Standard Specification for

Superpave Volumetric Mix Design

AASHTO Designation: M 323-12

AASHTO
THE VOICE OF TRANSPORTATION

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1. SCOPE

1.1. This specification for Superpave volumetric mix design uses aggregate and mixture properties to produce a hot mix asphalt (HMA) job-mix formula.

1.2. This standard specifies minimum quality requirements for binder, aggregate, and ~~HMA~~ asphalt materials for Superpave volumetric mix designs.

1.3. *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety concerns associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards*:

- M 320, Performance-Graded Asphalt Binder
- R 28, Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)
- R 35, Superpave Volumetric Design for Hot Mix Asphalt (HMA)
- R 59, Recovery of Asphalt Binder from Solution by Abson Method
- T 11, Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing
- T 27, Sieve Analysis of Fine and Coarse Aggregates
- T 164, Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA)
- T 176, Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test
- T 240, Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)
- T 283, Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage
- T 304, Uncompacted Void Content of Fine Aggregate
- T 308, Determining the Asphalt Binder Content of Hot Mix Asphalt (HMA) by the Ignition Method
- T 312, Preparing and Determining the Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor
- T 319, Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures

2.2. *ASTM Standards*:

- D 4791, Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate
- D 5821, Standard Test Method for Determining the Percentage of Fractured Particles in Coarse Aggregate

2.3. *Asphalt Institute Publication*:

- MS-2, *~~Mix~~ Asphalt Mix Design Methods ~~for Asphalt Concrete and Other Hot-Mix~~* ~~Types~~

2.4. *National Asphalt Pavement Association Publication*:

- IS 128, HMA Pavement Mix Type Selection Guide

2.5. *Other References*:

- *LTPP Seasonal Asphalt Concrete Pavement Temperature Models*. LTPPBind ~~3.1~~Latest Version, http://ltpp-products.com/OtherProducts.asp
- *NCHRP Report 452: Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual*. National Cooperative Highway Research Program Project D9-12, Transportation Research Board, Washington, DC, 2001.
- *NCHRP Report 752: Improved Mix Design, Evaluation and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content.* National Cooperative Highway Research Program Project 9-46, Transportation Research Board, Washington, DC, 2013.

3. TERMINOLOGY

3.1. *~~HMA~~asphalt materials*—~~hot mix~~various asphalt mixtures used by Agencies.

3.2. *design ESALs*—design equivalent (80 kN) single-axle loads.

3.2.1. *~~Discussion~~discussion*—Design ESALs are the anticipated project traffic level expected on the design lane over a 20-year period. For pavements designed for more or less than 20 years, determine the design ESALs for 20 years when using this standard.

3.3. *air voids* (V_a)—the total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as a percent of the bulk volume of the compacted paving mixture ~~(Note 1).~~ AI new MS-2 document referees to air voids as P_a not V_a. Refer to Full ETG as this is not a RAP taskforce issue.

~~**Note 1**—Term defined in Asphalt Institute Manual MS-2, *Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types*.~~

3.4. *voids in the mineral aggregate (VMA)*—the volume of the intergranular void space between the aggregate particles of a compacted paving mixture that includes the air voids and the effective binder content, expressed as a percent of the total volume of the specimen (Note 1).

3.5. *voids filled with asphalt (VFA)*—the percentage of the VMA filled with binder (the effective binder volume divided by the VMA).

3.6. *dust-to-binder ratio* ($P_{0.075}/P_{be}$)—by mass, the ratio between the percent of aggregate passing the 75-µm (No. 200) sieve ($P_{0.075}$) and the effective binder content (P_{be}).

3.7. *nominal maximum aggregate size*—one size larger than the first sieve that retains more than 10 percent aggregate (Note ~~2~~1).

3.8. *maximum aggregate size*—one size larger than the nominal maximum aggregate size (Note ~~2~~1).

Note ~~2~~1—The definitions given in Sections 3.7 and 3.8 apply to Superpave mixes only and differ from the definitions published in other AASHTO standards.

3.10. *reclaimed asphalt pavement (RAP)*—removed and/or processed pavement materials containing asphalt binder and aggregate.

3.11 *reclaimed asphalt pavement binder ratio (RAPBR)*—the ratio of the RAP binder in the mixture divided by the mixture's total binder content.

3.12. *primary control sieve (PCS)*—the sieve defining the break point between fine- and coarse-graded mixtures for each nominal maximum aggregate size.

3.13. *reagent-grade solvent*—A solvent meeting the level of chemical purity as to conform to the specifications for "reagent grade" as referenced in T 319. ~~as established by the *Committee on Analytical Reagents of the American Chemical Society* and used to extract the asphalt binder from the mixture.~~

4. SIGNIFICANCE AND USE

4.1. This standard may be used to select and evaluate materials for Superpave volumetric mix designs.

5. BINDER REQUIREMENTS

5.1. The binder shall be a performance-graded (PG) binder, meeting the requirements of M 320, which is appropriate for the climate and traffic-loading conditions at the site of the paving project or as specified by the contract documents.

5.1.1. Determine the mean and the standard deviation of the yearly, 7-day-average, maximum pavement temperature, measured 20 mm below the pavement surface, and the mean and the standard deviation of the yearly, 1-day-minimum pavement temperature, measured at the pavement surface, at the site of the paving project. These temperatures can be determined by use of the LTPPBind ~~3.1~~ software or can be supplied by the specifying agency. If the LTPPBind software is used, the LTPP high- and low-temperature models should be selected in the software when determining the binder grade. Often, actual site data are not available, and representative data from the nearest weather station will have to be used.

5.1.2. Select the design reliability for the high- and low-temperature performance desired. The design reliability required is established by agency policy.

Note 21—The selection of design reliability may be influenced by the initial cost of the materials and the subsequent maintenance costs.

5.1.3. Using the pavement temperature data determined, select the minimum required PG binder that satisfies the required design reliability.

5.2. If traffic speed or the design ESALs warrant, increase the high-temperature grade by the number of grade equivalents indicated in Table 1 to account for the anticipated traffic conditions at the project site.

Table 1—Binder Selection on the Basis of Traffic Speed and Traffic Level

	Adjustment to the High-Temperature Grade of the Binder[a]		
	Traffic Load Rate		
Design ESALs[b] (Million)	Standing[c]	Slow[d]	Standard[e]
<0.3	—[f]	—	—
0.3 to <3	2	1	—
3 to <10	2	1	—
10 to <30	2	1	—[f]
≥30	2	1	1

[a] Increase the high-temperature grade by the number of grade equivalents indicated (one grade is equivalent to 6˚C). Use the low-temperature grade as determined in Section 5.

[b] The anticipated project traffic level expected on the design lane over a 20-year period. Regardless of the actual design life of the roadway, determine the design ESALs for 20 years.

[c] *Standing Traffic*—where the average traffic speed is less than 20 km/h.

[d] *Slow Traffic*—where the average traffic speed ranges from 20 to 70 km/h.

[e] *Standard Traffic*—where the average traffic speed is greater than 70 km/h.

[f] Consideration should be given to increasing the high-temperature grade by one grade equivalent.

Note 32—Practically, PG binders stiffer than PG 82-xx should be avoided. In cases where the required adjustment to the high-temperature binder grade would result in a grade higher than a PG 82, consideration should be given to specifying a PG 82-xx and increasing the design ESALs by one level (e.g., 10 to <30 million increased to ≥30 million).

5.3. For mixtures containing RAP, select the appropriate grade of virgin binder using the guidelines in Table 2. RAP Binder Ratio is the ratio of the RAP binder in the mixture divided by the total binder content and calculated according to equation 1. ~~RAP Binder Ratio is defined as the ratio of the RAP binder in the mixture divided by the mixture's total binder content. If RAP is to be used in the mixture, it may be specified according to percent dry weight (mass) of the mixture or percent binder replacement. Binder replacement is reclaimed asphalt binder from RAP that replaces virgin binder in asphalt mixtures.~~

~~5.3.1. *Percent dry weight (mass) of mixture)*—If the agency elects to use RAP adjustments by percent dry weight (mass) of the mixture, the binder grade selected in Sections 5.1.3 and 5.2 needs to be adjusted according to Table 2 to account for the amount and stiffness of the RAP binder. Procedures for developing a blending chart are included in Appendix X1.~~

~~**Note 5**—Research conducted as part of NCHRP Project 9-12 indicated that the high stiffness RAP (PG 88-4 after recovery) used in the study had a greater effect on the low-temperature properties of the blended asphalt binder than the medium and low stiffness RAP (PG 82-16 and PG 82-22, respectively). This data suggests that the limiting RAP values in Table 2 may be modified depending on the low-temperature stiffness of the recovered RAP binder. Refer to NCHRP Report 452 for more details.~~

$$RAPBR = \frac{(Pb_{RAP} \times P_{RAP})}{Pb_{Total}} \quad (1)$$

where:

$RAPBR$ = Reclaimed asphalt pavement (RAP) binder ratio

Pb_{RAP} = Binder content of the RAP

P_{RAP} = RAP percentage by weight of mixture

Pb_{Total} = Total binder content in the mixture

Table 2—Binder Selection Guidelines for Reclaimed Asphalt Pavement (RAP) Mixtures

Recommended Virgin Asphalt Binder Grade	RAP ~~Percentage~~Binder Ratio
No change in binder selection	<15
Select virgin binder one grade softer than normal (e.g., select a PG 58-28 if a PG 64-22 would normally be used)	15 to 25
Follow recommendations from blending charts	>25

Table 3—Virgin Binder Selection Guidelines for Reclaimed Asphalt Pavement (RAP) Mixtures

Recommended Virgin Asphalt Binder Grade	RAP Binder Ratio~~Percentage~~
No change in binder selection	< ~~1~~0.25
~~Select virgin binder one grade softer than normal (e.g., select a PG 58-28 if a PG 64-22 would normally be used)~~	~~15 to 25~~
Follow recommendations from X1~~blending charts~~	≥ ~~>~~0.25

Note 4— An Agency may alter the virgin binder selection criteria from Table 2 based on the research procedures provided in X2 and field experiences.

~~5.3.2. *Percent binder replacement*—If the agency elects to use the percent binder replacement method, percent binder replacement is determined by the ratio of reclaimed binder to the total binder in the mixture. Local or regional evaluations need to be completed to determine the maximum RAP amounts allowed or the minimum percentage of virgin binder.~~

~~**Note 6**—If recycled binder properties are not available, effort should be undertaken to characterize typical stockpiled materials. RAP samples should be taken from typical stockpiles in various geographical locations within the state and evaluated to determine the effect of various percentages of RAP binder on typical virgin PG binders. Details on the RAP evaluation process are contained in Appendix X2.~~

6. COMBINED AGGREGATE REQUIREMENTS

6.1. *Size Requirements:*

6.1.1. *Nominal Maximum Size*—The combined aggregate shall have a nominal maximum aggregate size of 4.75 to 19.0 mm for ~~HMA~~ asphalt materials surface courses and no larger than 37.5 mm for ~~HMA~~ asphalt materials subsurface courses.

Note ~~7~~5—Additional guidance on selection of the appropriate nominal maximum size mixture can be found in the National Asphalt Pavement Association's IS 128.

6.1.2. *Gradation Control Points*—The combined aggregate shall conform to the gradation requirements specified in Table 3 when tested according to T 11 and T 27.

Table 4—Aggregate Gradation Control Points

	Nominal Maximum Aggregate Size—Control Points (Percent Passing)											
	37.5 mm		25.0 mm		19.0 mm		12.5 mm		9.5 mm		4.75 mm	
Sieve Size	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
50.0 mm	100	—	—	—	—	—	—	—	—	—	—	—
37.5 mm	90	100	100	—	—	—	—	—	—	—	—	—
25.0 mm	—	90	90	100	100	—	—	—	—	—	—	—
19.0 mm	—	—	—	90	90	100	100	—	—	—	—	—
12.5 mm	—	—	—	—	—	90	90	100	100	—	100	—
9.5 mm	—	—	—	—	—	—	—	90	90	100	95	100
4.75 mm	—	—	—	—	—	—	—	—	—	90	90	100
2.36 mm	15	41	19	45	23	49	28	58	32	67	—	—
1.18 mm	—	—	—	—	—	—	—	—	—	—	30	55
0.075 mm	0	6	1	7	2	8	2	10	2	10	6	13

6.1.3. *Gradation Classification*—The combined aggregate gradation shall be classified as coarse-graded when it passes below the Primary Control Sieve (PCS) control point as defined in Table 4. All other gradations shall be classified as fine-graded.

Table 5—Gradation Classification

PCS Control Point for Mixture Nominal Maximum Aggregate Size (% Passing)					
Nominal Maximum Aggregate Size	37.5 mm	25.0 mm	19.0 mm	12.5 mm	9.5 mm
Primary Control Sieve	9.5 mm	4.75 mm	4.75 mm	2.36 mm	2.36 mm
PCS Control Point (% Passing)	47	40	47	39	47

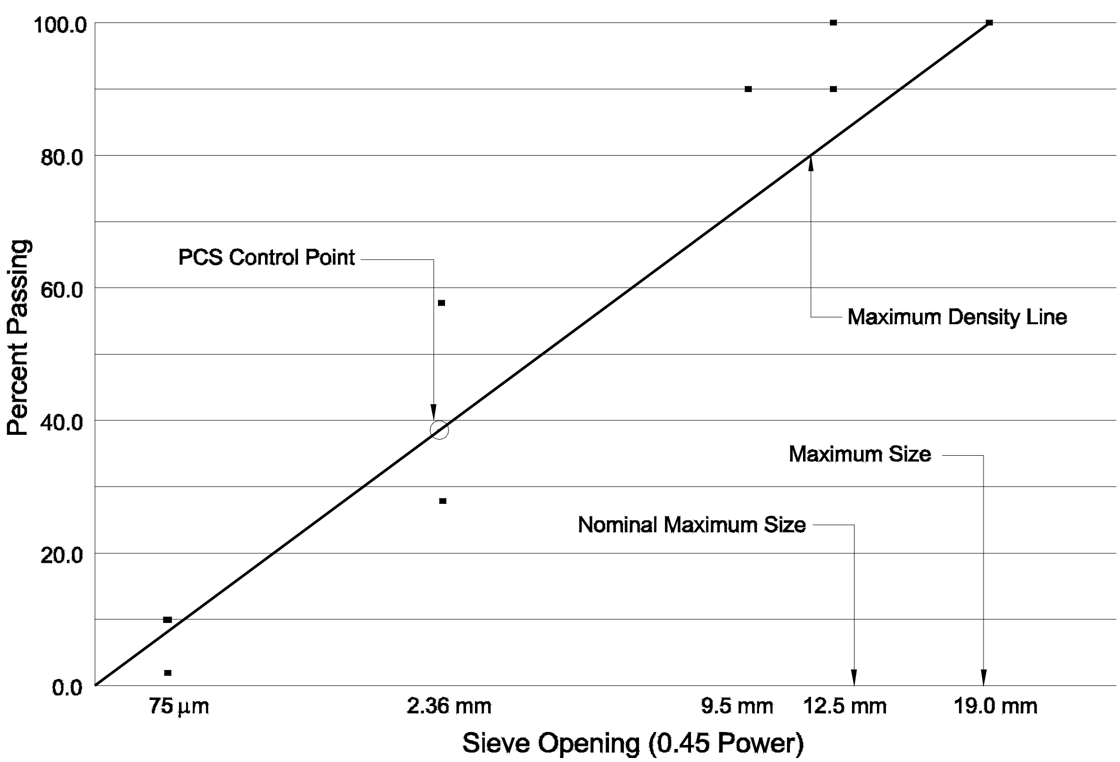

Figure 1—Superpave Gradation Control Points for a 12.5-mm Nominal Maximum Size Aggregate Gradation

6.2. *Coarse Aggregate Angularity Requirements*—The aggregate shall meet the percentage of fractured faces requirements, specified in Table 5, measured according to D 5821.

6.3. *Fine Aggregate Angularity Requirements*—The aggregate shall meet the uncompacted void content of fine aggregate requirements, specified in Table 5, measured according to T 304, Method A.

6.4. *Sand Equivalent Requirements*—The aggregate shall meet the sand equivalent (clay content) requirements, specified in Table 5, measured according to T 176.

6.5. *Flat-and-Elongated Requirements*—The aggregate shall meet the flat-and-elongated requirements, specified in Table 5, measured according to D 4791, with the exception that the material passing the 9.5-mm sieve and retained on the 4.75-mm sieve shall be included. The aggregate shall be measured using the ratio of 5:1, comparing the length (longest dimension) to the thickness (smallest dimension) of the aggregate particles.

6.6. When RAP is used in the mixture, the RAP aggregate shall be extracted from the RAP using a solvent extraction (T 164) or ignition oven (T 308) as specified by the agency. The RAP aggregate shall be included in determinations of gradation, coarse aggregate angularity, fine aggregate angularity, and flat-and-elongated requirements. The sand equivalent requirements shall be waived for the RAP aggregate but shall apply to the remainder of the aggregate blend.

Table 6—Superpave Aggregate Consensus Property Requirements

Design ESALs[a] (Million)	Fractured Faces, Coarse Aggregate,[c] Percent Minimum — Depth from Surface ≤100 mm	Fractured Faces, Coarse Aggregate,[c] Percent Minimum — Depth from Surface >100 mm	Uncompacted Void Content of Fine Aggregate, Percent Minimum — Depth from Surface ≤100 mm	Uncompacted Void Content of Fine Aggregate, Percent Minimum — Depth from Surface >100 mm	Sand Equivalent, Percent Minimum	Flat and Elongated,[c] Percent Maximum
<0.3	55/—	—/—	—[d]	—	40	—
0.3 to <3	75/—	50/—	40[e]	40	40	10
3 to <10	85/80[b]	60/—	45	40	45	10
10 to <30	95/90	80/75	45	40	45	10
≥30	100/100	100/100	45	45	50	10

[a] The anticipated project traffic level expected on the design lane over a 20-year period. Regardless of the actual design life of the roadway, determine the design ESALs for 20 years.

[b] 85/80 denotes that 85 percent of the coarse aggregate has one fractured face and 80 percent has two or more fractured faces.

[c] This criterion does not apply to 4.75-mm nominal maximum size mixtures.

[d] For 4.75-mm nominal maximum size mixtures designed for traffic levels below 0.3 million ESALs, the minimum Uncompacted Void Content is 40.

[e] For 4.75-mm nominal maximum size mixtures designed for traffic levels equal to or above 0.3 million ESALs, the minimum Uncompacted Void Content is 45.

Note ~~8~~6—If less than 25 percent of a construction lift is within 100 mm of the surface, the lift may be considered to be below 100 mm for mixture design purposes.

7. ~~HMA~~ ASPHALT MATERIALS DESIGN REQUIREMENTS

7.1. The binder and aggregate in the ~~HMA~~ asphalt materials shall conform to the requirements of Sections 5 and 6.

7.2. The ~~HMA~~ asphalt materials design, when compacted in accordance with T 312, shall meet the relative density, VMA, VFA, and dust-to-binder ratio requirements specified in Table 6. The initial, design, and maximum number of gyrations are specified in R 35.

Table 7—Superpave ~~HMA~~ Asphalt Materials Design Requirements

Design ESALs[a] (Million)	Required Relative Density, Percent of Theoretical Maximum Specific Gravity			Voids in the Mineral Aggregate (VMA), Percent Minimum						Voids Filled with Asphalt (VFA) Range,[b] Percent	Dust-to-Binder Ratio Range[c]
				Nominal Maximum Aggregate Size, mm							
	$N_{initial}$	N_{design}	N_{max}	37.5	25.0	19.0	12.5	9.5	4.75		
<0.3	≤91.5	96.0	≤98.0	11.0	12.0	13.0	14.0	15.0	16.0	70–80[d,e]	0.6–1.2
0.3 to <3	≤90.5	96.0	≤98.0	11.0	12.0	13.0	14.0	15.0	16.0	65–78[f]	0.6–1.2
3 to <10	≤89.0	96.0	≤98.0	11.0	12.0	13.0	14.0	15.0	16.0	65–75[e,f,g]	0.6–1.2
10 to <30	≤89.0	96.0	≤98.0	11.0	12.0	13.0	14.0	15.0	16.0	65–75[e,f,g]	0.6–1.2
≥30	≤89.0	96.0	≤98.0	11.0	12.0	13.0	14.0	15.0	16.0	65–75[g]	0.6–1.2

[a] Design ESALs are the anticipated project traffic level expected on the design lane over a 20-year period. Regardless of the actual design life of the roadway, determine the design ESALs for 20 years.

[b] For 37.5-mm nominal maximum size mixtures, the specified lower limit of the VFA range shall be 64 percent for all design traffic levels.

[c] For 4.75-mm nominal maximum size mixtures, the dust-to-binder ratio shall be 1.0 to 2.0, for design traffic levels <3 million ESALs, and 1.5 to 2.0 for design traffic levels ≥3 million ESALs.

[d] For 4.75-mm nominal maximum size mixtures, the relative density (as a percent of the theoretical maximum specific gravity) shall be within the range of 94.0 to 96.0 percent.

[e] For design traffic levels <3 million ESALs, and for 25.0-mm nominal maximum size mixtures, the specified lower limit of the VFA range shall be 67 percent, and for 4.75-mm nominal maximum size mixtures, the specified VFA range shall be 67 to 79 percent.

[f] For design traffic levels >3 million ESALs,and for 4.75-mm nominal maximum size mixtures, the specified VFA range shall be 66 to 77 percent.

[g] For design traffic levels ≥3 million ESALs, 9.5-mm nominal maximum size mixtures, the specified VFA range shall be 73 to 76 percent.

Note ~~9~~7—If the aggregate gradation passes beneath the PCS Control Point specified in Table 4, the dust-to-binder ratio range may be increased from 0.6–1.2 to 0.8–1.6 at the agency's discretion.

Note ~~10~~8—Mixtures with VMA exceeding the minimum value by more than 2 percent may be prone to flushing and rutting. Unless satisfactory experience with high VMA mixtures is available, mixtures with VMA greater than 2 percent above the minimum should be avoided.

7.3. The ~~HMA~~ asphalt materials design, when compacted according to T 312 at 7.0 ± 0.5 percent air voids and tested in accordance with T 283, shall have a minimum tensile strength ratio of 0.80.

APPENDIX

(Nonmandatory Information)

X1. PROCEDURES FOR ESTIMATING THE PROPERTIES OF BLENDED RAP AND VIRGIN BINDERS~~DEVELOPING A BLENDING CHART~~

X1.1. ~~Blending of RAP binders can be accomplished by knowing the desired final grade (critical temperature) of the blended binder, the physical properties (and critical temperatures) of the recovered RAP binder, and either the physical properties (and critical temperatures) of the virgin asphalt binder or the desired percentage of RAP in the mixture.~~Selection of the appropriate grade of virgin binder for ~~high RAP content~~ mixes with RAP binder ratios ≥0.25 can be based on knowledge of the true grade of the RAP binder, the high and low critical temperatures for the project location and pavement layer, and either the approximate RAP binder ~~R~~ratio or the high and low critical temperatures for the available virgin binder(s).

Note X1—The high and low critical temperatures for a project location and pavement layer can be determined using the latest version of LTPP Bind ~~version.~~ ~~3.1~~

Note X2—Agencies may elect to establish typical RAP binder properties for specific geographic areas based on testing and analysis of RAP binders from numerous stockpiles within ~~the~~each area. Detailed~~s~~ procedures on the geographic RAP evaluation ~~process~~ are contained in Appendix X2.

~~X1.1.~~X1.2. *Determine the physical properties and critical temperatures of the RAP binder*.

~~X1.1.1.~~X1.2.1. Recover the RAP binder using T 319 (Note ~~X1~~X3) with an ~~appropriate~~ *reagent-grade solvent*~~solvent~~. At least 50 g of recovered RAP binder are needed for testing. Perform binder classification testing using the tests in M 320. Rotational viscosity, flash point, and mass loss tests are not required.

Note X3~~1~~—While T 319 is the preferred method, at the discretion of the agency, R 59 may be used. Research conducted under NCHRP 9-12 indicated that R 59 might affect recovered binder properties.

~~X1.1.2.~~X1.2.2. Perform original dynamic shear rheometer (DSR) testing on the recovered RAP binder to determine the critical high temperature, $T_c(High)$, based on original DSR values where G*/sin δ = 1.00 kPa. Calculate the critical high temperature as follows:

~~X1.1.2.1.~~X1.2.2.1. Determine the slope of the Stiffness-Temperature curve as follows:

~~$a = \Delta\log(G^*/\sin\delta)/\Delta T$~~ ~~(X1.1)~~

$$a = \frac{\Delta \log\left(\frac{G^*}{\sin\delta}\right)}{\Delta T} \quad \text{(X1.1)}$$

~~X1.1.2.2.~~X1.2.2.2. Determine $T_c(High)$ to the nearest 0.1°C using the following equation:

~~$Tc(High) = \left\{\frac{Log(1.00) - Log(G1)}{a}\right\} + T1$~~ ~~(X1.2)~~

$$Tc(High) = \left\{\frac{Log\ (1.00) - Log\ (G_1)}{a}\right\} + T_1 \qquad (X1.2)$$

where:

G_1	=	*the G*/sin δ value at a specific temperature* ~~T_1, and~~
a	=	*the slope as described in Equation X1.1*
T_1	=	*specific temperature*

Note X~~4~~2—Although any temperature (T_1) and the corresponding stiffness (G_1) can be selected, it is advisable to use the G*/sin δ value closest to the criterion (1.00 kPa) to minimize extrapolation errors.

~~X1.1.3.~~X1.2.3. Perform rolling thin-film oven (RTFO) aging on the remaining binder.

~~X1.1.4.~~X1.2.4. Perform RTFO DSR testing on the RTFO-aged recovered binder to determine the critical high temperature (based on RTFO DSR). Calculate the critical high temperature (RTFO DSR).

~~X1.1.4.1.~~X1.2.4.1. Determine the slope of the Stiffness-Temperature curve as follows:

~~$a = \Delta\log(G^*/\sin\delta)/\Delta T$ (X1.3)~~

$$a = \frac{\Delta \log\left(\frac{G^*}{\sin\delta}\right)}{\Delta T} \qquad (X1.3)$$

~~X1.1.4.2.~~ Determine $T_c(High)$ based on RTFO DSR, to the nearest 0.1°C using the following equation:

~~X1.1.4.3.~~ ~~$T_c(High) = \left(\frac{Log(2.20) - Log(G_1)}{a}\right) + T_1$ (X1.4)~~

$$Tc(High) = \left\{\frac{Log\ (2.20) - Log\ (G_1)}{a}\right\} + T_1 \qquad (X1.4)$$

where:

G_1	=	*the G*/sin δ value at a specific temperature* ~~T_1, and~~
a	=	*the slope as described in Equation X1.3*
T_1	=	*specific temperature*

Note X~~3~~5—Although any temperature (T_1) and the corresponding stiffness (G_1) can be selected, it is advisable to use the G*/sin δ value closest to the criterion (2.20 kPa) to minimize extrapolation errors.

~~X1.1.5.~~X1.2.5. Determine the critical high temperature of the recovered RAP binder as the lowest of the original DSR and RTFO DSR critical temperatures. Determine the high-temperature performance grade (PG) of the recovered RAP binder based on this single critical high temperature.

~~X1.1.6.~~X1.2.6. Perform intermediate temperature DSR testing on the RTFO-aged recovered RAP binder to determine the critical intermediate temperature T_c (*Int*), as if the RAP binder were pressure aging vessel (PAV) aged.

~~X1.1.6.1.~~X1.2.6.1. Determine the slope of the Stiffness-Temperature curve as follows:

~~$a = \Delta\log(G^*/\sin\delta)/\Delta T$ (X1.5)~~

$$a = \frac{\Delta \log\left(\frac{G^*}{\sin\delta}\right)}{\Delta T} \qquad (X1.5)$$

~~X1.1.6.2.~~X1.2.6.2. Determine T_c (*Int*) to the nearest 0.1°C using the following equation:

~~$T_c(Int) = \left(\frac{Log(5000) - Log(G_1)}{a}\right) + T_1$ (X1.6)~~

$$Tc(Int) = \left\{\frac{Log\ (5000) - Log\ (G_1)}{a}\right\} + T_1 \qquad (X1.6)$$

where:

T_c(Int)	=	critical intermediate temperature with PAV aged RAP binder
G_1	=	*the G*/sin δ value at a specific temperature* ~~T_1, and~~
a	=	*the slope as described in Equation X1.5*
T_1	=	*specific temperature*

Note X~~4~~6—Although any specific temperature (T_1) and the corresponding stiffness (G_1) can be selected, it is advisable to use the G*/sin δ value closest to the criterion (5000 kPa) to minimize extrapolation errors.

~~X1.1.7.~~X1.2.7. Perform BBR testing on the RTFO-aged recovered RAP binder to determine the critical low temperature, T_c (*S*) or T_c (*m*), based on bending beam rheometer (BBR) Stiffness or *m*-value.

~~X1.1.7.1.~~X1.2.7.1. Determine the slope of the Stiffness-Temperature curve as follows:

~~$a = \Delta\log(S)/\Delta T$ (X1.7)~~

$$a = \frac{(\Delta \log S)}{\Delta T} \qquad (X1.7)$$

~~X1.1.7.2.~~X1.2.7.2. Determine $T_c(S)$ to the nearest 0.1°C using the following equation:

~~$T_c(S) = \left(\frac{Log(300) - Log(S_1)}{a}\right) + T_1$ (X1.8)~~

$$Tc(S) = \left\{\frac{Log\ (300) - Log\ (S_1)}{a}\right\} + T_1 \qquad (X1.8)$$

where:

S_1	=	*the S-value at a specific temperature* T_1~~, and~~
a	=	*the slope as described in Equation X1.7*
T_1	=	*specific temperature*

Note X57—Although any specific temperature (T_1) and the corresponding stiffness (S_1) can be selected, it is advisable to use the S-value closest to the criterion (300 MPa) to minimize extrapolation errors.

X1.1.7.3.X1.2.7.3. Determine the slope of the m-value-Temperature curve as follows:

$a = \Delta m\text{-value}/\Delta T$ (X1.9)

$$a = \frac{(\Delta m - \text{value})}{\Delta T} \quad (X1.9)$$

X1.1.7.4.X1.2.7.4. Determine $T_c(m)$ to the nearest 0.1°C using the following equation:

$$T_c(m) = \left(\frac{0.300 - m_1}{a}\right) + T_1 \quad (X1.10)$$

$$T_c\,(m) = \left\{\frac{0.300 - m_1}{a}\right\} + T_1 \quad (X1.10)$$

when:

$T_c(m)$	=	*critical temperature for the m-value*
m_1	=	*the* m*-value at a specific temperature* T_1*, and*
a	=	*the slope as described in Equation X1.9*
T_1	=	*specific temperature*

Note X68—Although any specific temperature (T_1) and the corresponding m-value (m_1) can be selected, it is advisable to use the m-value closest to the criterion (0.300) to minimize extrapolation errors.

X1.1.7.5.X1.2.7.5. Select the higher of the two low critical temperatures, $T_c(S)$ or $T_c(m)$, to represent the low critical temperature for the recovered asphalt binder, $T_c(Low)$. Determine the low-temperature PG of the recovered RAP binder based on this single critical low temperature.

X1.1.8.X1.2.8. Once the physical properties and critical temperatures of the recovered RAP binder are known, proceed with blending at a known RAP percentage or with a known virgin binder grade.

X1.2.X1.3. *Determination of the appropriate virgin binder grade using Blending at a known an approximate RAP Binder Ratiopercentage*.

X1.2.1.X1.3.1. If the desired compositefinal blended binder grade, the desired percentage of RAP, and the recovered RAP binder properties are known, then the required properties of an appropriate virgin binder grade can be determined.

X1.3.1.1. Determine the critical temperatures of the virgin asphalt binder at high, intermediate, and low properties using the following equation:

$$T_c(\text{virgin}) = \frac{T_c(need) - (RAPBR \times T_c(RAP\ Binder))}{(1 - RAPBR)} \quad (X1.11)$$

$$T_{Virgin} = \frac{T_{Blend} - (\%RAP \times T_{RAP})}{(1 - \%RAP)} \quad (X1.11)$$

where:

T_c(vVirgin) = critical temperature of virgin asphalt binder (high, intermediate, or low);

T_{Blendc}(need) = critical temperature needed for the climate and pavement layerof blended asphalt binder (final desired) (high, intermediate, or low);

RAPBR = RAP Binder Ratio - the ratio of the RAP binder in the mixture divided by the mixture's total binder content. The mixture's total binder content is an unknown prior to mix design but can be estimated based on historical data for the aggregate type and NMAS.

%RAP = percentage of RAP expressed as a decimal; and

T_c(RAP_binder) = critical temperature of recovered RAP binder (high, intermediate, or low)

X1.2.1.1.X1.3.1.2. Using Equation X1.11 for the high, intermediate, and low critical temperatures, respectively, the properties of the virgin asphalt binder needed can be determined.

X1.3.X1.4. *Blending with a known virgin binder.*

X1.3.1.X1.4.1. If the final blended binder grade, virgin asphalt binder grade, and recovered RAP properties are known, then the maximum RAP binder ratioallowable RAP percentage can be determined.

X1.4.1.1. Determine the maximum RAP binder ratioallowable RAP percentage using the following equation:

$$RAPBR_{max.} = \frac{T_c(need) - T_c(virgin)}{T_c(RAP\ Binder) - T_c(virgin)} \qquad (X1.12)$$

$$\%RAP = \frac{T_{Blend} - T_{Virgin}}{T_{RAP} - T_{Virgin}} \qquad (X1.12)$$

where:

$RAPBR_{max}$ = maximum RAP binder ratio

T_c(need) = critical temperature needed for the climate and pavement layer (high, intermediate, or low)

T_c(virgin) = critical temperature of virgin asphalt binder (high, intermediate, or low)

T_c(RAP_binder) = critical temperature of recovered RAP binder (high, intermediate, or low)

T_{Virgin} = critical temperature of virgin asphalt binder (high, intermediate, or low);

T_{Blend} = critical temperature of blended asphalt binder (high, intermediate, or low); and

T_{RAP} = critical temperature of recovered RAP binder (high, intermediate, or low).

X1.3.1.1.X1.4.1.2. Using Use Equation X1.12 for the high, intermediate, and low critical temperatures, respectively, to determine the maximum RAP binder ratio allowable RAP percentage that will satisfyto satisfy all temperatures requirements can be determined.

X2. ~~PROCEDURES FOR ESTABLISHING TYPICAL RAP BINDER PROPERTIES FOR SPECIFIC GEOGRAPHIC AREAS EVALUATING RAP STOCKPILES~~ PROCEDURE TO DETERMINE REPRESENTATIVE PROPERTIES OF RAP BINDERS WITHIN A GEOGRAPHICAL AREA TO SET LIMITING PERCENTAGES OF RAP BINDER RATIO AND/OR APPROPRIATE GRADE OF VIRGIN BINDER FOR MIXTURES CONTAINING RAP

X2.1. RAP stockpile locations should be selected throughout the geographical area. Geographical areas should be selected with consideration to climatic zones and material sources. The number of stockpile locations may depend upon size of the geographic area and variability of climate and other ~~within the area and variation of~~ factors within the area.

~~X1.4.~~X2.2. Evaluation of the physical properties of the recovered RAP binder begins with the sampling and testing of the stockpiles within the ~~state~~geographical area. ~~The s~~Samples should be large enough to provide sufficient asphalt binder for PG grading~~. Project locations and PG binder grades of the stockpile materials should be noted.~~ Number of samples should be sufficient in number to evaluate the results.

~~X1.5. The samples should be large enough that a sufficient amount of binder can be extracted for a full PG binder classification. The samples can be taken from RAP stockpiles at plants or roadway cores from pavements.~~

~~X1.6.~~X2.3. In ~~states~~ locations where RAP ~~sources~~ containing different binders such as polymer-modified ~~binders~~or different grades ~~are~~ is stockpiled separately ~~from RAP sources with neat binders~~, ~~the~~ evaluation of the ~~materials~~ asphalt binder should be performed separately from other stockpiles.

X2.4. Solvent extractions should be performed on the RAP samples to acquire recovered binder samples. Reagent-grade solvents should be used to reduce the potential of the extraction process changing the properties of the recovered binder.

~~X1.7.~~X2.5. Determine the physical properties and critical failure temperatures of the RAP binders as outlined in Appendix X1.

~~X1.8. Solvent extractions should be performed on the RAP samples to acquire recovered binder samples for PG grading. Reagent-grade solvents should be used to reduce the potential of the extraction process changing the properties of the recovered binder.~~

~~X1.9. The recovered binder from the RAP should be fully graded to determine its aged properties. To grade the recovered RAP binder, RTFOT conditioning according to T 240 and PAV aging according to R 28 are not required. The grade of the binder as aged on the roadway is to be determined. The high temperature DSR and intermediate temperature DSR according to T 315, and the BBR according to T 313, should be performed on the as recovered binder.~~

X2.6. In some cases the high temperature DSR grade of the recovered binder may be higher than the temperature range of the DSR equipment. For these cases, the binder should be tested at three temperatures: –3, –9, and –15°C from the high temperature limit of the equipment. Plot the log of the test temperature versus the log of the binder property to project the temperature at which the binder will meet the grade requirements. All binder grading should be performed to provide the actual continuous grades of the RAP binder.

~~Analyze the recovered RAP binder data to determine the typical grade of binder that can be expected in the RAP in general geographic locations. For states with uniform climates, this process may require only determining typical aged grades for RAP containing standard neat~~

~~binders and for RAP containing polymer modified binders. For states with varied climates, four or more typical aged grades may be required to fully characterize the expected RAP binders in those different areas. Neat and modified RAP binder grades may be needed for each climatic or geographic area.~~

X2.7. Determine the distribution of RAP binder grades from stockpiles within the geographical area of study. From the distribution of low temperature grades, calculate the average continuous low temperature grade from the stockpiles. The average low temperature grade plus two standard deviations will provide ~~96~~95 percent reliability of the low temperature grade of the RAP binders in the geographic area. ~~The RAP binder grade should be compared to the environmental conditions of the climate area. Extra care should be given to the low temperature properties of the binder as they may dominate the typical failure mechanisms of RAP mixtures. For example, a 98 percent reliability for thermal cracking may be found with a low temperature grade of PG XX-22, but if a PG XX-16 grade is evaluated, it may only provide up to 89 percent reliability~~.

X2.8. Collect multiple representative samples of asphalt binder for each grade supplied into the geographical area. Determine the continuous low temperature grade for each binder. The average low temperature grade plus two standard deviations will provide ~~96~~95 percent reliability of the low temperature grade of the virgin binders in the geographic area. Use the highest or the ~~96~~95 percent reliability continuous low temperature grade in the blending analysis. ~~The Evaluations using the means and standard deviations of the recovered RAP binder property data should be conducted to estimate the impacts of varying proportions of the RAP binder with typical virgin binder grades for the general climatic conditions. From these evaluations general can be more accurately established on the amount of RAP binder that can be incorporated in the new mix and when adjustments to the virgin binder grade are needed to accommodate higher percentages of RAP.~~

~~X1.10.~~X2.9. ~~Evaluation~~ Perform blending analysis using equation ~~X1.412~~ X1.12 to determine the maximum allowable percent of RAP binder to be added to a virgin asphalt binder to meet the ~~needed~~ low temperature grade according to LTPP Bind ~~vrs. 3.1~~.

Note X9~~7~~ – For example, PG xx-22 may be specified however a RAP Blend that produces a PG xx-16 may provide 98 percent reliability according to the latest version of LTPP Bind ~~vrs. 3.1~~. In most cases, the reliabilities of less than 98 percent are acceptable and will only provide minor temperature differences.

~~X1.11.~~X2.10. Evaluation of asphalt binder in RAP stockpiles in a typical geographic area may provide the necessary information to establish the maximum RAP binder ratio limit for a given virgin binder grade in that area ~~area allows on asphalt binder replacement from RAP based on properties of both RAP and virgin binders. This allows determination of maximum asphalt binder replacement limits without changing the virgin binder grade. It also establishes the maximum amount of asphalt binder replacement that can be used with a virgin binder that is one low temperature grade lower.~~ This information can be used to establish design criteria within a specific geographical area. In areas where the recovered RAP binder properties vary significantly, ~~establishing~~ a general RAP binder ratio ~~percentage use~~ may not be appropriate. In these cases, the analysis should be on a project by project basis.