the virgin binder with the extracted/recovered RAP binder. Test results in Table 8 show that all the blended binders have met or exceeded the target binder grades of PG64-22 and PG64-28NV.

Table 8 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	PG64-28	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	PG64-28	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. These extracted/recovered binders were tested and compared to the target binder grades. 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 9 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 mixing process. Therefore, the extracted/recovered binders were only subjected to the PAV test to simulate long term aging condition. Test results in Table 9 shows that all the blended binders have exceeded the target binder grades of PG64-22 and PG64-28NV, thus confirming that the blending chart method is a conservative approach to identify the appropriate grade of the virgin binder. For example in the case of the target binder grade of PG64-28NV, the blended binder for the SI-28-30 mixture had a high performance temperature of 70°C which is one grade warmer than 68°C and a low performance temperature of -34°C which is one grade colder than -28°C hence covering a wider range of performance temperature.

Table 9 Summary of PG Grading of Recovered Binders from Final Blended 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 bin percentages of the various RAP and virgin aggregates stockpiles for each mix, b) measuring and checking the specific gravities of the RAP and virgin aggregates, and c) determining the optimum binder contents.

DETERMINING DESIGN AGGREGATE GRADATIONS

The various blends at the desired RAP percentages (0%, 15%, and 30%) for mix design are shown in Table 10. 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.

Figures 1-3 show the gradations of the various blends for each source of RAP material. Each blend gradation meets the Standard Specifications for Public Works Construction (Orange Book, 2004) for Type 2C gradation. All gradations are uniform and close to each others.

Table 10 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%	17%	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%

* PMA denotes “Plant Mix Aggregates”

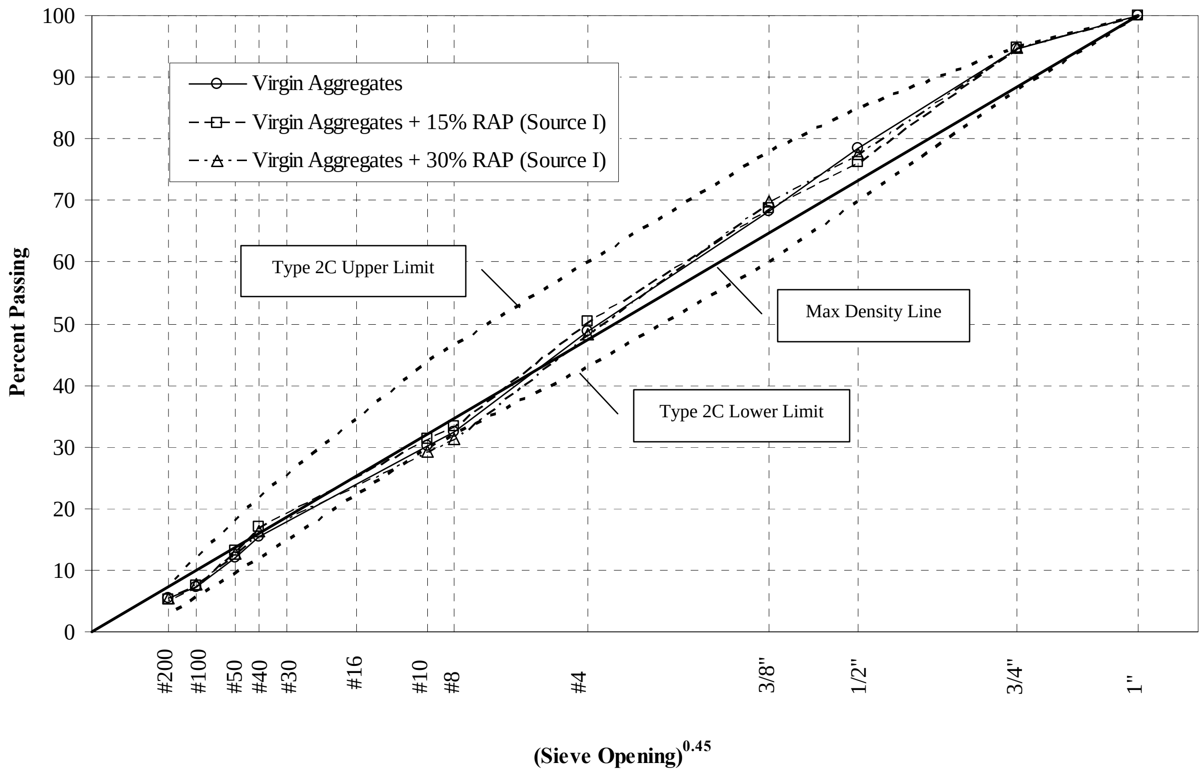

Figure 1. Design Gradations for Control Mixes, and 15 and 30% Source I RAP Mixes.

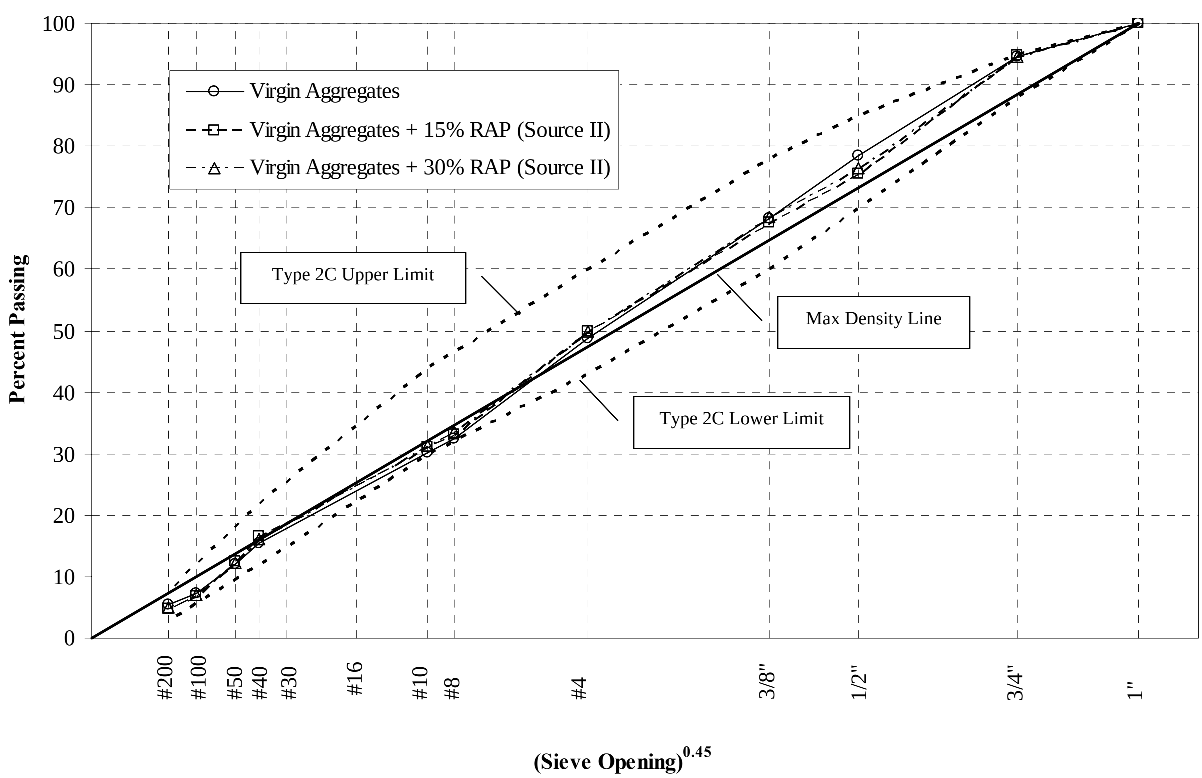

Figure 2. Design Gradations for Control Mixes, and 15 and 30% Source II RAP Mixes.

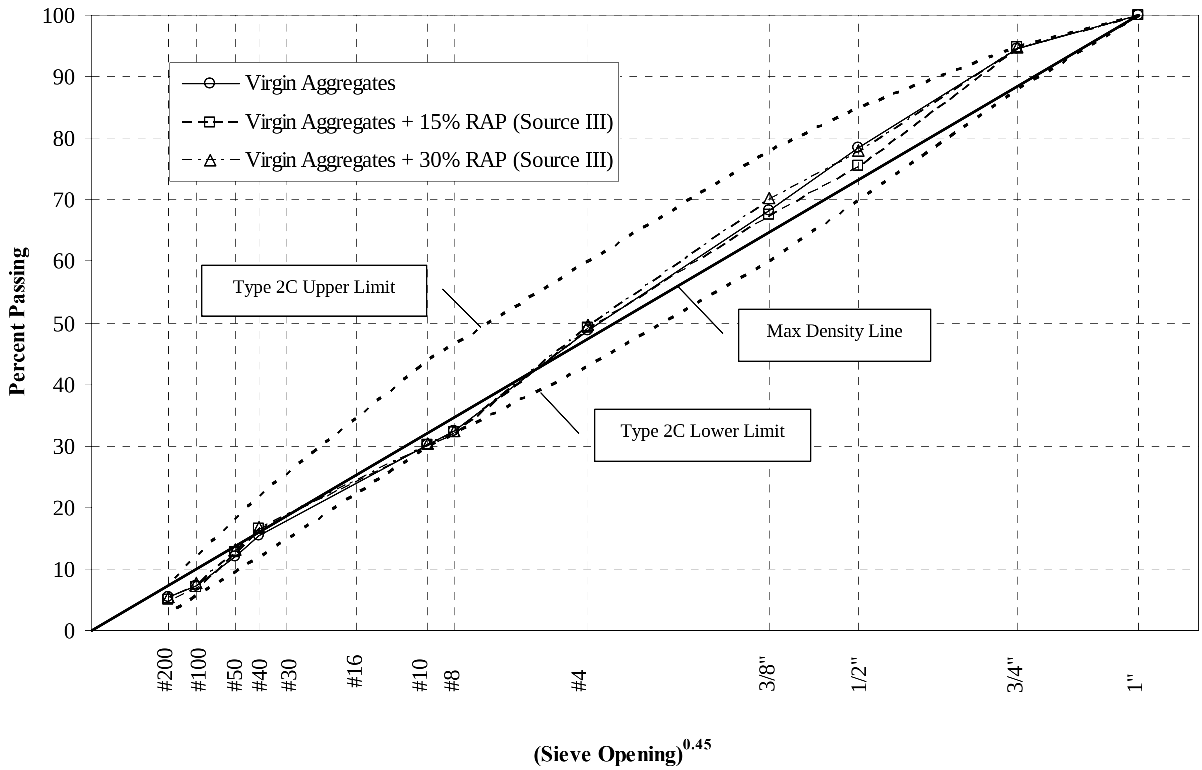

Figure 3. Design Gradations for Control Mixes, and 15 and 30% Source III RAP Mixes.

MEASURING AND CHECKING THE AGGREGATES SPECIFIC GRAVITIES

The specific gravities of the extracted RAP aggregates and the individual stockpiles of the virgin aggregates were measured in the laboratory in accordance with AASHTO T84 and T85. Table 11 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 would need to be converted to volume gradations to ensure the blend gradation specifications are met. Based on the data in Table 11, no conversions were required for these aggregate sources.

Table 11 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 included: 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 for air-voids between 3 and 5%. A 4% design air-voids was typically targeted for all mixes except for the case of SI-28-15 and SIII-28-15 mixtures for which optimum binder content was selected at a design air-voids of 3.5% in order to avoid the production of dry mixes. 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 12 and 13 summarize the mix design data for the target binder grades of PG64-22 and PG64-28NV along with the corresponding Orange Book specifications, respectively. The relationships between the measured properties and binder content of the various mixtures are presented in Appendix *A*.

Table 12 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 13 Mix Design Summary and Specifications for the Target Binder Grade 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%

As shown in Tables 12 and 13, all properties were met except for the minimum VMA criterion. For each mixture, the VMA was calculated using the combined aggregate bulk specific gravity which is calculated using the bulk specific gravity of each aggregate stockpile, including the RAP aggregates. However, it is difficult to accurately measure the bulk specific gravity of the RAP aggregates since the extraction process can change the aggregate properties and may also result in a change in the amount of fine material which could also affect the specific gravity. Consequently, because of the incapability of meeting the minimum VMA criterion of 13.0% with the actual aggregate stockpiles, besides the above-mentioned problem of measuring RAP specific gravities, a minimum VMA of 11.0% was selected for this study. A low VMA can help a mix improve rut resistance at the expense of durability. However, since the focus of this study is to relatively compare the various laboratory produced mixtures including control mixtures, it was felt that as long as all mixtures have close VMA, such comparison will be valid.

IMPACT OF RAP ON MIXTURES PROPERTIES

The objective of this 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 performances 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.

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. The AASHTO T-283 test method was used to evaluate the moisture sensitivity of the various mixtures. The following represents a summary of the major steps of the AASHTO T-283 test procedure.

- 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 14 summarizes the moisture sensitivity properties of the various mixtures. The RTC specifies a minimum value for the unconditioned TS at 77°F of 65 psi and a minimum TSR of 70% for the Truckee Meadows (Reno) area.

The level of variability in the measured data is indicated by the coefficient of variations (CV). The CV is defined as the ratio of the standard deviation over the average TS times 100. All samples tested in this study had a CV value below 10% indicating good repeatability of the measured data (Table 14).

The data in Table 14 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.

Table 14 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

Table 15 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. 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.