R 46

STANDARD PRACTICE FOR DESIGNING STONE MATRIX ASPHALT (SMA)
FOP FOR AASHTO R 46

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02

Superpave Gyratory Compactor (SGC)

Scope and Significance

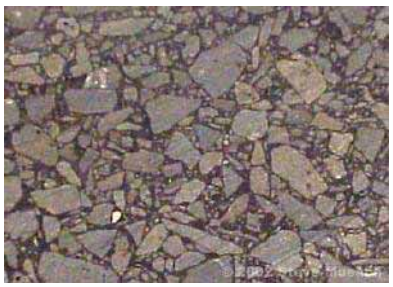
This FOP covers the design of Stone Matrix Asphalt (SMA). During the mix design process, aggregates and SMA mortar are combined to produce a mix formula based on volumetric properties in terms of air voids (V_a), voids in mineral aggregate (VMA), and the presence of stone-on-stone contact.

03 The Superpave Gyratory Compactor (SGC) is the method of compaction for fabricating specimens for the mix design process.

04

Terminology

- **G_{CA}** oven-dry bulk specific gravity (coarse aggregate fraction of combined grading).
- **P_{CA}** percent of coarse aggregate in the combined grading.
- **SMA Mortar**
  A mixture of asphalt binder, mineral filler, and stabilizing additive.
- **Stabilizing Additive**
  Either cellulose or mineral fiber.
- 05 **Stone Matrix Asphalt (SMA)**
  A Hot-Mix Asphalt (HMA) mixture consisting of a coarse aggregate skeleton with stone-on-stone contact, and a rich asphalt binder mortar.
- 06 **Stone-on-Stone Contact**
  The point where the VCA of the compacted mixture is less than the VCA of the dry-rodded coarse aggregate.
- 07 **VCA** Volume of voids between coarse aggregate particles in the combined grading.
- **VCA_{DRC}**
  Volume of voids between coarse aggregate particles in the combined gradation (dry-rodded condition).
- **VCA_{MIX}**
  Volume of voids between coarse aggregate particles of the compacted mixture (air voids, binder, fine aggregate, mineral filler,



SMA
Stone-On-Stone Contact

and stabilizing additive).

08 **Prerequisite Tests**

- **AASHTO T 2 –** Sampling of Aggregates
- **AASHTO T 248 –** Reducing Samples of Aggregate to Testing Size
- **AASHTO T 11 –** Materials Finer than No. 200 Sieve in Mineral Aggregate by Washing
- **AASHTO T 27 –** Sieve Analysis of Fine and Coarse Aggregates
- **AASHTO T 84 and T 85 –** Specific Gravity and Absorption of Fine and Coarse Aggregates
- 09 **AASHTO T 19 –** Bulk Density ("Unit Weight") and Voids in Aggregate
- **AASHTO T 89 and T 90 –** Liquid Limit, Plastic Limit and Plasticity Index
- **AASHTO T 96 –** Los Angeles Abrasion of Coarse Aggregate
- 10 **AASHTO T 104 –** Soundness of Coarse and Fine Aggregates
- **ASTM D 4791 –** Flat Particles, Elongated Particles, or Flat & Elongated Particles in Coarse Aggregate
- **ASTM D 5821 –** Determining the Percentage of Fractured Particles in Coarse Aggregate

11 **Mix Design Overview**

The major steps that must be conducted for successful completion of the SMA mix design process are:

- **Material Selection:** Select materials that meet specified requirements.
  - Aggregates, Binder, Mineral Filler and Stabilizing Additives.
- **Optimum Gradation Selection:** Produce three or more trial aggregate gradations.
- **Optimum Binder Content Selection:** Using the optimum gradation, produce specimens at a minimum of three varying binder contents.
- 12 **Evaluate Draindown:** Test mixture according to the FOP for T 305.
- **Evaluate Moisture Susceptibility:** Compact according to the FOP for T 312, test according to the FOP for T 283.
- **Evaluate Final Mix Properties:** Verify compliance with M 325. Final mixture must

meet all specified parameters.

13 ## Material Selection

Select materials meeting the provisions of AASHTO M 325 including the following. (Refer to M 325 for a more detailed description of required material properties).

- **Aggregates:** 100 percent crushed, meeting the specified requirements for L.A. Abrasion, Soundness, Flat and Elongated Particles, Crushed Content, Absorption, Liquid Limit, and Plasticity Index.
- **Binder:** Performance-graded meeting the requirements of M 320, appropriate for climate and traffic loading of the project.
- 14 **Mineral Filler:** Finely divided mineral matter such as crusher fines and fly ash.
- **Stabilizing Additive:** Stabilizer such as cellulose or mineral fiber to prevent excessive draindown, used at the appropriate dosage rate.

15 ## Optimum Gradation Selection

1. Perform prerequisite procedures / tests
2. Establish trial blend grading
3. Establish trial binder content
4. Mix and compact trial blend specimens
5. Evaluate compacted trial mixtures
6. Select optimum aggregate grading

16 ## Prerequisite Procedures / Tests

- Obtain the specific gravity of mineral filler (AASHTO T 100).
- Obtain appropriate samples of each material to be used in the SMA design.
- Perform G_{sb}(OD) Specific Gravity and Absorption tests for each aggregate. G_{sb}(SSD) and G_{sa} specific gravities are not required.
- Perform Sieve Analysis on each aggregate. Verify that grading of samples obtained for mix design is representative of the average
- 17 stockpile grading for each product.
- Separate aggregates into required size fractions. Recommended size fractions are

presented in Table 1.

Table 1 – Aggregate Size Fractions 18

Passing		Retained	
1½”	(37.5 mm)	1”	(25 mm)
1”	(25 mm)	3/4”	(19 mm)
3/4”	(19 mm)	1/2”	(12.5 mm)
1/2”	(12.5 mm)	3/8”	(9.5 mm)
3/8”	(9.5 mm)	No. 4	(4.75 mm)
No. 4	(4.75 mm)	No. 8	(2.36 mm)
No. 8	(2.36 mm)	No. 200	(0.075 mm)
Passing No. 200 (0.075 mm)			

19 **Establish Trial Blend Grading**

Specifications for aggregate gradation are given in M 325 as upper and lower limits on certain sieve sizes. Within these upper and lower limits, numerous aggregate gradations can be fabricated.

20 **Number and Types of Samples**

- Select a minimum of 3 trial blends.
- Calculate combined aggregate grading for each trial blend (See Note 1).

  It is recommended that one grading fall along the coarse limits, one along the fine limits, and one near the center of the grading bands contained in the FOP for M 325.
- Calculate the combined G_{sb}(OD) of each blend (See FOP for AASHTO R 35).
- For each trial blend, a minimum of two samples must be prepared for compaction by the SGC.
- Replicate samples must also be produced for theoretical maximum specific gravity for each of the trial blends.
- For each trial blend, prepare a sufficient quantity of material for determination of G_{CA} and VCA_{DRC} (See Note 2).
- Determine the G_{CA} of the coarse aggregate fraction of each trial blend (FOP for T 85).

Note 1: If the oven-dry bulk specific gravities of the different aggregates, including mineral filler, vary by more than 0.2 the combined grading should be calculated based on volume rather than mass.

Note 2: Quantity of material that must be prepared will be determined by the measure size required by T 19 for the nominal maximum aggregate size. The coarse aggregate (stone) fraction is that portion retained on the No. 4 (4.75mm) sieve for 3/4” (19mm) and 1/2” (12.5mm) mixtures. For 3/8” (9.5mm) mixtures it is the portion retained on the No. 8 (2.36mm) sieve. 21

- Determine the dry-rodded VCA of the coarse aggregate fraction of each trial blend by compacting the aggregate according to the dry-rodded method of the FOP for AASHTO T 19. Calculate VCA_{DRC} according to the formula presented below.

$$VCA_{DRC} = \frac{(G_{CA} \times \gamma_w) - \gamma_s}{(G_{CA} \times \gamma_w)} \times 100 \qquad 22$$

where:

VCA_{DRC} = volume of voids between coarse aggregate particles in the combined aggregate gradation, dry-rodded condition (percent)

G_{CA} = oven-dry bulk specific gravity of the coarse aggregate fraction of the aggregate blend tested according to the FOP for T 85

γ_s = unit weight of the coarse aggregate fraction of the aggregate blend, compacted according to the dry-rodded method of T 19 (lb/ft^3)

γ_w = unit weight of water (assumed to be 62.4 lb/ft^3)

23 **Preparing Aggregate Blend Gradations**

- If the specific gravities of the different aggregate components do not vary by more than 0.2, the combined grading for each trial blend may be calculated by mass as presented in the FOP for AASHTO R 35.
- If the specific gravities of the different aggregate components vary by more than 0.2, calculate the combined grading for each trial blend by volume.

24 **Calculating Aggregate Blend Gradations by Volume**

If the combined grading must be calculated by volume, do so according to the following steps: (A calculation example is provided at the end of the FOP).

1. Record the individual percent retained on every sieve size for each of the aggregates, including the minus No. 200 fraction. The sum of these individual values should equal 100 for each aggregate.
2. Consider the individual percentages retained as grams retained, where the total sample mass for each aggregate would be 100 grams.

Note 3: Be sure to use the G_{sb}(OD) of the appropriate aggregate when calculating individual volumes for that aggregate.

25 3. Calculate the individual volume retained for every sieve size of each aggregate according to the following formula:

$$V = \frac{M}{D}$$ 26

where:

V = volume retained on each individual sieve, (cm^3)

M = mass retained on individual sieve, (grams)

D = density of individual aggregate, ($grams/cm^3$), calculated as the G_{sb}(OD) times the density of water (assumed to be 1 $gram/cm^3$). In effect, the G_{sb}(OD) may be considered the equivalent of density for this calculation (See Note 3 above)

27 4. Record the individual volume retained for every sieve size of each aggregate, including that of the minus No. 200 fraction.
5. Sum the individual volumes and record as the total volume of each product.
6. Calculate the individual volumes retained for each sieve size in the combined aggregate blend using the following formula:

$$IVR = (VRA \times a) + (VRB \times b) + (VRC \times c) + ...(VRN \times n)$$ 28

where:

IVR	=	**I**ndividual **V**olume **R**etained for each sieve of the combined aggregate blend (cm^3)
VRA, VRB, VRC,……VRN	=	**V**olume **R**etained on each sieve size of each individual product **A, B, C**……**N** (cm^3)
a, b, c,….. n	=	Percentage of individual aggregates A, B, C……N used for the blend, expressed in decimal form, totaling 1.00

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7. Calculate the cumulative volume retained of the combined aggregate blend by summing the individual values calculated in step 6. This is the total volume of the blend, and will be used to calculate percent retained and passing by volume.
8. Calculate individual percent retained and percent passing for the blend. (See Note 4).
9. Record the combined percent passing and compare with the grading bands from M 325.

Note 4: The method of calculation is the same as used for a standard T 27 test, except that the units used for the calculation are volume (cm^3) rather than mass (grams).

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Establish Trial Binder Content

- M 325 states that binder content should be in the range from 6.0 to 7.0 percent.
- Where no previous history is available, a starting binder content between 6.0 and 6.5 percent is recommended. This is appropriate for aggregates having G_{sb}(OD) in the "normal" range of 2.55 to 2.75.
- Adjustment to the trial binder content may be required depending on the G_{sb}(OD) of the aggregate. Table 2 provides information that will be helpful in making such adjustments. Additional trial specimens may be required to establish appropriate binder content.

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Table 2 – Trial Binder Contents for Varying G_{sb}(OD) of Combined Aggregates

Combined Aggregate G_{sb}(OD)	Minimum Binder Content, %
2.40	6.8
2.45	6.7
2.50	6.6
2.55	6.5
2.60	6.3
2.65	6.2
2.70	6.1
2.75	6.0
2.80	5.9
2.85	5.8
2.90	5.7
2.95	5.6
3.00	5.5

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Note 5: The temperatures determined for mixing and compaction are appropriate for neat asphalt binders. When using modified asphalt binders, consult the manufacturer's guidelines, or those of the agency, for mixing and compaction temperatures.

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Compacted SMA Specimen

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Note 7: Compact specimens for 75 gyrations when the aggregate has a Los Angeles Abrasion loss greater than 30 percent.

Mix and Compact Trial Blend Specimens

1. Determine mixing and compaction temperatures for the binder (See Note 5).

   Mixing temperature: Temperature to which the binder must be heated to produce a viscosity of 170 ± 20 cSt.

   Compaction temperature: Temperature to which the binder must be heated to produce a viscosity of 280 ± 30 cSt.

2. Prepare at least two replicate specimens at the initial trial binder content for each trial blend for compaction using the SGC.

Note 6: 4500 to 4700 grams of aggregate will usually be sufficient to compact specimens of 110 to 120 mm height. Trial specimens may be necessary.

3. Prepare replicate specimens for theoretical maximum specific gravity (G_{mm}) (FOP for AASHTO T 209).
4. Mix and condition the loose mix (FOP for AASHTO R 30).
5. Compact specimens for 100 gyrations (FOP for AASHTO T 312). (See Note 7)

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Evaluate Compacted Trial Mixtures

- Determine G_{mb} of compacted specimens according to the FOP for T 166.
- Determine G_{mm} of replicate specimens according to the FOP for T 209.
- Calculate VMA according to the following formula:

$$VMA = 100 - \left(\frac{G_{mb}}{G_{sb(OD)}}\right)P_s \qquad 36$$

where:

VMA	=	Voids in the Mineral Aggregate, percent
G_{mb}	=	Bulk specific gravity of the compacted specimen
$G_{sb}(OD)$	=	Oven dry bulk specific gravity of the total aggregate
P_s	=	Percent of aggregate in the mixture

- Calculate VCA_{MIX} according to the following formula:

$$VCA_{MIX} = 100 - \left(\frac{G_{mb}}{G_{CA}}\right)P_{CA} \qquad 37$$

where:

VCA_{MIX}	=	Volume of voids between coarse aggregate particles of the compacted mixture (air voids, binder, fine aggregate, mineral filler, and stabilizing additive), percent
G_{mb}	=	Bulk specific gravity of the compacted specimen
G_{CA}	=	Oven dry bulk specific gravity of the coarse aggregate fraction
P_{CA}	=	Percent of coarse aggregate in the total mixture

- Calculate V_a according to the following formula:

$$V_a = 100 \times \left(1 - \left(\frac{G_{mb}}{G_{mm}}\right)\right) \quad 38$$

where:

V_a	=	Total air voids in the compacted mixture, percent
G_{mb}	=	Bulk specific gravity of the compacted specimen
G_{mm}	=	Theoretical maximum specific gravity of the mixture

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Select Optimum Aggregate Grading

Using the data from evaluation of the trial blends described above, select the optimum aggregate grading based on the following criteria:

- Select the blend with the lowest percentage of coarse aggregate that meets or exceeds minimum VMA requirements, and where the VCA_{MIX} is less than VCA_{DRC} (See Note 8).

Note 8: The VMA of the optimum blend should be somewhat higher than the minimum to allow for reduction in VMA during plant production.

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Selecting Optimum Binder Content

Using the optimum grading, the steps for selecting the optimum binder content are:

1. Select Binder Contents
2. Fabricate and Compact Specimens
3. Select Optimum Binder Content

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Select Binder Contents

Select at least three binder contents that will provide results encompassing the specified air void content (V_a).

- Prepare replicate samples for compaction in the SGC at each of the three binder contents.
- Prepare replicate samples at each binder content for determination of Theoretical Maximum Specific Gravity.

42 **Fabricate and Compact Specimens**

- Mix and condition specimens (FOP for AASHTO R 30).
- Compact replicate specimens according to the FOP for AASHTO T 312.
  1. A minimum of 2 specimens at each of the 3 binder contents.
  2. Compact the replicate specimens to 100 or 75 gyrations depending on L. A. Abrasion loss (See Note 7).

43 **Select Optimum Design Binder Content**

- Determine the binder content to the nearest 0.1 percent that corresponds with the specified air void requirement of the FOP for M 325, by graphical or mathematical interpolation.
- Verify that minimum VMA requirements are met, and that VCA_{MIX} is less than VCA_{DRC}.
- This is the Optimum Design Binder Content.

44 **Evaluate Draindown**

Evaluate draindown of the mixture at optimum binder content according to the FOP for AASHTO T 305.

45 **Evaluate Moisture Susceptibility**

Compact samples according to the FOP for AASHTO T 312 at V_a of 6.0 ± 1%.

Evaluate moisture susceptibility at optimum binder content by testing in accordance with the FOP for AASHTO T 283.

46 **Evaluate Final Mix Properties**

Compare final mixture properties with the requirements of AASHTO M 325 and those of the agency prior to submitting report.

Note 9: When aggregate specific gravity is outside the "normal" range, it may be appropriate to use a binder content not in compliance with requirements of M 325. Refer to Table 2 for guidance in selecting an appropriate binder content under these circumstances.

Adjusting the Mixture to Meet Properties

47 1. **Adjusting V_a.** V_a may be adjusted by raising or lowering the binder content. Binder content lower than the minimum required by M 325 should be avoided. If binder content less than the minimum specified by M 325 would be required to increase V_a to an acceptable level, the VMA should be increased instead. (See Note 9).

48 2. **Adjusting VMA.** An increase in VMA is usually obtained by raising the percentage of coarse aggregate in the blend. Under some circumstances, it may be required to select aggregate from another source.

49 3. **Adjusting VCA_{MIX}.** The VCA_{MIX} must be lower than VCA_{DRC}. When the reverse is true, the aggregate grading must be changed. This is usually accomplished by increasing the coarse aggregate content of the blend.

50 4. **Adjusting Draindown.** When draindown fails, increase the amount of, or select a different stabilizing additive.

5. **Adjusting Moisture Susceptibility.** If the requirement for moisture susceptibility is not met, increased Tensile Strength Ratio (TSR) may be achieved by adding anti-strip agents or by selecting aggregate and binder sources having better compatibility.

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Tips!

- Stone-on-Stone contact is defined as the condition where VCA_{MIX} is less than VCA_{DRC}
- It may be required to calculate combined aggregate grading based on volume rather than mass, depending on the difference between the G_{sb}(OD) of the aggregates
- Final binder content should not be lower than the minimum specified in AASHTO M 325. If lower binder content would be necessary to achieve proper air voids, then the VMA should be increased instead
- Compare final mixture properties with M 325 requirements prior to submitting report

Report

Project name and number
Mix design number
Design aggregate structure
    Source of aggregate
    Type of aggregate
Type and amount of stabilizing additive
Design binder source and grade
Optimum gradation and binder content
Volumetric properties of trial blends
Volumetric properties at optimum binder content
Draindown results
Moisture susceptibility results

Calculation Example (Aggregate Grading by Volume, 3/4" Mix) 55

Step-by-step instructions with calculation examples are presented for the gradation by volume procedure.

Table 3 illustrates individual aggregate properties for percent passing, G_{sb}(OD), and absorption.

Table 3 – Individual Product Properties 56

Sieve Size	Identification and Grading (Percent Passing)			
	Agg. A	Agg. B	Agg. C	Min. Filler
1"	100.0	100.0	100.0	100.0
3/4"	100.0	100.0	100.0	100.0
1/2"	65.8	71.2	97.4	100.0
3/8"	42.6	46.4	84.6	100.0
No. 4	9.3	6.0	48.9	100.0
No. 8	4.6	4.2	27.8	100.0
No. 16	2.6	3.7	16.6	100.0
No. 30	2.4	2.9	10.7	100.0
No. 50	2.1	2.6	7.6	100.0
No. 100	1.4	1.8	5.4	89.7
No. 200	1.2	1.7	4.6	72.5
Specific Gravity and Absorption				
G_{sb}(OD)	2.616	2.734	2.736	2.401
Absorption	1.20	0.50	0.50	1.00

Steps for Calculating Gradation by Volume (Data shown for No. 8 Sieve)

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1- Calculate or record the individual percent retained for every sieve of each product used. (The individual percentages, including the portion passing the No. 200 sieve, should equal 100.0).

   If calculating the individual percent retained from the cumulative percent passing, subtract the percent passing on the target sieve from the percent passing of the next larger sieve. Perform this operation for each sieve size in each product and record the data.

   Using the gradings shown in Table 3, the individual percent retained on the No. 8 sieve for the four products used would be as follows:

   Agg. A: 9.3 – 4.6 = 4.7

   Agg. B: 6.0 – 4.2 = 1.8

   Agg. C: 48.9 – 27.8 = 21.1

   Min. Filler: 100.0 – 100.0 = 0.0

   The data for all sieves of each material are illustrated in Table 4.

Table 4 – Product Grading (Individual Percent Retained) 58				
Sieve Size	**Identification and Grading**			
	Agg. A	**Agg. B**	**Agg. C**	**Min. Filler**
1”	0.0	0.0	0.0	0.0
3/4"	0.0	0.0	0.0	0.0
1/2"	34.2	28.8	2.6	0.0
3/8”	23.2	24.8	12.8	0.0
No. 4	33.3	40.4	35.7	0.0
No. 8	4.7	1.8	21.1	0.0
No. 16	2.0	0.5	11.2	0.0
No. 30	0.2	0.8	5.9	0.0
No. 50	0.3	0.3	3.1	0.0
No. 100	0.7	0.8	2.2	10.3
No. 200	0.2	0.1	0.8	17.2
– No. 200	1.2	1.7	4.6	72.5
Total	100.0	100.0	100.0	100.0

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2- Consider these individual percentages retained as being grams rather than percentages, where each product totals 100 grams. Using the data from Table 4, the individual grams retained for the four products would be the same values as those of the percentages calculated in step 1 above.

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3- Calculate the individual volume retained for every individual sieve size of each product by dividing the individual grams retained by the density of the respective products, where density of a given individual product equals G_{sb}(OD) times the density of water (water density is assumed to be 1 gram/cm^3).

Using the formula from page 9-6, the G_{sb}(OD) values from Table 3, and the individual masses retained from Table 4, the following volumes are obtained for the No. 8 sieve:

Formula for Volume calculation (cm^3): $V = \frac{M}{D}$

Agg. A: $V = \frac{4.7\text{ g}}{2.616\text{ g/cm}^3} = 1.80\text{ cm}^3$

Agg. B: $V = \frac{1.8\text{ g}}{2.734\text{ g/cm}^3} = 0.66\text{ cm}^3$

Agg. C: $V = \frac{21.1\text{ g}}{2.736\text{ g/cm}^3} = 7.71\text{ cm}^3$

Min. Filler: $V = \frac{0.0\text{ g}}{2.401\text{ g/cm}^3} = 0.00\text{ cm}^3$

Record the data thus calculated (See Table 5 for examples)

Table 5 – Product Volumes (Individual Volume Retained) 61

Sieve Size	Identification and Volume (cm^3)			
	Agg. A	Agg. B	Agg. C	Min. Filler
1”	0.00	0.00	0.00	0.00
3/4"	0.00	0.00	0.00	0.00
1/2"	13.07	10.53	0.95	0.00
3/8”	8.87	9.07	4.68	0.00
No. 4	12.73	14.78	13.05	0.00
No. 8	1.80	0.66	7.71	0.00
No. 16	0.76	0.18	4.09	0.00
No. 30	0.08	0.29	2.16	0.00
No. 50	0.11	0.11	1.13	0.00
No. 100	0.27	0.29	0.80	4.29
No. 200	0.08	0.04	0.29	7.16
– No. 200	0.46	0.62	1.68	30.20
Total Volume	38.23	36.57	36.54	41.65

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4- Calculate the combined volume retained for each individual sieve size using the individual volumes retained from Step 3 and the percent utilization of the various products expressed in decimal form.

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Using data from Tables 5 and 6, the following example is shown for the No. 8 sieve.

Product utilization (from Table 6) is as follows: Agg. A, 40%; Agg. B, 41%; Agg. C, 10%; Min. Filler, 9% (These percentages, expressed as decimals, are 0.40, 0.41, 0.10, and 0.09 respectively. Note that the decimal equivalents total 1.00).

The individual contribution from each product is shown below for the No. 8 sieve:

Agg. A: $1.80\ \text{cm}^3 \times 0.40 = 0.72\ \text{cm}^3$

Agg. B: $0.66\ \text{cm}^3 \times 0.41 = 0.27\ \text{cm}^3$

Agg. C: $7.71\ \text{cm}^3 \times 0.10 = 0.77\ \text{cm}^3$

Min. Filler: $0.00\ \text{cm}^3 \times 0.09 = 0.00\ \text{cm}^3$

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Using the formula from page 9-7, the combined Individual Volume Retained (IVR) for the No. 8 sieve is shown below. Table 6 summarizes the data thus calculated for all sieves in the combined grading.

$$\text{IVR} = (1.80 \times 0.40) + (0.66 \times 0.41) + (7.71 \times 0.10) + (0.00 \times 0.09) = 1.76\ \text{cm}^3$$

Table 6 – Trial Blend Grading by Volume 65

Sieve Size	Volume Retained by Product (cm^3)				Combined Grading		
	Agg. A (40%)	Agg. B (41%)	Agg. C (10%)	Min. Filler (9%)	Individ. Volume Retained (cm^3)	Individ. Percent Retained	Percent Passing
1”	0.00	0.00	0.00	0.00	0.00	0.0	100.0
3/4"	0.00	0.00	0.00	0.00	0.00	0.0	100.0
1/2"	5.23	4.32	0.10	0.00	9.65	25.6	74.4
3/8”	3.55	3.72	0.47	0.00	7.74	20.5	53.9
No. 4	5.09	6.06	1.30	0.00	12.45	33.0	20.9
No. 8	0.72	0.27	0.77	0.00	1.76	4.7	16.2
No. 16	0.30	0.07	0.41	0.00	0.78	2.1	14.1
No. 30	0.03	0.12	0.22	0.00	0.37	1.0	13.1
No. 50	0.04	0.05	0.11	0.00	0.20	0.5	12.6
No. 100	0.11	0.12	0.08	0.39	0.70	1.9	10.7
No. 200	0.03	0.02	0.03	0.64	0.72	1.9	8.8
– No. 200	0.18	0.25	0.17	2.72	3.32	-----	-----
				Total Volume	37.69		

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5- Sum the combined volumes calculated for all individual sieve sizes, including the fraction passing the No. 200 sieve. This is the total volume of the combined grading and will be used to calculate the individual percent retained by volume. (See Table 6 where total volume of the combined grading equals 37.69 cm^3).

Individual percent retained is calculated in the same fashion as for a conventional gradation, except that the units used for the calculation are in volume (cm^3) rather than mass (grams).

The following example illustrates the individual percent retained by volume for the No. 8 sieve.

$$\text{Individual Percent Retained} = \frac{1.76\ \text{cm}^3}{37.69\ \text{cm}^3} \times 100 = 4.7\ \text{percent}$$

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Once individual percent retained is calculated for each sieve size, percent passing is calculated as for any other gradation. See Table 6 for combined grading on all sieves.

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The difference between percent passing by volume and mass may or may not be substantially different, depending on how much the G_{sb}(OD) of the individual products varies. See Table 7 for a comparison of gradings calculated by mass and volume. In this table the gradation by mass failed to meet the requirement for the No. 8 sieve, and thus fails to meet M 325 grading requirements. The gradation by volume met all grading requirements.

Table 7 – Comparison of Gradings (Mass vs. Volume, 3/4" Mix) 69

Sieve Size	Combined Trial Blend Grading (Percent Passing)		
	Percent by Mass [a]	Percent by Volume [b]	M 325 Specification
1”	100.0	100.0	100
3/4"	100.0	100.0	90 – 100
1/2"	74.3	74.4	50 – 88
3/8”	53.5	53.9	25 – 60
No. 4	20.1	20.9	20 – 28
No. 8	15.3 [a]	16.2	16 – 24
No. 16	13.2	14.1	-----
No. 30	12.2	13.1	-----
No. 50	11.7	12.6	-----
No. 100	9.9	10.7	-----
No. 200	8.2	8.8	8 – 11

[a] Does not meet specification for No. 8 sieve

[b] Meets specification for all sieves

REVIEW QUESTIONS

1. Define Stone-on-Stone contact.

2. What is the difference between VCA_{DRC} and VCA_{MIX}?

3. How many trial blends are required? How are the trial gradations selected relative to the grading bands specified in M 325?

4. For a 3/8” (9.5 mm) mix, what size fraction is considered to be Coarse Aggregate?

5. How does one calculate the individual volume retained for a given sieve size of an aggregate product?

6. After selecting trial gradings and mixing & testing specimens, how is the optimum grading selected?

7. What criteria are used to select the optimum binder content?

8. Given the following, calculate the VCA_{MIX}.

   G_{mb} = 2.364 (Bulk Specific Gravity of Compacted Specimen)

   G_{CA} = 2.692 (Oven-Dry Bulk Specific Gravity of the Coarse Aggregate Fraction)

   P_{CA} = 78 percent (Percent Coarse Aggregate in the mixture)

9. If the VMA of the mixture is too low, how does one generally go about raising it to an acceptable level?