A LABORATORY EVALUATION ON THE USE OF RECYCLED ASPHALT PAVEMENTS IN HMA MIXTURES

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INTRODUCTION

Reclaimed asphalt pavement (RAP) is produced either by cold planning (CP) or by heating/softening and removal of the existing aged asphalt pavement. Recycling of the RAP has become more popular since the late 1970's although it had been practiced as early as 1915. The first sustained efforts to recover and reuse old asphalt paving materials were conducted during 1974 in Nevada and Texas *(1)*. The materials present in old asphalt pavements may have value, even when the pavements have reached the end of their service lives. Recognizing the value of those existing aggregate and asphalt resources increased the use of RAP in new asphalt pavements. Additionally, the increased prices of asphalts due to the escalating increases in crude oil prices as well as cost of energy in general, raised the interest in the use of RAP in asphalt pavements. By reusing aggregate and asphalt from deteriorated pavements, the need for new materials is appreciably reduced and the overall cost of the improved pavement will be less. Furthermore, several studies showed that asphalt mixtures containing RAP can have equivalent performance to virgin mixtures. Hence, since the use of RAP has proven to be economical and environmentally sound, different agencies and contractors have made extensive use of RAP in constructing highway pavements.

The overall goal of the mix design process of hot mixed asphalt (HMA) is to recommend a mix that can withstand the combined actions of traffic and environment. Therefore, it is critical to assess the impact of the various mix components on the performance of the constructed pavement (i.e. resistance to rutting, fatigue, and thermal cracking). The existence of RAP in the mix presents a challenge to the design engineer due to the complex interaction among the new and recycled components of the mix. The inclusion of RAP materials in the HMA mix can improve its resistance to rutting while it may greatly jeopardize its resistance to fatigue and thermal cracking. The key to successfully include RAP in the HMA mix is to be able to assess its impact on pavement's performance while recognizing the uniqueness of each project with respect to both materials and loading conditions.

One of the main concerns in RAP HMA mixtures is the effect of the RAP material on the mixture durability. Moisture susceptibility is regarded as the main cause of poor mixture durability. Moisture susceptibility can be evaluated by performing laboratory tests on unconditioned and moisture conditioned specimens. However, two recent research studies did not support the concerns over the durability of RAP containing HMA mixtures. Stroup-Gardner et al. *(2)* showed that the inclusion of coarse RAP decreased the moisture susceptibility of HMA mixtures. In 2000, Sondag *(3)* used the tensile strength ratio to evaluate the moisture sensitivity of 18 different mix designs incorporating three different asphalt binders, two sources of RAP and varying amounts of RAP. Sondag concluded that the addition of RAP to a mixture had no positive or negative influence on the mixture's moisture susceptibility.

The properties of RAP are largely dependent on the properties of the constituent materials (i.e. aggregate type, quality and size, extracted binder grade, etc.). The RAP composition is also affected by the previous maintenance and preservation activities that were applied to the existing pavement. Additionally, sometimes RAP from several projects are mixed in a single stockpile where deleterious materials or lower quality materials are also present. Consequently, a high variability is introduced in the RAP materials affecting the RAP properties and most likely resulting in a variable HMA mixture. Using low quality and/or highly variable RAP materials will definitely lead to premature failure of the HMA pavement. All these issues may limit the use of RAP in highway pavements and require the implementation of an effective quality control program.

Recognizing the fact that RAP usage conserves natural resources and can reduce disposal problems and associated costs, along with the identified concerns associated with the use of RAP in HMA pavements, the Regional Transportation Commission (RTC) of Washoe County, Nevada, decided to assess the feasibility of using recycled asphalt pavements in RTC projects and to develop guidelines for mix designs and quality control specifications.

OBJECTIVES

The laboratory experiment documented in this report was conducted to achieve the following objectives:

- Can the blending chart method be used to determine the grade of the virgin binder required for a given combination of RAP source and RAP content.
- Can the RTC Marshall mix design method be used to design HMA mixtures containing 15 and 30% RAP.
- Is the mixing process of virgin and RAP materials effective in producing a final binder meeting the target binder grade.
- What impact the RAP source and content have on the following properties of the final mix:
    - Moisture sensitivity
    - Resistance to rutting
    - Resistance to fatigue cracking
    - Resistance to thermal cracking
- Can the resilient modulus property be used as a surrogate test to estimate the performance of HMA mixtures containing RAP.

EXPERIMENTAL PROGRAM

In order to achieve the objectives of the research, the following experimental program was established:

- Identify three local RAP sources to cover a wide range of properties.
- Extract and recover the binder from the RAP materials.

- Evaluate the PG grades of the extracted /recovered binders from the RAP materials.

- Identify the required grade of the virgin binder to produce the specified grade of the blended binder using the blending chart technique with the desired RAP content and the known target binder grade.

- Evaluate the gradations of the aggregates from the RAP materials.

- Measure the specific gravity of the extracted RAP aggregate. The difference in the specific gravities between the aggregate of the RAP materials and the virgin source should not exceed 0.30.

- Identify the required gradation of the virgin aggregate to produce the specified gradation of the final blended mix.

- Conduct a mix design to identify the optimum binder content of the final blended mix following the RTC's Marshall mix design method.

- Measure the moisture sensitivity properties of the final blended mixtures at the optimum binder content using the AASHTO T-283 method.

- Measure the rutting resistances of the final blended mixtures at the optimum binder content using the asphalt pavement analyzer (APA).

- Measure the fatigue resistances of the final blended mixtures at the optimum binder content using the flexural beam fatigue test.

- Measure the thermal cracking resistance of the final blended mixtures at the optimum binder content using the thermal stress restrained specimen test (TSRST).

- Measure the resilient modulus (Mr) property of the final blended mixtures at the optimum binder content at 40, 77, and 104°F.

MATERIALS

Currently, the RTC specifies two binder grades for all HMA mixtures: PG64-22 and PG64-28NV. The PG64-22 is a neat asphalt binder to be used in the bottom lift of the HMA layer. The PG64-28NV is a polymer-modified binder to be used in the top and middle lifts of the HMA layer. The "NV" extension indicates that the binder is graded with the PG-special system which includes the Superpave PG binder system plus the following properties: toughness, tenacity, and ductility on original and RTFO binder at 40°F. The aggregate gradation can be either a Type 2 or a Type 2C. The Type 2C gradation was selected for this experiment.

RAP SOURCES

RAP material samples were obtained from 3 different local sources:

- Source I: plant waste from the Lockwood quarry located approximately ten miles east of Reno, Nevada, along Interstate 80.
- Source II: regular source from a 15-year old HMA pavement located at Flint Street in Reno, Nevada.
- Source III: regular source from a 20-year old HMA pavement located at Keitzke Lane in Reno, Nevada.

AGGREGATES

Each mix will have a virgin aggregate portion and a RAP aggregate portion except for the mix containing 0% RAP which will only have virgin aggregates.

Virgin Aggregates

The virgin aggregates came from a source located in Lockwood, Nevada, owned and operated by the Granite Construction Company. The RTC Type 2C gradation was used for all mixtures. Table 1 summarizes the gradation of the various stockpiles used in this study.

Table 1 Gradation of the Virgin Aggregate Stockpiles.

Sieve Size		Percent Passing					
No	**mm**	**1" PMA**	**3/4" PMA**	**1/2" PMA**	**3/8" PMA**	**Crushed Fines**	**Wade Sand**
1"	25.00	100.0	100.0	100.0	100.0	100.0	100.0
3/4"	19.00	69.9	100.0	100.0	100.0	100.0	100.0
1/2"	12.50	18.7	29.9	100.0	100.0	100.0	100.0
3/8"	9.50	2.8	1.9	55.5	100.0	100.0	99.6
#4	4.75	0.8	0.7	1.5	44.7	95.8	98.5
#8	2.36	0.8	0.7	1.4	2.7	70.6	97.3
#10	2.00	0.7	0.7	1.4	1.6	63.5	96.7
#40	0.425	0.7	0.6	1.4	1.0	26.5	61.7
#50	0.300	0.7	0.6	1.3	1.0	23.1	42.0
#100	0.150	0.7	0.6	1.3	0.9	18.3	12.8
#200	0.075	0.7	0.6	1.3	0.9	15.1	4.9

RAP Aggregates

The aggregates from the RAP materials were extracted in accordance with the AASHTO T164 standard test method using the centrifuge apparatus and trichloroethylene as a solvent. The gradation of the extracted aggregates from the RAP material was determined in accordance with AASHTO T30 standard test method for mechanical size analysis of extracted aggregates. Table 2 summarizes the aggregate gradation of the RAP materials.

Table 2 Aggregate Gradation of the Various RAP Materials.

Sieve Size		**Percent Passing**		
No	**mm**	**RAP Source I**	**RAP Source II**	**RAP Source III**
1"	25.00	100.0	100.0	100.0
3/4"	19.00	100.0	100.0	99.7
1/2"	12.50	99.6	93.8	93.9
3/8"	9.50	93.8	85.9	85.6
#4	4.75	64.4	61.2	57.1
#8	2.36	45.9	44.1	38.5
#10	2.00	42.6	41.0	35.5
#40	0.425	23.3	19.8	19.7
#50	0.300	19.4	15.2	16.8
#100	0.150	13.8	9.4	12.1
#200	0.075	10.5	6.7	8.6

TYPES OF MIXTURES

The laboratory experiment evaluated two distinct types of mixtures: a PG64-22/Type 2C and a PG64-28NV/Type 2C. Each mix was evaluated at three RAP contents of 0, 15, and 30% using three different sources of RAP. The following presents the labeling and definitions of the various mixtures.

> C-22 and C-28: represent the 100% virgin mixtures (Control Mix) produced with binder grades of PG64-22 and PG64-28NV, respectively.
>
> SI-22-15 and SI-28-15: represent the 15% of Source I RAP mixtures produced with the required virgin binder grades to meet the target grades of PG64-22 and PG64-28NV, respectively.

SI-22-30 and SI-28-30: represent the 30% of Source I RAP mixtures produced with the required virgin binder grades to meet the target grades of PG64-22 and PG64-28NV, respectively.

SII-22-15 and SII-28-15: represent the 15% of Source II RAP mixtures produced with the required virgin binder grades to meet the target grades of PG64-22 and PG64-28NV, respectively.

SII-22-30 and SII-28-30: represent the 30% of Source II RAP mixtures produced with the required virgin binder grades to meet the target grades of PG64-22 and PG64-28NV, respectively.

SIII-22-15 and SIII-28-15: represent the 15% of Source III RAP mixtures produced with the required virgin binder grades to meet the target grades of PG64-22 and PG64-28NV, respectively.

SIII-22-30 and SIII-28-30: represent the 30% of Source III RAP mixtures produced with the required virgin binder grades to meet the target grades of PG64-22 and PG64-28NV, respectively.

IDENTIFYING THE GRADES OF BINDERS

This task covers three separate steps: a) identifying the grade of the binders recovered from the RAP sources, b) identifying the required grades of the virgin binders to achieve the target binder grades and c) assessing the effectiveness of the blending chart method. The Superpave PG system is used to evaluate the properties of the recovered and virgin binders.

IDENTIFYING THE GRADES OF THE RECOVERED BINDERS

The asphalt binders from the RAP materials were extracted in accordance with the AASHTO T164 standard test method using the centrifuge apparatus and trichloroethylene as a solvent. Once the asphalt binder is extracted from the aggregate, it is recovered using the rotary evaporator according to the ASTM D5404 testing procedure. The recovered RAP binder was graded according to the Superpave PG system by testing the RAP binder as original, after short-term aging through the Rolling Thin Film Oven (RTFO), and after long-term aging through the

Pressure Aging Vessel (PAV). Table 3 summarizes the test results and the PG grades of the recovered RAP binders.

Table 3 Extracted/Recovered RAP Binders Test Results and Grades.

Aging	**Performance Criteria**	**Test Method**	**Property**	**PG Specification**	**Critical Temperature, °C**		
					RAP Source I	**RAP Source II**	**RAP Source III**
Original	Rutting	DSR[+]	G*/sinδ	≥ 1.0 kPa	83.5	82.2	83.5
RTFO	Rutting	DSR	G*/sinδ	≥ 2.2 kPa	82.0	82.2	82.0
RTFO +PAV	Fatigue	DSR	G*sinδ	≤ 5000 kPa	26.1	32.2	30.1
	Thermal Cracking	BBR[#]	S-value	≤ 300 MPa	-12.3	-8.6	-12.0
			m-value	≥ 0.3	-9.7	-6.7	-8.7
Superpave Performance Asphalt Binder Grade					PG82-16	PG82-16	PG82-16

[+] DSR Denotes “Dynamic Shear Rheometer”
[#] BBR Denotes “Bending Beam Rheometer”

IDENTIFYING THE REQUIRED GRADES OF THE VIRGIN BINDERS

The blending chart technique with the desired RAP content was used to identify The PG grades of the virgin binders required to blend with the RAP binders in order to achieve the target binder grades of PG64-22 and PG64-28NV. The blending chart process used the equation developed in the NCHRP 9-12 report and is given by:

$$T_{virgin} = \frac{T_{Blend} - \left(\%RAPbinder \times T_{RAP}\right)}{\left(1 - \%RAPbinder\right)}$$

where: T_{Blend} = the critical temperature of the blended asphalt binder
T_{virgin} = the critical temperature of the virgin asphalt binder
T_{RAP} = the critical temperature of the recovered RAP binder
$\%RAPbinder$ = percent RAP binder in the RAP expressed as a decimal

Table 4 summarizes, for each source of RAP material, the required virgin asphalt binder grade supplied by Paramount Petroleum Company, Nevada, at the desired RAP percent.

Table 4 Required Virgin Binders Grades for Various RAP sources.

RAP	**RAP Binder Grade**	**Required Virgin Binder Grade**			
		Target Binder: PG64-22		**Target Binder: PG64-28NV**	
		15% RAP	**30% RAP**	**15% RAP**	**30% RAP**
RAP Source I	PG82-16	PG64-22	PG58-28	PG64-34	PG58-34
RAP Source II	PG82-16	PG64-28NV	PG58-28	PG64-34	PG58-34
RAP Source III	PG82-16	PG64-28NV	PG58-28	PG64-34	PG58-34

ASSESSING THE EFFECTIVENESS OF THE BLENDING CHART METHOD

The objective of this effort was to assess the effectiveness of the blending chart method in identifying the appropriate grade of the virgin binder required to achieve the target binder grade for the various RAP sources and contents. This objective was achieved by conducting two experiments as described below.

Blending Virgin RAP Binders

In order to check if the target binder grade was achieved with the proposed blending chart method, the required virgin binder for each RAP source was mixed with the recovered asphalt binder from RAP material at their blending proportions and graded according to the Superpave PG system. Table 5 shows the PG grade for the blended binder obtained by mixing the virgin binder with the extracted/recovered RAP binder. Test results in Table 5 shows that all the blended binders have met or exceeded the target binder grade of PG64-22 and PG64-28NV.

Table 5 Summary of PG Grading of Actual Blended Binders.

Target Binder Grade	RAP Source-RAP%	Virgin Binder Grade	Critical Temperature, °C					Blended Binder PG grade
			Original Binder	RTFO	RTFO+PAV			
			G*/sinδ ≥ 1.0	G*/sinδ ≥ 2.2	G*sinδ ≤ 5000	S-value	m-value	
PG64-22	SI-15	PG64-22	70.8	69.9	24.5	-14.6	-13.4	PG64-22
	SI-30	PG58-28	68.0	67.6	21.0	-17.6	-16.0	PG64-22
	SII-15	PG64-28NV	70.1	69.7	19.9	-18.0	-15.2	PG64-22
	SII-30	PG58-28	67.9	67.3	21.2	17.0	-16.6	PG64-22
	SIII-15	PG64-28NV	71.3	70.2	19.6	-18.5	-15.7	PG70-22
	SIII-30	PG58-28	69.8	68.3	21.5	-17.3	-15.5	PG64-22
PG64-28NV	SI-15	PG64-34	66.0	69.2	7.0	-29.0	-29.0	PG64-34
	SI-30	PG58-34	68.5	68.7	8.6	-26.9	-25.0	PG64-34
	SII-15	PG64-34	64.9	64.9	7.0	-27.5	-27.3	PG64-34
	SII-30	PG58-34	67.2	66.8	11.7	-23.9	-22.0	PG64-28
	SIII-15	PG64-34	65.7	65.3	5.5	-28.1	-27.9	PG64-34
	SIII-30	PG58-34	68.8	67.4	10.4	-25.0	-22.1	PG64-28

Grading the Recovered Binder from the Final Blended Mix

This effort measured the grades of the binders recovered from the final blended mixtures. The process consisted of extracting and recovering the binders from the final blended mixtures for each of the twelve mixtures and identifying their PG. This effort is aimed to check the entire process from the point of identifying the required grade of the virgin binder through the mixing of the various mixtures. In other words this process assumes that if the grades of the binders recovered from the final blended mixtures coincide with the target grades, then the entire process is effective.

Table 6 summarizes the grades of the binders extracted and recovered from the various final blended mixtures. The extracted/recovered binder was considered at the RTFO aged condition since it has already been through the mixture short term aging. Therefore, the extracted/recovered binders were only subjected to the PAV test to simulate long term aging condition. Test results in Table 6 shows that all the blended binders have exceeded the target binder grades of PG64-22 and PG64-28NV, thus confirming the effectiveness of the blending chart method in identifying the appropriate grade of the virgin binder and the effectiveness of the mixing process in producing a homogeneous mix.

Table 6 Summary of PG Grading of Blended Binders Extracted/Recovered from Various Mixtures.

Target Binder Grade	**Mix**	**Critical Temperature, °C**					**Extracted/recovered Binder PG grade**
		Original Binder	**RTFO**	**RTFO+PAV**			
		G*/sinδ ≥ 1.0	**G*/sinδ ≥ 2.2**	**G*sinδ ≤ 5000**	**S-value**	**m-value**	
PG64-22	SI-22-15	N/A	74.1	27.5	-12.0	-11.8	PG70-22
	SI-22-30	N/A	75.5	27.0	-13.5	-12.5	PG70-22
	SII-22-15	N/A	75.6	24.1	-15.4	-12.3	PG70-22
	SII-22-30	N/A	71.7	23.5	-15.4	-15.2	PG70-22
	SIII-22-15	N/A	76.3	20.4	-14.0	-14.8	PG76-22
	SIII-22-30	N/A	76.6	25.0	-14.5	-12	PG76-22
PG64-28NV	SI-28-15	N/A	67.2	7.0	-29.3	-30.8	PG64-34
	SI-28-30	N/A	71.9	10.0	-25.6	-25.8	PG70-34
	SII-28-15	N/A	71.8	7.0	-27.8	-29.5	PG70-34
	SII-28-30	N/A	71.9	12.6	-24.0	-24.0	PG70-34
	SIII-28-15	N/A	74.7	7.7	-26.5	-31.5	PG70-34
	SIII-28-30	N/A	75.5	8.8	-26.5	-26.0	PG70-34

MIX DESIGNS

The mix design process covered three steps: a) identifying the percentages of the various stockpiles for each mix, b) measuring and checking the specific gravities of the aggregates, and c) determining the optimum binder contents.

DETERMINING PERCENTAGES OF STOCKPILES

The various blends at the desired RAP percentages (0%, 15%, and 30%) for mix design are shown in Table 7. It should be noted that the RAP content is considered as a percentage of the total aggregate and not a percentage of the total mix. For example, a RAP content of 15% means that the RAP aggregates will represent 15% of the total aggregate in the mix.

Table 7 Blend Percentages of the Various Mixtures.

Aggregate Source	**Blend Percentages**						
	RAP	**1" PMA**	**3/4" PMA**	**1/2" PMA**	**3/8" PMA**	**Crushed Fines**	**Wade Sand**
Virgin	0%	18%	10%	10%	22%	28%	12%
RAP Source I	15%	17%	14%	0%	23%	14%	14%
	30%	17%	12%	0%	21%	10%	10%
RAP Source II	15%	17%	14%	0%	23%	17%	14%
	30%	18%	10%	0%	18%	14%	10%
RAP Source III	15%	17%	14%	0%	23%	17%	14%
	30%	17%	9%	0%	20%	12%	12%

Figures 1-3 show the gradations of the various blends for each source of RAP material. It should be noted that all blend gradations meet the Standard Specifications for Public Works Construction (Orange Book, 2004) for Type 2C gradation.

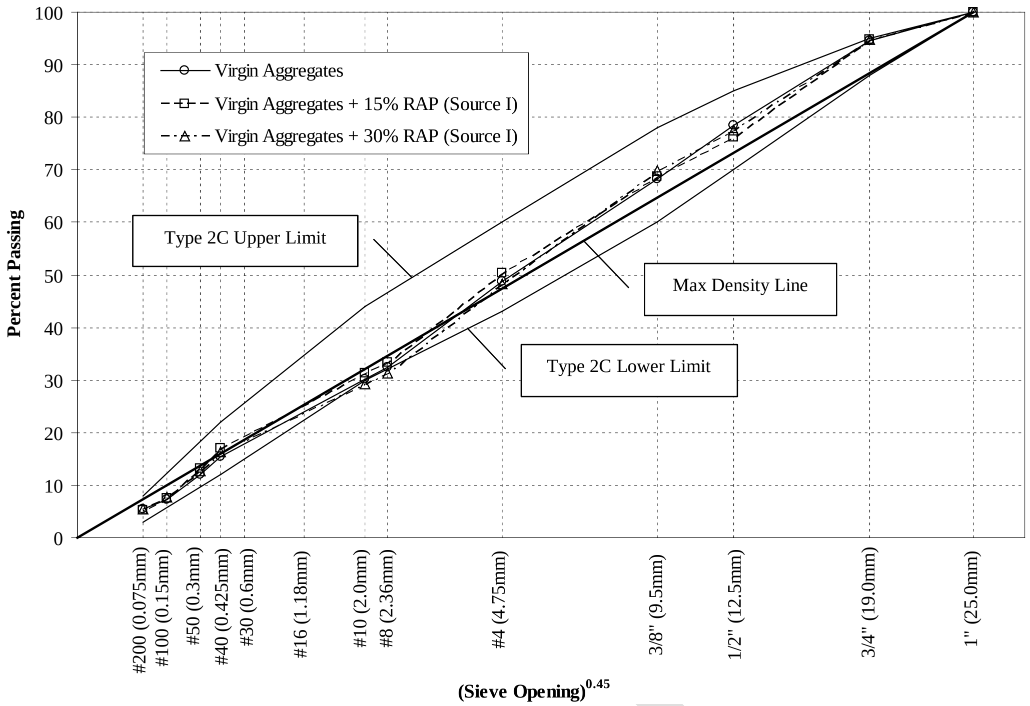

Figure 1. Gradations of Virgin Aggregates, Virgin Aggregates+15% RAP, and Virgin Aggregates+30% RAP from Source I.

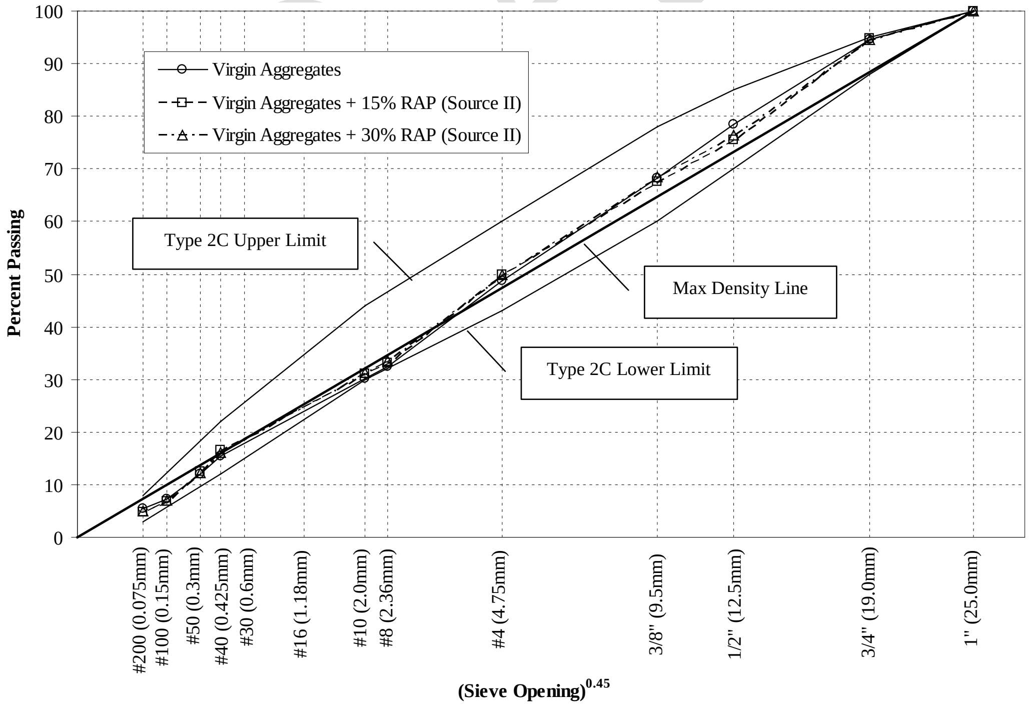

Figure 2. Gradations of Virgin Aggregates, Virgin Aggregates+15% RAP, and Virgin Aggregates+30% RAP from Source II.

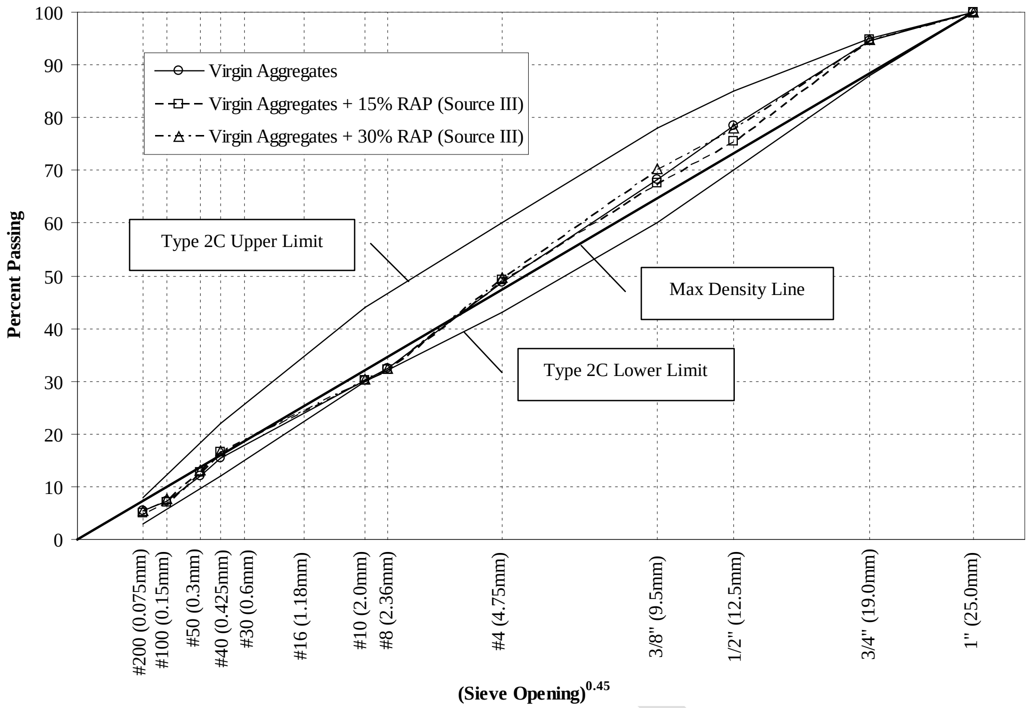

Figure 3. Gradations of Virgin Aggregates, Virgin Aggregates+15% RAP, and Virgin Aggregates+30% RAP from Source III.

MEASURING AND CHECKING THE AGGREGATES SPECIFIC GRAVITIES

The specific gravities of the extracted aggregates and the individual stockpiles of the virgin aggregates were measured in the laboratory in accordance with AASHTO T84 and T85. Table 8 shows the specific gravities for the various stockpiles and RAP materials. A maximum difference of 0.24 was found between the specific gravities of the aggregate of the RAP materials and the virgin aggregate stockpiles. If component specific gravities were to differ by 0.30 or more then the weight gradations need to be converted to by volume gradations to ensure blend gradation specifications are met.

Table 8 Specific Gravities of the Various Stockpiles and RAP Materials.

RAP Source I	**RAP Source II**	**RAP Source III**	**1" PMA**	**3/4" PMA**	**1/2" PMA**	**3/8" PMA**	**Crushed Fines**	**Wade Sand**
2.556	2.547	2.433	2.673	2.659	2.616	2.613	2.535	2.546

DETERMINING THE OPTIMUM BINDER CONTENTS

The Marshall mix design method as outlined in the Asphalt Institute's Mix Design Methods Manual MS-2 was used to design the mixtures. The heated RAP and virgin aggregate samples were mixed with various amounts of asphalt binder so that at least two were above and at least two were below the expected optimum asphalt content. All mixtures were treated with 1.5% of hydrated lime by the dry weight of the virgin aggregates. The samples were compacted with 75 blows on each side with the standard Automated Marshall hammer. Three samples were prepared at each asphalt content. The measured properties include: Marshall stability and flow, air-voids, voids filled with asphalt binder (VFA), voids in mineral aggregate (VMA), and unit weight.

The optimum binder content was selected at 4% air-voids. The selected binder content was then used to determine the corresponding values for Marshall stability and flow, VMA, VFA, and unit weight of the mix from the appropriate relationships.

Tables 9 and 10 summarize the mix design data for the target binder grade of PG64-22 and PG64-28NV along with the corresponding Orange Book specifications, respectively. Because of the incapability of meeting the minimum VMA criterion of 13.0% with the actual aggregate gradations, a minimum VMA of 11.0% was selected for this study. The relationships between the measured properties and binder content are presented in Appendix *A*.

Based on researchers' previous experience with Nevada's mixtures and in order to avoid the production of dry mixes, the design air-voids were dropped from 4.0% to 3.5% for some of the mixes with the target binder grade of PG64-28NV.

Table 9 Mix Design Summary and Specifications for the Target Binder Grade of PG64-22.

Property	**C-22**	**SI-22-15**	**SI-22-30**	**SII-22-15**	**SII-22-30**	**SIII-22-15**	**SIII-22-30**	**Requirements**
Optimum Binder Content (% TWM)	4.5	4.4	4.5	4.4	4.5	4.2	4.4	
Air Void (%)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Voids in Mineral Aggregates (%)	12.2	12.0	11.0	12.1	11.4	11.4	11.0	≥ 11.0*
Voids Filled with Asphalt (%)	68.0	66.0	65.0	67.0	65.0	66.0	65.0	65-75
Marshal Stability (lbf)	2800	3450	2850	3970	3360	4700	4700	> 1800
Marshall Flow (0.01 inch)	13.2	17.2	16.2	16.7	14.2	15.5	15.0	8-20
Unit weight (pcf)	149.3	149.1	151.0	149.0	149.9	149.0	148.5	

* Minimum VMA dropped from 13.0% to 11.0%

Table 10 Mix Design Summary and Specifications for the Target Binder Grade of PG64-28NV.

Property	**C-28**	**SI-28-15**	**SI-28-30**	**SII-28-15**	**SII-28-30**	**SIII-28-15**	**SIII-28-30**	**Requirements**
Optimum Binder Content (% TWM)	4.7	4.3	4.5	4.2	4.3	4.2	4.4	
Air Void (%)	4.0	3.5#	4.0	4.0	4.0	3.5#	4.0	4.0
Voids in Mineral Aggregates (%)	12.8	11.4	11.2	11.7	11.3	11.0	11.3	≥ 11.0*
Voids Filled with Asphalt (%)	68.0	71.0	65.0	67.0	65.0	71.0	65.0	65-75
Marshal Stability (lbf)	3250	3980	2790	4390	4380	3950	4300	> 1800
Marshall Flow (0.01 inch)	14.0	13.0	17.3	11.5	15.4	15.2	15.4	8-20
Unit weight (pcf)	148.5	150.0	150.8	149.3	149.7	149.5	147.7	

Design binder content selected at 3.5% air-voids to avoid production of dry mixes
* Minimum VMA dropped from 13.0% to 11.0%

IMPACT OF RAP ON MIXTURES PROPERTIES

The objective of the task is to evaluate the impact of the RAP source and content on the following properties of the final produced mixtures:

- Moisture sensitivity
- Resistance to rutting
- Resistance to fatigue cracking
- Resistance to thermal cracking

For each binder grade, the various performance of the RAP mixtures are compared to the performance of the control mixtures that are manufactured with 100% virgin aggregates.

In addition to simply comparing the properties of the various mixtures, a statistical analysis was performed to evaluate the significance of the differences among the properties of the various mixtures. The statistical analysis was conducted at a 5% significance level (α = 0.05) which means that for each comparison reported as being significantly different or not significantly different, there is only a 5% chance that is not true. The following nomenclature will be used in the statistical tables:

> H: the property of the mix listed in the row is significantly higher than the property of the mix listed in the column.
>
> L: the property of the mix listed in the row is significantly lower than the property of the mix listed in the column.
>
> NS: the property of the mix listed in the row is not significantly different from the property of the mix listed in the column.

MOISTURE SENSITIVITY

Moisture sensitivity of HMA mixtures is defined as the reduction in the internal strength of the mix due to moisture damage. As the moisture enters the HMA mix, it tends to weaken the bond between the asphalt binder and the aggregates leading to a reduction in the overall strength of the mix. This experiment used the AASHTO T-283 test method to evaluate the moisture sensitivity of the various mixtures. The following represents a summary of the major steps of the AASHTO T-283.

- Compact a total of 10 samples to air-voids of 6.5 to 7.5%
- Measure the tensile strength (TS) of 5 unconditioned samples at 77^{o}F
- Subject a set of 5 samples to 70-80% saturation
- Subject the saturated samples to a freeze-thaw cycle; freezing at 0^{o}F for 16 hours followed by 24 hours thawing at 140^{o}F and 2 hours at 77^{o}F
- Measure the TS of the 5 samples after conditioning
- Calculate the tensile strength ratio (TSR) as the ratio of the average TS of the conditioned samples over the average TS of the unconditioned samples.

Table 11 summarizes the moisture sensitivity properties of the various mixtures. The Washoe Regional Transportation Commission (RTC) specifies a minimum value of the unconditioned TS at 77°F of 65 psi and a minimum TSR of 70% for the Reno area.

Table 11 Moisture Sensitivity Properties of the Various Mixtures.

Target Binder Grade	**Mix**	**Mix Proportions**	**Tensile Strength, TS @ 77°F, psi**				**Tensile Strength Ratio, TSR (%)**
			Unconditioned		**Conditioned**		
			average	**CV* (%)**	**average**	**CV* (%)**	
PG64-22	C-22	0% RAP	194	7	168	5	86
	SI-22-15	15%RAP	224	8	174	8	78
	SI-22-30	30%RAP	179	9	135	7	76
	SII-22-15	15%RAP	157	9	139	3	89
	SII-22-30	30% RAP	107	5	84	10	78
	SIII-22-15	15%RAP	180	5	160	10	89
	SIII-22-30	30% RAP	184	5	129	4	70
PG64-28NV	C-28	0% RAP	167	8	137	9	82
	SI-28-15	15%RAP	75	5	50	8	66
	SI-28-30	30%RAP	91	7	69	3	76
	SII-28-15	15%RAP	79	8	63	9	80
	SII-28-30	30% RAP	180	9	146	10	81
	SIII-28-15	15%RAP	86	10	71	6	83
	SIII-28-30	30% RAP	131	8	94	8	72

* CV denotes Coefficient of Variation

The data in Table 11 indicate that all mixtures meet the RTC specification for moisture sensitivity except for the SI-28-15 mix which failed to meet the minimum TSR value of 70%. This indicates that except for the mix SI-28-15, all mixtures would have acceptable resistance to moisture damage. In practice, additional lime will have to be added for the SI-28-15 mix. The coefficient of variations (CV) is defined as the ratio of the average TS over the standard deviation times 100. The CV is an indication of the level of variability in the measured data. A CV value below 10% indicates excellent repeatability of the measured data.

Table 12 summarizes the statistical analysis of the moisture sensitivity properties of the various mixtures. The unconditioned tensile strength property is used in the statistical analysis since it was already shown that, except for the case of the SI-28-15 mix, all mixtures exhibited TSR values higher than the minimum required of 70%. Therefore, there is no need to also check the differences in the conditioned TS. Consequently, a higher unconditioned TS will most likely result in a better resistant mixture to moisture damage.

Table 12 Statistical Analysis of the Moisture Sensitivity Properties of the Various Mixtures.

Mix	**C-22**	**SI-22-15**	**SI-22-30**	**SII-22-15**	**SII-22-30**	**SIII-22-15**	**SIII-22-30**
C-22	▨	L	H	H	H	H	NS
SI-22-15	▨	▨	H	H	H	H	H
SI-22-30	▨	▨		H	H	NS	NS
SII-22-15	▨	▨	▨	▨	H	L	L
SII-22-30	▨	▨	▨	▨	▨	L	L
SIII-22-15	▨	▨	▨	▨	▨	▨	NS
SIII-22-30	▨	▨	▨	▨	▨	▨	▨
Mix	**C-28**	**SI-28-15**	**SI-28-30**	**SII-28-15**	**SII-28-30**	**SIII-28-15**	**SIII-28-30**
C-28	▨	H	H	H	L	H	H
SI-28-15	▨	▨	L	NS	L	NS	L
SI-28-30	▨	▨	▨	NS	L	NS	L
SII-28-15	▨	▨	▨	▨	L	NS	L
SII-28-30	▨	▨	▨	▨	▨	H	H
SIII-28-15	▨	▨	▨	▨	▨	▨	L
SIII-28-30	▨	▨	▨	▨	▨	▨	▨

The statistical analysis data in Table 12 leads to the following conclusions:

- In the case of the target binder grade of PG64-22, the 100% virgin aggregate mixture exhibited higher unconditioned TS property than the RAP mixtures except for the 15% RAP from source I and 30% RAP from source III where a lower and a non-significant unconditioned TS property for the control mix was observed, respectively. In general, this may result in better resistance to moisture damage of the 100% virgin aggregates mixture. Additionally the 15% RAP mixtures exhibited similar or better unconditioned TS property than the 30% RAP mixtures.

- In the case of the target binder grade of PG64-28NV, the 100% virgin aggregate mixture exhibited higher unconditioned TS property than the RAP mixtures except for the 30% RAP from source II where a lower unconditioned TS property for the control mix was observed. In general, this may result in better resistance to moisture damage of the 100% virgin aggregates mixture. Additionally the 15% RAP mixtures exhibited lower unconditioned TS property than the 30% RAP mixtures.

The mixtures with the target binder grade of PG64-22 showed significantly higher TS than the mixtures with the target binder grade of PG64-28NV. This may result in brittle mixtures that have reduced resistance to fatigue and thermal cracking.

RESISTANCE TO RUTTING

Rutting of HMA pavements is represented by a permanent deformation that develops gradually in the longitudinal direction under the wheel paths due to heavy traffic loads associated with high pavement temperatures. Rutting leads to safety problems when water collects in the ruts and creates dangerous driving conditions like hydroplaning and increased splash and spray.

This research evaluated the resistance of HMA mixtures to rutting using the asphalt pavement analyzer (APA) which subjects the mixture to repeated wheel loads and measures the resulting permanent deformation at elevated temperatures.

The APA test is standardized under AASHTO TP63-03, where a loaded concave wheel travels along a pressurized rubber hose that rests upon the HMA sample. Four 6-inch diameter cylindrical samples were compacted from each mix using the Superpave Gyratory Compactor to a height of 3 inches. Samples are secured within form-fitting acrylic blocks during testing. The APA wheel load is 100-lb and the hose pressure is 100 psi. The samples were conditioned for six hours before being tested in the dry condition at 140°F under 8,000 cycles. A data acquisition program records rut depths at 2 points within each sample and their average is reported. Four specimens were tested for every mix making four replicates per combination. Figure B1 in Appendix *B* shows the schematics of the Asphalt Pavement Analyzer.

Table 13 summarizes the rutting resistance of the various mixtures. Nevada DOT uses a maximum criterion of 8 mm (0.3 inch) rut depth in the APA under 8,000 cycles at 140^{o}F. The APA data in Table 13 indicate that all mixtures meet the NDOT APA criterion with three mixtures from the target binder grade of PG64-22 being close to the failure criterion. All mixtures are expected to perform well in rutting except for the SI-22-15, SI-22-30 and SII-22-30 mixtures for the target binder grade PG64-22.

Additionally, the APA data in Table 13 show that the mixtures with a target binder of PG64-28NV have a significantly better resistance to rutting than the mixtures with a target binder of PG64-22. This observation supports RTC's recommendation to use the PG64-28NV grade in the top lift where rutting potential is very high.

Table 13 Rutting Resistance of the Various Mixtures.

Target Binder Grade	Mix	Mix Proportions	APA Rut Depth under 8,000 Cycles @ 140°F	
			mm	inch
PG64-22	C-22	0% RAP	4.6	0.18
	SI-22-15	15%RAP	5.9	0.23
	SI-22-30	30%RAP	6.0	0.24
	SII-22-15	15%RAP	2.2	0.09
	SII-22-30	30% RAP	7.3	0.29
	SIII-22-15	15%RAP	1.4	0.06
	SIII-22-30	30% RAP	2.1	0.08
PG64-28NV	C-28	0% RAP	2.1	0.08
	SI-28-15	15%RAP	2.1	0.08
	SI-28-30	30%RAP	3.1	0.12
	SII-28-15	15%RAP	2.1	0.08
	SII-28-30	30% RAP	2.4	0.09
	SIII-28-15	15%RAP	2.1	0.08
	SIII-28-30	30% RAP	2.2	0.08

The statistical analysis ranked the various mixtures in terms of their resistance to rutting (from best to worst), based on their APA rut depth at 140°F, as follows:

Target Binder Grade: PG64-22

1. SIII-22-15
2. SIII-22-30, SII-22-15
3. C-22
4. SI-22-15, SI-22-30
5. SII-22-30

Target Binder Grade: PG64-28NV

1. SIII-28-15, C-28, SII-28-15, SI-28-15, SIII-28-30, SII-28-30
2. SI-28-30

In the case of the target binder PG64-22, the RAP mixtures exhibited significantly better rutting resistance than the control mix (C-22) except for the SI-22-15, SI-22-30, and SII-22-30 mixtures. In the case of the target binder PG64-28NV, the RAP mixtures exhibited rutting resistance similar to the control mix (C-28) under the APA test at 140°F.

RESISTANCE TO FATIGUE CRACKING

The resistance of the HMA mixtures to fatigue cracking is defined as the ability of the mix to resist repeated tensile strains without cracking. As the HMA pavement is subjected to traffic loads, tensile strains at the bottom of the HMA layer are generated. If the HMA mix can not resist these strains, fatigue cracking will generate at the bottom of the layer and will propagate to the surface.

The resistances of the mixtures to fatigue cracking were evaluated using the flexural beam fatigue test (AASHTO T321-03). The 2.5 by 2.0 by 15 inches beam specimen is subjected to a 4-point bending with free rotation and horizontal translation at all load and reaction points. This produces a constant bending moment over the center portion of the specimen. In this study, constant strain tests were conducted at different strain levels; using a repeated haversine load at a frequency of 10 Hz, and a test temperature of 72°F. Initial flexural stiffness was measured at the 50th load cycle. Fatigue life or failure is defined as the number of cycles corresponding to a 50%

reduction in the initial stiffness. The following model was used to characterize the fatigue behavior of the HMA mixtures:

$$N_f = k_1 \left(\frac{1}{\varepsilon_t} \right)^{k_2}$$

where N_f is the fatigue life (number of load repetitions to 50% reduction in the initial stiffness), ε_t is the applied tensile strain, and k_1 and k_2 are experimentally determined coefficients. Figure B2 in Appendix *B* shows the schematics of the flexural beam fatigue test and a typical fatigue curve for HMA mixtures

Figures 4-9 show the fatigue relationships for the various mixtures tested in this study for each source of RAP material and target binder grade.

Table 14 summarizes the fatigue data of the various mixtures in terms of the number of cycles to failures under tensile strains of 300, 500, and 700 microns, representing low, medium, and high levels of strains in HMA pavements, respectively.

Table 14 Laboratory Measured Fatigue Life of Mixtures at 72°F.

Target Binder Grade	**Mix**	**Mix Proportions**	**Number of Cycles to Failure**		
			Strain Level		
			300 microns	**500 microns**	**700 microns**
PG64-22	C-22	0% RAP	191,520	20,700	4,780
	SI-22-15	15%RAP	510,980	12,550	1,090
	SI-22-30	30%RAP	311,000	43,330	11,830
	SII-22-15	15%RAP	530,000	59,690	14,160
	SII-22-30	30% RAP	126,770	23,520	7,760
	SIII-22-15	15%RAP	546,670	49,520	10,180
	SIII-22-30	30% RAP	2,635,400	39,200	2,450
PG64-28NV	C-28	0% RAP	will not fail	1,683,400	119,850
	SI-28-15	15%RAP	3,827,100	925,600	363,400
	SI-28-30	30%RAP	9,545,000	669,000	116,180
	SII-28-15	15%RAP	will not fail	3,715,000	918,750
	SII-28-30	30% RAP	13,194,000	419,850	43,340
	SIII-28-15	15%RAP	3,621,100	773,400	279,800
	SIII-28-30	30% RAP	1,611,200	165,925	37,120

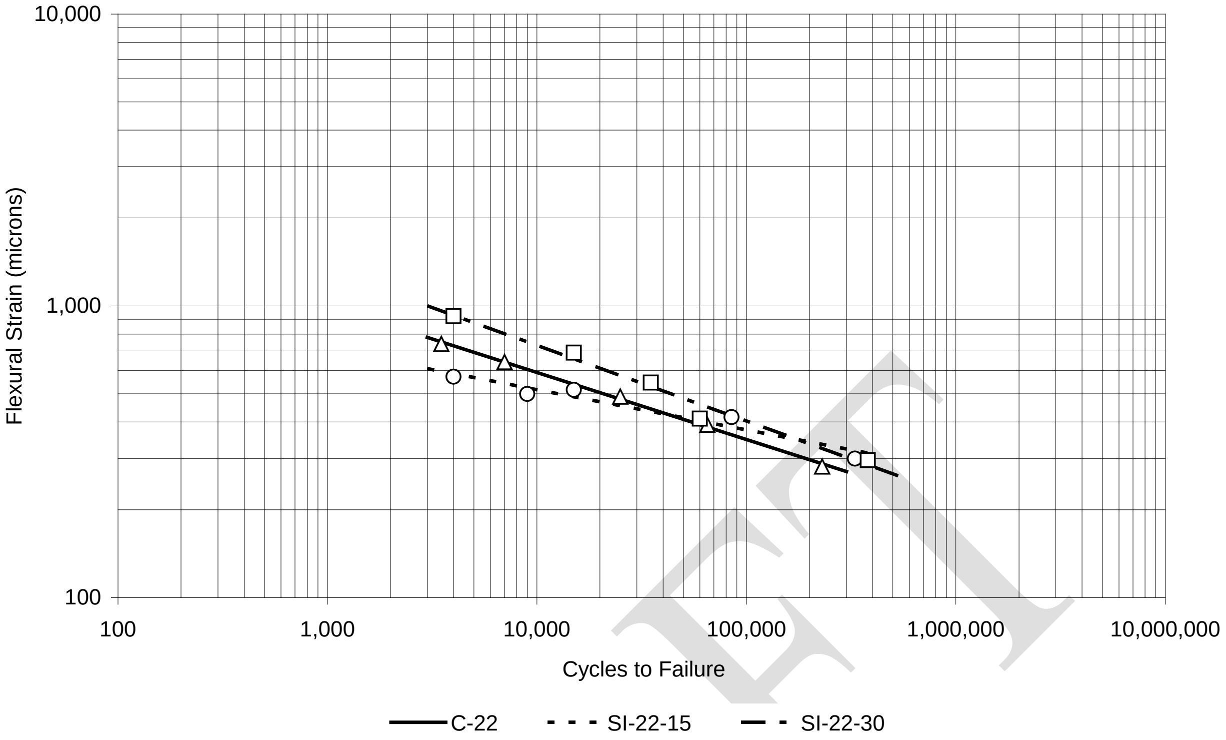

Figure 4. Fatigue relationships of source I RAP mixtures for target binder grade PG64-22.

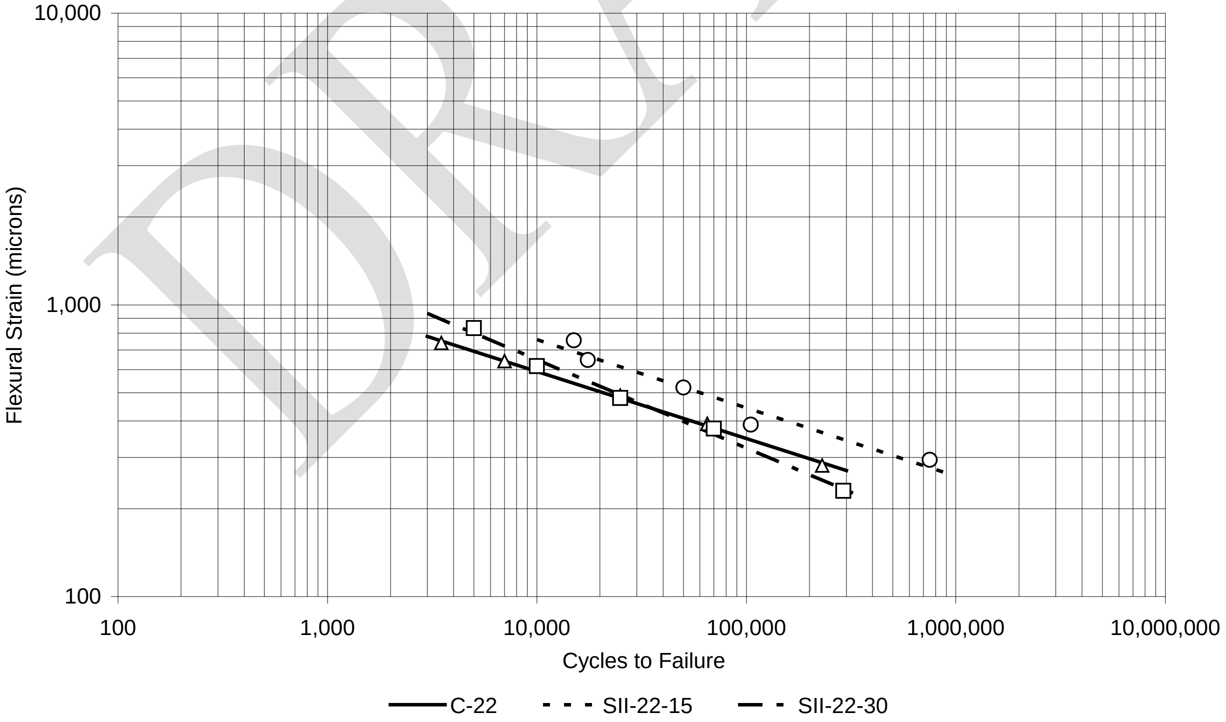

Figure 5. Fatigue relationships of source II RAP mixtures for target binder grade PG64-22.

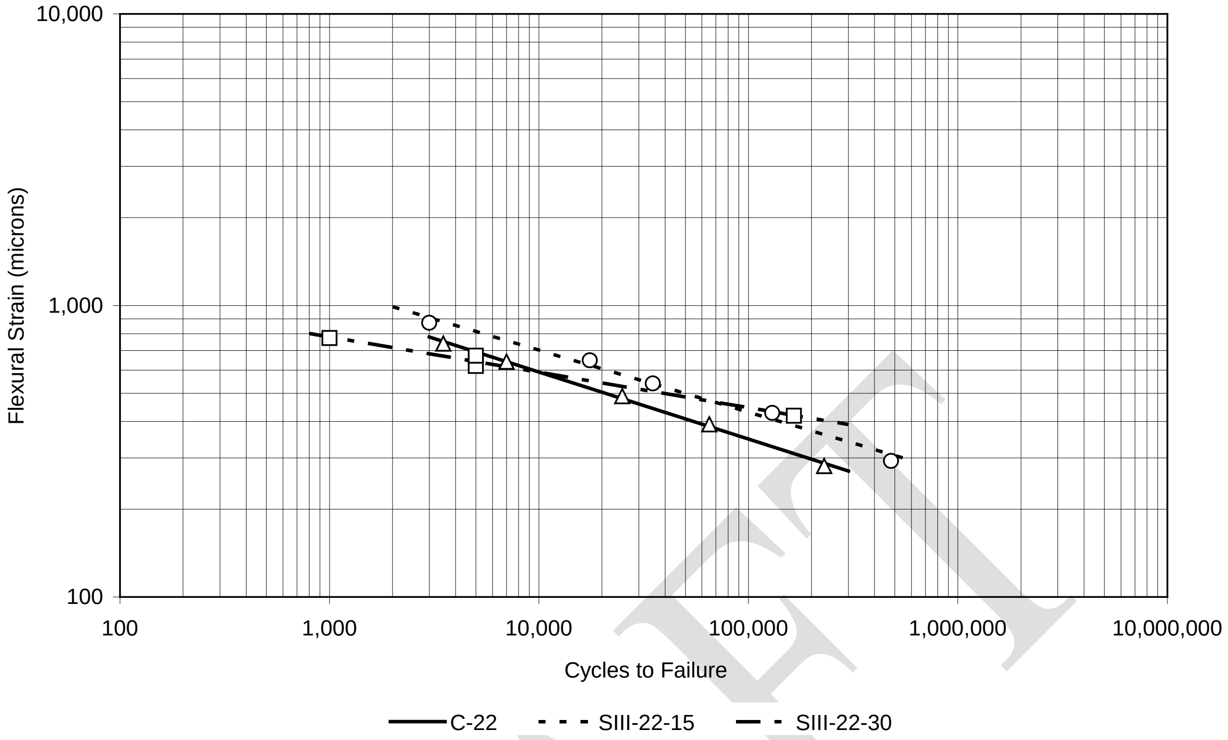

Figure 6. Fatigue relationships of source III RAP mixtures for target binder grade PG64-22.

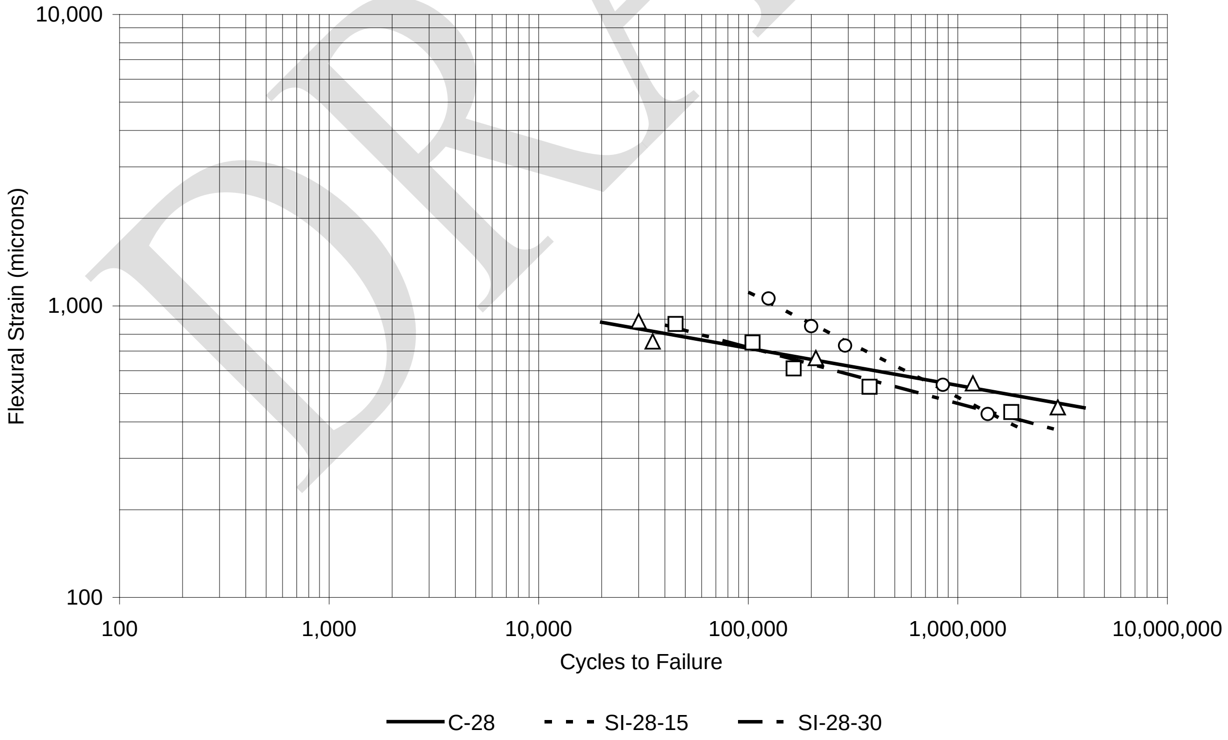

Figure 7. Fatigue relationships of source I RAP mixtures for target binder grade PG64-28NV.

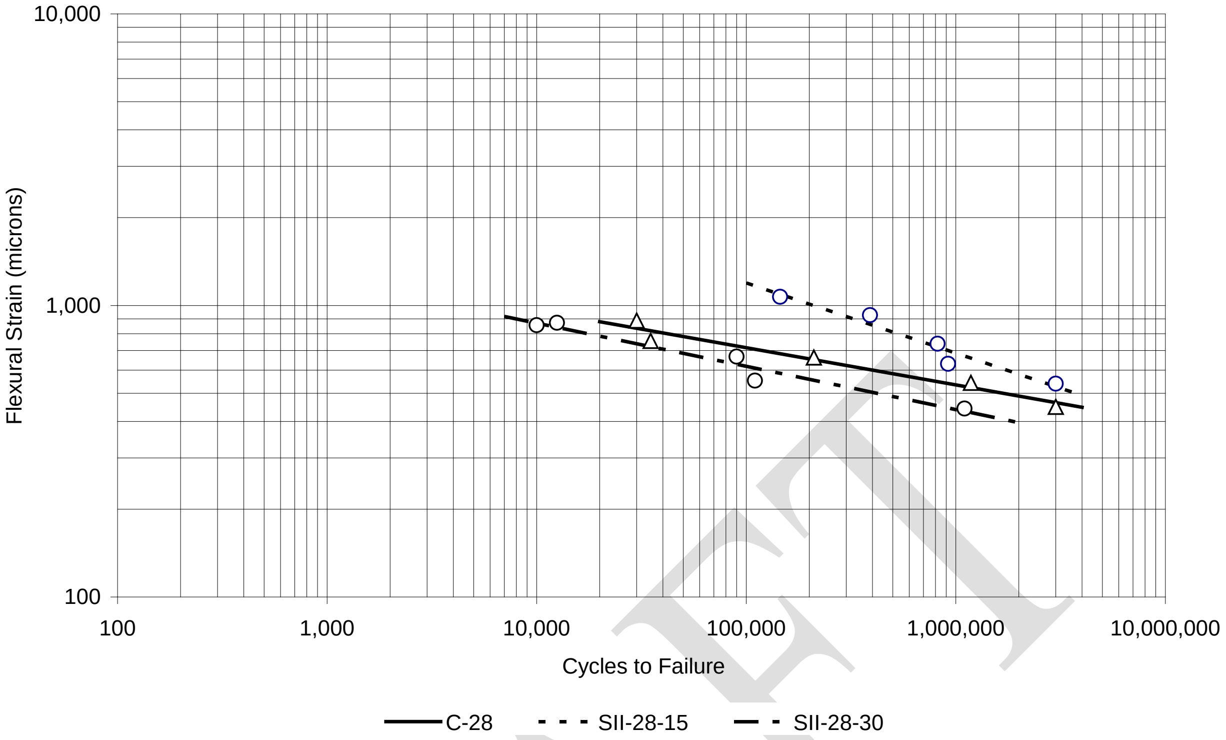

Figure 8. Fatigue relationships of source II RAP mixtures for target binder grade PG64-28NV.

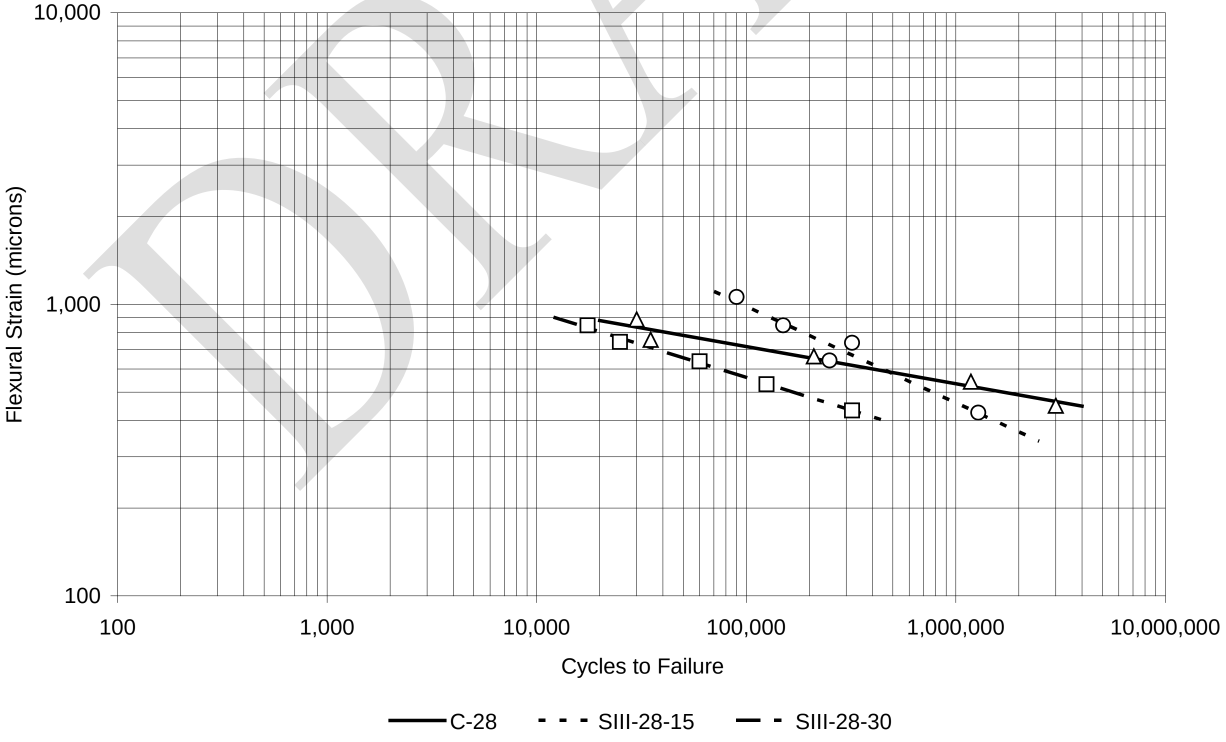

Figure 9. Fatigue relationships of source III RAP mixtures for target binder grade PG64-28NV.

By comparing the number of cycles to failure at the various strain levels the following observations can be made:

- In the case of target binder grade of PG64-22, the fatigue data show that, except for the case of SI-22-15 and SII-22-30 mixes, both the 15% and the 30% RAP mixtures exhibited similar or better laboratory fatigue resistance than the control mixture (C-22). The SI-22-15 mix exhibited a lower number of cycles to failure at a strain level higher than 500 microns whereas the SII-22-30 mix exhibited lower number of cycles to failure at 300 microns.
- In the case of target binder grade of PG64-28NV, the 30% RAP mixture exhibited lower laboratory fatigue resistance than the control mixture (C-28) at all three strain levels. On the other hand the 15% RAP mixture exhibited a better laboratory fatigue resistance than the control mixture only at a strain level of 700 microns.

In other words, the addition of 15 and 30% RAP to a mixture with a target binder grade of PG64-22 had no effect or improved the laboratory fatigue resistance in four mixtures out of six. On the other hand, the addition of RAP to a mixture with a target binder grade of PG64-28NV reduced the laboratory resistance of the mix to fatigue at low strain levels for the 15% RAP material and at all strain levels for the 30% RAP material. However, a better laboratory fatigue resistance will not necessarily translate to a better fatigue performance in the field as the fatigue life of an asphalt pavement is highly dependent on both the modulus and the fatigue characteristics of the HMA mixture and their interaction. In a mechanistic pavement analysis, an HMA layer with a higher stiffness will show a lower laboratory fatigue life but on the other hand it will produce a lower tensile strain under field loading. Therefore, depending on the magnitude of strain reduction, the HMA layer with the higher stiffness may result in a longer fatigue life in the field or vise versa.

Therefore, a mechanistic analysis is needed to effectively evaluate the impact of RAP on the fatigue performance of an HMA pavement. The mechanistic-empirical analysis will be used in conjunction with the resilient modulus (Mr) at 77°F and fatigue characteristics data that were measured on all fourteen mixtures to assess the fatigue performance of an HMA pavement. The pavement structure consists of 4 inches of HMA on top of 10 inches of a granular base course representing a typical section in the Truckee Meadows region.

The mechanistic-empirical method of design is based on the multi-layer elastic solution that relates an input, such as a wheel load, to pavement responses, such as stresses, strains, and deflections. In this analysis, the axle load was assumed at 22,000 lb/single axle and tire inflation pressure of 125 psi. These conditions represent the most common legal load limits in the U.S. The modulus properties of the base course and subgrade were assumed at 30,000 and 10,000 psi, respectively. The Poisson's ratio of the HMA mixture is assumed at a constant value of 0.35. The Poisson's ratio of the base course and subgrade were assumed at 0.40 and 0.45, respectively.

First, the tensile strain at the bottom of the HMA is calculated under the tire load. Second, the calculated tensile strain is input into the corresponding fatigue relationship to calculate the number of load repetitions to fatigue failure. Finally, the numbers of load repetitions to fatigue failure from each structure are compared. Table 15 summarizes the pavement materials properties used in the mechanistic analyses. The repeated-load indirect tension test was used to determine the resilient modulus of the various HMA mixtures at 77°F. The Mr is an engineering property that describes the stress-strain relationship of the HMA mix.

Table 16 summarizes the number of load repetitions to fatigue failure for all the mixtures covered in this study. The impact of using RAP was evaluated in terms of the ratio of fatigue life of the RAP mixture over the control mixture. A fatigue life ratio greater than one indicates a better fatigue life for the RAP mixture.

Table 15 Properties of Pavement Materials Used in the Mechanistic Analyses.

Target Binder Grade	**HMA Layer (4-inch Thick)**		**Base Layer (10-inch Thick)**	**Subgrade Layer**
	Mix	**Resilient Modulus at 77°F (ksi)**	**Resilient Modulus (ksi)**	**Resilient Modulus (ksi)**
PG64-22	C-22	1,091	30,000	10,000
	SI-22-15	1,086		
	SI-22-30	392		
	SII-22-15	730		
	SII-22-30	340		
	SIII-22-15	873		
	SIII-22-30	672		
PG64-28NV	C-28	668	30,000	10,000
	SI-28-15	211		
	SI-28-30	296		
	SII-28-15	279		
	SII-28-30	849		
	SIII-28-15	249		
	SIII-28-30	516		

Table 16 Number of Load Repetitions to Fatigue Failure in the HMA layer.

Target binder grade	**Mix**	**Resilient modulus at 77°F (ksi)**	**Tensile strain at the bottom of HMA layer, 4"depth, (microns)**	**Number of repetitions to fatigue failure, N_f**	**Ratio of fatigue life**
PG64-22	C-22	1,091	264	337,000	--
	SI-22-15	1,086	264	1,280,000	3.80
	SI-22-30	392	458	61,000	0.18
	SII-22-15	730	333	338,000	1.01
	SII-22-30	340	488	25,500	0.08
	SIII-22-15	873	301	537,000	1.60
	SIII-22-30	672	349	757,000	2.25
PG64-28NV	C-28	668	350	27,600,000	--
	SI-28-15	211	587	592,000	0.02
	SI-28-30	296	517	556,000	0.02
	SII-28-15	279	530	2,920,000	0.11
	SII-28-30	849	306	11,570,000	0.42
	SIII-28-15	249	554	567,000	0.02
	SIII-28-30	516	401	444,400	0.02

Table 16 shows that for the case of target binder grade of PG64-22, the addition of 15% RAP to the mixture resulted in similar or higher fatigue life regardless of the RAP source. On the other hand, the addition of 30% RAP from source I and II resulted in a reduction in fatigue life except for the RAP mixture from source III where the fatigue resistance improved by a ratio of 2.25.

In the case of target binder grade of PG64-28NV, a significant reduction in fatigue life was found due to the addition of RAP to the mixture regardless of the RAP source and content. It should be noted that the low numbers for the fatigue life ratio were due to the significantly high number of repetitions to fatigue failure (27.6 millions) for the C-28 control mix when compared to the RAP mixes. However, the RAP mixtures with the target binder grade of PG64-28NV showed in general a better fatigue life than the corresponding RAP mixtures with the target binder grade of PG64-22.

On the other hand, the control mix C-28 showed significantly higher fatigue life than the control mix C-22 by a ratio of 82. The use of the polymer-modified asphalt binder PG64-28NV in the control mix offered significant advantage in fatigue life over the PG64-22 control mix and hence supporting RTC's previous research findings.

RESISTANCE TO THERMAL CRACKING

Thermal cracking of HMA pavements is defined as the formation of a transverse crack across the pavement surface as a result of the shrinkage stresses developed inside the HMA layer due to the reduction in the pavement temperature during the winter season. The resistance of HMA pavements to thermal cracking is defined as the ability of the HMA mix to absorb the tensile shrinkage stresses without cracking.

The Thermal Stress Restrained Specimen Test (TSRST) (AASHTO TP10-93) was used to determine the low-temperature cracking resistance of the various HMA mixtures. The test cools down a 2 by 2 by 10 inches beam specimen at a rate of 10°C/hour while restraining it from contracting. While the beam is being cooled down, tensile stresses are generated due to the ends being restrained. The HMA mixture would fracture as the internally generated stress exceeds its tensile strength. The temperature at which fracture occurs is referred to as "fracture temperature" and represents the field temperature under which the pavement will experience thermal cracking. Figure B3 in Appendix *B* shows the schematics of the TSRST. Table 17 summarizes the resistance to thermal cracking of the various mixtures.

For the target binder of PG64-22, the data in Table 17 indicate that RAP mixtures exhibited colder fracture temperatures than the control mix (C-22) in four out of six mixtures with practically unchanged in two mixes. The most significant improvement occurred with the 15% RAP mix from source II (SII-22-15). For the target binder of PG64-28NV, the addition of RAP to a mix resulted in a significant colder fracture temperature than the control mix (C-28), hence an increase in thermal cracking resistance.

Table 17 Thermal Cracking Fracture Temperatures of the Various Mixtures.

Target Binder Grade	**Mix**	**Mix Proportions**	**Fracture Temperature (°C)**
PG64-22	C-22	0% RAP	-18
	SI-22-15	15%RAP	-17
	SI-22-30	30%RAP	-26
	SII-22-15	15%RAP	-29
	SII-22-30	30% RAP	-22
	SIII-22-15	15%RAP	-16
	SIII-22-30	30% RAP	-23
PG64-28NV	C-28	0% RAP	-24
	SI-28-15	15%RAP	-39
	SI-28-30	30%RAP	-35
	SII-28-15	15%RAP	-40
	SII-28-30	30% RAP	-40
	SIII-28-15	15%RAP	-39
	SIII-28-30	30% RAP	-28

The statistical analysis of the thermal cracking data ranked the various mixtures in terms of their resistance to thermal cracking (best to worst) as follows:

Target Binder Grade: PG64-22

1. SII-22-15
2. SI-22-30
3. SIII-22-30, SII-22-30
4. C-22
5. SI-22-15, SIII-22-15

Target Binder Grade: PG64-28NV

1. SII-28-15, SII-28-30 , SIII-28-15
2. SI-28-15, SI-28-30
3. SIII-28-30
4. C-28

On the other hand, the mixtures with the target binder grade of PG64-28NV exhibited significantly colder fracture temperature than the corresponding mixtures with the target binder grade of PG64-22. Additionally the RAP mixtures with the target binder grade of PG64-28NV exhibited significantly colder fracture temperature than the control mix C-22.

ASSESSMENT OF RESILIENT MODULUS AS A VIABLE TEST TO ESTIMATE MIX PERFORMANCE

The purpose of this analysis is to assess whether the resilient modulus property can be used as a surrogate test to estimate the performance of the HMA mixtures containing RAP. This task is conducted to assess if the more complex tests for rutting, fatigue, and thermal cracking can be replaced with the simpler test of resilient modulus.

The temperature susceptibility of HMA mixtures is defined as the relationship between the resilient modulus (Mr) of the mixture and temperature. The Mr is an engineering property that describes the stress-strain relationship of the HMA mix. An HMA mix having a high Mr at low and intermediate temperatures (40-77^{o}F) may be too brittle and susceptible to cracking while an HMA mix having a low Mr at elevated temperatures (77-104^{o}F) may be too soft and susceptible to rutting. The repeated-load indirect tension test for determining the Mr property of HMA mixtures was used in this research. Figure B4 in Appendix *B* shows the resilient modulus schematics along with the formula used to calculate the Mr from the measured deflections and applied load. The test is conducted by applying a compressive load with a haversine waveform (loading = 0.1 sec and rest = 0.9 sec) on the vertical diametral plane of a cylindrical specimen.

Table 18 and Figure 10 summarize the temperature susceptibility of the various mixtures. A Mr property at 77°F in the range of 350-600 ksi represents a good HMA mix, a Mr property at 104°F above 150 ksi indicates good resistance to rutting and a Mr property at 40°F below 1,000 ksi indicates good potential resistance to thermal cracking.

Table 18 Temperature Susceptibility Properties of the Various Mixtures.

Target Binder Grade	**Mix**	**Mix Proportions**	**Resilient Modulus, Mr, ksi**[+]					
			40°F		**77°F**		**104°F**	
			average	**CV* (%)**	**average**	**CV* (%)**	**average**	**CV* (%)**
PG64-22	C-22	0% RAP	2,507	6	1,091	8	495	8
	SI-22-15	15%RAP	2,020	9	1,086	7	440	8
	SI-22-30	30%RAP	1,030	4	392	7	168	9
	SII-22-15	15%RAP	1,648	3	730	5	274	8
	SII-22-30	30% RAP	1,315	13	340	6	144	7
	SIII-22-15	15%RAP	1,611	3	873	7	338	2
	SIII-22-30	30% RAP	1,952	6	672	10	311	7
PG64-28NV	C-28	0% RAP	1,767	9	668	5	274	10
	SI-28-15	15%RAP	905	4	211	6	118	2
	SI-28-30	30%RAP	940	2	296	5	123	5
	SII-28-15	15%RAP	1,067	9	279	4	155	7
	SII-28-30	30% RAP	1,217	5	849	9	306	7
	SIII-28-15	15%RAP	846	7	249	9	125	9
	SIII-28-30	30% RAP	1,245	1	516	7	257	5

* CV denotes Coefficient of Variation
[+] 1 ksi = 1,000 psi

The Mr data show that the 15 and 30% RAP mixtures are more flexible at the low and intermediate temperatures and have lower stability at high temperatures when compared to the virgin mixtures for both grades. These observations will be checked using the other performance testing data.

Additionally, the data in Table 18 indicate that the PG64-22 mixtures are significantly stiffer than the PG64-28NV mixtures.

The Mr data can be used to indirectly evaluate the potential resistance of the mixtures to thermal cracking, fatigue cracking, and rutting as follows.

- The Mr property at 40^{o}F is an indication of the mix resistance to thermal cracking, the lower the Mr at 40^{o}F the higher the resistance to thermal cracking.
- The Mr property at 77^{o}F is an indication of the mix resistance to fatigue cracking, the lower the Mr at 77^{o}F the higher the resistance to fatigue cracking.
- The Mr property at 104^{o}F is an indication of the mix resistance to rutting, the higher the Mr at 104^{o}F the higher the resistance to rutting.

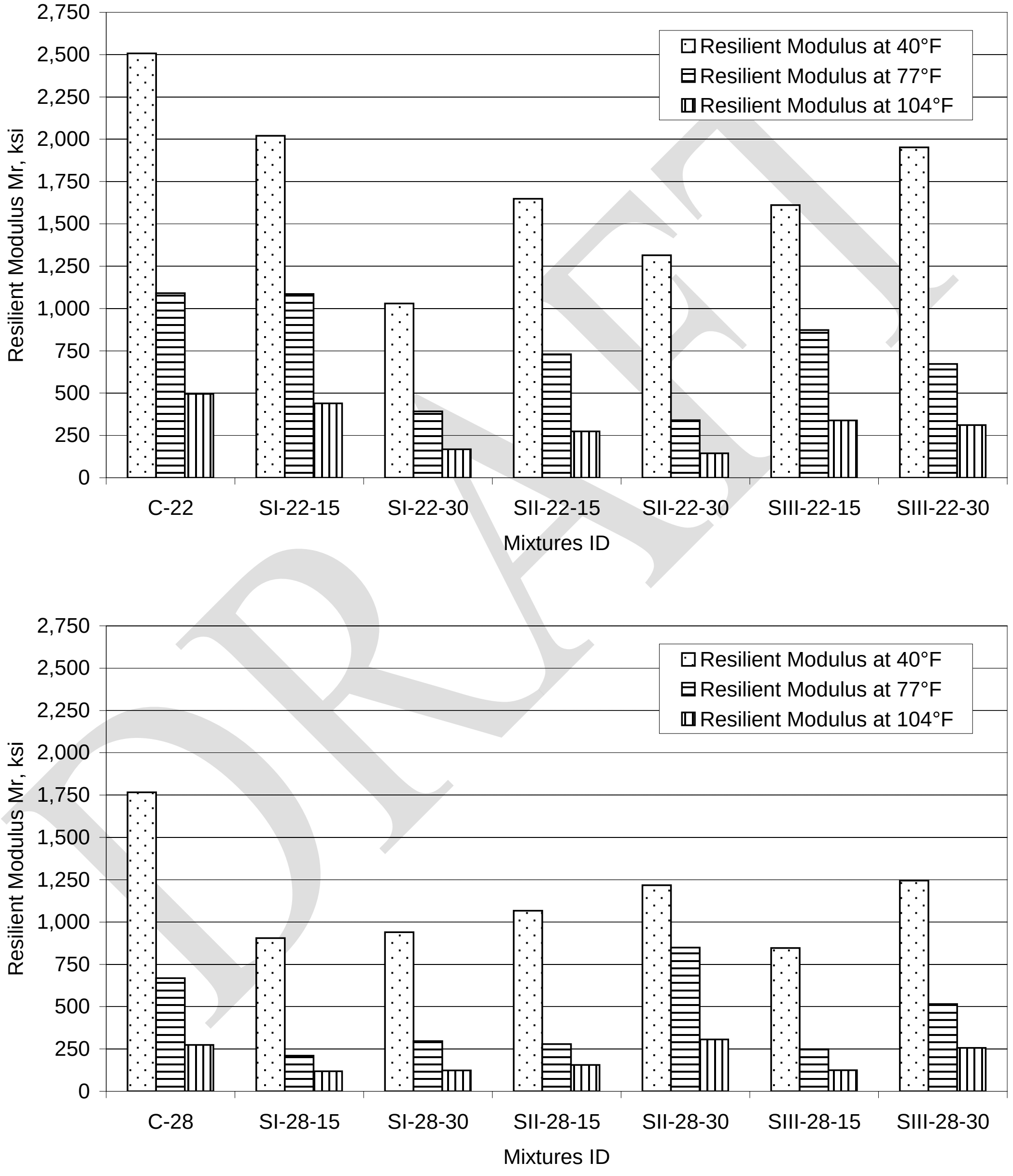

Figure 10. Temperature Susceptibility properties of the Various Mixtures at 40, 77 and 104°F.

The statistical analysis ranked the various mixtures in terms of their resistance to thermal cracking (best to worst), based on their Mr property at 40°F, as follows:

Target Binder Grade: PG64-22

1. SI-22-30
2. SII-22-30
3. SIII-22-15, SII-22-15
4. SIII-22-30
5. SI-22-15
6. C-22

Target Binder Grade: PG64-28NV

1. SIII-28-15, SI-28-15
2. SI-28-30
3. SII-28-15
4. SII-28-30, SIII-28-30
5. C-28

The statistical analysis ranked the various mixtures in terms of their resistance to fatigue cracking (best to worst), based on their Mr property at 77°F, as follows:

Target Binder Grade: PG64-22

1. SI-22-30, SII-22-30
2. SII-22-15
3. SIII-22-15, SIII-22-30
4. SI-22-15
5. C-22

Target Binder Grade: PG64-28NV

1. SIII-28-15, SI-28-15, SI-28-30
2. SII-28-15
3. SIII-28-30
4. SII-28-30
5. C-28

The statistical analysis ranked the various mixtures in terms of their resistance to rutting (best to worst), based on their Mr property at 104°F, as follows:

Target Binder Grade: PG64-22

1. C-22, SI-22-15
2. SIII-22-15, SII-22-15 , SIII-22-30
3. SI-22-30
4. SII-22-30

Target Binder Grade: PG64-28NV

1. SII-28-30
2. C-28, SIII-28-30
3. SI-28-30, SIII-28-15, SII-28-15
4. SI-28-15

The above statistical analysis based on the resilient modulus of the mixtures shows that RAP mixtures for both target binder grades are better than the control mixtures (100% virgin aggregates) in terms of their resistance to thermal cracking and Fatigue. However, in the case of resistance to rutting, the control mixtures have better or similar resistance than the RAP mixtures.

Comparison between the Mr Property at 104°F and the APA Rut Depth

In the case of target binder grade of PG64-22, the analysis of the Mr property at 104°F of the various mixtures shows that the SI-22-30 and the SII-22-30 mixes have a Mr value of 168 and 144 ksi, respectively leading to a marginal resistance to rutting. Additionally, those two mixes are expected to have a resistance to rutting lower than the control mix (C-22). Under the APA test, the same two mixtures showed a significantly high rut depth (6.0 and 7.3 mm) and lower rutting resistance than the C-22 mix, therefore, resulting in consistent results with the Mr test. On the other hand, the SIII-22-15, SIII-22-30, and SII-22-15 mixes had lower rut depth under the APA test when compared to the other mixtures whereas according to the Mr property, the C-22 and the SI-22-15 mixes were expected to have better rutting resistance than the other mixtures evaluated in this study.

In the case of the target binder grade of PG64-28NV, a significant difference was shown in the mixtures Mr property at 104°F with three mixes out of seven having a Mr value below 150 ksi. The Mr test results were not consistent with the APA test results where the various mixtures exhibited similar resistance to rutting.

Comparison between the Mr Property at 77°F and the Mixes Fatigue Performance

In the case of both target binder grades, the Mr value at 77°F predicts a lower fatigue resistance for the control mixes C-22 and C-28 as compared to RAP mixtures. The Mr results are not consistent with the fatigue analysis conducted previously which resulted in a lower fatigue performance for the 30% RAP mixes from sources I and II as compared to C-22 mix, and a better fatigue performance for the C-28 mix as compared to the RAP mixes.

Comparison between the Mr Property at 40°F and the Mixes Thermal Cracking Resistance

According to the statistical analysis of the Mr property at 40°F, the control mixes (C-22 and C-28) for both target binder grades of PG64-22 and PG64-28NV had the highest Mr values and exhibited a lower thermal cracking resistance than the RAP mixtures in the TSRST test as expected.

FINDINGS BASED ON THE LABORATORY STUDY

The performance of the control and RAP mixtures were evaluated in terms of their resistance to moisture damage, rutting, fatigue, and thermal cracking. Based on the data generated from this experiment, the following conclusions can be made:

- The RAP mixtures produced in this study according to the recommended mix design method for HMA containing 15 and 30% RAP are equivalent to the control mixture (100% virgin aggregate) in resistance to moisture damage. Only in the case of the target binder of PG64-28NV the mix with 15% RAP from source I, failed to pass the minimum imposed TSR requirement of 70%. However, in most cases, the addition of RAP to a mixture resulted in a reduction in the unconditioned tensile strength value and most likely a lower resistance to moisture damage and a less durable mix. Additionally, in the case of the target binder grade of PG64-22, the 15% RAP mixtures exhibited tensile strengths at the unconditioned and conditioned stages higher than the 30% RAP mixtures whereas the opposite was found in the case of the target binder grade of PG64-28NV

- In the case of resistance to rutting, none of the produced mixtures failed to pass the typically used failure criterion of 8 mm (0.30 inch) rut depth under 8,000 APA cycles. For the case of the target binder PG64-22, three out of six RAP mixes exhibited a lower rutting resistance than the control mix with an APA rut depth close to the 8 mm failure criterion. In the case of the target binder PG64-28NV, all RAP mixes exhibited a rutting resistance equivalent to the control mix and significantly lower than the 8 mm failure criteria.

- In the case of resistance to fatigue cracking, the addition of 15% RAP to a mixture with a target binder grade of PG64-22 either improved or did not affect the resistance of the mix to fatigue regardless of the RAP source. The addition of 30% RAP to a mixture with a target binder grade of PG64-22 reduced the resistance of the mix to fatigue for RAP sources I and II. For the case of PG64-28NV, the addition of RAP to a mixture significantly reduced the resistance of the mix to fatigue regardless of the RAP content and source.

- In the case of resistance to thermal cracking, the RAP mixtures exhibited better or equivalent resistance to the virgin mix in both target binder grades.

The temperature susceptibility of the various mixtures was evaluated using the resilient modulus (Mr) test at three different temperatures. The laboratory data covered in this report was used to check whether the Mr property at 104°F, 77°F, and 40°F can be used to indirectly evaluate the potential resistance of the mixtures to rutting, fatigue cracking, and thermal cracking, respectively. Based on the data generated from this experiment, the following conclusions can be made:

- In the case of resistance to rutting, the Mr property at 104°F did not correctly predict the rutting resistance of the various mixtures as measured by the APA test. The statistical analysis based on the resilient modulus of the mixtures at 104°F showed a better or similar resistance for the control mixtures than the RAP mixtures. However in the case of the target binder of PG64-22, three RAP mixtures out of six exhibited significantly better rutting resistance than the control mix under the APA test. In the case of the target binder of PG64-28NV, the RAP mixtures exhibited rutting resistance similar to the control mix under the APA test at 140°F.

- In the case of resistance to fatigue cracking the Mr property at 77°F for both target binder grades was not able to predict the fatigue resistance of the mixtures.

- In the case of resistance to thermal cracking, the Mr property correctly predicted the thermal cracking behavior of the mixtures where the mixes with the highest Mr property at 40°F exhibited a lower resistance to low-temperature cracking.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the laboratory evaluation and the analyses conducted in this report the following questions are answered.

Can the blending chart method be used to determine the grade of the virgin binder required for a given combination of RAP source and RAP content?

The blending chart method was found to be effective in identifying the appropriate grade of the virgin binder required to achieve the target binder grade for the various RAP sources and RAP contents. Laboratory test results covered in this report showed that binders obtained from mixing the required virgin binder for each RAP source with the recovered RAP binder at their blending proportions met or exceeded the target binder grades of PG64-22 and PG64-28NV.

Can the RTC Marshall mix design method be used to design HMA mixtures containing 15 and 30% RAP?

The Marshall mix design method as outlined in the Asphalt Institute's Mix Design Methods Manual MS-2 and implemented by the Washoe RTC can be used to design the various mixtures with 15 and 30% RAP. All measured properties for Marshall mix design met the corresponding Orange Book specifications except for the minimum VMA criterion of 13.0% that was not achieved with the gradation covered in this study. Instead, a minimum VMA of 11.0% was implemented in this study. The minimum required VMA of 13.0% could be achieved by changing the blend gradation. Additionally, the Marshall mix design method may have produced some dry mixes with RAP materials that was avoided by dropping the design air-voids for binder content selection by a half percent (i.e., from 4.0 to 3.5%).

Is the mixing process of virgin and RAP materials effective in producing a final binder meeting the target binder grade?

The mixing process in the laboratory was found to be effective in producing a final binder meeting the target binder grade. Laboratory test results covered in this report showed that binders extracted/recovered from twelve different final blended mixtures exceeded the target binder grades of PG64-22 and PG64-28NV.

What impact the RAP source and content have on the properties of the final mix?

Based on the data generated from this experiment, the following conclusions can be made.

- Impact of RAP on moisture resistance:

  - PG64-22 mixtures:
    - The addition of 15 or 30% RAP to a mixture resulted in an acceptable resistance to moisture damage regardless of the source of the RAP.
    - The addition of 15 or 30% RAP to a mixture resulted in a reduction in the unconditioned and conditioned tensile strengths.
    - The 15% RAP mixtures had higher resistance to moisture damage than the 30% RAP mixtures.
  - PG64-28NV mixtures:
    - The addition of 15 or 30% RAP to a mixture resulted in an acceptable resistance to moisture damage regardless of the source of the RAP.
    - The addition of 15 and 30% RAP to a mixture resulted in a reduction in the unconditioned and conditioned tensile strengths.
    - The 15% RAP mixtures had lower resistance to moisture damage than the 30% RAP mixtures.

- Impact of RAP on rutting resistance:
  - PG64-22 mixtures:
    - The addition of 15% RAP to a mixture resulted in better resistance to rutting than the virgin mix in two sources out of three.
    - The addition of 30% RAP to a mixture resulted in worst resistance to rutting than the virgin mix in two sources out of three.
  - PG64-28NV mixtures:
    - The addition of 15% and 30% RAP to a mixture resulted in rutting resistance equivalent to the virgin mix and significantly lower than the APA failure criteria regardless of the source of the RAP.

- Impact of RAP on fatigue resistance:
  - PG64-22 mixtures:
    - The addition of 15% RAP to a mixture resulted in better resistance to fatigue than the virgin mix regardless of the source of the RAP.
    - The addition of 30% RAP to a mixture resulted in worst resistance to fatigue than the virgin mix in two sources out of three.
  - PG64-28NV mixtures:
    - The addition of 15 or 30% RAP to a mixture resulted in a significant reduction in fatigue resistance regardless of the source of the RAP.

- Impact of RAP on thermal cracking resistance:
  - PG64-22 mixtures:
    - The addition of 15 or 30% RAP to a mixture resulted in either a better or equivalent resistance to thermal cracking regardless of the source of the RAP.
  - PG64-28NV mixtures:
    - The addition of 15 or 30% RAP to a mixture resulted in a significantly better resistance to thermal cracking regardless of the source of the RAP.

Can the resilient modulus property be used as a surrogate test to estimate the performance of HMA mixtures containing RAP?

The Mr property at 104°F and at 77°F, regardless of the source of the RAP, did not correctly predict the rutting resistance, as measured by the APA test, and the fatigue resistance of the various mixtures covered in this study, respectively. However, the Mr property at 40°F correctly predicted the thermal cracking behavior of the various mixtures.

RECOMMENDATIONS

The second phase of this research effort is to implement the mix design method and the QC/QA program on two RTC projects. The research team will develop the mix designs for the two projects and conducts the performance-based portion of the QA testing on field mixes from the two projects, which will include the resistance of the mixtures to moisture damage, fatigue, rutting, and thermal cracking.

Once the projects are constructed, the research team will assess the long-term performance of the HMA sections containing RAP materials through laboratory testing of field cores sampled at the following stages: a) immediately after construction, b) three years after construction, and c) six years after construction. The laboratory evaluation will include measuring the resilient modulus properties and moisture sensitivity of the cores. In addition, condition surveys will be conducted by the owner agency and used to assess the long-term performance. Based on the long-term performance of the RAP projects, the research team will modify the mix design process and the QC/QA program as necessary to ensure the optimum performance of the RAP mixtures on RTC projects. This effort will assess whether the tests conducted during the mix design process were effective in predicting the long-term performance of the RAP mixtures in the field. The analysis of the long-term performance may necessitate that new tests be included or the existing tests/criteria be modified.

CASE STUDY: STANFORD WAY FIELD PROJECT, RENO, NEVADA

Field mixtures were sampled from the RTC project at the Stanford way in the Reno Nevada area. The project used HMA mixtures with RAP material from Source I (plant waste from the Lockwood quarry). The Asphalt blending chart method was not used to determine the amount of RAP that could be incorporated into the mixture. Instead, the RAP was limited to 15% and no change in the specified standard asphalt binder grade was made. The material was sampled during paving, from the windrow on June 18 and 19 of 2005. The constructed HMA layer consisted of 3 lifts of 2.5 inch each. The bottom lift consisted of a type II dense graded HMA with 15% RAP material manufactured with an AC-20 asphalt binder. The middle and the top lifts consisted of a type II dense graded HMA with 15% RAP material manufactured with an AC-20P polymer modified asphalt binder. Both the AC-20 and AC-20P asphalt binders were supplied by Paramount Petroleum Company in Nevada and were graded as PG64-22 and PG64-28NV, respectively. The Marshal mix design method was used for all the HMA mixtures in accordance with the Standard Specifications for Public Works Construction (orange book), the Asphalt Institute’s Mix Design Methods Manual Series 2 (MS-2), and the national recycled asphalt research (NCHRP Project 9-12). The mix for the bottom lift was designed with 50 blows on each side with the standard Automated Marshall hammer. The mix for the middle/top lifts was designed with 75 blows on each side with the standard Automated Marshall hammer. All mixes were treated with hydrated lime at a rate of 1.5 percent by dry weight of aggregates. The following labeling was used to identify the bottom and the middle/top field mixtures:

> SI-AC20-15: represent the bottom lift field mixture with the 15% Source I RAP material produced with the neat AC-20 (PG64-22) asphalt binder.
>
> SI-AC20P-15: represent the middle/top lift field mixture with 15% Source I RAP material produced with the polymer modified AC-20P (PG64-28NV) asphalt binder.

In this part of the study, the SI-AC20-15 field mix and the SI-22-15 laboratory produced mix are compared to each other. Both mixtures were manufactured with the virgin asphalt binder of PG64-22 same as the specified target asphalt binder grade. On the other hand, for the target asphalt binder of PG64-28NV, the SI-AC20P-15 field mix and the SI-28-15 laboratory produced mix manufactured with PG64-28NV and PG64-34 virgin asphalt binders, respectively, are compared to each other. However, the aggregate blend gradations were different between the field mixtures and the laboratory produced mixtures. Additionally, for the target binder grade of PG64-22, field mixtures were designed with 50 blows per side as compared to 75 blows per side for the corresponding laboratory produced mixture. Therefore caution should be exercised when performing the comparison between the field and the laboratory produced mixtures.

MIX DESIGN

All mix designs were conducted by the Granite Construction Company using the aggregate source located in Lockwood, Nevada. The gradation of the aggregate followed the RTC Type 2 specification. The mix design used six stockpiles: 3/4”, 1/2”, 3/8”, Rock dust, Wade sand, and RAP material from source I. Table 19 summarizes the gradation of the various stockpiles.

The various blends at the desired RAP percentage (15%) for mix design of the bottom and middle/top layers are shown in Table 20.

Table 19 Gradation of the Aggregate Stockpiles.

Sieve Size		Percent Passing					
No	**mm**	**3/4" PMA**	**1/2" PMA**	**3/8" PMA**	**Rock Dust**	**Wade Sand**	**RAP**
1"	25.00	100.0	100.0	100.0	100.0	100.0	100.0
3/4"	19.00	100.0	100.0	100.0	100.0	100.0	100.0
1/2"	12.50	36.2	100.0	100.0	100.0	100.0	100.0
3/8"	9.50	2.7	53.8	100.0	100.0	100.0	97.0
#4	4.75	0.8	1.0	26.9	97.5	99.1	67.0
#8	2.36	0.7	1.0	1.3	73.5	97.6	48.0
#10	2.00	0.7	1.0	1.0	65.1	97.1	45.0
#40	0.425	0.7	1.0	0.8	25.4	60.4	23.0
#50	0.300	0.7	1.0	0.8	21.9	40.0	18.0
#100	0.150	0.7	1.0	0.8	16.8	11.9	15.0
#200	0.075	0.6	0.7	0.6	13.6	3.4	11.0

Table 20 Blend Percentages for the Bottom and Middle/Top layer Mixtures.

Mix	Mix Design	Blend Percentages					
		3/4" PMA	**1/2" PMA**	**3/8" PMA**	**Rock Dust**	**Wade Sand**	**RAP**
SI-AC20-15	Type 2, 50 Blows, AC-20	17%	10%	21%	27%	10%	15%
SI-AC20P-15	Type 2, 75 Blows, AC-20P	19%	12%	20%	26%	8%	15%

Table 21 summarizes the mix design data for the SI-AC20-15 and the SI-AC20P-15 mixtures along with the corresponding Orange Book specifications. It should be noted that the minimum VMA of 13.0 was achieved for both mixtures.

Table 21 Mix Design Summary and Specifications for Field Mixtures.

Property	**SI-AC20-15** (Type 2, 50 Blows, AC-20)	**SI-AC20P-15** (Type 2, 75 Blows, AC-20P)	Requirements
Optimum Binder Content % TWM % DWA	 5.3 5.6	 5.3 5.6	
Air Void (%)	4.0	4.0	4.0
Voids in Mineral Aggregates (%)	13.8	13.9	≥ 13.0
Voids Filled with Asphalt (%)	72.0	72.0	65-75
Marshal Stability (lbf)	3150	3375	> 1800
Marshall Flow (0.01 inch)	13.2	12.9	8-20
Unit weight (pcf)	146.8	147.0	NA

Both field mixtures had optimum asphalt binder contents that are higher than the laboratory produced mixtures by about 1.0% by total weight of mix.

EXTRACTED ASPHALT BINDERS PROPERTY

The asphalt binders were extracted and recovered from the field mixtures and graded using the Superpave PG system as an attempt to check the actual grade of the blended asphalt binders. Table 22 summarizes the test results and the PG grade of the extracted/recovered asphalt binders from both field mixtures. During the grading process, the extracted/recovered binder was considered as a RTFO binder since it already has been subjected to short-term aging during the mixing process. It should be reminded that the AC-20 and AC-20P binders supplied by Paramount Petroleum Company were also graded as PG64-22 and PG64-28NV, respectively. The test results in Table 22 show that both mixtures have a recovered binder grade of PG70-22. The binder extracted from the SI-AC20-15 mix met the required asphalt binder grade of PG64-22 whereas the binder extracted from the SI-AC20P-15 mix failed to meet the low temperature grade of 28°C by just 0.9°C even though it met the high and intermediate criteria temperature of the PG64-28NV binder. It is believed that the 0.9°C shortfall in the low temperature grade is not statistically significant to cause serious performance issues.

In the case of target binder grade of PG64-22, both, the laboratory and the field mixtures had the same grade for the binders recovered from the final blended mixtures. In the case of target binder grade of PG64-28NV, the use of the PG64-34 virgin asphalt binder in the SI-28-15 mix resulted in a recovered binder from the final blended mix of PG64-34 which is softer than the PG70-22 recovered asphalt binder from the field mixture SI-AC20-15.

Table 22 Field Mixtures Extracted/Recovered Asphalt Binder Test Results and Grade.

Aging	**Performance Criteria**	**Test Method**	**Property**	**PG Specification**	**Critical Temperature, °C**	
					SI-AC20-15	**SI-AC20P-15**
Original	Rutting	DSR[+]	G*/sinδ	≥ 1.0 kPa	NA	NA
RTFO	Rutting	DSR	G*/sinδ	≥ 2.2 kPa	72.4	70.6
RTFO +PAV	Fatigue	DSR	G*sinδ	≤ 5000 kPa	25.2	17.9
	Thermal Crack	BBR[#]	S-value	≤ 300 MPa	-15.0	-20.3
			m-value	≥ 0.3	-13.1	-17.1
Superpave Performance Asphalt Binder Grade					PG70-22	PG70-22

[+] DSR Denotes "Dynamic Shear Rheometer"
[#] BBR Denotes "Bending Beam Rheometer"

LABORATORY PERFORMANCE OF FIELD MIXTURES

The field mixtures were evaluated in the laboratory in terms of the following mixtures properties:

- Moisture sensitivity
- Resistance to rutting
- Resistance to fatigue cracking
- Resistance to thermal cracking

Moisture Sensitivity

The field mixtures were evaluated for moisture sensitivity using the AASHTO T-283 test method. The dry (unconditioned) tensile strength (TS) at 77°F was equal to 159 psi and 146 psi for the SI-AC20-15 mix and the SI-AC20P-15 mix, respectively. Both mixtures met the minimum required value of 65 psi for the unconditioned TS specified by RTC. The tensile strength ratio (TSR) was equal to 52% and 71% for the SI-AC20-15 mix and the SI-AC20P-15 mix, respectively. The SI-AC20-15 mix failed to pass the TSR requirement of 70% whereas the SI-AC20P-15 exhibited a TSR slightly above the criterion. This indicates that the SI-AC20-15 mix would have poor resistance to moisture damage whereas the SI-AC20P-15 mix would have acceptable/marginal resistance to moisture damage.

The SI-AC20-15 mix showed an unconditioned TS and a TSR value lower than the laboratory produced mix SI-22-15 (TS dry of 224 psi, and TSR of 78%) even though both mixtures were manufactured with the same binder grade of PG64-22. On the other hand, the SI-AC20P-15 mix showed an unconditioned TS and a TSR value higher than the laboratory produced mix SI-28-15 (TS dry of 75 psi, and TSR of 66%).

Additionally, none of the field mixtures exhibited better moisture resistance than the laboratory produced control/virgin mixtures (C-22 and C-28).

It should be reminded that the SI-AC20-15 mix is placed in the bottom lift whereas the SI-AC20P-15 mix is placed in the middle and top lifts of the project.

Resistance to Rutting

The resistance of the field mixtures to rutting is evaluated using the asphalt pavement analyzer (APA) test under 8,000 cycles at 140^{o}F.

The SI-AC20-15 mix exhibited a rut depth of 5.2mm (0.20 inch) while the SI-AC20P-15 mix exhibited a rut depth of 3mm (0.12 inch). Both mixtures met the NDOT APA criterion of 8 mm (0.30 inch). The pavement section at Stanford way is expected to perform well in rutting specifically that the SI-AC20P-15 is placed in the top 5 inches of the pavement.

Additionally, the APA data showed that the SI-AC20P-15 mix which is manufactured with the polymer modified binder has a significantly better resistance to rutting than the SI-AC20-15 mix that is manufactured with the neat asphalt binder. The use of polymer modified binder reduced the rut depth by about 42%.

On the other hand, the field mixture SI-AC20-15 had a rutting resistance slightly better than the laboratory produced SI-22-15 mix (APA rut depth of 5.9 mm) whereas the SI-AC20P-15 mix had a rutting resistance lower than the laboratory produced SI-28-15 mix

(APA rut depth of 2.1 mm). It should be noted that the field mixtures were manufactured with a blend of aggregate stockpiles different from the ones used to produce the laboratory mixtures.

Resistance to Fatigue Cracking

The resistance of the field mixtures to fatigue cracking was evaluated using the flexural beam fatigue test (AASHTO T321-03). Figure 11 shows the fatigue relationships for the SI-AC20-15 and SI-AC20P-15 mixtures at 72°F along with their laboratory counterparts. Figure 11 shows that the SI-AC20P-15 mix exhibited a significantly better fatigue resistance than the SI-AC20-15 mix. The use of polymer modified binder improved the laboratory fatigue resistance of the unmodified mixture by a factor of more than ten; however, for the Stanford Way project, the unmodified mix was placed at the bottom of the HMA layer eliminating the benefit of the polymer modified mixture.

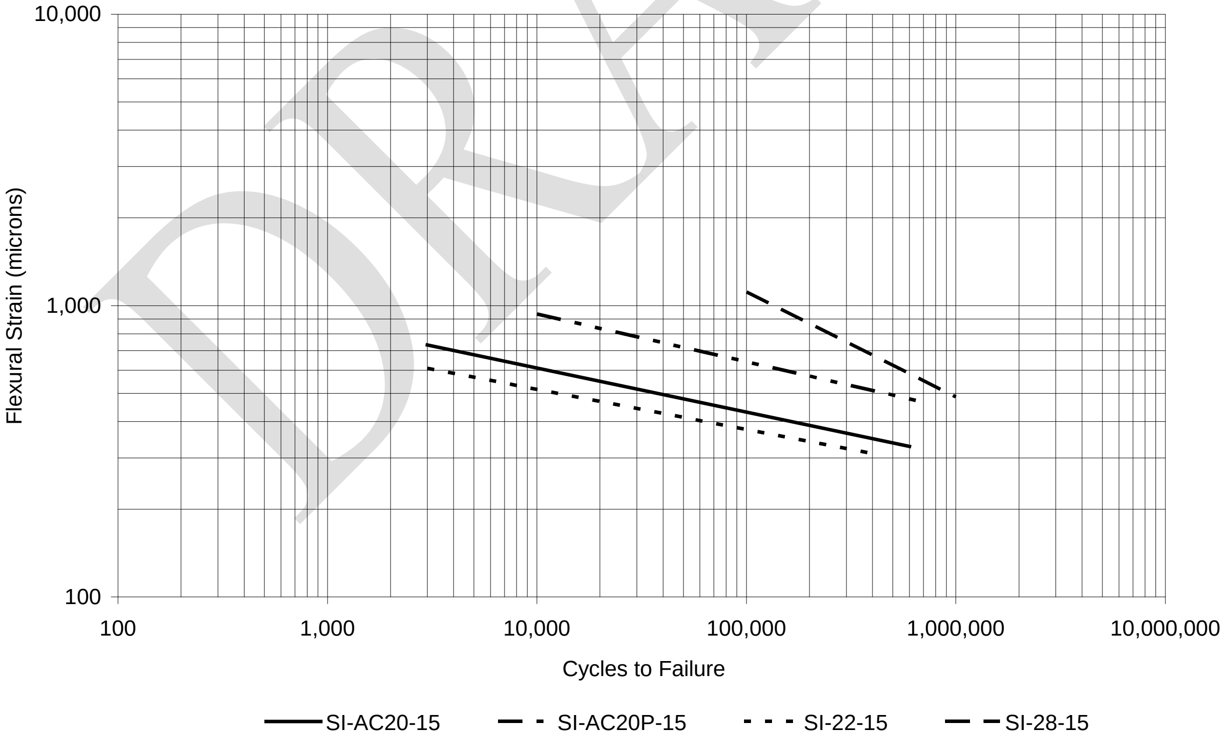

Figure 11. Fatigue relationships of the Stanford Way mixtures.

Additionally, the fatigue resistance of the SI-AC20-15 and SI-AC20P-15 field mixtures were compared to the fatigue resistance of the laboratory produced SI-22-15 and SI-28-15 mixtures, respectively. Figure 11 shows that the SI-AC20-15 mix exhibited a better fatigue resistance than the laboratory produced SI-22-15 mix. On the other hand, the SI-AC20P-15 mix exhibited significantly lower fatigue resistance than the laboratory produced SI-28-15 mix at strain levels above 400 microns.

A mechanistic analysis is conducted to evaluate the difference in fatigue performance between the laboratory produced and the field produced mixtures. The mechanistic-empirical analysis is conducted for the same pavement structure (4-inch HMA on top of 10-inch CAB) and materials properties for the base and the subgrade used before in conjunction with the resilient modulus of the field mixtures at 77°F. Table 23 summarizes the number of load repetitions to fatigue failure along with the ratio of fatigue life of the RAP mixture over the control mixture. A fatigue life ratio greater than one indicates a better fatigue life for the RAP mixture.

Table 23 Number of Load Repetitions to Fatigue Failure in the HMA layer.

Mix	**Resilient modulus at 77°F (ksi)**	**Tensile strain at the bottom of HMA layer, 4"depth, (microns)**	**Number of repetitions to fatigue failure, N_f**	**Ratio of fatigue life**
C-22	1,091	264	337,000	NA
SI-22-15	1,086	254	1,280,000	4.30
SI-AC20-15	893	297	1,170,000	3.48
C-28	668	327	27,600,000	NA
SI-28-15	211	527	592,000	0.02
SI-AC20P-15	520	399	1,807,000	0.07

Table 23 shows that similar fatigue life for the SI-22-15 and SI-AC20-15 mixes. Additionally, both mixtures exhibited better fatigue life than the control mix C-22. On the other hand, both, SI-28-15 and SI-AC20P-15 mixes exhibited lower fatigue life than the control mix

C-28. Additionally, the field mix SI-AC20P-15 exhibited significantly better fatigue life than the laboratory produced mix SI-28-15.

Resistance to Thermal Cracking

The Thermal Stress Restrained Specimen Test (TSRST) (AASHTO TP10-93) was used to determine the low-temperature cracking resistance of both field mixtures. Table 24 summarizes the resistance to thermal cracking of the SI-AC20-15 and SI-AC20P-15 mixtures. The Fracture temperatures of the SI-AC20-15 and SI-AC20P-15 mixtures were within 1°C of the low performance temperature of the PG64-22 and PG64-28NV binders, respectively.

Additionally, the SI-AC20-15 field mixture exhibited a fracture temperature colder than the laboratory produced SI-22-15 mix by a value of 4°C, hence promising a better resistance to low temperature cracking. On the other hand, the SI-AC20P-15 field mixture exhibited a fracture temperature warmer than the laboratory produced SI-28-15 mix by 10°C and therefore revealing a better resistance of the SI-28-15 mix to low temperature cracking than the SI-AC20P-15 mix.

Table 24 Thermal Cracking Resistance of the Field Mixtures.

Mix	RAP Percentage	Asphalt Binder	Fracture Temperature (°C)
SI-AC20-15	15%	AC-20 (PG64-22)	-21
SI-AC20P-15	15%	AC-20P (PG64-28NV)	-29

Temperature Susceptibility

Table 25 summarizes the temperature susceptibility of the field mixtures. A Mr property at 77^{o}F in the range of 350-600 ksi represents a good HMA mix, a Mr property at 104^{o}F above 150 ksi indicates good resistance to rutting and a Mr property at 40^{o}F below 1,000 ksi indicates good potential resistance to thermal cracking.

Table 25 Temperature Susceptibility Properties of the Various Mixtures.

Mix	Mix Proportions	Resilient Modulus, Mr, ksi$^+$					
		40°F		77°F		104°F	
		average	**CV* (%)**	**average**	**CV* (%)**	**average**	**CV* (%)**
C-22	0% RAP	2,507	6	1,091	8	495	8
SI-22-15	15%RAP	2,020	9	1,086	7	440	8
SI-AC20-15	15%RAP	2,430	5	893	5	340	8
C-28	0% RAP	1,767	9	668	5	274	10
SI-28-15	15%RAP	905	4	211	6	118	2
SI-AC20P-15	15%RAP	2,096	6	520	6	193	6

* CV denotes Coefficient of Variation
$^+$ 1 ksi = 1,000 psi

In case of target binder grade of PG64-22, Table 25 shows similar Mr values for the SI-22-15, SI-AC20-15, and C-22 mixes. In the case of target binder grade of PG64-28NV, the SI-AC20P-15 mix exhibited similar Mr values to C-28 but significantly higher Mr values than the SI-28-15 mix.

CONCLUSIONS FROM CASE STUDY

The performance of the field mixtures were evaluated in terms of their resistance to moisture damage, rutting, fatigue, and thermal cracking and compared to the corresponding laboratory produced RAP and virgin (control) mixtures. Based on the data generated from this experiment, the following conclusions can be made:

- The SI-AC20-15 mix failed to meet the minimum tensile strength ratio (TSR) required by RTC indicating a poor resistance to moisture damage. The SI-AC20P-15 mix barely passed the minimum required TSR indicating a marginal resistance to moisture damage. The SI-AC20-15 mix exhibited lower resistance to moisture damage than the laboratory produced mix SI-22-15 whereas the SI-AC20P-15 mix exhibited higher resistance to moisture damage than the laboratory produced mix SI-28-15. None of the field mixtures exhibited better moisture resistance than the laboratory produced virgin mixtures (C-22 and C-28).

- In the case of resistance to rutting, both field mixtures met the NDOT APA criterion. The use of polymer modified binder reduced the rut depth by about 42%. The field mixture SI-AC20-15 had a rutting resistance slightly better than the laboratory produced

SI-22-15 mix whereas the SI-AC20P-15 mix had a rutting resistance lower than the laboratory produced SI-28-15 mix.

- In the case of resistance to fatigue cracking, the SI-AC20-15 mix and the SI-22-15 mix exhibited similar fatigue resistance. Additionally, the addition of 15% RAP from Source I to the field mixture with target binder grade of PG64-22 improved the resistance of the mix to fatigue. On the other hand, the SI-AC20P-15 mix exhibited better fatigue resistance than the laboratory produced SI-28-15 mix. Both mixtures exhibited significantly lower fatigue life than the virgin mix (C-28)

- In the case of resistance to thermal cracking, the RAP field mixtures exhibited a fracture temperature within 1°C of the low performance temperature of the corresponding target binder grades. The SI-AC20-15 field mixture exhibited a better resistance to low temperature cracking than the laboratory produced SI-22-15 mix. On the other hand, the SI-AC20P-15 field mixture exhibited a lower resistance to low temperature cracking than the laboratory produced SI-28-15 mix. Both field mixtures exhibited a better resistance to low-temperature cracks than the corresponding laboratory produced virgin mixtures.

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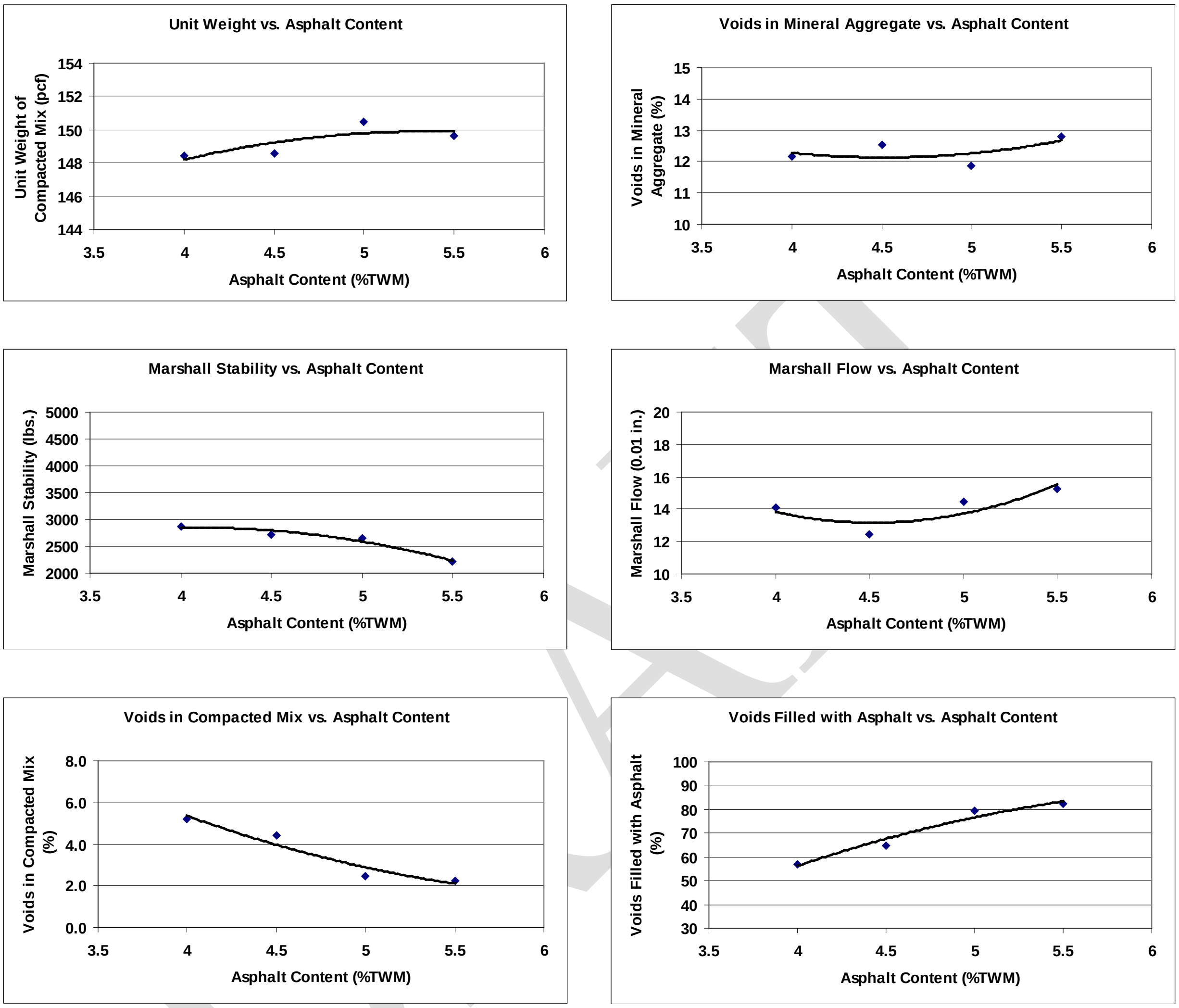
1. Transportation Research Board, "Recycling Materials from Highways", National Cooperative Highway Research Program Synthesis of Highway Practice No. 54, Washington, DC, 1978.

2. Stroup-Gardiner M. and Wagner C. 1999. Use of RAP in Superpave HMA Applications. Transportation Research Record 1681, pp. 1-9.

3. Sondag M. S. 2000. Investigation of Recycled Asphalt Pavement Mixtures. University of Minnesota, Final Report.

4. Sebaaly, P.E. and Shresta R. 2004. A literature Review on the Use of Recycled Asphalt Pavements in HMA mixtures. Washoe Regional Transportation Commission, Reno, Nevada.

APPENDIX A


Unit Weight vs. Asphalt Content

Voids in Mineral Aggregate vs. Asphalt Content

Marshall Stability vs. Asphalt Content

Marshall Flow vs. Asphalt Content

Voids in Compacted Mix vs. Asphalt Content

Voids Filled with Asphalt vs. Asphalt Content

Figure A1. Marshall Mix Design Relationships for the Control Mix C-22.

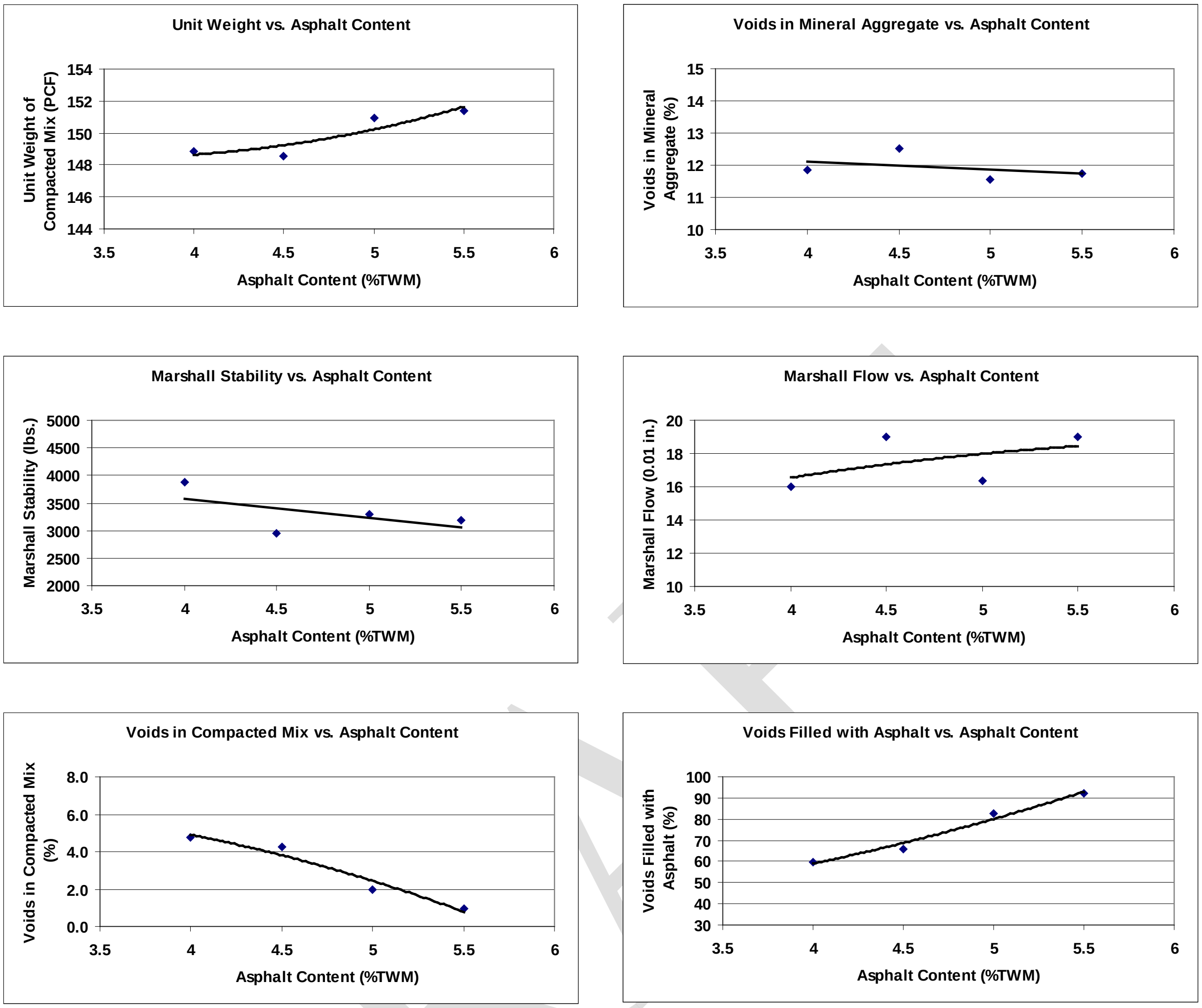


Figure A2. Marshall Mix Design Relationships for SI-22-15 Mix.

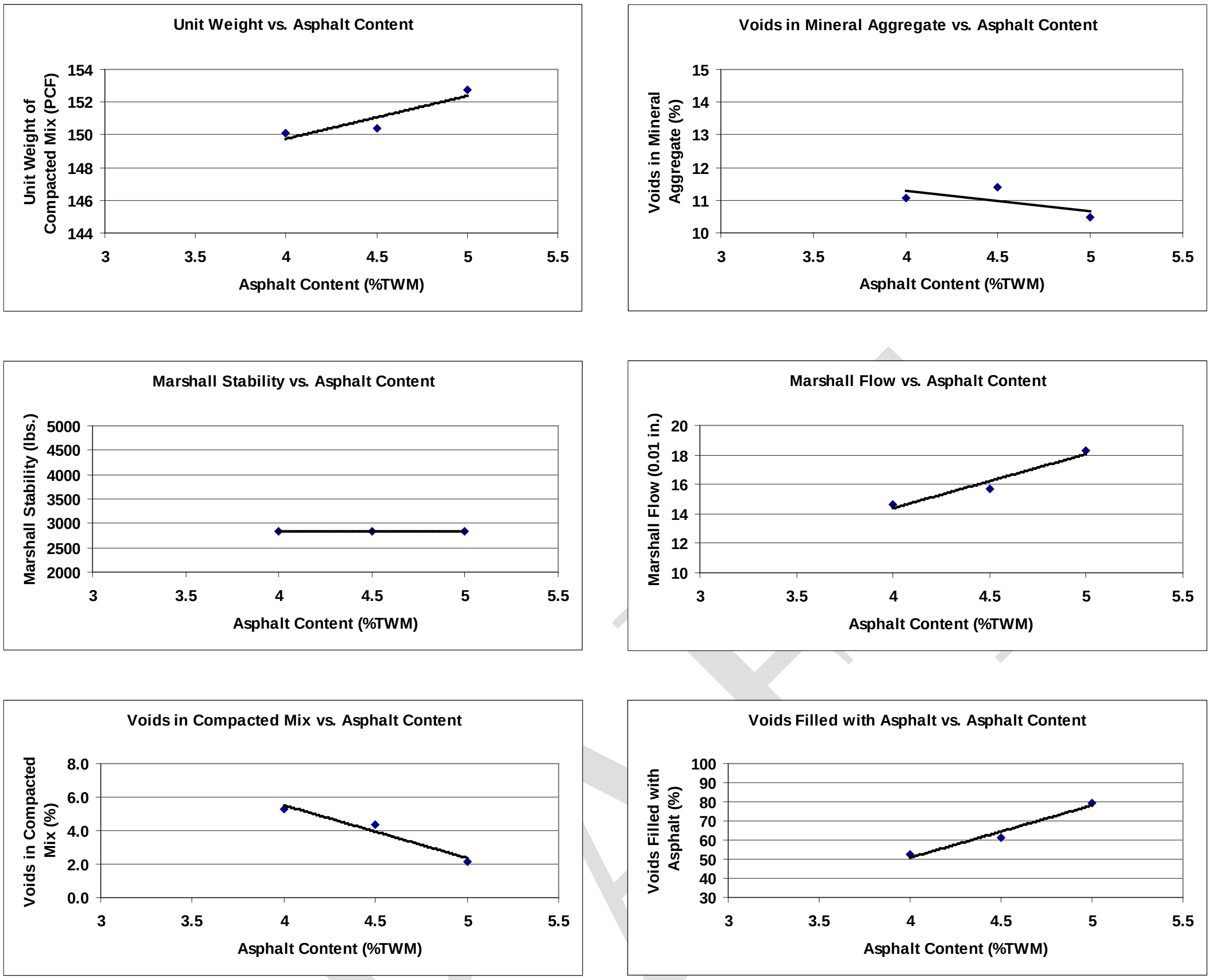


Figure A3. Marshall Mix Design Relationships for SI-22-30 Mix.

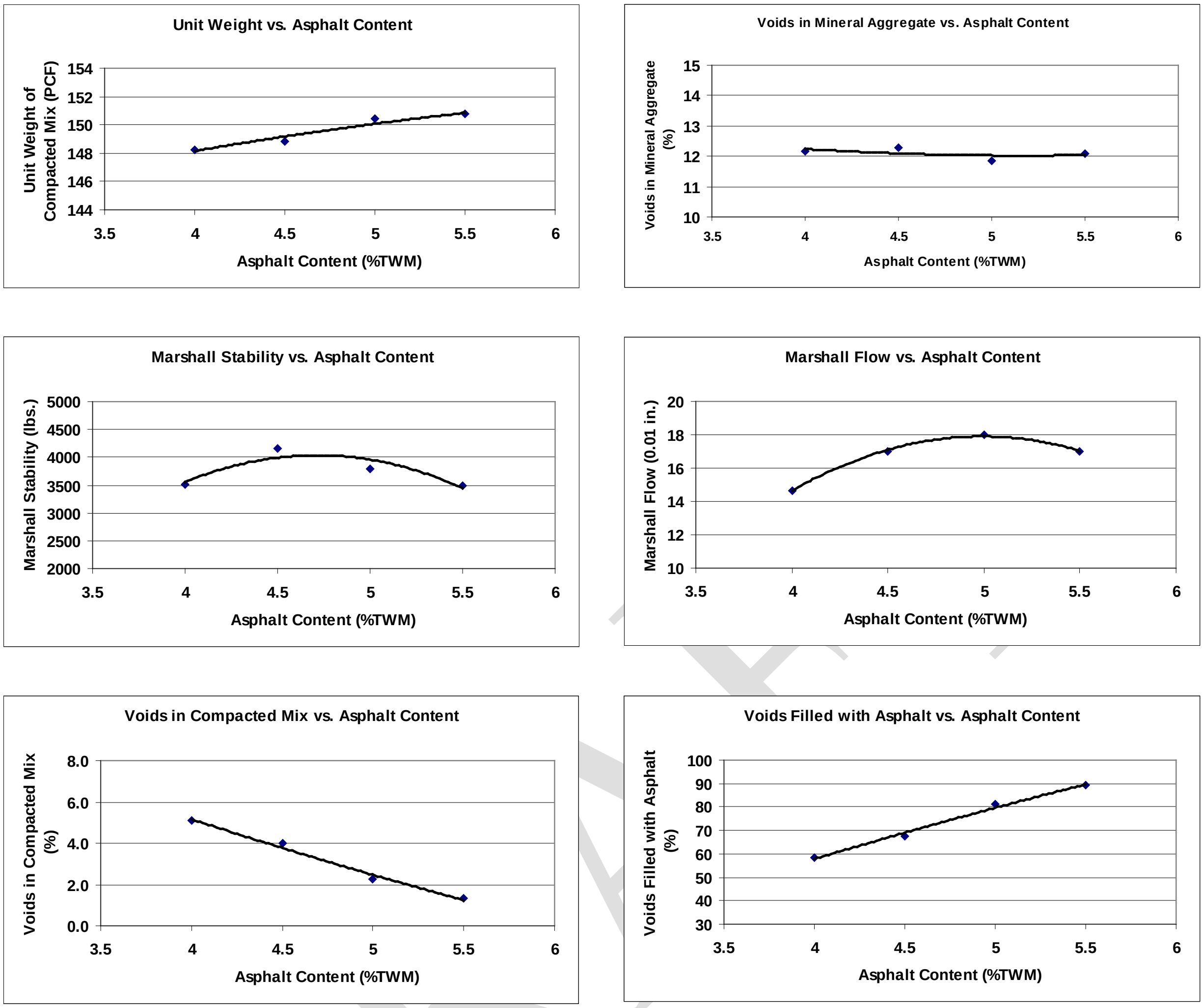


Figure A4. Marshall Mix Design Relationships for SII-22-15 Mix.

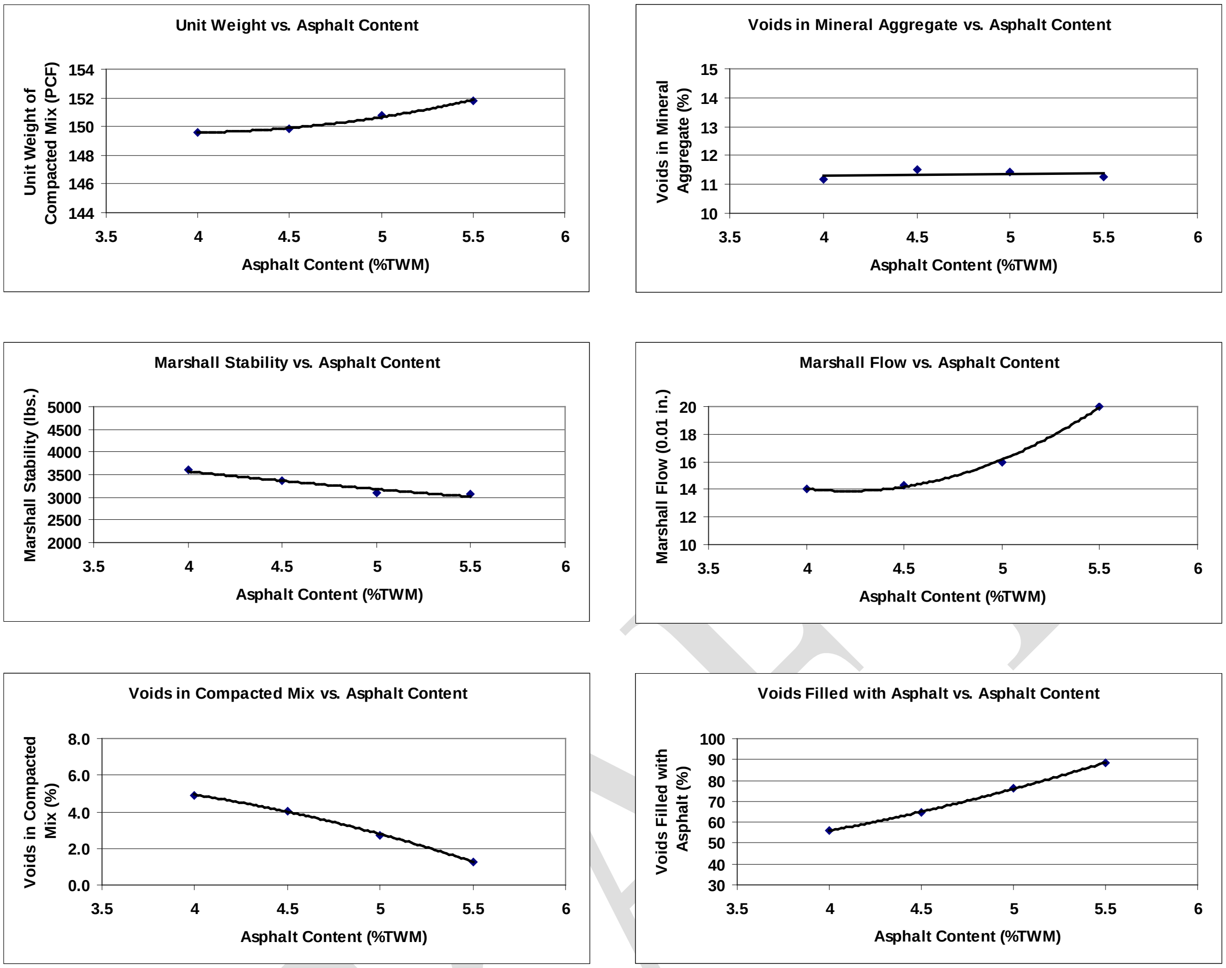


Figure A5. Marshall Mix Design Relationships for SII-22-30 Mix.

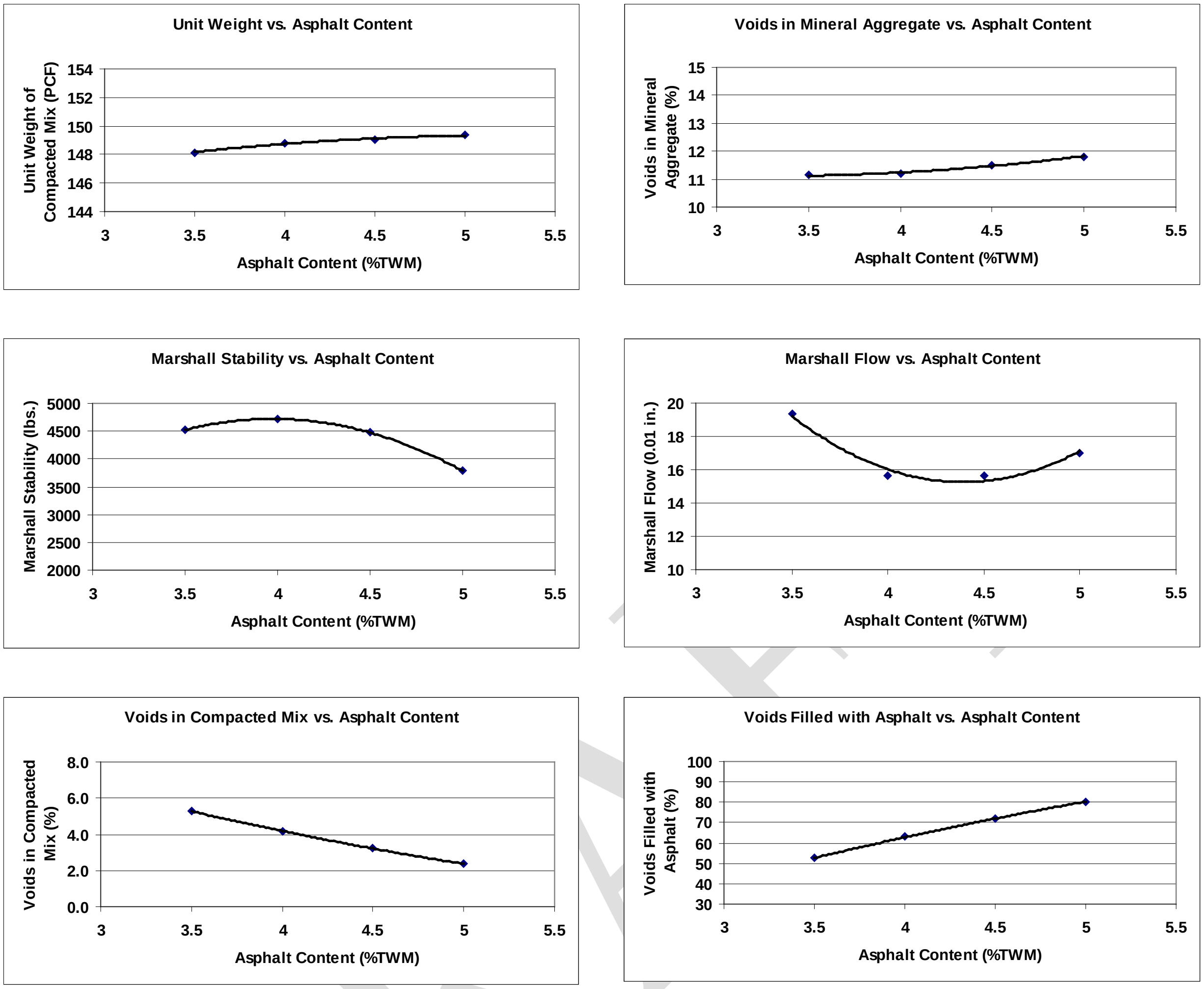


Figure A6. Marshall Mix Design Relationships for SIII-22-15 Mix.

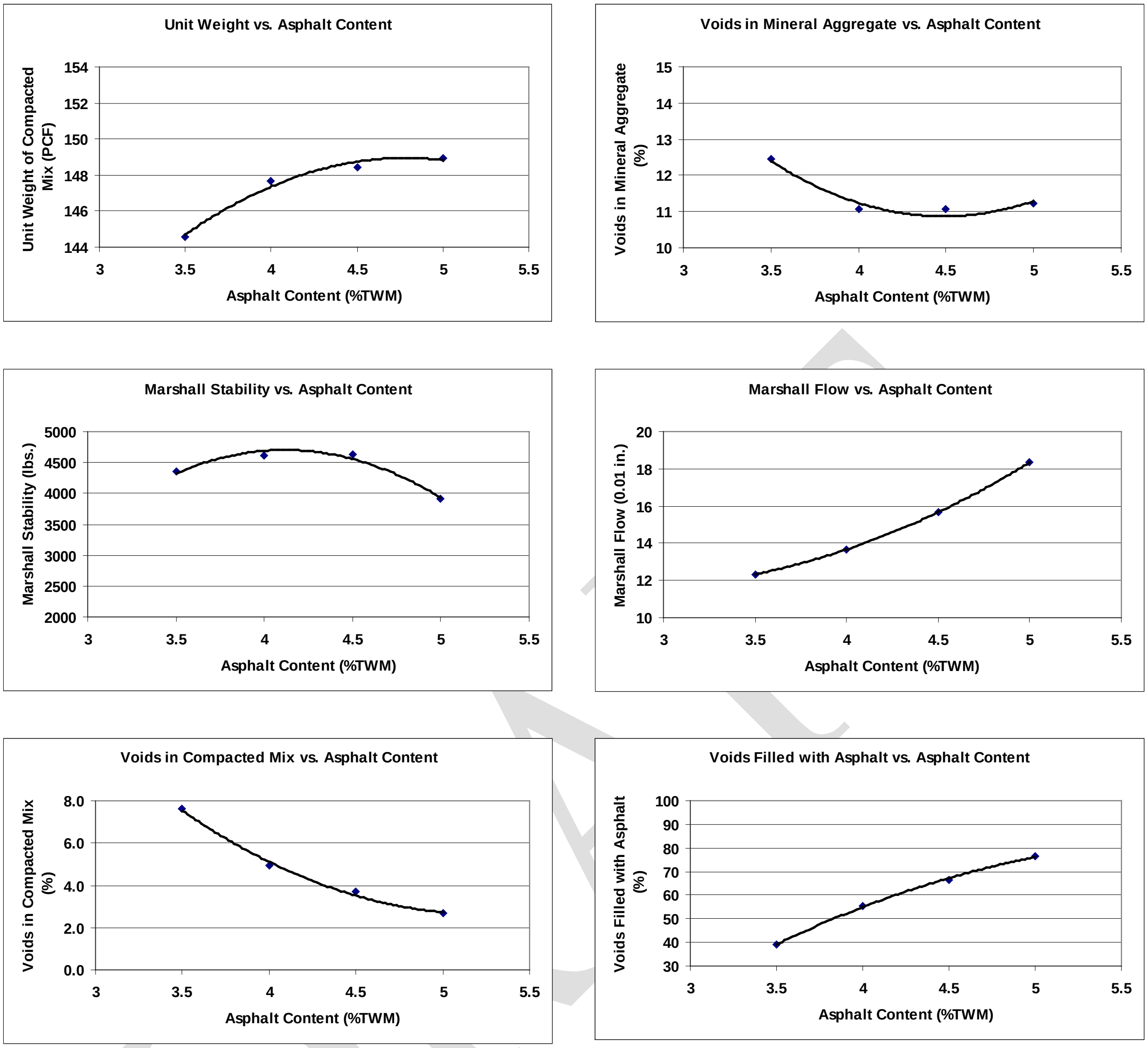


Figure A7. Marshall Mix Design Relationships for SIII-22-30 Mix.

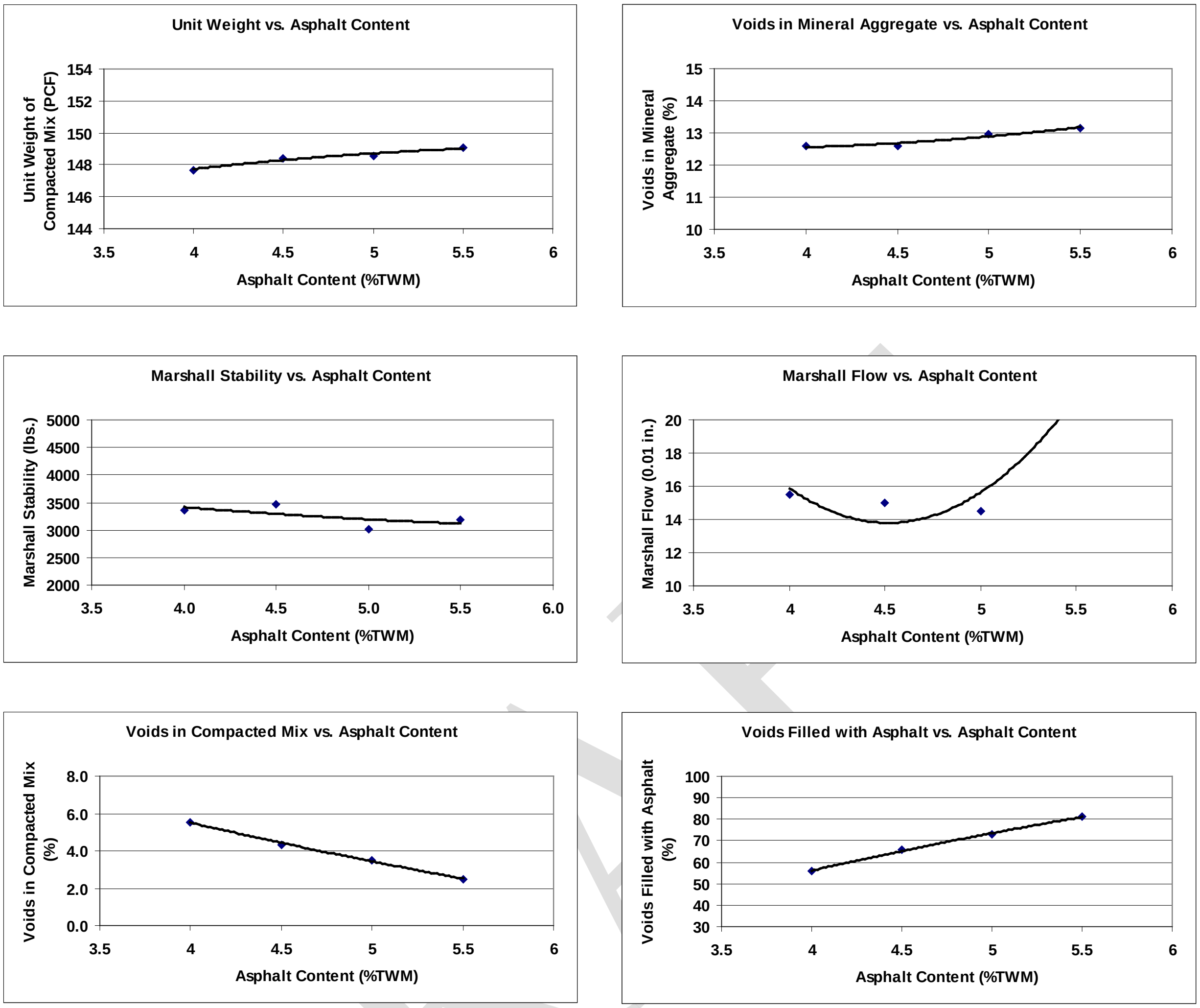


Figure A8. Marshall Mix Design Relationships for the Control Mix C-28.

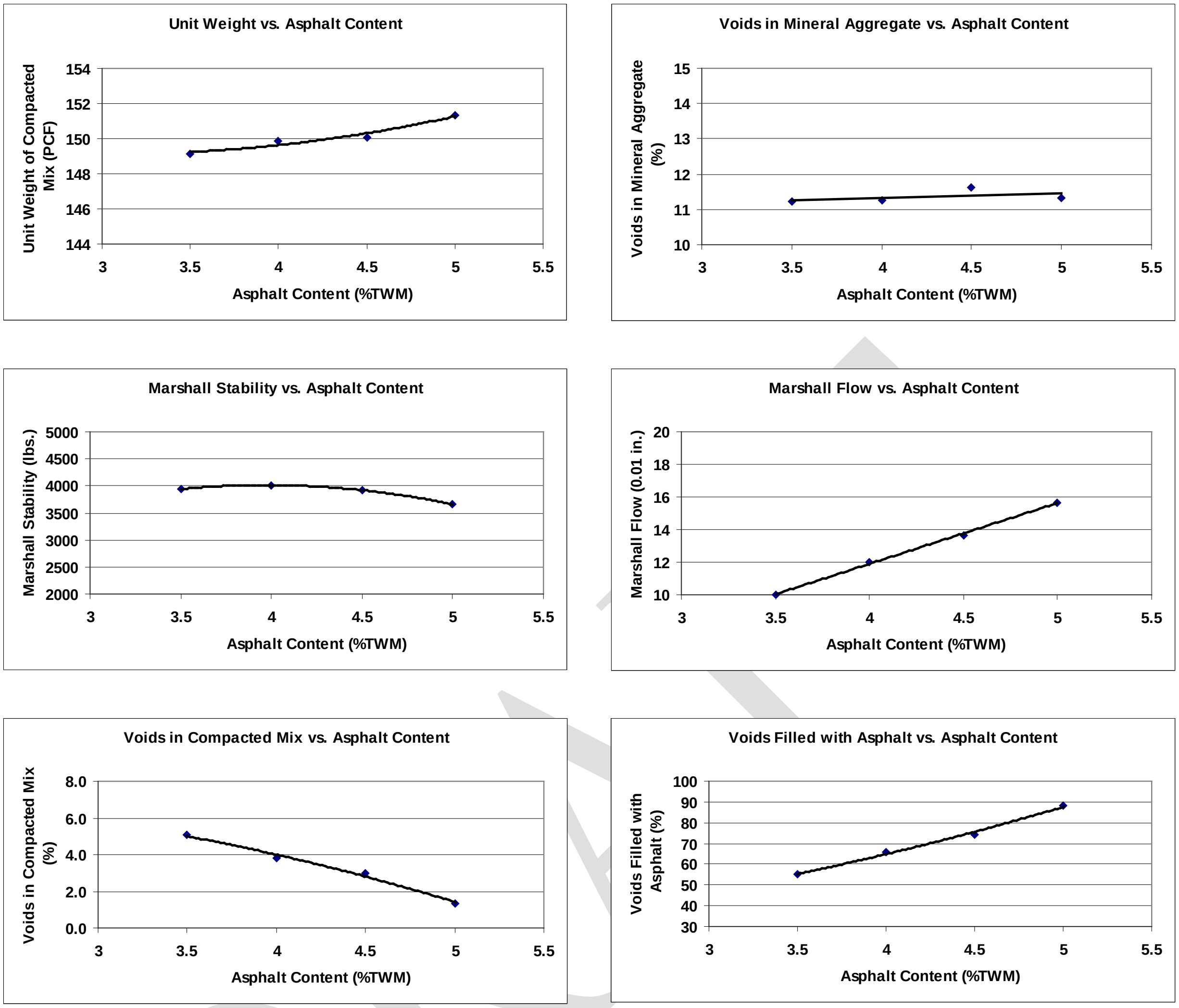


Figure A9. Marshall Mix Design Relationships for SI-28-15 Mix.

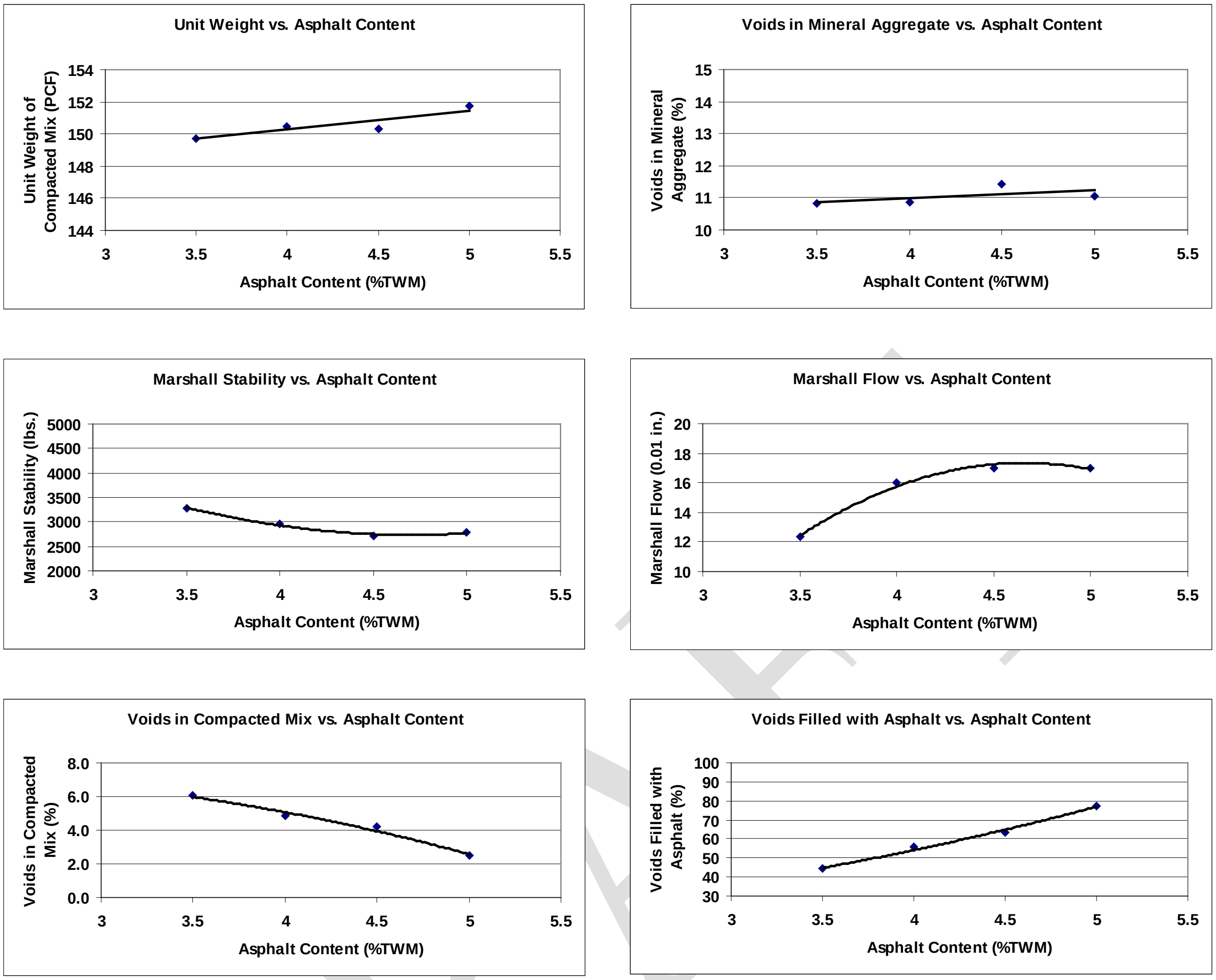


Figure A10. Marshall Mix Design Relationships for SI-28-30 Mix.

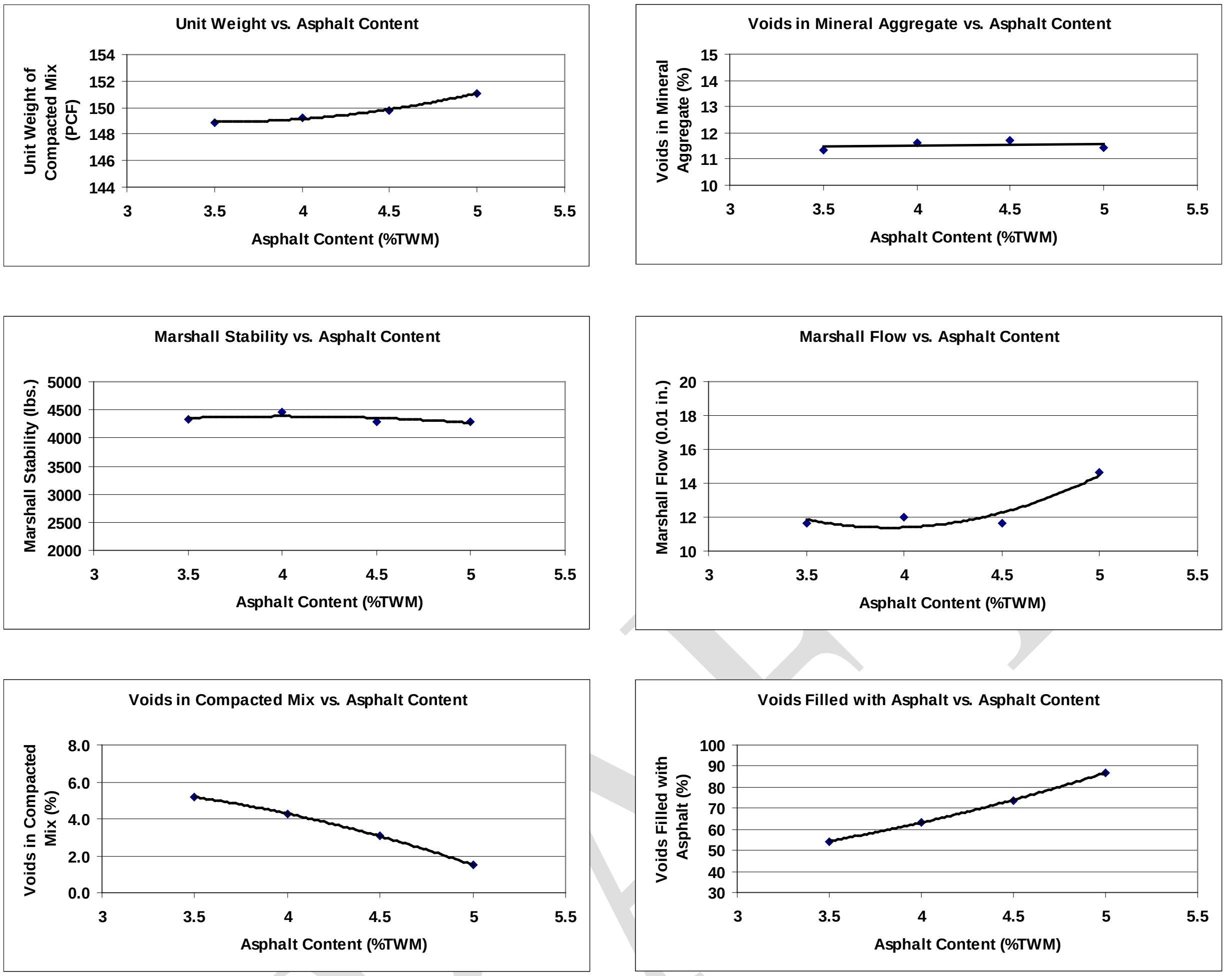


Figure A11. Marshall Mix Design Relationships for SII-28-15 Mix.

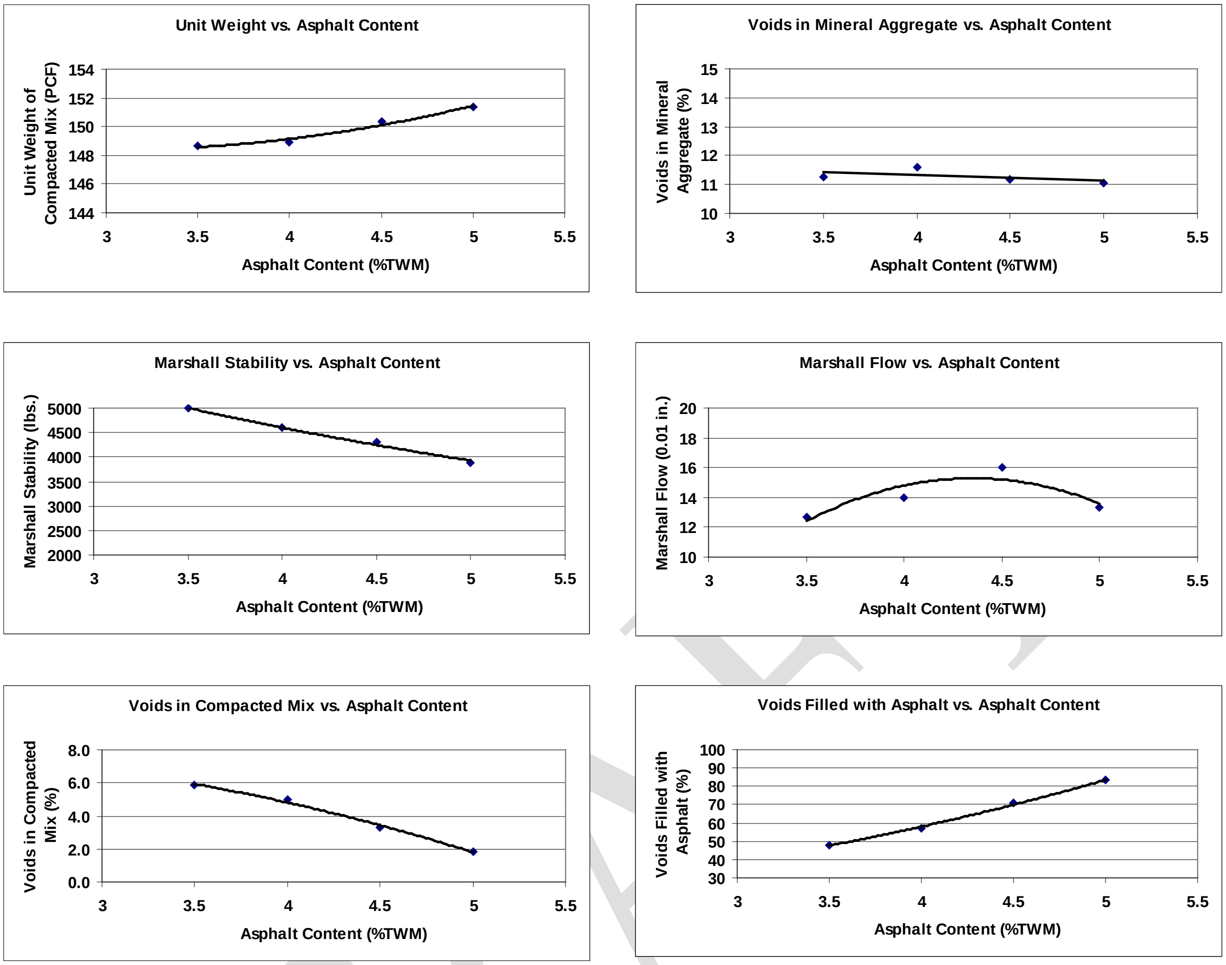


Figure A12. Marshall Mix Design Relationships for SII-28-30 Mix.

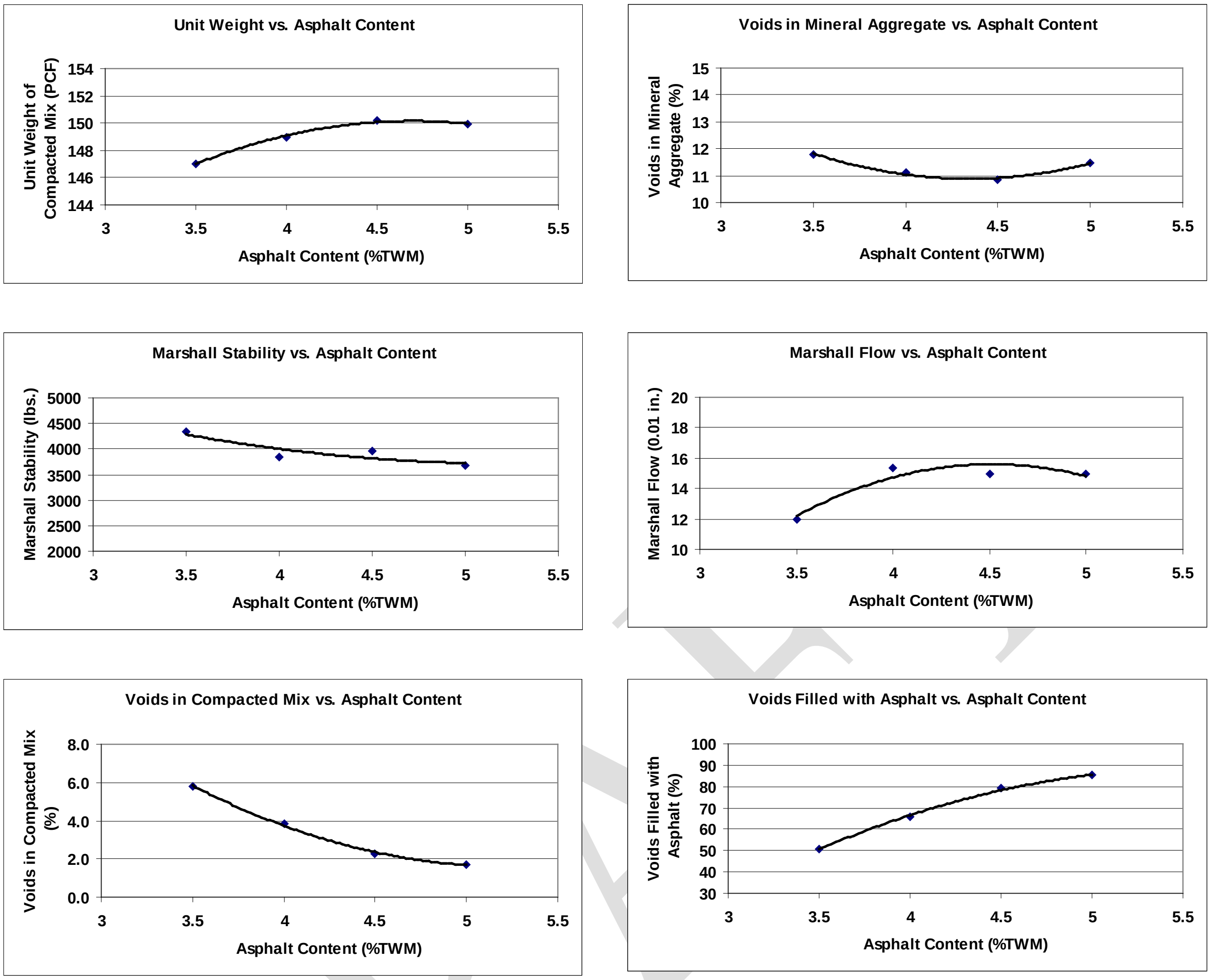


Figure A13. Marshall Mix Design Relationships for SIII-28-15 Mix.

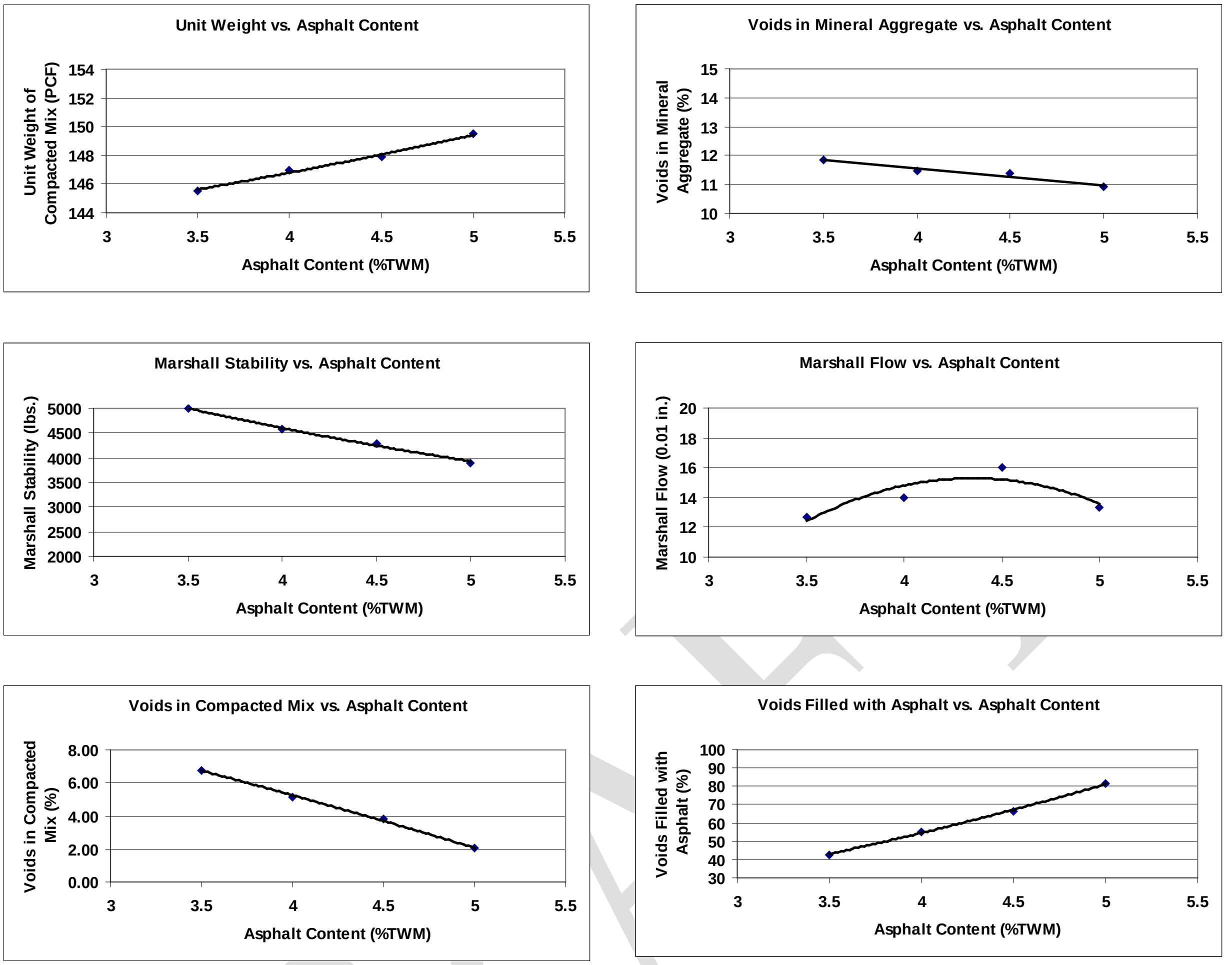


Figure A14. Marshall Mix Design Relationships for SIII-28-30 Mix.

APPENDIX B

Asphalt Pavement Analyzer (APA) Set-Up

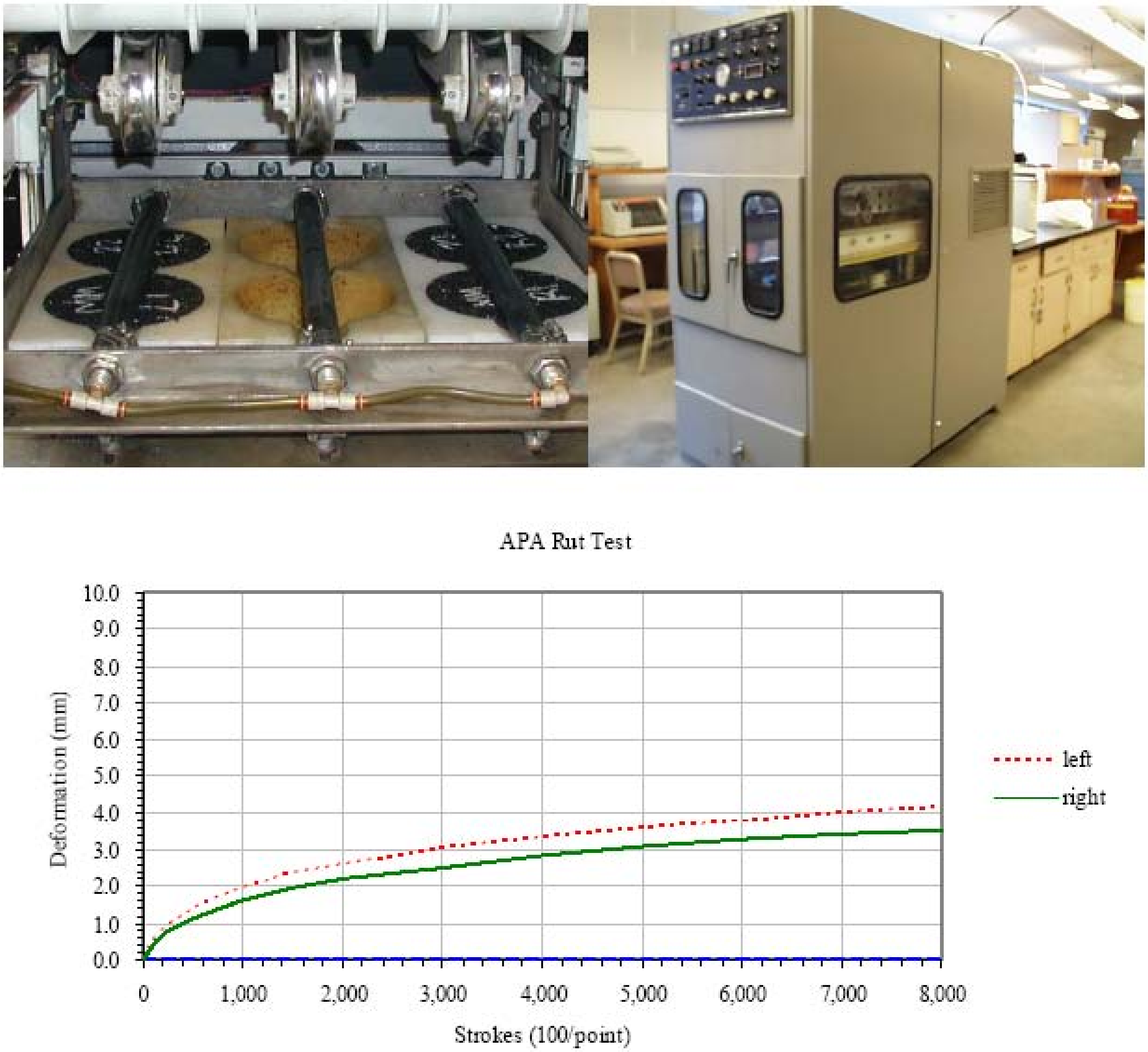


Figure B1. Components of the APA test and a typical curve for an HMA mix.

Beam Fatigue Set-Up

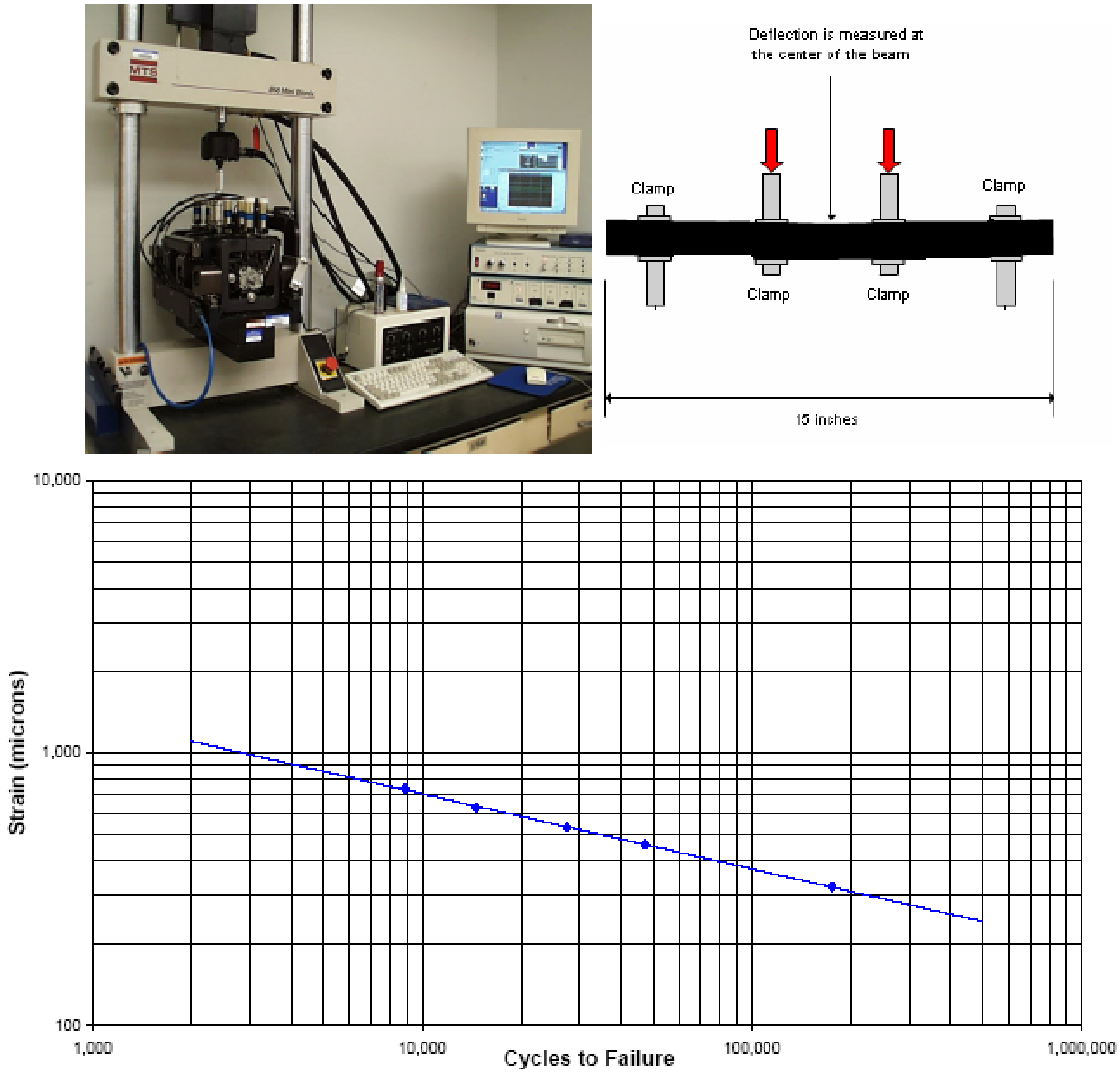


Figure B2. Components of the Beam Fatigue Test and a Typical Fatigue Curve for an HMA Mix.

TSRST Set-Up

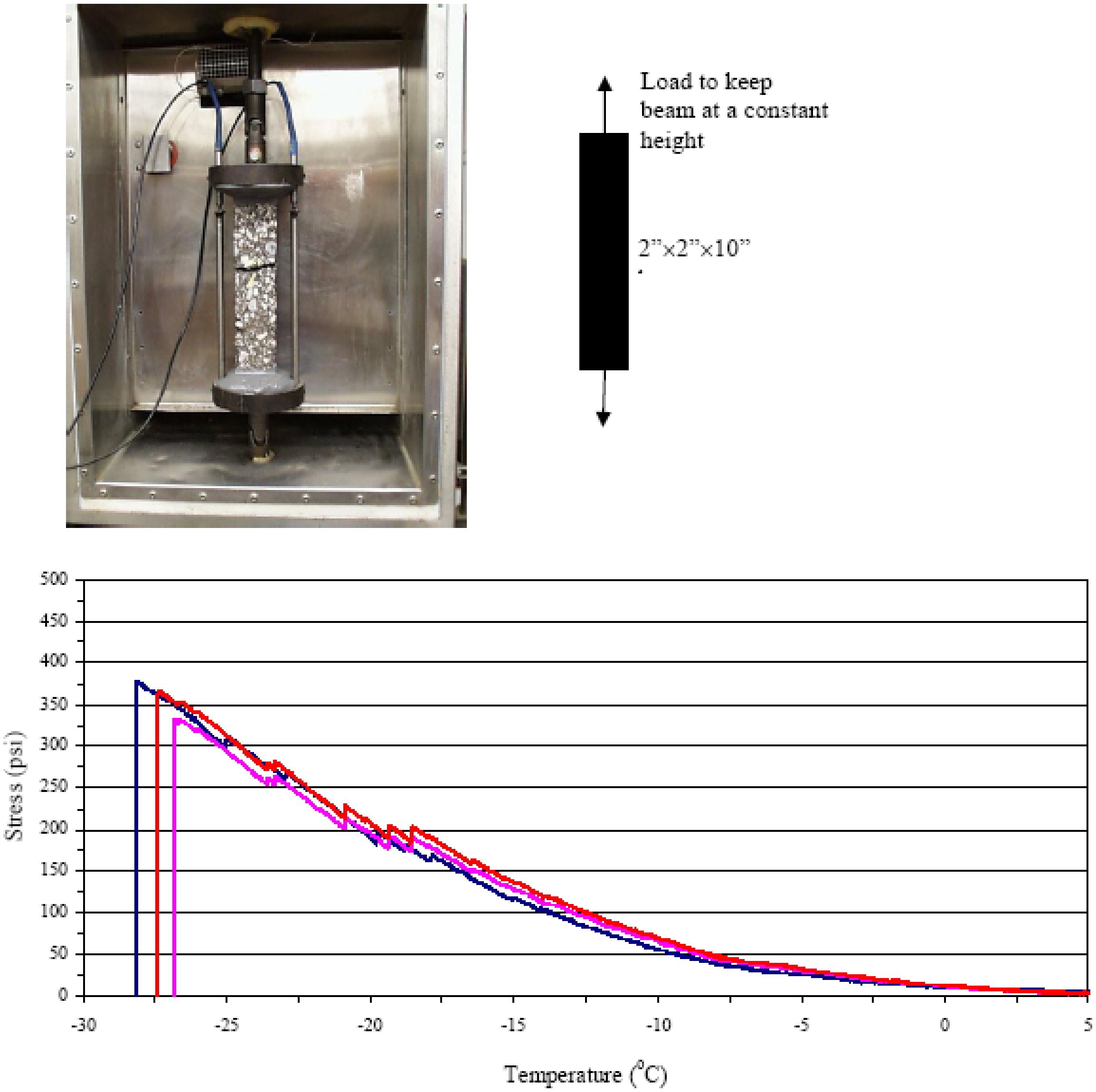
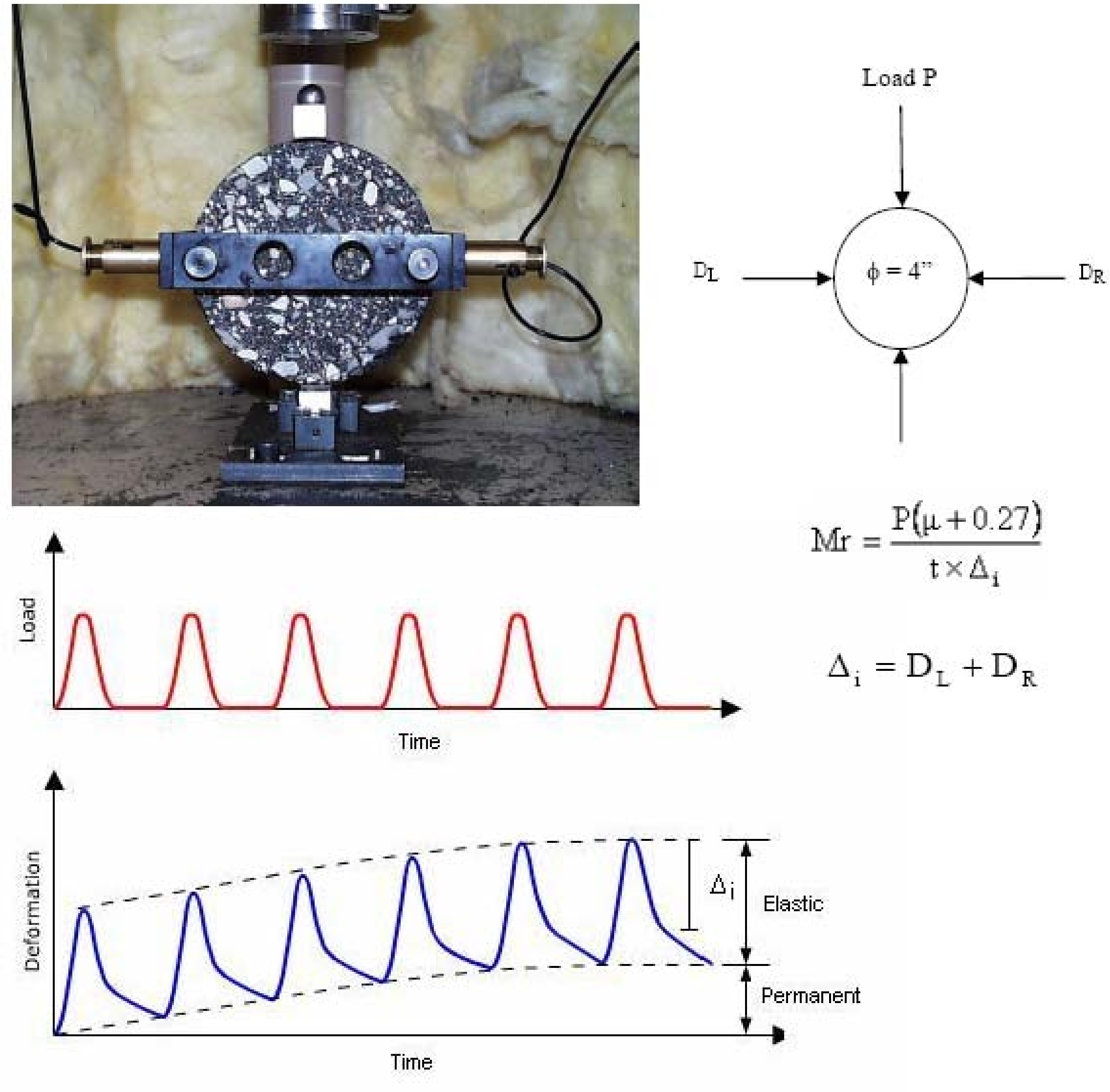


Figure B3. Components of the TSRST test and Typical Stress-Temperature Curve for a HMA mix.

Resilient Modulus Set-Up



$$Mr = \frac{P(\mu + 0.27)}{t \times \Delta_i}$$

$$\Delta_i = D_L + D_R$$

Figure B4. Components of the Resilient Modulus Test for an HMA mix.