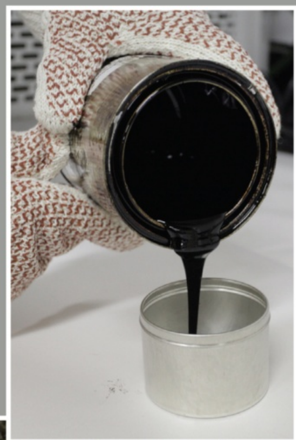
NCAT Report 16-02R



ENHANCED COMPACTION TO IMPROVE DURABILITY AND EXTEND PAVEMENT SERVICE LIFE: A LITERATURE REVIEW

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April 2016
(Revised October 2016)

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1. Report No. NCAT Report No. 16-02R	2. Government Accession No	3. Recipient's Catalog No

4. Title and Subtitle Enhanced Compaction to Improve Durability and Extend Pavement Service Life: A Literature Review	5. Report Date April 2016 (Revised October 2016) 6. Performing Organization Code
7. Authors Nam Tran, Ph.D., P.E., LEED GA; Pamela Turner; James Shambley	8. Performing Organization Report No. NCAT Report No. 16-02R
9. Performing Organization Name and Address National Center for Asphalt Technology at Auburn University 277 Technology Parkway Auburn, AL 36830	10. Work Unit No. 11. Contract or Grant No. DTFH61-11-H-00032
12. Sponsoring Agency Name and Address Federal Highway Administration Office of Asset Management, Pavements, and Construction 1200 New Jersey Avenue, SE Washington DC 20590	13. Type of Report and Period Covered Final 14. Sponsoring Agency Code FHWA

15. Supplementary Notes
FHWA Technical Contact: Timothy Aschenbrener, P.E.

16. Abstract

This literature review was conducted to provide information to support the FHWA Asphalt Pavement Technology Program strategic direction on extending pavement service life through enhanced field compaction. The results from the past studies clearly indicate the effect of low in-place air voids on the fatigue and rutting performance of asphalt pavements. A 1% decrease in air voids was estimated to improve the fatigue performance of asphalt pavements between 8.2 and 43.8% and the rutting resistance by 7.3 to 66.3%. In addition, a 1% reduction in in-place air voids can extend the service life by conservatively 10%. Based on these results, a life cycle cost analysis (LCCA) was conducted on two alternatives in which the exact same asphalt overlay would be constructed to 93% and 92% densities to illustrate the effect of in-place air voids on the life cycle cost of asphalt pavements. The LCCA results show that the user agency would see a net-present-value cost savings of $88,000 on a $1,000,000 paving project (or 8.8%) by increasing the minimum required density by 1%.

Due to its significant effect, the cost of providing increased in-place density can be significantly less than the operation, maintenance, and road user cost savings realized due to extended service life of the pavements. In an AASHTO survey of state agencies' targets for field compaction conducted in 2007, the majority of states responding to the survey had a compaction target of 92 percent, but over one-third of the responding agencies had compaction targets less than 92 percent. Most of these in-place density requirements currently adopted by states were determined based on what levels of in-place density could be achieved in the past using prior construction technologies. Since in-place density has a significant impact on the performance of asphalt pavements, agencies may consider implementing a higher in-place density requirement that can be achievable by following best practices and adopting new asphalt pavement technologies and knowledge gained from recent research. Some of these technologies and knowledge, including warm mix asphalt, intelligent compaction, improved construction joints, and improved agency specifications to incentivize achieving higher in-place densities, are briefly discussed in this report.

17. Key Words In-place density, air voids, field compaction, durability, service life	18. Distribution Statement No restriction. This document is available to the public through the National Technical Information Service 5285 Port Royal Road Springfield, VA 22161

19. Security Classif.(of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 25	22. Price

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Final Report

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April 2016
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ACKNOWLEDGEMENTS

This project was made possible by the Federal Highway Administration. The authors would like to thank the many personnel who contributed to the coordination and accomplishment of the work presented herein. Special thanks are extended to Timothy Aschenbrener, PE for serving as the technical representative.

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TABLE OF CONTENTS

1. INTRODUCTION 1

2. EFFECT OF AIR VOIDS ON PAVEMENT PERFORMANCE AND LIFE CYCLE COST 2
   2.1. Effect of Air Voids on Fatigue Performance 2
   2.2. Effect of Air Voids on Rutting Performance 4
   2.3. Effect of In-Place Air Voids on Service Life 6
   2.4. Effect of In-Place Air Voids on Life Cycle Cost 6
   2.4. Summary 7

3. NEW TECHNOLOGIES FOR ACHIEVING HIGHER IN-PLACE DENSITY 8
   3.1. Warm Mix Asphalt 8
   3.2. Field Compaction 10
   3.3. Improved Construction Joints 12
   3.4. Agency Specifications 13
      3.4.1. Project Selection 13
      3.4.2. Lift Thickness 13
      3.4.3. Mix Design 14
      3.4.4. Criteria 14
      3.4.5. Performance Incentives 15

4. SUMMARY 15

REFERENCES 17

1. INTRODUCTION

The Federal Highway Administration (FHWA) Pavement Policy in Title 23, Part 626, Code of Federal Regulations (23 CFR 626.3) states that “pavement shall be designed to accommodate current and predicted traffic needs in a safe, durable, and cost effective manner.” While safety is a paramount aspect of pavement that must always be maintained, improving the durability of pavement while maintaining cost effectiveness is becoming increasingly important due to financial realities currently facing state highway agencies (SHAs).

Significant advancements in technology and techniques related to asphalt pavement design and construction yield the potential for increasing both durability and cost effectiveness. Some of these advancements can be employed immediately to enhance field compaction to reduce in-place air voids and improve mixture durability and pavement service life.

Currently, most SHAs use a percentage of the theoretical maximum specific gravity (G_{mm}) to quantify in-place air voids (or in-place density) for acceptance of construction. Other agencies may use a control strip or method specifications to control density. Figure 1 shows the results of a 2007 American Association of State Highway Transportation Officials (AASHTO) Survey of SHAs’ targets for field compaction normalized to G_{mm}. The majority of states responding to the survey have a compaction target of 92%, but over one-third of the responding SHAs have compaction targets less than 92%.

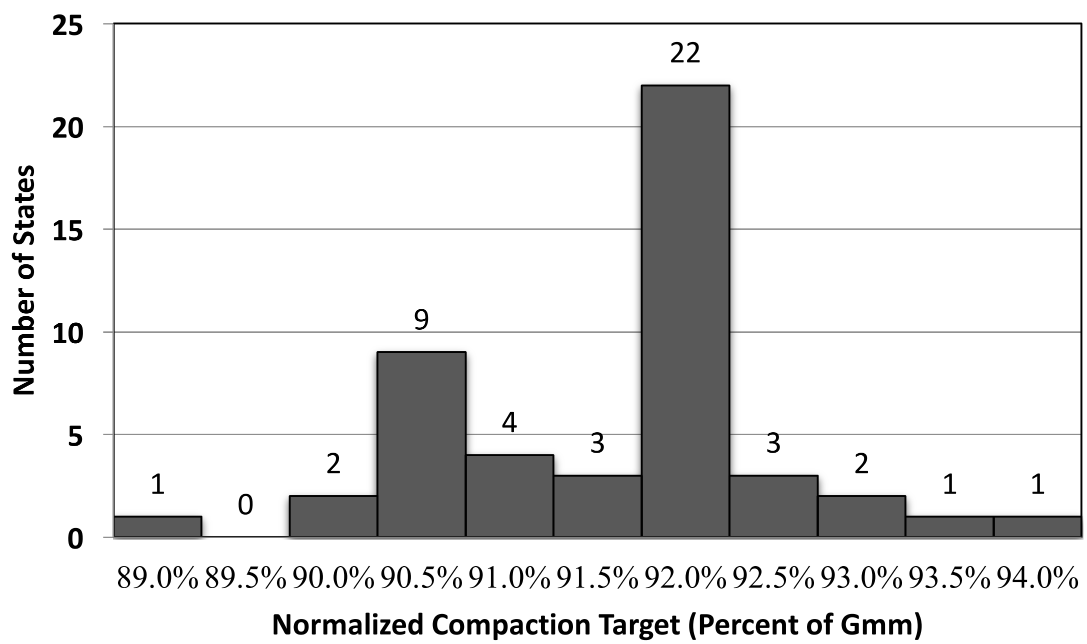

Figure 1. Normalized Compaction Targets by State (Source: AASHTO 2007 SOM Survey)

Most of the compaction targets shown in Figure 1 were determined based on historical data and experience with prior construction technologies. They were based more on what levels of in-place density could be achieved in the past than on optimal in-place densities. With modern design and construction methods and equipment, optimal in-place densities can be achievable with appropriate guidance, specifications, and incentives.

Past studies have shown that a small increase in in-place density through roadway design, mix design, and/or construction can lead to a significant increase in service life of asphalt pavements. According to Epps and Monismith (1971), Finn and Epps (1980), and Puangchi, et al. (1982), fatigue life (the time from original construction to significant fatigue cracking) of asphalt pavements is reduced approximately 10 to 30% for every 1% increase in in-place air voids. Thus, for the states currently requiring a compaction target below 92%, an increase of 10 to 30% in the pavement service life can be achieved by raising the compaction target by 1%.

Due to its significant effect, the cost of providing this increased in-place density can be significantly less than the operation, maintenance, and road user cost savings realized due to extended service life of the pavements. As Noel stated at the 1977 Association of Asphalt Paving Technologists (AAPT) meeting, "the single most important construction control that will provide for long-term serviceability is compaction" (Hughes et al. 1989).

Recognizing the importance of in-place density in building cost effective asphalt pavements, this literature review was tasked to provide information to support the FHWA Asphalt Pavement Technology Program strategic direction on extending pavement service life through enhanced field compaction. In the following sections, the effect of air voids on laboratory and field performance of asphalt mixtures is first discussed, followed by a summary of best practices for achieving higher in-place density.

2. EFFECT OF AIR VOIDS ON PAVEMENT PERFORMANCE AND LIFE CYCLE COST

Several studies have been conducted to determine the effect of air voids on performance characteristics of asphalt mixtures, including fatigue cracking and rutting. Key findings from past laboratory and field studies on the effect of air voids on each of the performance characteristics are first summarized in this section, followed by a life cycle cost analysis to quantify the effect of in-place air voids on the life cycle cost.

2.1. Effect of Air Voids on Fatigue Performance

Epps and Monismith (1969) conducted one of the first major laboratory studies on the effect of air voids on laboratory fatigue performance of asphalt mixtures at the University of California at Berkeley (UCB). In this study, constant stress fatigue testing was conducted on three asphalt mixtures. The first mix was referred to as British Standard 594 Grading with 7.9% binder content. The second mix was referred to as California Fine Grading with 6% binder content, and the third mix was referred to as California Coarse Grading with 6% binder content. Twenty-six tests were reported for the first mix with specimen air voids varied between 4% and 14%, 22 tests reported for the second mix with air voids varied between 5% and 8%, and 20 tests reported for the third mix with air voids varied between 2.5% and 7%. Based on the test results reported, the effect of 1% increase in air voids on fatigue performance reduction was estimated to be 20.6%, 43.8%, and 33.8% for the first, second, and third mix, respectively (Seeds et al. 2002).

Harvey and Tsai (1996) conducted another laboratory fatigue experiment at UCB using the flexural bending beam test developed under the Strategic Highway Research Program (SHRP). In this experiment, a dense-graded asphalt mixture with an AR-4000 binder was tested based on a full factorial design with three levels of air voids and five levels of binder contents. The three air void levels, including 1% to 3%, 4% to 6%, and 7% to 9%, were selected based on the range typically obtained in California with the specification at the time and to provide data for the evaluation of higher compaction standards. A relationship between cycles to fatigue failure, air voids, binder content, and applied strain was determined based on 97 fatigue test results. Based on this relationship, a 1% increase in air voids was estimated to result in a 15.1% reduction in fatigue performance (Seeds et al. 2002).

A major research effort that included both laboratory and field studies was conducted a few years later as part of the WesTrack project (Epps et al. 2002) to investigate the effect of changes in air void content, binder content, and aggregate gradation on mixture and pavement performance characteristics. Three asphalt mixtures with fine, fine-plus, and coarse aggregate gradations were evaluated. During construction, the binder content and in-place air void content were varied to yield seven unique treatment combinations for each mix. Three levels of in-place air voids were selected, including 4%, 8%, and 12%. The intermediate level (i.e., 8%) was selected to represent a typical in-place air void content in pavements. The low and high levels (i.e., 4% and 12%) were selected to represent expected extremes in in-place air voids experienced in asphalt pavement construction. The separation of 4% between the three air void levels was considered sufficient to ensure that statistical differences would exist between the low- and medium-level sections and between the medium- and high-level sections. The effect of changes in mixture properties on the fatigue performance was investigated both in the laboratory and in the field.

As part of the laboratory experiment, fatigue testing was conducted on beams extracted from the WesTrack (Epps et al. 2002). Seven unique mix combinations plus two replicates were tested for the fine mix, seven unique mix combinations plus one replicate tested for the fine-plus mix, and seven unique mix combinations plus two replicates tested for the coarse mix. Based on the laboratory test results, a relationship between cycles to failure, air void content, binder content, pavement temperature at 6-inch depth, and maximum strain was developed for each of the three mixes. Based on these relationships, a 1% increase in air voids was estimated to reduce the fatigue performance of fine, fine-plus, and coarse mixes by 13.5%, 13.3%, and 9%, respectively (Seeds et al. 2002).

For the field experiment, the performance of WesTrack test sections varied significantly, and some sections never showed fatigue cracking at the end of the experiment. The relationships between load applications or number of equivalent single axle loads (ESALs) to 10% fatigue cracking and other mixture properties, including air void content, binder content, and fines content, were developed based on a probabilistic regression approach to take into account the performance of sections that never exhibited fatigue cracking. Two models were developed: one for 17 test sections with fine and fine-plus mixes (14 unique mix combinations plus three replicates); and the other for nine test sections using coarse mixes (seven unique mix combinations plus two replicates) (Epps et al. 2002). Based on the relationships developed in the field experiment, the effect of 1% increase in in-place air voids on field fatigue performance reduction was estimated to be 21.3% and 8.2% for the fine/five-plus and coarse mixes, respectively (Seeds et al. 2002).

More recently, the Asphalt Institute (AI) conducted a laboratory study to evaluate the effect of air voids on the performance of a typical Kentucky asphalt mixture (Blankenship and Anderson 2010). The flexural bending beam test was conducted at five strain levels on beam specimens prepared at various air void levels between 4% and 11.5%. The laboratory testing results showed that the effect of air voids on the fatigue life of the asphalt mixture became more pronounced at lower strain levels (i.e., 350 and 400 microstrain). At 350 microstrain, the fatigue performance reduced by 42% as the air void content increased from 7% to 11.5% (Fisher et al. 2010). This corresponds to a 9.2% reduction in fatigue life for a 1% increase in air voids.

In summary, results from the past studies clearly indicate the adverse effect of increased in-place air voids on the fatigue performance of asphalt pavements. Table 1 summarizes these results. Depending on the mix type and experiment, a 1% decrease in air voids was estimated to improve the fatigue performance of asphalt pavements between 8.2 and 43.8%.

Table 1. Effect of Air Voids on Fatigue Performance

Study	Lab/Field Experiment	Mix Type	Air Voids Evaluated	Increase in Fatigue Life for 1% Decrease in Air Voids
UCB (Epps and Monismish 1969)	Lab	British Standard	4 - 14%	20.6%[1]
		California Fine	5 - 8%	43.8%[1]
		California Coarse	2.5 – 7%	33.8%[1]
UCB (Harvey and Tsai 1996)	Lab	California Dense-Graded	1 - 3% 4 - 6% 7 - 9%	15.1%[1]
WesTrack (Epps et al. 2002)	Lab	Fine	4, 8, 12%	13.5%[1]
		Fine-Plus	4, 8, 12%	13.3%[1]
		Coarse	4, 8, 12%	9.0%[1]
	Field	Fine/Fine-Plus	4, 8, 12%	21.3%[1]
		Coarse	4, 8, 12%	8.2%[1]
AI (Fisher et al. 2010)	Lab	9.5 mm Dense-Graded	4 – 11.5%	9.2%

[1] (Seeds et al. 2002)

2.2. Effect of Air Voids on Rutting Performance

The effect of changes in mixture properties, including air void content, binder content, and aggregate gradation, on rutting performance was also investigated in a field study as part of the WesTrack project (Epps et al. 2002). Unlike the fatigue cracking evaluation previously described, this investigation was only conducted based on rutting data measured on WesTrack test sections through the first two million equivalent single axle loads (ESALs). Three analyses were conducted for the rutting data. Level 1A analysis was based on a direct regression correlating rut depth to traffic, air temperature, and mixture properties. This analysis was conducted on 26 original and eight replacement sections. Level 2 analysis included mechanistic-empirical analyses of all the data assuming the pavement behaves as a multilayer elastic system. Level 1B analysis was a regression correlating rut depth to traffic, air temperature, and mixture information that was generated based on the Level 2 analysis of 23 test sections that exhibited no or little fatigue cracking. Results of Level 1A and 1B analyses are of particular interest to this literature review and are discussed in the following paragraphs.

For the Level 1A analysis, three separate rutting models were developed. The first one was developed for the fine and fine-plus mixes based on the data collected in 17 test sections (14 unique mix combinations plus three replicates). The second one was generated for nine original coarse mixtures (seven unique mix combinations plus two replicates). The third model was developed for eight coarse mixtures in the replacement sections (seven unique mix combinations plus one replicate) (Epps et al. 2002). Based on the Level 1A models, a 1% increase in in-place air voids was estimated to reduce the rutting resistance of fine/fine-plus, original coarse, and replacement coarse mixes by 11.5%, 9.6%, and 66.3%, respectively (Seeds et al. 2002).

From the Level 1B analysis, one model was developed with dummy variables (i.e., 0 or 1) to account for the effect of mix type on rutting. This model essentially consists of three separate models: one for fine and fine-plus mixes, one for original coarse mixes, and the other for replacement coarse mixes. Based on this model, a 1% increase in air voids corresponds to a 7.3% reduction in rutting resistance for the fine, fine-plus, and coarse mixes. In addition, a 1% increase in air voids was estimated to cause a 10.9% decrease in rutting resistance for the replacement coarse mixes (Seeds et al. 2002).

In the AI study (Blankenship and Anderson 2010), the effect of air voids on the rutting performance of an asphalt mixture was evaluated using the flow number test in accordance with AASHTP TP 79. The flow number test results showed that the rutting resistance of the mixture decreased by 34% as the air voids increased from 7% to 8.5%. This corresponds to a 22.7% reduction in rutting resistance for a 1% increase in air voids.

In summary, results from past studies clearly indicate the adverse effect of increased in-place air voids on the rutting of asphalt pavements. The effect is summarized in Table 2. Depending on the mix type and analysis, a 1% decrease in air voids was estimated to improve the rutting resistance of asphalt mixtures by 7.3 to 66.3%.

Table 2. Effect of Air Voids on Rutting Performance

Study	Lab/Field Experiment	Mix Type	Air Voids Evaluated	Final Field Rut Depth (mm)	Decrease in Rutting for 1% Decrease in Air Voids
WesTrack (Epps et al. 2002)	Field Level 1A	Fine/Fine-Plus	4, 8, 12%	9 - 35	11.5%[1]
		Original Coarse	4, 8, 12%	13 - 36	9.6%[1]
		Replacement Coarse	4, 8, 12%	12 - 26	66.3%[1]
	Field Level 1B	Fine/Fine-Plus/Coarse	4, 8, 12%	9 - 36	7.3%[1]
		Replacement Coarse	4, 8, 12%	12 - 26	10.9%[1]
AI (Fisher et al. 2010)	Lab	9.5 mm Dense-Graded	4 – 11.5%	N/A	22.7%

[1] (Seeds et al. 2002); N/A = Not Applicable

2.3. Effect of In-Place Air Voids on Service Life

In a recent study to develop performance-related pay adjustment factors for the New Jersey Department of Transportation (NJDOT), Wang et al. (2015) analyzed construction and performance data of pavements in New Jersey. Among several factors identified by the authors, the average in-place air voids measured through field core testing were found to impact the service life of asphalt mixtures, as illustrated in Figure 2. The service life is defined as the time from initial construction until the next rehabilitation activity for each pavement section. The data were mined from the NJDOT's pavement management system and Materials Bureau quality assurance testing database for 55 pavement sections. The correlation shown in Figure 2 indicates that the service life decreases approximately one year for every 1% increase in the in-place air voids. This corresponds to an approximate 10% increase in asphalt mixture service life for a 1% decrease in in-place air voids.

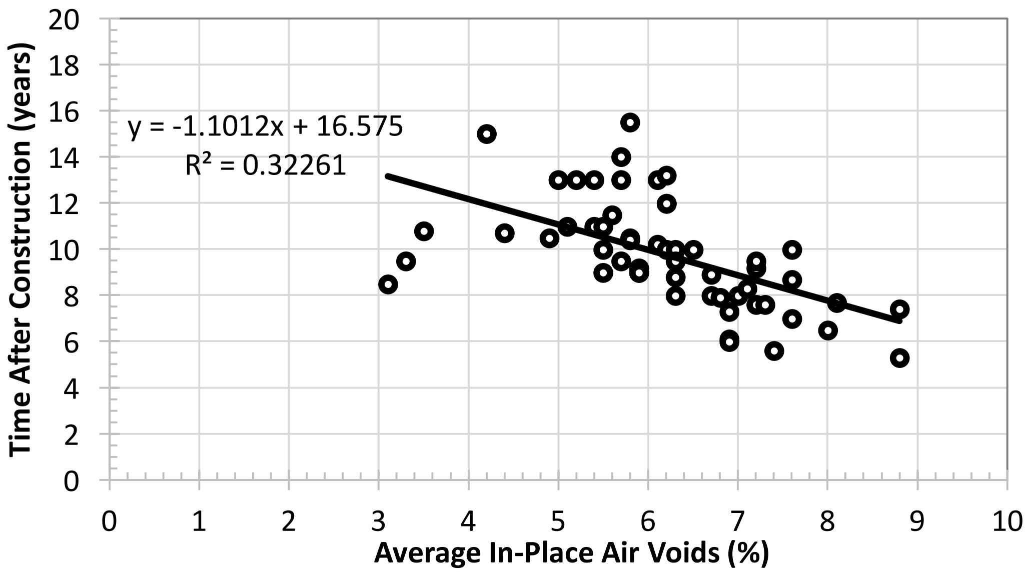

Figure 2. Correlations between Average Air Voids and Service Life of Asphalt Mixtures (Wang et al. 2015)

2.4. Effect of In-Place Air Voids on Life Cycle Cost

The results of the past studies on the effect of air voids on the fatigue and rutting performance and service life of asphalt mixtures, as discussed in the previous sections, suggested that increasing the asphalt pavement density by 1% would have the effect of increasing the service life of the asphalt mixture by conservatively 10%. For illustration purposes, this means that an asphalt overlay constructed to 93% density might be expected to last 20 years, while the exact same asphalt overlay constructed to 92% density would only be expected to last 18 years. Figure 3 shows an analysis comparing the life cycle costs of the two overlays over a period of 20 years. Also, it is assumed that the cost of providing a 1% increase in in-place density is negligible; therefore, the same initial cost is used for both the alternatives in this analysis.

In Alternative 1, the asphalt overlay constructed to 93% density was expected to last 20 years. The agency cost for the initial overlay construction (i.e., the present value (PV) at year 0) was assumed to be $1,000,000. At year 20, the overlay would be replaced; thus, the salvage value (SV) for this overlay at year 20 would be $0. The net present value (NPV) for Alternative 1 would be $1,000,000.

In Alternative 2, the exact same asphalt overlay would be constructed to 92% density. The initial construction cost for this overlay (i.e., PV at year 0) was assumed to be $1,000,000. This overlay was expected to last 18 years. At year 18, it would be replaced with a new one. The future cost (i.e., future value (FV) at year 18) for the exact same replacement overlay would be $1,000,000. It was also expected to last 18 years. Thus, at year 20, the remaining life for the replacement overlay would be 16 years, and its salvage value of $889,000 would be a prorated share of the replacement overlay cost. Using a real discount rate of 4%, the replacement overlay cost (i.e., FV at year 18) and its remaining value (i.e., RV at year 20) would be discounted back to year 0. The NPV for Alternative 2 would be $1,088,000.

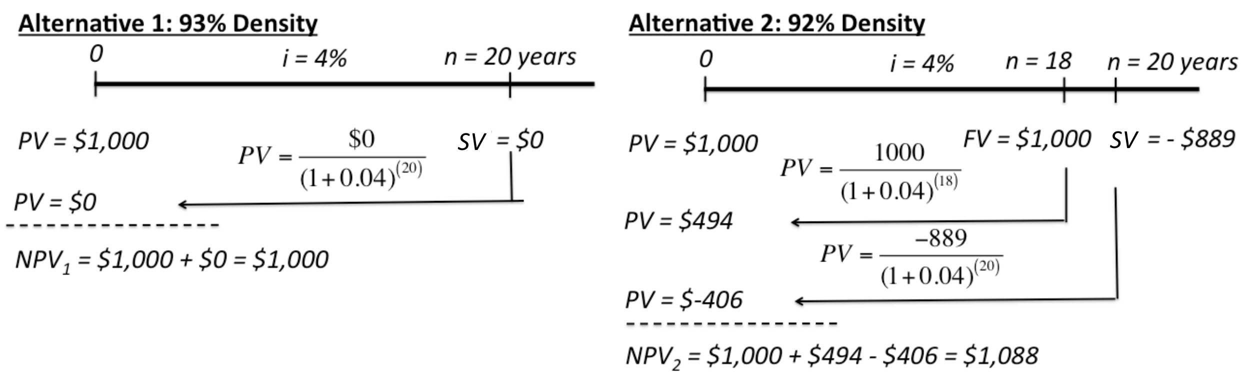

Figure 3. Life Cycle Cost Analysis (per $1,000)

Based on the life cycle cost analysis (LCCA) for the two alternatives, the user agency would see an NPV cost savings of $88,000 on a $1,000,000 paving project (or 8.8%) by simply increasing the minimum required density by 1%. This was a conservative estimate without taking into account potential higher user delay costs due to the earlier replacement overlay at year 18.

2.4. Summary

The results from the past studies clearly indicate the adverse effect of increased in-place air voids on the fatigue and rutting performance of asphalt pavements. A 1% decrease in air voids was estimated to improve the fatigue performance of asphalt pavements between 8.2 and 43.8%, to improve the rutting resistance by 7.3 to 66.3%, and to extend the service life by conservatively 10%.

To illustrate the effect of in-place air voids on the life cycle cost of asphalt pavements, an LCCA was conducted on two alternatives in which the exact same asphalt overlay would be constructed to 93% and 92% densities. Using the conservative 10% increase in service life, the

LCCA results showed that the user agency would see an NPV cost saving of $88,000 on a $1,000,000 paving project (or 8.8%) by increasing the minimum required density by 1%.

3. NEW TECHNOLOGIES FOR ACHIEVING HIGHER IN-PLACE DENSITY

Most of the in-place density requirements currently adopted by SHAs were determined based on what levels of in-place density could be achieved in the past using prior construction technologies. Since in-place density has a significant impact on the performance of asphalt pavements, a higher in-place density, which results in a longer pavement service life, may provide a significant cost saving to SHAs and the traveling public. Agencies may consider implementing a higher in-place density requirement, which can be achievable by following best practices and adopting new asphalt pavement technologies and knowledge gained from recent research. These technologies and knowledge include warm mix asphalt, intelligent compaction, improved construction joints, and improved agency specifications to incentivize achieving higher in-place densities. In the following sections, each of these technologies is briefly discussed.

3.1. Warm Mix Asphalt

The term warm mix asphalt (WMA) refers to asphalt mixtures that can be produced at temperatures that are typically 25°F to 90°F lower than standard hot mix asphalt (HMA) production temperatures. The WMA technologies can be considered compaction aids. They can be used to improve the workability of the asphalt binder, to increase time for mixture compaction during normal paving operations, and to enhance compaction during cold weather paving.

There are several categories of WMA technologies and processes commercially available, including asphalt foaming technologies, chemical additives, organic additives, and combinations of these technologies (Prowell et al. 2012). The asphalt foaming technologies may use water-injection systems, damp aggregate, or hydrophilic materials such as zeolite to foam asphalt. The foaming process temporarily expands the binder volume and fluid content, which helps improve coating and compaction. Available chemical additives often include surfactants to aid in coating and lubrication of the asphalt binder in the mixture. The organic additives are typically special types of waxes that cause a decrease in binder viscosity above the melting point of the wax. To use these additives, wax properties should be carefully selected based on the planned in-service pavement temperatures to reduce the risk of permanent deformation. Approximately 20 WMA technologies are currently marketed in the United States. More information about each WMA technology commercially available can be found in Quality Improvement Publication 125, *Warm-Mix Asphalt: Best Practices* (Prowell et al. 2012).

Several studies have been conducted to evaluate the ability of WMA to provide similar pavement quality as standard HMA mixtures. The WMA mixtures used in these studies were produced at much lower temperatures than the comparable HMA mixtures. Some recent studies are discussed in the following paragraphs.

In 2009, Estakhri et al. evaluated WMA for use in the state of Texas. A section of Old Austin Highway (Loop 368) was resurfaced by the Texas Department of Transportation (TxDOT) using a standard HMA mixture and an Evotherm WMA mixture. Both mixtures met the requirements for a TxDOT Item 341 Type C dense-graded mix, and both binders met the requirements for PG 76-22. The production temperature for the HMA was 320°F, while the production temperature for the WMA was reduced to 220°F. At the time of placement, the HMA temperature was around 305°F while the WMA temperature ranged from 170 °F to 210°F. Both mixes were compacted to a 2-inch mat thickness using the same roller pattern over the course of three nights. Nuclear density tests on the compacted mat showed that the control HMA mixture achieved an average in-place density of 94.2% and the WMA densities averaged approximately 93.6%. Overall it was determined that the WMA could be compacted to similar to slightly higher in-place densities as the HMA mixture at reduced compaction temperatures.

A study performed by the National Center for Asphalt Technology (NCAT) in 2010 evaluated three WMA technologies used in a field trial sponsored by the state of Missouri. The project began as an overlay of an existing concrete pavement that had previously been overlaid with HMA mix. During the overlay process, the contractor noticed that the pavement had poor initial smoothness results, which were believed to be due to the rubberized crack sealant used on the concrete pavement. The high temperatures used for the HMA caused the sealant to expand, increasing the roughness of the new overlay. The contractor then approached the state about the use of WMA, which they believed might reduce the softening of the crack sealant and provide a smoother pavement. The mix placed was a 12.5-mm Superpave mix with 10% reclaimed asphalt pavement (RAP) and a polymer modified PG 70-22 binder. The three WMA technologies evaluated were Aspha-min zeolite, Sasobit, and Evotherm ET. A control HMA section was placed for comparison. All sections were placed during a 10-day period in May of 2006. The control HMA was produced at 320°F, and the WMA mixes were initially produced at 275°F. Once it was determined that in-place densities and constructability were acceptable, the Evotherm and Sasobit production temperatures were lowered to 225 and 240°F, respectively. Field cores were used for evaluating in-place density. Overall, the researchers reported no difficulty obtaining the required in-place density values with the WMA mixes (Hurley 2010).

A similar study in Colorado evaluated Advera, Sasobit, and Evotherm DAT compared to a control mix placed on I-70, about 70 miles west of Denver. The project was approximately nine miles long and consisted of a 2.5” mill followed by a 2.5” overlay. Each WMA was placed in a one-mile test section adjacent to an HMA section for comparison purposes. The HMA mix was produced at a target temperature of 305°F, while the WMA mixes were produced approximately 50°F lower. In-place densities were measured using a nuclear density gauge. The initial construction data showed that the Advera and Sasobit sections had in-place densities that were similar or slightly lower than the HMA control section. The Evotherm in-place density was approximately 1% higher than that of the control section. All of the WMA and HMA sections easily met the target initial in-place density requirements (i.e., 92% to 96% of G_{mm}). A three-year evaluation of the test sections also found that the WMA performance during that time was similar to the HMA control section (Aschenbrener 2011).

An evaluation of pilot projects using WMA in the state of Connecticut in 2010 and 2011 evaluated the effect of warm mix additives on pavements placed in several locations throughout the state. Warm mix technologies used in this study included: Sasobit (with and without SBS polymer), Evotherm, Advera, SonneWarmix, and mechanical foaming (with and without SBS polymer). The pavements were placed over the course of two paving seasons, with

Connecticut Asphalt Paving Laboratory (CAPLab) personnel monitoring the placement of the pavement. Reduction in compaction temperature varied with WMA technology, but in most cases was around 30 to 50°F lower than the temperatures at which the HMA control sections were placed. The only exception was the mix containing Sasobit plus SBS polymer. This mix initially experienced difficulty achieving the target in-place density (92% of G_{mm}). To rectify this issue, the production temperature was increased. Construction records from the Connecticut projects showed that, with few exceptions, the mixes containing WMA additives provided comparable in-place densities to those with HMA (Zinke 2014).

In 2014, the Washington DOT published a report on the rehabilitation of approximately 10 miles of Interstate 90. For this project, three inches of existing pavement were milled off and replaced by an equal depth of either HMA or WMA (Sasobit). The project used a 12.5-mm mix placed over a 5-day period in June of 2008. The same equipment and methods were used for both mixes. Haul times for the HMA mix were around 30 – 45 minutes. Haul times for the WMA mix were around 30 minutes. The only issue reported during construction was the presence of clumps in the WMA mix. It was determined that the clumps had formed during the hauling of the WMA and were due to cooling of the mix. It was recommended that the WMA be remixed in a windrow device to reheat it prior to compaction in order to maintain a consistent temperature and to eliminate any clumps that had formed. Measurements of density showed that on average, the HMA was compacted to a density of 93.5% (standard deviation = 1.58) and the WMA was compacted to an average of 93.7% density (standard deviation = 1.36). It was also noted that the WMA had fewer instances of failing density than the HMA. Overall, the researchers felt that these results indicated that the WMA mix could be compacted to the same level of density as the HMA at lower compaction temperatures (Anderson 2014).

Based on a review of studies comparing the compaction of WMA to the compaction of HMA, it appears that WMA can be compacted to similar in-place densities at much lower compaction temperatures. The implications of this include improved in-place densities for projects requiring longer haul times (increased temperature loss during transit) and improved in-place densities during cold weather construction.

3.2. Field Compaction

Asphalt pavement density does not increase linearly with additional compaction; rather, it changes randomly “due to continuous reorientation of aggregates and the randomness of aggregate shapes and textures” (Beainy et al. 2014). In general, compaction uniformity and overall compaction are increased through additional roller passes. There have been many recent advances in compaction equipment, and construction practices regarding compaction have been analyzed much more closely. The use of vibratory rollers, oscillatory rollers, or vibratory pneumatic tire rollers can achieve optimized in-place density when properly employed.

The rolling pattern, frequency, drum spacing, amplitude, and temperature controls of vibratory rollers are critical to achieve proper compaction without causing aggregate damage to the asphalt pavement structure. Rolling patterns should be optimized based on the drum-width-to-panel-width relationship. Vibration frequency and drum diameter should be used to determine the appropriate rolling speed for double-drum vibratory rollers. Advances in vibratory roller manufacturing have led to the advent of high frequency rollers to enable faster rolling speeds where a vibratory roller can complete breakdown rolling and keep up with the paver, even while completing a seven-pass pattern. Vibratory drum spacing should be based on drum diameter to ensure the smoothness of pavement surfaces. Finally, monitoring the surface HMA pavement temperature zones through the use of real-time infrared sensors can allow operators to monitor ideal compaction times (Starry 2006). Whether asphalt mixtures are stiff or tender, breakdown or initial rollers should be used immediately following the paver to ensure that the mixture is compacted while hot (Scherocman 2006). By optimizing and automating these variables, the effectiveness of achieving higher in-place densities with vibratory rollers can be greatly improved.

The asphalt paving industry has also seen the introduction of new vibratory rollers equipped with an integrated Intelligent Compaction (IC) system. This system may include an onboard computer, Global Positioning System (GPS) based mapping, and optional feedback controls. It allows real-time monitoring of compaction and adjustments as needed to achieve optimum density and uniform coverage. In addition, color-coded mapping provides a continuous record showing the location of the roller, number of roller passes, and material stiffness measurements. During compaction, the location of the roller, its speed, number of passes, and coverage can be monitored using the GPS. Compaction meters or accelerometers mounted in the drum monitor the applied compaction effort, frequency, and material response. Some rollers also have temperature instrumentation that allows monitoring of the surface temperature of asphalt paving materials. Optional feedback controls can continuously adjust the force and frequency of the compactor drum. The IC display informs the operator when the desired level of compaction is reached, eliminating unnecessary passes and making the compaction process more efficient. The IC display also notifies the operator when the desired compaction level has not been reached, allowing for further analysis and remedial actions to correct the issue, thus potentially achieving better final density values.

Several studies have attempted to evaluate if a correlation could be developed between IC stiffness measurements and in-place density measurements, thereby eliminating the need for other quality control/quality assurance (QC/QA) density tests (Minchin et al. 2001, Maupin 2007, Chang et al. 2011, Chang et al. 2014). The results of these studies show that the relationship between IC measurements and in-place density is inconsistent. Several factors were found to affect the ability of the IC to correlate with traditional measurements (either nuclear density gauge (NDG) or laboratory testing of cores) of in-place density. These factors include the stiffness of the underlying layers, temperature of the pavement mat during compaction, reliability of the nuclear density gauge (NDG) readings, differences in material versus mechanical properties being measured, and instrumentation. For this reason, it appears that IC measurements are currently not a good candidate for replacing laboratory core density testing as an acceptance test for HMA paving. The use of IC does, however, show some potential as a real-time measure of compaction and may be useful for quality control and for identifying locations on the paving mat that may not have achieved the desired compaction level and that may not be identified by NDG testing.

In summary, there have been several advances, such as the integrated IC system, in compaction equipment and practices in the past few years. These new technologies make it easier to optimize and automate some compaction parameters, such as rolling pattern, frequency, drum spacing, amplitude, and temperature control, to achieve higher in-place densities. In addition, the use of GPS based mapping provides real-time monitoring of compaction and a continuous record that shows the location of the roller, the number of roller passes, and material stiffness measurements to achieve uniform coverage. While the IC system helps improve the compaction process, it is not used in place of traditional laboratory core density testing as an acceptance test for HMA paving at this time.

3.3. Improved Construction Joints

Many asphalt pavement failures can be attributed to insufficient compaction of longitudinal joints. These failures are primarily affected by the density of the free edge of a lane; the compaction of the material in the joint; and how well the hot side of the joint is compacted. The construction of longitudinal joints requires precise workmanship to achieve optimal compaction. One sequence of methods to achieve required compaction is to compact the first lane with the roller overhanging the edge by six inches, followed by placing the second layer with a one to one-and-a-half inch overlap of the first layer dictated by the edger plate on the paver screed. Finally, lane two should be compacted from the hot side with the outside tire of a rubber tire roller directly on the joint or by a steel drum roller with the drum extending six inches over the top of the joint (Benson and Scherocman 2006).

Several technologies have also been implemented in recent years to improve construction of longitudinal joints. One of these technologies employed to enhance the compaction of the free edge is the proper selection and application of tack coat or asphalt/rubberized sealants (Brown 2006). Tack coats can minimize movement of the asphalt mix under the roller; however, the application of tack coats does not necessarily lead to enhanced compaction. Another recent technology employed is the use of infrared heaters to reheat the edge of pavement when placing an adjacent lane. Historically, there have been many different types and sizes of joint heaters used to improve joint density and performance, and the results have been mixed. There have been some major improvements to joint heater equipment that includes longer, more efficient heaters, and automation with paver speed that greatly minimizes over and under-heating (AI 2016, Brown 2006). Recent longitudinal joint studies in Iowa (Williams 2013), Arkansas (Williams 2011), and Tennessee (Huang 2010) have shown that infrared heaters can increase longitudinal joint density. Yet another construction practice to improve longitudinal joint compaction is the use of a tapered joint to facilitate the transition and compaction from a previously placed asphalt lane to an adjacent hot lane (Brown 2006). The quality of compaction and alignment can be hard to achieve within this wedge joint; however, this practice also has the added benefit of easing the transition between lanes for the motoring public during construction. In this case, it may be beneficial to cut back the under-compacted mix in the wedge of the first lane as it is specified for airfields and by some state agencies.

Material directly in the longitudinal joint may lack proper compaction due to too small of an overlap between adjacent layers or too little asphalt being applied near the joint. These problems can be caused by poor screed alignment, poor auger operation on the paver, or lute operations that remove and starve the joint. The compaction of material on the hot side of the joint can also be significantly impacted by the quantity of material placed at the joint. When compacted, loose asphalt mix often decreases in volume by about 20%. If this volume change is not taken into account, too little asphalt mix may be placed adjacent to a previously placed layer causing an insufficient level of in-place density to be met. Once the newly placed asphalt is compacted to the same thickness as the previously placed asphalt lane, very little additional compaction can be achieved on the hot side of the joint (Brown 2006). More information about best practices for construction and specifying asphalt pavement longitudinal joints is available on Asphalt Institute's website (2016).

3.4. Agency Specifications

As early as 1989, Hughes et al. recommended a realistic target average value of 93% of theoretical maximum density with a standard deviation of 1.5%. While some states have adopted higher target values for in-place density, additional improvements in roadway service life could be realized if specifications required minor increases in the in-place densities. A lack of universal in-place density guidance has made implementation of standards difficult as construction practices, test protocols, and materials have resulted in changes to pavement structures (Seeds et al. 2002). With modern methods and equipment, these minor increases are very feasible if appropriate guidance and specifications are implemented.

It should be noted that several challenges may hinder the efficacy of increasing in-place density of asphalt pavements to increase service life in a cost effective manner. First, appropriate project selection must be considered. The structure of the pavement base must be considered as a primary criterion for implementing increased in-place density requirements. The use of increased in-place density is most applicable to structural overlays rather than functional overlays. If functional overlays are placed on weak bases, it may be very difficult to obtain even minimal in-place density requirements. As a part of project selection, the pavement design must consider appropriate lift thicknesses based on nominal maximum aggregate size (NMAS) and coarse gradations. Also, the mix design must include proper asphalt content for desired in-place air voids. Finally, to fully implement a requirement for increased in-place density, test methods for measuring field compaction must be standardized and acceptance criteria and performance incentives must be established to properly motivate and reward construction contractor performance (Aschenbrener et al. 2015).

3.4.1. Project Selection

When choosing a project targeted for higher in-place density, SHAs should evaluate the underlying base for new projects or asphalt layers during overlay operations. Optimal compaction may be difficult to achieve when underlying layers are not sufficiently supportive. Even if optimal compaction is achievable in the new asphalt layers, the overall gain in long-term performance may be minimized by defects in the underlying layers.

3.4.2. Lift Thickness

Based on studies by Moutier (1980) and further analysis by Zeinali (2014), compaction effectiveness could be directly improved by increasing lift thickness. Asphalt pavement compaction is primarily impacted by the absolute thickness of the layer being compacted, the thickness compared to the NMAS, and the uniformity of the thickness. As the absolute lift thickness increases, the time available for compaction increases due to the thicker lift cooling more slowly. To provide sufficient lift thickness for the aggregate particles to re-orient and pack together during the compaction process, the minimum lift thickness should be three and four times the nominal maximum aggregate size for fine and coarse dense-graded mixes, respectively. Ruts greater than one-half inch should be milled before overlays are placed due to the potential for roller bridging leading to uneven compaction. When using vibratory rollers, "the depth of penetration of the compaction energy imparted… depends on the weight of the roller as well as the amplitude and frequency of the vibrations. For a given setting of amplitude and frequency, the density achieved depends on the thickness of the mat and the underlying pavement layers" (Beainy et al. 2014).

3.4.3. Mix Design

Optimal field performance of asphalt mixtures can be achieved by using quality materials and properly controlling volumetric properties. Asphalt binders should be properly selected based on their performance properties related to the conditions under which they are used. Aggregates need to be hard, sound, durable, angular, and properly graded for best performance. Finally, these constituent materials need to be properly combined in mix designs to meet specific volumetric requirements. State DOTs have specification requirements to ensure that satisfactory quality materials and mixtures are used. The specification requirements are typically adopted from the recommended Superpave specifications or sometimes adopted from requirements based on experiences of the state DOT.

When a mix is produced in the field, it often has different properties than the mix design conducted in the laboratory. Some adjustments may be needed, but care should be taken when making these field adjustments as they can have a significant impact on the compactability of the mix.

During construction, it is essential that the gradation, binder content, and volumetric properties, such as air voids and voids in mineral aggregate, be closely controlled so that the variability is low. Most state DOTs have construction tolerance requirements and pay factors related to these properties. For example, laboratory air voids are generally controlled between 3 and 5% for dense-graded mixtures and the design is typically performed at 4% air voids. If the air voids are a little high, long term durability of the mix is typically reduced. If the air voids are a little low, bleeding (and possibly rutting) in the asphalt mixture may occur. Thus, the gradation, binder content, and volumetric properties must be uniform during construction for best field performance. These properties can also influence the compactability of the mix.

3.4.4. Criteria

Typical quality control (QC) and acceptance specifications rely on acceptance testing, comparison testing, quality level analysis, and pay factor determinations. Based on experience from the Port Authority of New York and New Jersey (PANYNJ), even with specifications of specific types of longitudinal joints, many projects had low density in these joints. PANYNJ has implemented an end-result specification and a specific joint type mandate to incentivize achievement of compaction criteria regardless of construction method (Bognacki 2006). Agency specifications must use appropriate measures for setting requirements for in-place pavement performance. In the past, state agencies used the density of laboratory samples for target density, but this had the potential for greater variation in field compaction (Santucci 1998). Recently, most agencies have compared field compaction with the maximum theoretical density.

3.4.5. Performance Incentives

Many SHAs have developed performance incentives based on various asphalt acceptance properties. These properties should include in-place density, asphalt content, and lift thickness (Santucci 1998). Construction performance incentives should be established based on the economic impact to the highway agency. In general, inferior performance penalties and superior performance bonuses should be based on the cost to the agency due to more frequent or less frequent anticipated rehabilitation requirements (Santucci 1998). When the Arizona Department of Transportation (ADOT) implemented a true incentive based specification in 1990, average in-place air voids decreased from 8.5% to 7.5%. This specification was based on in-place air voids instead of a percentage of in-place density. The ideal ADOT specification would yield an in-place air void target of 7%. The 1% increase in in-place compaction was a direct result of implementation of the compaction incentive (Nodes 2006). Further implementation of specific construction performance incentives should encourage attainment of enhanced compaction.

4. SUMMARY

This literature review was conducted to provide information to support the FHWA Asphalt Pavement Technology Program strategic direction on extending pavement service life through enhanced field compaction. Results from the past studies clearly indicate the adverse effect of increased in-place air voids on the fatigue and rutting performance of asphalt pavements. A 1% decrease in air voids was estimated to improve the fatigue performance of asphalt pavements between 8.2 and 43.8%, to improve the rutting resistance by 7.3 to 66.3%, and to extend the service life by conservatively 10%. Based on these results, an LCCA was conducted on two alternatives in which the exact same asphalt overlay would be constructed to 93% and 92% densities to illustrate the effect of in-place air voids on the life cycle cost of asphalt pavements. The LCCA results show that the user agency would see an NPV cost savings of $88,000 on a $1,000,000 paving project (or 8.8%) by increasing the minimum required density by 1%.

Due to its significant effect, the cost of providing increased in-place density can be significantly less than the operation, maintenance, and road user cost savings realized due to extended service life of the pavements. In a 2007 AASHTO survey of state agencies' targets for field compaction, the majority of responding states had a compaction target of 92% of G_{mm}, but over one-third of the responding agencies had compaction targets less than 92%. Most of the current in-place density requirements adopted by states were determined based on the levels of in-place density that could be achieved in the past using prior construction technologies.

Since in-place density has a significant impact on the performance of asphalt pavements, agencies may consider implementing a higher in-place density requirement that can be achievable by following best practices and adopting new asphalt pavement technologies and knowledge gained from recent research. Some of these technologies and knowledge were briefly discussed in this report, including warm mix asphalt, intelligent compaction, improved construction joints, and improved agency specifications to incentivize achieving higher in-place densities.

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