

# Superpave Volumetric Design for Asphalt Mixtures

AASHTO Designation: R 35-15



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## 1. SCOPE

- 1.1. This standard practice for mix design evaluation uses aggregate and mixture properties to produce a hot mix asphalt (HMA) job-mix formula. The mix design is based on the volumetric properties of the asphalt mixture in terms of the air voids, voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA).
- 1.2. This standard practice may also be used to provide a preliminary selection of mix parameters as a starting point for mix analysis and performance prediction analyses that primarily use T 320 and T 322.
- 1.3. Special mixture design considerations and practices to be used in conjunction with this standard practice for the volumetric design of Warm Mix Asphalt (WMA) are given in Appendix X2.
- 1.4. *This standard practice may involve hazardous materials, operations, and equipment. This standard practice does not purport to address all of the safety concerns, if any, 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.*

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## 2. REFERENCED DOCUMENTS

- 2.1. *AASHTO Standards:*
  - M 320, Performance-Graded Asphalt Binder
  - M 323, Superpave Volumetric Mix Design
  - PP 60, Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor (SGC)
  - R 30, Mixture Conditioning of Hot Mix Asphalt (HMA)
  - T 2, Sampling of Aggregates
  - T 11, Materials Finer Than 75- $\mu$ m (No. 200) Sieve in Mineral Aggregates by Washing
  - T 27, Sieve Analysis of Fine and Coarse Aggregates
  - T 84, Specific Gravity and Absorption of Fine Aggregate
  - T 85, Specific Gravity and Absorption of Coarse Aggregate
  - T 100, Specific Gravity of Soils
  - T 166, Bulk Specific Gravity ( $G_{mb}$ ) of Compacted Hot Mix Asphalt (HMA) Using Saturated Surface-Dry Specimens
  - T 195, Determining Degree of Particle Coating of Asphalt Mixtures
  - T 209, Theoretical Maximum Specific Gravity ( $G_{mm}$ ) and Density of Hot Mix Asphalt (HMA)
  - T 228, Specific Gravity of Semi-Solid Asphalt Materials
  - T 248, Reducing Samples of Aggregate to Testing Size

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- T 275, Bulk Specific Gravity ( $G_{mb}$ ) of Compacted Hot Mix Asphalt (HMA) Using Paraffin-Coated Specimens
- T 283, Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage
- T 312, Preparing and Determining the Density of Asphalt Mixture Specimens by Means of the Superpave Gyrotory Compactor
- T 320, Determining the Permanent Shear Strain and Stiffness of Asphalt Mixtures Using the Superpave Shear Tester (SST)
- T 322, Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device
- TP 79, Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)

2.2. *Asphalt Institute Standard:*

- SP-2, Superpave Mix Design

2.3. *Other References:*

- LTPP Seasonal Asphalt Concrete Pavement Temperature Models, LTPPBind 3.1, <http://www.ltpplibind.com>
- NCHRP Report 567: Volumetric Requirements for Superpave Mix Design

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### 3. TERMINOLOGY

3.1. *HMA*—hot mix asphalt.

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

3.2.1. *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 practice.

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).

**Note 1**—Term defined in Asphalt Institute Manual SP-2, Superpave Mix Design.

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. *absorbed binder volume ( $V_{ba}$ )*—the volume of binder absorbed into the aggregate (equal to the difference in aggregate volume when calculated with the bulk specific gravity and effective specific gravity).

3.6. *binder content ( $P_b$ )*—the percent by mass of binder in the total mixture, including binder and aggregate.

3.7. *effective binder volume ( $V_{be}$ )*—the volume of binder that is not absorbed into the aggregate.

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

- 3.9. *dust-to-binder ratio* ( $P_{0.075}/P_{be}$ )—by mass, the ratio between the percent passing the 75- $\mu\text{m}$  (No. 200) sieve ( $P_{0.075}$ ) and the effective binder content ( $P_{be}$ ).
- 3.10. *nominal maximum aggregate size*—one size larger than the first sieve that retains more than 10 percent aggregate (Note 2).
- 3.11. *maximum aggregate size*—one size larger than the nominal maximum aggregate size (Note 2).  
**Note 2**—The definitions given in Sections 3.10 and 3.11 apply to Superpave mixes only and differ from the definitions published in other AASHTO standards.
- 3.12. *reclaimed asphalt pavement (RAP)*—removed and/or processed pavement materials containing asphalt binder and aggregate.
- 3.13. *primary control sieve (PCS)*—the sieve defining the break point between fine and coarse-graded mixtures for each nominal maximum aggregate size.

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## 4. SUMMARY OF THE PRACTICE

- 4.1. *Materials Selection*—Binder, aggregate, and RAP stockpiles are selected that meet the environmental and traffic requirements applicable to the paving project. The bulk specific gravity of all aggregates proposed for blending and the specific gravity of the binder are determined.  
**Note 3**—If RAP is used, the bulk specific gravity of the RAP aggregate may be estimated by determining the theoretical maximum specific gravity ( $G_{mm}$ ) of the RAP mixture and using an assumed asphalt absorption for the RAP aggregate to back-calculate the RAP aggregate bulk specific gravity, if the absorption can be estimated with confidence. The RAP aggregate effective specific gravity may be used in lieu of the bulk specific gravity at the discretion of the agency. The use of the effective specific gravity may introduce an error into the combined aggregate bulk specific gravity and subsequent VMA calculations. The agency may choose to specify adjustments to the VMA requirements to account for this error based on experience with local aggregates.
- 4.2. *Design Aggregate Structure*—It is recommended that at least three trial aggregate blend gradations from selected aggregate stockpiles are blended. For each trial gradation, an initial trial binder content is determined, and at least two specimens are compacted in accordance with T 312. A design aggregate structure and an estimated design binder content are selected on the basis of satisfactory conformance of a trial gradation meeting the requirements given in M 323 for  $V_a$ , VMA, VFA, dust-to-binder ratio at  $N_{design}$ , and relative density at  $N_{initial}$ .  
**Note 4**—Previous Superpave mix design experience with specific aggregate blends may eliminate the need for three trial blends.
- 4.3. *Design Binder Content Selection*—Replicate specimens are compacted in accordance with T 312 at the estimated design binder content and at the estimated design binder content  $\pm 0.5$  percent and  $+1.0$  percent. The design binder content is selected on the basis of satisfactory conformance with the requirements of M 323 for  $V_a$ , VMA, VFA, and dust-to-binder ratio at  $N_{design}$ , and the relative density at  $N_{initial}$  and  $N_{max}$ .
- 4.4. *Evaluating Moisture Susceptibility*— Evaluate the moisture susceptibility of the design aggregate structure at the design binder content. Oven-condition the mixture according to the Mixture Conditioning for Volumetric Mixture Design procedure in R 30, Section 7.1. Compact specimens to  $7.0 \pm 0.5$  percent air voids according to T 312. Group, moisture-condition, test, and evaluate specimens according to T 283. The design shall meet the tensile strength ratio requirement of M 323.

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## 5. SIGNIFICANCE AND USE

- 5.1. The procedure described in this standard practice is used to produce asphalt mixtures that satisfy Superpave asphalt volumetric mix design requirements.

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## 6. PREPARING AGGREGATE TRIAL BLEND GRADATIONS

- 6.1. Select a binder in accordance with the requirements of M 323.
- 6.2. Determine the specific gravity of the binder according to T 228.
- 6.3. Obtain samples of aggregates proposed to be used for the project from the aggregate stockpiles in accordance with T 2.

**Note 5**—Each stockpile usually contains a given size of an aggregate fraction. Most projects employ three to five stockpiles to generate a combined gradation conforming to the job-mix formula and M 323.

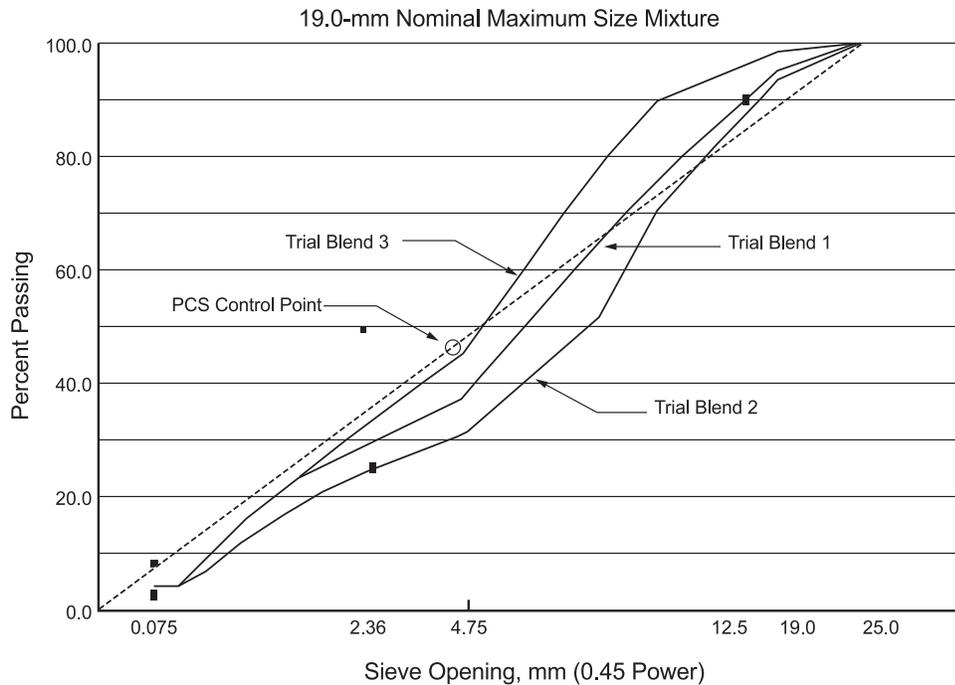
- 6.4. Reduce the samples of aggregate fractions according to T 248 to samples of the size specified in T 27.
- 6.5. Wash and grade each aggregate sample according to T 11 and T 27 for the purpose of materials characterization of the aggregates.
- 6.6. Determine the bulk and apparent specific gravity for each coarse and fine aggregate fraction in accordance with T 85 and T 84, respectively, and determine the specific gravity of the mineral filler in accordance with T 100.
- 6.7. Blend the aggregate fractions for design purposes using Equation 1:

$$P = Aa + Bb + Cc, \text{ etc.} \quad (1)$$

where:

- $P$  = percentage of material passing a given sieve for the combined aggregates A, B, C, etc.;
- $A, B, C, \text{ etc.}$  = percentage of material passing a given sieve for aggregates A, B, C, etc.; and
- $a, b, c, \text{ etc.}$  = proportions of aggregates A, B, C, etc., used in the combination, and where the total = 1.00.

- 6.8. Prepare a minimum of three trial aggregate blend gradations; plot the gradation of each trial blend on a 0.45-power gradation analysis chart, and confirm that each trial blend meets M 323 gradation controls (see Table 3 of M 323). Gradation control is based on four control sieve sizes: the sieve for the maximum aggregate size, the sieve for the nominal maximum aggregate size, the 4.75- or 2.36-mm sieve, and the 0.075-mm sieve. An example of three acceptable trial blends in the form of a gradation plot is given in Figure 1.



**Figure 1**—Evaluation of the Gradations of Three Trial Blends (Example)

- 6.9. Obtain a test specimen from each of the trial blends according to T 248, and conduct the quality tests specified in Section 6 of M 323 to confirm that the aggregate in the trial blends meets the minimum quality requirements specified in M 323.

**Note 6**—The designer has an option of performing the quality tests on each stockpile instead of the trial aggregate blend. The test results from each stockpile can be used to estimate the results for a given combination of materials.

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## 7. DETERMINING AN INITIAL TRIAL BINDER CONTENT FOR EACH TRIAL AGGREGATE GRADATION

- 7.1. Designers can either use their experience with the materials or the procedure given in Appendix X1 to determine an initial trial binder content for each trial aggregate blend gradation.

**Note 7**—When using RAP, the initial trial asphalt content should be reduced by an amount equal to that provided by the RAP.

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## 8. COMPACTING SPECIMENS OF EACH TRIAL GRADATION

- 8.1. Prepare replicate mixtures (Note 8) at the initial trial binder content for each of the chosen trial aggregate trial blend gradations. From Table 1, determine the number of gyrations based on the design ESALs for the project.

**Note 8**—At least two replicate specimens are required, but three or more may be prepared if desired. Generally, 4500 to 4700 g of aggregate is sufficient for each compacted specimen with a height of 110 to 120 mm for aggregates with combined bulk specific gravities of 2.55 to 2.70, respectively.

- 8.2. Condition the mixtures according to R 30, and compact the specimens to  $N_{\text{design}}$  gyrations in accordance with T 312. Record the specimen height to the nearest 0.1 mm after each revolution.

- 8.3. Determine the bulk specific gravity ( $G_{mb}$ ) of each of the compacted specimens in accordance with T 166 or T 275 as appropriate.

**Table 1**—Superpave Gyratory Compaction Effort

Design ESALs <sup>a</sup> (million)	Compaction Parameters			Typical Roadway Application <sup>b</sup>
	$N_{initial}$	$N_{design}$	$N_{max}$	
<0.3	6	50	75	Applications include roadways with very light traffic volumes, such as local roads, county roads, and city streets where truck traffic is prohibited or at a very minimal level. Traffic on these roadways would be considered local in nature, not regional, intrastate, or interstate. Special purpose roadways serving recreational sites or areas may also be applicable to this level.
0.3 to <3	7	75	115	Applications include many collector roads or access streets. Medium-trafficked city streets and the majority of county roadways may be applicable to this level.
3 to <30	8	100	160	Applications include many two-lane, multilane, divided, and partially or completely controlled access roadways. Among these are medium to highly trafficked city streets, many state routes, U.S. highways, and some rural Interstates.
$\geq 30$	9	125	205	Applications include the vast majority of the U.S. Interstate system, both rural and urban in nature. Special applications such as truck-weighing stations or truck-climbing lanes on two-lane roadways may also be applicable to this level.

<sup>a</sup> 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.

<sup>b</sup> As defined by *A Policy on Geometric Design of Highways and Streets*, 2004, AASHTO.

**Note 9**—When specified by the agency and the top of the design layer is  $\geq 100$  mm from the pavement surface and the estimated design traffic level is  $\geq 0.3$  million ESALs, decrease the estimated design traffic level by one, unless the mixture will be exposed to significant mainline construction traffic prior to being overlaid. 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.

**Note 10**—When the estimated design traffic level is between 3 and <10 million ESALs, the Agency may, at its discretion, specify  $N_{initial}$  at 7,  $N_{design}$  at 75, and  $N_{max}$  at 115.

- 8.4. Determine the theoretical maximum specific gravity ( $G_{mm}$ ) according to T 209 of separate samples representing each of these combinations that have been mixed and conditioned to the same extent as the compacted specimens.

**Note 11**—The maximum specific gravity for each trial mixture shall be based on the average of at least two tests.

## 9. EVALUATING COMPACTED TRIAL MIXTURES

- 9.1. Determine the volumetric requirements for the trial mixtures in accordance with M 323.

- 9.2. Calculate  $V_a$  and VMA at  $N_{design}$  for each trial mixture using Equations 2 and 3:

$$V_a = 100 \left( 1 - \left( \frac{G_{mb}}{G_{mm}} \right) \right) \quad (2)$$

$$VMA = 100 - \frac{G_{mb} P_s}{G_{sb}} \quad (3)$$

where:

$G_{mb}$  = bulk specific gravity of the extruded specimen;

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- $G_{mm}$  = theoretical maximum specific gravity of the mixture;  
 $P_s$  = aggregate content, percent by mass of total mixture; and  
 $G_{sb}$  = bulk specific gravity of the combined aggregate.

**Note 12**—Although the initial trial binder content was estimated for a design air void content of 4.0 percent, the actual air void content of the compacted specimen is unlikely to be exactly 4.0 percent. Therefore, the change in binder content needed to obtain a 4.0 percent air void content, and the change in VMA caused by this change in binder content, is estimated. These calculations permit the evaluation of VMA and VFA of each trial aggregate gradation at the same design air void content, 4.0 percent.

9.3. Estimate the volumetric properties at 4.0 percent air voids for each compacted specimen.

9.3.1. Determine the difference in average air void content at  $N_{\text{design}}$  ( $\Delta V_a$ ) of each aggregate trial blend from the design level of 4.0 percent using Equation 4:

$$\Delta V_a = 4.0 - V_a \quad (4)$$

where:

$V_a$  = air void content of the aggregate trial blend at  $N_{\text{design}}$  gyrations.

9.3.2. Estimate the change in binder content ( $\Delta P_b$ ) needed to change the air void content to 4.0 percent using Equation 5:

$$\Delta P_b = -0.4(\Delta V_a) \quad (5)$$

9.3.3. Estimate the change in VMA ( $\Delta VMA$ ) caused by the change in the air void content ( $\Delta V_a$ ) determined in Section 9.3.1 for each trial aggregate blend gradation, using Equation 6 or 7.

$$\Delta VMA = 0.2(\Delta V_a) \quad \text{if } V_a > 4.0 \quad (6)$$

$$\Delta VMA = -0.1(\Delta V_a) \quad \text{if } V_a < 4.0 \quad (7)$$

**Note 13**—A change in binder content affects the VMA through a change in the bulk specific gravity of the compacted specimen ( $G_{mb}$ ).

9.3.4. Calculate the VMA for each aggregate trial blend at  $N_{\text{design}}$  gyrations and 4.0 percent air voids using Equation 8:

$$VMA_{\text{design}} = VMA_{\text{trial}} + \Delta VMA \quad (8)$$

where:

$VMA_{\text{design}}$  = VMA estimated at a design air void content of 4.0 percent; and

$VMA_{\text{trial}}$  = VMA determined at the initial trial binder content.

9.3.5. Using the values of  $\Delta V_a$  determined in Section 9.3.1 and Equation 9, estimate the relative density of each specimen at  $N_{\text{initial}}$  when the design air void content is adjusted to 4.0 percent at  $N_{\text{design}}$ :

$$\%G_{mm_{\text{initial}}} = 100 \left( \frac{G_{mb} h_d}{G_{mm} h_i} \right) - \Delta V_a \quad (9)$$

where:

$\%G_{mm_{\text{initial}}}$  = relative density at  $N_{\text{initial}}$  gyrations at the adjusted design binder content;

$h_d$  = height of the specimen after  $N_{\text{design}}$  gyrations, from the Superpave gyratory compactor, mm; and

$h_i$  = height of the specimen after  $N_{\text{initial}}$  gyrations, from the Superpave gyratory compactor, mm.

- 9.3.6. Calculate the effective specific gravity of the aggregate ( $G_{se}$ ), the estimated percent of effective binder ( $P_{be_{est}}$ ), and the estimated dust-to-binder ratio ( $P_{0.075}/P_{be}$ ) for each trial blend using Equations 10, 11, and 12:

$$G_{se} = \frac{100 - P_b}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}} \quad (10)$$

$$P_{be_{est}} = -\left(P_s \times G_b\right) \left( \frac{(G_{se} - G_{sb})}{(G_{se} \times G_{sb})} \right) + P_{be_{est}} \quad (11)$$

where:

- $P_{be_{est}}$  = estimated effective binder content;
- $P_s$  = aggregate content, percent by mass of total mixture;
- $G_b$  = specific gravity of the binder;
- $G_{se}$  = effective specific gravity of the combined aggregate;
- $G_{sb}$  = bulk specific gravity of the combined aggregate; and
- $P_{be_{est}}$  = estimated binder content at 4 percent air voids.

$$P_{0.075}/P_{be} = \frac{P_{0.075}}{P_{be_{est}}} \quad (12)$$

where:

- $P_{0.075}$  = percent passing the 0.075-mm sieve.

- 9.3.7. Compare the estimated volumetric properties from each trial aggregate blend gradation at the adjusted design binder content with the criteria specified in M 323. Choose the trial aggregate blend gradation that best satisfies the volumetric criteria.

**Note 14**—Table 2 presents an example of the selection of a design aggregate structure from three trial aggregate blend gradations.

**Note 15**—Many trial aggregate blend gradations will fail the VMA criterion. Generally, the  $\%G_{mm_{initial}}$  criterion will be met if the VMA criterion is satisfied. Section 12.1 gives a procedure for the adjustment of VMA.

**Note 16**—If the trial aggregate gradations have been chosen to cover the entire range of the gradation controls, then the only remaining solution is to make adjustments to the aggregate production or to introduce aggregates from a new source. The aggregates that fail to meet the required criteria will not produce a quality mix and should not be used. One or more of the aggregate stockpiles should be replaced with another material that produces a stronger structure. For example, a quarry stone can replace a crushed gravel, or crushed fines can replace natural fines.

**Table 2**—Selection of a Design Aggregate Structure (Example)

Volumetric Property	Trial Mixture (19.0-mm Nominal Maximum Aggregate) 20-Year Project Design ESALs = 5 million			Criteria
	1	2	3	
	At the Initial Trial Binder Content			
$P_b$ (trial)	4.4	4.4	4.4	
% $G_{mm,initial}$ (trial)	88.3	88.0	87.3	
% $G_{mm,design}$ (trial)	95.6	94.9	94.5	
$V_a$ at $N_{design}$	4.4	5.1	5.5	4.0
VMA <sub>trial</sub>	13.0	13.6	14.1	
Adjustments to Reach Design Binder Content ( $V_a = 4.0\%$ at $N_{design}$ )				
$\Delta V_a$	-0.4	-1.1	-1.5	
$\Delta P_b$	0.2	0.4	0.6	
$\Delta VMA$	-0.1	-0.2	-0.3	
At the Estimated Design Binder Content ( $V_a = 4.0\%$ at $N_{design}$ )				
Estimated $P_b$ (design)	4.6	4.8	5.0	
VMA (design)	12.9	13.4	13.8	$\geq 13.0$
% $G_{mm,initial}$ (design)	88.7	89.1	88.5	$\leq 89.0$

- Notes:
1. The top portion of this table presents measured densities and volumetric properties for specimens prepared for each aggregate trial blend at the initial trial binder content.
  2. None of the specimens had an air void content of exactly 4.0 percent. Therefore, the procedures described in Section 9 must be applied to (1) estimate the design binder content at which  $V_a = 4.0$  percent, and (2) obtain adjusted VMA and relative density values at this estimated binder content.
  3. The middle portion of this table presents the change in binder content ( $\Delta P_b$ ) and VMA ( $\Delta VMA$ ) that occurs when the air void content ( $V_a$ ) is adjusted to 4.0 percent for each trial aggregate blend gradation.
  4. A comparison of the VMA and densities at the estimated design binder content to the criteria in the last column shows that trial aggregate blend gradation No. 1 does not have sufficient VMA (12.9 percent versus a requirement of  $\geq 13.0$  percent). Trial blend No. 2 exceeds the criterion for relative density at  $N_{initial}$  gyrations (89.1 percent versus a requirement of  $\leq 89.0$  percent). Trial blend No. 3 meets the requirement for relative density and VMA and, in this example, is selected as the design aggregate structure.

## 10. SELECTING THE DESIGN BINDER CONTENT

- 10.1. Prepare replicate mixtures (Note 8) containing the selected design aggregate structure at each of the following four binder contents: (1) the estimated design binder content,  $P_b$  (design); (2) 0.5 percent below  $P_b$  (design); (3) 0.5 percent above  $P_b$  (design); and (4) 1.0 percent above  $P_b$  (design).
  - 10.1.1. Use the number of gyrations previously determined in Section 8.1.
- 10.2. Condition the mixtures according to R 30, and compact the specimens to  $N_{design}$  gyrations according to T 312. Record the specimen height to the nearest 0.1 mm after each revolution.
- 10.3. Determine the bulk specific gravity ( $G_{mb}$ ) of each of the compacted specimens in accordance with T 166 or T 275 as appropriate.
- 10.4. Determine the theoretical maximum specific gravity ( $G_{mm}$ ) according to T 209 of each of the four mixtures using companion samples that have been conditioned to the same extent as the compacted specimens (Note 11).
- 10.5. Determine the design binder content that produces a target air void content ( $V_a$ ) of 4.0 percent at  $N_{design}$  gyrations using the following steps:

- 10.5.1. Calculate  $V_a$ , VMA, and VFA at  $N_{\text{design}}$  using Equations 2, 3, and 13:

$$VFA = 100 \left( \frac{VMA - V_a}{VMA} \right) \quad (13)$$

- 10.5.2. Calculate the dust-to-binder ratio using Equation 14:

$$P_{0.075} / P_{be} = \frac{P_{0.075}}{P_{be}} \quad (14)$$

where:

$P_{be}$  = effective binder content.

- 10.5.3. For each of the four mixtures, determine the average corrected specimen relative densities at  $N_{\text{initial}}$  ( $\%G_{mm_{\text{initial}}}$ ), using Equation 15:

$$\%G_{mm_{\text{initial}}} = 100 \left( \frac{G_{mb} h_d}{G_{mm} h_i} \right) \quad (15)$$

- 10.5.4. Plot the average  $V_a$ , VMA, VFA, and relative density at  $N_{\text{design}}$  for replicate specimens versus binder content.

**Note 17**—All plots are generated automatically by the Superpave software. Figure 2 presents a sample data set and the associated plots.

- 10.5.5. By graphical or mathematical interpolation (Figure 2), determine the binder content to the nearest 0.1 percent at which the target  $V_a$  is equal to 4.0 percent. This is the design binder content ( $P_b$ ) at  $N_{\text{design}}$ .

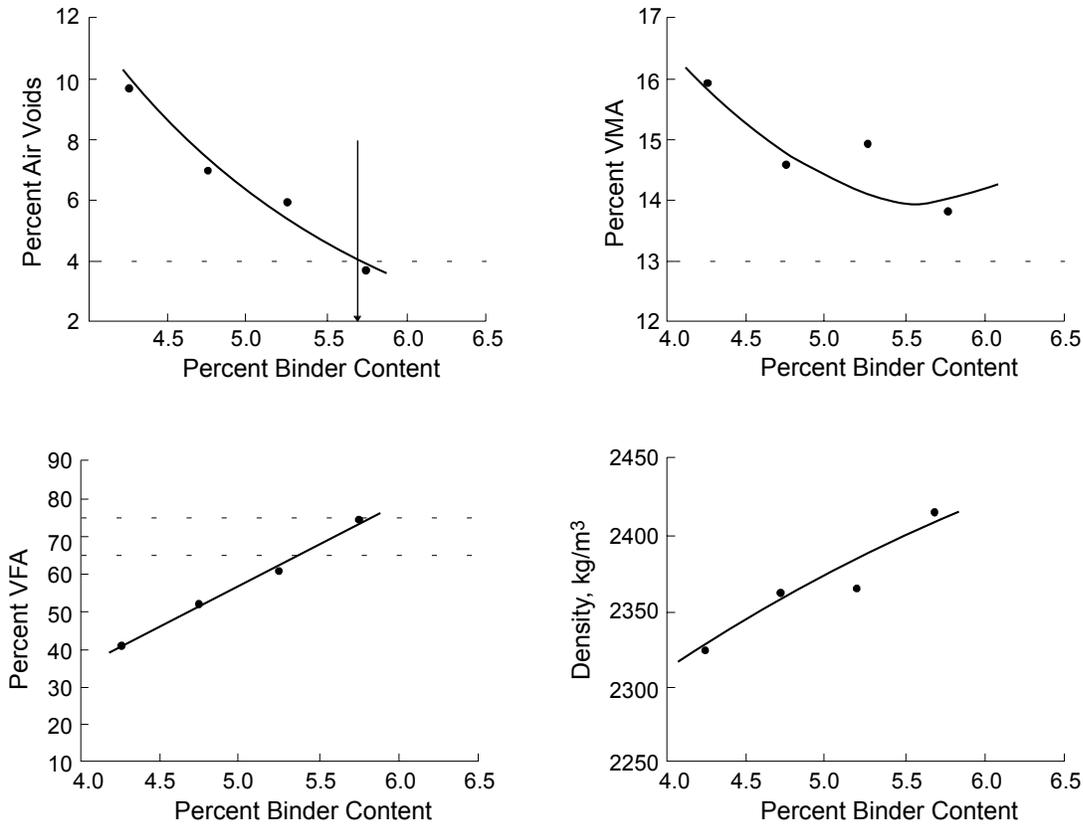
- 10.5.6. By interpolation (Figure 2), verify that the volumetric requirements specified in M 323 are met at the design binder content.

- 10.6. Compare the calculated percent of maximum relative density with the design criteria at  $N_{\text{initial}}$  by interpolation, if necessary. This interpolation can be accomplished by the following procedure.

- 10.6.1. Prepare a densification curve for each mixture by plotting the measured relative density at  $X$  gyrations,  $\%G_{mm_X}$ , versus the logarithm of the number of gyrations (see Figure 3).

- 10.6.2. Examine a plot of air void content versus binder content. Determine the difference in air voids between 4.0 percent and the air void content at the nearest, lower binder content. Determine the air void content at the nearest, lower binder content at its data point, not on the line of best fit. Designate the difference in air void content as  $\Delta V_a$ .

- 10.6.3. Using Equation 15, determine the average corrected specimen relative densities at  $N_{\text{initial}}$  ( $\%G_{mm_{\text{initial}}}$ ). Confirm that  $\%G_{mm_{\text{initial}}}$  satisfies the design requirements in M 323 at the design binder content.

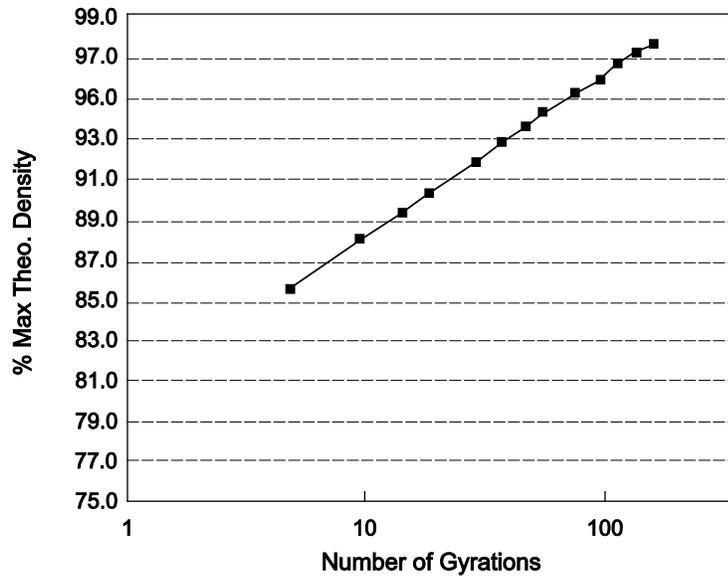


Average  $V_a$ , VMA, VFA, and Relative Density at  $N_{\text{design}}$

$P_b$ (%)	$V_a$ (%)	VMA (%)	VFA (%)	Density at $N_{\text{design}}$ (kg/m <sup>3</sup> )
4.3	9.5	15.9	40.3	2320
4.8	7.0	14.7	52.4	2366
5.3	6.0	14.9	59.5	2372
5.8	3.7	13.9	73.5	2412

- Notes:
1. In this example, the estimated design binder content is 4.8 percent; the minimum VMA requirement for the design aggregate structure (19.0-mm nominal maximum size) is 13.0 percent, and the VFA requirement is 65 to 75 percent.
  2. Entering the plot of percent air voids versus percent binder content at 4.0 percent air voids, the design binder content is determined as 5.7 percent.
  3. Entering the plots of percent VMA versus percent binder content and percent VFA versus percent binder content at 5.7 percent binder content, the mix meets the VMA and VFA requirements.

**Figure 2**—Sample Volumetric Design Data at  $N_{\text{design}}$



**Figure 3**—Sample Densification Curve

- 10.7. Prepare replicate (Note 8) specimens composed of the design aggregate structure at the design binder content to confirm that  $\%G_{mm_{max}}$  satisfies the design requirements in M 323.
- 10.7.1. Condition the mixtures according to R 30, and compact the specimens according to T 312 to the maximum number of gyrations,  $N_{max}$ , from Table 1.
- 10.7.2. Determine the average specimen relative density at  $N_{max}$ ,  $\%G_{mm_{max}}$ , by using Equation 16, and confirm that  $\%G_{mm_{max}}$  satisfies the volumetric requirement in M 323.

$$\%G_{mm_{max}} = 100 \left( \frac{G_{mb}}{G_{mm}} \right) \quad (16)$$

where:

$\%G_{mm_{max}}$  = relative density at  $N_{max}$  gyrations at the design binder content.

## 11. EVALUATING MOISTURE SUSCEPTIBILITY

- 11.1. Prepare six mixture specimens (nine are needed if freeze–thaw testing is required) composed of the design aggregate structure at the design binder content. Oven-condition the mixture according to the Mixture Conditioning for Volumetric Mixture Design procedure in R 30, Section 7.1, and compact the specimens to  $7.0 \pm 0.5$  percent air voids according to T 312.
- 11.2. Group, moisture-condition, test, and evaluate specimens according to T 283. The design shall meet the tensile strength ratio requirement of M 323.
- 11.3. If the tensile strength ratio is less than 0.80, as required in M 323, remedial action such as the use of antistripping agents is required to improve the moisture susceptibility of the mix. When remedial agents are used to modify the binder, retest the mix to assure compliance with the 0.80 minimum requirement.

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## 12. ADJUSTING THE MIXTURE TO MEET PROPERTIES

- 12.1. *Adjusting VMA*—If a change in the design aggregate skeleton is required to meet the specified VMA, there are three likely options: (1) change the gradation (Note 18); (2) reduce the minus 0.075-mm fraction (Note 19); or (3) change the surface texture and/or shape of one or more of the aggregate fractions (Note 20).
- Note 18**—Changing gradation may not be an option if the trial aggregate blend gradation analysis includes the full spectrum of the gradation control area.
- Note 19**—Reducing the percent passing the 0.075-mm sieve of the mix will typically increase the VMA. If the percent passing the 0.075-mm sieve is already low, this is not a viable option.
- Note 20**—This option will require further processing of existing materials or a change in aggregate sources.
- 12.2. *Adjusting VFA*—The lower limit of the VFA range should always be met at 4.0 percent air voids if the VMA meets the requirements. If the upper limit of the VFA is exceeded, then the VMA is substantially above the minimum required. If so, redesign the mixture to reduce the VMA. Actions to consider for redesign include: (1) changing to a gradation that is closer to the maximum density line; (2) increasing the minus 0.075-mm fraction, if room is available within the specification control points; or (3) changing the surface texture and shape of the aggregates by incorporating material with better packing characteristics, e.g., less thin, elongated aggregate particles.
- 12.3. *Adjusting the Tensile Strength Ratio*—The tensile strength ratio can be increased by (1) adding chemical antistripping agents to the binder to promote adhesion in the presence of water; or (2) adding hydrated lime to the mix.

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## 13. REPORT

- 13.1. The report shall include the identification of the project number, traffic level, and mix design number.
- 13.2. The report shall include information on the design aggregate structure including the source of aggregate, kind of aggregate, required quality characteristics, and gradation.
- 13.3. The report shall contain information about the design binder including the source of binder and the performance grade.
- 13.4. The report shall contain information about the HMA including the percent of binder in the mix; the relative density; the number of initial, design, and maximum gyrations; and the VMA, VFA,  $V_{be}$ ,  $V_{ba}$ ,  $V_a$ , and dust-to-binder ratio.

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## 14. KEYWORDS

- 14.1. Asphalt mix design; Superpave; volumetric mix design.

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## APPENDIXES

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(Nonmandatory Information)

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### X1. CALCULATING AN INITIAL TRIAL BINDER CONTENT FOR EACH AGGREGATE TRIAL BLEND

X1.1. Calculate the bulk and apparent specific gravities of the combined aggregate in each trial blend using the specific gravity data for the aggregate fractions obtained in Section 6.6 and Equations X1.1 and X1.2:

$$G_{sb} = \frac{P_1 + P_2 + \dots + P_n}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \dots + \frac{P_n}{G_n}} \quad (X1.1)$$

$$G_{sa} = \frac{P_1 + P_2 + \dots + P_n}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \dots + \frac{P_n}{G_n}} \quad (X1.2)$$

where:

$G_{sb}$  = bulk specific gravity for the combined aggregate;  
 $P_1, P_2, \dots, P_n$  = percentages by mass of aggregates 1, 2, . . .  $n$ ;  
 $G_1, G_2, \dots, G_n$  = bulk specific gravities (Equation X1.1) or apparent specific gravities (Equation X1.2) of aggregates 1, 2,  $n$ ; and  
 $G_{sa}$  = apparent specific gravity for the combined aggregate.

X1.2. Estimate the effective specific gravity of the combined aggregate in the aggregate trial blend using Equation X1.3:

$$G_{se} = G_{sb} + 0.8(G_{sa} - G_{sb}) \quad (X1.3)$$

where:

$G_{se}$  = effective specific gravity of the combined aggregate;  
 $G_{sb}$  = bulk specific gravity of the combined aggregate; and  
 $G_{sa}$  = apparent specific gravity of the combined aggregate.

**Note X1**—The multiplier, 0.8, can be changed at the discretion of the designer. Absorptive aggregates may require values closer to 0.6 or 0.5.

**Note X2**—The Superpave mix design system includes a mixture-conditioning step before the compaction of all specimens; this conditioning generally permits binder absorption to proceed to completion. Therefore, the effective specific gravity of Superpave mixtures will tend to be close to the apparent specific gravity in contrast to other design methods where the effective specific gravity generally will lie near the midpoint between the bulk and apparent specific gravities.

X1.3. Estimate the volume of binder absorbed into the aggregate,  $V_{ba}$ , using Equations X1.4 and X1.5:

$$V_{ba} = W_s \left( \frac{1}{G_{sb}} - \frac{1}{G_{se}} \right) \quad (X1.4)$$

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where:

$W_s$ , the mass of aggregate in 1 cm<sup>3</sup> of mix, g, is calculated as:

$$W_s = \frac{P_s (1 - V_a)}{\frac{P_b}{G_b} + \frac{P_s}{G_{se}}} \quad (X1.5)$$

and where:

$P_s$  = mass percent of aggregate, in decimal equivalent, assumed to be 0.95;

$V_a$  = volume of air voids, assumed to be 0.04 cm<sup>3</sup> in 1 cm<sup>3</sup> of mix;

$P_b$  = mass percent of binder, in decimal equivalent, assumed to be 0.05; and

$G_b$  = specific gravity of the binder.

**Note X3**—This estimate calculates the volume of binder absorbed into the aggregate,  $V_{ba}$ , and subsequently the initial, trial binder content at a target air void content of 4.0 percent.

X1.4. Estimate the volume of effective binder using Equation X1.6:

$$V_{be} = 0.176 - [0.0675 \log(S_n)] \quad (X1.6)$$

where:

$V_{be}$  = volume of effective binder, cm<sup>3</sup>; and

$S_n$  = nominal maximum sieve size of the largest aggregate in the aggregate trial blend, mm.

**Note X4**—This regression equation is derived from an empirical relationship between (1) VMA and  $V_{be}$  when the air void content,  $V_a$ , is equal to 4.0 percent:  $V_{be} = \text{VMA} - V_a = \text{VMA} - 4.0$  and (2) the relationship between VMA and the nominal maximum sieve size of the aggregate in M 323.

X1.5. Calculate the estimated initial trial binder ( $P_{bi}$ ) content for the aggregate trial blend gradation using Equation X1.7:

$$P_{bi} = 100 \left( \frac{G_b (V_{be} + V_{ba})}{(G_b (V_{be} + V_{ba})) + W_s} \right) \quad (X1.7)$$

where:

$P_{bi}$  = estimated initial trial binder content, percent by weight of total mix.

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## X2. SPECIAL MIXTURE DESIGN CONSIDERATIONS AND PRACTICES FOR WARM MIX ASPHALT (WMA)

X2.1. **Purpose:**

X2.1.1. This appendix presents special mixture design considerations and methods for designing warm mix asphalt (WMA) using R 35. WMA refers to asphalt mixtures that are produced at temperatures approximately 50°F (28°C) or more lower than typically used in the production of HMA (hot mix asphalt). The goal of WMA is to produce mixtures with equivalent strength,

durability, and performance characteristics as HMA using substantially reduced production temperatures.

These special mixture design considerations and practices are applicable anytime a WMA technology is being used. The WMA technologies may be used as coating and compaction aids without lowering the production temperature by 50°F (28°C).

X2.1.2. The practices in this appendix are applicable to a wide range of WMA technologies including:

- WMA additives that are added to the asphalt binder,
- WMA additives that are added to the mixture during production,
- Wet aggregate mixtures, and
- Plant foaming processes.

X2.1.3. The information in this appendix supplements the procedures in R 35. This appendix assumes the user is proficient with the standard procedures in R 35.

X2.2. **Summary:**

X2.2.1. This appendix includes separate sections addressing the following aspects of WMA mixture design:

- Additional Laboratory Equipment;
- WMA Technology Selection;
- Binder Grade Selection;
- RAP in WMA;
- Technology-Specific Specimen Fabrication Procedures;
- WMA Mixture Evaluations:
  - Coating,
  - Compactability,
  - Evaluating of Moisture Sensitivity,
  - Evaluation of Rutting Resistance; and
- Adjusting the Mixture to Meet Specification Requirements.

X2.2.2. In each section, reference is made to the applicable section of R 35.

X2.3. **Additional Laboratory Equipment:**

X2.3.1. **All WMA Processes:**

X2.3.1.1. *Mechanical Mixer*—A planetary mixer with a wire whip having a capacity of 20-qt or a 5-gal bucket mixer.

**Note X5**—The mixing times in this appendix were developed using a planetary mixer with a wire whip, Blakeslee Model B-20 or equivalent. Appropriate mixing times for bucket mixers should be established by evaluating the coating of asphalt mixtures prepared at the viscosity-based mixing temperatures specified in T 312.

X2.3.2. **Binder Additive WMA Processes:**

X2.3.2.1. *Low-Shear Mechanical Stirrer*—A low-shear mechanical stirrer with appropriate impeller to homogeneously blend the additive in the binder.

**X2.3.3. Plant Foaming Processes:**

X2.3.3.1. *Laboratory Foamed Asphalt Plant*—A laboratory-scale foamed asphalt plant capable of producing consistent foamed asphalt at the water content used in field production. The device should be capable of producing foamed asphalt for laboratory batches ranging from approximately 10 to 20 kg.

**X2.4. WMA Technology Selection:**

X2.4.1. There are more than 20 WMA technologies being marketed in the United States. Select the WMA technology that will be used in consultation with the specifying agency and technical representatives from the WMA technology providers. Consideration should be given to a number of factors including (1) available performance data, (2) the cost of the WMA additives, (3) planned production and compaction temperatures, (4) planned production rates, (5) plant capabilities, and (6) modifications required to successfully use the WMA technology with available field and laboratory equipment.

X2.4.2. Determine the planned production and field compaction temperatures.

**X2.5. Binder Grade Selection:**

X2.5.1. Use the same grade of binder normally used with HMA. Select the performance grade of the binder in accordance with M 323, considering the environment and traffic at the project site.

**Note X6**—For WMA technologies having production temperatures that are 100°F (56°C) or more lower than HMA production temperatures, it may be necessary to increase the high-temperature performance grade of the binder one grade level to meet the rutting resistance requirements included in this appendix.

**X2.6. RAP in WMA:**

X2.6.1. For WMA mixtures incorporating RAP, the planned field compaction temperature shall be greater than the as-recovered high-temperature grade of the RAP binder.

**Note X7**—This requirement is included to ensure mixing of the new and reclaimed binders. Laboratory studies showed that new and reclaimed binders do mix at WMA process temperatures provided this requirement is satisfied and the mixture remains at or above the planned compaction temperature for at least 2 h. Plant mixing should be verified through an evaluation of volumetric or stiffness properties of plant-produced mixtures.

X2.6.2. Select RAP materials in accordance with M 323.

X2.6.3. For blending chart analyses, the intermediate and low-temperature properties of the virgin binder may be improved using Table X2.1.

**Note X8**—The intermediate and low-temperature grade improvements given in Table X2.1 will allow additional RAP to be used in WMA mixtures when blending chart analyses are used. An approximate 0.6°C improvement in the low-temperature properties will allow approximately 10 percent additional RAP binder to be added to the mixture based on blended binder grade requirements.

**Table X2.1**—Recommended Improvement in Virgin Binder Low-Temperature Continuous Grade for RAP Blending Chart Analysis for WMA Production Temperatures

Virgin binder PG grade	58-28	58-22	64-22	64-16	67-22
Average HMA production temperature, °F	285	285	292	292	300
Rate of improvement of virgin binder low-temperature grade per 1°C reduction in plant temperature	0.035	0.025	0.025	0.012	0.025
Recommended Improvement in Virgin Binder Low-Temperature Continuous Grade for RAP Blending Chart Analysis, °C					
WMA Production Temperature, °F					
300	NA	NA	NA	NA	0.0
295	NA	NA	NA	NA	0.1
290	NA	NA	0.0	0.0	0.1
285	0.0	0.0	0.1	0.0	0.2
280	0.1	0.1	0.2	0.1	0.3
275	0.2	0.1	0.2	0.1	0.3
270	0.3	0.2	0.3	0.1	0.4
265	0.4	0.3	0.4	0.2	0.5
260	0.5	0.3	0.4	0.2	0.6
255	0.6	0.4	0.5	0.2	0.6
250	0.7	0.5	0.6	0.3	0.7
245	0.8	0.6	0.7	0.3	0.8
240	0.9	0.6	0.7	0.3	0.8
235	1.0	0.7	0.8	0.4	0.9
230	1.1	0.8	0.9	0.4	1.0
225	1.2	0.8	0.9	0.4	1.0
220	1.3	0.9	1.0	0.5	1.1
215	1.4	1.0	1.1	0.5	1.2
210	1.5	1.0	1.1	0.5	1.3

**X2.6.4. Blending Chart Example:**

**X2.6.4.1. Problem Statement**—A producer will be producing WMA using a virgin PG 64-22 binder at a temperature of 250°F. In the mixture, 35 percent of the total binder will be replaced with RAP binder, so according to M 323 a blending chart analysis is needed. The continuous grade of the recovered RAP binder is PG 93.0 (29.4) – 18.1. The continuous grade of the virgin PG 64-22 binder is PG 66.2 (21.1) – 23.9. The specified grade for the blended binder in the mixture is PG 64-22. Use the M 323 blending chart analysis to determine if the proposed RAP and virgin binder provide an acceptable blended binder.

**X2.6.4.2. Solution as WMA**—Because the mixture will be produced as WMA at 250°F, determine the virgin binder grade improvement for the blending chart analysis by entering Table X2.1 in the PG 64-22 column and reading the intermediate- and low-temperature improvement from the row for 250°F. The intermediate- and low-temperature grade improvement is 0.6°C. For WMA at 250°F, perform the M 323 blending chart analysis using PG 66.2 (20.5) – 24.5 for the virgin binder and PG 93.0 (29.4) – 18.1 for the RAP Binder. Because a PG 64-XX virgin binder is being used and a PG 64-XX is specified, it is not necessary to check the high-temperature grade. Use Equation X1.12 from M 323 to determine the maximum allowable RAP content based on the intermediate and low temperatures. For PG 64-22, 25°C is the maximum allowable blended binder intermediate-temperature grade and –22°C the maximum allowable blended binder low-temperature grade.

$$\% \text{RAP} = \frac{(T_{\text{blend}} - T_{\text{virgin}})}{(T_{\text{RAP}} - T_{\text{virgin}})} \times 100 \quad (\text{Eq. X1.12 from M 323})$$

where:

- $T_{\text{blend}}$  = continuous grade temperature of the blended binder (high, intermediate, low);  
 $T_{\text{virgin}}$  = continuous grade temperature of the virgin binder (high, intermediate, low); and  
 $T_{\text{RAP}}$  = continuous grade temperature of the RAP binder (high, intermediate, low).

Maximum RAP Binder Based on Intermediate-Temperature Grade:

$$\% \text{RAP} = \frac{(25 - 20.5)}{(29.4 - 20.5)} \times 100 = \frac{4.5}{8.9} \times 100 = 50.5\%$$

Maximum RAP Binder Based on Low-Temperature Grade:

$$\% \text{RAP} = \frac{(-22 - (-24.5))}{(-18.1 - (-24.5))} \times 100 = \frac{2.5}{6.4} \times 100 = 39.0\%$$

The critical property is the low-temperature grade, which allows 39.0 percent of the binder to be RAP binder. The proposed mixture contains only 35 percent RAP binder; therefore, it is acceptable.

- X2.6.4.3. *Solution as HMA*—If the mixture were produced as HMA, the blending chart analysis would be completed using PG 66.2 (21.1)–23.9 for the virgin binder and PG 93.0 (29.4)–18.1 for the RAP binder.

Maximum RAP Binder Based on Intermediate-Temperature Grade:

$$\% \text{RAP} = \frac{(25 - 21.1)}{(29.4 - 21.1)} \times 100 = \frac{3.9}{8.3} \times 100 = 47.0\%$$

Maximum RAP Binder Based on Low-Temperature Grade:

$$\% \text{RAP} = \frac{(-22 - (-23.9))}{(-18.1 - (-23.9))} \times 100 = \frac{1.9}{5.8} \times 100 = 32.7\%$$

Again the critical property is the low-temperature grade, but this time the proposed RAP binder content of 35 percent exceeds the maximum allowable of 32.7 percent; therefore, the HMA mixture is not acceptable.

## X2.7. Technology-Specific Specimen Fabrication Procedures:

### X2.7.1. Batching:

- X2.7.1.1. Determine the number and size of specimens that are required. Table X2.2 summarizes approximate specimen sizes for WMA mixture design.

**Note X9**—The mass of mixture required for the various specimens depends on the specific gravity of the aggregate and the air void content of the specimen. Trial specimens may be required to determine appropriate batch weights for T 283 and flow number testing.

**Table X2.2**—Specimen Requirements

Specimen Type	Gyratory Specimen Size	Approximate Specimen Mass	Number Required
Maximum specific gravity	NA	500 to 6000 g depending on maximum aggregate size	2 per trial blend, plus 8 to determine design binder content, plus 1 at the design binder content for compactability evaluation
Volumetric design	150-mm diameter by 115 mm high	4700 g	2 per trial blend, plus 8 to determine design binder content
Coating	NA	500 to 6,000 g depending on maximum aggregate size	1 at the design binder content
Compactability	150-mm diameter by 115 mm high	4700 g	4 at the design binder content
T 283	150-mm diameter by 95 mm high	3800 g	6 at the design binder content
Flow number	150-mm diameter by 175 mm high	7000 g	4 at the design binder content

- X2.7.1.2. Prepare a batch sheet showing the batch weight of each aggregate fraction, RAP, and the asphalt binder.
- X2.7.1.3. Weigh into a pan the weight of each aggregate fraction.  
**Note X10**—For WMA processes that use wet aggregate, weigh the portion of the aggregate that will be heated into one pan and weigh the portion of the aggregate that will be wetted into a second pan.
- X2.7.1.4. Weigh into a separate pan, the weight of RAP.
- X2.7.2. **Heating:**
- X2.7.2.1. Place the aggregate in an oven set at approximately 15°C higher than the planned production temperature.  
**Note X11**—The aggregate will require 2 to 4 h to reach the temperature of the oven. Aggregates may be placed in the oven overnight.
- X2.7.2.2. Heat the RAP in the oven with the aggregates, but limit the heating time for the RAP to 2 h.
- X2.7.2.3. Heat the binder to the planned production temperature.
- X2.7.2.4. Heat mixing bowls and other tools to the planned production temperature.
- X2.7.2.5. Preheat a forced draft oven and pans to the planned field compaction temperature for use in short-term conditioning the mixture.
- X2.7.3. **Preparation of WMA Mixtures with WMA Additive Added to the Binder:**  
**Note X12**—If specific mixing and storage instructions are provided by the WMA additive supplier, follow the supplier’s instructions.
- X2.7.3.1. *Adding WMA Additive to Binder:*
- X2.7.3.1.1. Weigh the required amount of the additive into a small container.  
**Note X13**—The additive is typically specified as a percent by weight of binder. For mixtures containing RAP, determine the weight of additive based on the total binder content of the mixture.

- X2.7.3.1.2. Heat the asphalt binder in a covered container in an oven set at 135°C until the binder is sufficiently fluid to pour. During heating occasionally stir the binder manually to ensure homogeneity.
- X2.7.3.1.3. Add the required amount of additive to the binder, and stir it with a mechanical stirrer until the additive is totally dispersed in the binder.
- X2.7.3.1.4. Store the binder with WMA additive at room temperature in a covered container until needed for use in the mixture design.

X2.7.3.2. *Preparing WMA Specimens:*

- X2.7.3.2.1. Heat the mixing tools, aggregate, RAP, and binder in accordance with Section X2.7.2.
- X2.7.3.2.2. If a liquid antistripping additive is required, add it to the binder per the manufacturer's instructions.
- X2.7.3.2.3. Place the hot mixing bowl on a scale, and tare the scale.
- X2.7.3.2.4. Charge the mixing bowl with the heated aggregates and RAP, and dry-mix thoroughly.
- X2.7.3.2.5. Form a crater in the blended aggregate, and weigh the required amount of asphalt binder into the mixture to achieve the desired batch weight.

**Note X14**—If the aggregates and RAP have been stored for an extended period of time in a humid environment, then it may be necessary to adjust the weight of binder based on the oven-dry weight of the aggregates and RAP as follows:

Record the oven-dry weight of the aggregates and RAP,  $w_i$ .

Determine the target total weight of the mixture as follows:

$$w_t = \frac{w_i}{\left(1 - \frac{P_{b_{\text{new}}}}{100}\right)} \quad (X2.1)$$

where:

$w_t$  = target total weight, g;

$w_i$  = oven-dry weight from Step 1, g; and

$P_{b_{\text{new}}}$  = percent by weight of total mix of new binder in the mixture.

Add new binder to the bowl to reach  $w_t$ .

- X2.7.3.2.6. Remove the mixing bowl from the scale, and mix the material with a mechanical mixer for 90 s.
- X2.7.3.2.7. Oven-condition the mixture by placing it in a flat, shallow pan at an even thickness of 25 to 50 mm, and place the pan in the forced-draft oven for 2 h ± 5 min at the planned field compaction temperature ± 3°C. Stir the mixture once after 1 h ± 5 min to maintain uniform conditioning.

X2.7.4. **Preparation of WMA Mixtures with WMA Additive Added to the Mixture:**

**Note X15**—If specific mixing and storage instructions are provided by the WMA additive supplier, follow the supplier's instructions.

- X2.7.4.1. Weigh the required amount of the additive into a small container.

**Note X16**—The quantity of additive may be specified as a percent by weight of binder or a percent by weight of total mixture.

- X2.7.4.2. If a liquid antistripping additive is required, add it to the binder per the manufacturer's instructions.
- X2.7.4.3. Heat the mixing tools, aggregate, RAP, and binder in accordance with Section X2.7.2.
- X2.7.4.4. Place the hot mixing bowl on a scale, and tare the scale.
- X2.7.4.5. Charge the mixing bowl with the heated aggregates and RAP, and dry-mix thoroughly.
- X2.7.4.6. Form a crater in the blended aggregate, and weigh the required amount of asphalt binder into the mixture to achieve the desired batch weight.
- Note X17**—If the aggregates and RAP have been stored for an extended period of time in a humid environment, then it may be necessary to adjust the weight of binder based on the oven-dry weight of the aggregates and RAP as follows:  
Record the oven-dry weight of the aggregates, and RAP,  $w_i$ .  
Determine the target total weight of the mixture as follows:

$$w_t = \frac{w_i}{\left(1 - \frac{P_{b_{\text{new}}}}{100}\right)} \quad (X2.2)$$

where:

$w_t$  = target total weight, g;

$w_i$  = oven-dry weight from Step 1, g; and

$P_{b_{\text{new}}}$  = percent by weight of total mix of new binder in the mixture.

Add new binder to the bowl to reach  $w_t$ .

- X2.7.4.7. Pour the WMA additive into the pool of new asphalt binder.
- X2.7.4.8. Remove the mixing bowl from the scale, and mix material with a mechanical mixer for 90 s.
- X2.7.4.9. Oven-condition the mixture by placing it in a flat, shallow pan at an even thickness of 25 to 50 mm, and place the pan in the forced-draft oven for 2 h  $\pm$  5 min at the planned field compaction temperature  $\pm$  3°C. Stir the mixture once after 1 h  $\pm$  5 min to maintain uniform conditioning.
- X2.7.5. **Preparation of WMA Mixtures with a Wet Fraction of Aggregate:**  
**Note X18**—Consult the WMA process supplier for appropriate additive dosage rates, mixing temperatures, percentage of wet aggregate, and wet aggregate moisture content.
- X2.7.5.1. *Adding WMA Additive to Binder:*
- X2.7.5.1.1. Weigh the required amount of the additive into a small container.  
**Note X19**—The additive is typically specified as a percent by weight of binder. For mixtures containing RAP, determine the weight of additive based on the total binder content of the mixture.
- X2.7.5.1.2. Heat the asphalt binder in a covered container in an oven set at 135°C until the binder is sufficiently fluid to pour. During heating occasionally stir the binder manually to ensure homogeneity.
- X2.7.5.1.3. Add the required amount of additive to the binder, and stir it with a mechanical stirrer until the additive is totally dispersed in the binder.

X2.7.5.2. *Preparing WMA Specimens:*

X2.7.5.2.1. Add the required amount of moisture to the wet fraction of the aggregate. Mix it thoroughly, then cover and let stand for at least 2 h before mixing it with the heated fraction.

X2.7.5.2.2. Heat the mixing tools, dry aggregate portion, and dry RAP portion to the initial mixing temperature in accordance with Section X2.7.2.

X2.7.5.2.3. Place the hot mixing bowl on a scale, and tare the scale.

X2.7.5.2.4. Charge the mixing bowl with the heated aggregates and RAP, and dry-mix thoroughly.

X2.7.5.2.5. Form a crater in the blended aggregate, and weigh the required amount of asphalt binder into the mixture to achieve the desired batch weight.

**Note X20**—If the aggregates and RAP have been stored for an extended period of time in a humid environment, it may be necessary to adjust the weight of binder based on the oven-dry weight of the aggregates and RAP as follows:

Record the oven-dry weight of the aggregates and RAP,  $w_i$ .

Determine the target total weight of the mixture as follows:

$$w_t = \frac{(w_i + w_{dwf})}{\left(1 - \frac{P_{b_{new}}}{100}\right)} \quad (X2.3)$$

where:

$w_t$  = target total weight, g;

$w_i$  = oven-dry weight from Step 1, g;

$w_{dwf}$  = oven-dry weight of the wet fraction from the batch sheet, g; and

$P_{b_{new}}$  = percent by weight of total mix of new binder in the mixture.

Determine the target weight of the heated mixture:

$$w_{thm} = w_t - w_{dwf} \quad (X2.4)$$

where:

$w_{thm}$  = target weight of the heated mixture, g;

$w_t$  = target total weight, g; and

$w_{dwf}$  = oven-dry weight of the wet fraction from the batch sheet.

Add new binder to the bowl to reach  $w_{thm}$ .

X2.7.5.2.6. Add the additive to the binder immediately before mixing it with the heated fraction of the aggregate according to Section X2.7.5.1.

X2.7.5.2.7. Remove the mixing bowl from the scale, and mix the material with a mechanical mixer for 30 s.

X2.7.5.2.8. Stop the mixer, and immediately add the wet fraction aggregate.

X2.7.5.2.9. Restart the mixer, and continue to mix for 60 s.

X2.7.5.2.10. Place the mixture in a flat, shallow pan at an even thickness of 25 to 50 mm.

X2.7.5.2.11. Check the temperature of the mixture in the pan to ensure it is between 90 and 100°C.

X2.7.5.2.12. Oven-condition the mixture by placing the pan in the forced-draft oven for  $2 \text{ h} \pm 5 \text{ min}$  at the planned field compaction temperature  $\pm 3^\circ\text{C}$ . Stir the mixture once after  $1 \text{ h} \pm 5 \text{ min}$  to maintain uniform conditioning.

**X2.7.6. Preparation of Foamed Asphalt Mixtures:**

X2.7.6.1. The preparation of foamed asphalt mixtures requires special asphalt binder foaming equipment that can produce foamed asphalt using the amount of moisture that will be used in field production.

X2.7.6.2. Prepare the asphalt binder foaming equipment, and load it with binder per the manufacturer's instructions.

X2.7.6.3. If a liquid antistripping additive is required, add it to the binder in the foaming equipment according to the manufacturer's instructions.

X2.7.6.4. Heat the mixing tools, aggregate, and RAP in accordance with Section X2.7.2.

X2.7.6.5. Prepare the foamed asphalt binder according to the instructions for the foaming equipment.

X2.7.6.6. Place the hot mixing bowl on a scale, and tare the scale.

X2.7.6.7. Charge the mixing bowl with the heated aggregates and RAP, and dry-mix thoroughly.

X2.7.6.8. Form a crater in the blended aggregate, and add the required amount of foamed asphalt into the mixture to achieve the desired batch weight.

**Note X21**—The laboratory foaming equipment uses a timer to control the amount of foamed asphalt produced. Ensure the batch size is large enough that the required amount of foamed asphalt is within the calibrated range of the foaming device. This operation may require producing one batch for the two gyratory specimens and the two maximum specific gravity specimens at each asphalt content, then splitting the larger batch into individual samples.

**Note X22**—If the aggregates and RAP have been stored for an extended period of time in a humid environment, then it may be necessary to adjust the weight of binder based on the oven-dry weight of the aggregates and RAP as follows:

Record the oven-dry weight of the aggregates and RAP,  $w_i$ .

Determine the target total weight of the mixture as follows:

$$w_t = \frac{w_i}{\left(1 - \frac{P_{b_{\text{new}}}}{100}\right)} \quad (\text{X2.5})$$

where:

$w_t$  = target total weight, g;

$w_i$  = oven-dry weight from Step 1, g; and

$P_{b_{\text{new}}}$  = percent by weight of total mix of new binder in the mixture.

Add foamed binder to the bowl to reach  $w_t$ .

X2.7.6.9. Remove the mixing bowl from the scale, and mix the materials with a mechanical mixer for 90 s.

X2.7.6.10. Oven-condition the mixture by placing it in a flat, shallow pan at an even thickness of 25 to 50 mm, and place the pan in the forced-draft oven for  $2 \text{ h} \pm 5 \text{ min}$  at the planned field compaction temperature  $\pm 3^\circ\text{C}$ . Stir the mixture once after  $1 \text{ h} \pm 5 \text{ min}$  to maintain uniform conditioning.

X2.8. **WMA Mixture Evaluations:**

X2.8.1. At the optimum binder content determined in accordance with R 35, prepare WMA mixtures in accordance with the appropriate procedure from Section X2.7 for the following evaluations:

- Coating
- Compactability
- Moisture sensitivity
- Rutting resistance

X2.8.2. **Coating:**

X2.8.2.1. Prepare a sufficient amount of mixture at the design binder content to perform the coating evaluation procedure in T 195 using the appropriate WMA fabrication procedure from Section X2.7. Do not oven-condition the mixture.

X2.8.2.2. Evaluate the coating in accordance with T 195.

X2.8.2.3. The recommended coating criterion is at least 95 percent of the coarse aggregate particles being fully coated.

X2.8.3. **Compactability:**

X2.8.3.1. Prepare a sufficient amount of mixture at the design binder content for four gyratory specimens and one maximum specific gravity measurement using the appropriate WMA fabrication procedure from Section X2.7 including oven-conditioning for  $2 \text{ h} \pm 5 \text{ min}$  at the planned field compaction temperature.

X2.8.3.2. Determine the theoretical maximum specific gravity ( $G_{mm}$ ) according to T 209.

X2.8.3.3. Compact duplicate specimens at the planned field compaction temperature to  $N_{\text{design}}$  gyrations according to T 312. Record the specimen height for each gyration.

X2.8.3.4. Determine the bulk specific gravity ( $G_{mb}$ ) of each specimen according to T 166.

X2.8.3.5. Allow the mixture to cool to  $30^\circ\text{C}$  below the planned field compaction temperature. Compact duplicate specimens to  $N_{\text{design}}$  gyrations according to T 312. Record the specimen height for each gyration.

X2.8.3.6. Determine the bulk specific gravity ( $G_{mb}$ ) of each specimen according to T 166.

X2.8.3.7. For each specimen, determine the corrected specimen relative densities for each gyration using Equation X2.6:

$$\%G_{mm_N} = 100 \left( \frac{G_{mb} h_d}{G_{mm} h_N} \right) \quad (X2.6)$$

where:

$\%G_{mm_N}$  = relative density at  $N$  gyrations;

$G_{mb}$  = bulk specific gravity of the specimen compacted to  $N_{\text{design}}$  gyrations;

$h_d$  = height of the specimen after  $N_{\text{design}}$  gyrations, from the Superpave gyratory compactor, mm; and

$h_N$  = height of the specimen after  $N$  gyrations, from the Superpave gyratory compactor, mm.

- X2.8.3.8. For each specimen, determine the number of gyrations needed to reach 92 percent relative density.
- X2.8.3.9. Determine the average number of gyrations needed to reach 92 percent relative density at the planned field compaction temperature.
- X2.8.3.10. Determine the average number of gyrations needed to reach 92 percent relative density at 30°C below the planned field compaction temperature.

- X2.8.3.11. Determine the gyration ratio using Equation X2.7:

$$\text{ratio} = \frac{(N_{92})_{T-30}}{(N_{92})_T} \quad (X2.7)$$

where:

ratio = gyration ratio;

$(N_{92})_{T-30}$  = gyrations needed to reach 92 percent relative density at 30°C below the planned field compaction temperature; and

$(N_{92})_T$  = gyrations needed to reach 92 percent relative density at the planned field compaction temperature.

- X2.8.3.12. The recommended compactability criterion is a gyration ratio less than or equal to 1.25.

**Note X23**—The compactability criterion limits the temperature sensitivity of WMA to that for a typical HMA mixture. The criterion is based on limited research conducted in NCHRP 9-43. The criterion should be considered tentative and subject to change as additional data on WMA mixtures are collected.

#### X2.8.4. **Evaluating Moisture Sensitivity:**

- X2.8.4.1. Prepare a sufficient amount of mixture at the design binder content for six gyratory specimens using the appropriate WMA fabrication procedure from Section X2.7, including oven-conditioning for 2 h ± 5 min at the planned field compaction temperature.

- X2.8.4.2. Compact test specimens to 7.0 ± 0.5 percent air voids according to T 312.

- X2.8.4.3. Group, moisture-condition, test, and evaluate the specimens according to T 283.

- X2.8.4.4. The recommended moisture sensitivity criteria are a tensile strength ratio greater than 0.80 and no visual evidence of stripping.

#### X2.8.5. **Evaluating Rutting Resistance:**

- X2.8.5.1. Evaluate rutting using the flow number test in TP 79.

**Note X24**—WMA additives and processes may affect the rutting resistance of the mixture and rutting resistance should be evaluated. Agencies with established criteria for other test methods, such as T 320 (SST), T 324 (Hamburg), and T 340 (APA), may specify those methods in lieu of TP 79.

- X2.8.5.2. Prepare a sufficient amount of mixture at the design binder content for four flow number test specimens using the appropriate WMA fabrication procedure from Section X2.7 including oven-conditioning for 2 h ± 5 min at the planned field compaction temperature.

- X2.8.5.3. The test is conducted on 100-mm diameter by 150-mm-high test specimens that are sawed and cored from larger gyratory specimens that are 150-mm diameter by at least 160 mm high. Refer to PP 60 for detailed test specimen fabrication procedures. Do not oven-condition the mixture according to PP 60, Section 9.2.3. Oven-condition WMA mixtures according to Section X2.7.

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- X2.8.5.4. Prepare the flow number test specimens to  $7.0 \pm 1.0$  percent air voids.
- X2.8.5.5. Perform the flow number test at the design temperature at 50 percent reliability as determined using LTPP Bind Version 3.1. The temperature is computed at 20 mm for surface courses, and the top of the pavement layer for intermediate and base courses.
- X2.8.5.6. Perform the flow number test unconfined using a repeated deviatoric stress of 600 kPa with a contact deviatoric stress of 30 kPa.
- X2.8.5.7. Determine the flow number for each specimen; then average the results. Compare the average flow number with the criteria given in Table X2.3.

**Table X2.3**—Minimum Flow Number Requirements

Traffic Level, Million ESALs	Minimum Flow Number
<3	NA
3 to <10	30
10 to <30	105
$\geq 30$	415

X2.9. **Adjusting the Mixture to Meet Specification Properties:**

- X2.9.1. This section provides guidance for adjusting the mixture to meet the evaluation criteria contained in Section X2.8. For WMA mixtures, this section augments Section 12 in R 35.
- X2.9.2. *Improving Coating*—Most WMA processes involve complex chemical reactions, thermodynamic processes, or both. Consult the WMA additive supplier for methods to improve coating.
- X2.9.3. *Improving Compactability*—Most WMA processes involve complex chemical reactions, thermodynamic processes, or both. Consult the WMA additive supplier for methods to improve compactability.
- X2.9.4. *Improving the Tensile Strength Ratio*—Some WMA processes include adhesion promoters to improve resistance to moisture damage. Consult the WMA additive supplier for methods to improve the tensile strength ratio.
- X2.9.5. *Improving Rutting Resistance*—The rutting resistance of WMA can be improved through changes in binder grade and volumetric properties. The following rules of thumb can be used to identify mixture adjustments that improve rutting resistance.
- Increasing the high-temperature performance grade by one grade level improves rutting resistance by a factor of 2.
  - Adding 25 to 30 percent RAP will increase the high-temperature performance grade by approximately one grade level.
  - Increasing the fineness modulus (sum of the percent passing the 0.075-, 0.150-, and 0.300-mm sieves) by 50 improves rutting resistance by a factor of 2.
  - Decreasing the design VMA by 1 percent will improve rutting resistance by a factor of 1.2.
  - Increasing  $N_{\text{design}}$  by one level will improve rutting resistance by a factor of 1.2.

**Note X25**—These rules for mixture adjustment are documented in *NCHRP Report 567: Volumetric Requirements for Superpave Mix Design*.

X2.10. **Additional Reporting Requirements for WMA:**

- X2.10.1. For WMA mixtures, report the following information in addition to that required in R 35.
  - X2.10.1.1. WMA process description;
  - X2.10.1.2. Planned production temperature;
  - X2.10.1.3. Planned field compaction temperature;
  - X2.10.1.4. High-temperature grade of the recovered binder in the RAP for mixtures incorporating RAP;
  - X2.10.1.5. Coating at the design binder content;
  - X2.10.1.6. Gyration needed to reach 92 percent relative density for the design binder content at the planned field compaction temperature and 30°C below the planned field compaction temperature;
  - X2.10.1.7. Gyration ratio;
  - X2.10.1.8. Dry tensile strength, tensile strength ratio, and observed stripping at the design binder content; and
  - X2.10.1.9. Flow number test temperature and the flow number at the design binder content.