Data Analysis of Nebraska Pavements Containing RAP

FINAL REPORT

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16. Abstract

Nebraska has used reclaimed asphalt pavement (RAP) materials (in a range of 20-50%) over more than 10 years in pavement construction. Despite the immediate economic and environmental benefits it has been reported that incorporating RAP may reduce pavement durability and crack resistance. This study used NDOT's database to investigate the effect of RAP amount on the overall behavior of pavement performance. Toward that end, we collected data of pavement performance, mixture design, traffic, and environment of a total 254 pavement projects constructed between 2009 and 2012. Using the data, several analyses (such as descriptive, inferential, and life cycle cost) were conducted by interrelating field performance (for the last 10 years) with mixture design where RAP contents vary. Results showed that sections with high RAP content (up to 45%) presented no significant difference regarding IRI and rut depth when they were compared with other RAP sections. However, projects constructed with 45% RAP in northern Nebraska reached the cracking limit (40%) and severity limit (0.4) after around 5-6 years in service. Projects constructed with 25-45% RAP in southern Nebraska showed satisfactory performance in both cracking and severity up to 8 years in service. The LCCA results showed that SPR sections with RAP up to 45 percent could reduce costs by approximately 14% due to the reduced mixture costs compared to SP4/SP5 mixtures with lower RAP content, and it can further reduce costs when it is constructed in southern Nebraska due to lower aggregate costs. Mixtures in northern Nebraska indicated a slightly increased cost compared to mixtures in southern Nebraska. It is to be noted that the collected projects are subjected to traffic levels of ADT less than 1600 and truck traffic less than 200.

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Abstract

Nebraska has used reclaimed asphalt pavement (RAP) materials (in a range of 20-50%) over more than 10 years in pavement construction. Despite the immediate economic and environmental benefits it has been reported that incorporating RAP may reduce pavement durability and crack resistance. This study used NDOT's database to investigate the effect of RAP amount on the overall behavior of pavement performance. Toward that end, we collected data of pavement performance, mixture design, traffic, and environment of a total 254 pavement projects constructed between 2009 and 2012. Using the data, several analyses (such as descriptive, inferential, and life cycle cost) were conducted by interrelating field performance (for the last 10 years) with mixture design where RAP contents vary. Results showed that sections with high RAP content (up to 45%) presented no significant difference regarding IRI and rut depth when they were compared with other RAP sections. However, projects constructed with 45% RAP in northern Nebraska reached the cracking limit (40%) and severity limit (0.4) after around 5-6 years in service. Projects constructed with 25-45% RAP in southern Nebraska showed satisfactory performance in both cracking and severity up to 8 years in service. The LCCA results showed that SPR sections with RAP up to 45 percent could reduce costs by approximately 14% due to the reduced mixture costs compared to SP4/SP5 mixtures with lower RAP content, and it can further reduce costs when it is constructed in southern Nebraska due to lower aggregate costs. Mixtures in northern Nebraska indicated a slightly increased cost compared to mixtures in southern Nebraska. It is to be noted that the collected projects are subjected to traffic levels of ADT less than 1600 and truck traffic less than 200.

Chapter 1: Introduction

Background

For the last about 10 years, Nebraska has used reclaimed asphalt pavement (RAP) materials in mixes at approximately 20-40% to produce asphalt concrete (AC) mixtures for flexible pavements. The expanded use of RAP materials in the production of AC mixtures brought significant economic benefits and environmental advantages through the reduction of material costs and environmental impacts associated with production, transportation, and processing of the conventional asphalt materials. It has been reported that about $30-50 million were saved annually due to the use of RAP materials. This infers that more use of RAP materials in the mixes is favorable to reducing costs and environmental impacts.

Despite the immediate cost saving and environmental benefits attributed to the use of RAP, it has also been reported that using a higher percentage of RAP may reduce the resistance of asphalt mixtures to cracking and durability. This in turn, can result in reduced pavement lifespan and/or earlier needs of maintenance (or rehabilitation). As a result, to avoid misleading practices in the use of RAP, a more rational approach that can evaluate the true economic benefits of using RAP materials in pavements should be pursued, and the approach needs to take into account not only the initial costs associated with materials and production, but also later-stage costs related to in-service performance of pavements.

Problem Statements

The idea of recycling materials and use them to reduce costs and environmental impacts has been introduced for several decades. The implementation of recycling concept in roadway materials and pavement construction has been started at the end of the 20th century. However, many questions have been raised on the effect of incorporating RAP into pavement mixtures on the performance of pavement structures and economic benefits for the entire life of pavements. Nebraska Department of Transportation (NDOT) has constructed asphalt pavements with RAP in a range from 0% to 50% between the years 2009-2010. Using RAP can certainly provide more cost-effective AC production due to lower material costs compared to conventional AC mixes; however, AC mixtures with RAP may diminish the resistance to cracking and durability (aging, moisture damage, etc.), which can increase the ultimate costs due to the shorter life and a need of more frequent maintenances. Despite the immediate cost savings gained by using more RAP, it is not certain if ultimate costs associated with in-service performance reduce the total economic benefits.

Objectives and Tasks

This project aims to conduct a comprehensive data analysis of Nebraska pavements containing RAP materials. Toward that end, the research team and NDOT engineers worked together to select pavement sections in service for the last about 10 years. A complete set of data were collected and used to perform data analyses. The data analysis included typical statistical evaluation as well as the life cycle cost analysis, so that the practices for the last 10 years with RAP can be examined and improved for future projects. The objectives of this report were achieved through the following three major tasks:

Task 1: Literature Review

The focus of this task was to thoroughly review the published relevant studies. Literature review included regional (e.g., State Departments of Transportation (DOTs) research reports) and national studies related to the use of and cost-benefit analysis of RAP in pavements. Literature review on different methods of LCC analysis was also conducted in this task. This task was conducted in the early stage of this project to more optimally plan the later tasks: Tasks 2 and 3.

Task 2: Selection and Data Collection of In Service Pavement Sections

From the TAC meetings to discuss the work scope, a total of 254 pavement projects constructed between 2009 and 2012 were selected as the target in-service pavement sections. The selection of pavement sections covered different types of AC mixtures that include different amounts/sources of RAP. All the necessary data including: mixture type, mixture design, component materials, the amount of RAP in the mixture, RAP source, pavement design, pavement performance period and history, traffic, and climate were collected for comprehensive statistical-cost analyses. The selection of target sections in this task was optimized by discussions with the TAC members so that the resulting dataset can be used to best review the state's RAP practices for the last 10 years and develop any better plans for future pavement projects incorporated with RAP.

Task 3: Analysis of Collected Data (i.e., Statistical, LCC)

The data gathered in the previous task were analyzed in this task. The first part of Task 3 was dedicated to statistical analyses of collected data. This further helps to objectively identify the factors and parameters that significantly contribute to the difference in pavement performance when RAP is related. The LCC analysis was also performed using the data to obtain cost comparisons among several alternatives that differ RAP practices. To conduct the LCCA, we used the PAVEXpress, which is a user-friendly web-based software to design pavements using the AASHTO 93/98 method with cost modules.

Organization of This Report

This report is organized into five chapters. Following this Chapter 1 (introduction), Chapter 2 presents the literature review on RAP, design of RAP mixtures, characterization and performance of RAP mixtures, and a summary of LCCA studies that evaluated the economic and environmental impacts using RAP in pavement mixtures. Chapter 3 presents the methodology to carry out the statistical analyses and LCCA for the data collected in this study. Chapter 4 presents the results of data analyses and LCCA. Chapter 5 presents a summary of main findings from this study.

Chapter 2: Literature Review

Design of RAP Mixture

Due to the fact that RAP incorporation was not considered in the original mix design of the Strategic Highway Research Program (SHRP) program in 1993, the state Departments of Transportation (DOTs) avoided using RAP (Hansen & Newcomb, 2011). Later McDaniel, Soleymani, Anderson, Turner, and Peterson (2000) conducted a National Cooperative Highway Research Program (NCHRP project D9-12) project and developed a procedure to incorporate RAP into the asphalt concrete mix design. The following guideline was presented in the NCHRP study. The guideline is subjected to each DOT's local conditions.

- No change in binder grade is needed if RAP content is less than 15%.
- One grade softer binder should be selected if RAP content is between 15% to 25%.
- Blending charts should be used if RAP content is more than 25%.

The blending chart presented in the appendix of AASHTO M 323 states that virgin binder grade should be determined at every temperature using Eq. 2.1 if the desired final binder grade, RAP percentage, and recovered RAP binder properties are known.

$$T_{virign} = \frac{T_{blend} - \%RAP * T_{RAP}}{1 - \%RAP} \quad \text{Eq. 2.1}$$

where:

T_{virgin} = Critical temperature of virgin asphalt binder.

T_{blend} = Critical temperature of blended asphalt binder.

T_{RAP} = Critical temperature of recovered RAP binder.

The above equation can be rewritten in terms of RAP percentages, as seen in Eq. 2.2, because, in most cases, it is the required parameter to be calculated, and the percentage of RAP that satisfies the requirements at all temperatures (high, intermediate, and low) should be selected.

$$\%RAP = \frac{T_{blend} - T_{virgin}}{T_{RAP} - T_{virgin}} \quad \text{Eq. 2.2}$$

Because RAP binder has aged and stiffened, it is more susceptible to cracking. On the other hand, the rut resistance of the mixture is enhanced (Zhou et al., 2006); further, the excessive amount of asphalt binder will increase susceptibility to rutting. Thus, a balanced design should be approached to provide the percentage of asphalt content at which both rutting and crack resistance are satisfied, as shown in Figure 2.1. The procedure for a balanced mixture design is described elsewhere (Zhou et al., 2006).

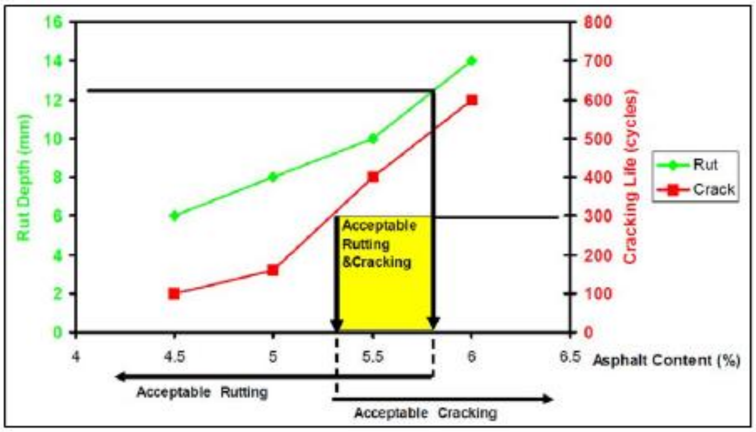


Figure 2.1 - Balanced Mixture Design Concept (Zhou et al., 2006).

RAP Characterization

RAP mixtures have high stiffness due to usage of an aged binder and reduced workability, which can lead to failure due to lack of proper compaction (Mogawer et al., 2012; Al-Qadi, Aurangzeb, Carpenter, Pine, and Trepanier, 2012). RAP can also increase susceptibility to fatigue and thermal cracking (Khosla, Nair, Visintine, and Malpass, 2012; Daniel, Pochily, and Boisvert, 2010). X. Li, Clyne, and Marasteanu (2005) conducted a study in Minnesota on asphalt mixtures and concluded that the dynamic modulus increases when percentage of RAP increases. Al-Qadi et al. (2009) conducted a study in Illinois and reported that no significant changes in dynamic modulus were observed with mixtures up to 20% RAP. However, the dynamic modulus increases significantly with higher RAP contents. A similar finding was observed by Boriack, Katicha, Flintsch, & Tomlinson (2014). Stimilli, Canestrari, Teymourpour, and Bahia (2015) reported that crack resistance can be improved at low temperature with proper selection of RAP material and the type and quality of virgin binder. As for rutting resistance, many studies concluded that more RAP in mixtures increases rutting resistance (Zhou, Hu, Das, and Scullion, 2011; McDaniel et al., 2000; Al-Qadi et al., 2012; and Randy West et al., 2012).

Several strategies can be attempted to increase crack resistance for RAP mixtures, e.g., optimizing RAP content, using soft virgin binder, decreasing design mixture air voids, using RAP in warm mix asphalt (WMA), and rejuvenating RAP binder (Zhou, Estakhri, & Scullion, 2014). Rejuvenating agents act as softening agents and reduce aged binder viscosity and improve mechanical properties of RAP mixture. Uzarowsk, Prilesky, Berube, Henderson, and Rizvi (2010) observed significant decrease in rutting resistance, despite cracking resistance improvement. On the other hand, Im and Zhou (2014) reported that both cracking and rutting resistance improve when rejuvenators are added to the mixture. Several types of rejuvenators are summarized in Table 2.1.

Table 2.1 - Types of Rejuvenators (NCAT, 2014)

Category	Examples	Description
Paraffinic Oils	Waste Engine Oil (WEO) Waste Engine Oil Bottoms (WEOB) Valero VP 165 Storbit	Refined used lubricating oils
Aromatic Extracts	Hydrolene Reclamite Cyclogen L ValAro 130A	Refined crude oil products with polar aromatic oil components
Naphthenic Oils	SonneWarmix RJ™ Ergon HyPrene	Engineered hydrocarbons for asphalt modification
Triglycerides & Fatty Acids	Waste Vegetable Oil Waste Vegetable Grease Brown Grease	Derived from vegetable oils; has other key chemical elements in addition to triglycerides and fatty acids
Tall Oils	Sylvaroad™ RP1000 Hydrogreen	Paper industry byproducts; same chemical family as liquid antistrip agents and emulsifiers

As for combining RAP with WMA, this technology is used to reduce asphalt viscosity, thus lowering compaction temperature (more information about WMA can be obtained elsewhere: Prowell, Hurley, & Frank, 2011). Due to binder viscosity reduction, more RAP content can be added to the mixture (Zaumanis and Smirnovs, 2011). Furthermore, Mogawer, Booshehrian, Vahidi, and Austerman (2013) found that incorporating high percentages of RAP (e.g., 40%) with WMA reduces crack resistance without affecting moisture susceptibility and rutting. Research by Penn State showed that combining RAP with WMA increases tensile strength ratio (TSR) compared with hot mix asphalt (HMA) (Solaimanian, Milander, Boz, & Stoffels, 2011).

Al-Qadi et al. (2012) and Mogawer et al. (2012) reported that moisture resistance of a RAP mixture can be improved by increasing the RAP percentage. Ghabchi, Singh, and Zaman (2014) reported that the increase in moisture susceptibility is a function of both coating binder quality and RAP percentage. Several studies are summarized in Table 2.2 in terms of resistance to moisture damage.

Table 2.2 - Effect of RAP on Mixture Resistance to Moisture Damage (Bonaquist, 2013)

Study	Mixture Type	% RAP	Test Method	
			Tensile Strength Ratio	Hamburg
Gardiner and Wanger (1999)	Lab HMA	0, 15-40	Improves	
West et al. (2013)	Lab HMA	0, 25, 40, 55	Mixture dependent	
Mogawer et al. (2012)	Plant HMA	0-40		No difference
Zhao et al. (2012)	Plant HMA	0, 30, 40, 50	Improves	Improves
	Plant HMA	0, 30	Improves	Improves
Hajj et al. (2011)	Plant and Lab HMA	0, 15, 30	No difference	

Kandhal and Foo (1997) investigated the effect of RAP on performance grading of binder using dynamic shear rheometer (DSR), suggesting that the asphalt grade does not change when up to 15% RAP is used. On the other hand, McDaniel and Anderson (2001) showed that, if more than 25% is used, the physical properties of the asphalt binder are significantly affected.

Shu, Huang, and Vukosavljevic (2008) carried out a laboratory evaluation to investigate the fatigue characteristics of RAP mixtures. Samples with RAP percentages from 0% to 30% were prepared and tested using indirect tensile strength (ITS), toughness index (TI), resilience modulus, failure strain, and other methods and concluded that RAP mixtures have higher tensile strength. However, the dissipated creep strain energy decreased, resulting in decrease in fatigue life. Xiao, Putman, and Amirkhanian (2015) conducted a laboratory investigation on the effect of RAP percentages up to 50% using two different sources (HMA and WMA) on rutting and fatigue resistance, viscosity, and failure temperature. Results showed that, with increase in RAP content, the rutting resistance increases while the fatigue resistance decreases. However, using the WMA can offset the characteristics. Despite the fact that numerous studies investigated the effect of RAP in asphalt mixture, few have verified these findings through field observations.

Field Performance of RAP Mixtures

Use of the RAP mixture started in the 1970s by FHWA in New Jersey as shoulder mixtures with high percentages of RAP (up to 50%). Because it was reported to have good performance, further investigation on recycled materials was encouraged (Hellriegel, 1980). Several studies have been conducted since then to evaluate the performance for RAP mixtures— not just for shoulder mixes but also in main traffic lanes and to optimize the dosage of RAP at which these mixes perform well similar to virgin mixes (0% RAP).

Kandahl, Rao, Watson, and Young (1995) compared five test sections in the state of Georgia with varying percentages of RAP content ranging from 10% to 25% and virgin mixes. Results showed that no significant fatigue cracking, rutting, and raveling were observed after two and a half years in service. However, the observed time-span is relatively short, and further investigation is required for long-term performance of RAP mixtures. West (2009) conducted a study on 18 projects across the United States to compare virgin and mixtures with 30% RAP in terms of fatigue, longitudinal, transverse, block cracking, rutting, and raveling over six to 17 years in performance, showing that RAP mixes performed similarly to virgin mixes.

Musselman (2009) investigated pavement sections constructed between 1991 and 1999 in Florida with RAP percentages between 30% and 50% and revealed no significant difference in performance between virgin and 30% RAP mixtures. However, performance decreases for mixes with higher percentages of RAP. Another study by West, Michael, Turochy, and Maghsoodloo (2011) reported the same conclusion. On the other hand, Hong, Chen, and Mikhail (2010) studied the performance of 16-year old pavement sections with 35% RAP in Texas and concluded that the sections with high percentage of RAP had higher cracking amounts and less rutting. However, the overall performance of the sections was satisfactory compared with that of virgin mixes.

Chen and Daleiden (2005) investigated two RAP overlay rehabilitation projects in Dallas with one mixture containing 75% RAP and the other containing 30% RAP; both were compared with virgin mixes. Table 2.3 shows that reflective cracks were observed after two weeks of opening to traffic for overlay with 75% RAP. On the other hand, no significant cracks were observed for an overly with 30% RAP and virgin mixes for 10 years of service.

Zhou et al. (2011) compared two sets of field test sections with different RAP contents, traffic levels, and environmental zone. The first set, which consisted of four sections constructed on IH 40 in Amarillo, Texas in 2009, was subjected to heavy traffic and cold weather that is further subjected to several freeze-thaw cycles and blizzards during the winter season. The second set consisted of three RAP sections on FM1017 in the south of Texas, which had been subjected to light traffic and hot weather. The first overlays were constructed over an 8-in. thick HMA, which were milled and filled for 4 inches using a dense-graded type C mixes and RAP content of 0%, 20%, 20%, and 35% for designed sections. The first two were designed by a contractor following a Tex-204-F mix design procedure; the others were designed by the Texas A&M Transportation Institute (TTI) following the proposed mix design method, as shown in Figure 2.2 (Zhou et al., 2011). Field observations for three years showed no rutting. However, reflective cracking was observed on the third year of inspection. Table 2.4 details the field observation results, wherein the numbers indicate the ratio of reflective cracks to the original number of cracks prior to the 4-in. overlay. It can be noticed that the higher the overlay tester (OT) cycles, the lower the reflective cracking. On the other hand, the second set constructed on FM1017 was newly constructed with 1.5-in. thick asphalt surface using dense-graded type D mixes. Both rutting and cracking had not occurred even after two years in service in contrast with what had been observed in IH40. As the observed performance period is short, further inspection is required including the impact of climate effects on pavement performance from RAP mixtures.

Table 2.3 – Comparison of Various RAP Performance (Chen & Daleiden, 2005)

Section	SPS-5	Remixer	Remixer
Mix	Plant	HIP	HIP
Highway	US-175	US-175, US-84	US-281
Year constructed	1991	1999	1996
RAP contents	30%	75%	75%
Performance	Excellent	Poor (reflected cracking)	Good
Condition before overlay	Longitudinal and transverse crack	US-175: Extensive Longitudinal Crack. US-84: transverse crack	Few transverse thermal crack
Penetration No.	30-45	20-21	20-21
Overlay tester	300 repetition to failure	Two repetitions to failure	NA
Virgin asphalt	AC-5	PG 64-22 + 0.5% polymer-modifier	NA

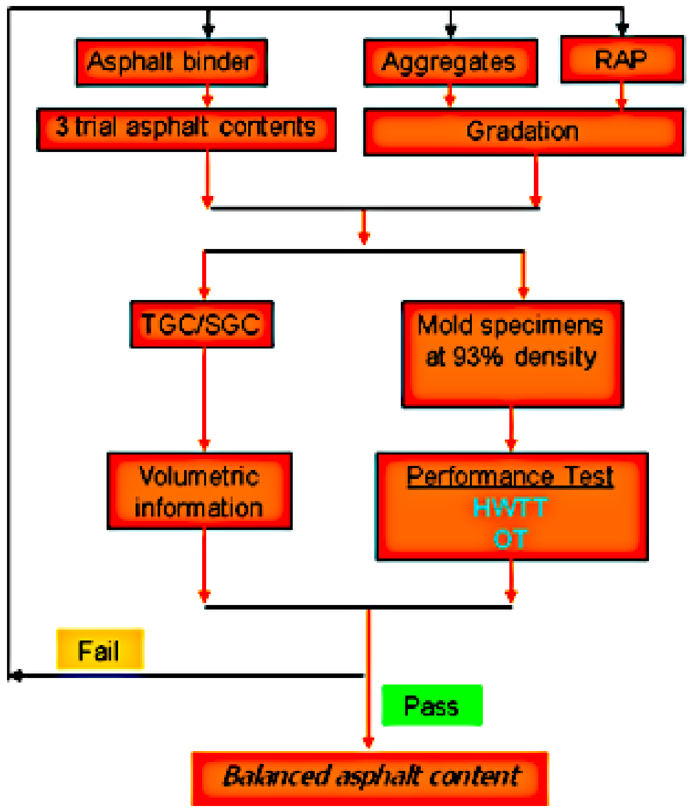


Figure 2.2 – Balanced RAP Mix Design Flow Chart (Zhou et al., 2011).

Table 2.4 – Field Performance Survey: Reflective Cracking Rate (%) (Zhou et al., 2011)

Sections	8/11/2009	4/22/2010	9/8/2010	4/5/2011	OT Cycles
20% RAP- Contractor	0	0	34	87	10
0% RAP-Contractor	0	0	18	55	50
35% RAP-TTI	0	0	0	27	200
20% RAP-TTI	0	0	4	54	125

Saeedzadeh, Romanoschi, Akbariyeh, Khajeh-Hosseini, and Abdullah (2018) assessed the sustainability of three different RAP mixtures and compared them with virgin mixes. Twelve pavement sections were constructed and evaluated in terms of rutting, fatigue cracking, and reflective cracking using an accelerated pavement testing (APT) facility located near SH-820 on the east side of Fort Worth, Texas. Sections tested for similar performance consisted of the same structural design, as shown in Figure 2.3 and detailed in Table 2.5.

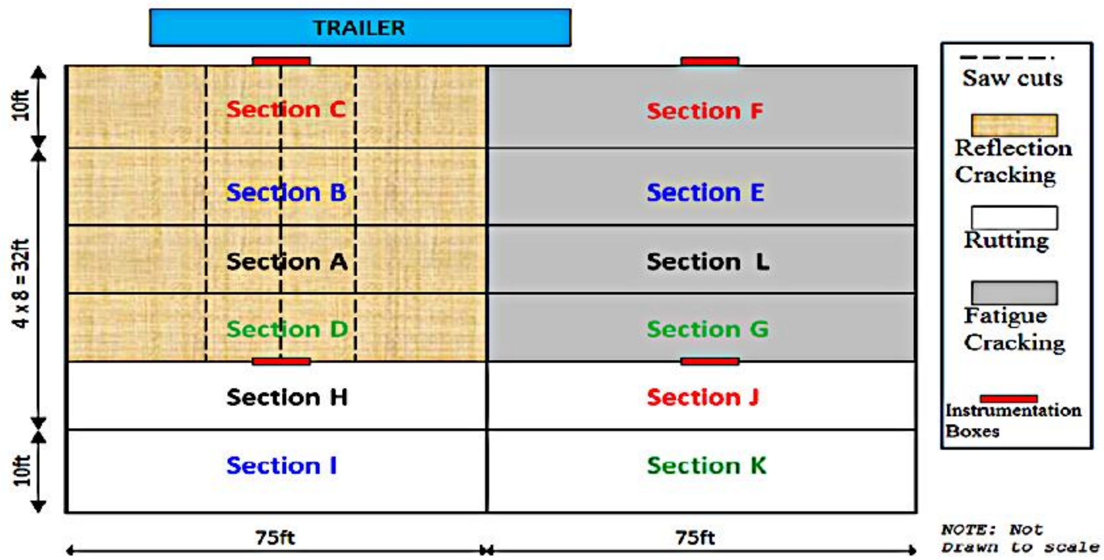


Figure 2.3 – Test Sections Built at the APT Facility (Saeedzadeh et al., 2018).

Table 2.5 - Details of Mixtures at APT Facility (Saeedzadeh et al., 2018)

Reflection Cracking Experiment			
Test Section	Surface 2 in	Intermediate 2 in	Base 8 in
A	Type D	Type C	Cement (3.5%) Treated Base
B	High RAP		
C	RAP & RAS		
D	BMD		
Rutting Experiment			
Test Section	Surface 2 in	Intermediate 6 in	Base 7 in
H	Type D	Type B	Cement (3.5%) Treated Base
I	High RAP		
J	RAP & RAS		
K	BMD		
Fatigue Cracking Experiment			
Test Section	Surface 3 in	Base 8 in	Sub-base 8 in
L	Type D	Bridgeport Rock	Cement (2%) Treated Sub-base
E	High RAP		
F	RAP & RAS		
G	BMD		
Type D contains no RAP/RAS High RAP = 19% RAP RAP & RAS = 15% RAP + 3% RAS w/WMA BMD = 15% RAP + 3% RAS TTI Design			

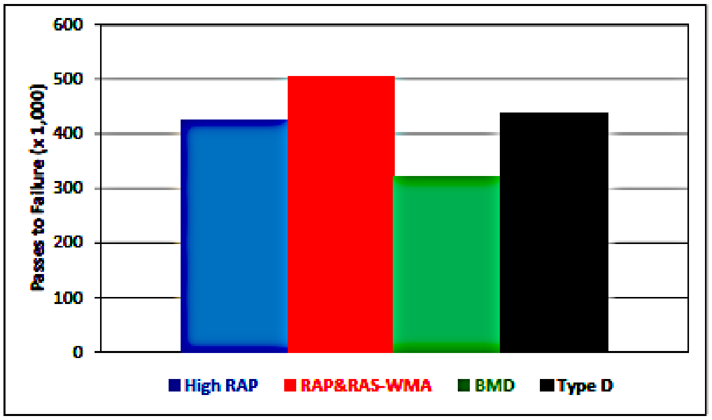
Several cores were also collected by the TTI to investigate laboratory performance of the mixture using the Hamburg wheel tracking test (HWTT), OT, resilient modulus, and indirect tensile test (IDT). The results are tabulated in Table 2.6 for each mixture type. It can be observed that the BMD mixture performed the best in regard to cracking and rutting resistance. Moreover, the high RAP mixture has better rutting resistance than the type D. However, the type D showed better cracking resistance than high RAP mixtures.

Table 2.6 – Lab Tests Results on APT Field Cores (Saeedzadeh et al., 2018)

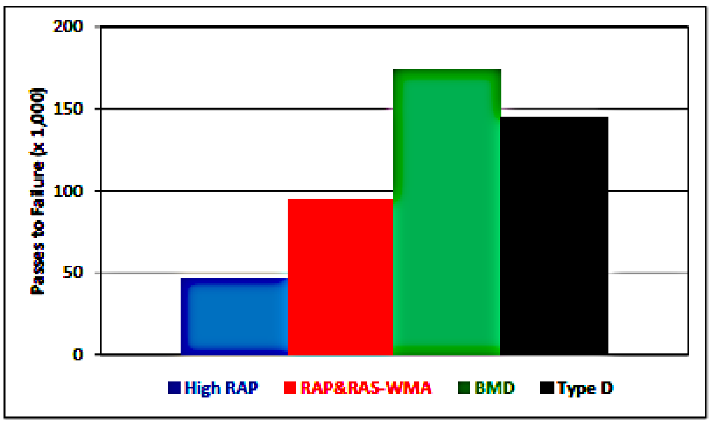
Mixture Type	HWTT	OT	Resilience Modulus (ksi)	IDT (psi)
Type D	4600	383	416.7	120.9
High RAP	11216	108	478.1	117.75
RAP & RAS - WMA	5350	175	385.7	106.7
BMD	11400	442	354.7	121.1

Field results shown in Figure 2.4 reveal no significant difference in regard to fatigue cracking and rutting between the high RAP mixtures and type D mixtures, with the type D mixture showing a slight increase in fatigue resistance. However, the high RAP mixtures show poor resistance to reflective cracking among all test sections. Moreover, incorporating RAS (recycled asphalt shingles) in pavement mixtures increases fatigue resistance.

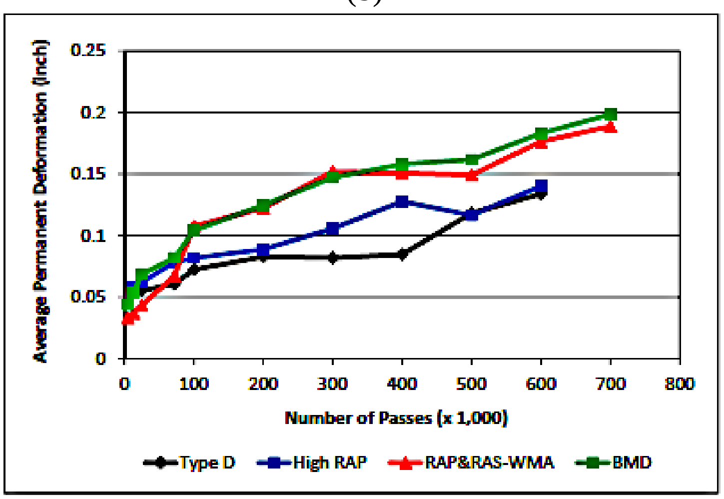
Qiao et al. (2019) investigated several test sections located on Interstate 95 in New Hampshire with two types of asphalt mixtures, i.e., virgin HMA and HMA with 40% RAP, that were applied to four pavement structures (i.e., standard strength, medium strength, deep strength, and full depth), as shown in Table 2.7. Dynamic modulus for test section was conducted under different temperatures and evaluated using Pavement ME software. Figure 2.5 shows that virgin HMA reaches the maintenance threshold for rutting earlier than HMA with 40% RAP. On the other hand, HMA with 40% RAP reaches a thermal cracking threshold earlier than virgin HMA.



(a)



(b)



(c)

Figure 2.4 – Filed Performance of Mixtures at APT Facility: (a) Resistance of Mixtures to Fatigue Cracking; (b) Resistance of Mixtures to Reflective Cracking; (c) Average Permanent Deformation of Mixtures (Qiao et al., 2019).

Table 2.7 – List of Different Pavement Structure (Qiao et al., 2019)

Structure	Asphalt Concrete (in)	Granular Base (in)	Subbase (in)
Standard Strength (SS)	6	28	8
Medium Strength (MS)	9	18	8
Deep Strength (DS)	12	12	8
Full Depth (FD)	16	8	Without Subbase

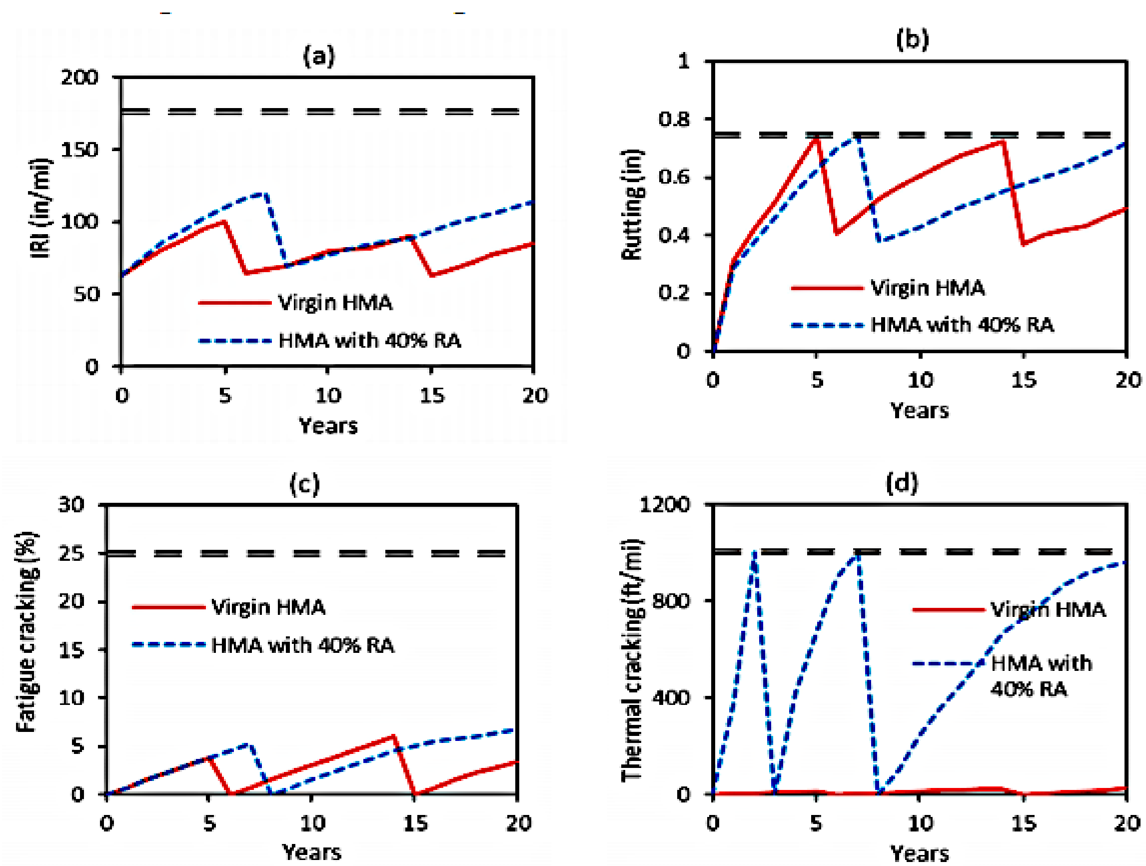


Figure 2.5 – Life Cycle Performance: (a) IRI Curve; (b) Rutting Curve; (c) Fatigue Cracking Curve; and (d) Thermal Cracking Curve (Qiao et al., 2019).

Similar analysis was carried out for different pavement designs, as shown in Table 2.7, for a design life of 20 years without maintenance, which were predicted using Pavement ME under future climates for different performance indices. Results are presented in Figure 2.6. It can be observed that rutting resistance increases with RAP incorporation and thermal cracking resistance decreases with the use of RAP.

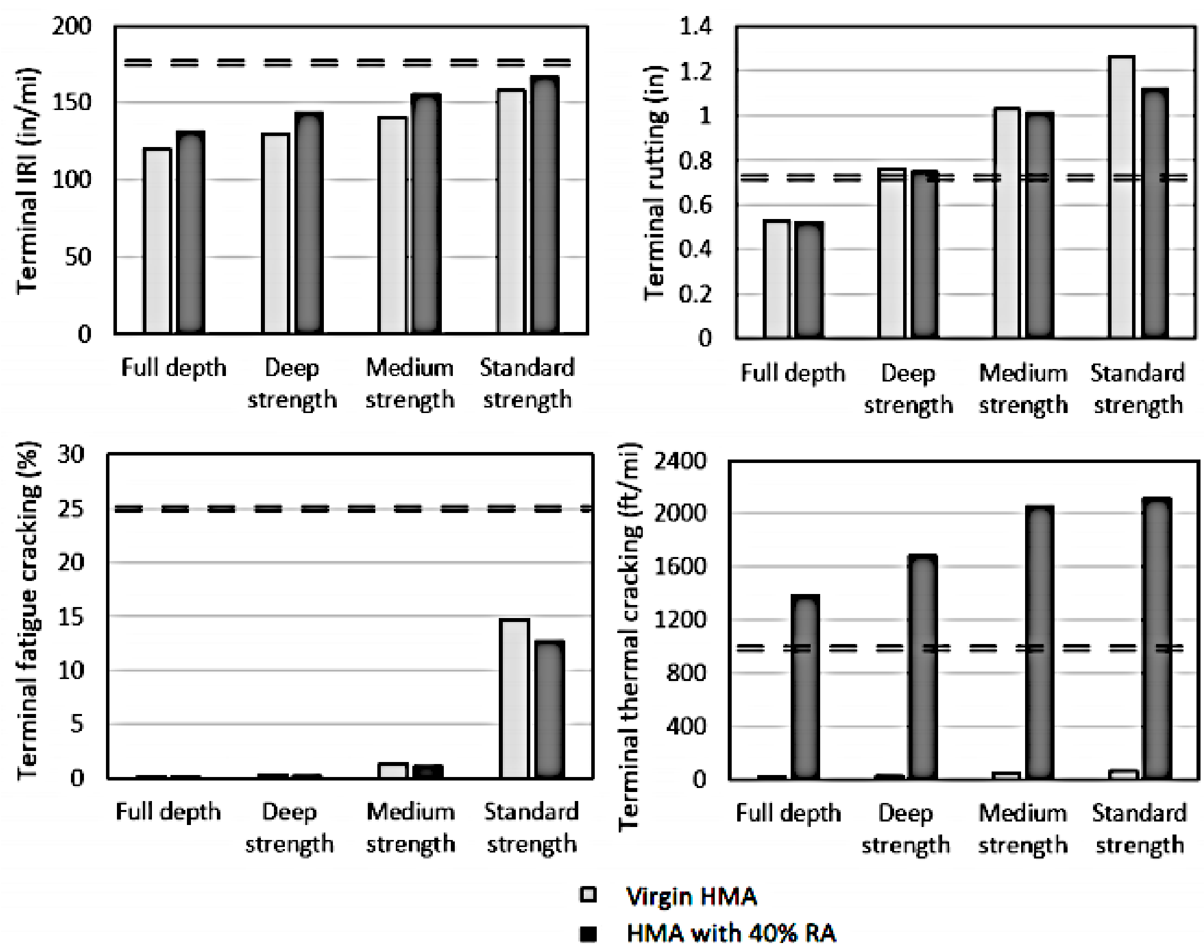


Figure 2.6 – Terminal Values of Performance Indices (Qiao et al., 2019).

Life Cycle Cost Analysis

Life cycle assessment (LCA) is used to evaluate industrial systems for gathering raw materials, along with manufacture processing, maintenance, and final disposal (EPA, 2006). The LCA is broken down into four phases:

1. Goal definition and scoping.
2. Inventory analysis
3. Impact assessment
4. Interpretation

LCA transform has an impact from one stage to another. Although the impact of a certain decision and saving of material in early stages looks convenient, in the long run, it causes more maintenance and rehabilitation. Therefore, examining the impact of one stage does not reflect the overall impact of the process. LCA is dependent on the accuracy and precision of collected data. Moreover, it is time-consuming and resource-intensive. Therefore, evaluation of the financial benefits against the cost of performing certain analysis is critical. Details about LCA approaches and available tools can be found elsewhere (Saeedzadeh et al., 2018).

Unlike LCA, there are no standards for life cycle cost analysis (LCCA). However, the Federal Highway Administration (FHWA) define it as an engineering economic analysis technique that builds on the well-grounded principles of economic analysis to evaluate the long-term costs of different alternative strategies throughout the selected analysis period (Walls & Smith, 1998). The LCCA is broken into five steps as stated below. Readers may refer to Beatty (2002) for detailed information about LCCA.

1- *Establish design alternatives*: A set of possible alternatives is selected to complete the improvement plans. A minimum of two mutually exclusive alternatives should be considered where the economic difference between them is assumed to be attributed to the total cost. First, the activities associated with each alternative are determined as well as the analysis period, which represents the time the asset will remain open to public use, which can be equal to or different between alternatives. However, it is recommended for the analysis period to be equal between alternatives to assess cost differences between them, so that the results can be fairly compared. The analysis period should be long enough and demonstrate the total cost differences between the proposed alternatives. The agency activity for each alternative is to be defined and determined such as initial construction, rehabilitation, and periodic maintenance. However, the distribution of these activities is not required to be equal between alternatives and should be assigned to each alternative based on agency policy, research, and historic data.

2- *Determine activity timing:* After defining the component and the activity associated with each alternative, these activities are to be developed and set in a time schedule by defining the timeframe for each of these activities and how long will the agency need to establish work zones and when agency funds will be expended. The timeframe of these activities should be based on existing performance records and as accurately as possible, as the expenses associated with them can account for a sizeable portion of a project's total life cycle cost (LCC).

3- *Estimate costs (agency and user):* Life cycle cost analysis does not require calculating all the costs associated with each alternative. However, those that demonstrate the differences between the alternatives need to be investigated. Thus, one must simplify the analysis and reduce the required data. Moreover, the estimated future costs should be estimated in constant dollar. Costs are divided into two categories, i.e., agency costs and user costs. Agency costs are those associated with initial construction, periodic maintenance, and rehabilitation activities, which can be obtained from historical records, engineering judgment, and bids. Moreover, the value of each analysis period, known as the salvage value as well as the remaining service life value for each alternative, affects the total agency costs. On the other hand, user costs include the vehicle operating, travel time, and crash costs, which usually arise from the timing, duration and number of construction and rehabilitation work zones. Since the work zone restricts the capacity and reduces traffic flow, it can be related to speed changes, stops, delays, detours, and incidents. However, incorporating of user costs is challenging, but it enhances the validity of the LCCA results.

4- *Compute LCC:* Now that all alternatives as well as the associated agency and related user costs have been defined and determined, the LCCA analysis can be conducted. However, since the dollar value spent at different timeframes has different present values, the projected costs of each activity cannot simply be added together and thus need to be converted to equivalent present costs using economical methods in order to compare the life cycle costs between alternatives. Nominal dollar value is subjected to inflation and discounts, where the inflation is the increase of dollar price over time, while the discounting represents the interest that could be earned on funds. The nominal dollar can be converted by multiplying it with applicable indexes, as shown in Eq. 2.3 which is typically between 3% to 5% for LCCA. The formula to discount future costs to present value is given in Eq. 2.4 where *r* is the real discount rate, and *n* is the number of years in the future the cost will be incurred.

$$Dollars_{base\ year} = Dollars_{data\ year} * \frac{Price\ Index_{base\ year}}{Price\ Index_{data\ year}} \qquad \text{Eq. 2.3}$$

$$Present\ Value = \frac{Future\ Value}{(1+r)^n} \qquad \text{Eq. 2.4}$$

The LCCA can be analyzed using either a deterministic or probabilistic approach. The deterministic approach is assigned a fixed discrete value for each LCCA input variable. However, it fails to convey the degree of uncertainty in the present value. The deterministic results can be enhanced using sensitivity analysis. On the other hand, in the probabilistic approach, the value of each input variable is defined by probability distribution, and the resulting present value distribution for each alternative can be compared at a certain risk level to identify the most economical alternative.

5- *Analyze the results:* The present value can be compared after being computed across different alternatives. However, since the deterministic approach has a single present value, while the probabilistic approach has present value distribution for each alternative, the analysis is different. The analysis of deterministic LCCA results is simply done by comparing the resulting present work for agency and user costs between alternatives, where ideally the alternative with the lowest present value is selected. However, the result does not address the uncertainty, and it is recommended to be associated with sensitivity analysis. On the other hand, the probabilistic approach examines the full range of present value outcomes and gives an estimated likelihood for any given outcome to occur, which assesses decision-makers based on the level of risk they are willing to take.

Compared with LCA, fewer studies have been conducted for LCCA involving highway pavement constructed using RAP. Thus, it is easier to carry out LCCA as long as the expenditure information of each process is available (J. Li, Xiao, Zhang, & Amirkhanian, 2019).

Life Cycle Cost Analysis of Pavements with RAP

Chou and Lee (2013) discussed the benefits of using RAP for different price levels by developing and calculating a life cycle cost saving (LCCS) to compare pavements containing RAP with virgin pavement to determine the financial benefit of using RAP mixtures relative to using virgin mixtures. The results showed that, once RAP mixtures cost ratios and service life exceed certain thresholds, it will have a greater advantage over the virgin mix. Moreover, from a financial perspective, the performance ratio of RAP to virgin mixtures must be larger than the cost ratio of these two materials. Similarly Lee, Edil, Tinjum, and Benson (2010) reported that incorporating RAP in pavement mixture reduces life cycle costs by approximately 20%. Moreover, Santos, Bryce, Flintsch, and Ferreira (2017) conducted similar LCCA by including both agency and user costs and concluded that using RAP can reduce both agency and user costs.

Aurangzeb and Al-Qadi (2014) evaluated the environmental and economic feasibility of mixtures with 30%, 40%, and 50% RAP compared with virgin mixtures through life cycle cost analysis (LCCA) and LCA. Although the initial cost was different for mixtures, the maintenance cost was assumed identical between different mixtures. Results showed that, as the RAP percentage increased, the overall cost decreased. Moreover, the environmental impact reduced by

28% when using RAP mixtures. However, the study did not consider the agency and user costs, although they contribute to 50% of the total project cost.

Rand (2011) estimated the cost of different asphalt mixtures in Texas. The mixtures considered in the study are virgin mixes, 20% RAP, 5% RAS, and 15% RAP with 5% RAS. Results showed that usage of RAP and RAS mixtures reduces the mixture cost significantly, as shown in Table 2.8.

Table 2.8 - Asphalt Pavement Cost Estimates (Rand, 2011)

Cost of Mix ($ Per Ton)				
Binder Grade	Virgin Mix	20% RAP	5% RAS	15% RAP + 5% RAS
PG 76-22	47.80	41.24	42.54	37.64
PG 70-22	44.90	38.92	40.22	35.74
PG 64-22	39.75	34.80	36.10	32.39

Im and Zhou (2014) evaluated the cost benefits of 19% RAP mixture with and without rejuvenators compared with virgin mixes. The costs of rejuvenator, asphalt binder, recycled, and virgin material were only considered in the study. Results showed that RAP reduces the costs by 17.5%, while the use of a rejuvenator incurred additional costs in the mixture. A similar study was conducted by DeDene, Goh, Hasan, Rosli, and You (2015). They conducted a cost assessment for different mixtures that incorporate both RAP and different WMA technologies of Advera, Cecabase, Sasobit, and direct injection (Double Barrel Green) based on laboratory performance, e.g., rutting resistance, fatigue resistance, and moisture susceptibility, which was compared with HMA control mixtures. Although the authors assumed that the construction cost is twice the material cost, using analysis of variance (ANOVA), they revealed that mixing temperature is the dominant factor in cost reduction. Moreover, a lower dosage of WMA reduces costs from 2% to 7%. The authors concluded that the implementation of WMA technology improves the performance of the mix and thus reduces the overall cost. This agrees with a study by Robinette and Epps (2010), in which an LCCA was carried out to compare cold in-place recycling (CIPR) and hot in-place recycling (HIPR). They presented a reduction in total cost of nearly 6.5% for CIPR and 6% for HIPR when compared with virgin asphalt mixture.

Visintine (2011) compared the economic feasibility of asphalt mixtures with 30% and 40% RAP with virgin mixes by taking the initial construction and future maintenance and repair (M&R) costs and salvage value into consideration. They concluded that the higher the percentage of RAP used the higher net cost saving, as the 30% RAP mixture showed a 19% savings, while the 40% RAP mixtures showed a 40% saving.

Qiao et al. (2019) used the dynamic modulus test result as a key input into the Pavement ME to model the long-term performance of two asphalt mixture alternatives; based on the result, an appropriate maintenance model of the alternative was build and implemented in LCCA. The alternatives included a virgin HMA and an HMA with 40% RAP. Results in Figure 2.7 show that agency cost and net present value are reduced by 18.3% and 15% to 25%, respectively, for pavement with 40% RAP. However, the effect of user cost was found to be insignificant between the two alternatives.

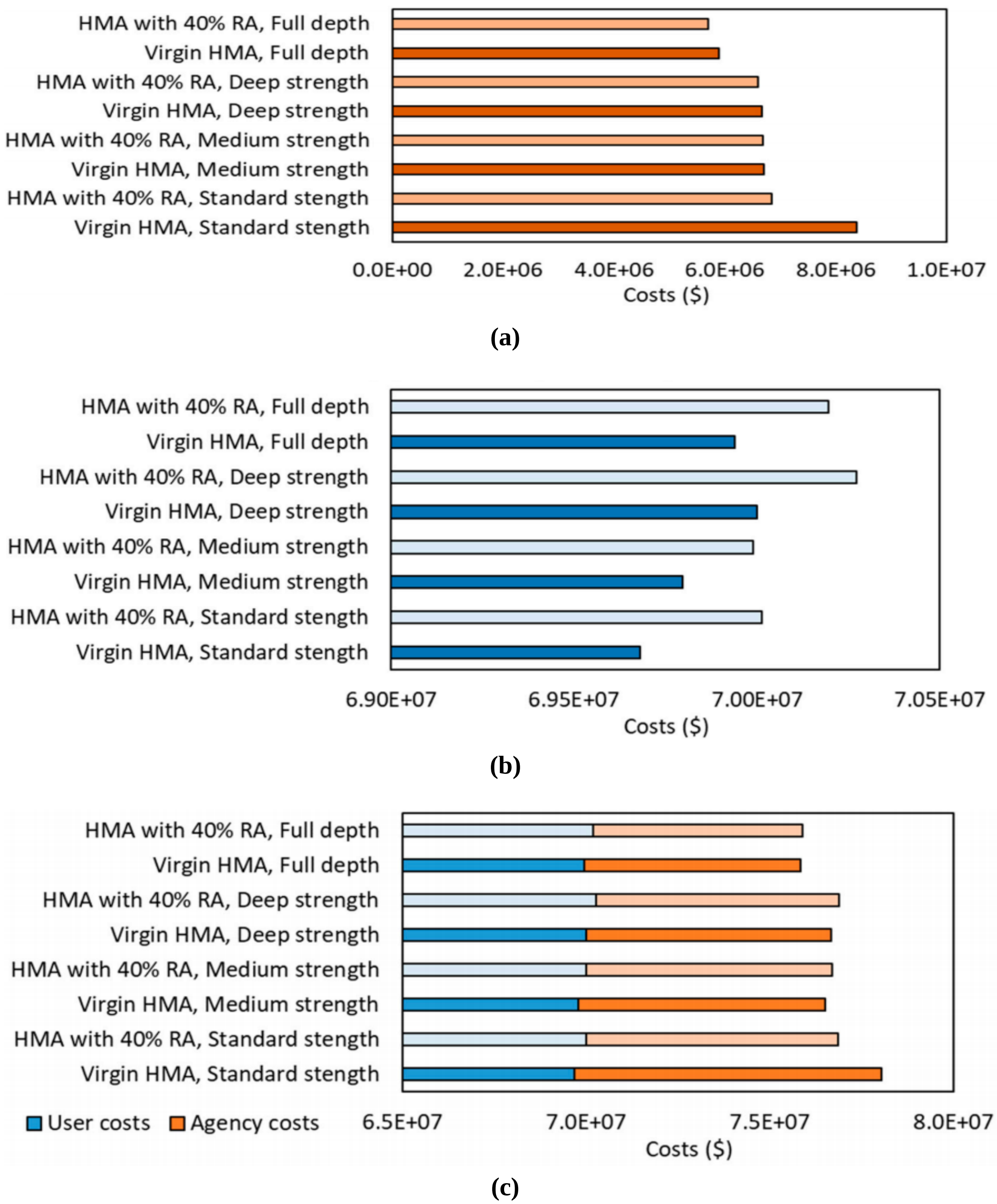


Figure 2.7 – Summary of LCCA Results: (a) Agency Costs; (b) User Costs; (c) Total Costs (Qiao et al., 2019).

Chapter 3: Research Methodology

The state of Nebraska has been using RAP mixtures for more than ten years. In this study, in order to evaluate the effects of RAP on pavement performance related to climatic conditions, a total of eight districts were considered into two primary temperature zones: northern Nebraska (districts of 3, 5, 6, and 8) and southern Nebraska (districts of 1, 2, 4, and 7) as shown in Figure 3.1 and Figure 3.2.

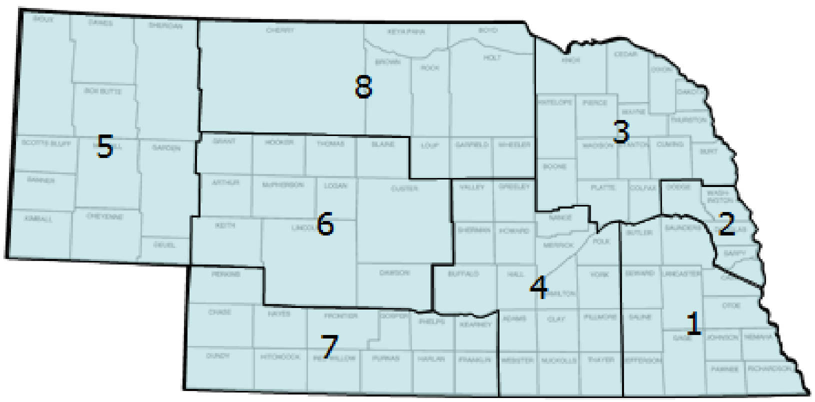


Figure 3.1 - Eight Districts in Nebraska.

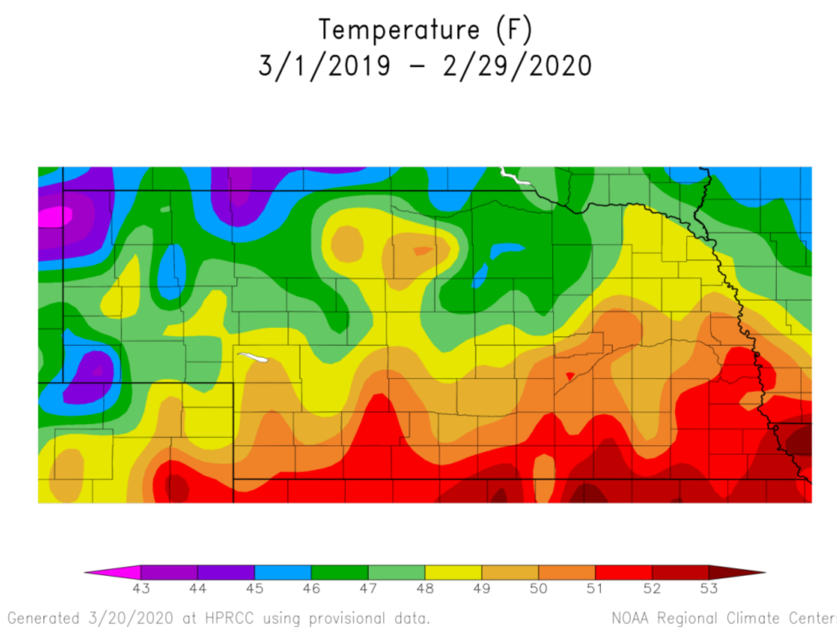


Figure 3.2 - Temperature Distribution of Nebraska (HPRCC, 2019).

As Table 3.1 indicates, a total of 254 pavement projects were selected in different districts with RAP percentages varying from 0 to 50%. It should be noted that projects with 35% RAP (10 sections) and 50% RAP (6 sections) were excluded in the data analysis due to their small number of sections that might affect statistical analyses in a biased manner. For each project, a comprehensive set of data including project history, mixture design (gradation, binder content, binder source, RAP percent, RAP source), traffic (ADT and ADTT), pavement structural design, and pavement performance results were collected. The pavement performance data include roughness (IRI), rut depth, fatigue cracking, and severity (transverse cracking) over the performance period. Figure 3.3 shows the data category collected for this study, and Figure 3.4 shows data inserted and sorted in a spread sheet to be used for further data analyses. Statistical analyses and life cycle cost analyses were then conducted to evaluate the effects of using RAP and different percentages of RAP in mixtures on the pavement performance.

Table 3.1 - Number of Sections of Each RAP Category

% RAP	0	10	13	15	20	25	35	40	45	50
No. of Sections	25	18	20	30	52	48	10	24	21	6

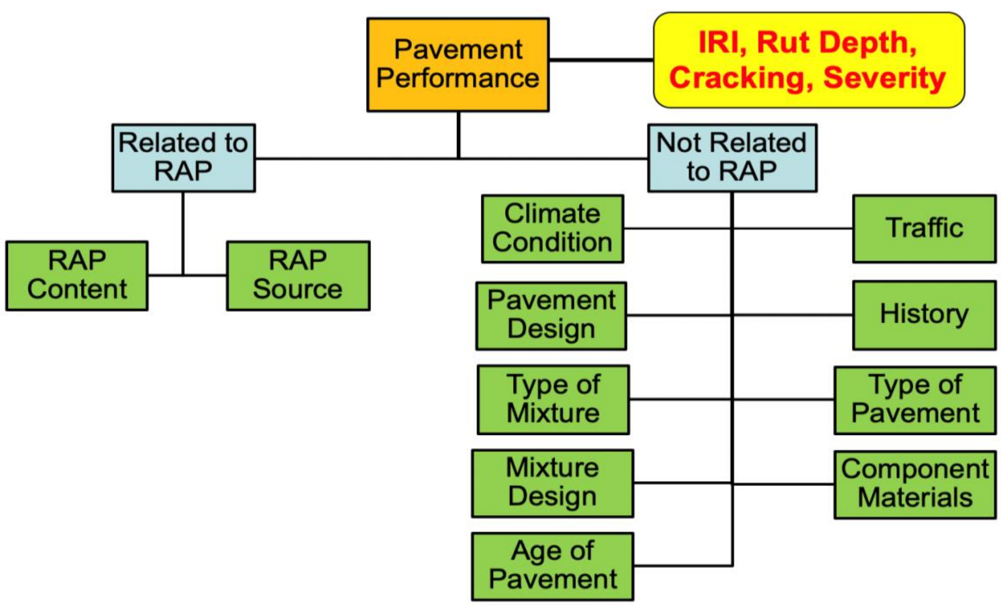
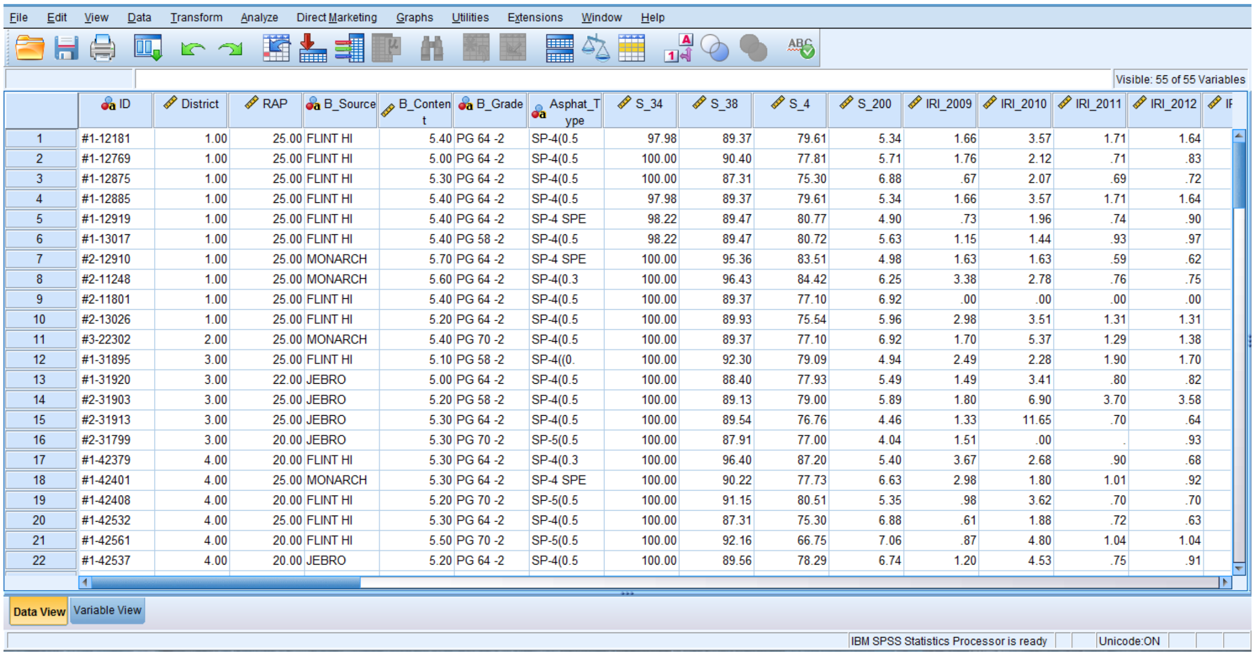


Figure 3.3 – Data Category Collected in This Study.



	ID	District	RAP	B_Source	B_Content	B_Grade	Asphat_Type	S_34	S_38	S_4	S_200	IRI_2009	IRI_2010	IRI_2011	IRI_2012	IF
1	#1-12181	1.00	25.00	FLINT HI	5.40	PG 64 -2	SP-4(0.5	97.98	89.37	79.61	5.34	1.66	3.57	1.71	1.64	
2	#1-12769	1.00	25.00	FLINT HI	5.00	PG 64 -2	SP-4(0.5	100.00	90.40	77.81	5.71	1.76	2.12	.71	.83	
3	#1-12875	1.00	25.00	FLINT HI	5.30	PG 64 -2	SP-4(0.5	100.00	87.31	75.30	6.88	.67	2.07	.69	.72	
4	#1-12885	1.00	25.00	FLINT HI	5.40	PG 64 -2	SP-4(0.5	97.98	89.37	79.61	5.34	1.66	3.57	1.71	1.64	
5	#1-12919	1.00	25.00	FLINT HI	5.40	PG 64 -2	SP-4 SPE	98.22	89.47	80.77	4.90	.73	1.96	.74	.90	
6	#1-13017	1.00	25.00	FLINT HI	5.40	PG 58 -2	SP-4(0.5	98.22	89.47	80.72	5.63	1.15	1.44	.93	.97	
7	#2-12910	1.00	25.00	MONARCH	5.70	PG 64 -2	SP-4 SPE	100.00	95.36	83.51	4.98	1.63	1.63	.59	.62	
8	#2-11248	1.00	25.00	MONARCH	5.60	PG 64 -2	SP-4(0.3	100.00	96.43	84.42	6.25	3.38	2.78	.76	.75	
9	#2-11801	1.00	25.00	FLINT HI	5.40	PG 64 -2	SP-4(0.5	100.00	89.37	77.10	6.92	.00	.00	.00	.00	
10	#2-13026	1.00	25.00	FLINT HI	5.20	PG 64 -2	SP-4(0.5	100.00	89.93	75.54	5.96	2.98	3.51	1.31	1.31	
11	#3-22302	2.00	25.00	MONARCH	5.40	PG 70 -2	SP-4(0.5	100.00	89.37	77.10	6.92	1.70	5.37	1.29	1.38	
12	#1-31895	3.00	25.00	FLINT HI	5.10	PG 58 -2	SP-4((0.	100.00	92.30	79.09	4.94	2.49	2.28	1.90	1.70	
13	#1-31920	3.00	22.00	JEBRO	5.00	PG 64 -2	SP-4(0.5	100.00	88.40	77.93	5.49	1.49	3.41	.80	.82	
14	#2-31903	3.00	25.00	JEBRO	5.20	PG 58 -2	SP-4(0.5	100.00	89.13	79.00	5.89	1.80	6.90	3.70	3.58	
15	#2-31913	3.00	25.00	JEBRO	5.30	PG 64 -2	SP-4(0.5	100.00	89.54	76.76	4.46	1.33	11.65	.70	.64	
16	#2-31799	3.00	20.00	JEBRO	5.30	PG 70 -2	SP-5(0.5	100.00	87.91	77.00	4.04	1.51	.00	.	.93	
17	#1-42379	4.00	20.00	FLINT HI	5.30	PG 64 -2	SP-4(0.3	100.00	96.40	87.20	5.40	3.67	2.68	.90	.68	
18	#1-42401	4.00	25.00	MONARCH	5.30	PG 64 -2	SP-4 SPE	100.00	90.22	77.73	6.63	2.98	1.80	1.01	.92	
19	#1-42408	4.00	20.00	FLINT HI	5.20	PG 70 -2	SP-5(0.5	100.00	91.15	80.51	5.35	.98	3.62	.70	.70	
20	#1-42532	4.00	25.00	FLINT HI	5.30	PG 64 -2	SP-4(0.5	100.00	87.31	75.30	6.88	.61	1.88	.72	.63	
21	#1-42561	4.00	20.00	FLINT HI	5.50	PG 70 -2	SP-5(0.5	100.00	92.16	66.75	7.06	.87	4.80	1.04	1.04	
22	#1-42537	4.00	20.00	JEBRO	5.20	PG 64 -2	SP-4(0.5	100.00	89.56	78.29	6.74	1.20	4.53	.75	.91	

Figure 3.4 – An Exemplary View of Spread Sheet of the Data Collected.

Regarding the statistical analyses, as the comparison between different groups is required, independent sample *t*-test was conducted. The *t*-test is a type of inferential statistic that is used to determine if the mean of two sets of data are significantly different from each other. *t*-score is an extension of *z*-score and represents the number of standard units. The means of the two groups are computed using Eq. 3.1 and Eq. 3.2. The *t*-test requires normality of data (i.e., the distribution of each group came from normal distribution) and homogeneity of variance (equal between groups). When one of the assumptions is violated, *t*-test is not recommended and non-parametric test such as Wilcoxon signed rank test should be used.

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sigma_p \sqrt{\frac{1}{N_1} + \frac{1}{N_2}}} \qquad \text{Eq. 3.1}$$

$$\sigma_p = \sqrt{\frac{(N_1 - 1){\sigma^2}_{x_1} + (N_2 - 1){\sigma^2}_{x_2}}{N_1 + N_2 - 2}} \qquad \text{Eq. 3.2}$$

where:

N_1 and N_2 = sample size of each group,

σ_p = the pooled standard deviation,

$\bar{x}_1$ *and* $\bar{x}_2$ = the mean of group 1 and group 2, and

σ^2_{x1} and σ^2_{x2} = the variance of group 1 and group 2.

Levene test described in Eq. 3.3 through Eq. 3.6 is an inferential statistic test that is used to check the homogeneity of variance. It is described under a degree of freedom of k-1 and N-1 with certain level of confidence (α) which is usually set to be 0.05. When the test statistic (W), which is approximately F-distributed, is significant (less than 0.05), the test rejects the null hypothesis of homogeneity of variance and accepts the alternative indicating that the variance between two groups is different. Therefore, the equal variance assumption is violated, and Welch's signed ranked test should be used instead of t-test. In this case, rather than using the pooled standard deviation, the statistic uses variance of each group as shown in Eq. 3.7 with a degree of freedom in Eq. 3.8.

$$W = \frac{N-k}{k-1} . \frac{\sum_{i=1}^{k} N_i (Z_{i.} - Z_{..})^2}{\sum_{i=1}^{k} \sum_{j=1}^{N_i} \left(Z_{ij} - Z_{i.}\right)^2} \quad \text{Eq. 3.3}$$

$$Z_{ij} = \left|Y_{ij} - \bar{Y}_{i.}\right| \quad \text{Eq. 3.4}$$

$$Z_{i.} = \frac{1}{N_i} \sum_{j=1}^{N_i} Z_{ij} \quad \text{Eq. 3.5}$$

$$Z_{..} = \frac{1}{N} \sum_{i=1}^{k} \sum_{j=1}^{N_i} Z_{ij} \quad \text{Eq. 3.6}$$

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{\sigma_1^2}{N_1} + \frac{\sigma_2^2}{N_2}}} \quad \text{Eq. 3.7}$$

$$df = \frac{\left(\frac{\sigma_1^2}{N_1} + \frac{\sigma_2^2}{N_2}\right)^2}{\frac{\sigma_1^4}{N_1^2(N_1 - 1)} + \frac{\sigma_2^4}{N_2^2(N_2 - 1)}} \quad \text{Eq. 3.8}$$

where:

k = the number of different groups to which the sample cases belong,

N_i = the number of cases in the i^{th} group,

N = total number of cases in all groups,

Y_{ij} = the value of the measured variable from the j^{th} case from the i^{th} group,

Z_{ij} = the mean of the i^{th} group,

Z_i = the mean of the Z_{ij} for group *i*, and

$Z_{..}$ = the mean of all Z_{ij}.

Shapiro Wilk test described in Eq. 3.9 to Eq. 3.11 is used to test the data normality. Unlike other statistics, the Shapiro Wilk test statistic does not have a well-defined distribution and it uses the Monte-Carlo simulation to calculate the cutoff values. However, if the sample size is sufficiently large, the Shapiro Wilk test can detect trivial departure from normal distribution. Therefore, additional investigation such as Q-Q plot is necessary. When the test statistic (*W*) is less than the desired level of confidence α (i.e., P-value < 0.05), the test rejects the null hypothesis. Therefore, the normality assumption is violated, and the Mann-Whitney *U* test (also known as Mann-Whitney-Wilcoxon test) can be used to compares the mean rank between two groups.

$$W = \frac{\left(\sum_{i=1}^{n} a_i x_{(i)}\right)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad \text{Eq. 3.9}$$

$$(a_1, a_2, \ldots, a_n) = \frac{m^T V^{-1}}{C} \quad \text{Eq. 3.10}$$

$$C = \left||V^{-1}m|\right| = (m^T V^{-1} V^{-1} m)^{1/2} \quad \text{Eq. 3.11}$$

where:

$x_{(i)}$ = the order statistics,

C = the vector norm,

m = the transpose of the m vector = $(m_1, m_2, \ldots, m_n)^T$, and

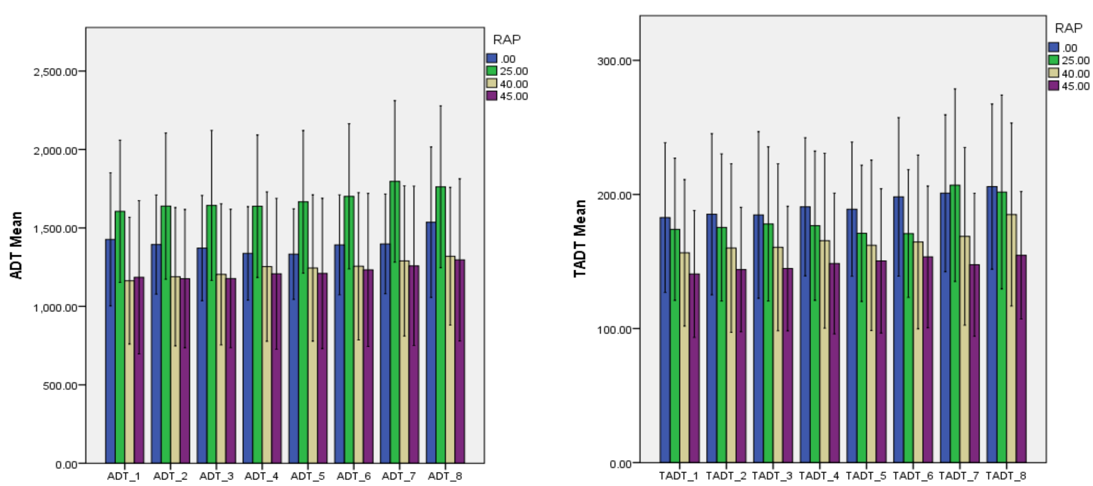
V = the covariance matrix of the normal order statistics.

Regarding the LCCA, statistical analysis results were used along with other data such as the initial costs (e.g., construction/material costs) and maintenance costs/cycles. The maintenance cycles for each mix type (e.g., SP4, SP4-Special, SP5, and SPR) were reasonably determined based on NDOT maintenance practices and results from statistical analyses. The agency costs resulting from different alternatives were compared in order to examine the economic benefits in using RAP in pavement projects. To conduct the LCCA, we used the PAVEXpress, which is a user-friendly web-based software to design pavements using the AASHTO 93/98 method with cost modules.

Chapter 4: Results and Discussion

Introduction

This chapter presents the data analysis results. The effects of incorporating RAP on pavement field performance and life cycle costs are discussed. A total of 254 pavement projects built between 2009 and 2012 across the state of Nebraska were selected to collect data including asphalt mixtures, pavement field performance, pavement design, traffic, and districts (for climate). The selected projects contained RAP in different percentages in their mixture design: from 0% to 50%. Pavement performance includes roughness (IRI), rut depth, cracking, and severity. The acceptable limits for IRI, rut depth, cracking (fatigue cracking), and severity (transverse thermal cracking) are 1.5 mm/m, 5 mm, 40%, and 0.4, respectively. It should also be noted that the majority of projects collected for this study was subjected to traffic level: ADT less than 1,600 and TADT (truck traffic) less than 200 as shown in Figure 4.1. Using the collected data, statistical tests were also conducted to more scientifically evaluate if there is a threshold percentage of RAP in asphalt mixtures that significantly affects pavement performance. Moreover, any changes in construction costs due to the use of RAP (in different parentages) and NDOT's typical maintenance practices and their costs were collected to conduct the LCCA, which can estimate the economic feasibility of RAP.

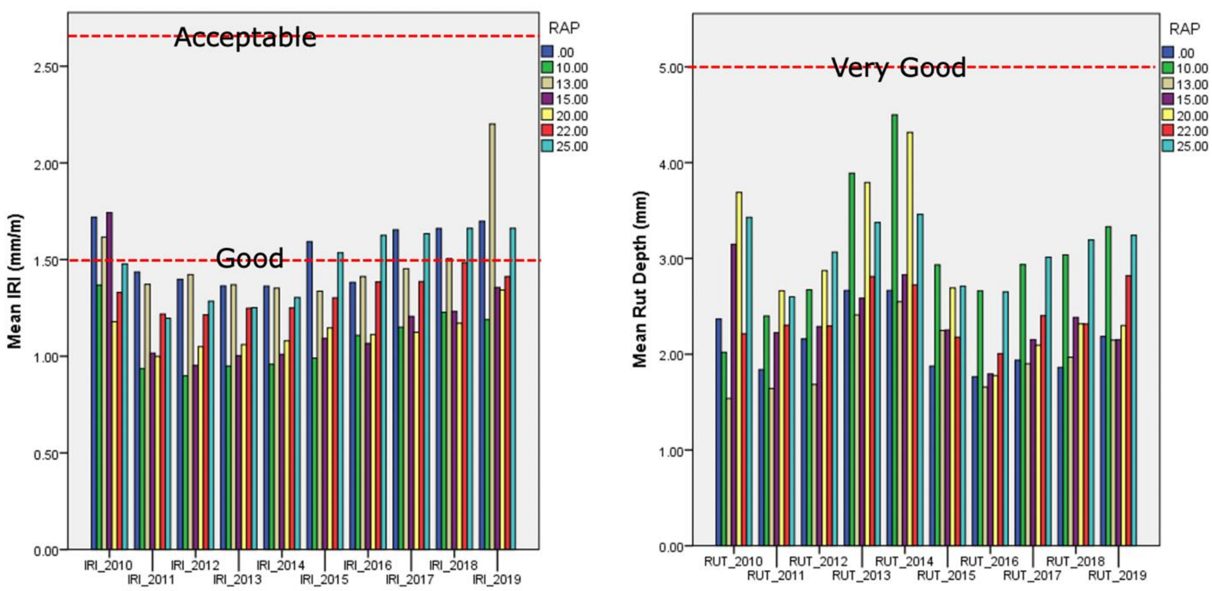


(a) ADT (b) TADT

Figure 4.1 – Average Daily Traffic Count for (a) ADT and (b) Truck ADT.

Analysis of RAP Performance

The initial approach was to compare the performance of pavement sections with asphalt mixtures less than 25% RAP. Since cracking data was not available for these sections, the analysis was limited to IRI and rut depth. Figure 4.2 present the mean IRI and rut depth. Both IRI and rut depth for pavement sections containing 0-25% RAP showed no statistical significance between different RAP percentages. In general, all sections performed well within the acceptable limits. This finding is also consistent with other studies in the literature which showed no significant impact on pavement performance when RAP is less than 30%.



(a) mean IRI (b) mean rut depth

Figure 4.2 – IRI Mean Value of Pavement Sections with Less than 25% RAP.

In order to examine the effects of high-RAP on pavement performance, the next analysis was conducted with pavement sections with asphalt mixtures containing RAP up to 50%. To avoid the effects of traffic in the analysis, pavement projects with the similar level of traffic were sorted, which resulted in exclusion of pavement sections with 35 and 50% RAP as the number of sections of the 35 and 50% RAP was small. The mean values of each performance index over the service years are shown in Figures 4.3 to 4.6. It can be inferred from the bar graph (Figure 4.3) that IRI does not change vastly throughout the service years. Furthermore, sections that have higher RAP contents show less IRI values. Considering the acceptable IRI limit of 2.68 mm/m, the overall IRI performance of the sections is within the acceptable range for all RAP percentages.

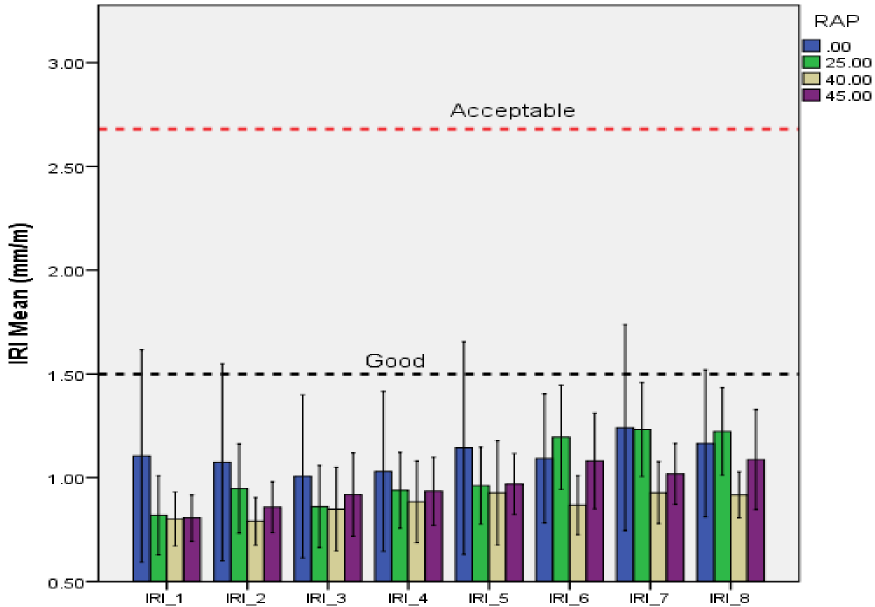


Figure 4.3 – Mean IRI Values of Sections with RAP of 0% to 45%.

Similar finding was observed for rutting as shown in Figure 4.4. Rutting increased slightly after being opened to traffic in the early stage of pavement life then decreased. Pavement sections with higher RAP showed less rutting in the later stage of service. All values of rutting measure from different RAP percentages fall below the 5 mm acceptable rut depth.

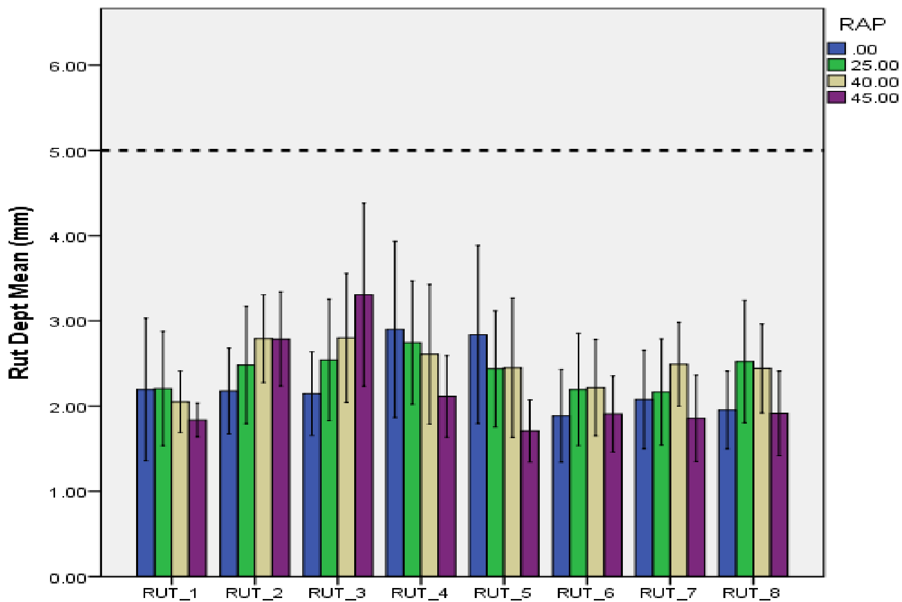


Figure 4.4 – Mean Rut Depths of Sections with RAP of 0% to 45%.

Regarding the fatigue cracking, it can be noticed that the percentage of cracking area increases with service years, as clearly shown in Figure 4.5. The fatigue cracking measures drastically increase in sections with 45% RAP and they exceed the acceptable limit (i.e., 40%) after about 5-6 years of service. Regarding the severity (Figure 4.6) which is an indication of transverse cracking (mostly due to thermal loads), an increasing trend was observed from projects with 45% RAP content. Some sections with 45% RAP exceeded the transverse cracking limit after about 3-4 years of service. It should be noted that routine maintenance activities were conducted, which reflected the decrease in both fatigue cracking and transverse cracking after the routine maintenance.

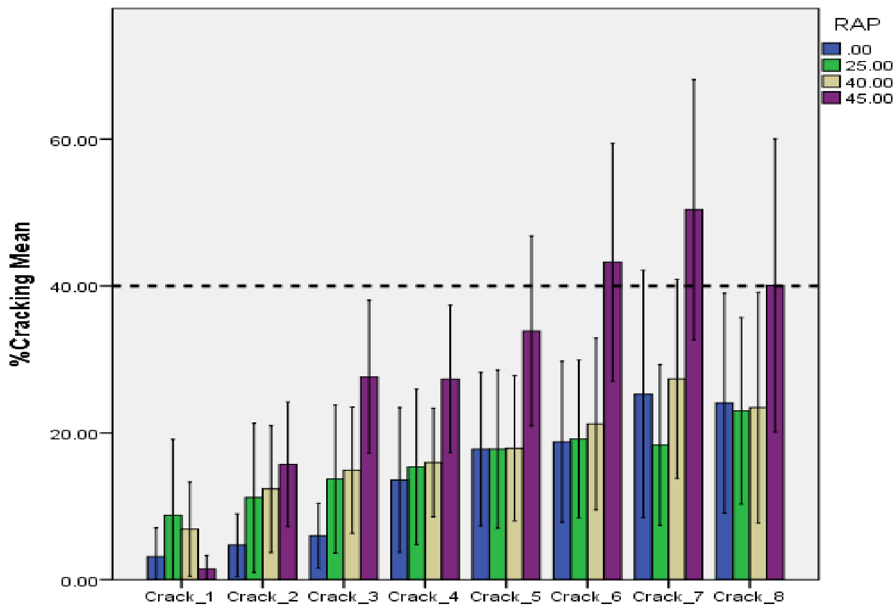


Figure 4.5 – Mean % Cracking Area of Sections with RAP of 0% to 45%.

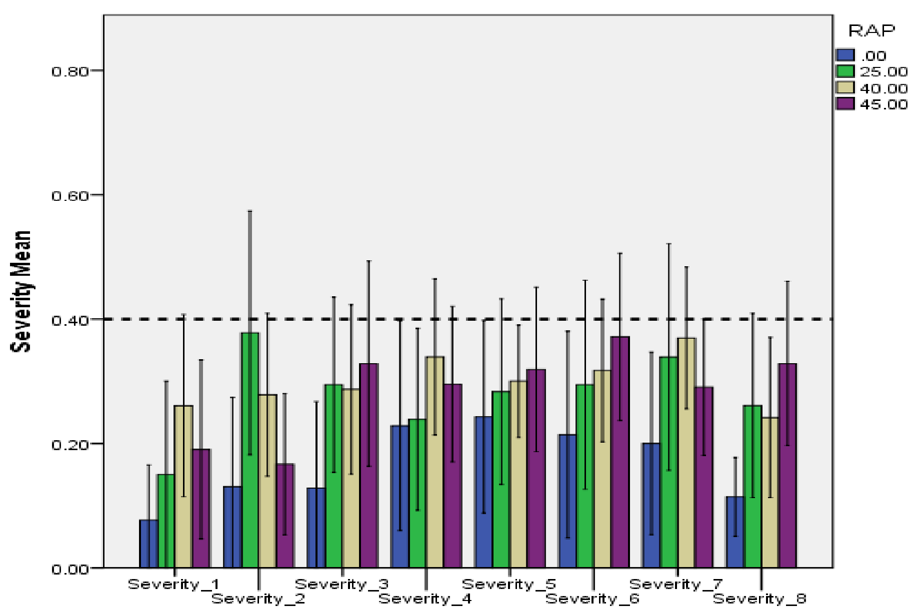
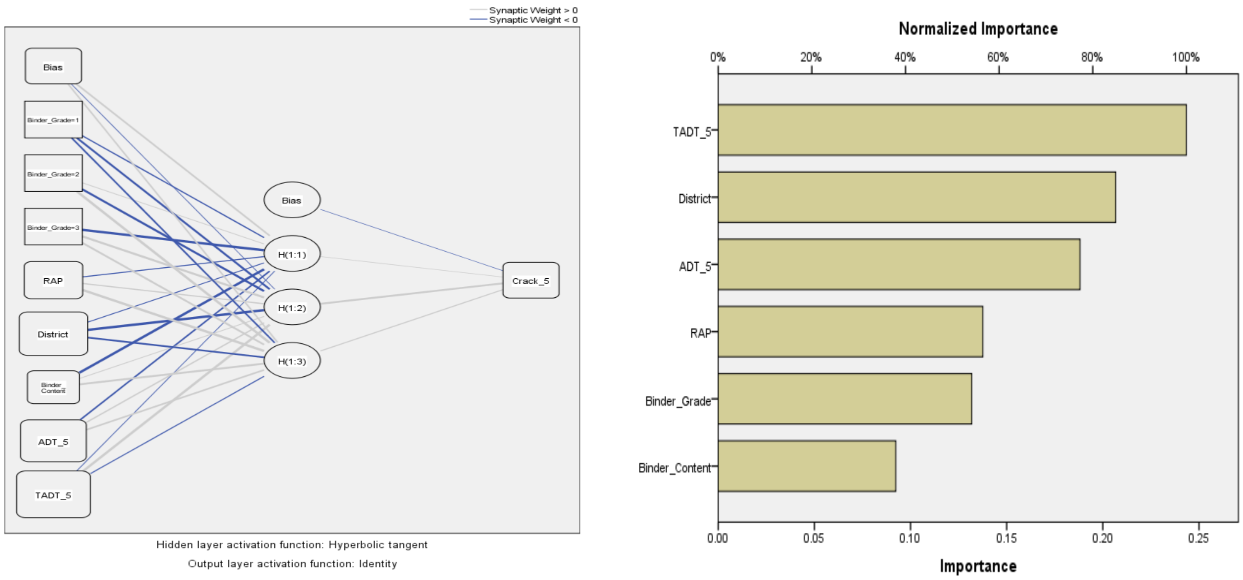
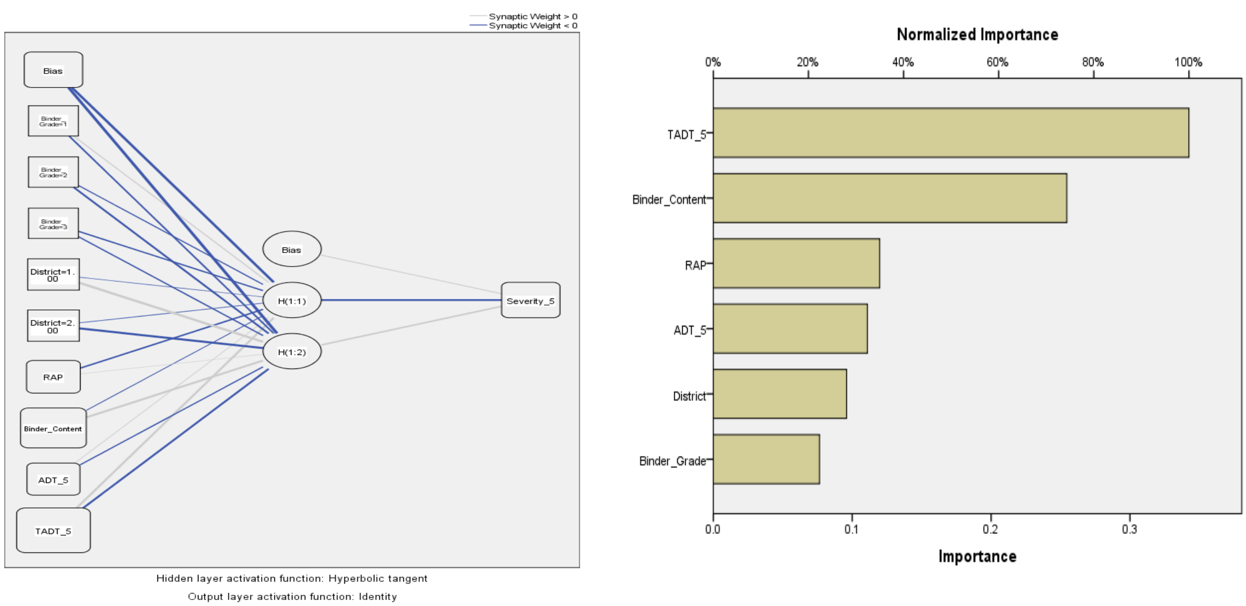


Figure 4.6 – Mean Severity of Sections with RAP of 0% to 45%.

A neural network analysis was carried out to further examine the sensitivity of factors that have more impact on overall fatigue and transverse cracking of pavement after 5 years in service. Analysis results indicate that the fatigue cracking was mainly governed by truck traffic and climatic zone as shown in Figure 4.7(a). The transverse cracking (represented by severity) was mainly affected by truck traffic and binder content as shown in Figure 4.7(b).



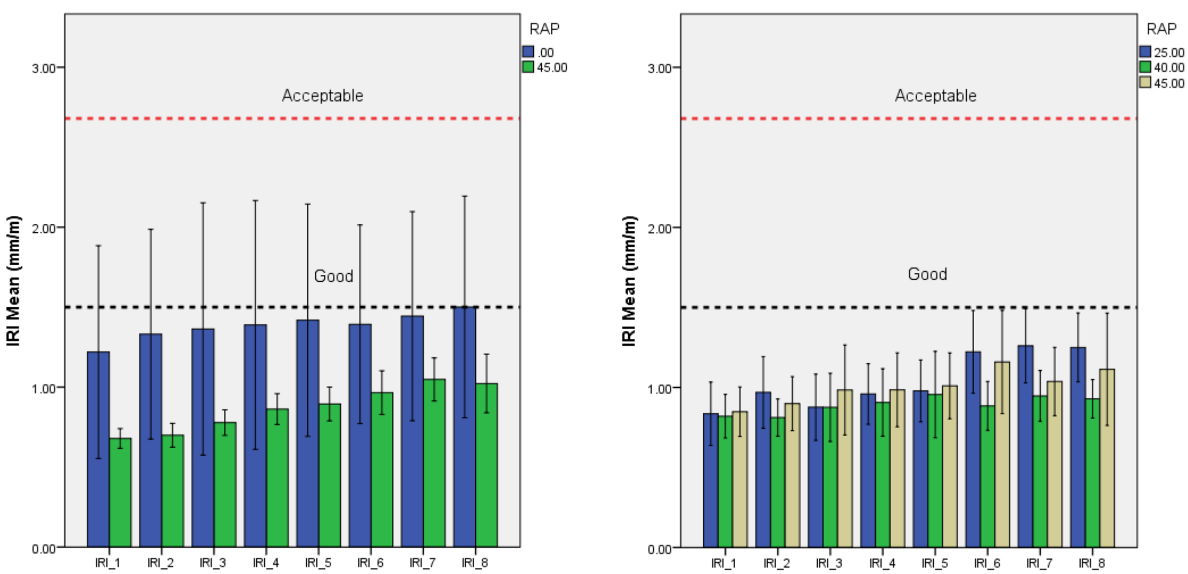
(a)



(b)

Figure 4.7 – Sensitivity Analysis: (a) Cracking; and (b) Severity.

Further investigation were conducted by separating the collected projects into two climatic zones: northern Nebraska (lower temperature zone, districts: 3, 5, 6, and 8) and southern Nebraska (higher temperature zone, districts: 1, 2, 4, and 7). Upon grouping of projects it was observed that majority of 40% and 25% RAP sections were located in southern Nebraska with very few in northern Nebraska. Moreover, the majority of 0% RAP sections with a similar level of traffic is located in northern Nebraska. Therefore, the analysis was conducted by comparing 0% RAP sections with 45% RAP sections in northern Nebraska, and sections between 25 to 45% RAP were used to compare pavement performance in southern Nebraska. Figure 4.8 presents the IRI values from different RAP contents at the two different climatic zones. Generally the IRI remains almost similar throughout the performance years with all projects in both climatic zones within the acceptable limit. Figure 4.9 presents the rutting results from different RAP contents at the two climatic zones. All projects were generally under the acceptable 5 mm rut depth limit, and there was no clear trend in relation to the RAP content and climatic zone.



(a) Northern NE (b) southern NE

Figure 4.8 – Mean IRI of Projects in (a) Northern Nebraska; and (b) Southern Nebraska.

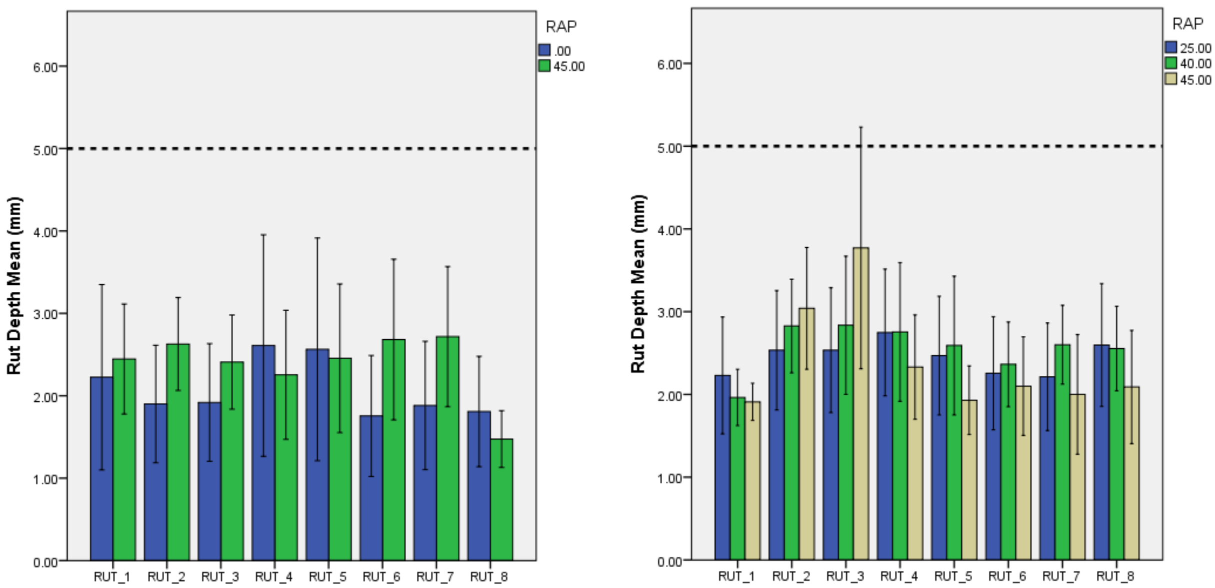


Figure 4.9 – Mean Rut Depths of Projects in (a) Northern Nebraska; and (b) Southern Nebraska.

Fatigue cracking presented in Figure 4.10 shows that cracking in northern Nebraska is obviously more severe than southern Nebraska. When high-RAP (45%) was used, fatigue cracking in northern Nebraska exceeds the limit (40%) after 3-4 years in service. On the other hand, fatigue cracking in southern Nebraska was mostly within the acceptable limit for 7-8 years in service. In term of severity, as presented in Figure 4.11, sections with 45% RAP in northern Nebraska showed an increasing damage over the service life and reached the limit (0.4) in the early stage. After about 5 years in service, mean value of the sections passed the limit. On the other hand, sections built in southern Nebraska were generally acceptable except several sections over the limit, and there was no clear trend on the severity rank among the three RAP contents (25, 40, and 45%).

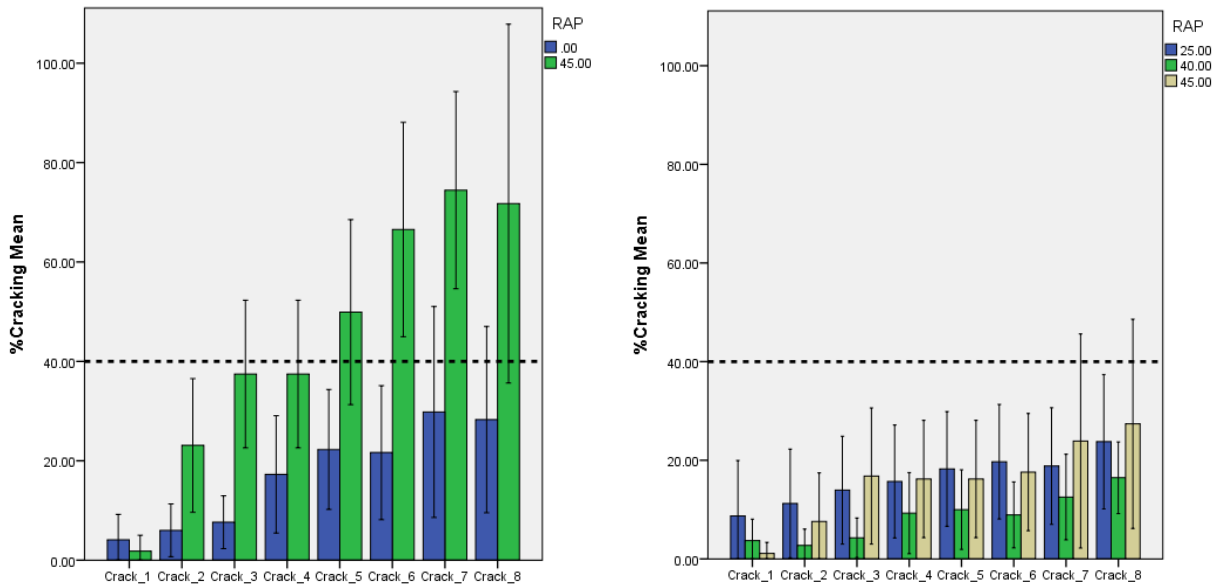


Figure 4.10 – % Cracking Area of Projects in (a) Northern Nebraska; and (b) Southern Nebraska.

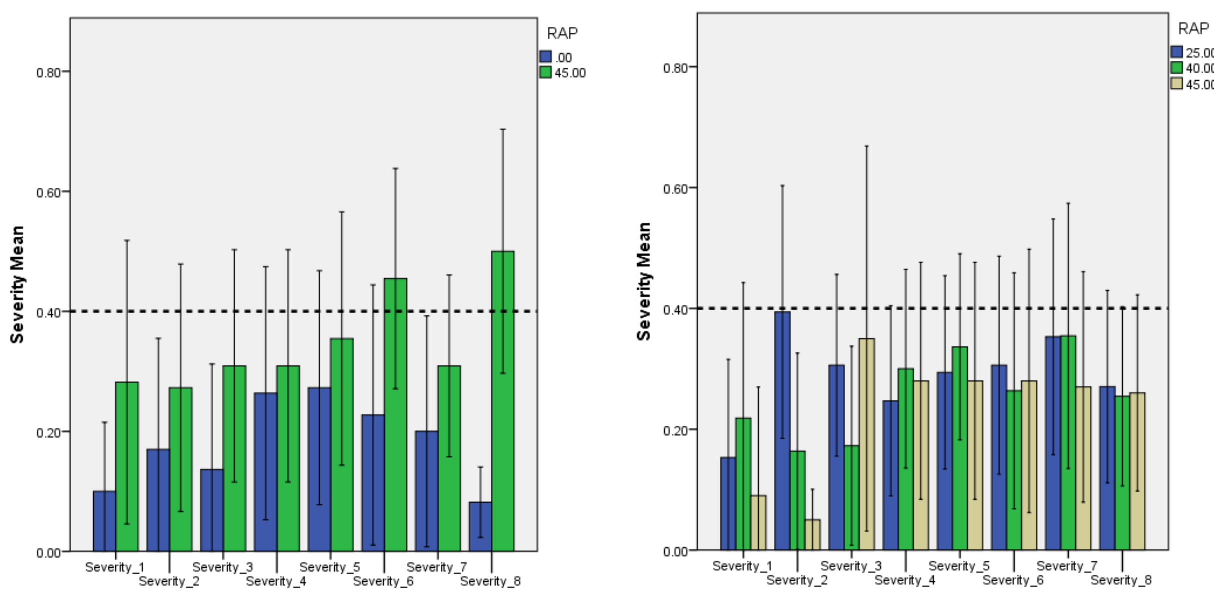


Figure 4.11 – Severity of Projects in (a) Northern Nebraska; and (b) Southern Nebraska.

Although the bar charts presented in Figures 4.8 to 4.11 can demonstrate general trends and differences among cases to evaluate the effects of RAP contents on pavement performance, it is necessary to examine the impact of RAP in a more scientific manner. Toward that end, inferential statistics were used to investigate if there is statistical significance to prove if the mean value of each performance indicator is similar or different when the RAP contents in asphalt mixtures vary. In many cases, an independent sample *t*-test is used for such statistics when the data set satisfies homogeneity of variant and normality. In order to first check if the independent sample *t*-test can be used for the dataset, Shapiro Wilk test was conducted to check data normality. Analysis results showed that for both IRI and severity of 0% RAP projects in northern Nebraska rejected the null hypothesis (i.e., the data follow normal distribution) at 95 percent level of confidence (P-value < 0.05). Therefore, the independent sample *t*-test should not be used for the analysis of IRI and severity. Instead, the Mann-Whitney U test was chosen for the IRI and severity, while the majority of statistical tests were conduct with the independent sample *t*-test. The Mann-Whitney test is a nonparametric alternative for the traditional *t*-test. It compares median of groups rather than mean. It is advantageous when variables are not normally distributed.

Statistical test results indicated insignificant difference when comparing the 45% RAP sections with 0% RAP sections in northern Nebraska regarding IRI, rut depth, and severity at 95 percent level of confidence. However, cracking showed statistical difference between 45% RAP sections and 0% RAP sections in northern Nebraska sections. Regarding projects in southern Nebraska, no significant difference was observed between the three RAP contents (25%, 40%, and 45%) at 95 percent level of confidence (P-value > 0.05) for all performance indicators. Statistical analysis results support the visual observations and inferences made from the bar charts in Figures 4.8 to 4.11.

Life Cycle Cost Analysis (LCCA) Results

LCCA was conducted using the PAVEXpress for ten alternatives as summarized in Table 4.1. Alternatives 1 to 3 are the typical SP4/SP5 cases with different initial construction costs due to aggregates available in either southern or northern district of Nebraska. Alternatives 4 to 6 were included to examine the LCC effects of SPR mixture when the RAP percentage varies from 35% to 45%. Alternatives 7 and 8 are cases when SPR mixture is used in pavement sections located in southern Nebraska while alternatives 9 and 10 are cases when SPR mixture is used in pavement sections located in northern Nebraska. Two different RAP percentages (i.e., 40% and 45%) were included in the analysis. In this study, only user cost was considered by assuming that all pavement sections for the LCCA were subjected to the similar traffic level. A total analysis period for all alternatives was set to be 50 years. Initial costs mostly related to materials and construction were informed by NDOT's typical pavement construction projects, and maintenance cycles/costs were determined based on NDOT's maintenance practices and the results from data analyses for the corresponding sections (e.g., southern or northern). A discount rate of 2 percent was used. Figure 4.12 presents the resulting cash flow diagram of each alternative.

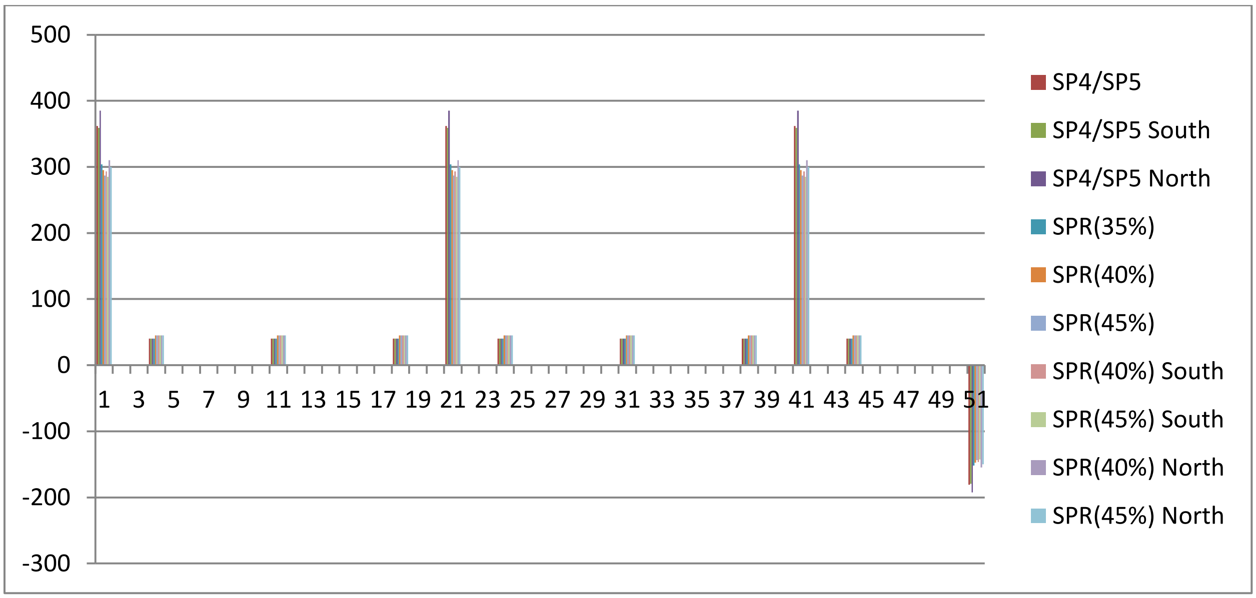


Figure 4.12 - Cash Flow Diagram for Each Alternative.

Table 4.1 – LCCA Alternatives Considered and Their Costs (Initial and Maintenance)

	Alt.1	**Alt.2**	**Alt.3**	**Alt.4**	**Alt.5**	**Alt.6**	**Alt.7**	**Alt.8**	**Alt.9**	**Alt.10**
Description	SP4/SP5	SP4/SP5 South	SP4/SP5 North	SPR (35%)	SPR (40%)	SPR (45%)	SPR(40%) South	SPR(45%) South	SPR(40%) North	SPR(45%) North
Initial Costs	362	359	385	304	295	287	293	285	310	300
1st Maintenance (Costs)	40	40	40	40	45	45	45	45	45	45
1st Maintenance (Interval)	3	3	3	3	3	3	3	3	3	3
2nd Maintenance (Costs)	40	40	40	40	45	45	45	45	45	45
2nd Maintenance (Interval)	10	10	10	10	10	10	10	10	10	10
3rd Maintenance (Costs)	40	40	40	40	45	45	45	45	45	45
3rd Maintenance (Interval)	17	17	17	17	17	17	17	17	17	17
Major Rehab (Costs)	362	359	385	304	295	287	293	285	310	300
Major Rehab (Interval)	20	20	20	20	20	20	20	20	20	20
Net Present Worth	**885**	**879**	**930**	**773**	**778**	**762**	**774**	**759**	**807**	**788**

Note: Costs (in $1,000 per mile), Interval (in year)

The Net Present Worth (NPW) for each alternative and % saving in LCC compared to the control case (i.e., Alternative 1: SP4/SP5) were computed and presented in Figure 4.13. Comparing to the control case, SP4/SP5 sections built in southern Nebraska showed a little saving, while SP4/SP5 sections in northern Nebraska presented about 5% increase in LCC, which is due to aggregate costs. Alternatives 4 to 6 clearly presented the economic benefits of RAP mixtures. By adding RAP of 35%, 40%, and 45% in SPR mixture, LCC decreased by 12.71%, 12.1% and 13.86%, respectively. The slight higher cost of SPR sections with 40% than SPR with 35% RAP is because of the higher maintenance cost to mitigate pavement damage when RAP content is 40% or more. However, the same SPR sections with 45% RAP can reduce LCC by 14.3% if they were built in southern area of Nebraska, as the sections were not quite susceptible to crack damage compared to the sections in northern Nebraska. Among all ten alternatives, it was the case presented the lowest LCC. This is due to the lowest mixture costs and marginal need of maintenance over the entire analysis period (50 years). The cost saving decreased when the pavement sections were built in northern Nebraska, as the sections require more intensive maintenance to mitigate crack damage observed in the colder region of Nebraska. Approximately 9-11% cost saving is expected from the northern sections with 40-45% RAP.

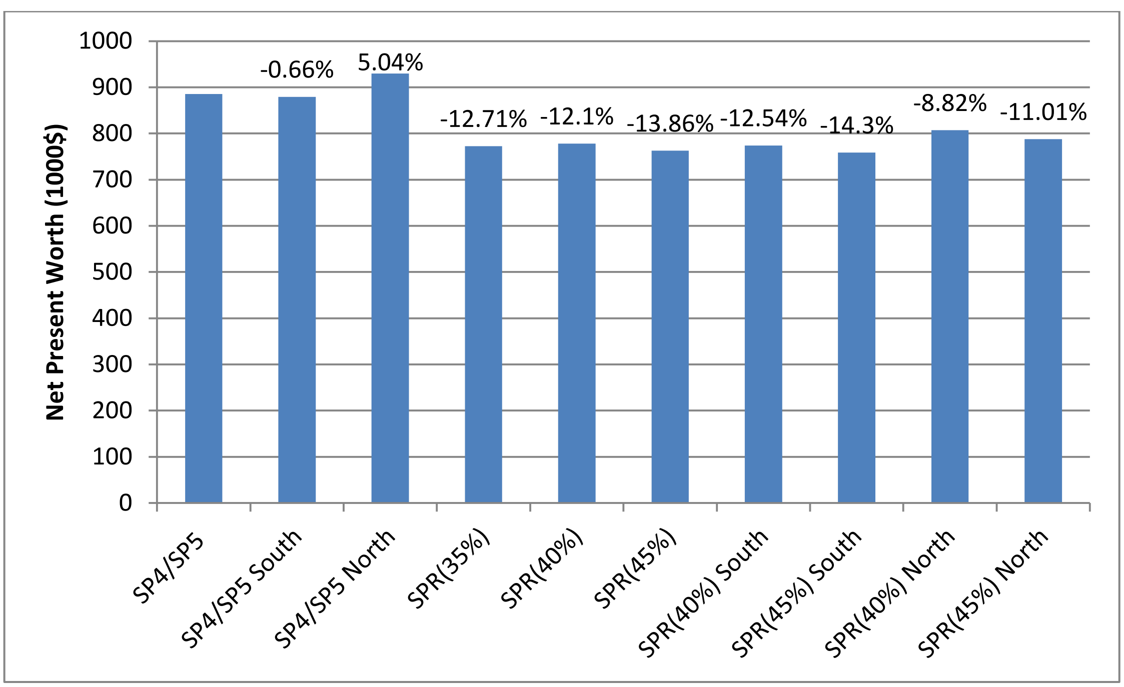


Figure 4.13 – Net Present Worth (NPW) Resulting from Each Alternative.

Chapter 5: Summary and Conclusions

This study used NDOT's database to investigate the effect of RAP amount (from 0% to 50%) on the overall behavior of pavement performance. Toward that end, we collected data of pavement performance, mixture design, traffic, and environment of total 254 pavement projects constructed between 2009 and 2012. Using the data, several analyses (such as descriptive, inferential, and life cycle cost) were conducted by interrelating field performance with mixture design where RAP contents vary. Based on the investigations conducted in this study, the following conclusions can be drawn:

- IRI and rutting were generally within the acceptable limits for all sections examined. Sections with high RAP content (up to 45%) showed no significant difference regarding IRI and rut depth when they were compared with other RAP sections. This may be because of their higher stiffness and resistance to permanent deformation.
- Projects constructed with 45% RAP in northern Nebraska reached the cracking limit (40%) and severity limit (0.4) after around 5-6 years in service. However, projects constructed with 25-45% RAP in southern Nebraska showed satisfactory performance in both cracking and severity up to 8 years in service.
- The LCCA results showed that SPR sections with RAP up to 45 percent could reduce costs by approximately 14% due to the reduced mixture costs compared to SP4/SP5 mixtures with lower RAP content, and it can further reduce costs when it is constructed in southern Nebraska due to lower aggregate costs. Mixtures in northern Nebraska indicated a slightly increased cost compared to mixtures in southern Nebraska.
- It should be noted that data collected and analyzed are for projects with ADT < 1600 and TADT < 200.

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