LABORATORY PERFORMANCE EVALUATION OF

SMA MIXTURES IN

OKLAHOMA

By

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CHAPTER I

INTRODUCTION

PROBLEM STATEMENT

There has been reluctance on the part of some in Oklahoma to use stone matrix asphalt (SMA) mixtures. There are several factors that could be involved in the slow acceptance of SMA mixtures in Oklahoma. These factors are 1) the extra expense associated with the higher binder contents and better quality aggregates required, 2) a lack of data indicating that SMA mixtures perform substantially better than conventional SuperPave mixtures and 3) a lack of guidance on thickness design benefits, including appropriate local input parameters for the MEPDG (Mechanistic empirical design guide).

OBJECTIVE

The objective of this study is to determine if SMA mixtures have better rutting performance than S-4 mixes made with the same PG grade of binder. The objective of this project would be met by evaluating the rutting performance of Oklahoma SMA and S-4 mixes made with the same source of PG 76-28 binder using the Hamburg rut tester.

SCOPE

Different SMA and S-4 mixtures were collected from different parts of Oklahoma. The mixtures could either belt feed and/or sampled from stockpiles. All mixtures were made with PG 76-28 asphalt cement. To evaluate the performance properties of the mixtures, samples were made and tested for Hamburg rutting resistance using the Hamburg rut tester.

CHAPTER II

LITERATURE REVIEW

In the early 1960's, the European asphalt industry recognized a critical need for pavements which would be resistant to rutting, abrasion, and various pavement distresses induced by heavy traffic and studded tires. To address this need, roadway pavement contractors developed a mix called stone mastic asphalt (SMA). It was first developed in Germany [1]. This mix is a gap graded mix containing a high concentration of coarse aggregate (>70%), which maximizes stone to stone contact and provides an efficient network for load distribution [1, 2]. It is gap-graded for the fact that this mix has very little material that is retained on the sand sized sieves (between 2.36 to 0.075mm) [1]. The coarse aggregate particles are held together by a rich matrix (mastic) of mineral filler, fiber, and polymer in a thick asphalt film [2]. The difference between SMA and dense graded mixes is the stone skeleton in which the load is carried and the higher asphalt content which is 6-7.5% by weight of the total mix [1].

According to the European study tour report [3], SMA in the United States was adopted after the 1990 European asphalt study tour of six European nations. This study tour played a major role in the USA, adoption of SMA as alternative asphalt mixture. SMA in the United States reads stone matrix asphalt; it is just the Americanized version of stone mastic asphalt of Europe.

FINDINGS FROM THE EUROPEAN ASPHALT STUDY TOUR

Most of the countries visited in Europe used a 40 years design period for their pavement construction as opposed to the 20 year US design period. The most common problem that was recognized in the European nations was rutting due to high traffic and studded snow tires. Hence, five of the six countries had banned the use of studded tires with the exception of Sweden where; there was a faster rate of replacing the wearing surface [4].

All the countries visited during the study tour, used special-purpose mix designs, particularly in surface courses, to enhance the resistance of high traffic volume pavements to rutting, skidding, and, to a lesser degree, fatigue and thermal cracking. Examples of such mix designs are SMA in Sweden, Denmark and Germany; hot rolled asphalt (HRA) and penetration macadam in the United Kingdom; gussasphalt in Germany; and special thin and very thin asphalt overlays in France. To achieve performance, these mix designs tend to feature gap-graded aggregate blends and modified or low penetration grade binders, sometimes with the addition of fibers, as in the case of SMA [4].

During the summer 1991, after the European asphalt study tour, some pilot projects of SMA (test sections) were placed in four states: Wisconsin, Georgia, Michigan, and Missouri for evaluation of the new mix [5].

In Wisconsin, a 4000-ft test section of SMA was placed on a section of Interstate I-94 west of Milwaukee in 1991. The mix was placed as a binder course about 1-1/2 inch thick and was overlaid with SMA surface mix. The mix was made in a batching facility, transported to the site, placed and compacted in much the same manner as a conventional

HMA. No fibers were used but instead a polyolefin additive was added to the batch at the rate of 7 percent by weight of AC. Slightly lower mix temperatures (275 degree F in the hopper) were used to prevent AC draining off the aggregate [5].

In 1991 in Georgia, approximately one mile of a Coarse (3/4 inch) SMA was placed on the southbound lane of Interstate I-85 toward Atlanta. The mix was placed in the travel lane as a binder course approximately 2-1/4 to 2-1/2 inches thick. Later on, it was overlaid by a fine SMA (1/2 inch minus vs. ¾ inch minus). The mix was made at a batching facility at about 325 degrees F and placed at about 295 degrees. The mix was modified with a polymer (5 percent by weight of AC) and mineral wool fibers at a rate of 0.46 percent by weight of mix [5].

In 1991 in Michigan, two 1000-ft test sections were placed on highway M-52, south of Interstate I-96, between Lansing and Detroit. The mix, containing a cellulose fiber, was placed over a milled surface on both lanes at a thickness of 1-1/2 inches. Cellulose fiber was added at a rate of 0.3 percent by weight [5].

In Missouri, two SMA mixes were placed on I-70 west of St. Louis, near the I-270 interchange in 1991. The mixes (approximately 450 tons each) were placed in the westbound driving lane and were manufactured in a batch facility. The first SMA placed contained cellulose fibers (0.3 percent by weight of mix) and the second SMA contained mineral wool (0.5 percent by weight of mix) [5].

SMA PERFORMANCE MEASUREMENT

Consequently, several states expressed interest in constructing SMA pending the results of the pilot projects. In 1994, NCAT began a performance evaluation of 86 SMA projects that had been constructed since 1991. NCAT used different parameters for performance including; surface uniformity (evaluation of segregation), quality of longitudinal joints, cracking, rutting, raveling, and fat spots. All pavements had been subjected to significant amount of traffic after construction and the overall performance of SMA since 1991 to 1996 was found to be satisfactory [4].

Surface Uniformity

The SMA pavements that had been constructed since 1991 were evaluated for surface uniformity and they were found to exhibit good uniformity. These pavements were observed to have a coarse aggregate surface since SMA constitutes coarser aggregates and hence tends to help keep surface water below the pavement-tire interface which in turn helps to reduce the skid problems [4]. Figure 1 shows a typical SMA pavement surface texture.

Figure 1, Coarse Aggregate Surface Texture [4]

Fat Spots

Some pavements that were inspected and evaluated were found to have localized fat spots which affect the overall friction characteristics of the pavement. Larger fat spots should be replaced in response to the lost friction. Fat spots are usually created due to drain down when there is insufficient fiber or polymer, high asphalt content, low coarse aggregate content, excessive temperature, and excessive moisture. Fibers or polymers are used to protect drain down of asphalt through the stone matrix. SMA mixes are susceptible to excessive drain down unless the proper amount of fiber or stabilizing polymer is added to the mix. High asphalt content in asphalt mixtures lowers the voids in the mix which results in flushing of the binder during compaction that creates fat spots.

High temperature in asphalt mixtures promote drain down which makes the mix prone to fat spot problems so the temperature should be within the required range. Moisture in the mixture or in the base surface creates when it evaporates during compaction due to high temperature. This tends to separates the asphalt from the aggregate surface from the mix and comes out to the top under traffic loading which creates localized fat spots [4]. Figure 2 shows fat spots on SMA pavement.

Figure 2, Localized fat spot [4]

Longitudinal joints

Quality longitudinal joints are hard to achieve in SMA and conventional dense graded mixes as well. Since SMA has larger aggregates and also relatively stiffer asphalt binder, getting a good longitudinal joint is relatively more difficult. But the inspected pavements in the pilot projects were mostly satisfactory with only a few being unsatisfactory [4].

Cracking

According to NCAT's evaluation, cracking was not a problem in the SMA pavements. Some cracks that had been observed were reflected cracks because some of the SMA pavements were placed as an overlay on old pavements. The cracks remained intact in the pavements and did not ravel. Therefore, cracking was not a problem on SMA pavements [4].

Rutting

The rutting was measured on most of the SMA pavements and it showed superior results, 90 percent of the pavements measured had rutting less than 4mm but only 6 of the pavements showed rutting more than 6mm. These figures show that SMA pavements are highly resistant of possible rutting problems when used on interstate highways and high traffic pavements. Figure 3 shows the results of rutting measurement on the SMA pavements.

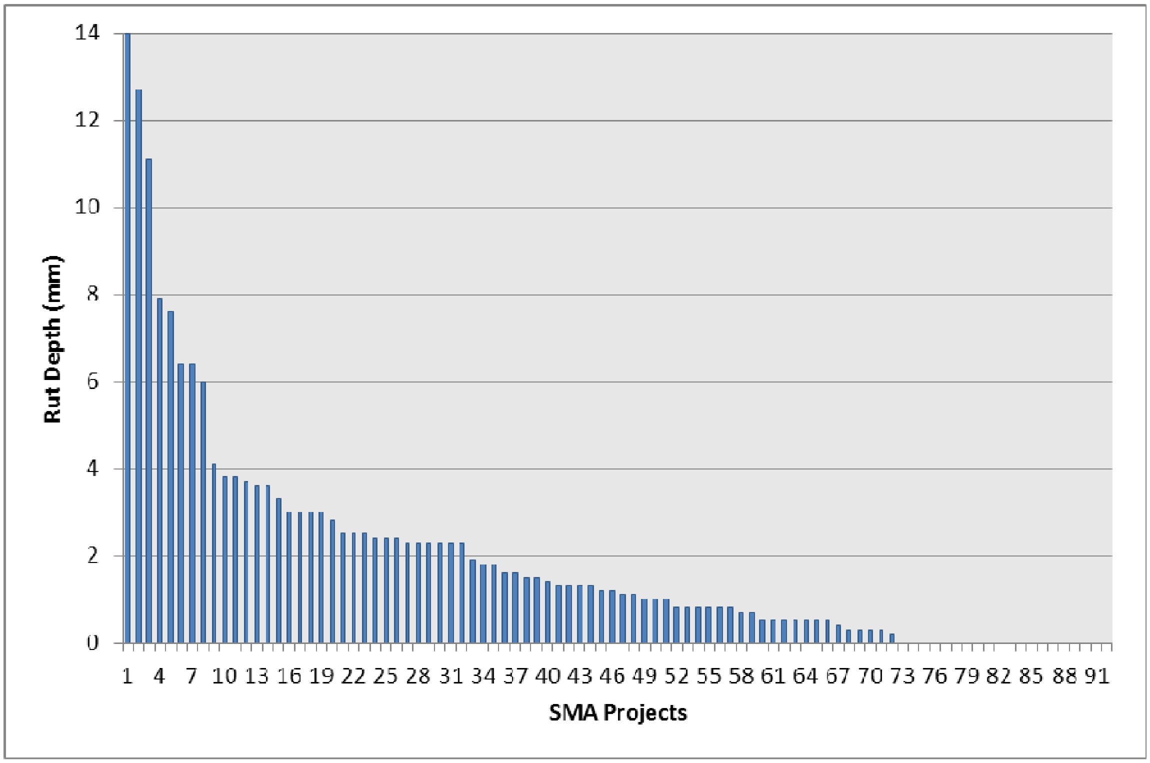

Figure 3, Rut Depth of SMA Projects from 1991 to 1996 [4]

ADVANTAGES OF SMA

Performance

The evaluation of different SMA pavements by NCAT showed outstanding performance when compared to conventional HMA mixes. This has led to the expanded use of SMA in different states and DOTs.

According to the performance evaluation by NCAT [4], SMA is found to be highly resistant to rutting, cracking and other distresses compared to conventional HMA mixes. Wisconsin's evaluation of their trial projects [6], resulted in better performance of SMA with respect to cracking and other distresses. Quantitatively, SMA reduced cracking that occurred in conventional HMA pavements by 50 percent.

When used as overlays on concrete and on another HMA pavement, SMA exhibited better crack resistant characteristic than conventional HMA. It also showed significant improvement in frictional characteristics [6]. SMA also has a higher macro texture [average 1.26mm reported] than dense graded mixes for improved friction [7].

According to state department of highways [7], SMA provided 33 to 103% longer service life than conventional dense-graded mixes.

Figure 4 shows that, according to VDOT's study, the trend of distress of SMA and dense graded mixes with age based on critical condition index (CCI). A CCI of 100 being like new and requiring maintenance when it reaches a CCI of 60 [8]. Figure 4 shows that SMA degrades at a lower rate than the conventional dense graded mixes.

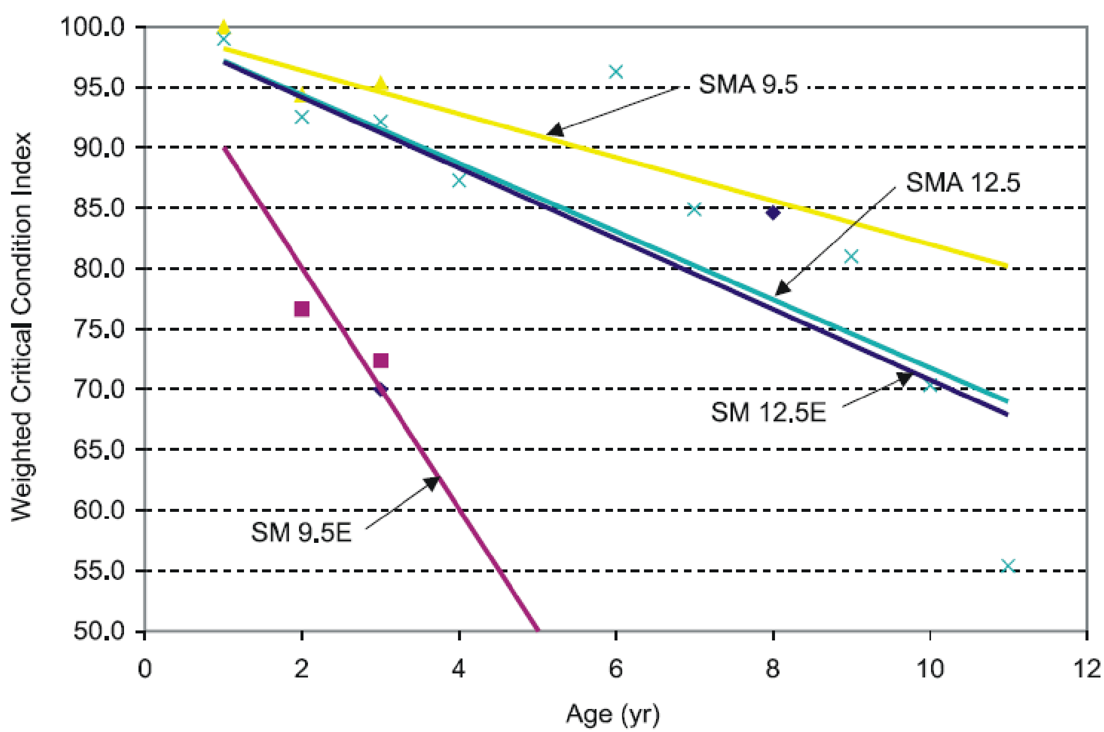

Figure 4, Performance trends for SMA and "E" mixes (dense graded) 2006 [6]

Furthermore, according to study made on SMA for airfield pavements [1], it was found to perform superior to dense graded (P401) mixes. SMA was evaluated for permanent deformation, moisture damage, cracking, fuel resistance, deicer resistance and texture. The additional different performance tests than the ordinary tests for highway pavements were fuel resistance and deicer resistance. As shown in table 2 below, SMA was observed to have a better resistance to fuel and deicer than the dense graded ones. It is found to have a better rutting, moisture damage and cracking resistance.

Table 1, Summary of SMA and P401 Performance Comparison [1]

Property	Performance Worse than P401	Performance Similar to P401	Performance Better than P401
Permanent Deformation		X	X
Moisture Damage			X
Cracking			X
Fuel Resistance			X
Deicer Resistance		X	
Texture			X

Cost

Although, SMA pavements are costly initially, life cycle cost analysis data show that SMA would still be cost effective even if the initial cost of SMA were 82 to 94% higher than conventional dense graded mixes [7]. Figure 5 shows that based on research conducted by VDOT [8], the equivalent annual costs for an initial cost of SMA is considerably lower than conventional dense graded mixes.

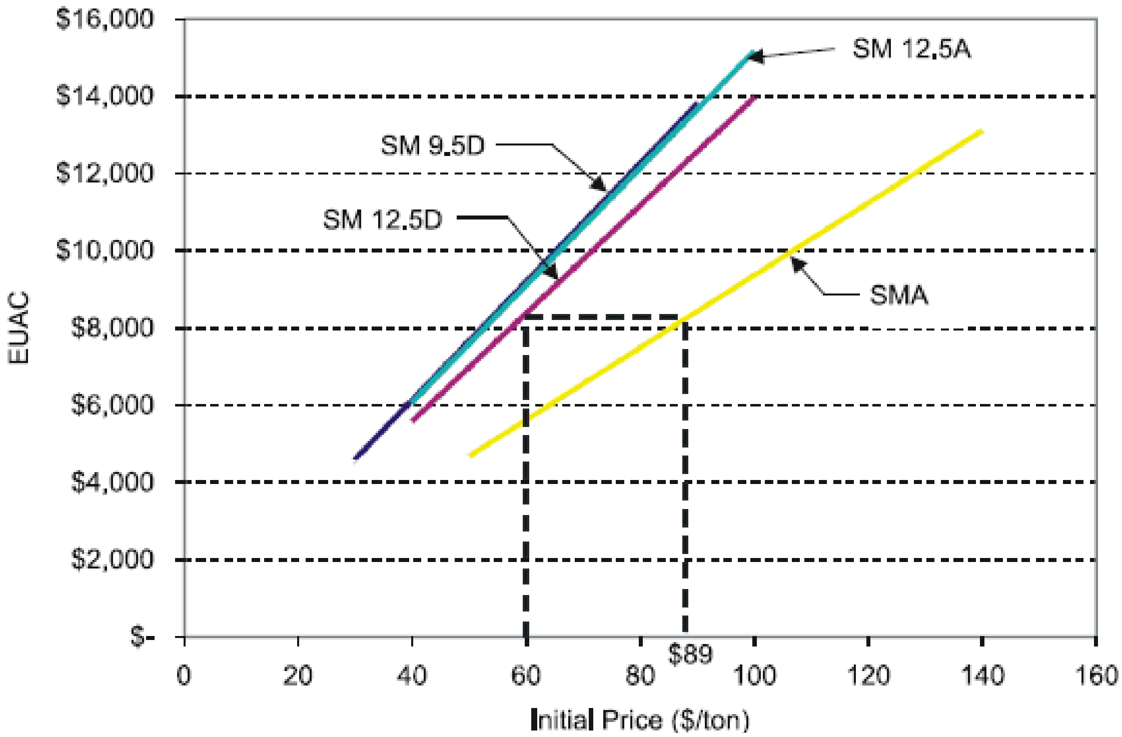

Figure 5, Equivalent uniform annual costs (EUAC): Interstate 2006 [8]

It was found that SMA is the most cost effective HMA for pavement maintenance purposes on Virginia interstate system [8]. This mix was observed to outperform the conventional dense graded mixes when placed under the same conditions and the high cost associated with this mix was justified by the increased predicted performance [8].

The higher cost of SMA is due to the numerous material, design, production and placement differences and the higher AC content, higher-quality aggregates, mineral filler, and fibers. There is also different equipment necessary for production and placement like fiber feeder, material transfer vehicles (MTV) [9].

LOADED WHEEL TESTERS

Hot mix asphalt (HMA) pavements have always been affected by their susceptibility for permanent deformation or rutting in the United States. Rutting is defines as the accumulation of small amounts of unrecoverable strain that is caused by applied wheel loads. The strain is caused by consolidation or lateral movement, or both, of the HMA under traffic loading. The potential for rutting has recently increased in the nation's highways due to higher traffic volumes and increased use of radial tires that typically exhibit higher inflation pressures. Hence, a standardized laboratory equipment and test procedure that predicts rutting potential in the field would be of great benefit to the HMA industry. The most common types of Laboratory equipment of this nature currently used are loaded wheel testers [10].

There are different kinds of loaded wheel testers that are currently being used in the United States. These are the Georgia Loaded Wheel Tester (GLWT), Asphalt Pavement Analyzer (APA), Hamburg Wheel Tracking Device (HWTD), LCPC (French) Wheel Tracker, Purdue University Laboratory Wheel Tracking Device (PURWheel), and one-third scale Model Mobile Load Simulator (MMLS3) [10].

Georgia Loaded Wheel Tester

Developed during the mid-1980s through a cooperative research study between the Georgia Department of Transportation and the Georgia Institute of Technology, the GLWT is capable of testing HMA beam or cylindrical specimens. Beam dimensions are generally 125 mm wide, 300 mm long and 75 mm high. The cylindrical samples are generally 150 mm in diameter and 75 mm high. Both specimen types are commonly compacted to either 4 or 7 percent air void content. Testing consists of applying 100-lb. load onto a pneumatic linear hose pressurized to 100 psi. The load is applied through an aluminum wheel onto the linear hose, which resides on the sample. The test specimens in GWLT are tracked back and forth under the applied stationary loading. Typically, testing in GLWT is run for 8000 cycles under temperatures of 35 to 60 degree Celsius [10].

Asphalt Pavement Analyzer (APA)

The APA is one of the loaded wheel testers in the United States which is a modification of the GLWT and was first manufactured in 1996 by pavement technology, Inc. The APA follows the same rut testing procedure since it is the second generation of GLWT. A wheel is loaded onto a pressurized linear hose and tracked back and forth over a testing sample. Samples also can be tested submerged in water unlike the GLWT. The specimen in the APA can either be cylindrical or beam. The test temperatures range from 40.6 to 64 degree Celsius and the wheel load and hose pressure is like GLWT. Figure 6 shows an APA.

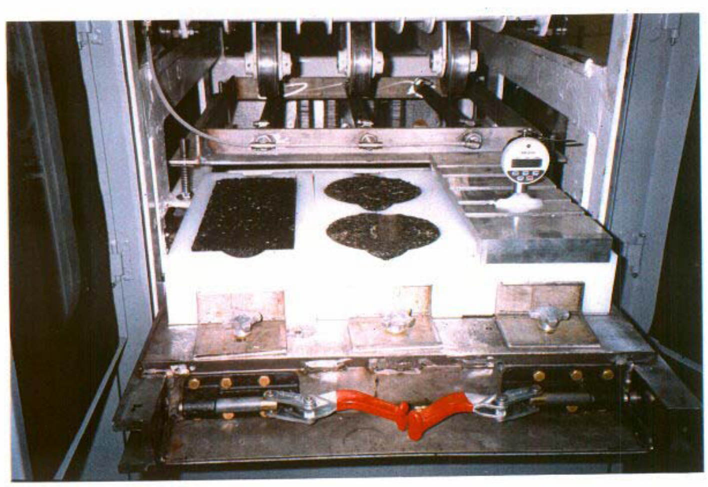

Figure 6, Asphalt Pavement Analyzer [10]

LCPC (French) Wheel Tracker

The Laboratoire Central des et Chausees (LCPC) wheel tracker [also known as the French Rutting Tester (FRT)] has been used in France for over 15 years to successfully prevent rutting in HMA pavements. The FRT has recently been used in United States, especially in state of Colorado and FHWA's Turner Fairbank Highway Research Center. The FRT is capable of simultaneously testing two HMA slabs with dimensions typically 180 mm wide, 50 mm long, and 20 to 100 mm thick (7.1 in x 19.7 in x 0.8 to 3.9 in) and the samples are compacted with a LCPC laboratory-tired compactor. Loading of samples is accomplished by applying a 1124-lb. load onto a 400x8 Treb Smooth pneumatic tire inflated to 87 psi. The pneumatic tire passes over the center of the sample twice per second [10].

Purdue University Laboratory Wheel Tracking Device (PURWheel)

The PURWheel was developed at Purdue University and tests slab specimens that can be compacted in the laboratory or cut from the roadway. The specimens are 290 mm wide by 310 mm long and the thickness being dependent upon the type of mixture as for surface course a thickness of 1.5 in while for binder and base course a thicknesses of 2 in and 3 in respectively. The PURWheel evaluates rutting and moisture sensitivity and testing in PURWheel takes place either in dry or wet conditions. Loading of the specimen is conducted using a pneumatic tire that creates a gross contact pressure of 90 psi [10].

Model Mobile Load Simulator (MMLS3)

The MMLS3 was developed in South Africa for testing HMA in the Laboratory or in the field in dry or wet conditions. Samples tested in MMLS3 are 47 inches in length, 9.5

inches in width. The device applies 7200 single-wheel loads per hour by means of a 12-in diameter, 3-in wide tire at inflation pressures up to 116 psi with a typical value being 100psi [10].

Hamburg Wheel Tracking Device (HWTD)

The Hamburg Wheel Tracking Device (HWTD) is one of the load wheel testers in the United States that is used to evaluate rutting in Asphalt mixtures. It was originally developed by the City of Hamburg, Germany in 1970 based on a similar British device that had a rubber tire [11]. Helmut-Wind Incorporated of Hamburg finalized the test method and developed specification requirements for rutting and stripping susceptibility [11]. HWTD was used as a specification requirement for some of the most traveled roadways in Germany to evaluate rutting and stripping [10]. The HWTD is used to measure the combined effects of rutting and moisture damage on asphalt mixtures by simulating the real pavement conditions such as heavy rain and heavy use in a controlled environment. It has two stainless steel wheels (8-in diameter x 1.85-in wide) that simulate the road wear by rolling and pressing against the samples with 158 pounds of contact pressure [12]. Tests in HWTD are conducted on a slab whose dimension is 260 mm wide, 320 mm long, and 40 mm high (10.2 in x 12.6 in x 1.6 in). The slabs are normally compacted to 7±1 percent air voids using a linear kneading compactor. HWTD was slightly modified by the Superfos Construction, U.S. and was referred to as the Superfos Construction Rut Tester (SCRT). The SCRT used slab specimen like the HWTD with the same dimensions. The difference between the two rut testers was the loading mechanism in which the SCRT used a 180-lb. vertical load onto a solid rubber wheel with diameter of 194 mm and width of 46 mm. Another slight modification of the HWDT is the evaluator of Rutting and Stripping (ERSA) equipment which was built by the Department of Civil Engineering at the University of Arkansas. Testing within the ESRA is conducted on either cylindrical or beam samples in dry or wet conditions [10]. Figure 7 shows typical ESRA equipment that I have used in my research.

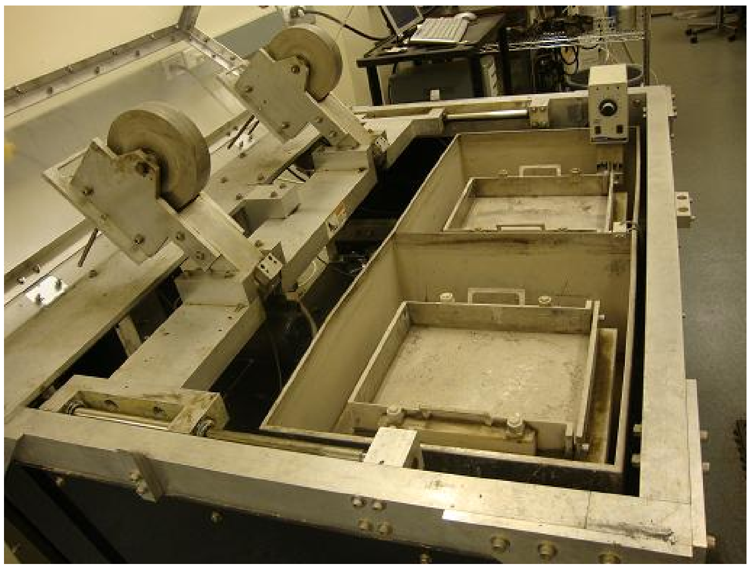

Figure 7, Hamburg Wheel Tracking Device (ERSA)

Each wheel is connected to a separate Linear Value Displacement Transducer (LVDT) to measure the deformation of the samples with each wheel pass. Testing in HWTD is done under water with temperatures of 25 to 70 degrees Celsius 50 being the most common. About an inch of water is kept above the specimen during the test. The temperature is kept constant with a water bath that has two heaters at either side. Tests are typically run up to 20,000 loaded wheel passes at a rate of approximately 50 passes across the specimen per minute [13].

Specimens that undergo Hamburg wheel tracking test look like the figure below, figure 8 being a sample which did not rut and figure 9 being a sample which rutted and hence failed.

Figure 8, Passed Sample

Figure 9, Failed Sample

The results obtained from HWTD include: rut depth, creep slope, stripping inflection Point, and Stripping slope. The creep slope is the inverse of the deformation rate within the linear region of the deformation curve after post compaction and prior to stripping (if stripping happens). The stripping slope is the inverse of the deformation rate within the linear region of the deformation curve, after the onset of stripping. The stripping, inflection point is the number of wheel passes corresponding to the intersection of the creep slope and the stripping slope. This point indicates the relative resistance of the HMA sample to moisture-induced damage [11]. Figure 10 shows typical Hamburg rut testing result.

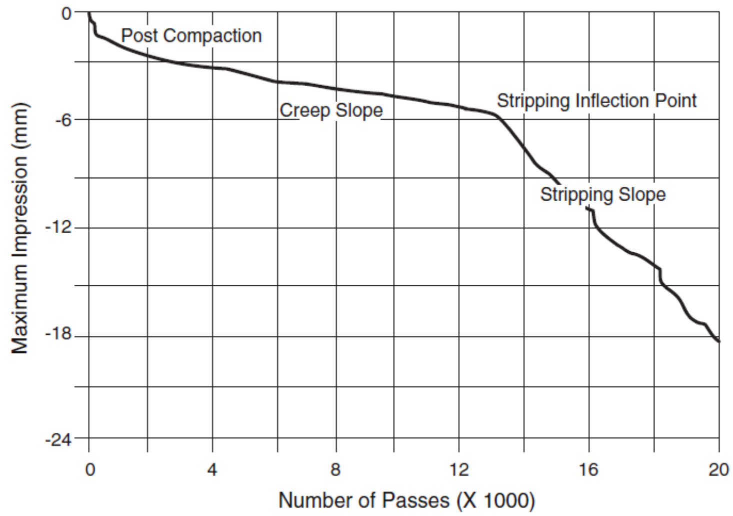

Figure 10, Typical Hamburg Wheel Tracking Results [11]

CHAPTER III

TEST PLAN

OBJECTIVE

The objective of this study is to determine if SMA mixtures have better rutting performance than S-4 mixes made with the same PG grade of binder. The objective of this project would be met by evaluating the rutting performance of Oklahoma SMA and S-4 mixes made with the same source of PG 76-28 binder using the Hamburg rut tester.

MATERIALS

Asphalt

The asphalt cement (AC) used in this study was a PG 76-28 from Valero.

Mixes

Six different SMA mixes and four ODOT S-4 mixes were evaluated. Table 2 shows the different mixes and their producers. All of the S-4 mixes and two of the SMA mixes were obtained from contractors as belt feed aggregate samples. Four of the SMA mixes were sampled from individual stockpiles of aggregates. Table 3 shows the individual aggregates that made up the SMA mixes and the percentages used to blend the aggregates and table 4 shows the individual aggregates that made up the S-4 mixes and the percentages used to blend the aggregates.

Table 2, Mixes that were used for the study

Mix type	Producer	Design No.	Design traffic	Ndes	Mix ID
SMA	PMI-Silver Star	M2PV0160702600	10M+	50	SS
SMA	Cornell Const. Co.	M2PV0160600100	30M+	50	CL-1
SMA	Cornell Const. Co.	M2PV0110700100	30M+	50	CL-2
SMA	Haskell Lemon Const. Co.	M2QC0130702700	3M+	50	HL-1
SMA	Haskell Lemon Const. Co.	M2QC0130600101	10M+	50	HL-2
SMA	Cummins Const. Co.	M2QC0101004010	.	50	CU
S-4	T.J. Campbell Const. Co.	S4QC0190900600	3M+	100	TJC
S-4	Cornell Const. Co.	S4PV0110902000	30M+	125	CL-3
S-4	APAC-Oklahoma	S4QC0061003500	3M+	100	APAC
S-4	Haskell Lemon Const. Co.	S4QC0130902000	3M+	75	HL-3

Table 3, Aggregate sources of SMA mixes

Mix Code	Aggregate	Supplier	Source	Pit	% Used
SS	5/8 Chips	Hanson	Davis	5080	34
	5/8 Chips	Martin-Marietta	Davis	5005	15
	3/8 Chips	Martin-Marietta	Davis	5005	32
	Screenings	Falcon	Bowlegs	6709	8
	Agg. Lime	Dolese	Davis	5002	11
CL-1	5/8" Chips	Dolese	Cooperton	3801	35
	D Rock	Martin-Marietta	Snyder	3802	15
	Shot	Dolese	Cooperton	3801	27
	Screenings	Dolese	Cooperton	3801	18
	Agg. Lime	Dolese	Davis	5002	5
CL-2	3/4" Chips	Dolese	Cooperton	3801	17
	5/8" Chips	Martin-Marietta	Snyder	3802	56
	#4 Screenings	Dolese	Cyril	801	10
	Shot	Dolese	Cooperton	3801	10
	Mineral Filler	Dolese	Davis	5002	7
HL-1	3/4" Chips	Dolese	Cooperton	3801	15
	5/8" Chips	Hanson	Davis	5080	55
	Screenings	Martin-Marietta	Troy	3506	10
	Shot	Martin-Marietta	Mill Creek	3502	12
	Mineral Filler	Dolese	Davis	5002	8
HL-2	3/4" Chips	Dolese	Davis	5002	15
	5/8" Chips	Martin-Marietta	Snyder	3802	55
	#4 Screenings	Dolese	Cyril	801	11
	Shot	Dolese	Davis	5002	12
	Mineral Filler	Dolese	Davis	5002	7
CU	3/4" Chips	Dolese	Coleman	302	13
	5/8" Chips	Dolese	Coleman	302	45
	3/8" Chips	Dolese	Coleman	302	20
	Screenings	Dolese	Coleman	302	10
	Mineral Filler	Cummins	Plant Site		12

Table 4, Aggregate sources of S-4 mixes

Mix type	Aggregate	Supplier	Source	Pit	% Used
TJC	5/8 Rock	Hanson	Davis	5008	19
	3/8 Chips	Martin-Marietta	Davis	5005	29
	Screenings	Hanson	Davis	5008	37
	Sand	GMI	Sooner Rd.	5514	15
CL-3	5/8" Chips	Martin-Marietta	Snyder	3802	30
	Shot	Dolese	Cooperton	3801	15
	Screenings	Dolese	Cooperton	3801	30
	C-33 Screenings	Martin-Marietta	Snyder	3802	10
	Sand	Mac Lemore Pit	Elk City		15
APAC	3/4" Chips	APAC-Oklahoma	Tulsa	7204	15
	Mine Chat		Tri-City Area		28
	Man. Sand	APAC-Oklahoma	Tulsa	7204	25
	Drag Sand		Tri-City Area		5
	Screenings	APAC-Oklahoma	Tulsa	7204	10
	Screenings	Holiday S&G	Bixby	7212	15
	Bag House Fines	APAC-Oklahoma	Tulsa	7204	2
HL-3	5/8" Chips	Martin-Marietta	Snyder	3802	34
	Stone Sand	Dolese	Cyril	801	26
	Man. Sand	Martin-Marietta	Davis	5005	15
	Screenings	Martin-Marietta	Mill Creek	3502	10
	Sand	GMI	OKC	1402	15

Verification of Belt Feed Mixes

For the belt feed mix samples, the mixes were verified to determine if they met ODOT's mix requirements. To accomplish this, the aggregates were sieved through the No. 50 sieve. Then, the aggregates were recombined to the JMF (Job mix formula) and samples were compacted with 0.5% AC above and below the JMF optimum asphalt content and the asphalt content that gave a 4.0% VTM (voids in the total mix) was selected as the optimum asphalt content. Finally, it was checked to see if the mixes met ODOT's void and mix requirements at optimum AC and if so, the mix was used. Otherwise the gradation and asphalt content were altered until the mix met specifications.

For the mixes samples from stockpiles, the aggregates were recombined by the job mix formula percentage (ODOT's batching option 1) and the above procedure was repeated. The aggregates and the asphalt are mixes together in a bucket mixer for approximately 2 minutes at temperature of 325 degrees. The test samples were oven aged for two hours at 300 degrees prior to compaction according to AASHTO R 30. After the two hour oven aging, the samples were compacted in a SuperPave Gyratory compactor (SGC) to 60±2mm in height at 7.0±1% air voids. The air voids were checked by running the bulk specific gravity of the samples in accordance with OHD L-14.

$$\%VTM = 100x\ [1 - Gmb/Gmm]$$

Where: %VTM is percent air voids in the total mix, Gmb is bulk specific gravity of the compacted sample and Gmm is the maximum theoretical specific gravity. The maximum theoretical specific gravity (Gmm) was found according to AASHTO T 209.

Tables 5 and 6 show the gradations and volumetric properties for the SMA and S-4 mixes, respectively.

Table 5, Gradation and Volumetric properties of the SMA mixes

Mix Code	SS	CL-1*	CL-2	HL-1	HL-2	CU	ODOT spec
Sieve size	Percent Passing						
3/4"	100	100	100	100	100	100	100
1/2"	91	96	90	90	90	90	90-100
3/8"	75	73	68	65	69	71	65-80
No. 4	30	30	30	29	30	30	22-30
No. 8	21	21	17	21	19	20	16-24
No. 16	18	14	15	16	16	17	
No. 30	16	12	14	14	15	15	
No. 50	15	10	13	13	14	15	
No. 100	13	9	12	11	13	14	
No. 200	11.1	8.1*	9.6	9.9	9.7	11.0	9-12
% AC	6.0	6.6	6.5	6.2	6.3	6.0	min 6.0
% Fiber	0.3	0.3	0.3	0.3	0.3	0.3	0.3-0.4
Ndes	50	50	50	50	50	50	50
VTM	4.1	4.0	4.0	4.0	4.0	4.0	4
VMA	17.5	17.1	18.1	17.5	18.1	17.9	≥ 17.0
VFA	76.6	76.6	78	77.1	77.8	77.7	NR

*Produced under old SMA Specification

NR-No requirement

Table 6, Gradation and Volumetric properties of the S-4 mixes

Mix Code	TJC	CL-3	APAC	HL-3	ODOT spec
Sieve size	Percent Passing				
3/4"	100	100	100	100	100
1/2"	97	96	95	97	90-100
3/8"	90	87	90	90	≤ 90
No. 4	52	69	63	70	
No. 8	36	47	39	47	34-58
No. 16	28	36	27	35	
No. 30	24	28	17	27	
No. 50	19	16	10	19	
No. 100	11	9	6	9	
No. 200	4.6	5.2	4.6	3.2	2-10
% AC	4.6	4.9	5.2	5.1	min. 4.6
Ndes	100	125	100	100	
% VTM	4.0	4.0	4.0	4.0	4.0
% VMA	14.4	14.7	14.6	14.8	≥ 14.0
% VFA	72.3	72.8	72.5	73.1	65-75

HAMBURG RUT TESTING

Sample Preparation

Four samples of each mix were prepared for Hamburg Rut Testing. Two gyratory samples were used for each specimen, two for right wheel and two for the left wheel. All samples were compacted to 60±2mm in height at 7.0±1% air voids using SuperPave gyratory compactor.

Rut Testing

The objective of this study is to determine if SMA mixtures have better rutting performance than S-4 mixes made with the same PG grade of binder. To meet the objective of the study, rutting tests were performed using the Hamburg Rut Tester in accordance with OHD L-55.

The compacted specimens were mounted in the Hamburg Rut Tester and submerged in the water bath at 50 degree Celsius for 30 minutes before testing.

Figure 11 shows left and right samples mounted in the molds in the Hamburg rut tester.

Figure 11, Samples Mounted In HWTD

Each specimen was subjected to one reciprocating wheel that weighs a total of 158±5 lbs. with the weights on it. All the samples were tested for 20,000 passes or 10,000 cycles. The rut depth at the required number of passes (20,000) was reported to the nearest 0.001 mm and/or the number of passes when the rut depth reached 12.5 mm, if less than the required number of passes. The impression (rut depth) is plotted with the number of wheel cycles. A sudden increase in the rate of deformation can coincide with stripping of the asphalt from the aggregate in the specimen. Figure 12 shows Hamburg samples the loaded ready for testing.

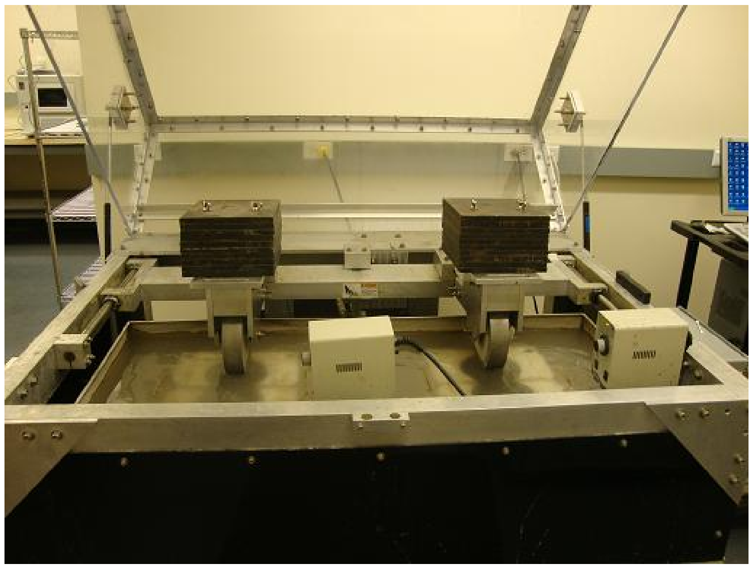

Figure 12, Hamburg samples ready for testing.

CHAPTER IV

TEST RESULTS AND DISCUSSIONS

HAMBURG WHEEL TRACKING TEST

The Hamburg Wheel Tracking Rutting Test was performed to evaluate the rutting and moisture damage susceptibility of the SMA and S-4 mixes. The test was conducted in accordance with OHD L-55 or AASHTO T 324-04 and the results for the S-4 and SMA mixes are summarized in tables 7 and 8, respectively.

Table 7, Results of Hamburg Rut Testing for S-4 mixes

Passes	Rut Depth (mm)							
	TJC		CL-3		APAC		HL-3	
	L	R	L	R	L	R	L	R
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.10	0.07	0.11	0.10	0.06	0.10	0.09	0.19
50	0.24	0.16	0.22	0.26	0.09	0.20	0.11	0.33
100	0.39	0.27	0.33	0.53	0.16	0.32	0.40	0.33
200	0.56	0.40	0.45	0.74	0.27	0.41	0.62	0.49
400	0.75	0.53	0.56	0.90	0.35	0.54	0.73	0.60
600	0.86	0.65	0.60	1.02	0.44	0.65	0.88	0.77
800	0.96	0.73	0.63	1.12	0.45	0.72	0.85	0.84
1000	1.04	0.81	0.70	1.23	0.51	0.78	0.93	0.99
1200	1.10	0.88	0.72	1.31	0.54	0.83	1.00	1.05
1400	1.16	0.93	0.76	1.36	0.59	0.86	1.15	1.21
1600	1.22	0.98	0.78	1.42	0.64	0.90	1.33	1.25
1800	1.28	1.05	0.81	1.48	0.72	0.91	1.39	1.32
2000	1.32	1.09	0.82	1.52	0.75	0.93	1.43	1.37
2200	1.37	1.14	0.85	1.57	0.77	0.97	1.47	1.46
2400	1.44	1.20	0.87	1.63	0.83	1.00	1.68	1.52
2600	1.53	1.27	0.90	1.69	0.81	1.02	1.77	1.46
2800	1.63	1.35	0.94	1.73	0.85	1.06	1.90	1.60
3000	1.71	1.42	0.96	1.79	0.90	1.09	1.94	1.65
3200	1.79	1.49	0.98	1.85	0.94	1.12	1.96	1.69
3400	1.89	1.55	1.02	1.92	0.95	1.14	1.89	1.74
3600	1.96	1.63	1.05	2.00	1.02	1.20	1.94	1.86
3800	2.06	1.73	1.08	2.08	1.04	1.18	2.11	1.88
4000	2.15	1.83	1.10	2.15	1.07	1.23	2.09	1.94
4200	2.22	1.93	1.13	2.21	1.09	1.22	2.12	1.97
4400	2.32	2.03	1.16	2.27	1.07	1.26	2.18	2.05
4600	2.40	2.17	1.19	2.32	1.11	1.27	2.31	1.98
4800	2.53	2.30	1.22	2.39	1.11	1.27	2.34	2.06
5000	2.68	2.45	1.26	2.46	1.15	1.29	2.54	2.14
5200	2.80	2.59	1.31	2.53	1.15	1.32	2.49	2.24
5400	2.93	2.78	1.36	2.60	1.16	1.32	2.37	2.29
5600	3.10	2.92	1.42	2.68	1.14	1.32	2.60	2.26
5800	3.30	3.10	1.46	2.75	1.20	1.36	2.56	2.30
6000	3.44	3.25	1.53	2.84	1.18	1.38	2.56	2.35

Table 7 Continued, Results of Hamburg Rut Testing for S-4 mixes

Passes	Rut Depth (mm)							
	TJC		CL-3		APAC		HL-3	
	L	R	L	R	L	R	L	R
6200	3.64	3.48	1.60	2.91	1.20	1.39	2.62	2.43
6400	3.84	3.68	1.68	3.00	1.26	1.41	2.64	2.46
6600	4.08	3.91	1.80	3.10	1.24	1.40	2.89	2.53
6800	4.33	4.05	1.94	3.17	1.30	1.43	2.72	2.53
7000	4.51	4.32	2.07	3.30	1.31	1.44	2.80	2.57
7200	4.79	4.52	2.22	3.44	1.38	1.46	2.88	2.59
7400	5.05	4.71	2.40	3.57	1.36	1.49	2.77	2.61
7600	5.26	4.90	2.57	3.68	1.43	1.50	2.88	2.60
7800	5.50	5.13	2.75	3.81	1.46	1.51	2.89	2.65
8000	5.67	5.24	2.92	3.97	1.49	1.52	2.99	2.66
8200	5.96	5.49	3.15	4.15	1.52	1.55	2.92	2.80
8400	6.20	5.68	3.30	4.32	1.51	1.54	3.10	2.77
8600	6.52	5.84	3.43	4.51	1.53	1.56	2.90	2.87
8800	6.74	6.03	3.59	4.61	1.59	1.57	3.11	2.91
9000	7.04	6.28	3.63	4.82	1.61	1.59	3.10	2.86
9200	7.28	6.53	3.90	5.05	1.66	1.59	3.23	2.86
9400	7.51	6.77	4.03	5.28	1.66	1.62	3.31	2.84
9600	7.76	7.00	4.16	5.49	1.68	1.62	3.34	2.92
9800	7.96	7.22	4.28	5.72	1.73	1.65	3.49	2.75
10000	8.27	7.53	4.38	5.90	1.82	1.65	3.49	2.94
10200	8.62	7.75	4.52	6.07	1.86	1.68	3.52	2.74
10400	8.90	7.96	4.66	6.29	1.89	1.66	3.51	2.85
10600	9.25	8.15	4.78	6.46	1.93	1.71	3.60	2.93
10800	9.50	8.36	4.71	6.66	1.96	1.70	3.58	2.96
11000	9.82	8.59	5.04	6.83	1.99	1.75	3.76	3.03
11200	9.93	8.84	5.16	6.96	2.01	1.78	3.67	3.09
11400	10.20	9.05	5.40	7.15	2.03	1.71	3.68	3.18
11600	10.45	9.25	5.49	7.28	2.06	1.74	3.67	3.40
11800	10.62	9.39	5.67	7.36	2.11	1.75	3.79	3.44
12000	10.81	9.56	5.78	7.72	2.13	1.80	3.82	3.53
12200	11.03	9.64	5.90	7.99	2.21	1.79	3.85	3.62
12400	11.16	9.77	5.99	8.26	2.21	1.81	3.89	3.72
12600	11.40	9.86	6.16	8.44	2.26	1.82	3.87	3.57
12800	11.47	9.94	6.19	8.57	2.31	1.86	3.97	3.62

Table 7 Continued, Results of Hamburg Rut Testing for S-4 mixes

Passes	Rut Depth (mm)							
	TJC		CL-3		APAC		HL-3	
	L	R	L	R	L	R	L	R
13000	11.60	10.02	6.33	8.79	2.34	1.85	3.95	3.61
13200	11.52	10.06	6.48	8.85	2.36	1.88	3.93	3.61
13400	11.86	10.16	6.55	9.08	2.45	1.87	3.96	3.67
13600	11.97	10.27	6.65	9.22	2.50	1.90	4.01	3.69
13800	12.08	10.38	6.75	9.45	2.53	1.92	4.11	3.71
14000	12.17	10.44	6.77	9.62	2.55	1.93	4.06	3.75
14200	12.24	10.47	6.83	9.74	2.63	1.93	4.11	3.88
14400	12.30	10.65	6.88	9.85	2.69	1.95	4.29	3.82
14600	12.41	10.71	6.95	10.01	2.73	1.95	4.35	4.04
14800	12.50	10.73	7.02	10.12	2.78	1.97	4.28	3.98
15000		10.83	7.31	10.25	2.80	1.99	4.31	4.17
15200		10.87	7.36	10.33	2.86	2.01	4.37	3.96
15400		10.94	7.46	10.43	2.92	2.02	4.49	4.20
15600		11.03	7.56	10.49	2.98	2.02	4.39	4.11
15800		11.07	7.68	10.55	2.98	2.03	4.62	4.18
16000		11.22	7.69	10.61	3.06	2.05	4.56	4.28
16200		11.28	7.74	10.62	3.11	2.07	4.71	4.35
16400		11.35	7.83	10.63	3.15	2.09	4.74	4.50
16600		11.42	7.93	10.71	3.24	2.09	4.54	4.53
16800		11.48	7.95	10.73	3.26	2.10	4.64	4.51
17000		11.50	8.05	10.80	3.38	2.11	4.66	4.64
17200		11.63	8.10	10.87	3.36	2.14	4.72	4.56
17400		11.54	8.23	10.88	3.55	2.13	4.59	4.86
17600		11.79	8.27	10.92	3.55	2.15	4.64	4.86
17800		11.87	8.34	10.97	3.68	2.16	4.59	4.95
18000		11.95	8.44	11.01	3.85	2.16	4.87	4.80
18200		11.95	8.51	11.08	3.85	2.20	4.65	4.85
18400		11.99	8.60	11.14	4.12	2.21	4.74	4.92
18600		12.07	8.62	11.23	4.23	2.23	5.11	5.03
18800		12.06	8.73	11.28	4.66	2.24	5.07	5.04
19000		12.12	8.78	11.25	4.87	2.25	5.09	5.13
19200		12.17	8.85	11.30	4.97	2.27	5.19	5.35
19400		12.18	8.91	11.35	5.16	2.29	4.56	5.23
19600		12.33	8.97	11.43	5.30	2.31	5.11	5.45
19800		12.34	9.06	11.47	5.59	2.32	5.39	5.58
20000		12.38	9.13	12.50	5.81	2.32	5.63	5.52

Table 8, Results of Hamburg Rut Testing for SMA mixes

Passes	Rut Depth (mm)										
	HL-1		CL-2		HL-2		SS		CL-1	CU	
	L	R	L	R	L	R	L	R	R	L	R
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.19	0.15	0.11	0.14	0.00	0.11	0.13	0.10	0.09	0.16	0.17
50	0.40	0.28	0.24	0.27	0.09	0.29	0.28	0.22	0.22	0.32	0.31
100	0.61	0.42	0.33	0.44	0.24	0.47	0.45	0.39	0.36	0.49	0.47
200	0.89	0.64	0.46	0.63	0.39	0.69	0.64	0.60	0.53	0.66	0.67
400	1.22	1.01	0.63	0.03	0.54	0.90	0.89	0.89	0.70	0.87	0.89
600	1.45	1.20	0.72	1.10	0.64	1.04	1.08	1.09	0.85	1.02	1.01
800	1.53	1.30	0.80	1.23	0.70	1.16	1.23	1.24	0.97	1.19	1.12
1000	1.62	1.48	0.88	1.36	0.78	1.23	1.38	1.37	1.12	1.32	1.26
1200	1.76	1.53	0.94	1.50	0.86	1.35	1.55	1.47	1.21	1.41	1.30
1400	1.80	1.57	0.97	1.59	0.96	1.43	1.70	1.56	1.29	1.50	1.37
1600	1.89	1.64	1.02	1.72	1.05	1.57	1.85	1.64	1.37	1.59	1.37
1800	1.88	1.72	1.06	1.80	1.11	1.62	1.99	1.73	1.46	1.68	1.43
2000	2.28	1.77	1.11	1.89	1.21	1.70	2.11	1.79	1.52	1.76	1.44
2200	2.42	1.81	1.18	1.99	1.26	1.79	2.22	1.89	1.60	1.84	1.47
2400	2.66	1.90	1.25	2.10	1.32	1.85	2.35	1.96	1.69	1.90	1.49
2600	2.77	1.95	1.32	2.19	1.40	1.92	2.46	2.02	1.75	1.97	1.53
2800	2.95	2.02	1.37	2.27	1.44	1.96	2.58	2.10	1.83	2.04	1.55
3000	3.01	2.06	1.42	2.36	1.48	2.03	2.66	2.20	1.92	2.10	1.63
3200	3.08	2.14	1.47	2.46	1.53	2.07	2.76	2.33	1.98	2.16	1.69
3400	3.21	2.16	1.52	2.54	1.59	2.11	2.89	2.43	2.03	2.23	1.73
3600	3.28	2.22	1.57	2.58	1.65	2.15	3.00	2.52	2.09	2.29	1.75
3800	3.35	2.25	1.61	2.63	1.69	2.18	3.14	2.62	2.15	2.34	1.66
4000	3.43	2.30	1.65	2.67	1.75	2.21	3.24	2.72	2.20	2.40	1.70
4200	3.53	2.32	1.70	2.74	1.83	2.27	3.33	2.79	2.26	2.45	1.69
4400	3.57	2.41	1.76	2.78	1.86	2.28	3.45	2.88	2.30	2.49	1.68
4600	3.62	2.46	1.80	2.84	1.90	2.32	3.56	2.94	2.36	2.57	1.78
4800	3.66	2.50	1.84	2.86	1.95	2.34	3.65	3.04	2.40	2.64	1.77
5000	1.89	2.56	1.88	2.90	2.00	2.38	3.77	3.10	2.45	2.66	1.80
5200	2.83	2.58	1.93	2.94	2.02	2.42	3.87	3.17	2.48	2.70	1.81
5400	3.84	2.63	1.95	2.98	2.06	2.43	3.95	3.26	2.53	2.75	1.80
5600	3.88	2.71	2.00	3.01	2.09	2.46	4.07	3.32	2.57	2.80	1.95
5800	3.89	2.70	2.02	3.05	2.13	2.49	4.18	3.38	2.61	2.84	1.90
6000	3.91	2.75	2.04	3.09	2.16	2.53	4.28	3.46	2.64	2.89	1.95

Table 8 Continued, Results of Hamburg Rut Testing for SMA mixes

Passes	Rut Depth (mm)										
	HL-1		CL-2		HL-2		SS		CL-1	CU	
	L	R	L	R	L	R	L	R	R	L	R
6200	3.97	2.81	2.09	3.15	2.18	2.56	4.36	3.54	2.69	2.93	2.05
6400	4.04	2.82	2.13	3.20	2.21	2.57	4.47	3.61	2.72	2.98	2.04
6600	4.11	2.86	2.16	3.23	2.24	2.63	4.57	3.68	2.74	3.03	2.07
6800	4.18	2.90	2.19	3.27	2.25	2.65	4.68	3.77	2.75	3.07	2.03
7000	4.21	2.96	2.50	3.30	2.28	2.67	4.76	3.84	2.78	3.12	2.03
7200	4.23	2.99	2.28	3.34	2.34	2.69	4.89	3.93	2.83	3.16	2.11
7400	4.36	3.05	2.32	3.40	2.35	2.70	5.00	3.99	2.88	3.20	2.18
7600	4.42	3.08	2.34	3.43	2.38	2.74	5.05	4.07	2.90	3.25	2.17
7800	4.44	3.12	2.37	3.47	2.41	2.76	5.15	4.14	2.93	3.28	2.24
8000	4.50	3.15	2.41	3.51	2.42	2.79	5.20	4.21	2.97	3.32	2.21
8200	4.54	3.19	2.46	3.54	2.45	2.82	5.28	4.27	2.99	3.35	2.42
8400	4.59	3.23	2.49	3.58	2.50	2.85	5.39	4.35	3.02	3.38	2.24
8600	4.62	3.33	2.59	3.64	2.51	2.87	5.46	4.41	3.05	3.42	2.42
8800	4.67	3.32	2.61	3.67	2.55	2.90	5.55	4.49	3.07	3.45	2.35
9000	4.73	3.39	2.63	3.71	2.59	2.95	5.60	4.57	3.11	3.51	2.50
9200	4.78	3.45	2.69	3.76	2.61	2.94	5.68	4.66	3.14	3.54	2.41
9400	4.80	3.56	2.73	3.79	2.63	2.96	5.80	4.72	3.19	3.56	2.55
9600	4.84	3.65	2.78	3.83	2.67	2.98	5.88	4.79	3.24	3.60	2.57
9800	4.88	3.66	2.80	3.88	2.71	3.02	5.98	4.87	3.27	3.62	2.55
10000	4.95	3.72	2.84	3.93	2.74	3.03	6.10	4.95	3.30	3.66	2.60
10200	5.01	3.80	2.89	3.99	2.77	3.03	6.18	5.03	3.32	3.70	2.68
10400	5.09	3.83	2.96	4.02	2.79	3.07	6.26	5.08	3.34	3.74	2.66
10600	5.11	3.88	3.00	4.06	2.84	3.11	6.33	5.14	3.38	3.78	2.79
10800	5.12	3.94	3.03	4.11	2.87	3.15	6.39	5.21	3.42	3.82	2.70
11000	5.17	3.97	3.07	4.15	2.93	3.15	6.58	5.29	3.44	3.84	2.82
11200	5.19	4.00	3.10	4.19	2.95	3.17	6.73	5.39	3.47	3.87	2.80
11400	5.25	4.05	3.14	4.24	2.99	3.21	6.77	5.47	3.48	3.92	2.84
11600	5.28	4.11	3.17	4.27	3.02	3.27	6.83	5.54	3.52	3.96	2.94
11800	5.39	4.19	3.20	4.33	3.06	3.31	6.87	5.62	3.56	3.99	2.93
12000	5.51	4.26	3.25	4.37	3.09	3.33	6.96	5.69	3.58	4.01	2.90
12200	5.62	4.31	3.30	4.40	3.15	3.38	7.01	5.76	3.61	4.03	2.99
12400	5.69	4.39	3.30	4.46	3.19	3.43	7.10	5.83	3.65	4.06	2.96
12600	5.74	4.47	3.35	4.50	3.23	3.48	7.21	5.91	3.67	4.09	3.02
12800	5.80	4.55	3.38	4.56	3.26	3.47	7.30	5.99	3.69	4.12	3.09

Table 8 Continued, Results of Hamburg Rut Testing for SMA mixes

Passes	Rut Depth (mm)										
	HL-1		CL-2		HL-2		SS		CL-1	CU	
	L	R	L	R	L	R	L	R	R	L	R
13000	5.88	4.55	3.42	4.60	3.31	3.54	7.34	6.06	3.71	4.16	3.19
13200	5.94	4.67	3.51	4.62	3.35	3.57	7.38	6.15	3.75	4.18	3.21
13400	6.02	4.76	3.50	4.66	3.39	3.60	7.43	6.24	3.78	4.21	3.17
13600	6.08	4.82	3.53	4.72	3.41	3.62	7.50	6.30	3.81	4.23	3.25
13800	6.16	4.87	3.54	4.77	3.44	3.65	7.59	6.40	3.83	4.27	3.34
14000	6.20	5.04	3.56	4.79	3.51	3.69	7.67	6.47	3.84	4.28	3.29
14200	6.21	5.08	3.61	4.83	3.52	3.72	7.68	6.56	3.89	4.31	3.33
14400	6.25	5.20	3.61	4.86	3.56	3.78	7.75	6.61	3.90	4.33	3.30
14600	6.27	5.29	3.65	4.91	3.60	3.78	7.82	6.68	3.91	4.37	3.32
14800	6.31	5.45	3.72	4.94	3.65	3.82	7.87	6.79	3.93	4.39	3.31
15000	6.353	5.55	3.75	4.97	3.68	3.85	7.95	6.85	3.95	4.44	3.34
15200	6.39	5.61	3.80	4.99	3.71	3.86	8.05	6.93	3.98	4.45	3.38
15400	6.436	5.65	3.85	5.02	3.75	3.90	8.10	6.98	4.00	4.49	3.43
15600	6.465	5.74	3.94	5.05	3.79	3.94	8.16	7.05	4.03	4.51	3.44
15800	6.498	5.74	4.00	5.09	3.81	3.98	8.22	7.11	4.06	4.55	3.46
16000	6.546	5.78	4.03	5.10	3.85	4.02	8.31	7.17	4.08	4.58	3.54
16200	6.61	5.89	4.10	5.12	3.89	4.05	8.33	7.25	4.09	4.61	3.54
16400	6.705	6.01	4.19	5.16	3.93	4.08	8.43	7.33	4.11	4.64	3.57
16600	6.789	6.01	4.27	5.18	3.96	4.11	8.44	7.36	4.13	4.66	3.64
16800	6.862	6.00	4.36	5.20	4.01	4.14	8.48	7.43	4.15	4.70	3.68
17000	6.948	6.02	4.42	5.23	4.03	4.16	8.57	7.48	4.18	4.73	3.70
17200	7.023	6.14	4.51	5.24	4.06	4.19	8.57	7.56	4.19	4.76	3.71
17400	7.022	6.23	4.55	5.28	4.09	4.24	8.63	7.62	4.20	4.79	3.69
17600	7.074	6.22	4.63	5.28	4.13	4.29	8.70	7.70	4.22	4.83	3.74
17800	7.12	6.28	4.71	5.31	4.15	4.32	8.68	7.79	4.22	4.89	3.76
18000	7.168	6.39	4.75	5.32	4.19	4.36	8.73	7.85	4.24	4.91	3.76
18200	7.241	6.51	4.81	5.34	4.23	4.40	8.80	7.90	4.26	4.93	3.77
18400	7.306	6.58	4.85	5.36	4.25	4.42	8.82	7.98	4.29	4.96	3.76
18600	7.378	6.57	4.91	5.38	4.27	4.43	8.81	8.02	4.31	4.99	3.80
18800	7.445	6.70	4.96	5.40	4.30	4.47	8.84	8.09	4.33	5.02	3.76
19000	7.515	6.79	5.05	5.42	4.32	4.50	8.89	8.15	4.35	5.06	3.77
19200	7.59	6.73	5.08	5.45	4.36	4.55	8.92	8.21	4.37	5.09	3.84
19400	7.643	6.79	5.12	5.43	4.38	4.58	8.93	8.25	4.38	5.15	3.88
19600	7.695	6.84	5.19	5.52	4.39	4.62	8.97	8.31	4.40	5.16	3.87
19800	7.754	6.89	5.25	5.55	4.42	4.66	8.97	8.36	4.43	5.19	3.90
20000	7.81	7.01	5.31	5.55	4.46	4.69	8.96	8.43	4.44	5.22	3.87

Plots of Rut Depth and Number of Passes for S-4 Mixes

The plots of rut depth verses number of passes for the S-4 mixes are shown in figures 13 to 16.

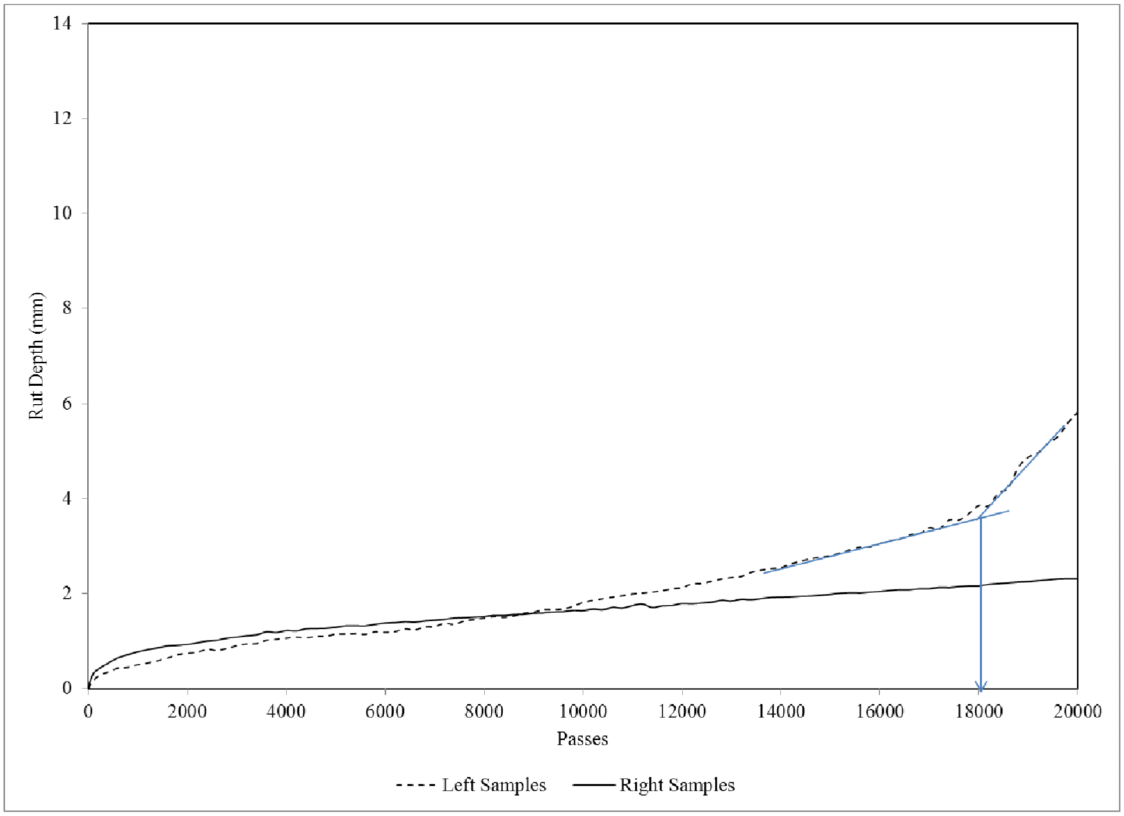

Figure 13, Hamburg Rut Depth VS Number of Passes for APAC Mix

Figure 13 shows that APAC mix left sample might have stripped around 18,000 passes.

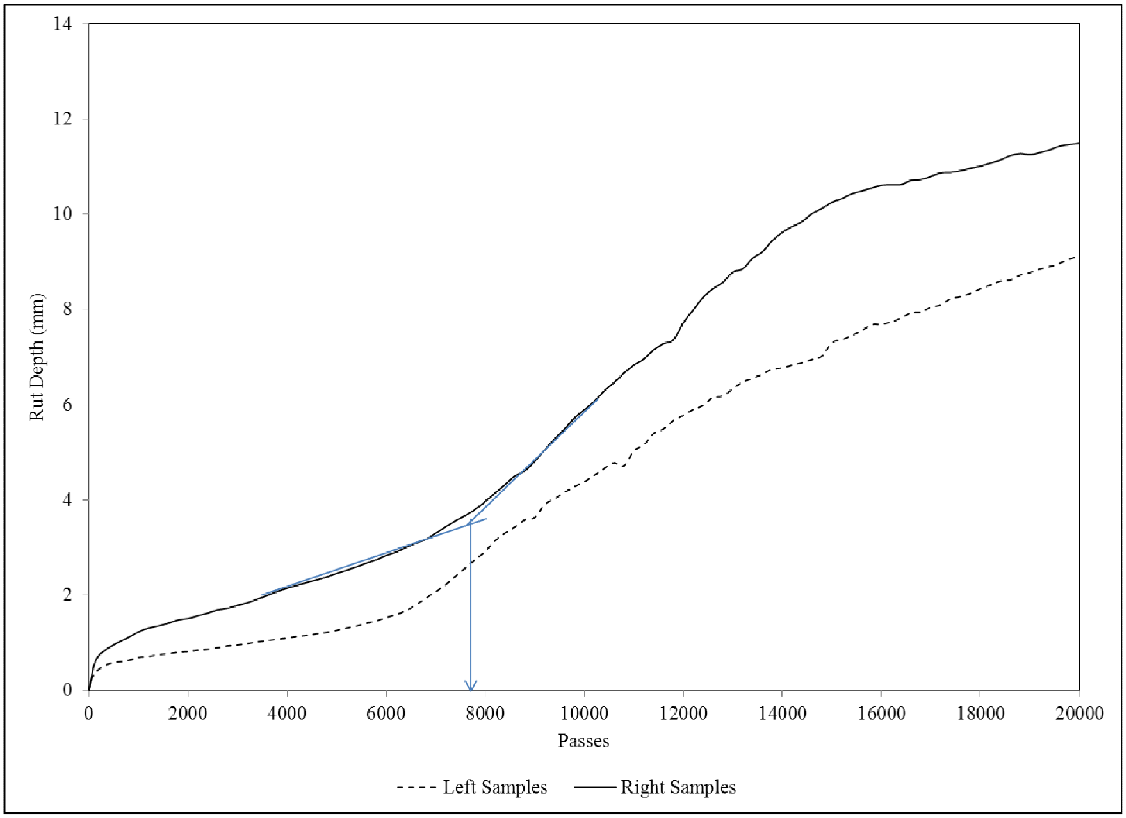

Figure 14, Hamburg Rut Depth VS Number of Passes for CL-3 mix

According to Figure 14, CL-3 mix possibly stripped around 8000 passes. It exhibited a higher average rut depth of 10.3 mm.

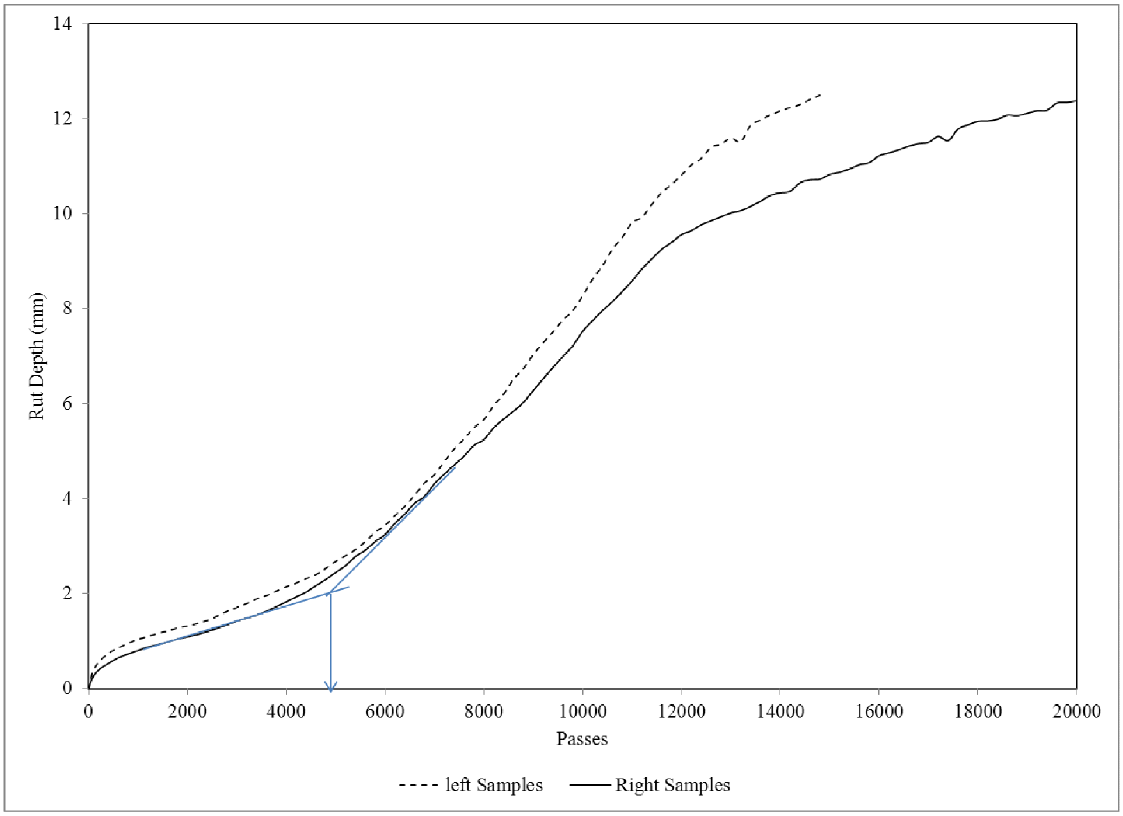

Figure 15, Hamburg Rut Depth VS Number of Passes for TJC mix

According to figure 15, TJC mix possibly stripped around 5000 passes.

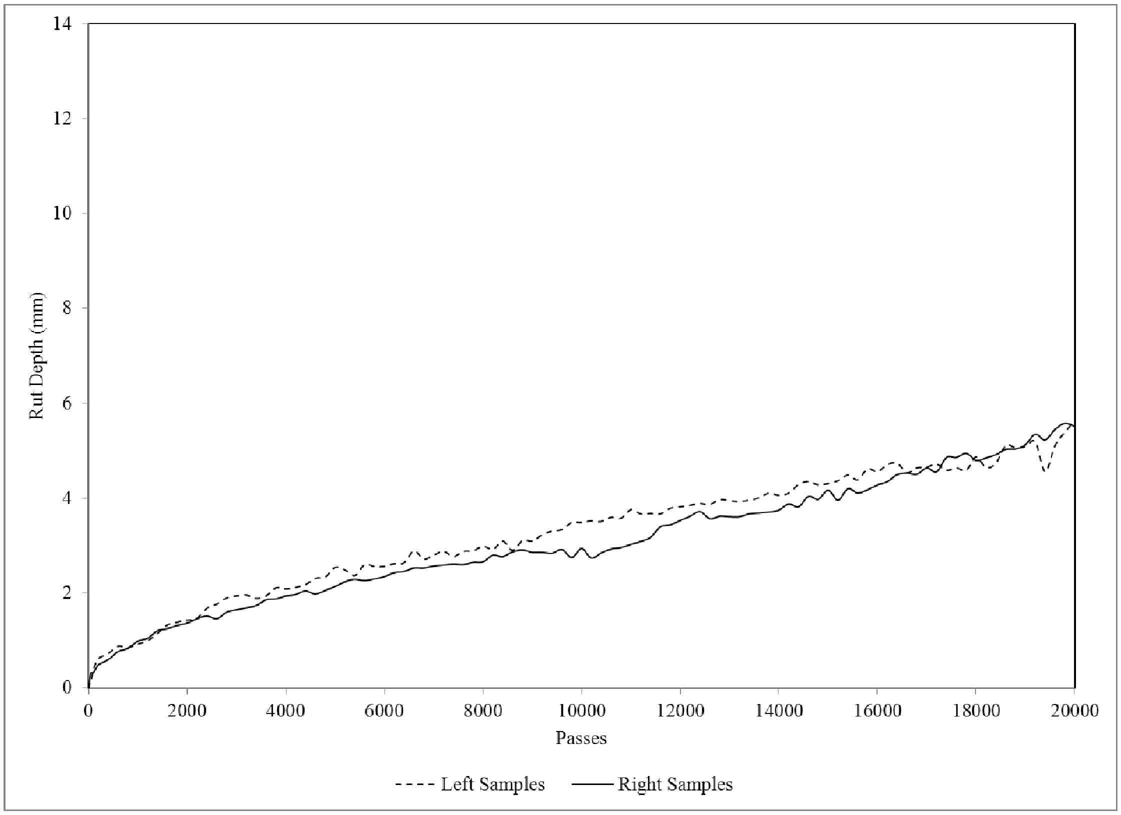

Figure 16, Hamburg Rut Depth VS Number of Passes for HL-3 mix

According to figure 16, HL-3 mix did not strip during the test.

Plots of Rut Depth and number of Passes for SMA Mixes

The plots of rut depth verses number of passes for the SMA mixes are shown in figures 17 to 22.

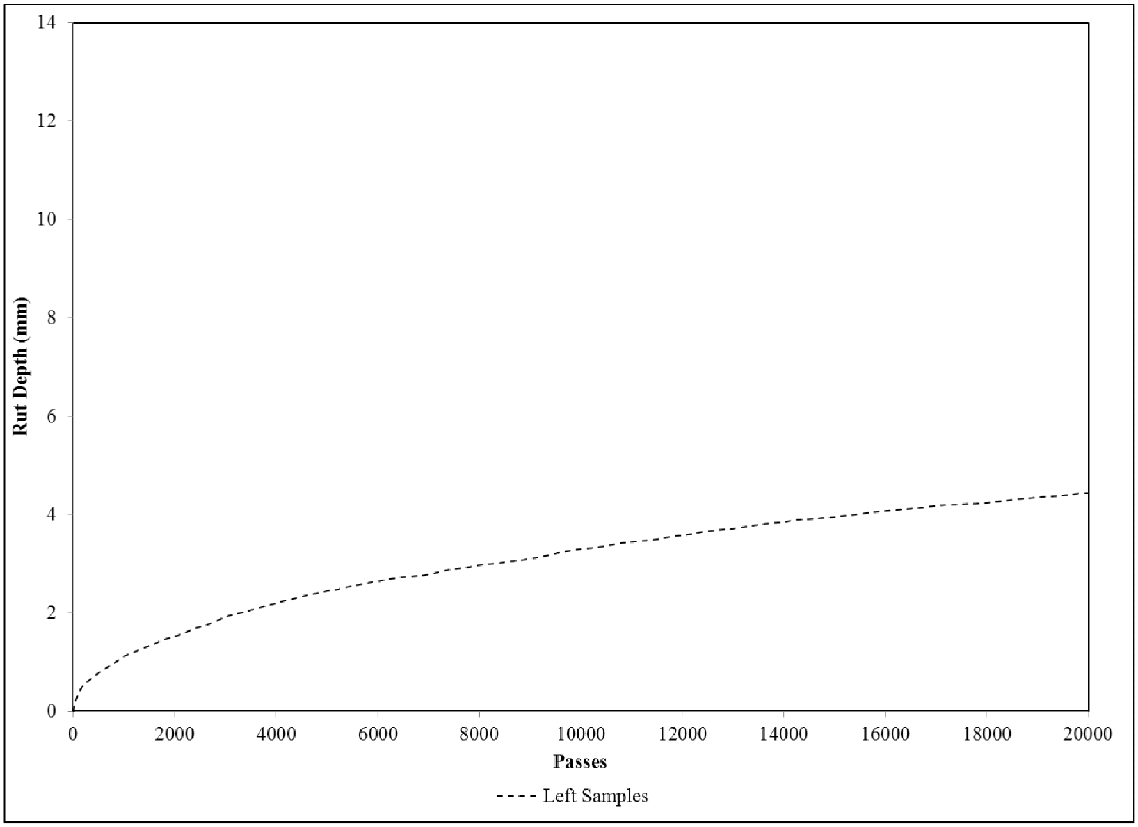

Figure 17, Hamburg Rut Depth VS Number of Passes for CL-1 mixes

According to figure 17, CL-1 mix did not strip during the test.

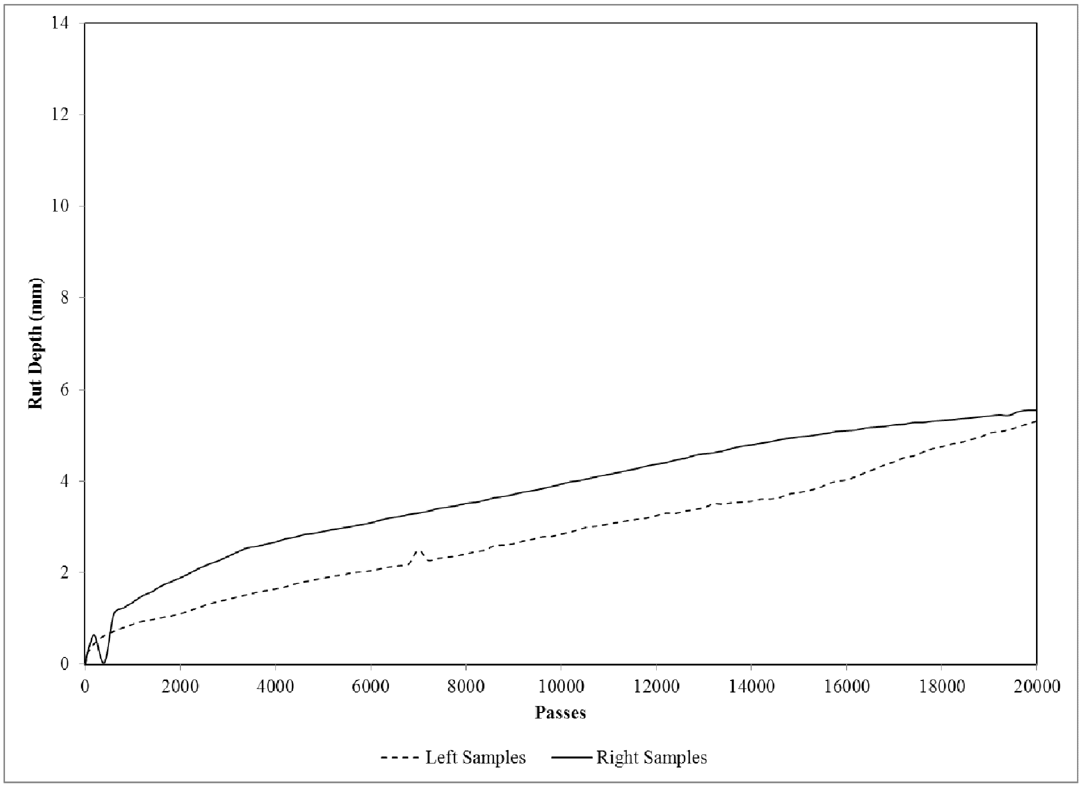

Figure 18, Hamburg Rut Depth VS Number of Passes for CL-2 mixes

As shown in figure 18, CL-2 did not strip during the test.

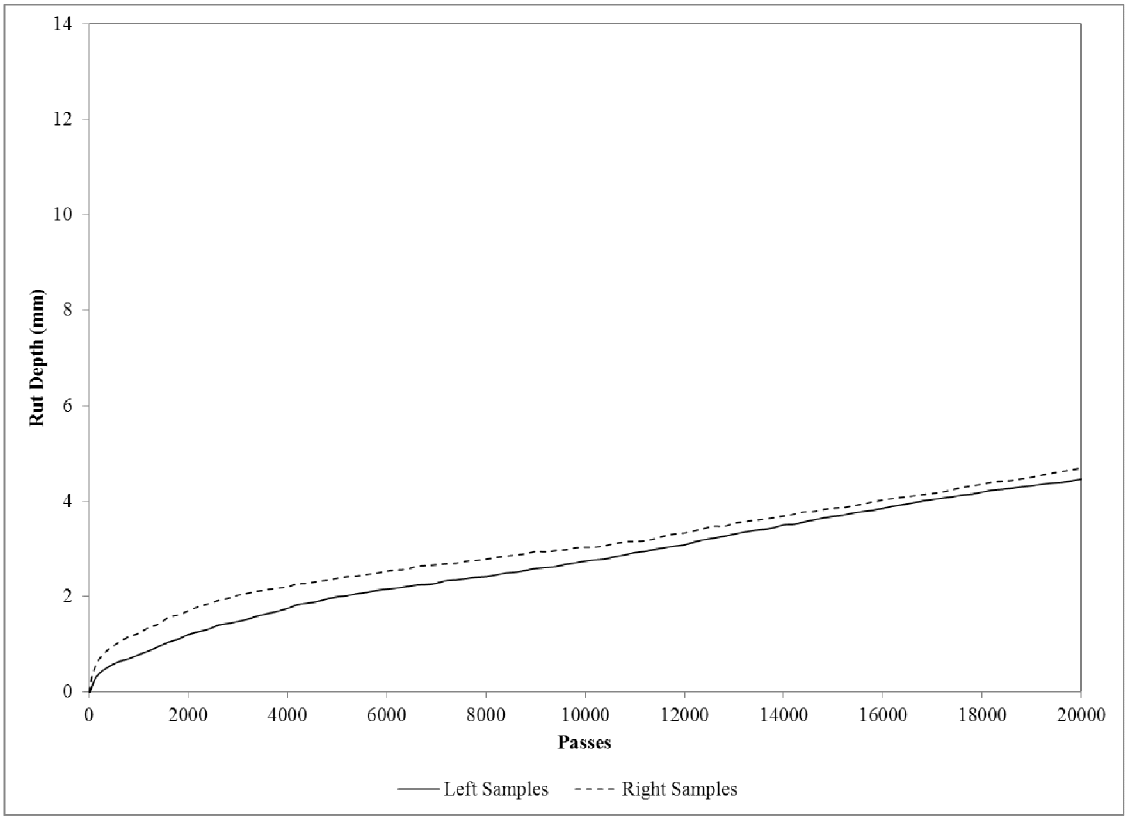

Figure 19, Hamburg Rut Depth VS Number of Passes for HL-2 mixes

According to figure 19, HL-2 mix did not strip during the test.

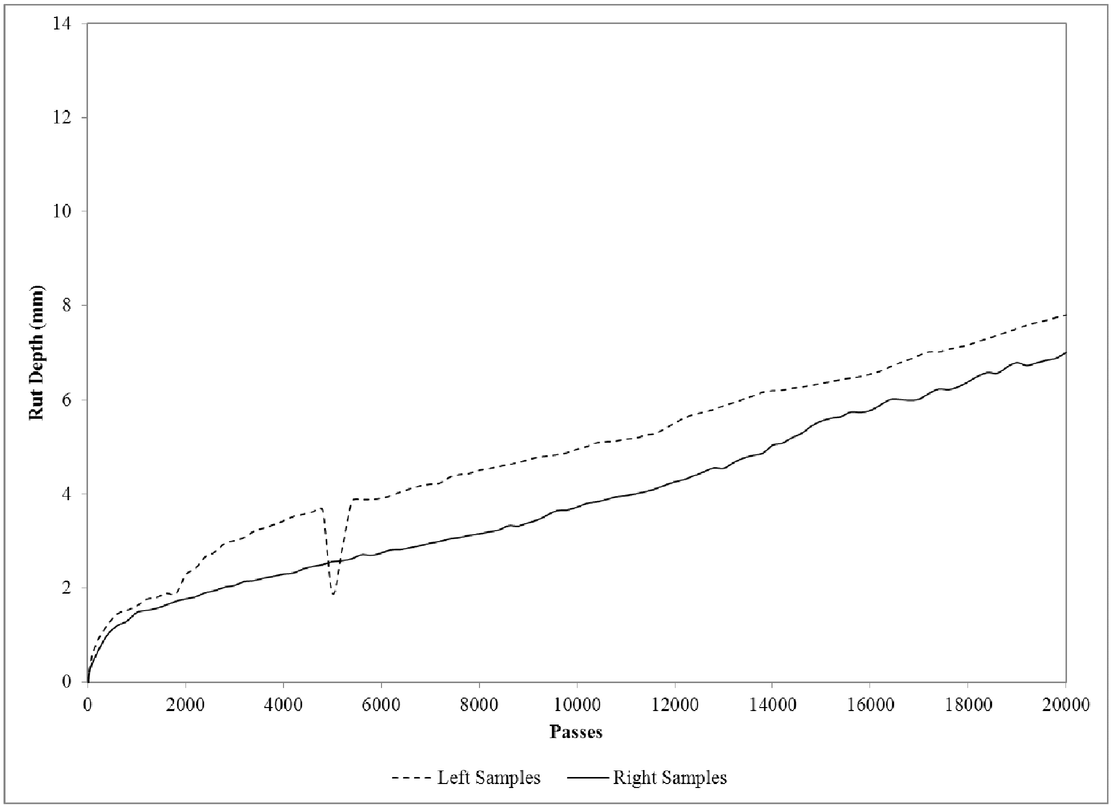

Figure 20, Hamburg Rut Depth VS Number of Passes for HL-1 mixes

According to figure 20, HL-1 performed very well without stripping.

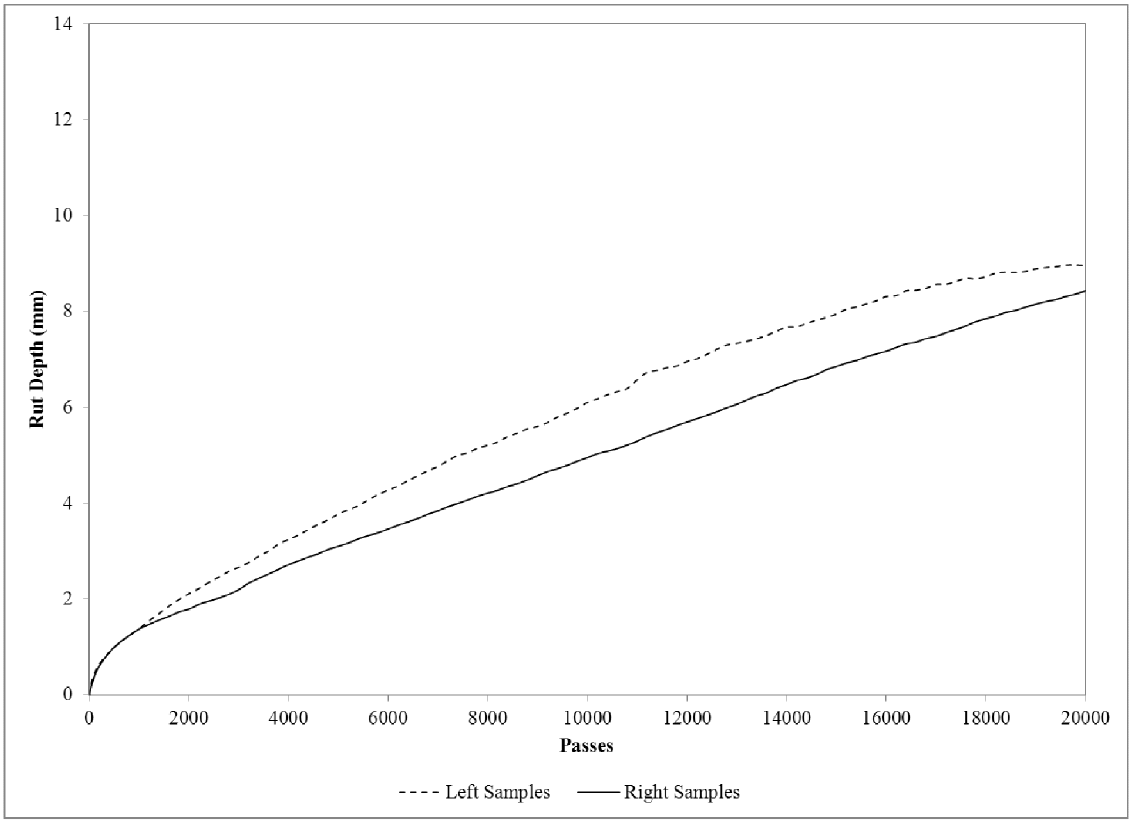

Figure 21, Hamburg Rut Depth VS Number of Passes for SS mixes

According to figure 21, SS Mix did not strip during the test.

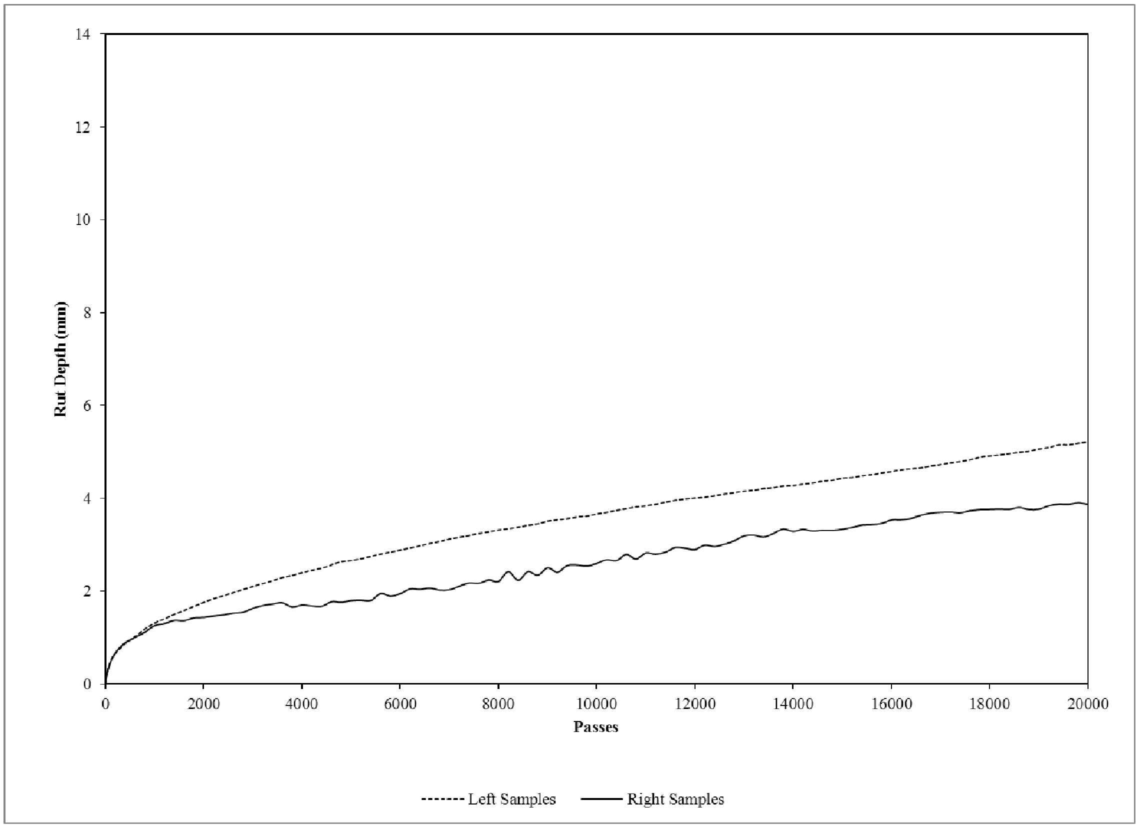

Figure 22, Hamburg Rut Depth VS Number of Passes for CU mixes

According to figure 22, CU mix did not strip.

CHAPTER V

ANALYSIS OF RESULTS

This chapter provides the analysis of the experimental data. The analysis was performed to determine the effect of mix type, i.e. S-4 & SMA, on rutting performance. Rut depth values of the different mix types from the laboratory experiment were compared with each other. Finally, it was investigated if the rut depth values for the different mixes are significantly different by using ANOVA (Analysis of variance) techniques. The Hamburg rut testing results, i.e. the maximum rut depth at 20,000 load passes, of S-4 and SMA, mixes are summarized in table 9.

Table 9, Hamburg Rut Testing Results for S-4 and SMA Mixes

	Mix Type	Rut Depth @ 20,000 Passes		Average Rut Depth
		Left	Right	
S-4	APAC	5.81	2.32	4.07
	CL-3	9.13	11.50	10.31
	TJC	15.00	12.38	13.69
	HL-3	5.63	5.52	5.58
SMA	HL-1	7.81	7.01	7.41
	CL-1	4.44	*	4.44
	HL-2	4.46	4.69	4.58
	SS	8.96	8.43	8.70
	CL-2	5.31	5.55	5.43
	CU	5.22	3.87	4.55

*****data not available

Figure 23 shows the average maximum rut depths at 20,000 passes for each S-4 and SMA mixes.

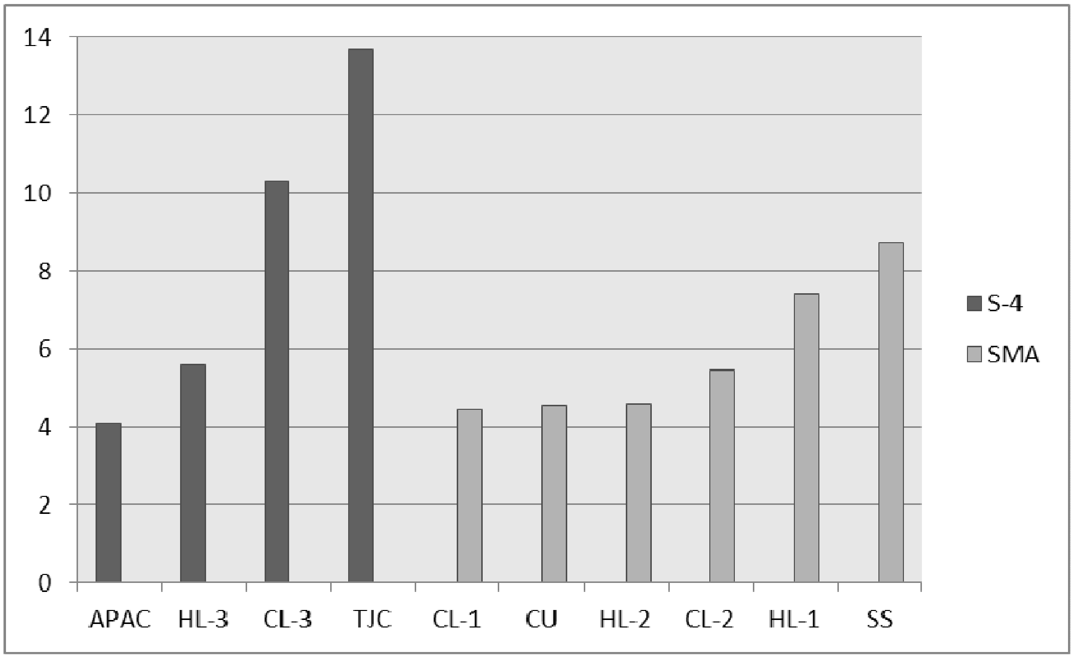

Figure 23, Plot of average Rut depth for all mixes

According to the laboratory experiment results, which are shown in table 9 and figure 23, two of the S-4 mixes performed very poorly while the remaining two performed very well. In addition, almost all the SMA mixes performed well. This scenario indicates that SMA mixes are more rut resistant than S-4 mixes but that some S-4 mixes can perform as well as SMA.

STATISTICAL ANALYSIS

To see if there is a significant difference in the rut depths of the mixes as a group (S-4 and SMA), a 1-way ANOVA was run on the laboratory data. The results of the ANOVA, shown in table 10, indicate that SMA and S-4 mixes are not significantly different at α = 0.10 but are significantly different at α = 0.11.

Table 10, ANOVA for Mix Rut Depth as a group S-4 & SMA

Mix	Degrees of Freedom	Sum Squares	Mean Squares	F Value	Prob. > F
Mix	1	27.4386101	27.4386101	2.91	0.1064
Error	17	160.4863057	9.4403709		
Total	18	187.9249158			

Table 10 shows that rut depth results from the Hamburg rut testing were not significantly different for S-4 and SMA. The mean rut depth of S-4 and SMA were 8.4 mm and 5.9 mm, respectively. Although, the results of the ANOVA showed there is not a significant difference between S-4 and SMA at 95% confidence level, the mean rut depths show that SMA was more resistant to rutting that S-4.

To see if there is any significant difference in the rut depths of the individual mixes, a 1-way ANOVA was run on the laboratory data. The results are shown in table 11.

Table 11, ANOVA for individual mixes Rut Depth

Source	Degrees of Freedom	Sum Squares	Mean Squares	F Value	Prob. > F
Source	9	174.1612158	19.3512462	12.65	0.0004
Error	9	13.7637	1.5293		
Total	18	187.9249158			

Table 11 shows that there is a significant difference among the mixes at $\alpha = 0.05$. To determine which mixes are significantly different from the other, Duncan's multiple range test was performed. The results are shown in table 12. Means with the same letter are not significantly different at $\alpha = 0.05$.

Table 12, Results of Duncan's Multiple Range Test for individual Mixes Rut Depth

Duncan* Grouping	Mean Rut Depth (mm)	N	Source	Mix Type
A	13.69	2	TJC	S-4
B	10.315	2	CL-3	S-4
B	8.695	2	SS	SMA
C & B	7.41	2	HL-1	SMA
C & D	5.575	2	HL-3	S-4
C & D	5.43	2	CL-2	SMA
C & D	4.575	2	HL-2	SMA
C & D	4.545	2	CU	SMA
C & D	4.44	1	CL-1	SMA
D	4.065	2	APAC	S-4

*Means with the same letter not significantly different

Table 12 shows that 5 of the 6 SMA mixes were not significantly different and all of the S-4 mixes were significantly different from each other. The best performing mix was an S-4 mix (APAC) but it was not significantly different from 4 of the SMA mixes. The S-4 mix from TJC was the poorest performing mix and it was significantly different from the remaining mixes.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Based on the materials tested using the Hamburg Wheel Tracking Rut test; the following conclusions and recommendations have been made.

Conclusions

- Generally, SMA mixes have been shown to perform better with respect to rutting resistance than S-4 mixes. SMA mixes showed lower average rut depth than S-4 mixes.
- Two of the S-4 mixes showed the poorest rutting performance and two of the S-4 mixes performed similar to the SMA mixes.
- S-4 mixes can be made to perform as well as SMA, as can be seen from the results of APAC and HL-3 mixes. APAC and HL-3 mix had average rut depths at 20,000 passes of 4.1 mm and 5.6 mm, respectively.

Recommendations

- SMA mixes should be considered for use in Oklahoma where high rut resistance is needed.
- Further studies have to be done on the causes of differences in performance of S-4 and SMA mixes including repeatability of Hamburg Rut Tester for performance.

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VITA

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Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: LABORATORY PERFORMANCE EVALUATION OF SMA IN OKLAHOMA

Pages in Study: 53 Candidate for the Degree of Master of Science

Major Field: Civil Engineering

Scope and Method of Study: The objective of this study is to determine if SMA mixtures have better rutting performance than S-4 mixes made with the same PG grade of binder. Different SMA and S-4 mixtures were collected from different parts of Oklahoma. All mixtures were made with PG 76-28 asphalt cement. To evaluate the performance properties of the mixtures, samples were made and tested for Hamburg rutting resistance using the Hamburg rut tester.

Findings and Conclusions: Generally, SMA mixes have been shown to perform better with respect to rutting resistance than S-4 mixes. SMA mixes showed lower average rut depth than S-4 mixes.

ADVISER'S APPROVAL: Dr. Stephen A. Cross