426	4.38	45,358	4.29	45,251	4.18	45,115
Collector	100	1.0	5.58	242,571	5.14	241,893	5.08	241,760	4.98	241,519	4.86	241,197
Minor Arterial	250	1.0	6.52	1,168,275	6.03	1,171,100	5.95	1,171,412	5.85	1,171,734	5.72	1,172,036
Major Arterial	500	1.0	7.16	2,703,173	6.63	2,712,564	6.55	2,714,039	6.44	2,716,070	6.31	2,718,461
Major Arterial 2	1000	1.0	7.35	5,400,218	6.82	5,418,194	6.74	5,421,096	6.63	5,425,127	6.49	5,430,293

90% Reliability

Road Classification	ADTT	ESAL Factor	Resilient Modulus, M_r (psi)									
			M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
			Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Recommend Thickness (in)	ESALs	Recommend Thickness (in)	ESALs
Residential	20	1.0	5.11	46,035	4.69	45,690	4.63	45,631	4.53	45,526	4.42	45,404
Collector	100	1.0	5.89	242,729	5.43	242,399	5.36	242,298	5.26	242,130	5.14	241,893
Minor Arterial	250	1.0	6.86	1,165,604	6.36	1,169,355	6.28	1,169,841	6.17	1,170,446	6.04	1,171,058
Major Arterial	500	1.0	7.53/1.0	2,697,421	6.99	2,706,076	6.91	2,707,486	6.79	2,709,639	6.66	2,712,012
Major Arterial 2	1000	1.0	7.74/1.0	5,389,176	7.19	5,405,350	7.10	5,408,364	6.99	5,412,153	6.85	5,417,114

Table 12. Sensitivity analysis results of concrete pavement thickness for design life of 40 years using StreetPave Software

50% Reliability — Resilient Modulus, M_r (psi)

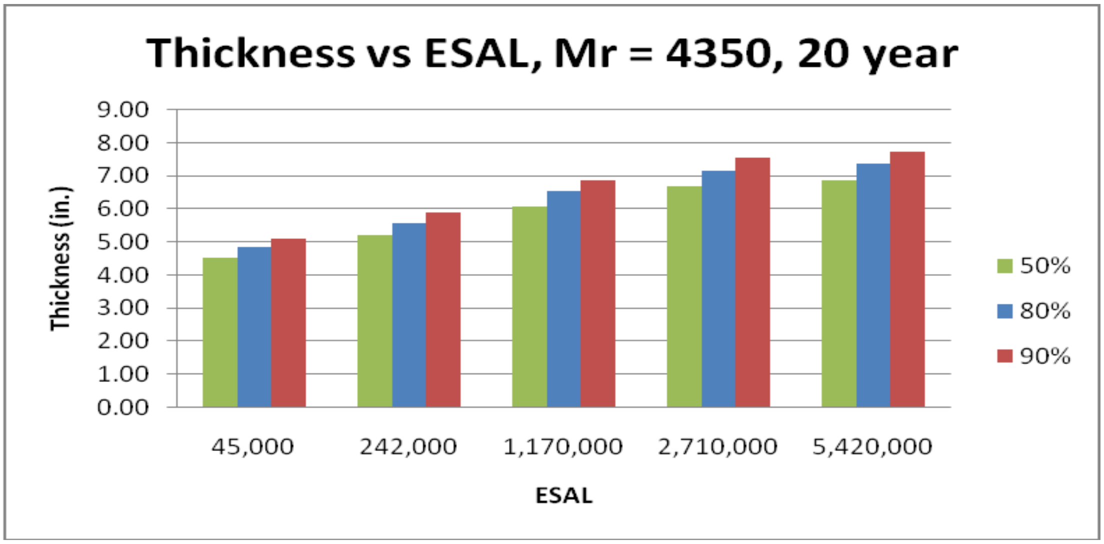
Road Classification	ADTT	ESAL Factor	M_R=4,350 Thickness(in)/ Dowel (in)	M_R=4,350 ESALs	M_R=7,950 Thickness(in)/ Dowel(in)	M_R=7,950 ESALs	M_R=8,735 Thickness(in)/ Dowel(in)	M_R=8,735 ESALs	M_R=10,020 Thickness (in)/ Dowel(in)	M_R=10,020 ESALs	M_R=11,820 Thickness (in)/ Dowel(in)	M_R=11,820 ESALs
Residential	20	1.0	4.70	113,608	4.30	112,521	4.24	112,340	4.15	112,060	4.05	111,740
Collector	100	1.0	5.41	602,523	4.97	600,339	4.91	599,946	4.81	599,245	4.70	598,411
Minor Arterial	250	1.0	6.30	2,907,870	5.86	2,912,797	5.82	2,913,071	5.76	2,913,424	5.68	2,913,783
Major Arterial	500	1.0	6.92/1.0	6,730,226	6.40/1.0	6,753,840	6.33/1.0	6,757,039	6.50	6,749,253	6.42	6,752,924
Major Arterial 2	1000	1.0	7.09/1.0	13,445,753	6.57/1.0	13,492,079	6.50/1.0	13,498,505	6.38/1.0	13,509,511	6.25/1.0	13,521,344

80% Reliability — Resilient Modulus, M_r (psi)

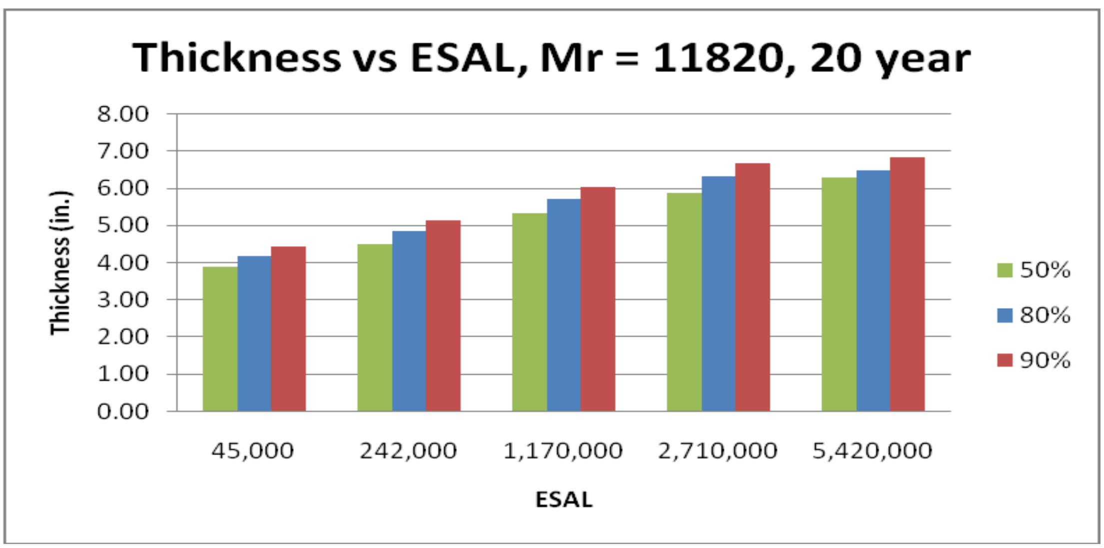
Road Classification	ADTT	ESAL Factor	M_R=4,350 Design Thickness (in)	M_R=4,350 ESALs	M_R=7,950 Design Thickness (in)	M_R=7,950 ESALs	M_R=8,735 Design Thickness (in)	M_R=8,735 ESALs	M_R=10,020 Design Thickness (in)	M_R=10,020 ESALs	M_R=11,820 Design Thickness (in)	M_R=11,820 ESALs
Residential	20	1.0	5.05	114,339	4.63	113,435	4.57	113,281	4.48	113,039	4.37	112,728
Collector	100	1.0	5.80	603,365	5.35	602,30	5.28	602,011	5.18	601,539	5.07	600,945
Minor Arterial	250	1.0	6.76	2,899,694	6.26	2,908,451	6.18	2,909,539	6.07	2,910,864	5.95	2,912,068
Major Arterial	500	1.0	7.41	6,710,040	6.88	6,731,995	6.80	6,735,571	6.68	6,741,007	6.55	6,746,957
Major Arterial 2	1000	1.0	7.60/1.25	13,406,408	7.05	13,449,156	6.97/1.0	13,456,068	6.86/1.0	13,465,770	6.72/1.0	13,478,375

90% Reliability — Resilient Modulus, M_r (psi)

Road Classification	ADTT	ESAL Factor	M_R=4,350 Design Thickness (in)	M_R=4,350 ESALs	M_R=7,950 Design Thickness (in)	M_R=7,950 ESALs	M_R=8,735 Design Thickness (in)	M_R=8,735 ESALs	M_R=10,020 Recommend Thickness (in)	M_R=10,020 ESALs	M_R=11,820 Recommend Thickness (in)	M_R=11,820 ESALs
Residential	20	1.0	5.33	114,750	4.90	114,054	4.83	113,906	4.74	113,703	4.62	113,410
Collector	100	1.0	6.12	603,295	5.65	603,164	5.58	603,018	5.47	602,720	5.35	602,301
Minor Arterial	250	1.0	7.12	2,891,971	6.60	2,902,812	6.52	2,904,271	6.41	2,906,15	6.28	2,908,163
Major Arterial	500	1.0	7.81/1.25	6,696,451	7.25	6,716,272	7.16	6,719,945	7.05	6,724,578	6.91	6,730,667
Major Arterial 2	1000	1.0	8.00/1.25	13,382,264	7.43	13,418,580	7.35	13,424,658	7.23	13,434,157	7.09	13,445,753



a. Low subgrade strength



b. High subgrade strength

Figure 10. Impacts of traffic level and reliability on concrete pavement thickness given low and high subgrade strength for 20 years of design life

Figure 11 shows an impact of traffic level and subgrade strength on concrete pavement thickness given the reliability of 80% and the design life of 20 years. It can be seen that the concrete pavement thickness was sensitive to the subgrade strength, with a decrease in thickness up to 1.0 inch, at the higher traffic level but not as sensitive to the subgrade strength, decreasing by only 0.5 inch at the lower traffic level. Figure 12 shows an impact of design life on concrete pavement thickness and, given 80% reliability, to double the design life, the pavement thickness needs to be increased by only 0.25 inch.

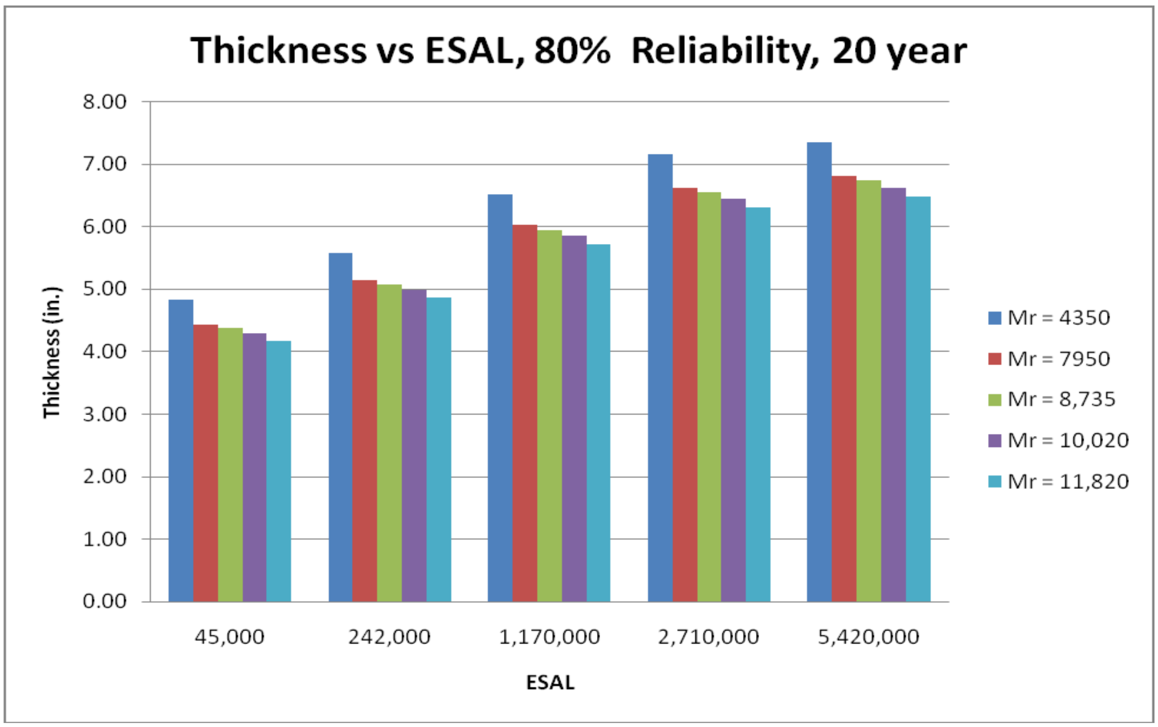


Figure 11. Impact of traffic level and subgrade strength on concrete pavement thickness given reliability of 80% and the design life of 20 years

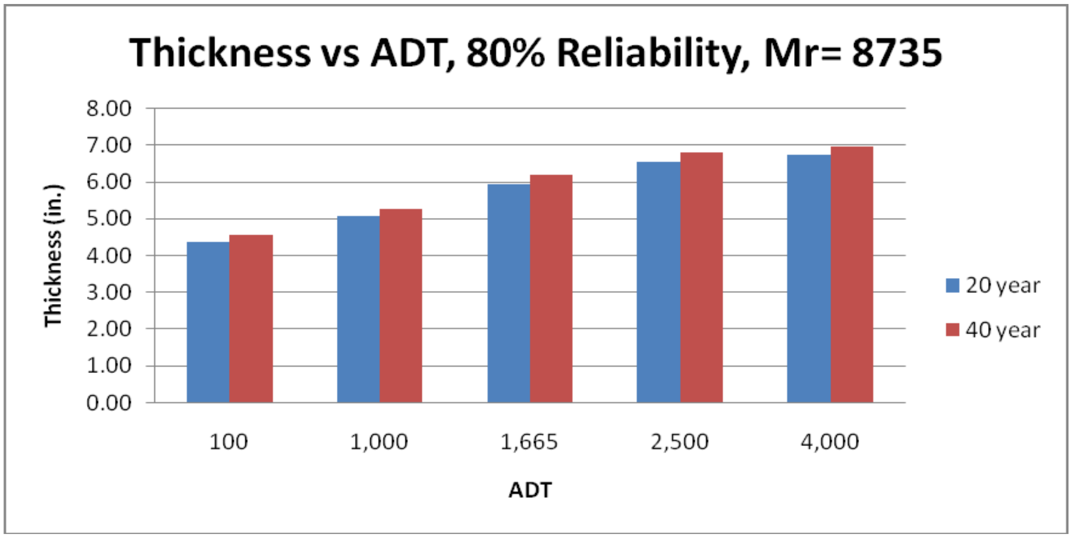


Figure 12. Impact of traffic level and design life at 80% reliability on concrete pavement thickness

Analysis Results Using StreePave Software - Asphalt

For the lowest traffic level, the minimum thickness for asphalt pavement is 1.2 inches at 50% reliability and the best subgrade strength (3.5 inches for concrete pavement). Table 13 and Table 14 show the sensitivity analysis results of asphalt pavement thickness with 6-inch granular base for design life of 20 and 40 years, respectively.

Figure 13 shows impacts of traffic level and reliability on the asphalt pavement thickness for a given low and high subgrade strengths. The asphalt pavement thickness increased more rapidly at the low traffic level than at the high traffic level. Contrary to the concrete pavement, the reliability had a greater impact on the pavement thickness at the lower traffic level where asphalt pavement thickness increased by about 2.0 inches when the reliability increased from 50% to 90%. At the higher traffic level, asphalt pavement thickness increased by about 1.5 inches when the reliability increased from 50% to 90%.

Table 13. Sensitivity analysis results of asphalt pavement thickness for design life of 20 years using StreetPave software

50% Reliability

Road Classification	ADTT	ESAL Factor	Resilient Modulus, M_r (psi)									
			M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
			Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	4.75	45,504	3.11	45,039	2.87	44,962	2.54	44,843	2.16	44,723
Collector	100	1.0	6.52	242,016	4.95	240,964	4.71	240,749	4.37	240,458	3.98	240,082
Minor Arterial	250	1.0	8.67	1,170,882	7.21	1,172,185	6.98	1,172,229	6.65	1,172,220	6.26	1,172,101
Major Arterial	500	1.0	10.06	2,711,829	8.68	2,721,003	8.46	2,722,254	8.14	2,724,185	7.76	2,726,231
Major Arterial 2	1000	1.0	11.36	5,416,756	10.05	5,431,032	9.84	5,423,509	9.53	5,434,719	9.15	5,438,018

80% Reliability

Road Classification	ADTT	ESAL Factor	Resilient Modulus, M_r (psi)									
			M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
			Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	5.87	45,829	4.14	45,426	3.88	45,358	3.51	45,251	3.08	45,115
Collector	100	1.0	7.55	242,571	5.94	241,893	5.70	241,760	5.34	241,519	4.92	241,197
Minor Arterial	250	1.0	9.58	1,168,275	8.14	1,171,100	7.92	1,171,412	7.58	1,171,734	7.18	1,172,036
Major Arterial	500	1.0	10.90	2,703,173	9.57	2,712,564	9.35	2,714,039	9.04	2,716,070	8.65	2,718,461
Major Arterial 2	1000	1.0	12.13	5,400,218	10.90	5,418,194	10.70	5,421,096	10.39	5,425,127	10.02	5,430,293

90% Reliability

Road Classification	ADTT	ESAL Factor	Resilient Modulus, M_r (psi)									
			M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
			Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	6.71	46,035	4.93	45,690	4.66	45,631	4.28	45,526	3.82	45,404
Collector	100	1.0	8.30	242,729	6.69	242,399	6.44	242,298	6.08	242,130	5.64	241,893
Minor Arterial	250	1.0	10.21	1,165,604	8.82	1,169,355	8.60	1,169,841	8.27	1,170,446	7.87	1,171,058
Major Arterial	500	1.0	11.46	2,697,421	10.20	2,706,076	9.99	2,707,486	9.68	2,709,639	9.31	2,712,012
Major Arterial 2	1000	1.0	12.63	5,389,176	11.49	5,405,350	11.30	5,408,364	11.01	5,412,153	10.65	5,417,114

Table 14. Sensitivity analysis results of asphalt pavement thickness for design life of 40 years using StreetPave software

50% Reliability

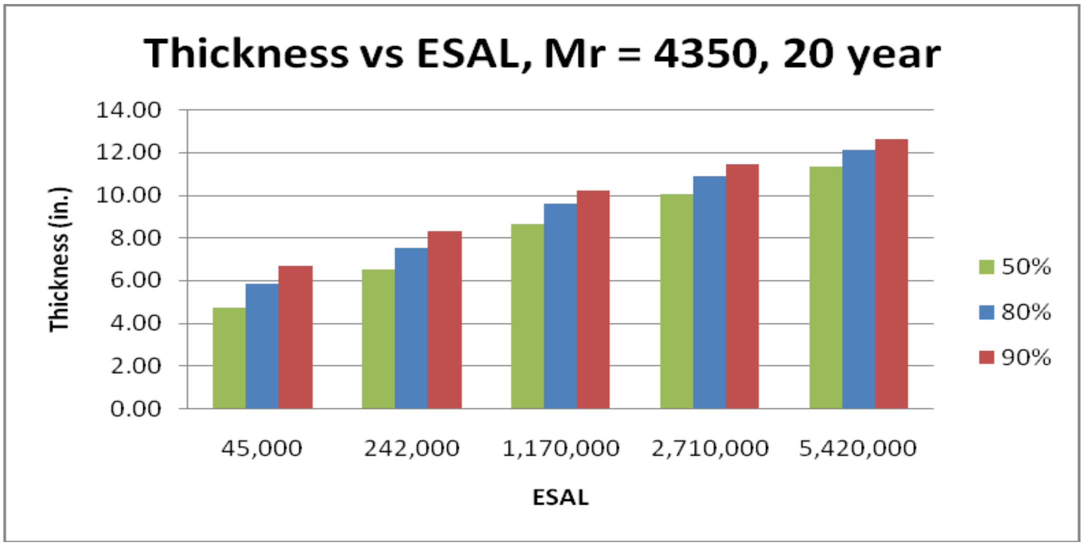
Road Classification	ADTT	ESAL Factor	Resilient Modulus, M_r (psi)									
			M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
			Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	5.66	113,608	4.05	112,521	3.81	112,340	3.48	112,060	3.09	111,740
Collector	100	1.0	7.70	602,523	6.18	600,339	5.95	599,946	5.61	599,245	5.22	598,411
Minor Arterial	250	1.0	10.19	2,907,870	8.81	2,912,797	8.59	2,913,071	8.27	2,913,424	7.89	2,913,783
Major Arterial	500	1.0	11.80	6,730,226	10.52	6,753,840	10.31	6,757,039	10.00	6,749,253	9.62	6,752,924
Major Arterial 2	1000	1.0	13.30	13,445,753	12.10	13,492,079	11.90	13,498,505	11.61	13,509,511	11.25	13,521,344

80% Reliability

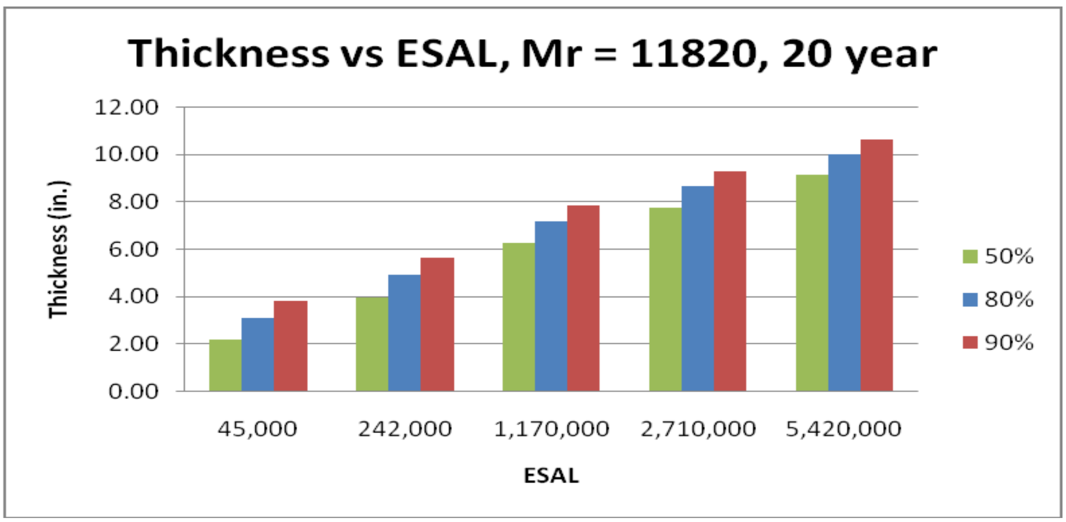
Road Classification	ADTT	ESAL Factor	Resilient Modulus, M_r (psi)									
			M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
			Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	6.74	114,339	5.07	113,435	4.81	113,281	4.45	113,039	4.03	112,728
Collector	100	1.0	8.66	603,365	7.15	602,30	6.91	602,011	6.56	601,539	6.15	600,945
Minor Arterial	250	1.0	11.01	2,899,694	9.70	2,908,451	9.48	2,909,539	9.17	2,910,864	8.78	2,912,068
Major Arterial	500	1.0	12.54	6,710,040	11.35	6,731,995	11.15	6,735,571	10.85	6,741,007	10.49	6,746,957
Major Arterial 2	1000	1.0	13.97	13,406,408	12.88	13,449,156	12.70	13,456,068	12.42	13,465,770	12.07	13,478,375

90% Reliability

Road Classification	ADTT	ESAL Factor	Resilient Modulus, M_r (psi)									
			M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
			Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	7.54	114,750	5.84	114,054	5.58	113,906	5.21	113,703	4.76	113,410
Collector	100	1.0	9.35	603,295	7.86	603,164	7.62	603,018	7.28	602,720	6.86	602,301
Minor Arterial	250	1.0	11.57	2,891,971	10.33	2,902,812	10.12	2,904,271	9.81	2,906,15	9.43	2,908,163
Major Arterial	500	1.0	13.03	6,696,451	11.93	6,716,272	11.74	6,719,945	11.45	6,724,578	11.10	6,730,667
Major Arterial 2	1000	1.0	14.39	13,382,264	13.42	13,418,580	13.24	13,424,658	12.98	13,434,157	12.65	13,445,753



a. Low subgrade strength



b. High subgrade strength

Figure 13. Impacts of traffic level and reliability on asphalt pavement thickness given low and high subgrade strength and design life of 20 years

Figure 14 shows an impact of traffic level and subgrade strength on asphalt pavement thickness given a reliability of 80% and design life of 20 years. Contrary to the concrete pavement, the subgrade strength had the greatest impact on the pavement thickness at the lowest traffic level where the asphalt pavement thickness decreased by up to 3.0 inches. At the high traffic level, however, the asphalt pavement thickness decreased by up to 2.0 inches when the subgrade strength increased from 4,350psi to 11,820psi.

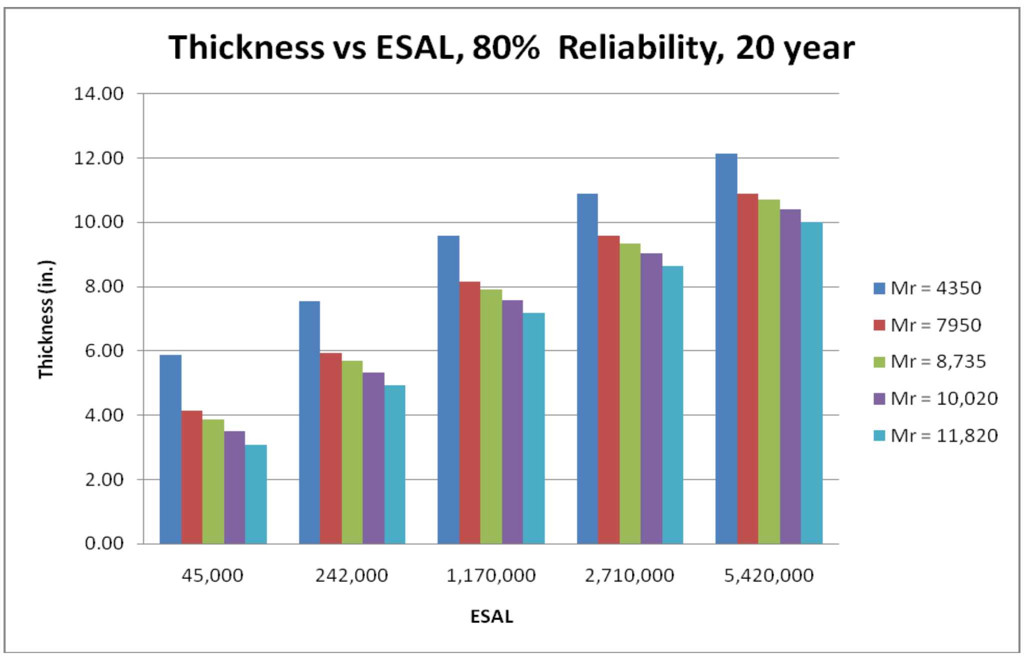


Figure 14. Impact of traffic level and subgrade strength on asphalt pavement thickness given reliability of 80% and design life of 20 years

Analysis Results Using WinPAS Software - Concrete

The minimum concrete pavement design thickness allowed is 4.0 inches at a traffic level of 1000 ADT with 2% truck. Table 15 and Table 16 show the sensitivity analysis results of the concrete pavement thicknesses without dowel (load transfer factor of 3.2) and with dowel (load transfer factor of 2.7) for design life of 20 years and 40 years, respectively. As can be seen from these tables, the use of dowel would consistently reduce the pavement thickness by 0.5 to 0.75 inch. Unless mentioned otherwise, the default load transfer value used for WinPAS software is 3.2. Figure 15 shows impacts of traffic level and reliability on the concrete pavement thickness for a given low and high subgrade strengths. As shown in Figure 15, traffic had the greatest impact on the concrete pavement thickness as the concrete pavement thickness increased by 3.0 to 4.0 inches when traffic increased from low to high level. Reliability had the greater impact at the higher traffic level, with the thickness increasing by about 1.25 inches when the reliability increased from 50% to 90%. At the low traffic level, the pavement thickness increased by only 0.5 to 1.0 inch when the reliability increased from 50% to 90%.

Table 15. Sensitivity analysis results of concrete pavement thickness for design life of 20 years using WinPAS software

50% Reliability

Road Classification	ADTT	ESAL Factor	k-value (pci): k-value = 97		k-value = 146		k-value = 190		k-value = 206		k-value = 222	
			Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	4.00/4.00	88,746	4.00/4.00	88,746	4.00/n.a.	88,746	4.00/n.a	88,746	N/A	N/A
Collector	100	1.0	4.98/4.47	443,731	4.78/4.23	443,731	4.57/4.02	443,731	4.50/4.00	443,731	4.44/4.00	443,731
Minor Arterial	250	1.0	5.85/5.26	1,109,327	5.64/5.04	1,109,327	5.47/4.86	1,109,327	5.42/4.74	1,109,327	5.36/4.74	1,109,327
Major Arterial	500	1.0	6.59/5.94	2,218,654	6.39/5.73	2,218,654	6.24/5.56	2,218,654	6.18/5.45	2,218,654	6.13/5.45	2,218,654
Major Arterial 2	1000	1.0	7.40/6.69	4,437,307	7.21/6.49	4,437,307	7.06/6.33	4,437,307	7.01/6.23	4,437,307	6.97/6.23	4,437,307

80% Reliability

Road Classification	ADTT	ESAL Factor	k-value (pci): k-value = 97		k-value = 146		k-value = 190		k-value = 206		k-value = 222	
			Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	4.21/4.00	88,746	4.00/4.00	88,746	4.00/4.00	88,746	4.00/4.00	88,746	4.00/4.00	88,746
Collector	100	1.0	5.61/5.04	443,731	5.40/4.82	443,731	5.23/4.63	443,731	5.17/4.57	443,731	5.11/4.50	443,731
Minor Arterial	250	1.0	6.58/5.32	1,109,327	6.37/5.71	1,109,327	6.22/5.54	1,109,327	6.16/5.49	1,109,327	6.11/5.43	1,109,327
Major Arterial	500	1.0	7.39/6.67	2,218,654	7.19/6.47	2,218,654	7.04/6.31	2,218,654	6.99/6.26	2,218,654	6.95/6.21	2,218,654
Major Arterial 2	1000	1.0	8.26/7.49	4,437,307	8.07/7.30	4,437,307	7.93/7.15	4,437,307	7.89/7.10	4,437,307	7.85/7.05	4,437,307

90% Reliability

Road Classification	ADTT	ESAL Factor	k-value (pci): k-value = 97		k-value = 146		k-value = 190		k-value = 206		k-value = 222	
			Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	4.49/4.02	88,746	4.25/4.00	88,746	4.05/4.00	88,746	4.00/4.00	88,746	4.00/4.00	88,746
Collector	100	1.0	5.97/5.37	443,731	5.76/5.15	443,731	5.60/4.97	443,731	5.54/4.91	443,731	5.48/4.85	443,731
Minor Arterial	250	1.0	6.98/6.30	1,109,327	6.78/6.09	1,109,327	6.63/5.93	1,109,327	6.58/5.88	1,109,327	6.53/5.82	1,109,327
Major Arterial	500	1.0	7.83/7.08	2,218,654	7.63/6.89	2,218,654	7.49/6.73	2,218,654	7.44/6.68	2,218,654	7.40/6.64	2,218,654
Major Arterial 2	1000	1.0	8.73/7.93	4,437,307	8.55/7.74	4,437,307	8.42/7.60	4,437,307	8.37/7.56	4,437,307	8.33/7.51	4,437,307

Table 16. Sensitivity analysis results of concrete pavement thickness for design life of 40 years using WinPAS software

50% Reliability

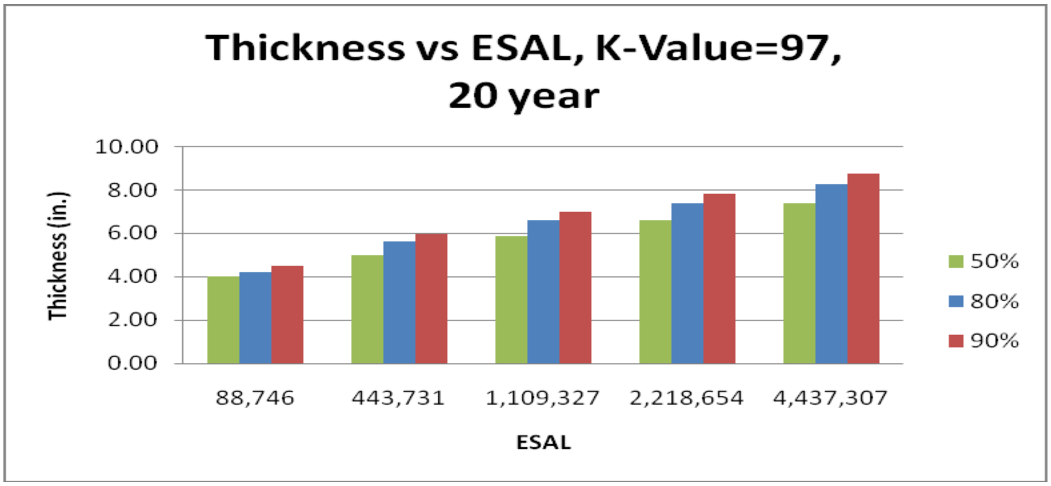
Road Classification	ADTT	ESAL Factor	k-value (pci)									
			k-value = 97		k-value = 146		k-value = 190		k-value = 206		k-value = 222	
			Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	4.40/4.00	220,618	4.15/4.00	220,618	4.00/4.00	220,618	4.00/4.00	220,618	4.00/4.00	220,618
Collector	100	1.0	5.85/5.25	1,103,091	5.63/5.03	1,103,091	5.46/4.86	1,103,091	5.41/4.79	1,103,091	5.35/4.73	1,103,091
Minor Arterial	250	1.0	6.84/6.17	2,757,728	6.64/5.96	2,757,728	6.49/5.80	2,757,728	6.44/5.74	2,757,728	6.39/5.69	2,757,728
Major Arterial	500	1.0	7.67/6.94	5,515,456	7.48/6.74	5,515,456	7.34/6.59	5,515,456	7.29/6.54	5,515,456	7.24/6.49	5,515,456
Major Arterial 2	1000	1.0	8.57/7.78	11,030,912	8.39/7.59	11,030,912	8.25/7.44	11,030,912	8.20/7.40	11,030,912	8.16/7.35	11,030,912

80% Reliability

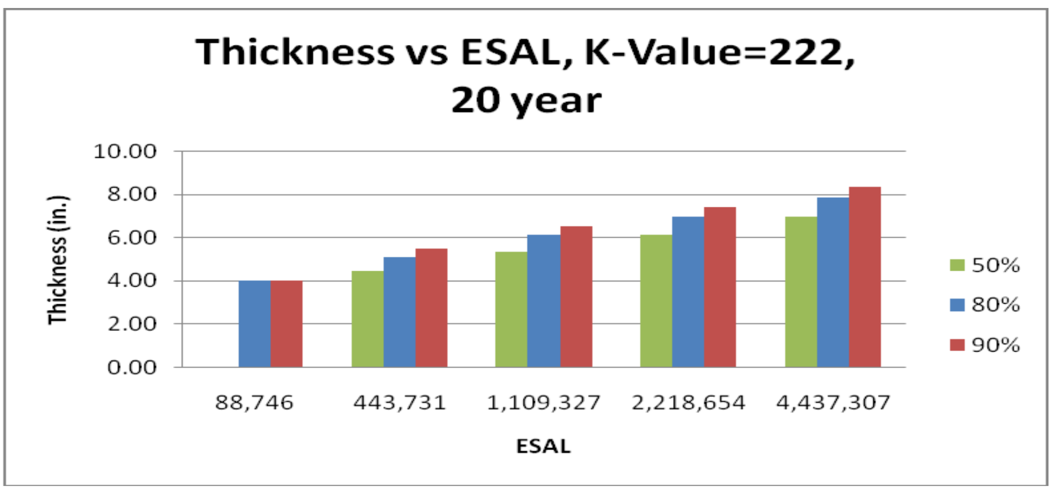
Road Classification	ADTT	ESAL Factor	k-value (pci)									
			k-value = 97		k-value = 146		k-value = 190		k-value = 206		k-value = 222	
			Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	4.96/4.45	220,618	4.73/4.21	220,618	4.55/4.00	220,618	4.48/4.00	220,618	4.42/4.00	220,618
Collector	100	1.0	6.57/5.92	1,103,091	6.375.70	1,103,091	6.21/5.54	1,103,091	6.16/5.48	1,103,091	6.10/5.43	1,103,091
Minor Arterial	250	1.0	7.65/6.92	2,757,728	7.46/6.72	2,757,728	7.32/6.57	2,757,728	7.27/6.52	2,757,728	7.22/6.47	2,757,728
Major Arterial	500	1.0	8.55/7.76	5,515,456	8.36/7.57	5,515,456	8.23/7.43	5,515,456	8.18/7.38	5,515,456	8.14/7.33	5,515,456
Major Arterial 2	1000	1.0	9.52/8.66	11,030,912	9.34/8.48	11,030,912	9.21/8.34	11,030,912	9.17/8.34	11,030,912	9.13/8.25	11,030,912

90% Reliability

Road Classification	ADTT	ESAL Factor	k-value (pci)									
			k-value = 97		k-value = 146		k-value = 190		k-value = 206		k-value = 222	
			Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	5.28/4.74	220,618	5.06/4.51	220,618	4.89/4.32	220,618	4.82/4.25	220,618	4.76/4.18	220,618
Collector	100	1.0	6.98/6.29	1,103,091	6.78/6.09	1,103,091	6.63/5.93	1,103,091	6.57/5.87	1,103,091	6.53/5.82	1,103,091
Minor Arterial	250	1.0	8.10/7.34	2,757,728	7.92/7.15	2,757,728	7.78/7.00	2,757,728	7.73/6.95	2,757,728	7.68/6.90	2,757,728
Major Arterial	500	1.0	9.04/8.21	5,515,456	8.86/8.03	5,515,456	8.72/7.89	5,515,456	8.68/7.84	5,515,456	8.63/7.80	5,515,456
Major Arterial 2	1000	1.0	10.06/9.16	11,030,912	9.88/8.98	11,030,912	9.75/8.84	11,030,912	9.71/8.80	11,030,912	9.66/8.76	11,030,912



a. Low subgrade strength



b. High subgrade strength

Figure 15. Impacts of traffic level and reliability on concrete pavement thickness given low and high subgrade strength and design life of 20 years

Figure 16 shows an impact of traffic level and subgrade strength on concrete pavement thickness given a reliability of 80% and design life of 20 years. Traffic had a greater impact on concrete pavement thickness than the subgrade strength. The concrete pavement thickness was not sensitive to subgrade strength because the thickness decreased by only 0.5 inch when the subgrade strength increased from 97 pci to 222 pci.

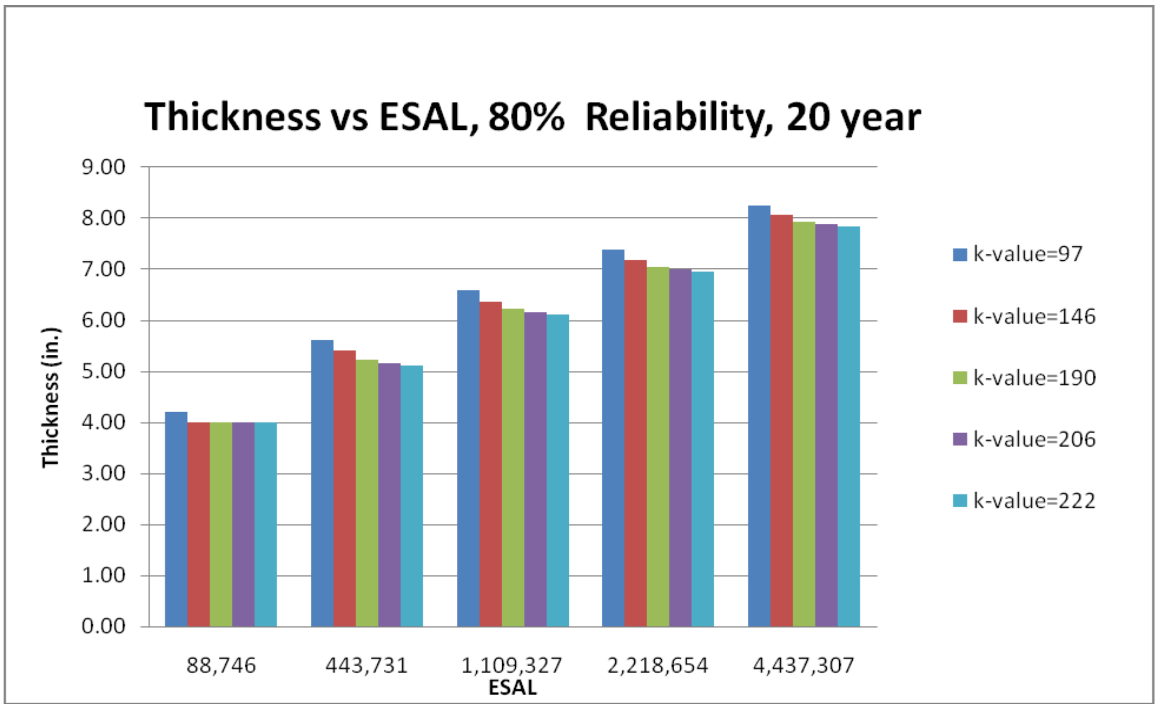


Figure 16. Impact of traffic level and subgrade strength on concrete pavement thickness given reliability of 80% and design life of 20 years

Analysis Results Using WinPAS Software - Asphalt

For the lowest traffic level, using the WinPAS software, the minimum asphalt pavement design thickness is 3.6 inches at a traffic level of 230 ADT with 1% truck. Table 17 and Table 18 show the sensitivity analysis results of asphalt pavement thickness for design life of 20 and 40 years, respectively.

Figure 17 shows impacts of traffic level and reliability on the asphalt pavement thickness for a given low and high subgrade strengths. As shown in Figure 17, traffic had the greatest impact on the asphalt pavement thickness as the asphalt pavement thickness was increased by 4.0 inches to 4.5 inches when traffic increased from low to high level. Reliability had the greater impact at the higher traffic level, with asphalt pavement thickness increasing by about 1.5 inches when the reliability increased from 50% to 90%.

Figure 18 shows an impact of traffic level and subgrade strength on the asphalt pavement thickness for a given a reliability of 80% and design life of 20 years. The subgrade strength had the greatest impact at the high traffic level, decreasing the thickness by 2.5 inches when the subgrade strength increased from 4,350psi to 11,820psi.

Table 17. Sensitivity analysis results of asphalt pavement thickness for design life of 20 years using WinPAS software

50% Reliability

Road Classification	ADTT	ESAL Factor	Resilient Modulus, M_r (psi)									
			M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
			Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	5.11	88,746	4.07	88,746	3.93	88,746	3.73	88,746	3.48	88,746
Collector	100	1.0	6.52	443,731	5.27	443,731	5.09	443,731	4.86	443,731	4.57	443,731
Minor Arterial	250	1.0	7.45	1,109,327	6.07	1,109,327	5.86	1,109,327	5.59	1,109,327	5.27	1,109,327
Major Arterial	500	1.0	8.23	2,218,654	6.73	2,218,654	6.52	2,218,654	6.20	2,218,654	5.86	2,218,654
Major Arterial 2	1000	1.0	9.05	4,437,307	7.43	4,437,307	7.20	4,437,307	6.89	4,437,307	6.50	4,437,307

80% Reliability

Road Classification	ADTT	ESAL Factor	Resilient Modulus, M_r (psi)									
			M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
			Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	5.84	88,746	4.70	88,746	4.55	88,746	4.32	88,746	4.05	88,746
Collector	100	1.0	7.41	443,731	6.02	443,731	5.84	443,731	5.57	443,731	5.25	443,731
Minor Arterial	250	1.0	8.43	1,109,327	6.91	1,109,327	6.68	1,109,327	6.39	1,109,327	6.02	1,109,327
Major Arterial	500	1.0	9.27	2,218,654	7.64	2,218,654	7.39	2,218,654	7.07	2,218,654	6.68	2,218,654
Major Arterial 2	1000	1.0	10.18	4,437,307	8.41	4,437,307	8.16	4,437,307	7.80	4,437,307	7.39	4,437,307

90% Reliability

Road Classification	ADTT	ESAL Factor	Resilient Modulus, M_r (psi)									
			M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
			Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	6.25	88,746	5.05	88,746	4.89	88,746	4.64	88,746	4.36	88,746
Collector	100	1.0	7.91	443,731	6.45	443,731	6.25	443,731	5.95	443,731	5.61	443,731
Minor Arterial	250	1.0	8.98	1,109,327	7.36	1,109,327	7.14	1,109,327	6.82	1,109,327	6.45	1,109,327
Major Arterial	500	1.0	9.86	2,218,654	8.14	2,218,654	7.89	2,218,654	7.55	2,218,654	7.14	2,218,654
Major Arterial 2	1000	1.0	10.82	4,437,307	8.95	4,437,307	8.68	4,437,307	8.32	4,437,307	7.89	4,437,307

Table 18. Sensitivity analysis results of asphalt pavement thickness for design life of 40 years using WinPAS software

50% Reliability

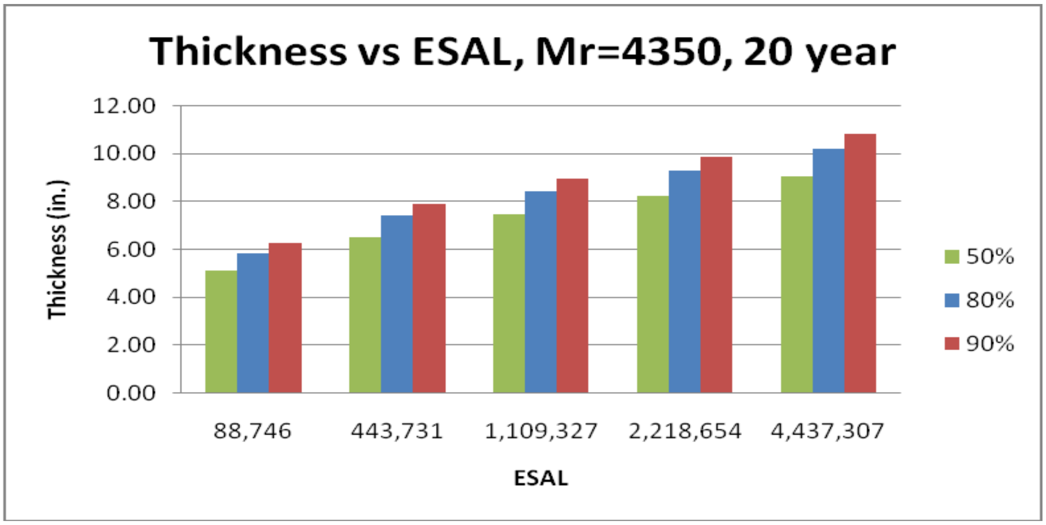
Road Classification	ADTT	ESAL Factor	Resilient Modulus, M_r (psi)									
			M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
			Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	5.89	220,618	4.73	220,618	4.57	220,618	4.34	220,618	4.07	220,618
Collector	100	1.0	7.43	1,103,091	6.07	1,103,091	5.86	1,103,091	5.59	1,103,091	5.27	1,103,091
Minor Arterial	250	1.0	8.48	2,757,728	6.93	2,757,728	6.73	2,757,728	6.41	2,757,728	6.07	2,757,728
Major Arterial	500	1.0	9.32	5,515,456	7.66	5,515,456	7.43	5,515,456	7.09	5,515,456	6.73	5,515,456
Major Arterial 2	1000	1.0	10.23	11,030,912	8.45	11,030,912	8.20	11,030,912	7.84	11,030,912	7.43	11,030,912

80% Reliability

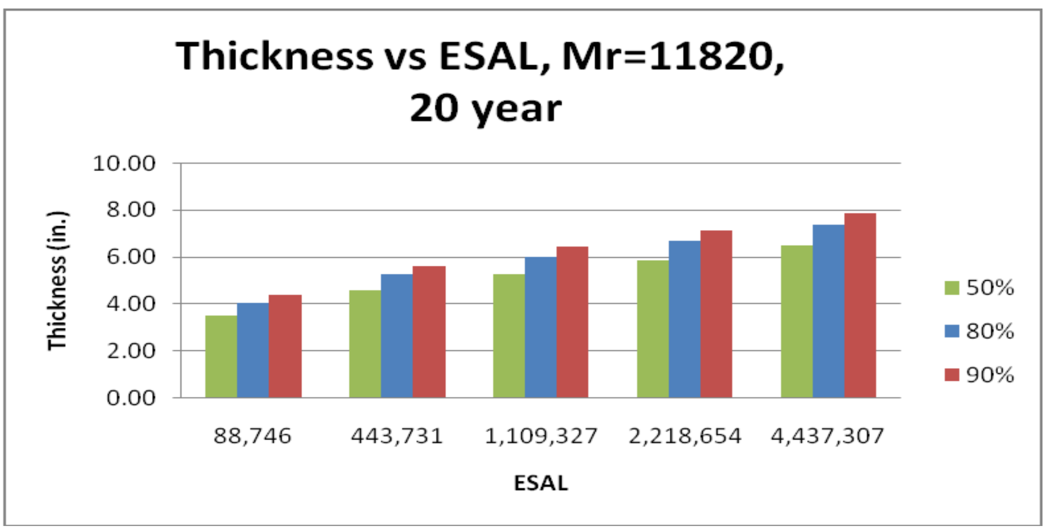
Road Classification	ADTT	ESAL Factor	Resilient Modulus, M_r (psi)									
			M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
			Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	6.68	220,618	5.43	220,618	5.25	220,618	4.98	220,618	4.68	220,618
Collector	100	1.0	8.41	1,103,091	6.89	1,103,091	6.68	1,103,091	6.39	1,103,091	6.02	1,103,091
Minor Arterial	250	1.0	9.55	2,757,728	7.86	2,757,728	7.64	2,757,728	7.30	2,757,728	6.89	2,757,728
Major Arterial	500	1.0	10.48	5,515,456	8.66	5,515,456	8.41	5,515,456	8.05	5,515,456	7.61	5,515,456
Major Arterial 2	1000	1.0	11.48	11,030,912	9.52	11,030,912	9.25	11,030,912	8.86	11,030,912	8.41	11,030,912

90% Reliability

Road Classification	ADTT	ESAL Factor	Resilient Modulus, M_r (psi)									
			M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
			Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	7.16	220,618	5.82	220,618	5.61	220,618	5.36	220,618	5.05	220,618
Collector	100	1.0	8.98	1,103,091	7.36	1,103,091	7.14	1,103,091	6.82	1,103,091	6.45	1,103,091
Minor Arterial	250	1.0	10.16	2,757,728	8.39	2,757,728	8.14	2,757,728	7.77	2,757,728	7.36	2,757,728
Major Arterial	500	1.0	11.14	5,515,456	9.23	5,515,456	8.95	5,515,456	8.57	5,515,456	8.11	5,515,456
Major Arterial 2	1000	1.0	12.18	11,030,912	10.14	11,030,912	9.84	11,030,912	9.43	11,030,912	8.95	11,030,912



a. Low subgrade strength



b. High subgrade strength

Figure 17. Impacts of traffic level and reliability on asphalt pavement thickness given low and high subgrade strength and design life of 20 years

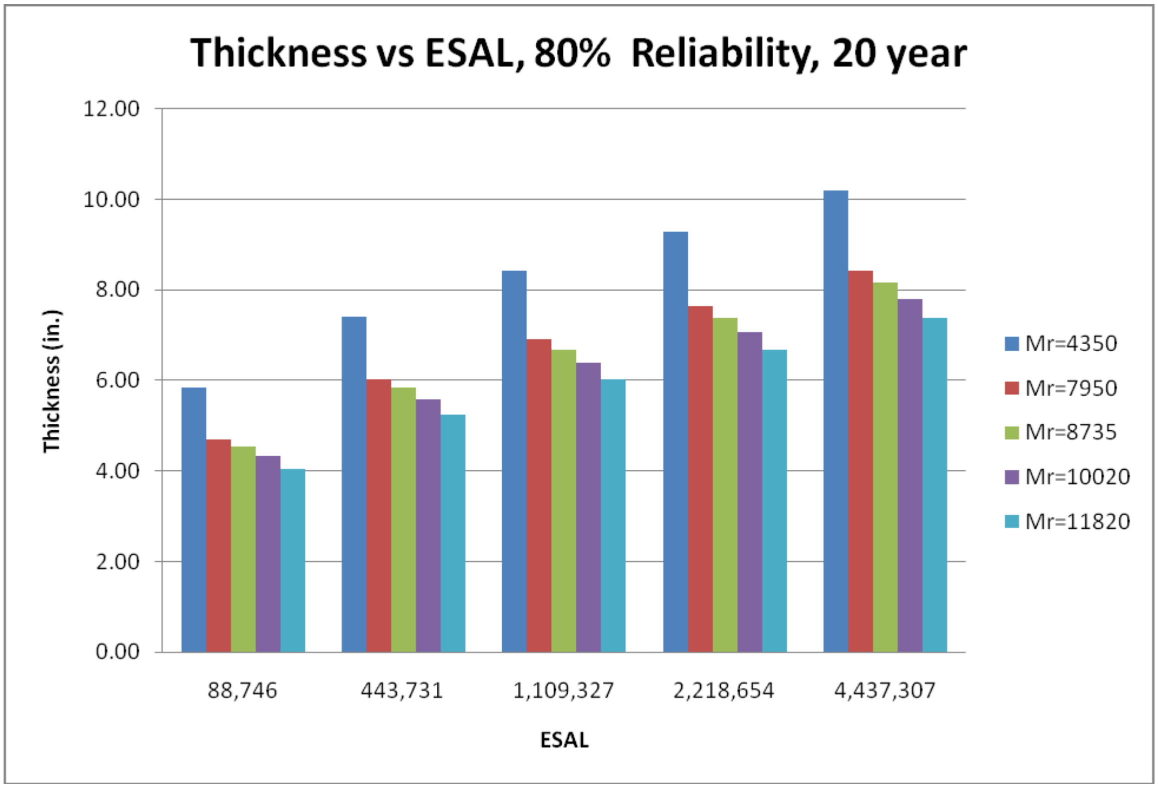


Figure 18. Impact of traffic level and subgrade strength on asphalt pavement thickness given reliability of 80% and design life of 20 years

Analysis Results Using I-Pave Software – Concrete

The minimum concrete pavement design thickness allowed is 6.0 inches. Table 19 and Table 20 show the sensitivity analysis results of the concrete pavement thicknesses with dowels for design life of 20 years and 40 years, respectively. The default load transfer value used for I-Pave software is 3.2. Figure 19 shows impacts of traffic level and reliability on the concrete pavement thickness for a given low and high subgrade strengths. As shown in Figure 19, traffic had the greatest impact on the concrete pavement thickness as the concrete pavement thickness increased by 6.0 to 8.0

inches when traffic increased from low to high level. Reliability had a minimal impact by increasing the thickness by 0.5 inches from 80% to 90%. Most low traffic level had the minimum thickness design of 6.0 inches.

Table 19. Sensitivity analysis results of concrete pavement thickness for design life of 20 years using I-Pave software

Road Classification	ADTT	ESAL Factor	Resilient Modulus, Mr (psi)					
			Mr=6,489		Mr=7,007		Mr=7,385	
			Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
80% Reliability								
Residential	20	1.0	6.00	11,436	6.00	11,436	6.00	11,436
Collector	100	1.0	6.00	228,729	6.00	228,729	6.00	228,729
Minor Arterial	250	1.0	6.00	571,249	6.00	571,249	6.00	571,249
Major Arterial	500	1.0	7.00	1,143,643	7.00	1,143,643	7.00	1,143,643
Major Arterial 2	1000	1.0	8.00	2,287,285	8.00	2,287,285	8.00	2,287,285
90% Reliability								
Residential	20	1.0	6.00	11,436	6.00	11,436	6.00	11,436
Collector	100	1.0	6.00	228,729	6.00	228,729	6.00	228,729
Minor Arterial	250	1.0	6.50	571,249	6.50	571,249	6.50	571,249
Major Arterial	500	1.0	7.50	1,143,643	7.50	1,143,643	7.50	1,143,643
Major Arterial 2	1000	1.0	8.50	2,287,285	8.50	2,287,285	8.00	2,287,285

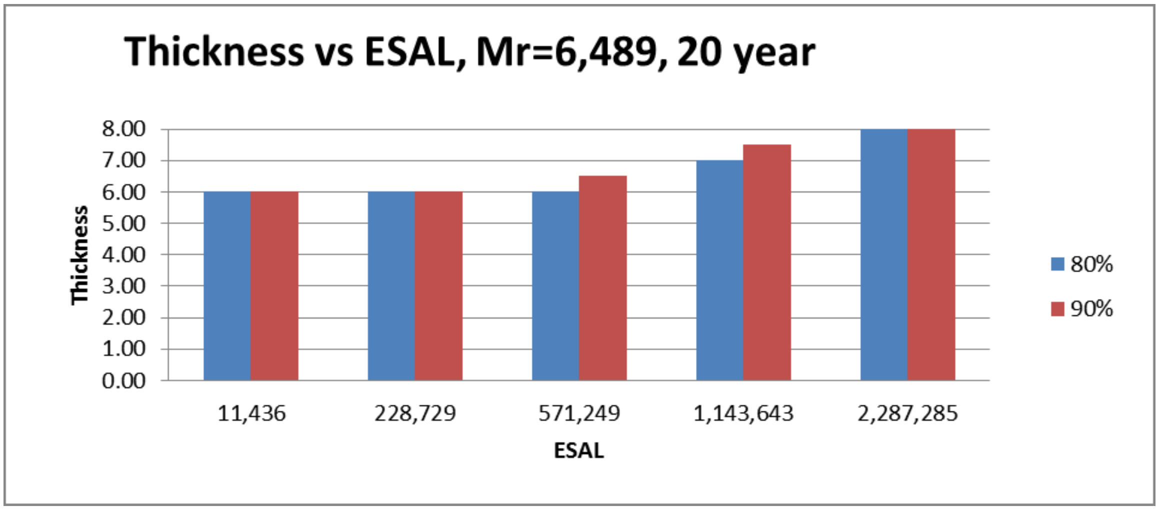
Table 20. Sensitivity analysis results of concrete pavement thickness for design life of 40 years using I-Pave software

80% Reliability

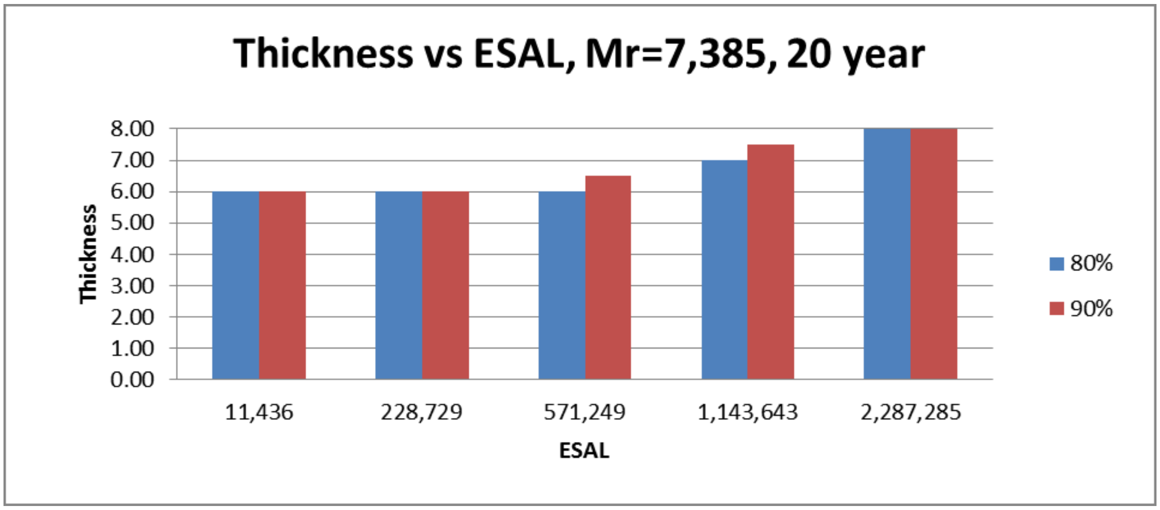
Road Classification	ADTT	ESAL Factor	Resilient Modulus, Mr (psi)					
			Mr=6,489		Mr=7,007		Mr=7,385	
			Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	6.00	28,430	6.00	28,430	6.00	28,430
Collector	100	1.0	6.00	568,607	6.00	568,607	6.00	568,607
Minor Arterial	250	1.0	7.50	1,420,096	7.00	1,420,096	7.00	1,420,096
Major Arterial	500	1.0	8.00	2,843,035	8.00	2,843,035	8.00	2,843,035
Major Arterial 2	1000	1.0	9.00	5,686,071	9.00	5,686,071	9.00	5,686,071

90% Reliability

Road Classification	ADTT	ESAL Factor	Resilient Modulus, Mr (psi)					
			Mr=6,489		Mr=7,007		Mr=7,385	
			Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	6.00	28,430	6.00	28,430	6.00	28,430
Collector	100	1.0	6.00	568,607	6.50	568,607	6.50	568,607
Minor Arterial	250	1.0	7.50	1,420,096	7.50	1,420,096	7.50	1,420,096
Major Arterial	500	1.0	8.50	2,843,035	8.50	2,843,035	8.50	2,843,035
Major Arterial 2	1000	1.0	9.50	5,686,071	9.50	5,686,071	9.50	5,686,071



a. Unsuitable Soil Subgrade Strength



b. Select Soil Subgrade Strength

Figure 19. Impacts of traffic level and reliability on concrete pavement thickness given unsuitable soil and select soil subgrade strength and design life of 20 years

Figure 20 shows an impact of traffic level and subgrade strength on concrete pavement thickness given a reliability of 80% and design life of 20 years. Traffic had a greater impact on concrete pavement thickness than the subgrade strength. The concrete pavement thickness was not sensitive to subgrade strength because the subgrade strengths are relatively close to each other.

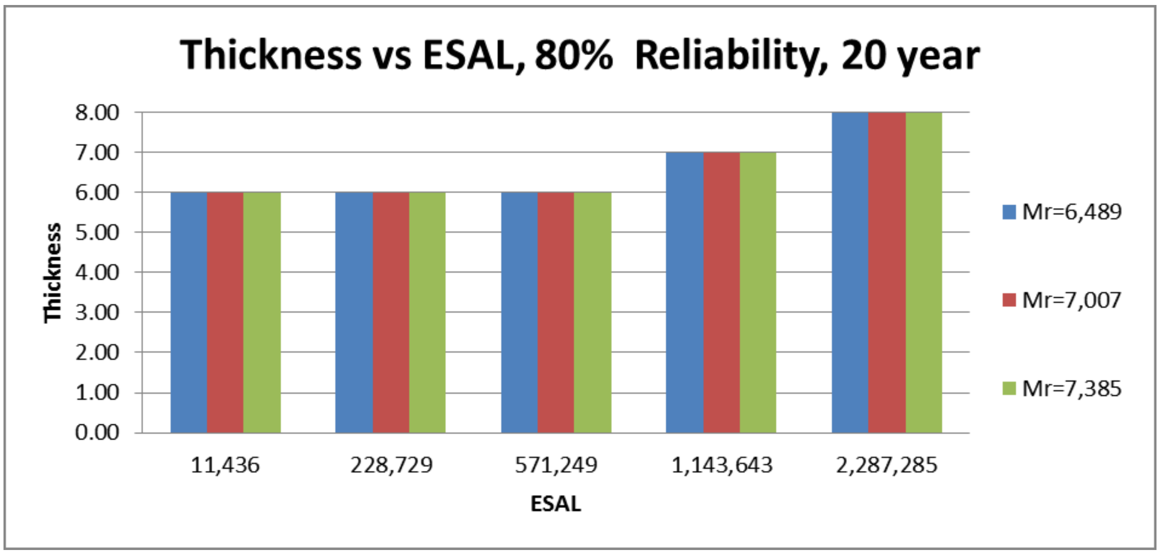


Figure 20. Impact of traffic level and subgrade strength on concrete pavement thickness given reliability of 80% and design life of 20 years

Figure 21 shows a comparison of 20 year and 40 year design lives for low subgrade strength at 80% reliability. As seen with the other subgrade strengths, a 40 year design life can be achieved with a 1 inch increase in thickness.

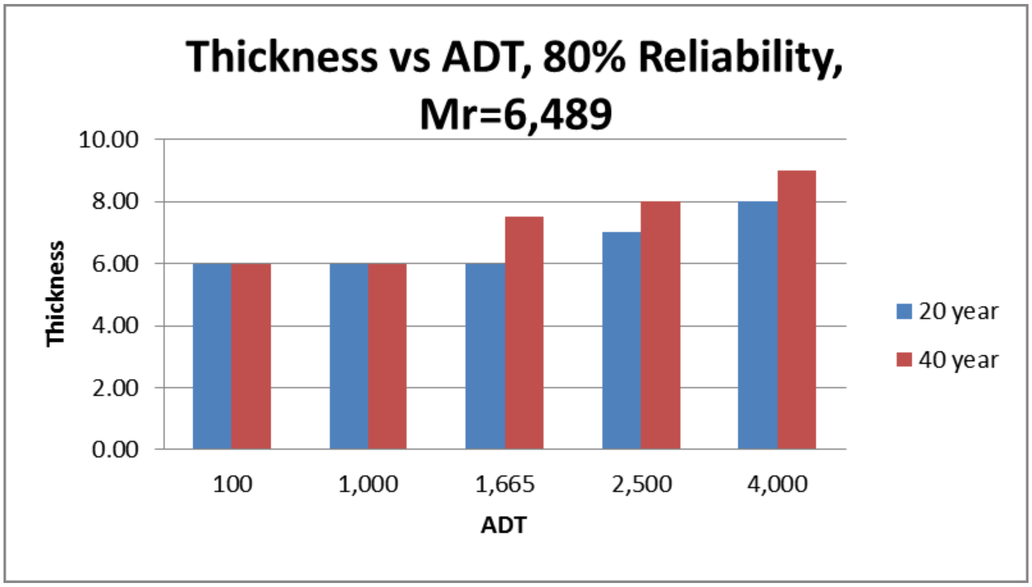


Figure 21. Impact of design life on concrete pavement thickness given reliability of 80% and low subgrade strength

Analysis Results Using I-Pave Software - Asphalt

The minimum design thickness for the I-Pave software is 3.0 inches. Table 21 and Table 22 show the sensitivity analysis results of asphalt pavement thickness for design life of 20 and 40 years, respectively.

Figure 22 shows impacts of traffic level and reliability on the asphalt pavement thickness for a given low and high subgrade strengths. As shown in Figure 22, traffic had the greatest impact on the asphalt pavement thickness as the asphalt pavement thickness was increased by 3.5 inches to 4.5 inches when traffic increased from low to high level. Reliability had the greater impact at the higher traffic level, with asphalt pavement thickness increasing by about 0.5 inches when the reliability increased from 80% to 90%.

Figure 23 shows an impact of traffic level and subgrade strength on the asphalt pavement thickness for a given a reliability of 80% and design life of 20 years. The subgrade strength did not have an impact on the thickness of the pavement design based on each traffic level.

Table 21. Sensitivity analysis results of asphalt pavement thickness for design life of 20 years using I-Pave software

80% Reliability

Road Classification	ADTT	ESAL Factor	Resilient Modulus, Mr (psi)					
			Mr=6,489		Mr=7,007		Mr=7,385	
			Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	3.00	11,436	3.00	11,436	3.00	11,436
Collector	100	1.0	4.50	228,729	4.00	228,729	4.00	228,729
Minor Arterial	250	1.0	5.00	571,249	5.00	571,249	5.00	571,249
Major Arterial	500	1.0	6.00	1,143,643	5.50	1,143,643	5.50	1,143,643
Major Arterial 2	1000	1.0	6.50	2,287,285	6.50	2,287,285	6.50	2,287,285

90% Reliability

Road Classification	ADTT	ESAL Factor	Resilient Modulus, Mr (psi)					
			Mr=6,489		Mr=7,007		Mr=7,385	
			Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	3.00	11,436	3.00	11,436	3.00	11,436
Collector	100	1.0	4.50	228,729	4.50	228,729	4.50	228,729
Minor Arterial	250	1.0	5.50	571,249	5.50	571,249	5.50	571,249
Major Arterial	500	1.0	6.50	1,143,643	6.00	1,143,643	6.00	1,143,643
Major Arterial 2	1000	1.0	7.50	2,287,285	7.00	2,287,285	7.00	2,287,285

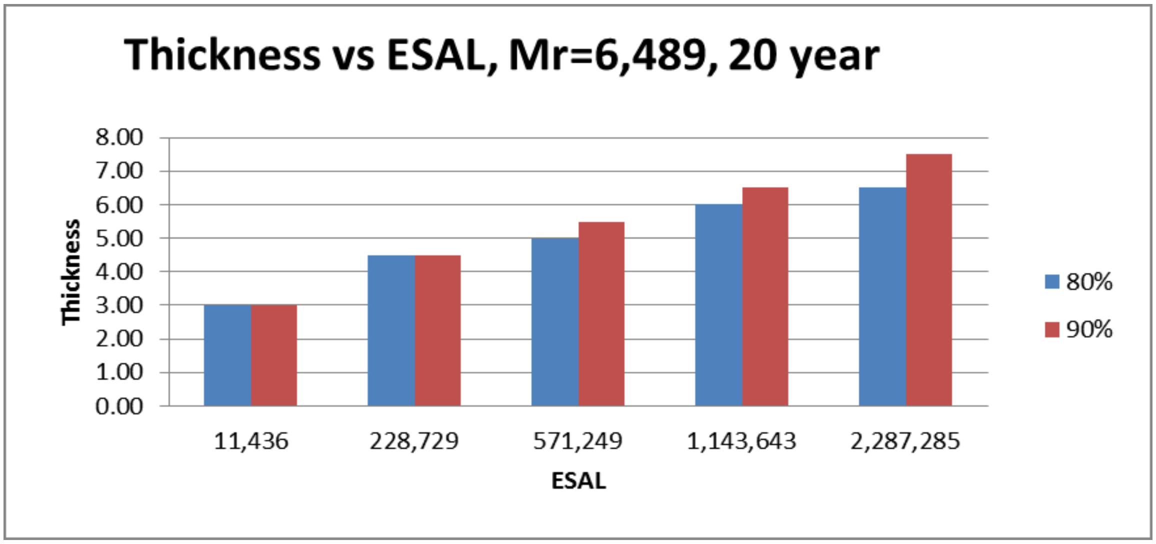
Table 22. Sensitivity analysis results of asphalt pavement thickness for design life of 40 years using I-Pave software

80% Reliability

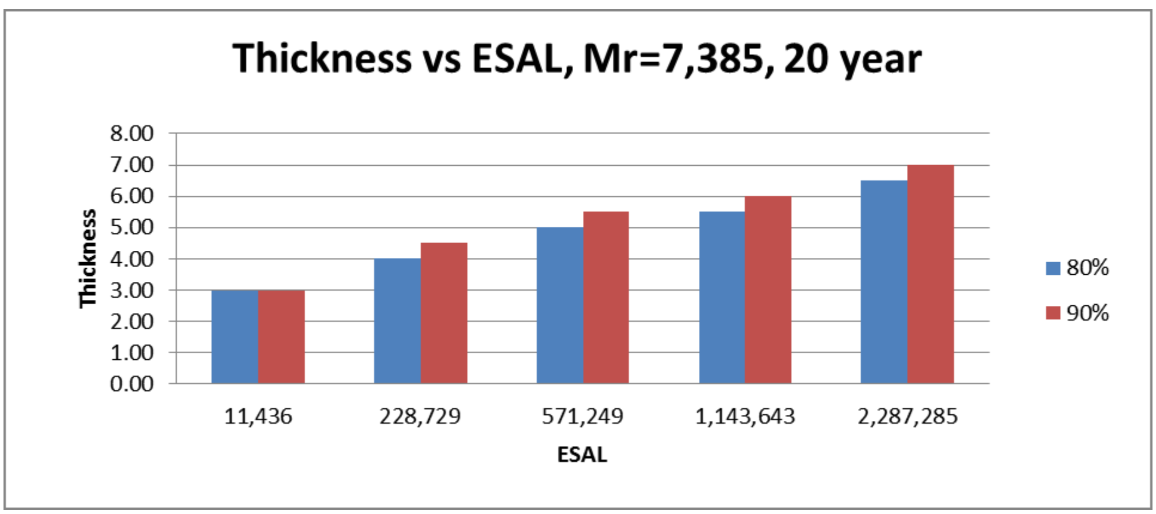
Road Classification	ADTT	ESAL Factor	Resilient Modulus, Mr (psi)					
			Mr=6,489		Mr=7,007		Mr=7,385	
			Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	3.00	28,430	3.00	28,430	3.00	28,430
Collector	100	1.0	5.00	568,607	5.00	568,607	5.00	568,607
Minor Arterial	250	1.0	6.00	1,420,096	6.00	1,420,096	6.00	1,420,096
Major Arterial	500	1.0	7.00	2,843,035	7.00	2,843,035	6.50	2,843,035
Major Arterial 2	1000	1.0	8.00	5,686,071	7.50	5,686,071	7.50	5,686,071

90% Reliability

Road Classification	ADTT	ESAL Factor	Resilient Modulus, Mr (psi)					
			Mr=6,489		Mr=7,007		Mr=7,385	
			Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	3.00	28,430	3.00	28,430	3.00	28,430
Collector	100	1.0	5.50	568,607	5.50	568,607	5.50	568,607
Minor Arterial	250	1.0	6.50	1,420,096	6.50	1,420,096	6.50	1,420,096
Major Arterial	500	1.0	7.50	2,843,035	7.50	2,843,035	7.00	2,843,035
Major Arterial 2	1000	1.0	8.50	5,686,071	8.50	5,686,071	8.00	5,686,071



a. Unsuitable Soil Subgrade Strength



b. Select Soil Subgrade Strength

Figure 22. Impacts of traffic level and reliability on asphalt pavement thickness given low and high subgrade strength and design life of 20 years

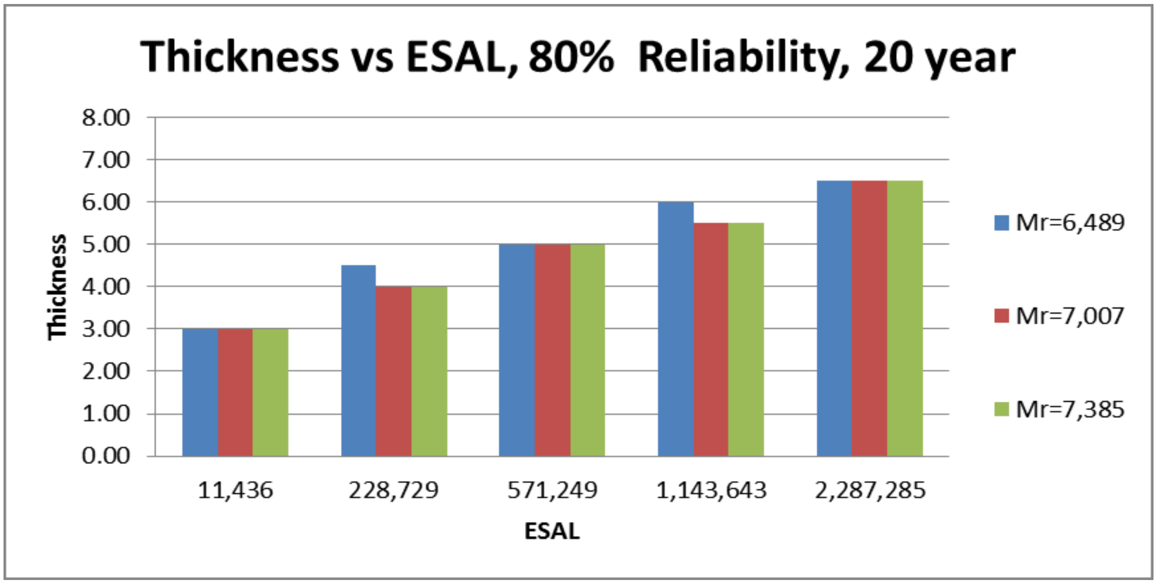


Figure 23. Impact of traffic level and subgrade strength on asphalt pavement thickness given reliability of 80% and design life of 20 years

Comparison of Sensitivity Analysis Results

As summarized in Table 23, WinPAS software provides a slightly wider range of concrete pavement thickness from 4.0 inches to 10.0 inches than StreetPave software with a thickness from 3.9 inches to 8.0 inches. The I-Pave software reported thicknesses from 6.0 inches to 9.5 inches. For both StreetPave and WinPAS software, the increased subgrade strength decreased the thickness by less than 1.0 inch. Subgrade strength had little impact on the I-Pave software design thicknesses. The impact of subgrade strength on concrete thickness was greater at the high traffic level for StreetPave software but similar for all traffic levels for WinPAS software. When the design life was doubled from 20 to 40 years, StreetPave software increased the thickness by 0.25 inch but

WinPAS software increased the thickness by up to 1.25 inches at high traffic level and by up to 1.0 inch at low traffic level. For the I-Pave software, the thickness increased by 1.0 inches from 20 to 40 year design life.

Using the same conditions for each software, concrete design thickness was compared at each traffic level. Design life of 20 years, 90% reliability, and fair subgrade strength was chosen. As shown in Figure 24, low volume traffic level reported thickness designs within 0.5 inches for each software. On the higher level of traffic the designs were within 1.0 inch. From the 250 -1000 ADTT, results were typical with WinPAS designing the thickest pavement and StreetPave the thinnest.

Table 23. Comparisons of sensitivity analysis results for concrete pavement using StreetPave, WinPAS, and I-Pave software

Input Parameter	StreetPave Software	WinPAS Software	I-Pave Software
Traffic	✓ Low to High Traffic levels: Δ 2.5 inches	✓ Low to High Traffic levels: Δ 3.5-4.5 inches	✓ Low to High Traffic levels: Δ 2.5-3.5 inches
Reliability	✓ Higher impact at higher traffic level: Δ 0.75 inch	✓ Higher impact at higher traffic level: Δ 1.25 inches	✓ Similar impact at each traffic level: Δ 0.5 inches
Subgrade Strength	✓ Higher impact at higher traffic level: Δ 1.0 inch	✓ Higher impact at higher traffic level: Δ 0.5 inch	✓No Impact
Design Life	✓ Constant change for all traffic levels: Δ 0.25 inch	✓ Constant change for all traffic levels: Δ 1.25 inches	✓ Constant change for all traffic levels: Δ 1.0 inches

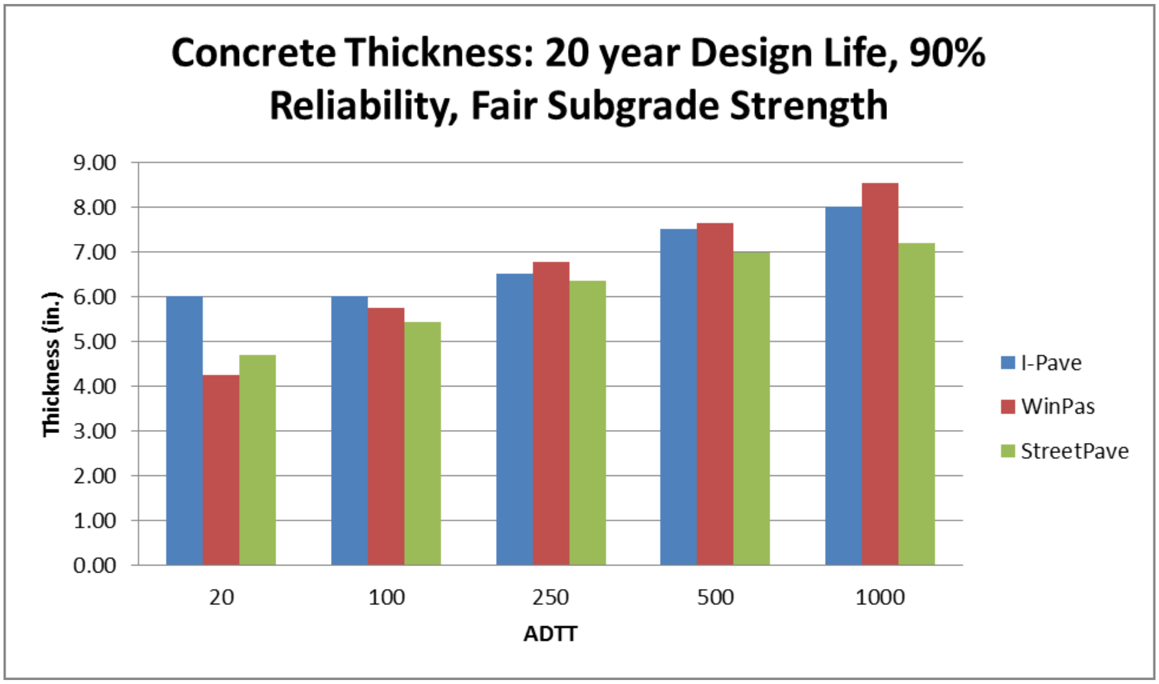


Figure 24. Comparison of Concrete Design Software under Similar Parameters

As summarized in Table 24, the sensitivity of traffic level on asphalt pavement thickness was highest with StreetPave software (thickness increase by up to 7.0 inches). Using the 80% reliability as the lowest level (I-Pave do not provide 50% reliability), the design thickness range was also highest with StreetPave software from 3.08 inches to 14.4 inches, followed by WinPAS software from 4.05 inches to 12.18 inches, and I-Pave from 3.0 inches to 8.5 inches.

Table 24. Comparisons of sensitivity analysis results for asphalt pavement using StreetPave, and WinPAS software

Input Parameter	StreetPave Software	WinPAS Software	I-Pave Software
Traffic	✓ Low to High Traffic: Δ 6.0-7.0 inches	✓ Low to High Traffic: Δ 4.0-5.0 inches	✓ Low to High Traffic: Δ 4.0-5.0 inches
Reliability	✓ Higher Impact at Lower Traffic Level: Δ 0.75 inch from 80% to 90%	✓ Higher impact at Higher Traffic Level: Δ 0.5 inch from 80% to 90%	✓ Higher impact at Higher Traffic Level: Δ 0.5 inch from 80% to 90%
Subgrade Strength	✓ Higher Impact at Lower Traffic Level: Δ 2.5-3.0 inches	✓ Higher Impact at Higher Traffic Level: Δ 2.5-3.0 inches	✓ Little Impact
Design Life	✓ Higher Impact at Higher Traffic: Δ 2.0 inches for high, Δ 1 inch for low traffic level	✓ Higher Impact at Higher Traffic Level: Δ 1.25 inches for high, Δ 0.75 inch for low traffic level	✓ Constant impact from: Δ0.5-1.0 inches

Using the same conditions for each software package, asphalt design thickness was compared at each traffic level. Design life of 20 years, 90% reliability, and fair subgrade strength was chosen. As shown in Figure 25, the reported design thicknesses varied by as much as 4.0 inches for each traffic level. The StreetPave software consistently had the highest design thickness and the I-Pave software had the lowest.

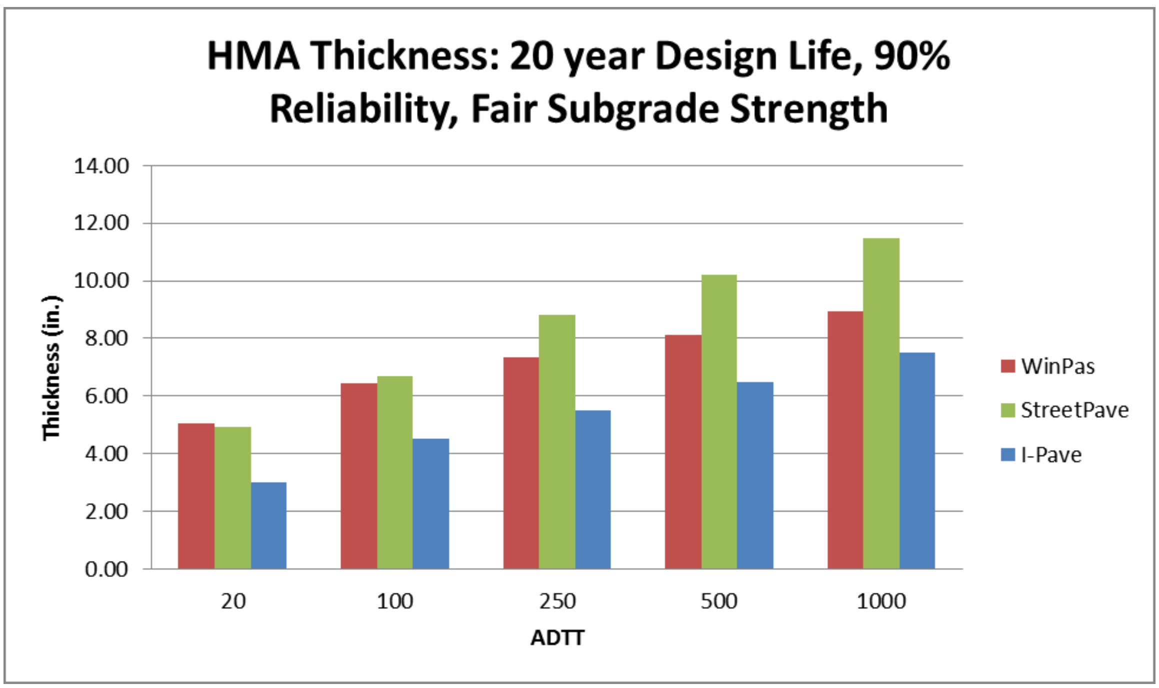


Figure 25. Comparison of Concrete Design Software under Similar Parameters

When comparing asphalt to concrete design thicknesses for each software package with the same given conditions as shown in Figure 26, 27, and 28, there were some clear observations for each software package. StreetPave software saw increasing differences in design thicknesses from 0.25 inches in difference to 4.25 inches when going from low traffic to higher traffic with asphalt being the thicker pavement design. The asphalt design was as much as 60% thicker than the concrete design thickness at the highest traffic level. WinPAS software had similar results in that the asphalt pavement was thicker than the concrete pavement, but it was consistently only 0.5 inch thicker. I-Pave software saw the concrete design thickness was thicker than the asphalt design, but the difference between the two decreased as traffic levels increased.

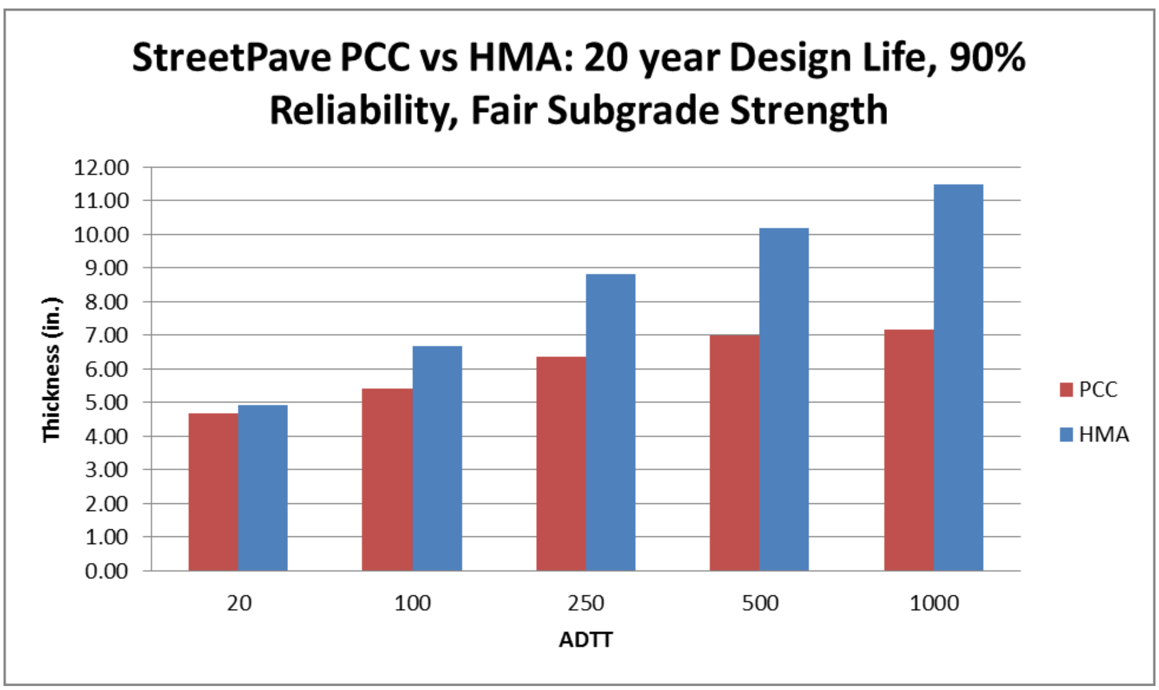


Figure 26. StreetPave PCC vs. HMA Specific Design Thickness

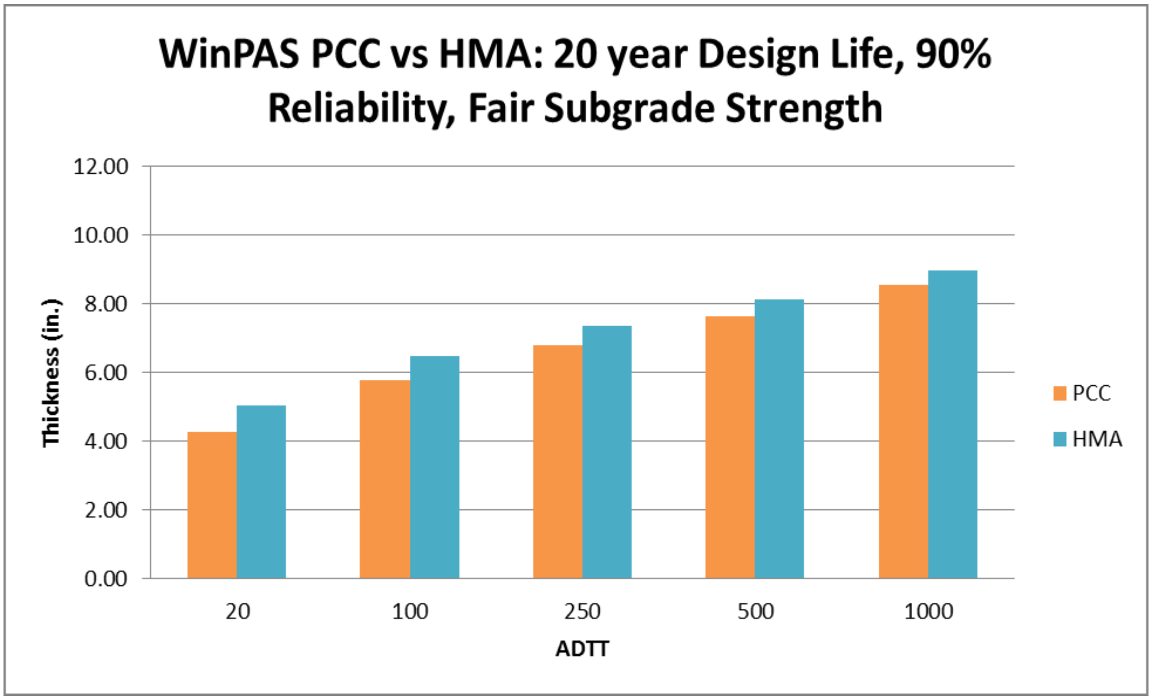


Figure 27. WinPAS PCC vs. HMA Specific Design Thickness

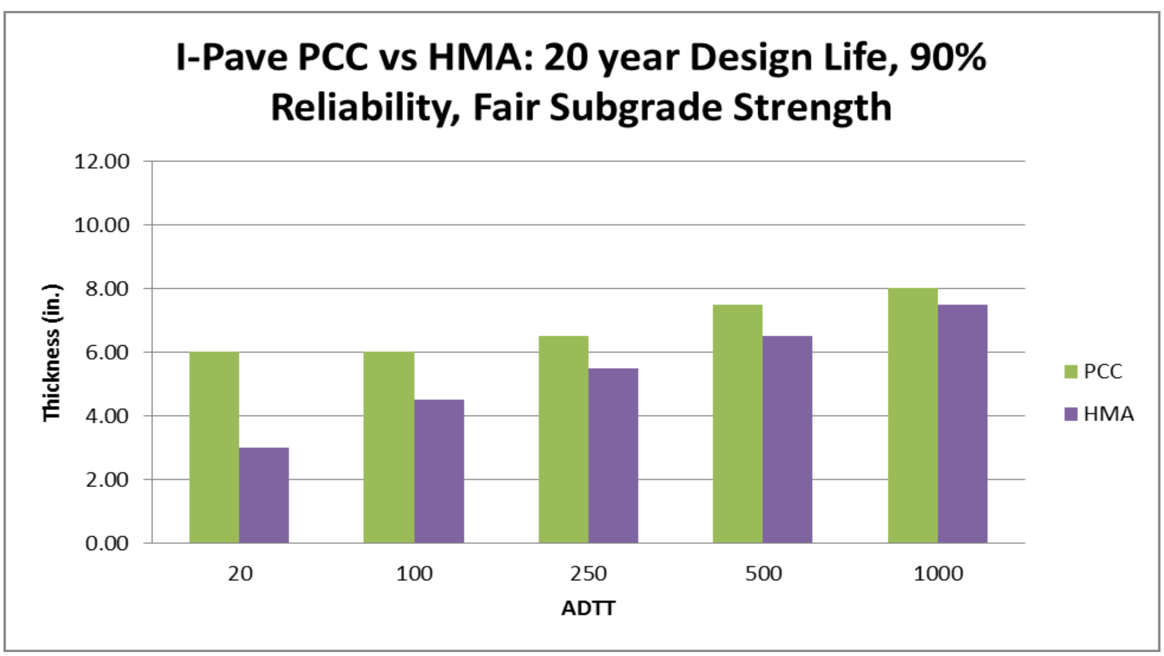


Figure 28. I-Pave PCC vs. HMA Specific Design Thickness

SUMMARY AND CONCLUSIONS

Statewide urban design and specifications (SUDAS) currently utilizes a simplified version of the AASHTO 1993 pavement design guide, which is conservative based on placement of the pavement on natural subgrade, distribution of truck classifications and other design parameters. Therefore, there is a need for a modified pavement design methodology to be used for determining the optimum pavement thickness in local roads in Iowa.

First, the survey was performed to identify pavement thickness design procedures for low volume roads and common input parameters from the adjoining state departments of transportation to Iowa. Another survey was performed to identify the minimum pavement thicknesses under the lowest traffic level and the strongest subgrade condition from 50 state departments of transportation. A third survey was performed for pavement design procedures used by counties and cities in Iowa

Three pavement design software packages were compared with respect to how they were different in determining design input parameters and their influences on the pavement thickness. StreetPave designs the concrete pavement thickness based on the PCA method and the equivalent asphalt pavement thickness. The WinPAS software performs both concrete and asphalt pavement following the AASHTO 1993 design method. I-Pave software also AASHTO 1993 design guide to determine pavement thicknesses for flexible and rigid pavement.

Four critical design input parameters were identified: traffic, subgrade strength, reliability and design life. The sensitivity analysis of these four design input parameters were performed using three pavement design software packages in order to identify which input parameters would require the most attention during pavement design and how these three software packages' design outputs differ.

Conclusions

Based on the limited research, the following conclusions are derived:

1. A sensitivity analysis revealed that three concrete pavement design software packages recommended similar concrete pavement thicknesses for similar condition. Any of the three software packages can be selected to design concrete pavements with high confidence.
2. The analysis also revealed the three software packages recommend very different asphalt pavement thicknesses for similar conditions, especially for higher traffic levels. The minimum recommended design thickness for asphalt by all three software packages was 3 inches for StreetPave and I-Pave and 4 inches for WinPAS at 80% reliability.
3. When the design life was doubled from 20 to 40 years, the StreetPave increased the concrete pavement thickness by 0.25 inch whereas the WinPAS software and I-Pave software increased the thickness by more than 1.0 inch.
4. For the same input parameters for designing asphalt pavements, the StreetPave software recommended the thickest asphalt pavement and the I-Pave software recommended the thinnest asphalt pavement.
5. Based on the sensitivity analysis result of three pavement design software packages, the traffic level has the highest impact on both concrete and asphalt pavement design followed by the subgrade strength, reliability and design life.

Future Studies

1. Additional sensitivity analysis using DARWIN and the Asphalt Institute software should be performed to be compared against the sensitivity analysis results from StreetPave, WinPAS, and I-Pave software packages.
2. Traffic mix and its conversion to ESAL should be clarified to determine their effects on the pavement thickness.
3. Traffic mix, ESAL conversion factor, equivalency of subgrade strengths should be investigated to ensure the design inputs for each software package would represent the equivalent traffic level and subgrade strength.

APPENDIX A - MINIMUM PAVEMENT THICKNESS

AASHTO 1993 pavement design guide lists a minimum asphalt pavement thickness as 1.0 inch and the minimum concrete pavement thickness as 5.0 inches for the lowest traffic level ranging from 50,000 to 100,000 ESAL's. However, for the similar traffic level, the asphalt institute (1983) recommends a minimum of 3.0 inches for asphalt pavement and the PCA (1984) recommends a minimum of 7.0 inches of concrete pavement. ACPA (2006) recommends a lower limit for pavement thickness of 4.0 inches for automobiles and 5.0 inches for limited truck traffic. According to the ACPA design table, a minimum concrete pavement thickness for light residential street is 4.0 inches.

Summary of Survey Results

To identify the minimum pavement thickness on the strongest subgrade under the lowest level of traffic, a survey was sent to fifty state DOT's. Fifty state DOT employees were asked about their minimum thicknesses for both asphalt and concrete pavements of roads with the lowest traffic loading that have 6" subgrade on good soil with a good drainage condition. It is cautioned, however, that our survey result should not be viewed as the representative value for each state because it was based on the survey of a single person from each state DOT, rather than local agency, who may not necessarily be familiar with the practices performed by all local agencies in her/his state.

As shown in Figure A1, 24 states have returned their responses. As can be seen from Table A1, there is a wide variation among states regarding minimum asphalt pavement thickness ranging from 1.25 inch to 6.0 inches but the minimum concrete pavement thickness ranges narrowly from 6.0 inches to 8.0 inches. The minimum thicknesses of asphalt and concrete pavements adopted by 24 states are plotted in Figure

A2 and A3, respectively. It should be noted that the state DOT's have jurisdiction over a limited amount of local roads. The survey of the state DOT's is used herein as a means to identify general design procedures that might be employed. Again, it should be emphasized that our survey result may not represent the practices by numerous local agencies in each state and the results are too variable to be useful.

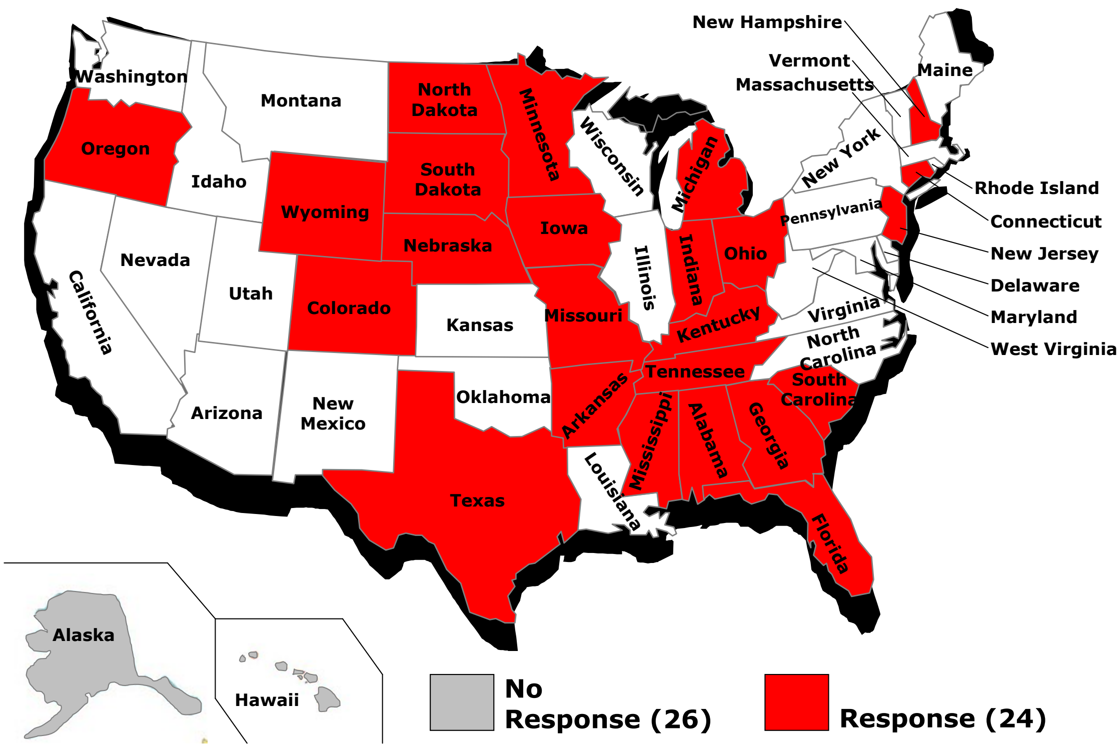


Figure A1. Survey responses on the status of minimum pavement thickness usage

Table A1. Survey results of minimum thickness for asphalt and concrete pavements adopted by 24 states

	State	Thickness (in.)	
		Asphalt Pavement	Concrete Pavement
	Alabama	4″	No Design
	Alaska		
	Arizona		
	Arkansas	2"	No Design
	California		
	Colorado	2"	6"
	Connecticut	4"	No Design
	Delaware		
	Florida		8″
0	Georgia		6″
1	Hawaii		
2	Idaho		
3	Illinois		
4	Indiana	4"	7"
5	Iowa	6″	7"
6	Kansas		
7	Kentucky	1.25"	8"
6	Montana		
7	Nebraska	6"	8″
8	Nevada		
9	New Hampshire	4"	No Design
0	New Jersey	4"	8"
1	New Mexico	3"	8"
2	New York	No minimum	8"
3	North Carolina		
4	North Dakota	4"	8"
5	Ohio		
6	Oklahoma		
7	Oregon	2"	No Design
8	Pennsylvania	3″	8″
9	Rhode Island	3.25″	No Design
0	South Carolina	No minimum	8″
1	South Dakota		
2	Tennessee	4"	No Design

Table A1. Continued

8	Louisiana		
9	Maine		
0	Maryland		
1	Massachusetts		
2	Michigan		8"
3	Minnesota	3.0"	7"
4	Mississippi	3.5"	No Design
5	Missouri		
3	Texas		
4	Utah		
5	Vermont		
6	Virginia		
7	Washington	4″	No Design
8	West Virginia	3"	8"
9	Wisconsin	No minimum	8"
0	Wyoming		

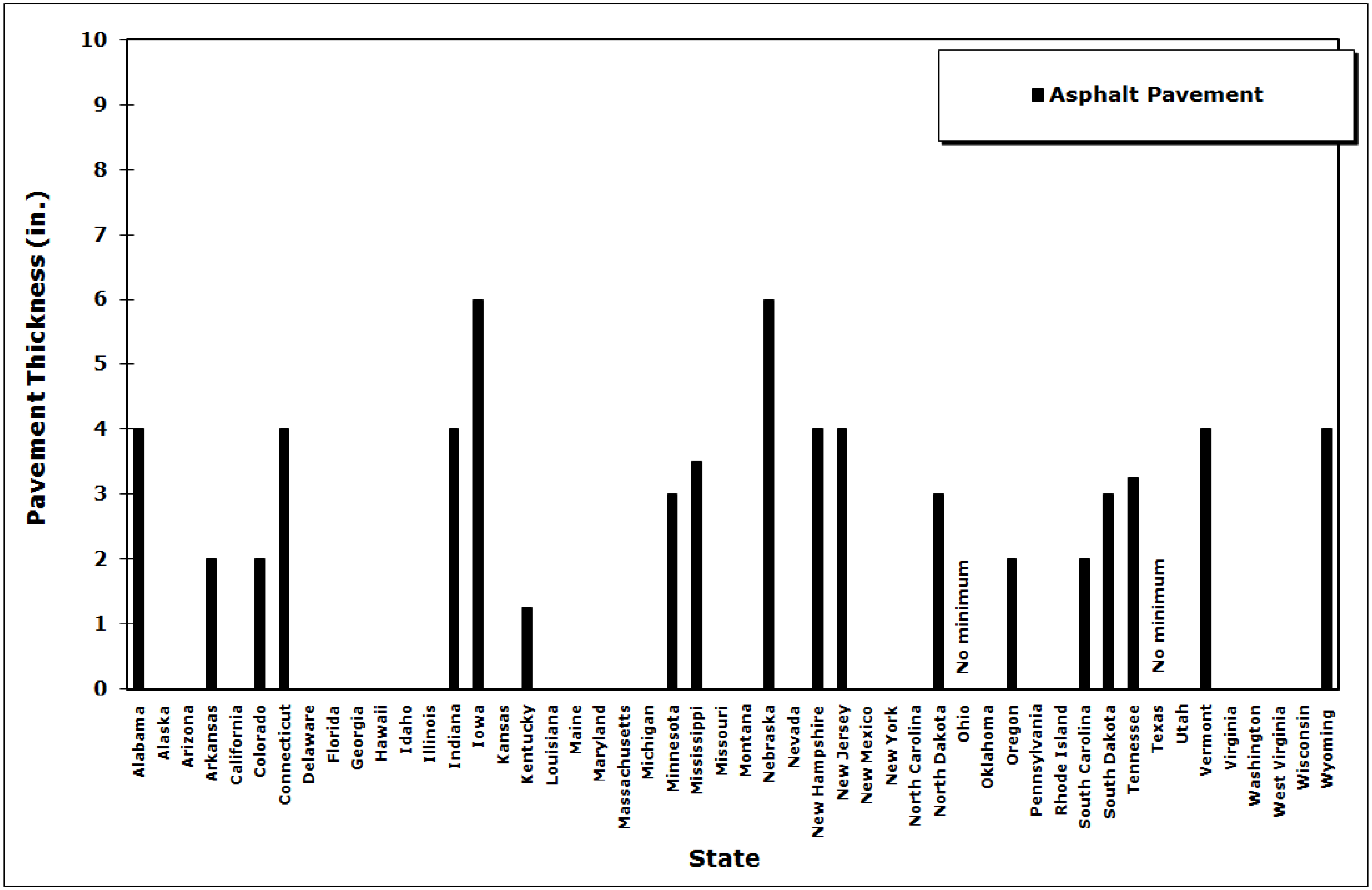


Figure A2. Comparisons of minimum thickness for asphalt pavement from 24 states

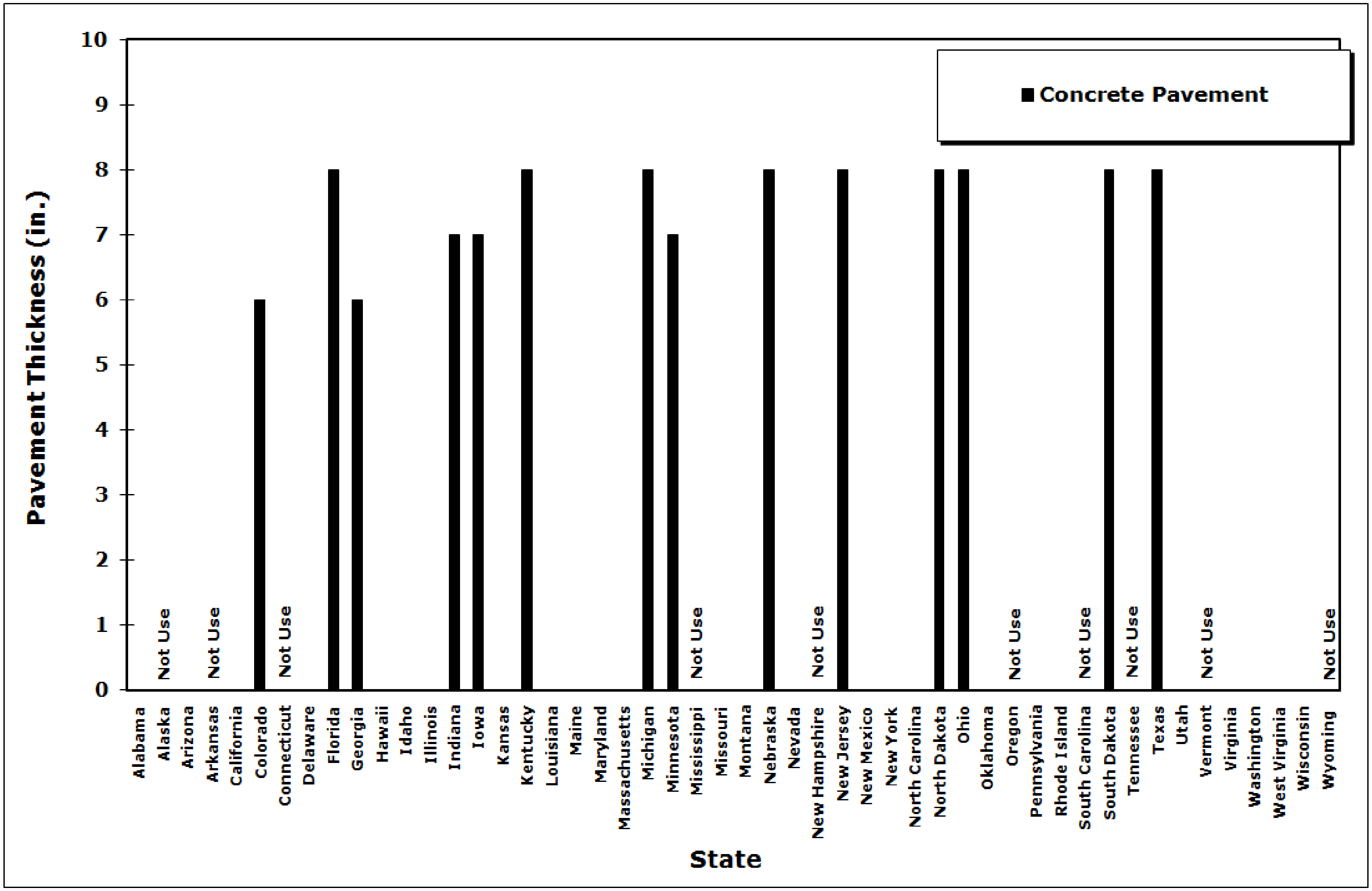
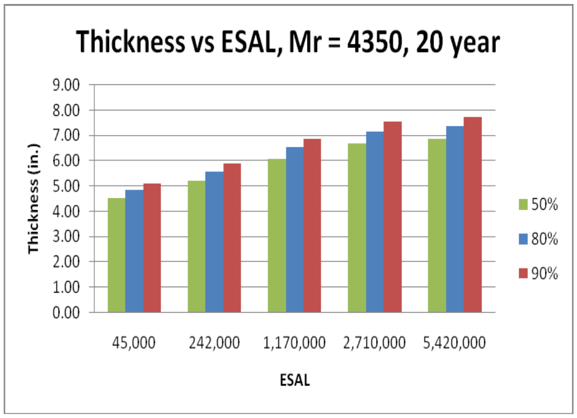
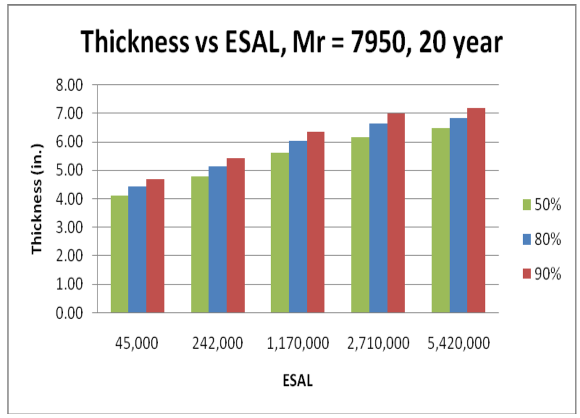


Figure A3. Comparisons of minimum thickness for concrete pavement from 24 states

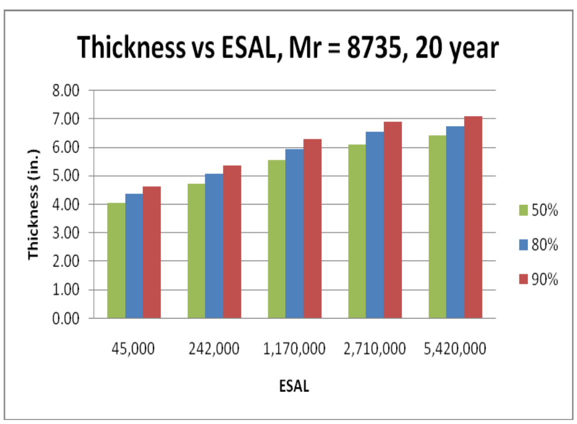
APPENDIX B - STREETPAVE SOFTWARE



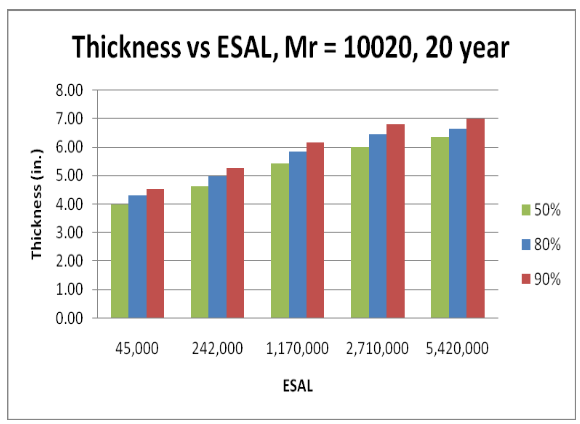
a. Mr=4350



b. Mr=7950

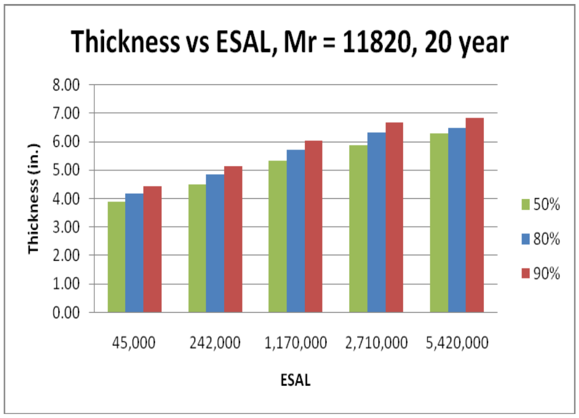


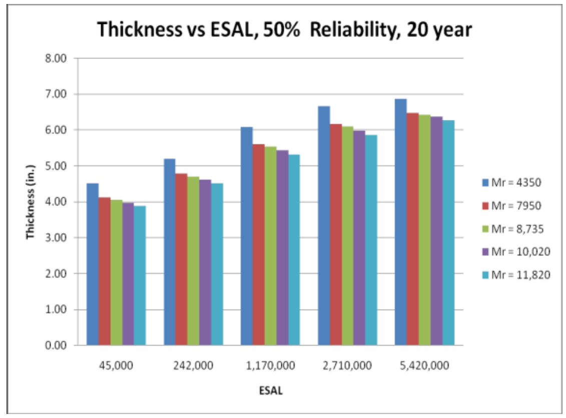
c. Mr=8735



d. Mr=10020

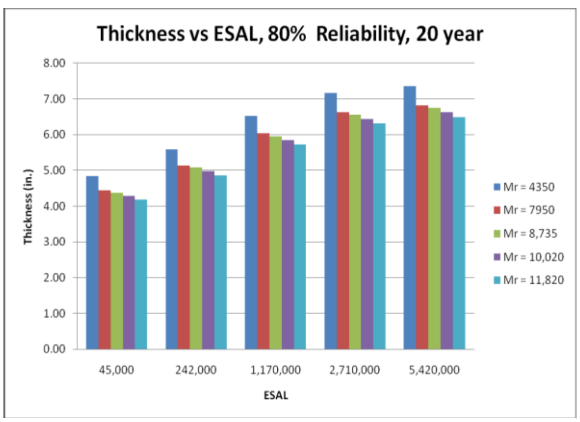
Figure B1. StreetPave Concrete Pavement, 20 year Design Life

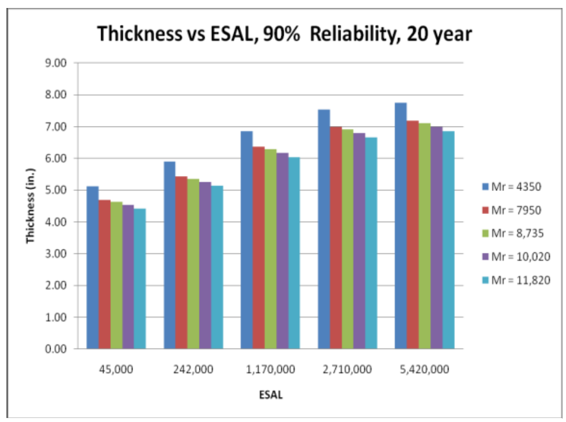




e. Mr=11820

f. Reliability: 50%

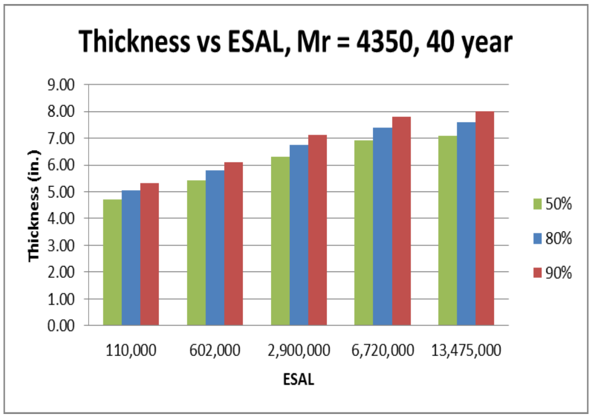




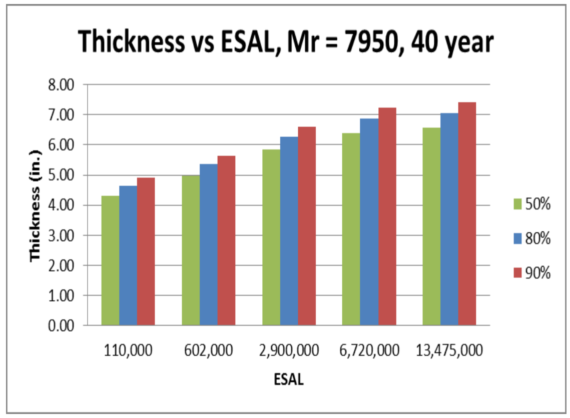
g. Reliability: 80%

h. Reliability: 90%

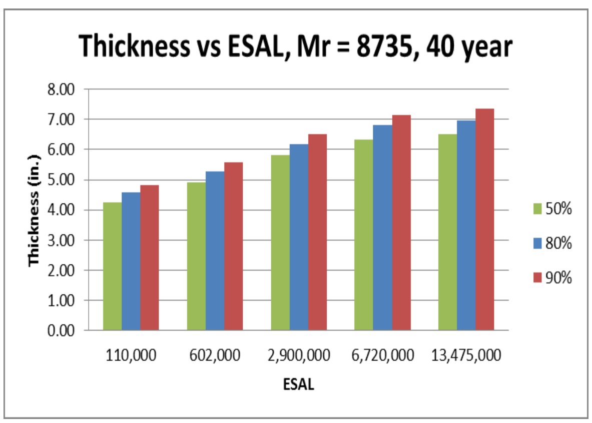
Figure B1. Continued



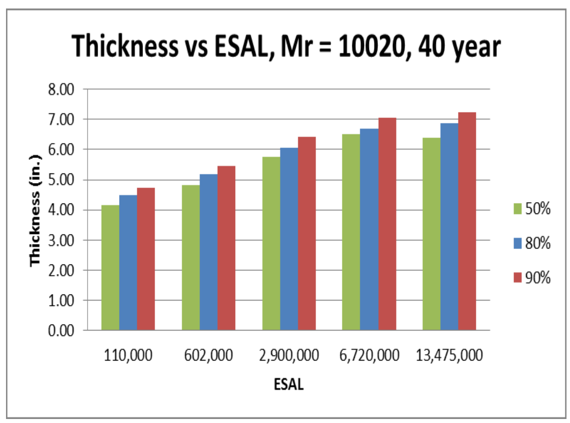
a. Mr=4350



b. Mr=7950

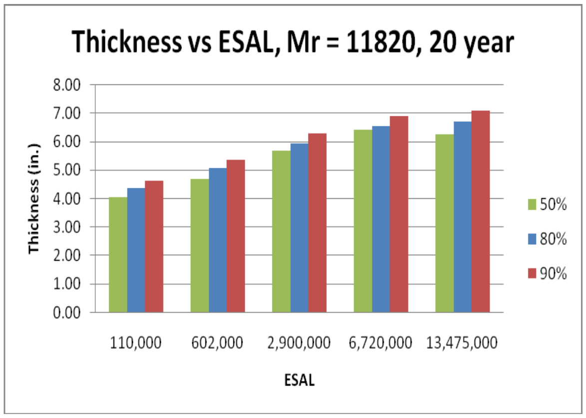


c. Mr=8735

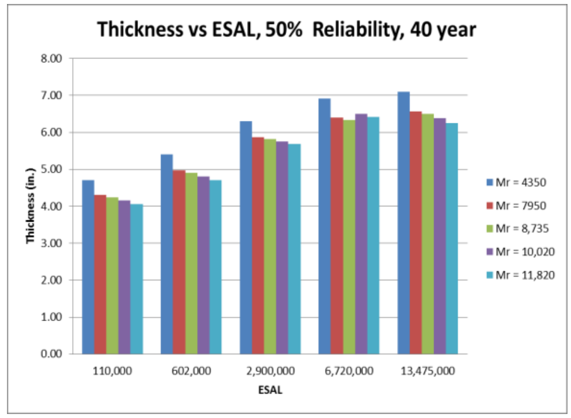


d. Mr=10020

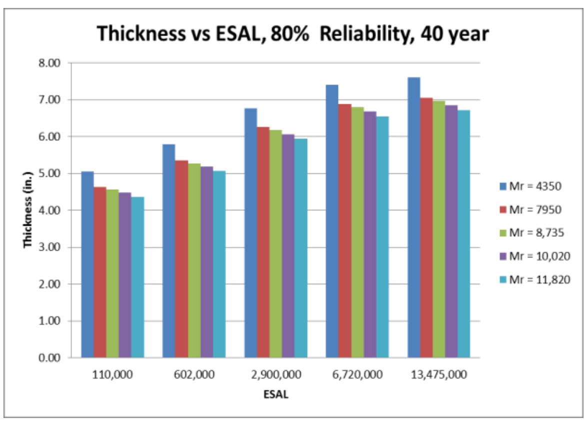
Figure B2. StreetPave Concrete Pavement, 40 year Design Life



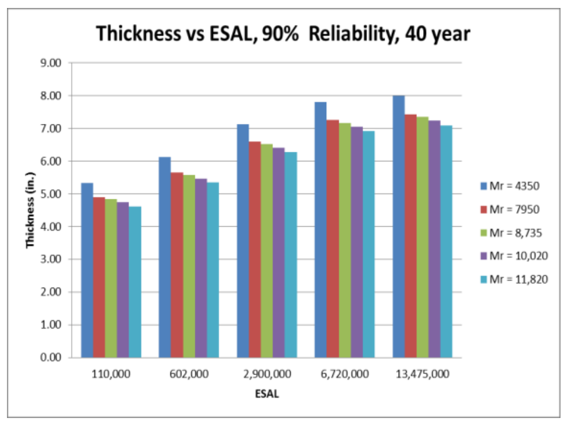
e. Mr=11820



f. Reliability: 50%

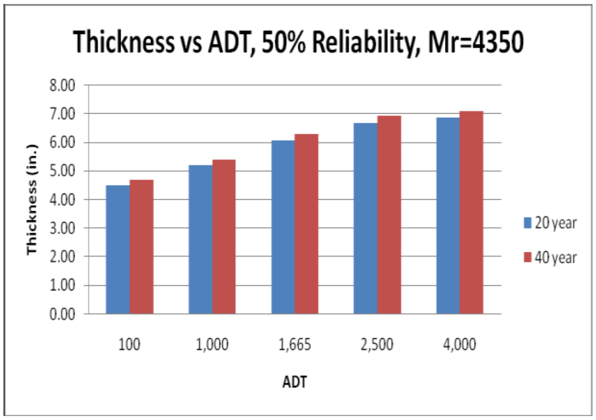


g. Reliability: 80%

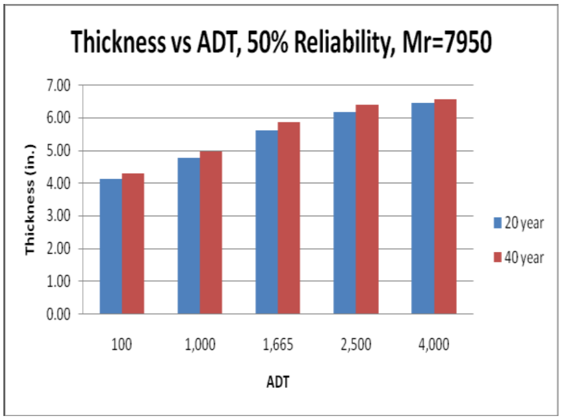


h. Reliability: 90%

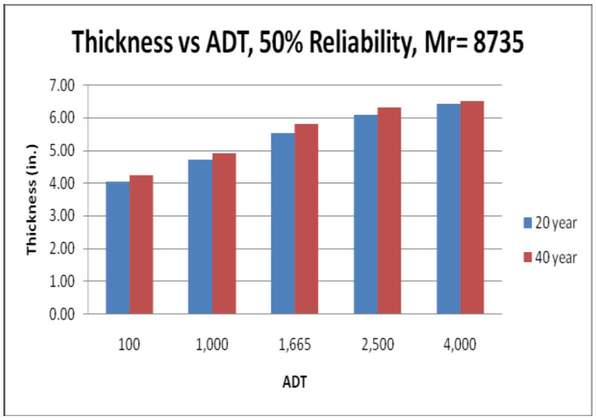
Figure B2. Continued



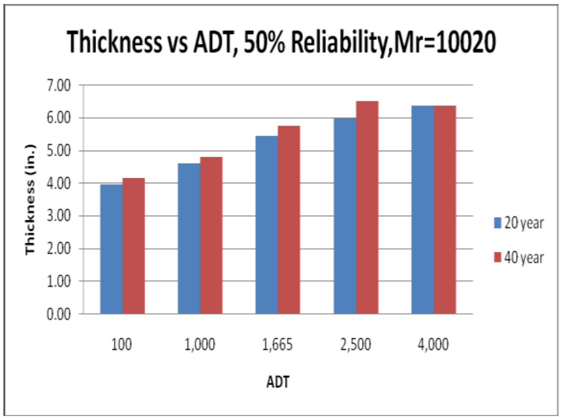
a. Mr=4350, Reliability 50%



b. Mr=7950, Reliability 50%

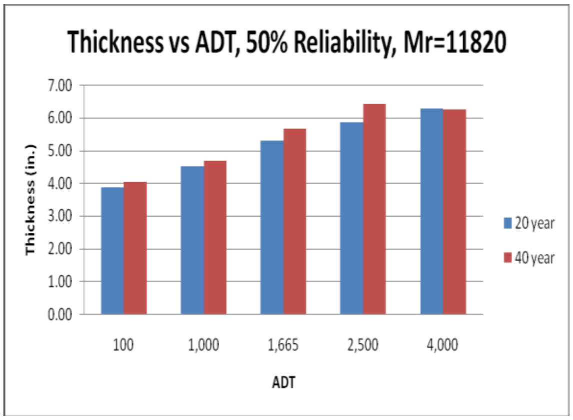


c. Mr=8735, Reliability 50%

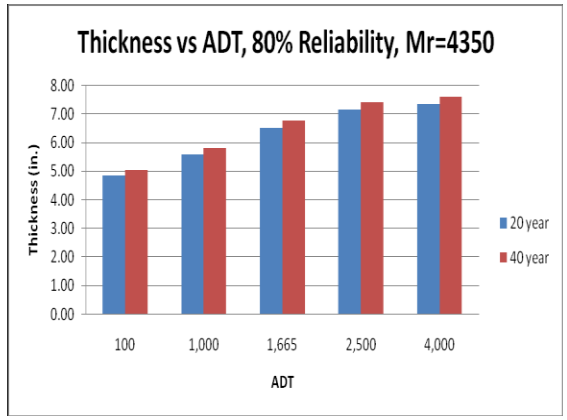


d. Mr=10020, Reliability 50%

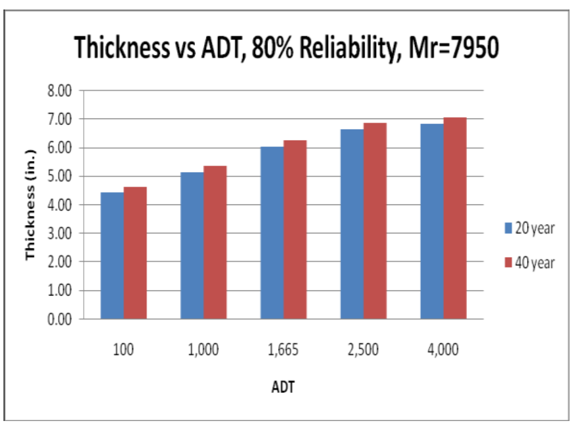
Figure B3. StreetPave Concrete Pavement, 20 years vs. 40 years



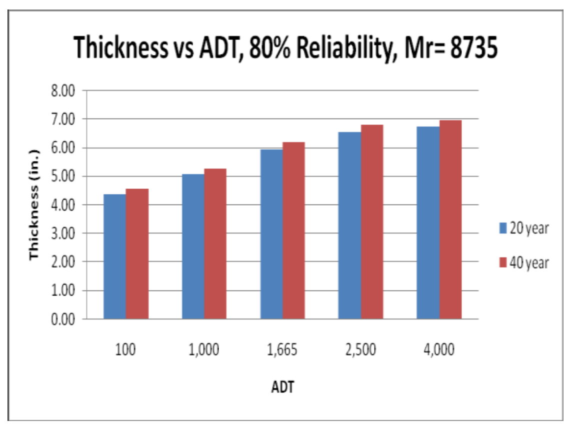
e. Mr=11820, Reliability 50%



f. Mr=4350, Reliability 80%

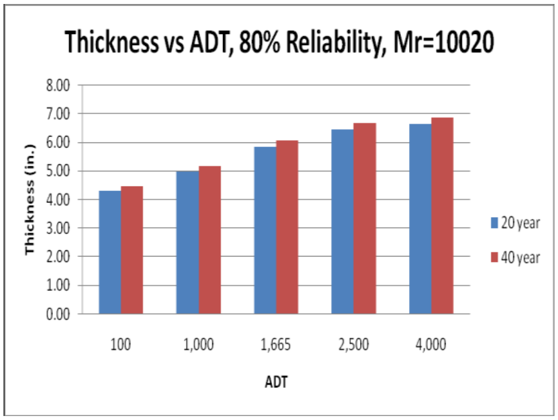


g. Mr=7950, Reliability 80%

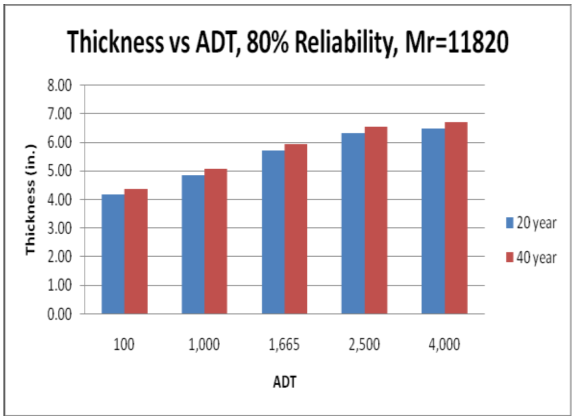


h. Mr=8735, Reliability 80%

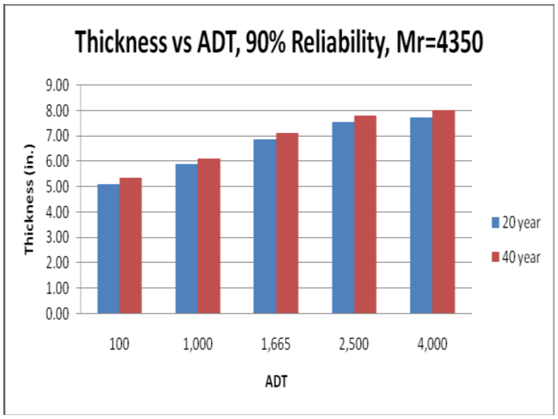
Figure B3. Continued



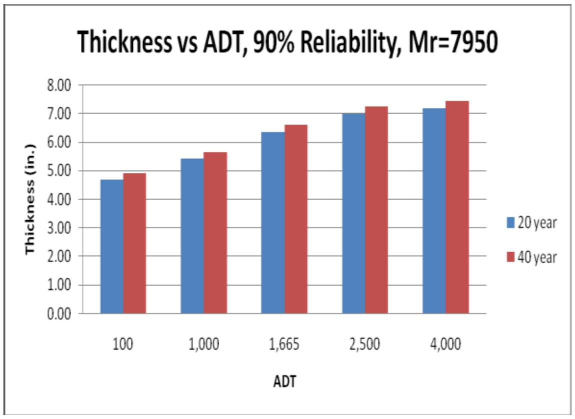
i. Mr=10020, Reliability 80%



j. Mr=11820, Reliability 80%

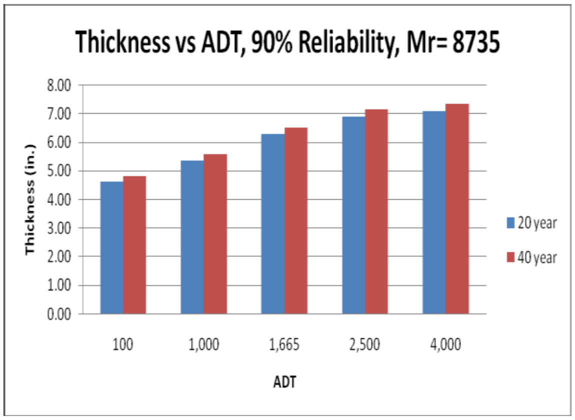


k. Mr=4350, Reliability 90%

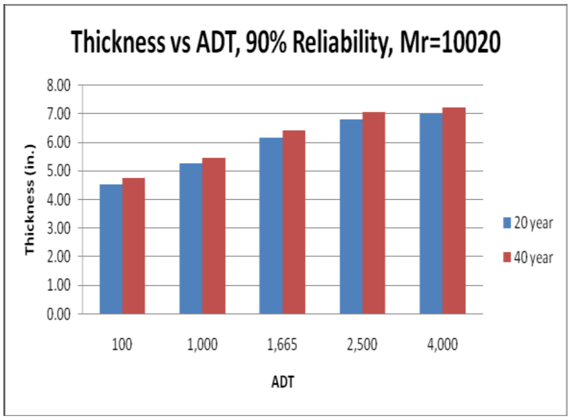


l. Mr=7950, Reliability 90%

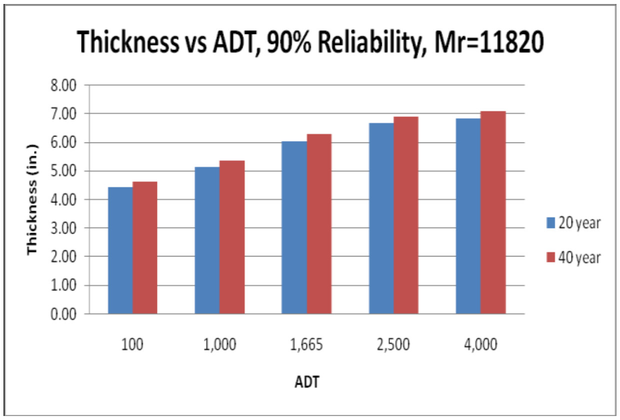
Figure B3. Continued



m. Mr=8735, Reliability 90%

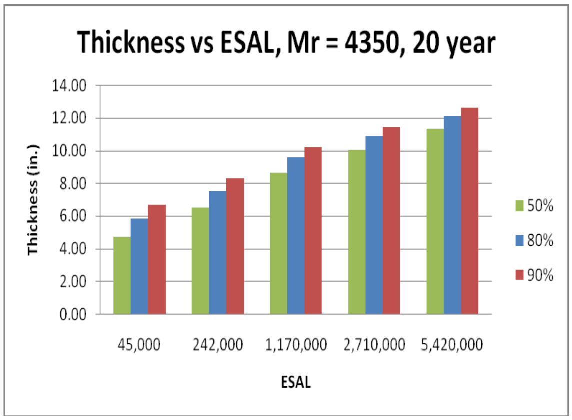


n. Mr=10020, Reliability 90%

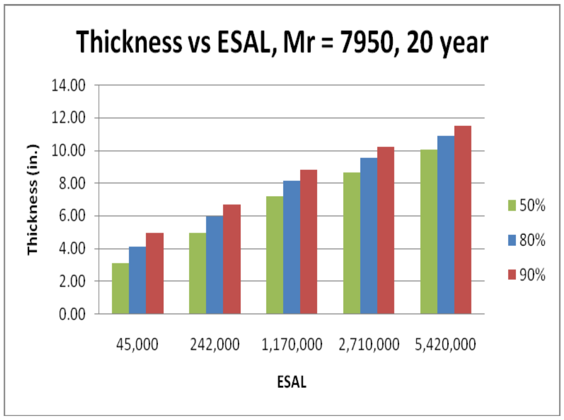


o. Mr=11820, Reliability 90%

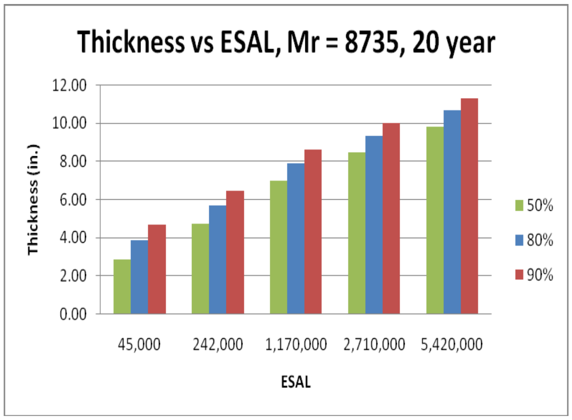
Figure B3. Continued



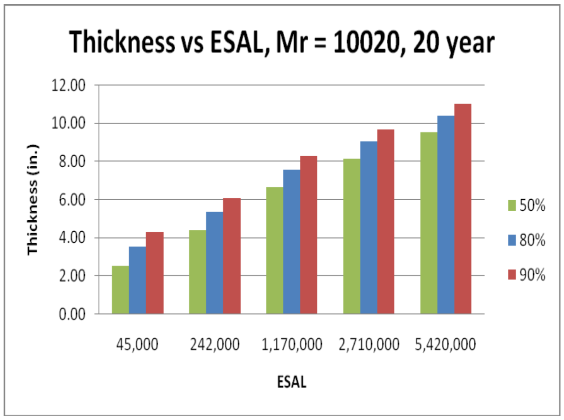
a. Mr=4350



b. Mr=7950

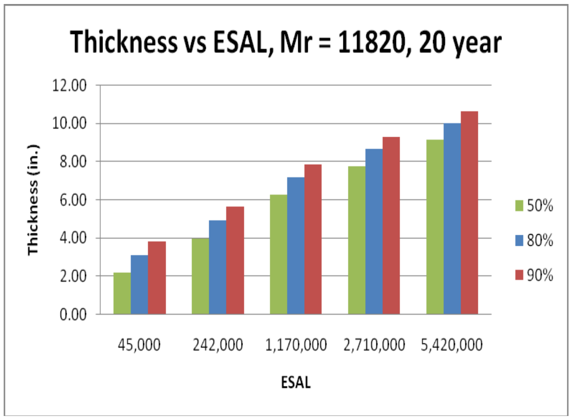


c. Mr=8735

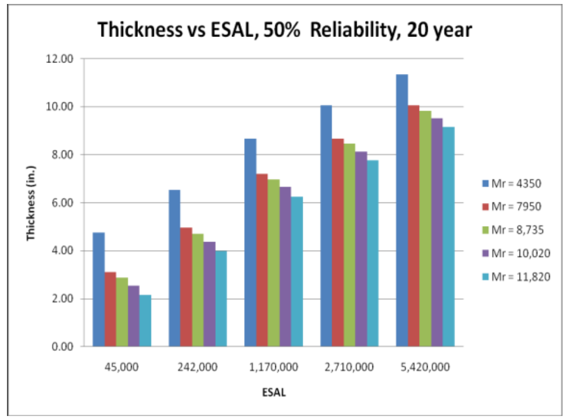


d. Mr=10020

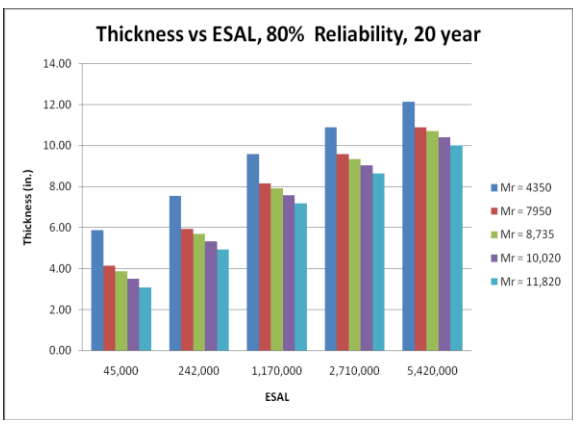
Figure B4. StreetPave Asphalt Pavement, 20 years Design Life



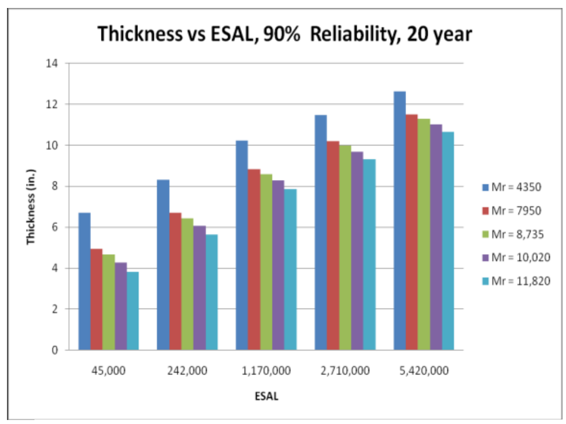
e. Mr=10020



f. Reliability: 50%

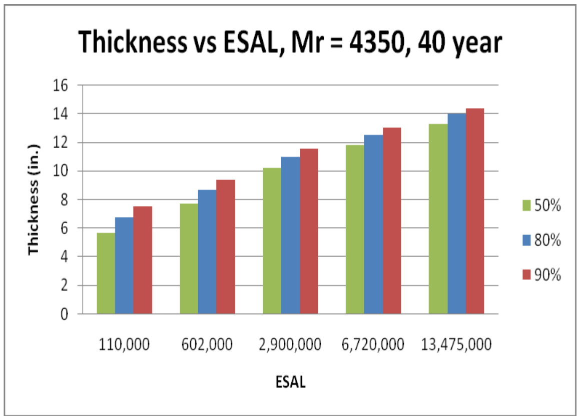


g. Reliability: 80%

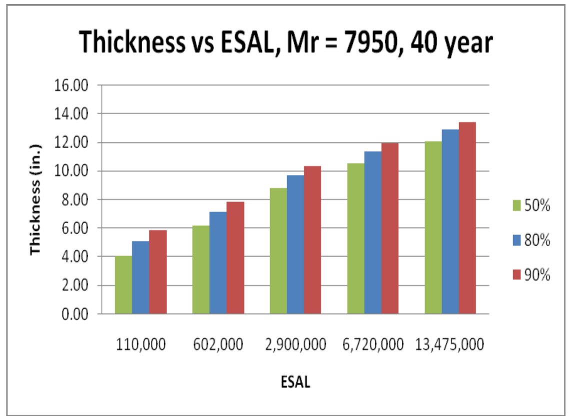


h. Reliability: 90%

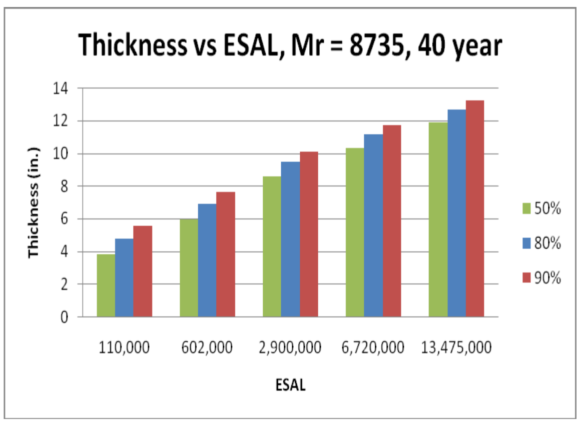
Figure B4. Continued



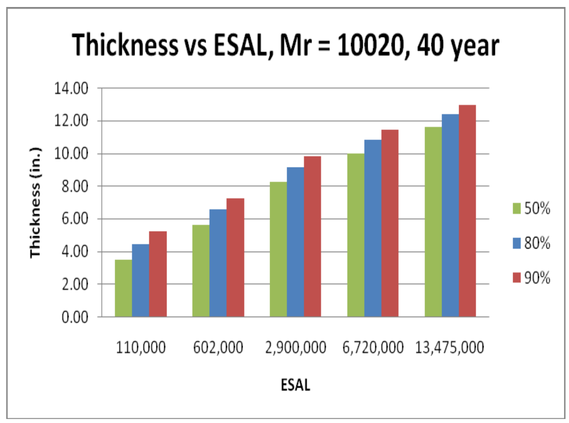
a. Mr=4350



b. Mr=7950

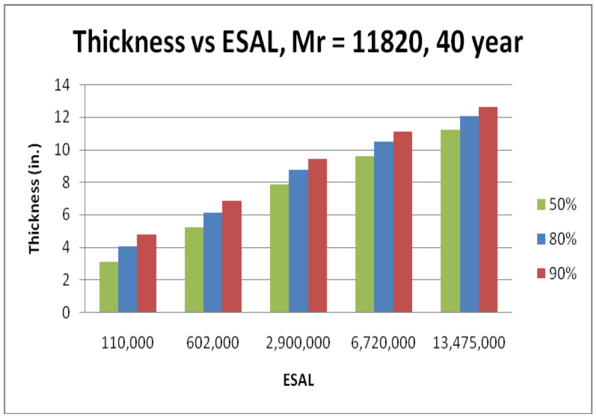


c. Mr=8735

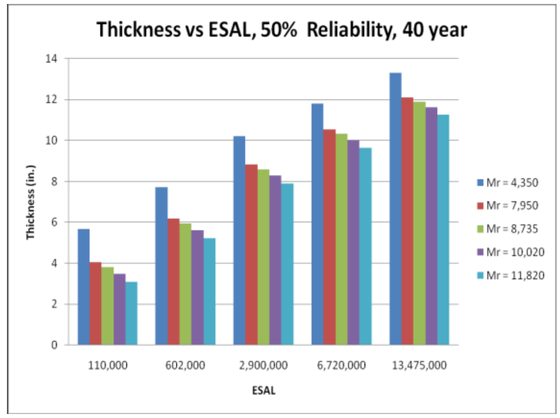


d. Mr=10020

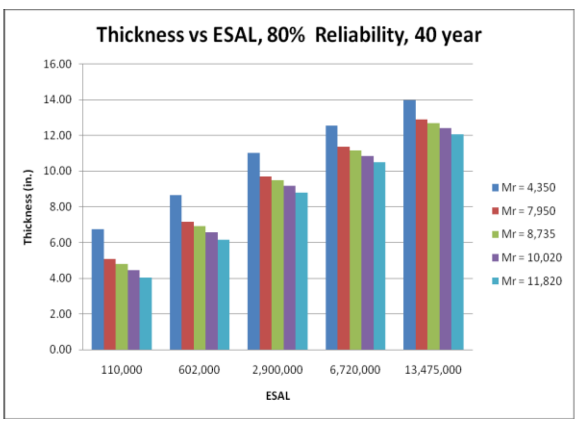
Figure B5. StreetPave Asphalt Pavement, 40 years Design Life



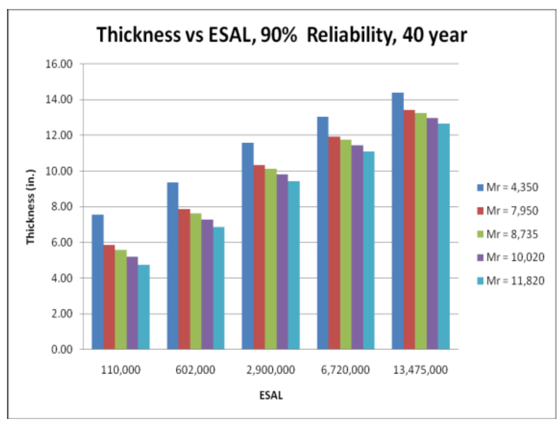
e. Mr=11820



f. Reliability: 50%

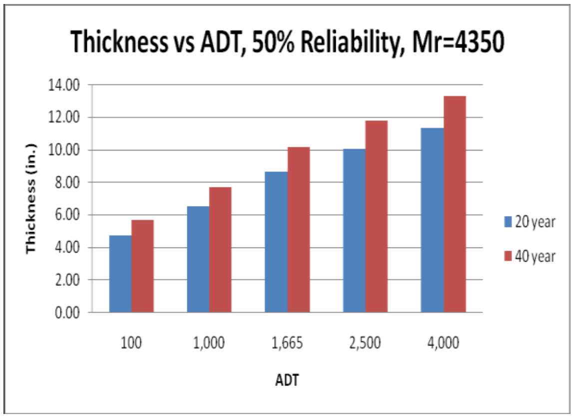


g. Reliability: 80%

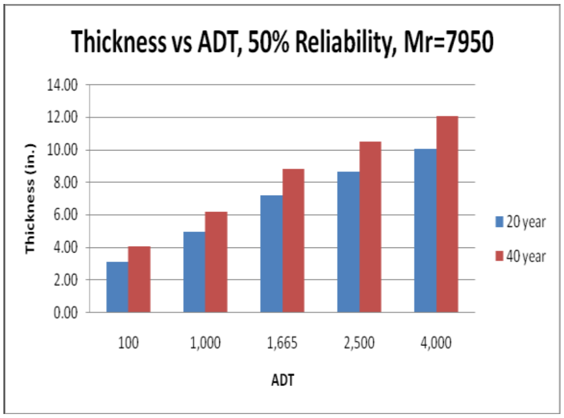


h. Reliability: 90%

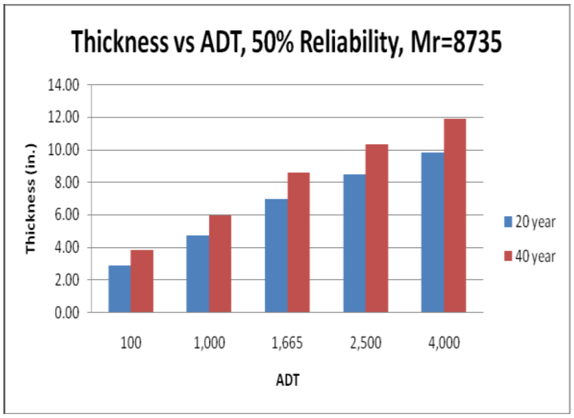
Figure B5. Continued



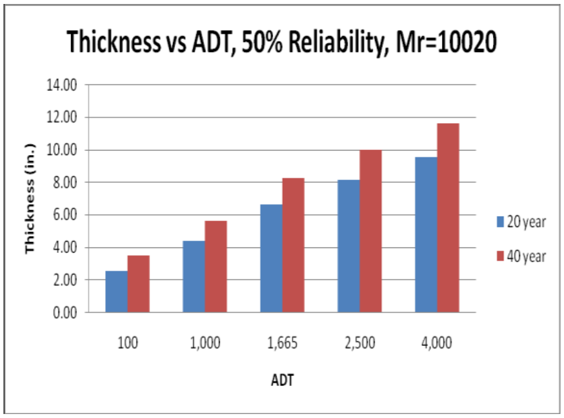
a. Mr=4350, Reliability: 50%



b. Mr=7950, Reliability: 50%

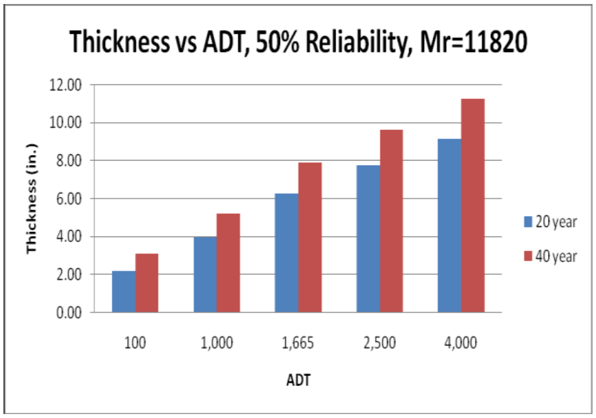


c. Mr=8735, Reliability: 50%

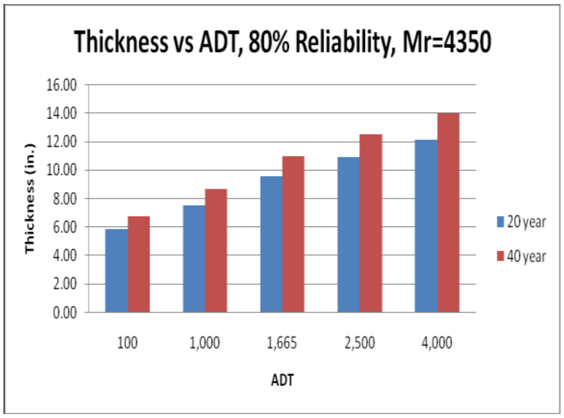


d. Mr=10020, Reliability: 50%

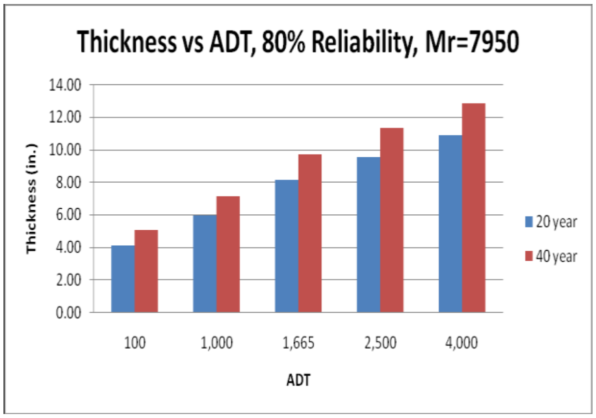
Figure B6. StreetPave Asphalt Pavement, 20 years vs. 40 years



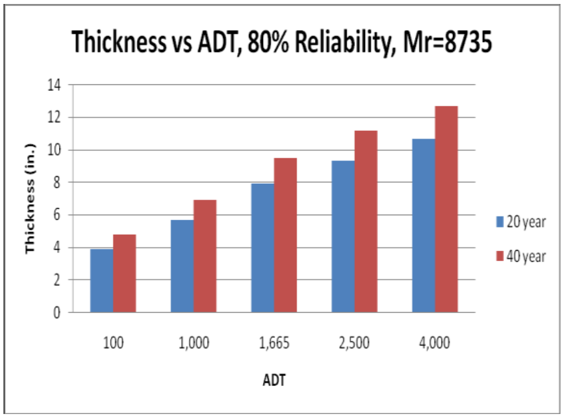
e. Mr=11820, Reliability: 50%



f. Mr=4350, Reliability: 80%

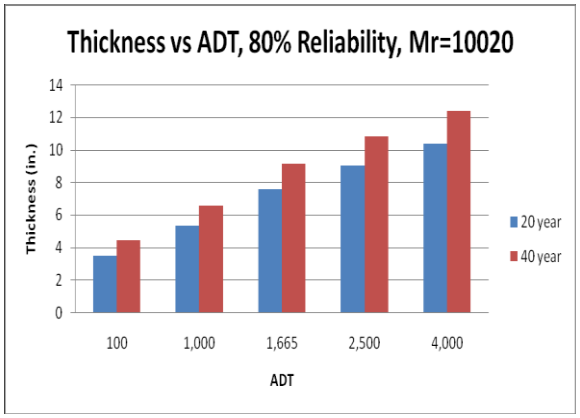


g. Mr=7950, Reliability: 80%

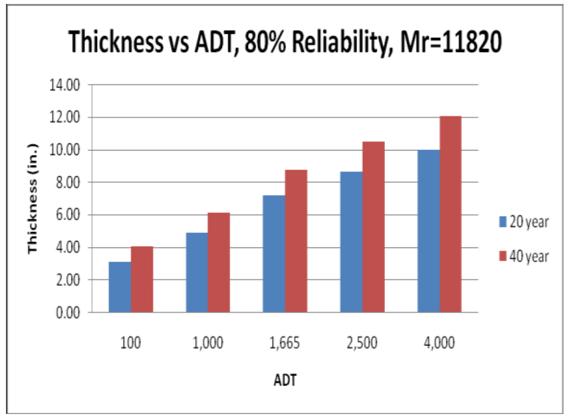


h. Mr=8735, Reliability: 80%

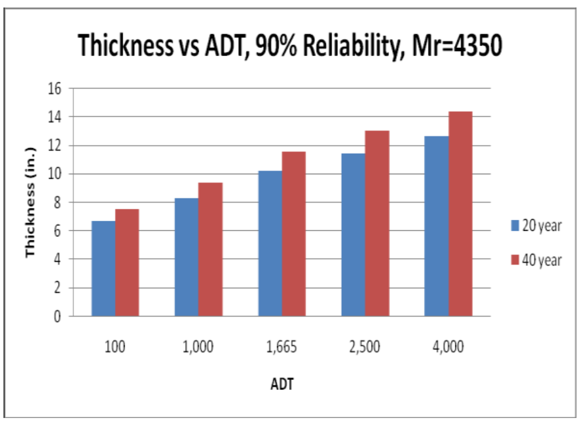
Figure B6. Continued



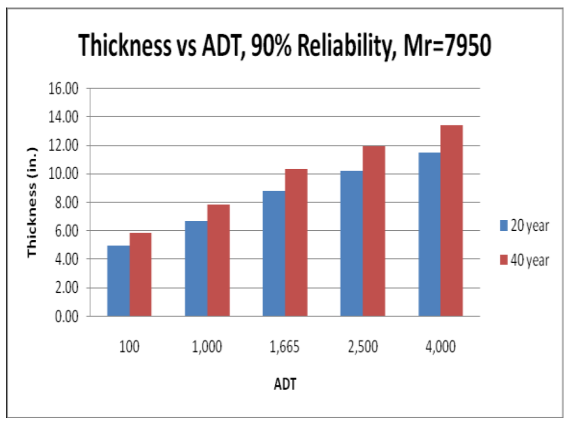
i. Mr=10020, Reliability: 80%



j. Mr=11820, Reliability: 80%

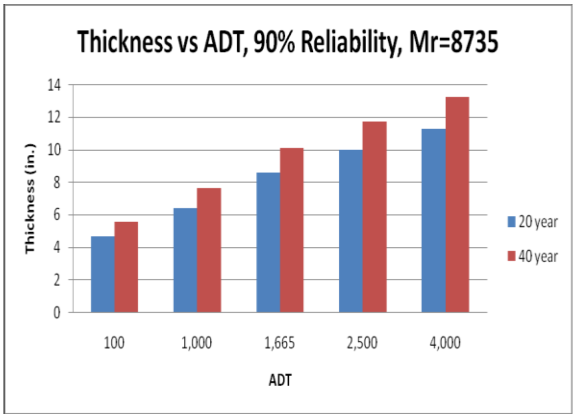


k. Mr=4350, Reliability: 90%

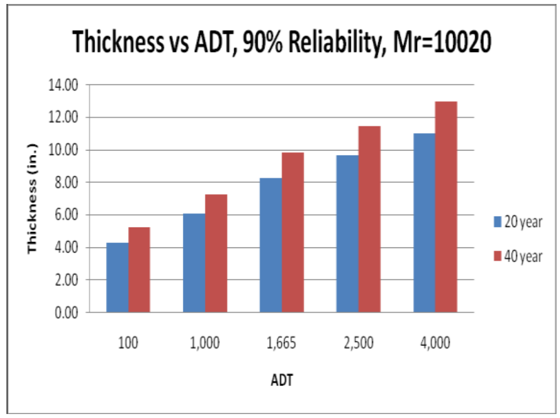


l. Mr=7950, Reliability: 90%

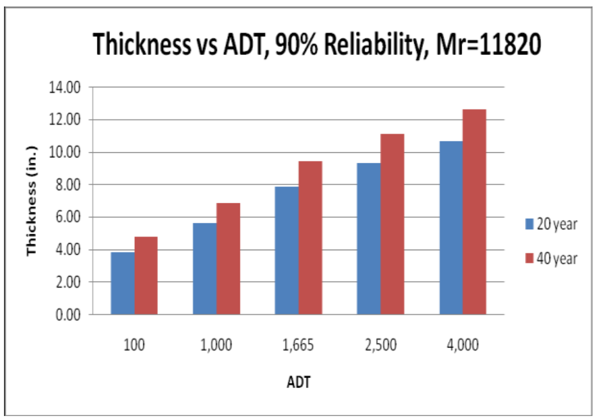
Figure B6. Continued



n. Mr=8735, Reliability: 90%



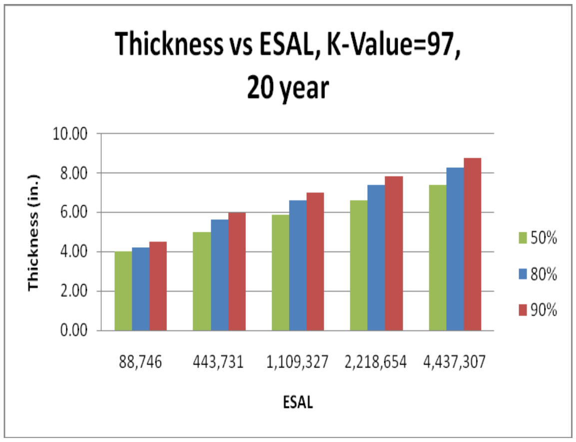
m. Mr=10020, Reliability: 90%



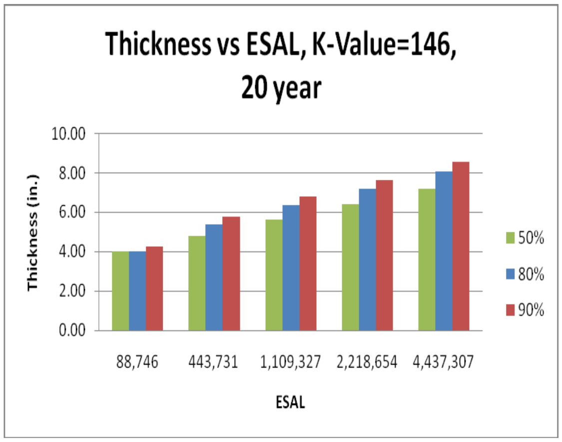
o. Mr=11820, Reliability: 90%

Figure B6. Continued

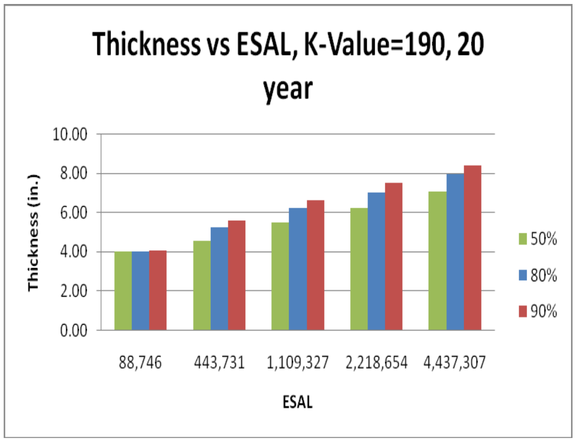
APPENDIX C - WINPAS SOFTWARE



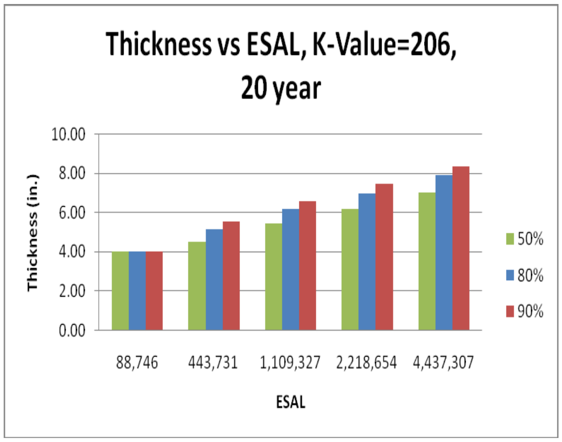
a. k-value=97



b. k-value=146

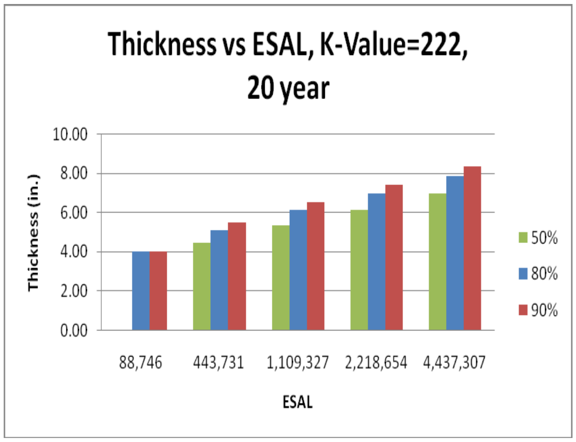


c. k-value=190

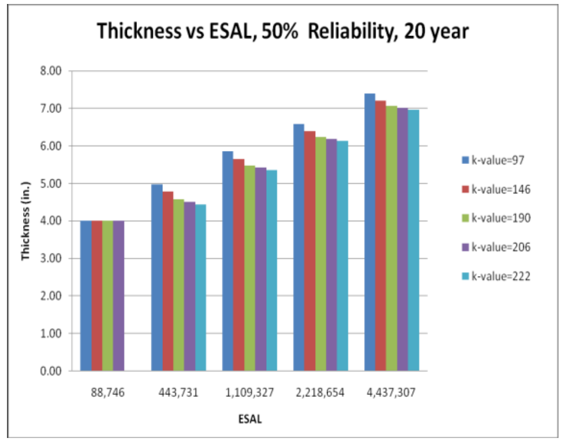


d. k-value=206

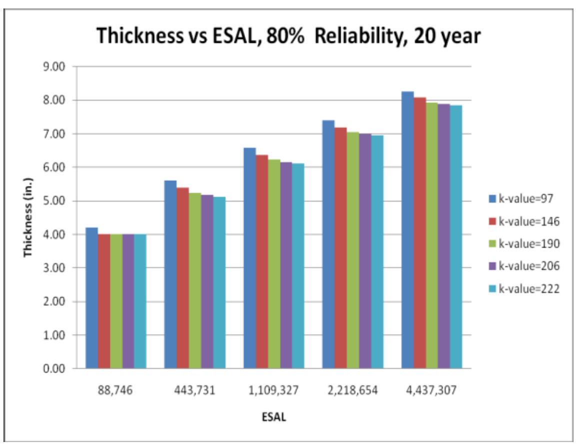
Figure C1. WinPAS Concrete Pavement, 20 year Design Life



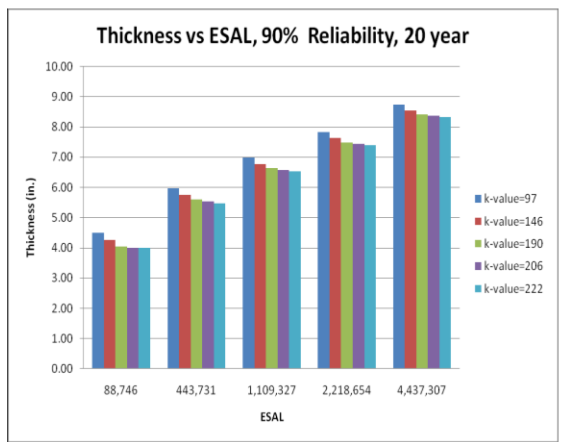
e. k-value=222



f. 50% Reliability

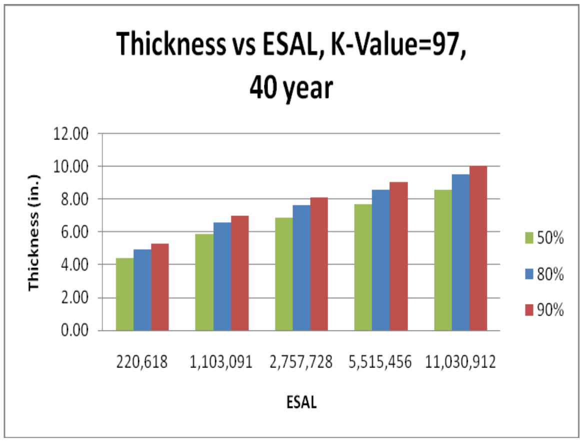


g. 80% Reliability

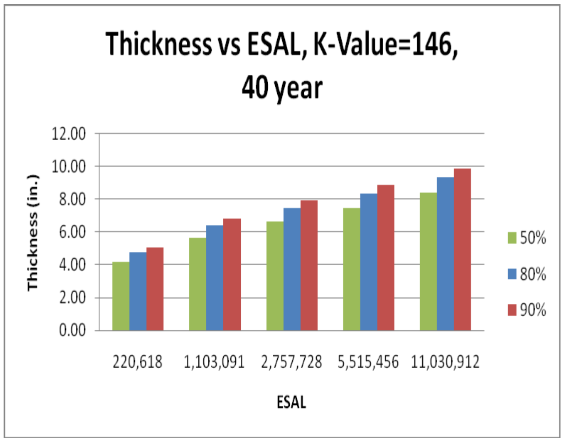


h. 90% Reliability

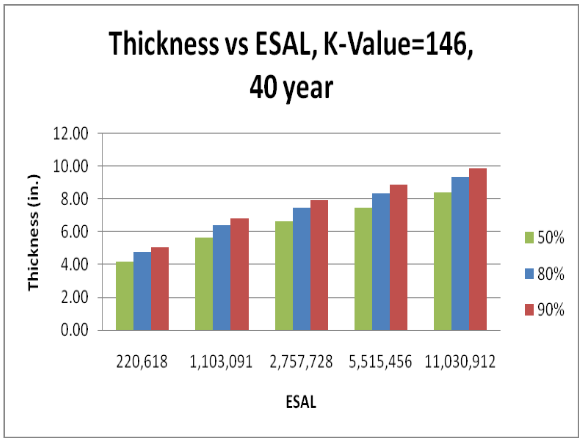
Figure C1. Continued



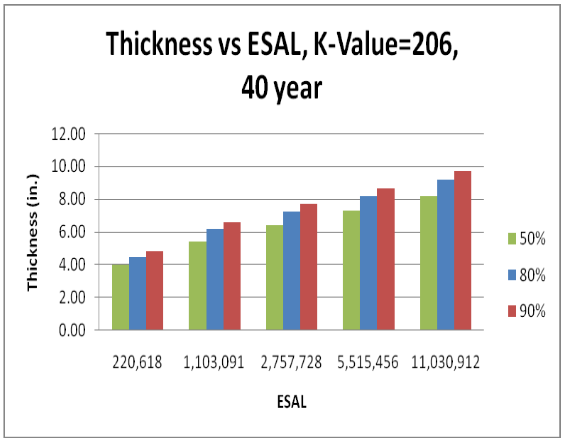
a. k-value=97



b. k-value=146

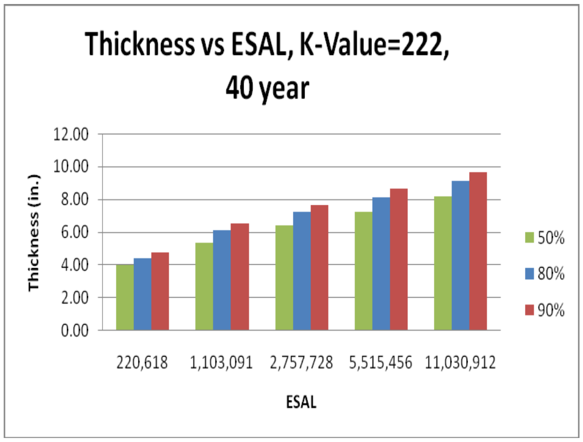


c. k-value=146

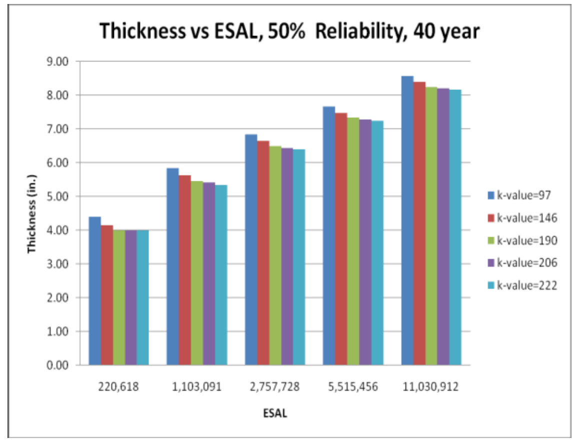


d. k-value=206

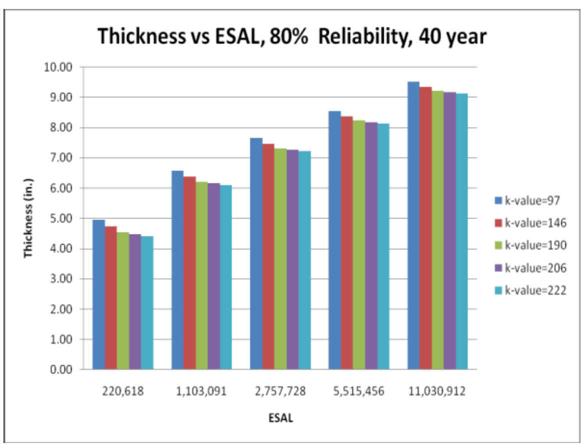
Figure C2. WinPAS Concrete Pavement, 40 year Design Life



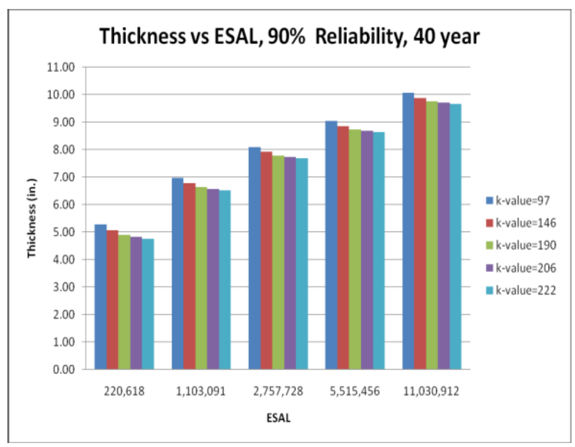
e. k-value=222



f. Reliability: 50%

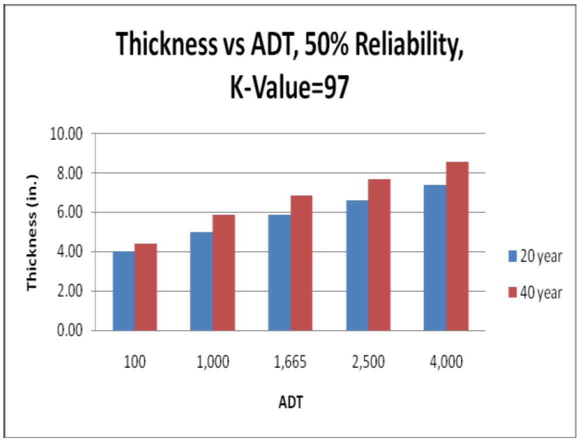


g. Reliability: 80%

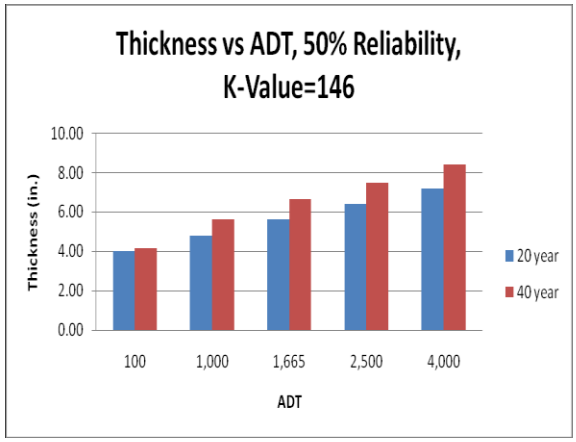


h. Reliability: 90%

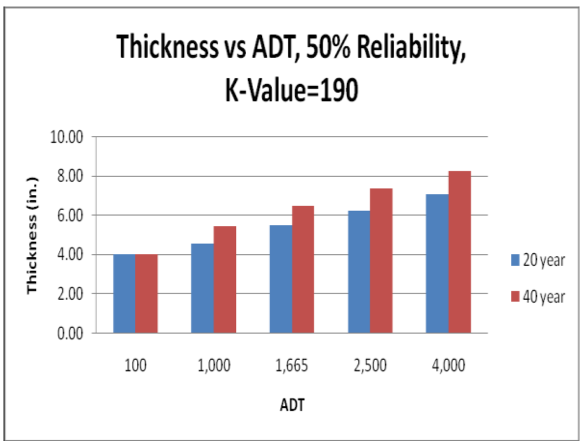
Figure C2. Continued



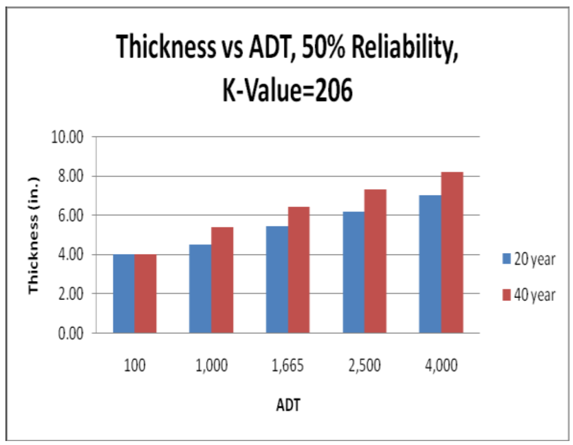
a. k-value=97, Reliability: 50%



b. k-value=146, Reliability: 50%

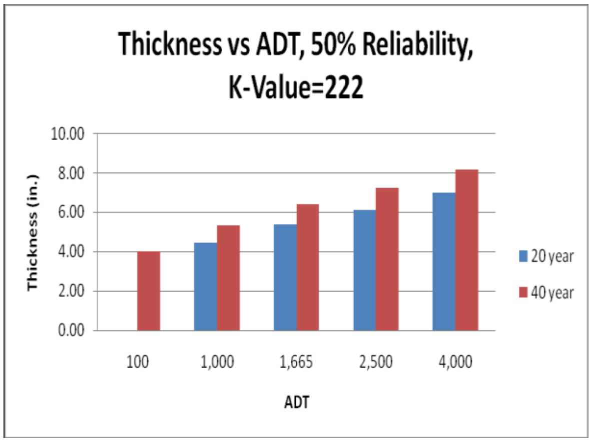


c. k-value=190, Reliability: 50%

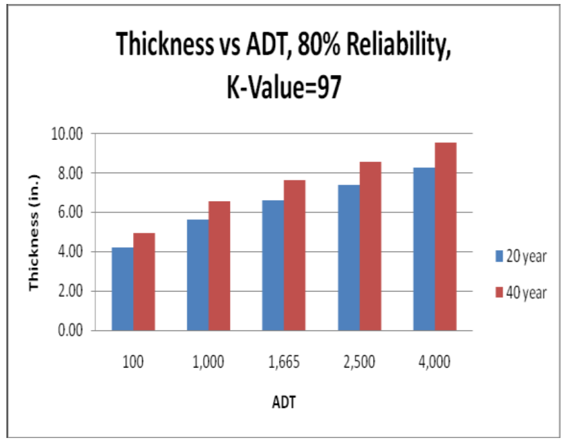


d. k-value=206, Reliability: 50%

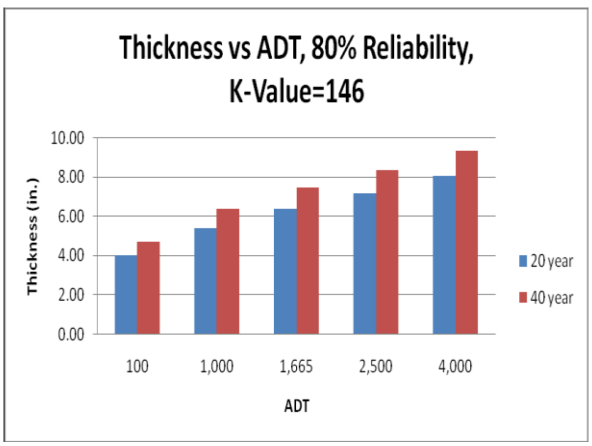
Figure C3. WinPAS Concrete Pavement, 20 years vs. 40 years



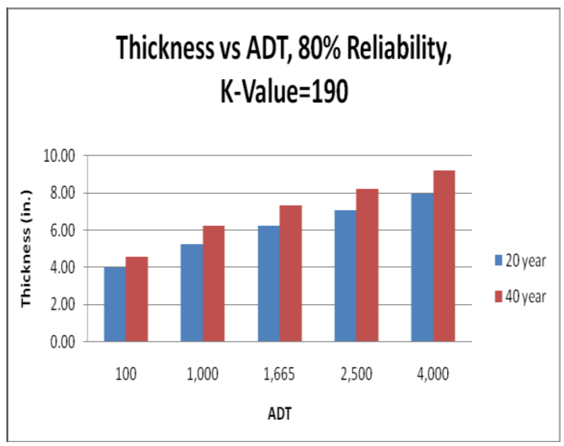
e. k-value=222, Reliability: 50%



f. k-value=97, Reliability: 80%

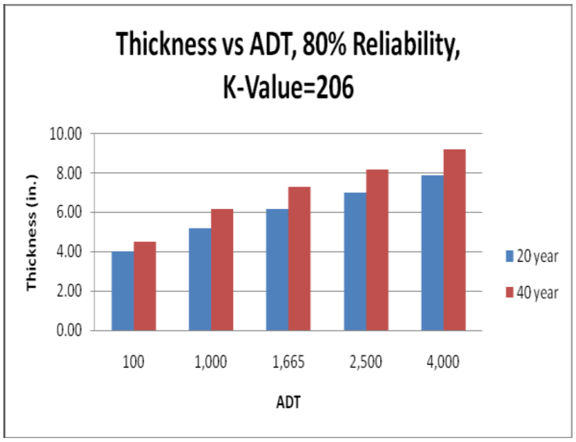


g. k-value=146, Reliability: 80%

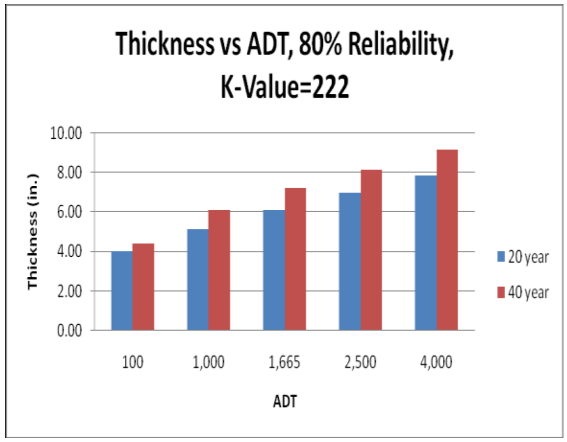


h. k-value=190, Reliability: 80%

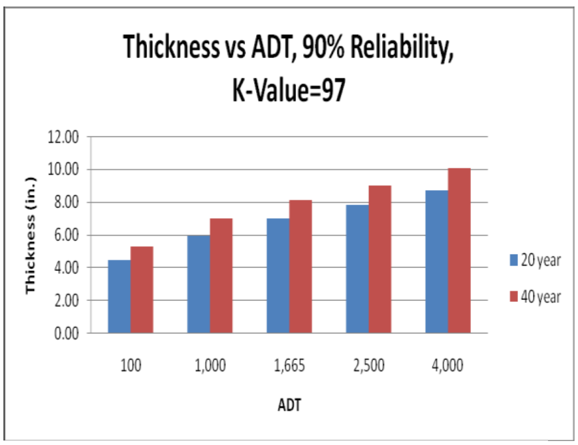
Figure C3. Continued



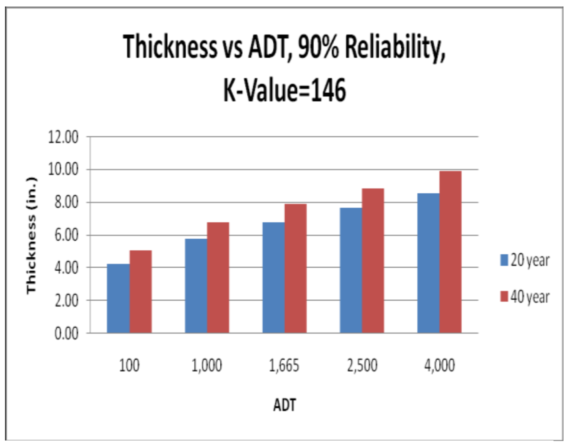
i. k-value=206, Reliability: 80%



j. k-value=222, Reliability: 80%

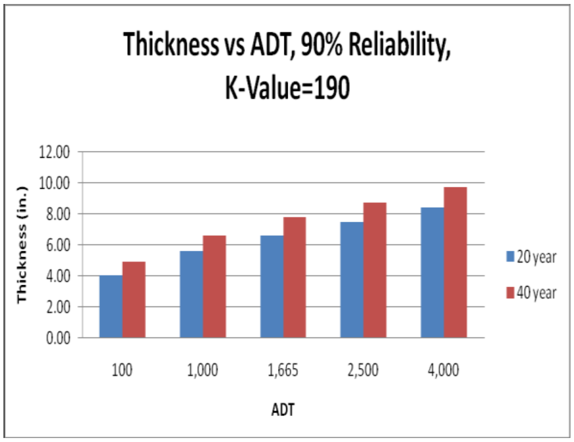


k. k-value=97, Reliability: 90%

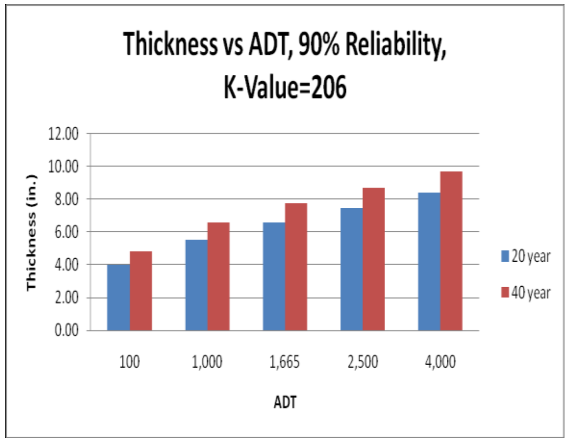


l. k-value=146, Reliability: 90%

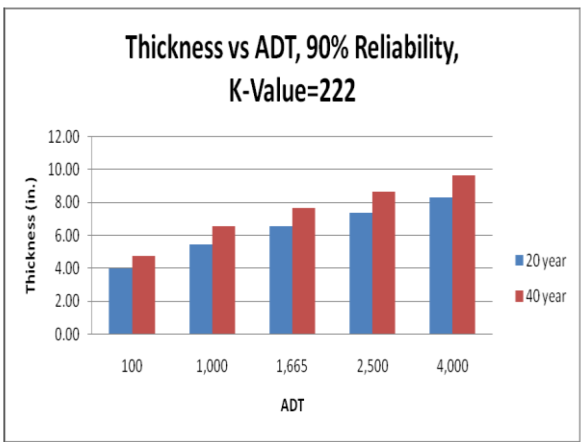
Figure C3. Continued



m. k-value=190 (Reliability: 90%)

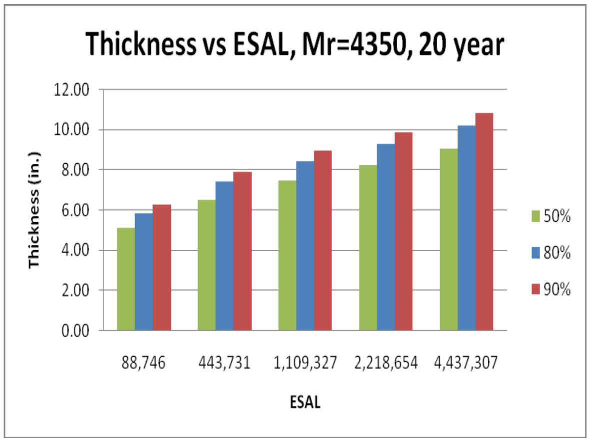


n. k-value=206 (Reliability: 90%)

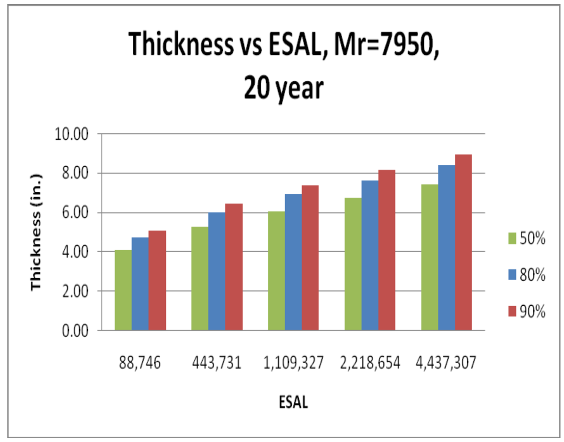


o. k-value=222 (Reliability: 90%)

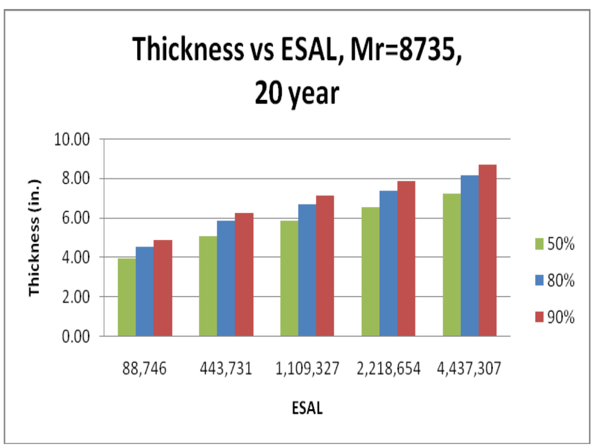
Figure C3. Continued



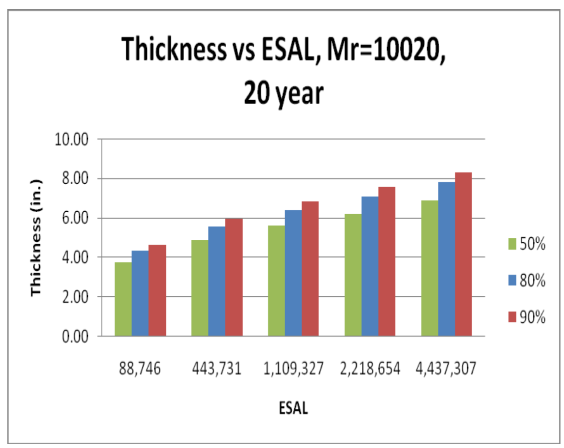
a. Mr=4350



b. Mr=7950

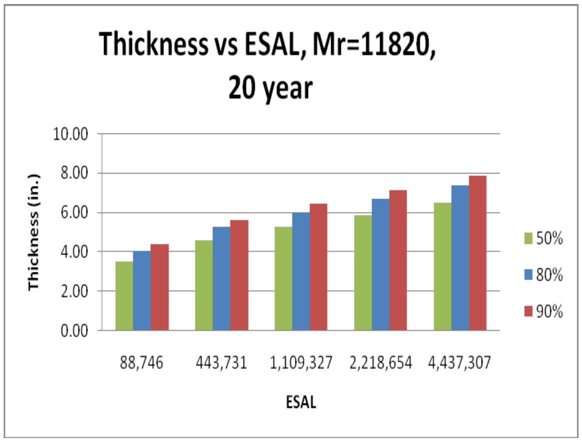


c. Mr=8735

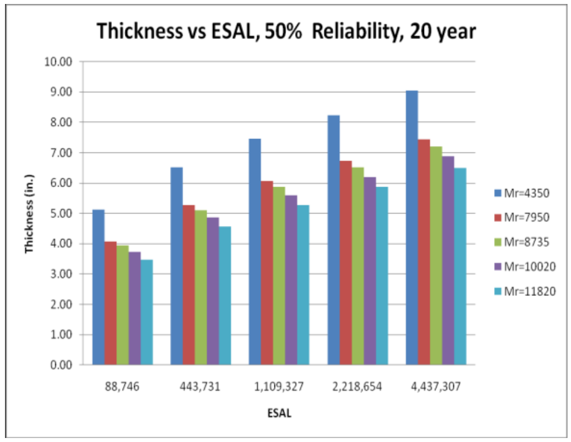


d. Mr=10020

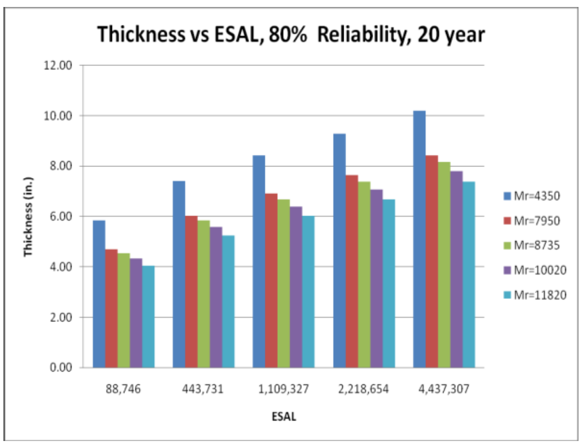
Figure C4. WinPAS Asphalt Pavement, 20 year Design Life



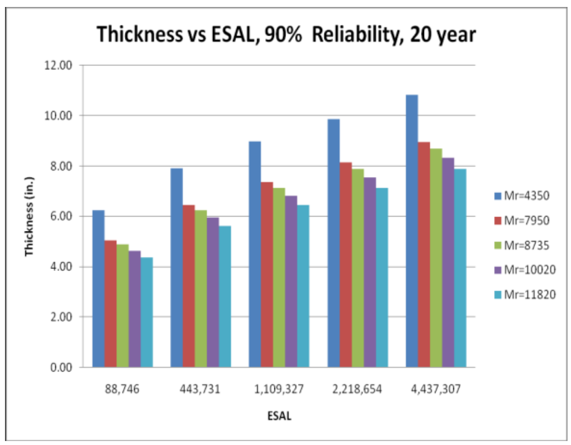
e. Mr=11820



f. Reliability: 50%

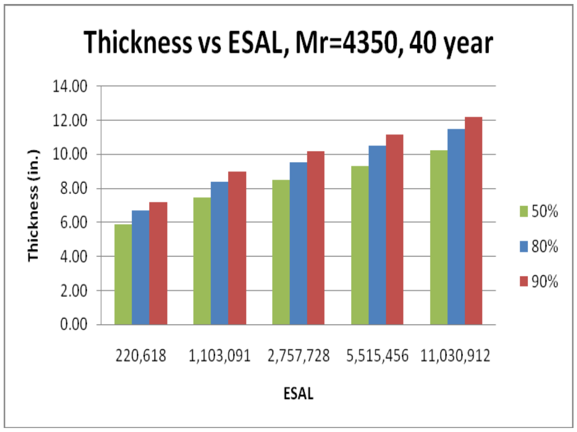


g. Reliability: 80%

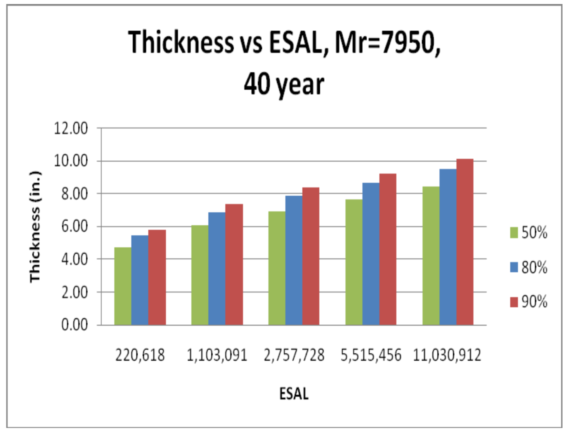


h. Reliability: 90%

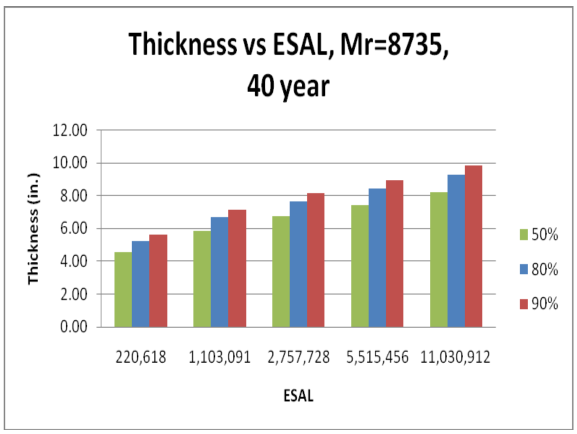
Figure C4. Continued



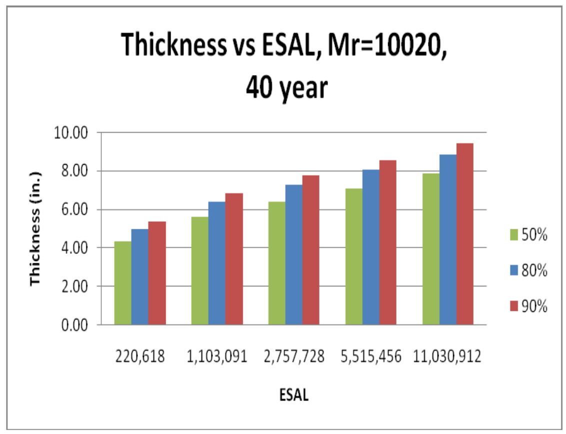
a. Mr=4350



b. Mr=7950

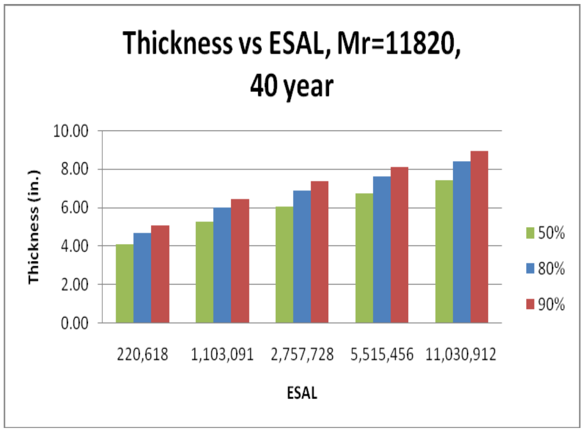


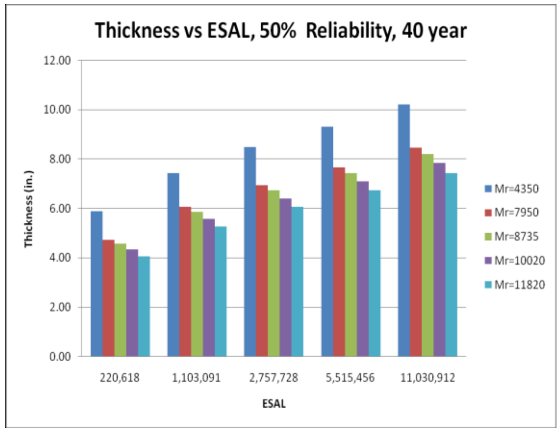
c. Mr=8735



d. Mr=10020

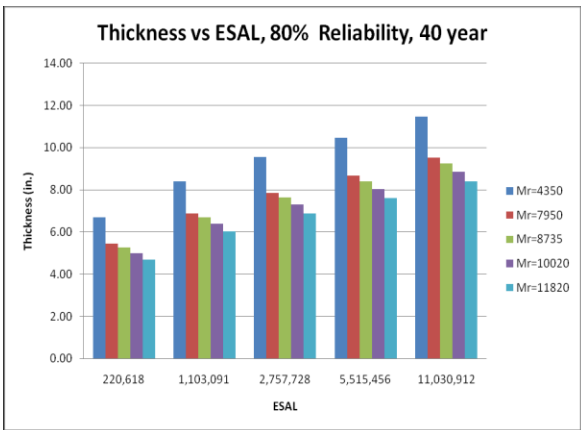
Figure C5. WinPAS Asphalt Pavement, 40 year Design Life

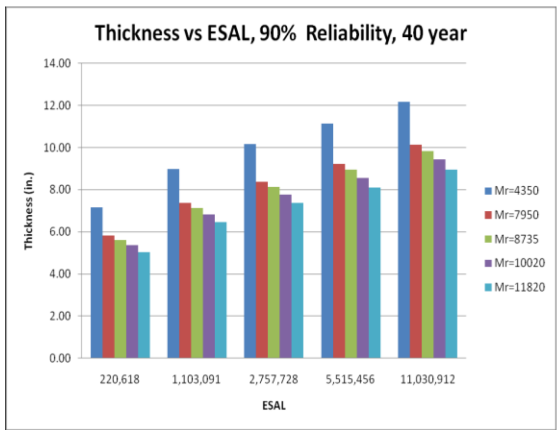




e. Mr=11820

f. Reliability: 50%

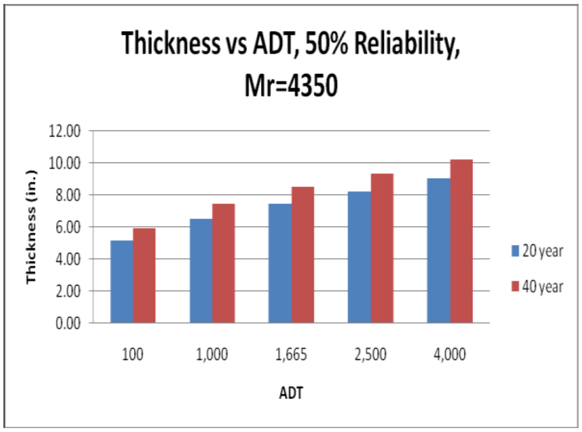




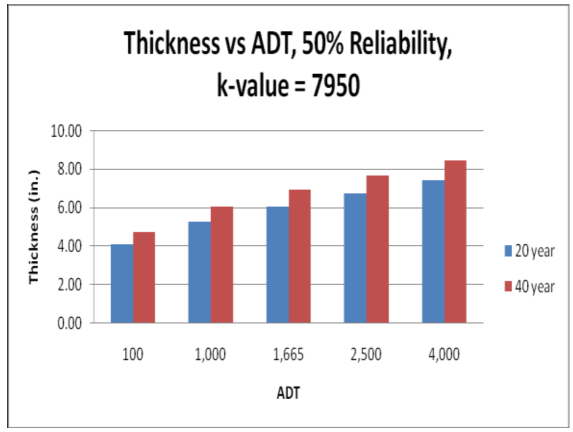
g. Reliability: 80%

h. Reliability: 90%

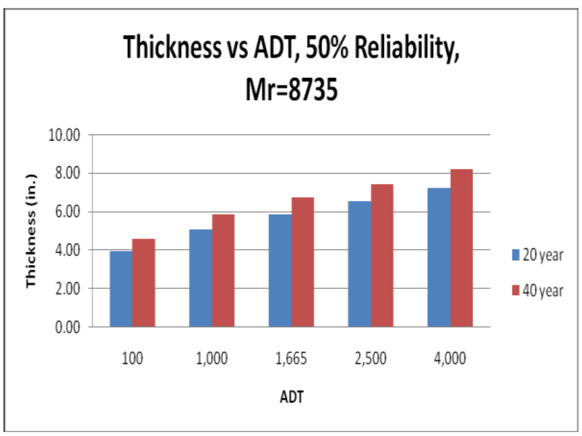
Figure C5. Continued



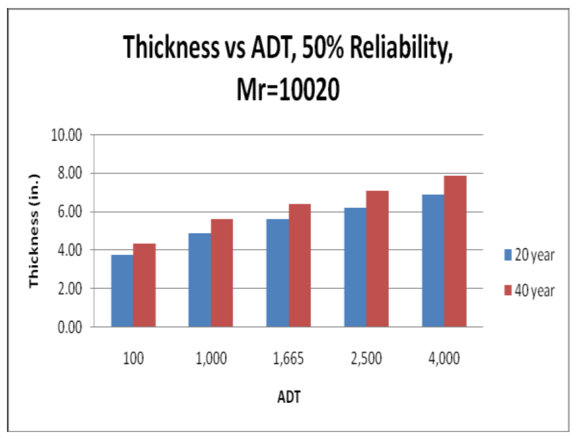
a. Mr=4350, Reliability: 50%



b. Mr=7950, Reliability: 50%

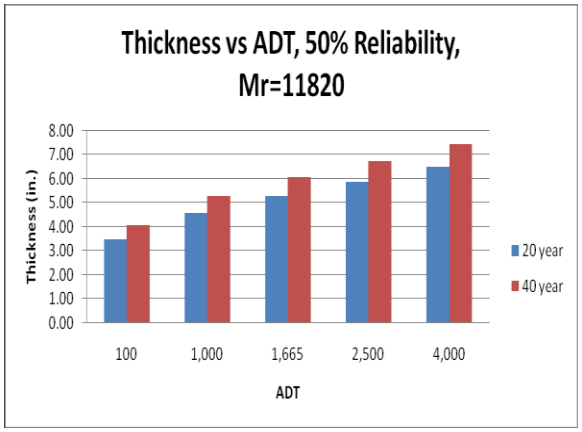


c. Mr=8735, Reliability: 50%

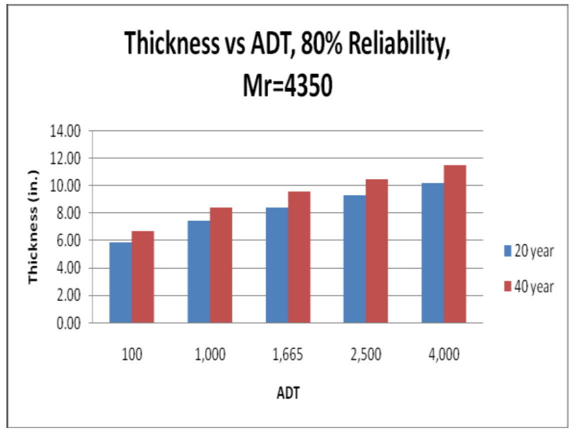


d. Mr=10020, Reliability: 50%

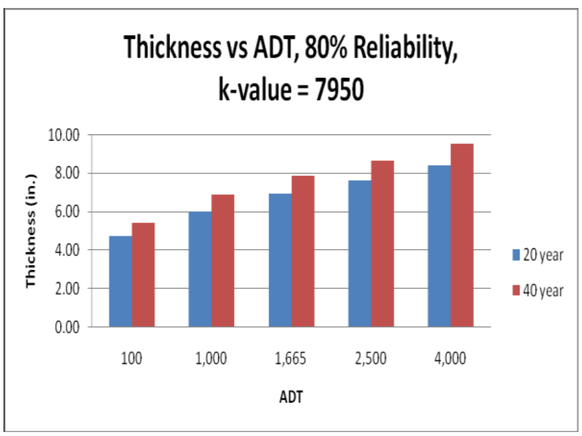
Figure C6. WinPAS Asphalt Pavement, 20 years vs. 40 years



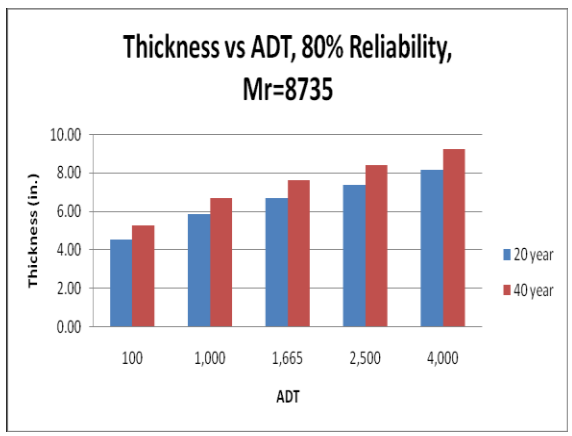
e. Mr=11820, Reliability: 50%



f. Mr=4350, Reliability: 80%

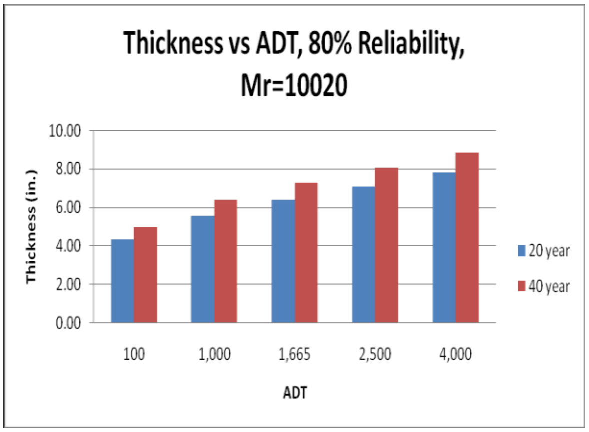


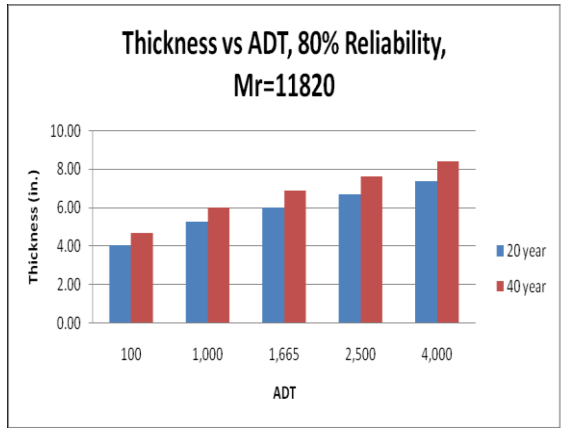
g. Mr=7950, Reliability: 80%



h. Mr=8735, Reliability: 80%

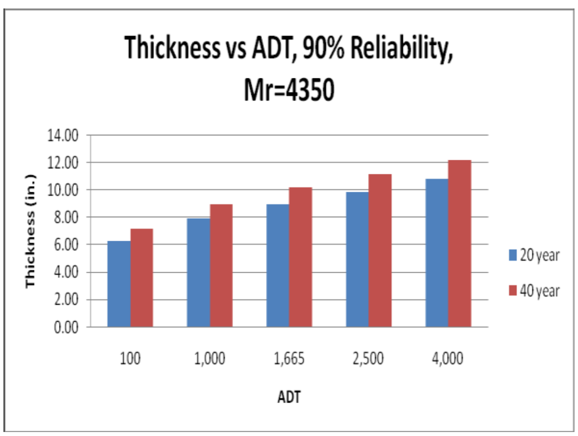
Figure C6. Continued

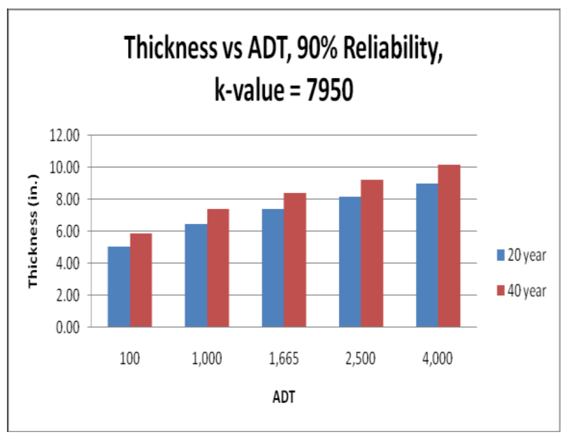




i. Mr=10020, Reliability: 80%

j. Mr=11820, Reliability: 80%

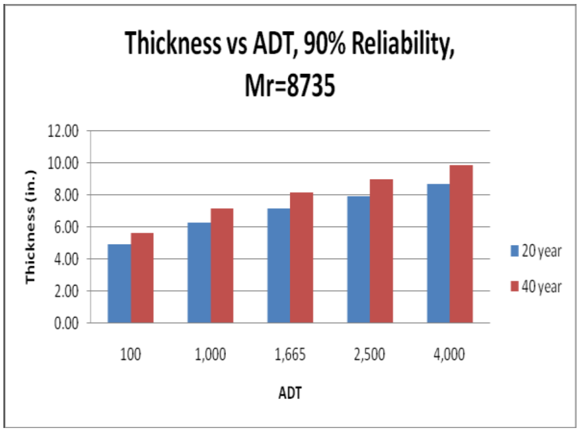


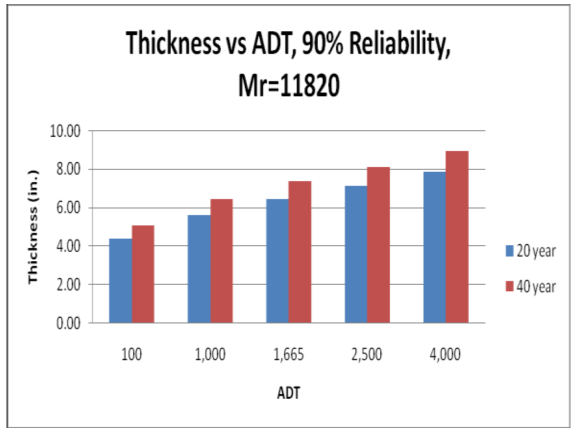


k. Mr=4350, Reliability: 90%

l. Mr=7950, Reliability: 90%

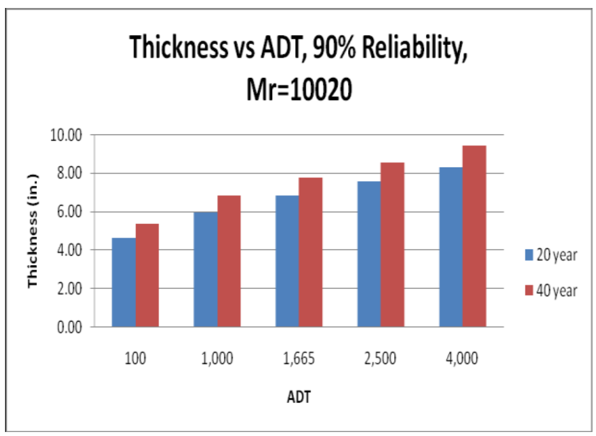
Figure C6. Continued





m. Mr=8735, Reliability: 90%

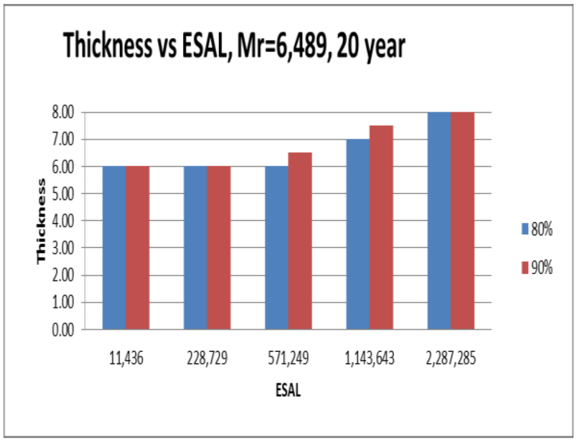
n. Mr=10020, Reliability: 90%



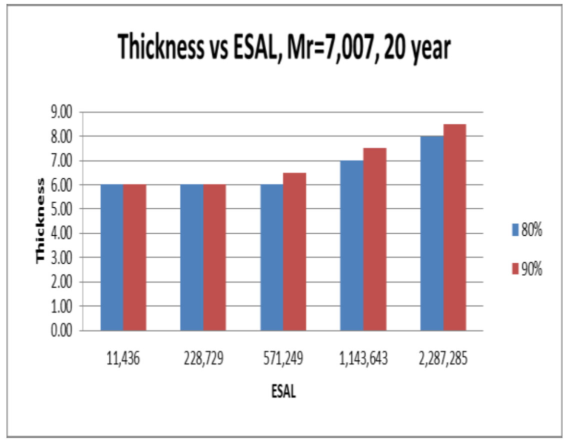
o. Mr=11820, Reliability: 90%

Figure C6. Continued

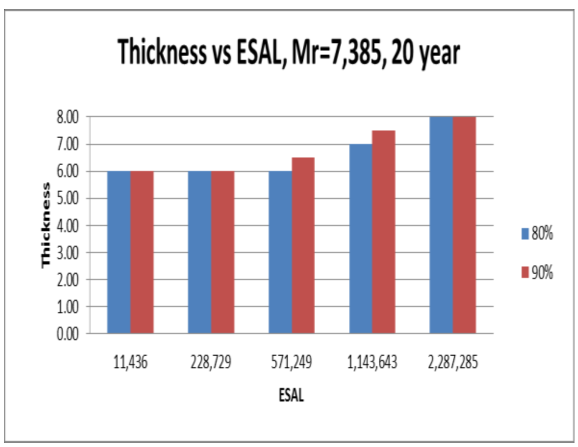
APPENDIX D - I-PAVE SOFTWARE



a. Mr=6,489

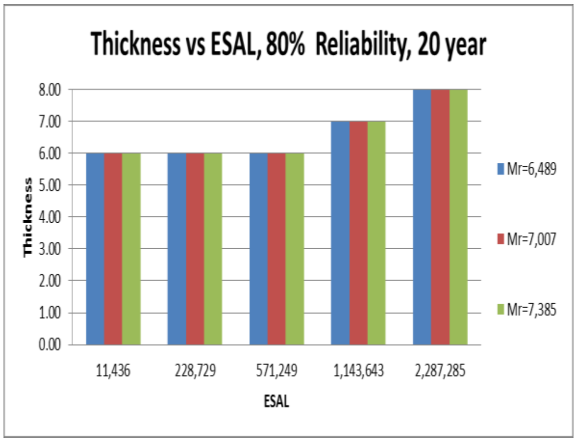


b. Mr=7,007

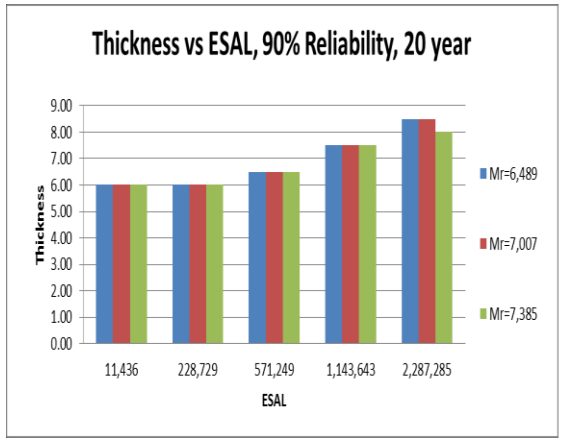


c. Mr=7,385

Figure D1. I-Pave Concrete Pavement, 20 year Design Life

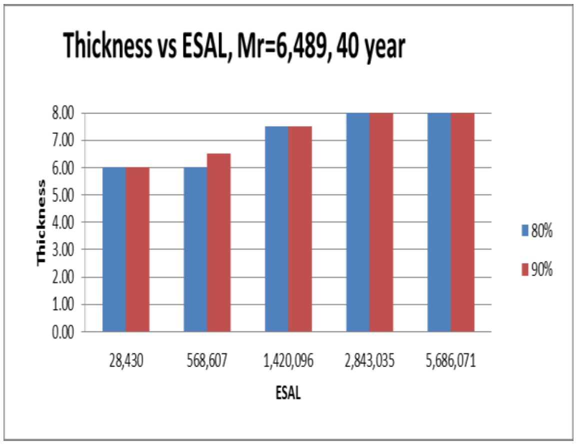


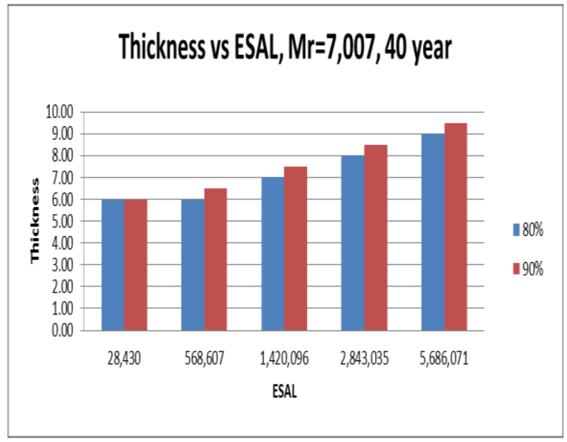
d. 80% Reliability



e. 90% Reliability

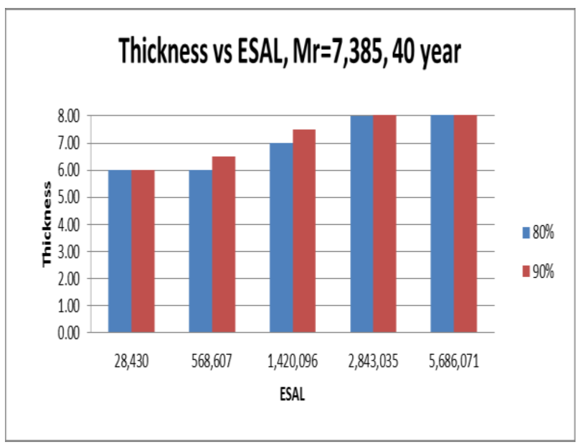
Figure D1. Continued





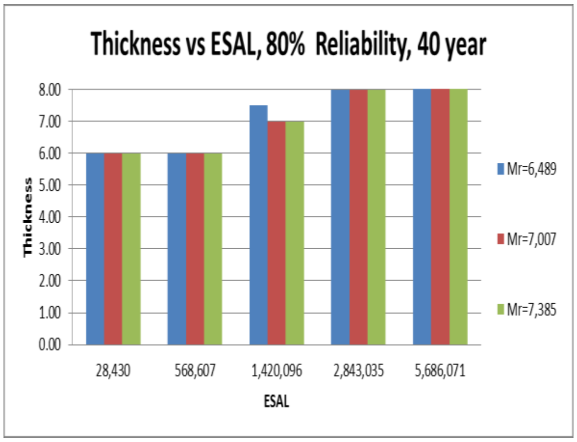
a. Mr=6,489

b. Mr=7,007

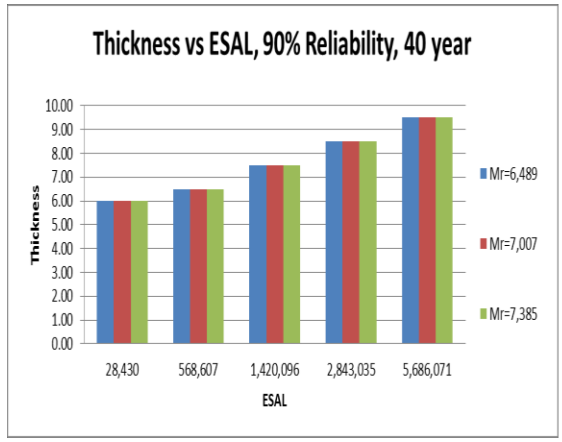


c. Mr=7,385

Figure D2. I-Pave Concrete Pavement, 40 year Design Life

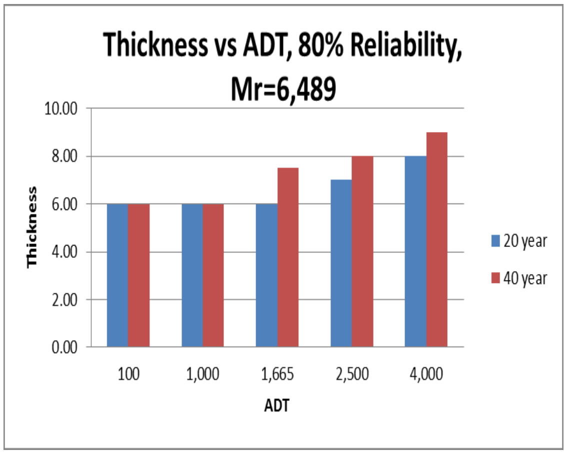


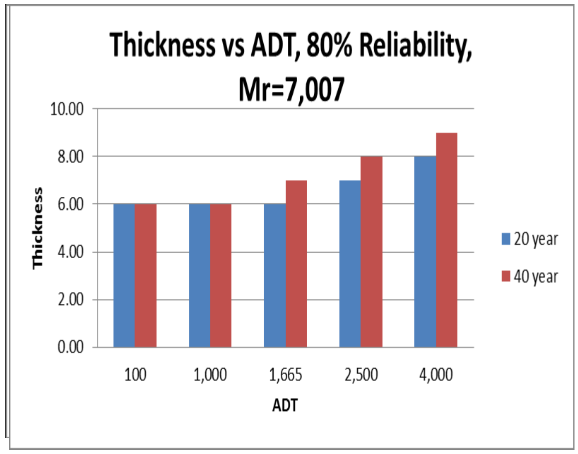
d. 80% Reliability



e. 90% Reliability

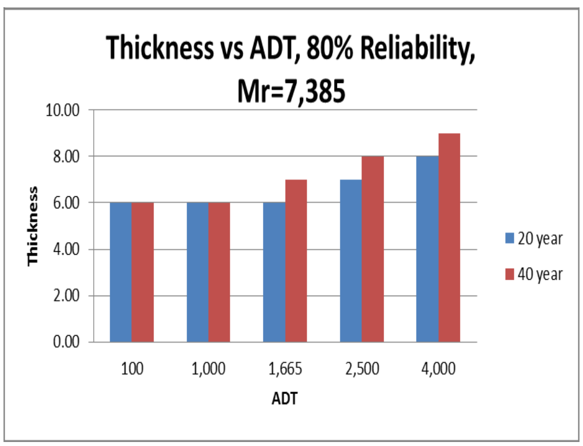
Figure D2. Continued





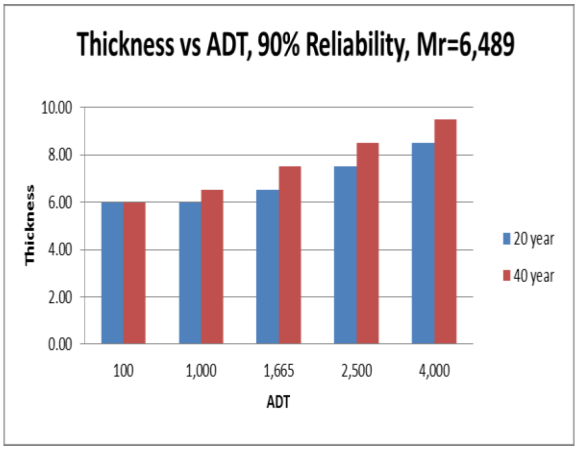
a. Mr=6,489, Reliability: 80%

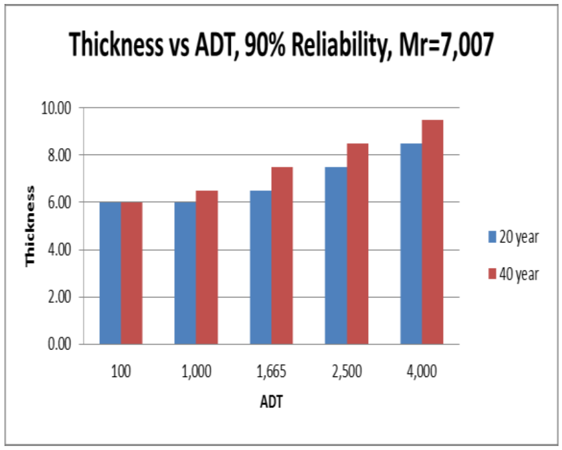
b. Mr=7,007, Reliability: 80%



c. Mr=7,385, Reliability: 80%

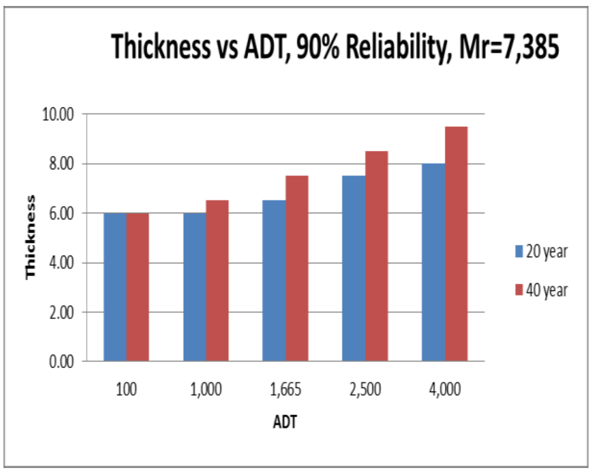
Figure D3. I-Pave Concrete Pavement, 20 years vs. 40 years





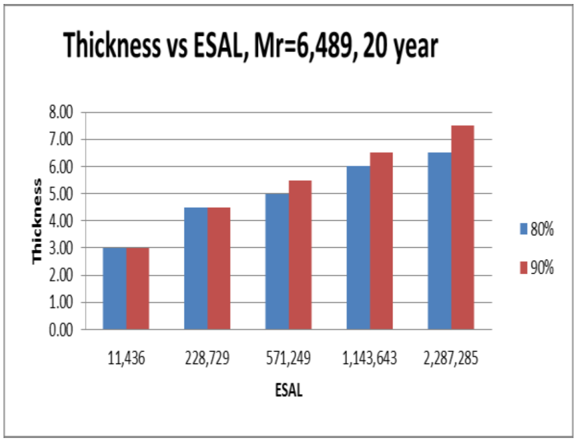
d. Mr=6,489, Reliability: 90%

e. Mr=7,007, Reliability: 90%

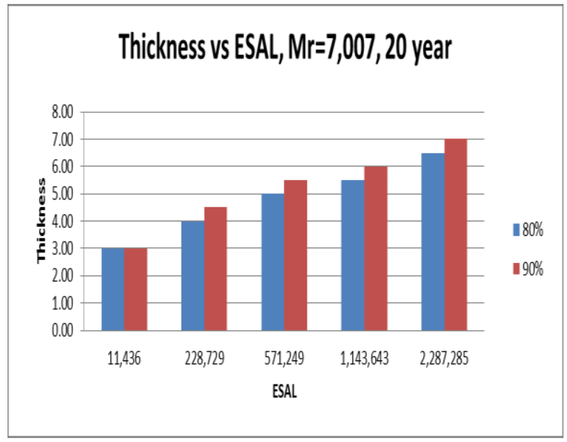


f. Mr=7,385, Reliability: 90%

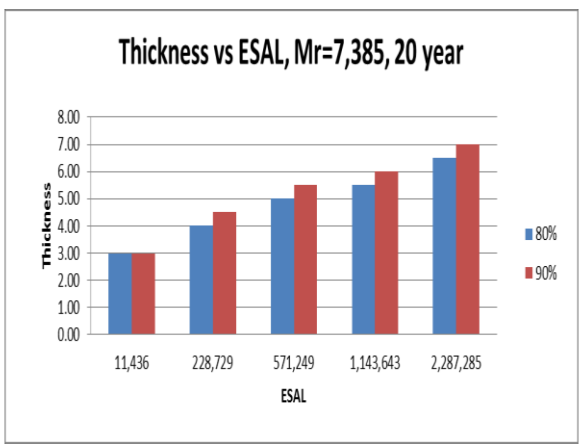
Figure D3. Continued



a. Mr=6,489

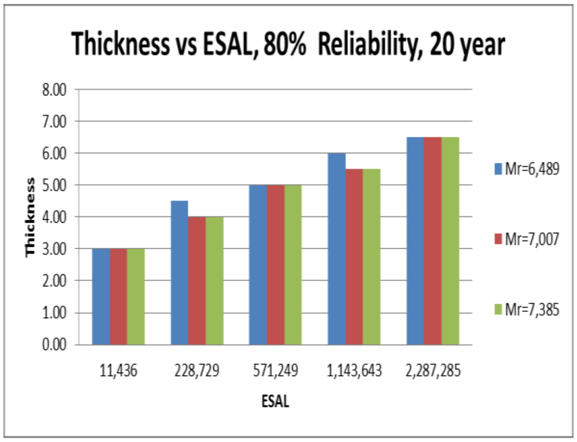


b. Mr=7,007

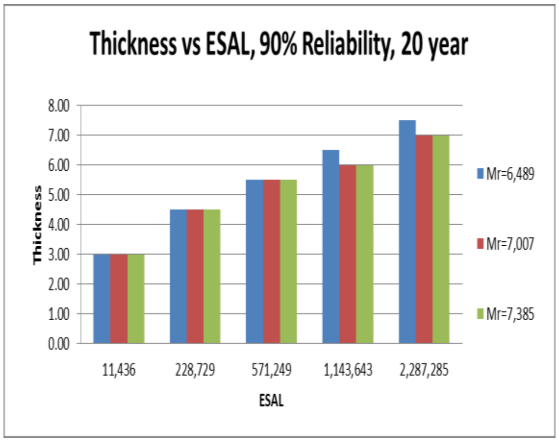


c. Mr=7,385

Figure D4. I-Pave Asphalt Pavement, 20 year Design Life

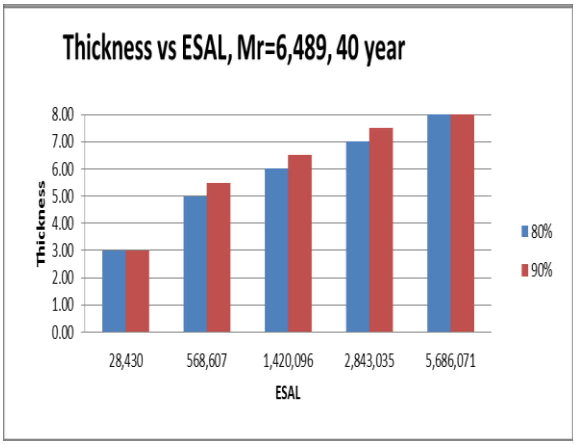


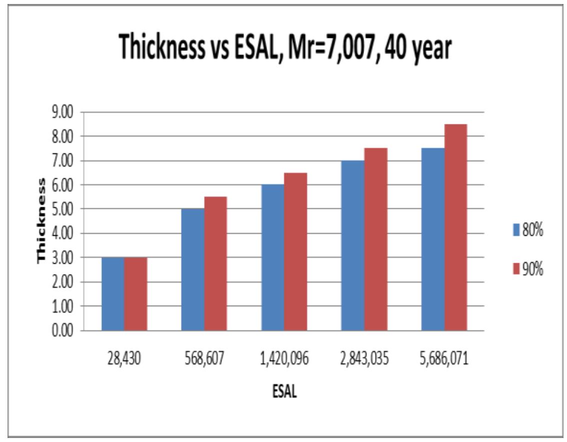
d. 80% Reliability



e. 90% Reliability

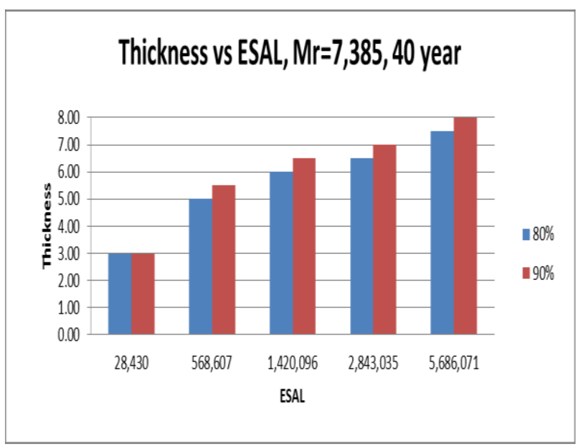
Figure D4. Continued





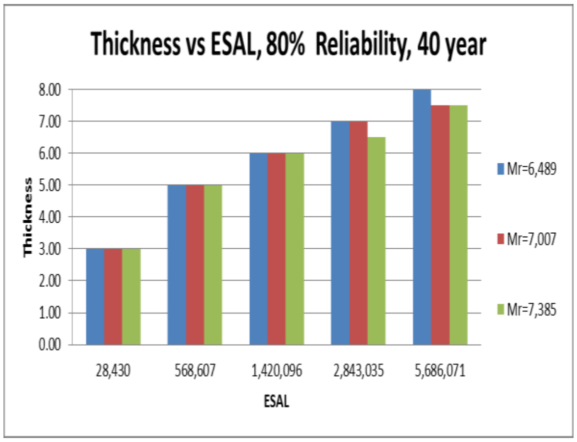
a. Mr=6,489

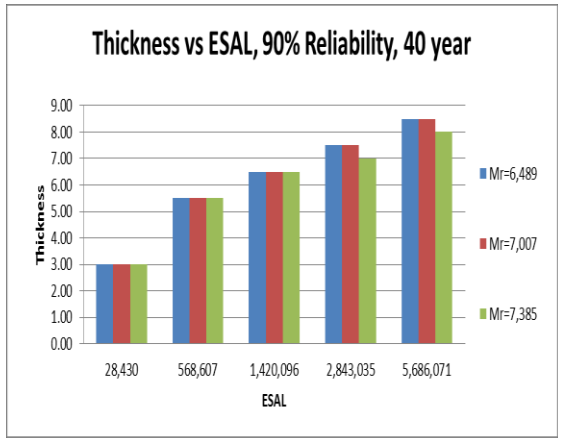
b. Mr=7,007



c. Mr=7,385

Figure D5. I-Pave Asphalt Pavement, 40 year Design Life

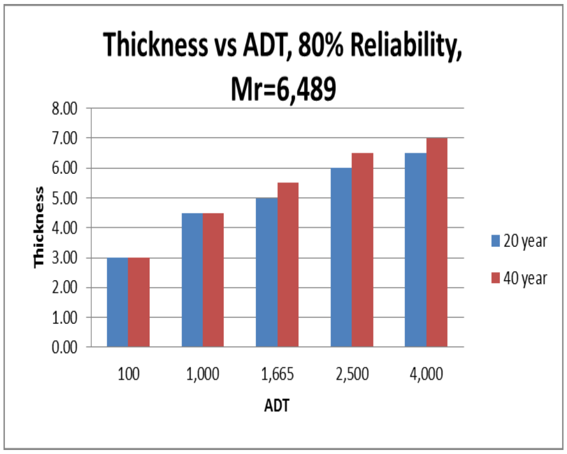




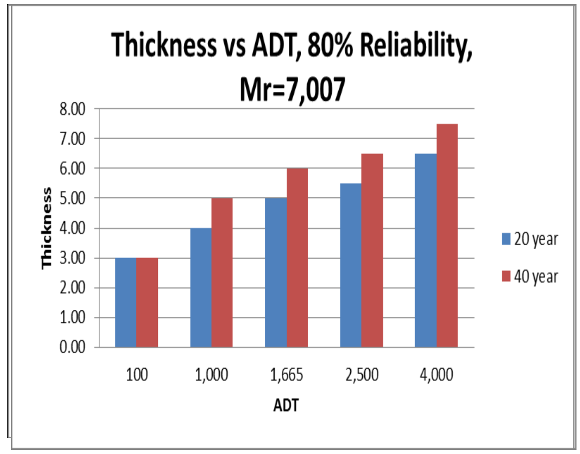
d. 80% Reliability

e. 90% Reliability

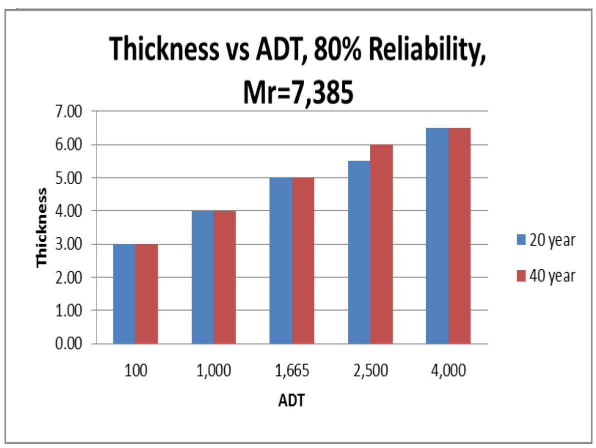
Figure D5. Continued



a. Mr=6,489, Reliability: 80%

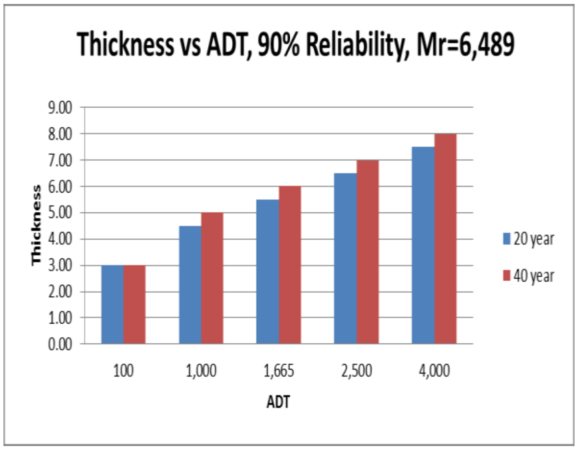


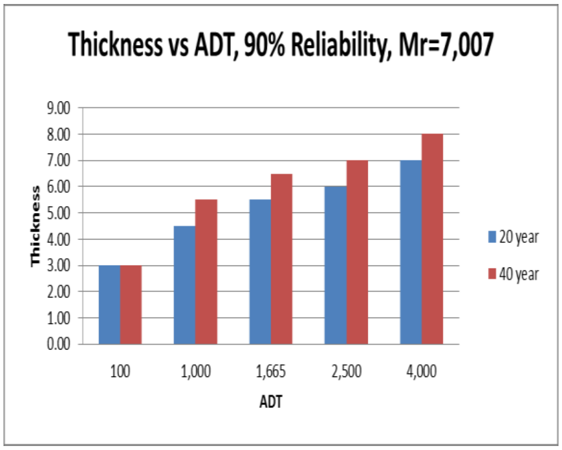
b. Mr=7,007, Reliability: 80%



c. Mr=7,385, Reliability: 80%

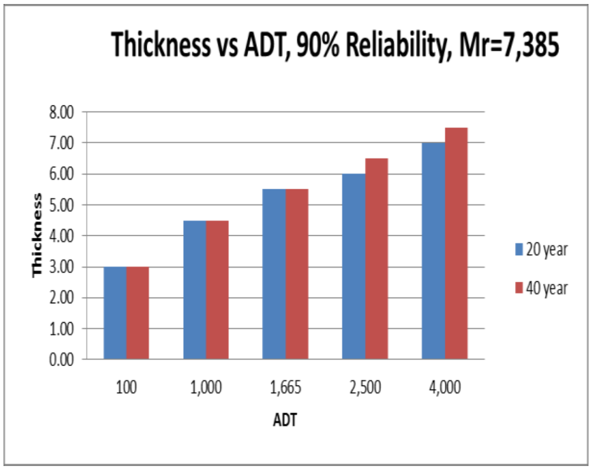
Figure D6. I-Pave Asphalt Pavement, 20 years vs. 40 years





d. Mr=6,489, Reliability: 90%

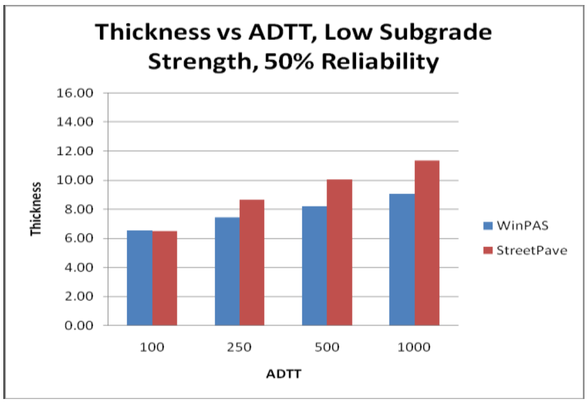
e. Mr=7,007, Reliability: 90%



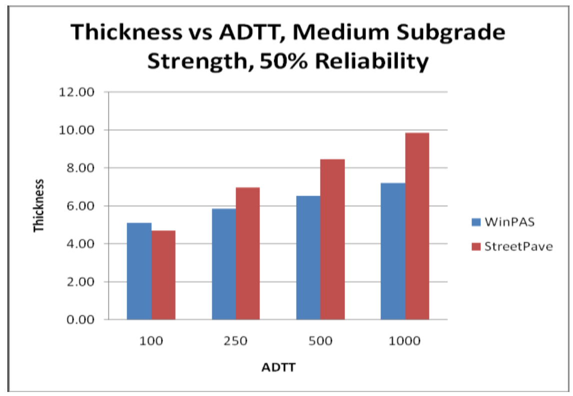
f. Mr=7,385, Reliability: 90%

Figure D7. Continued

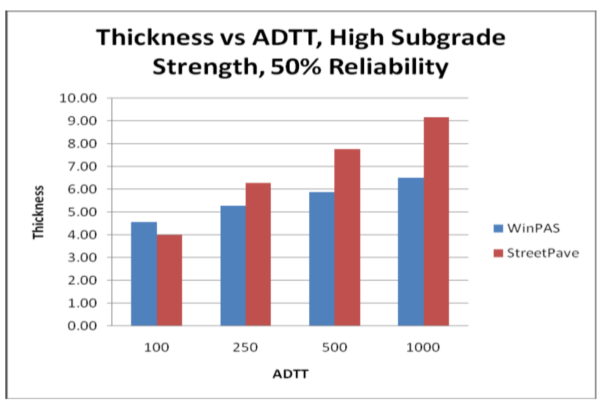
APPENDIX E - COMPARISON OF ASPHALT AND CONCRETE



a. Low subgrade, Reliability=50%

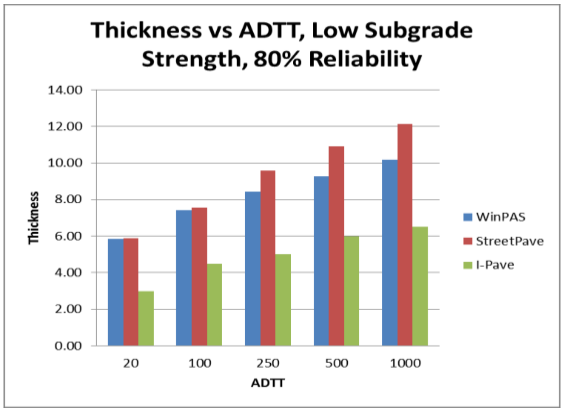


b. Medium subgrade, Reliability=50%

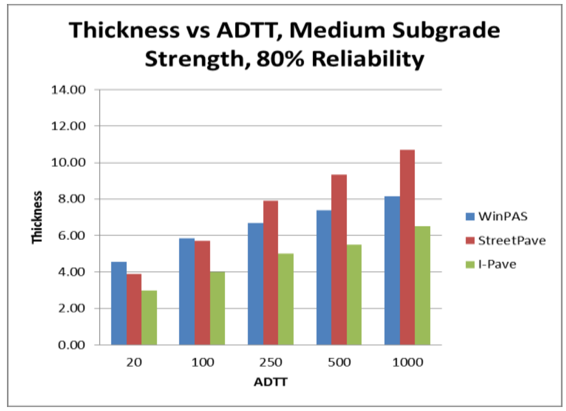


c. High subgrade, Reliability=50%

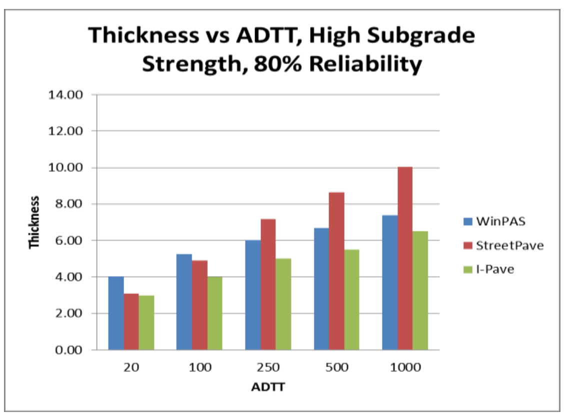
Figure E1. Comparison of Asphalt Pavement, WinPAS vs. StreetPave vs. I-Pave



d. Low subgrade, Reliability=80%

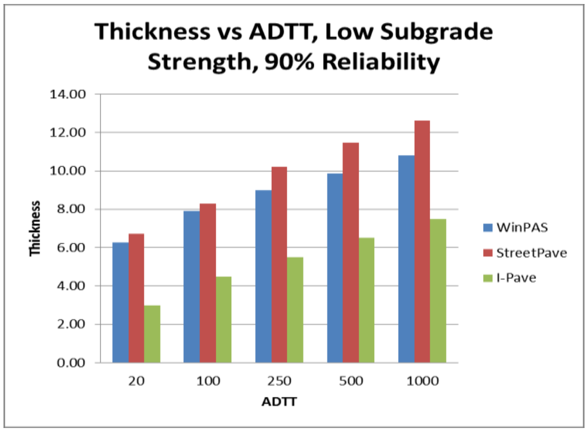


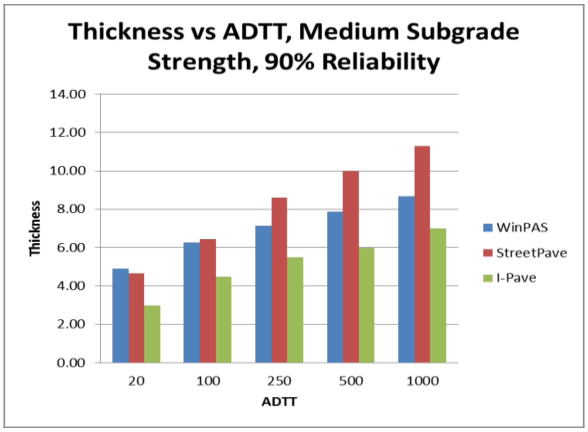
e. Medium subgrade, Reliability=80%



f. High subgrade, Reliability=80%

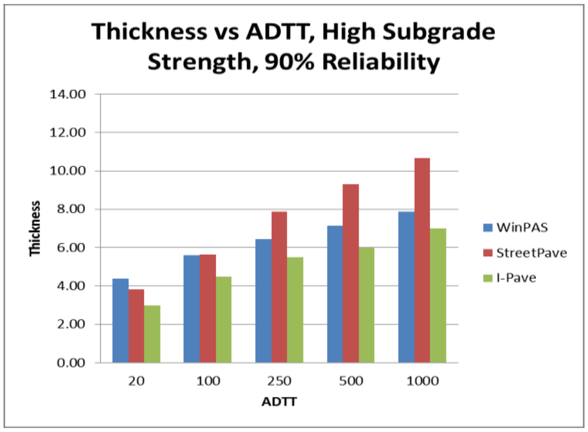
Figure E1. Continued





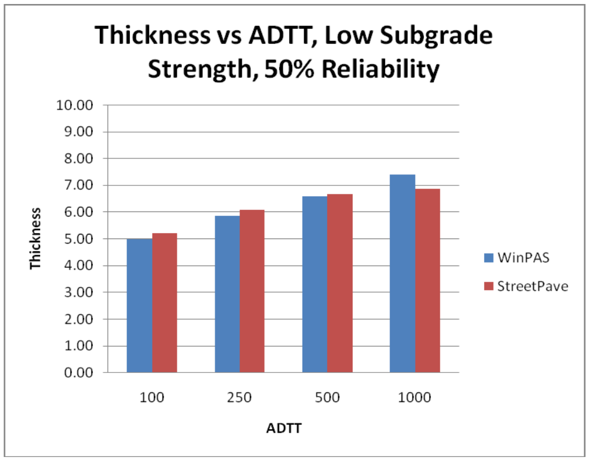
g. Low subgrade, Reliability=90%

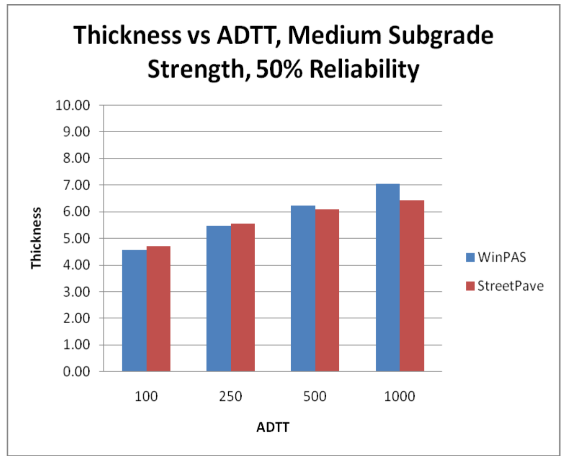
h. Medium subgrade, Reliability=90%



i. High subgrade, Reliability=90%

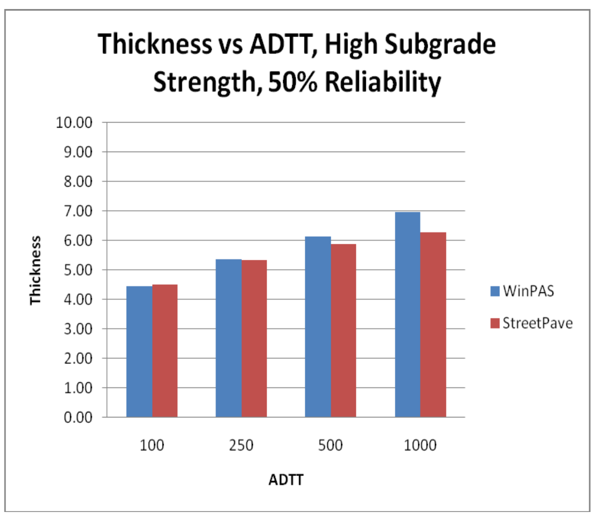
Figure E1. Continued





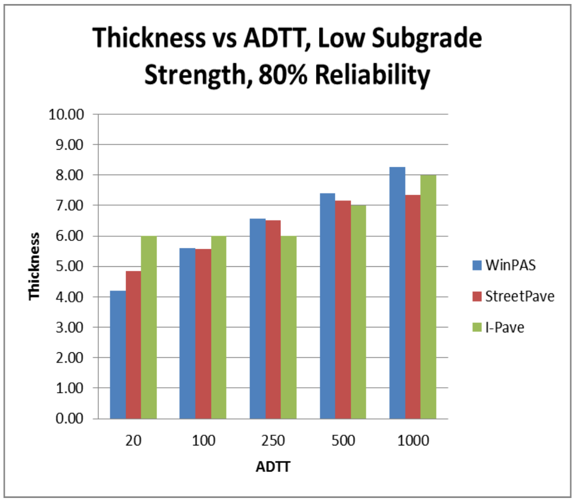
a. Low subgrade, Reliability=50%

b. Medium subgrade, Reliability=50%

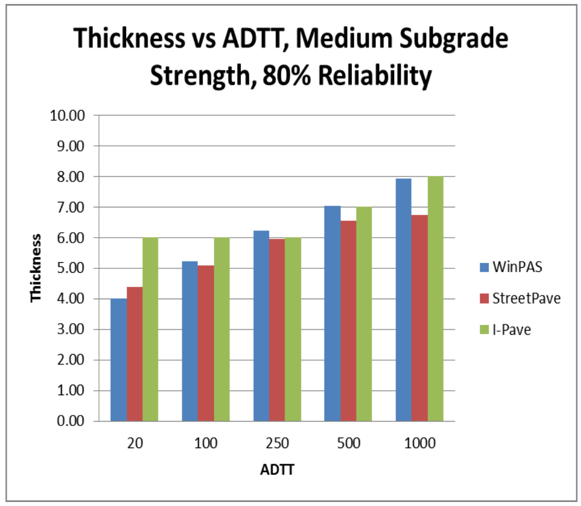


c. High subgrade, Reliability=50%

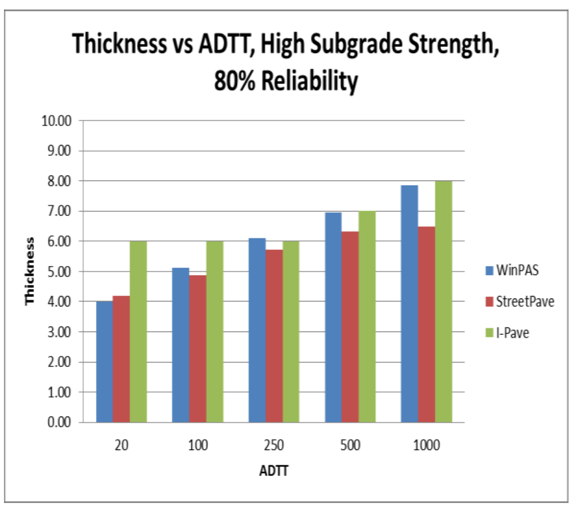
Figure E2. Comparison of Concrete Pavement, WinPAS vs. StreetPave vs. I-Pave



d. Low subgrade, Reliability=80%

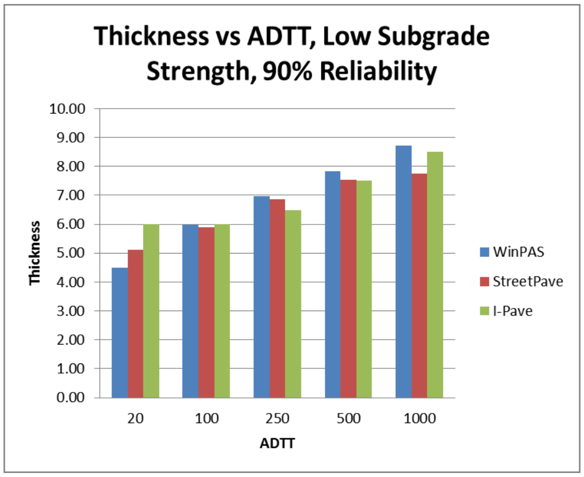


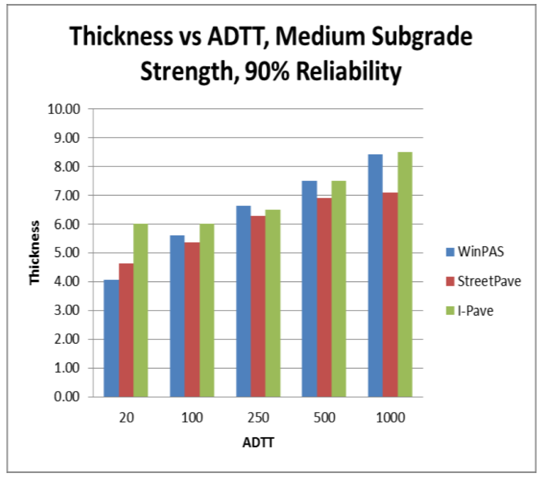
e. Medium subgrade, Reliability=80%



f. High subgrade, Reliability=80%

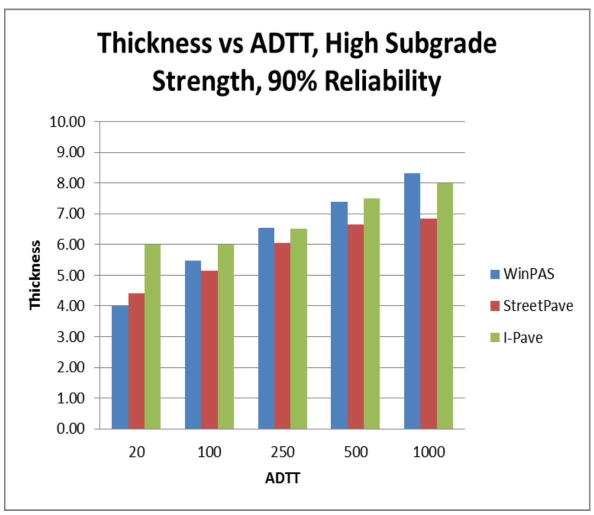
Figure E2. Continued





g. Low subgrade, Reliability=90%

h. Medium subgrade, Reliability=90%



i. High subgrade, Reliability=90%

Figure E2. Continue

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