Appendix C

RCC Pavement Mixture Proportioning Method

Several mixture proportioning procedures exist that have been used for RCC pavements. This method formulates RCC mixes based on the relative proportions of the paste volume to the aggregate void volume. The method is based on a combination of relationships developed by the Corps of Engineers for RCC and relationships specifically for RCC pavements developed in Quebec.[1] It relies heavily on experimental data shown on the enclosed figures. This approach requires that a number of laboratory batches be produced and adjustments made based on observed and tested performance. This method is only applicable to non-air-entrained RCC mixes.

The primary hypothesis is that the optimal RCC mixture should have just enough paste to fill the inter-granular spaces remaining after the aggregate skeleton has achieved maximum density after compaction. Consequently determining constituent material volumes and composite volumes is critical. If less paste than the optimal paste volume is used, the voids left after compaction will reduce the concrete's mechanical properties and increase its permeability. On the other hand, excessive paste content will increase the heat of hydration, increase workability, and increase constituent costs.

The method utilizes empirical relationships shown in Figures 2 through 5. The data is not applicable to all materials and all situations but is provided to establish initial proportions for trial mixing. As data for specific materials or methods is accumulated, these relationships should be adjusted.

Six steps are involved in the mixture proportioning method:

1. Determine the Target Aggregate Proportions. Establish the proportions of the different aggregate grading classes in order to produce a mix that, after compaction, will have a minimum number of voids.

2. Determine the Void Volume. Measure the void volume of the fully compacted aggregate blend.

3. Determine the Paste Volume. Compute the paste volume in order to achieve the desired workability.

4. Water/Binder Ratio. Select the water-binder ratio and the all Portland cement mixture proportions required to produce a paste that meets the mechanical requirements.

5. Determine the Pozzolan Replacement Percentage. Select the appropriate pozzolan replacement percentage based on the desired rate of strength development and other factors such as workability, ASR mitigation, and economic limits.

6. Perform trial batches and make adjustments.

[1] Design and Construction of Roller Compacted Concrete Pavements in Quebec, Roller Compacted Concrete Committee of the *Association des constructeurs de routes et grands travaux du Québec* (ACRGTQ), November 2005.

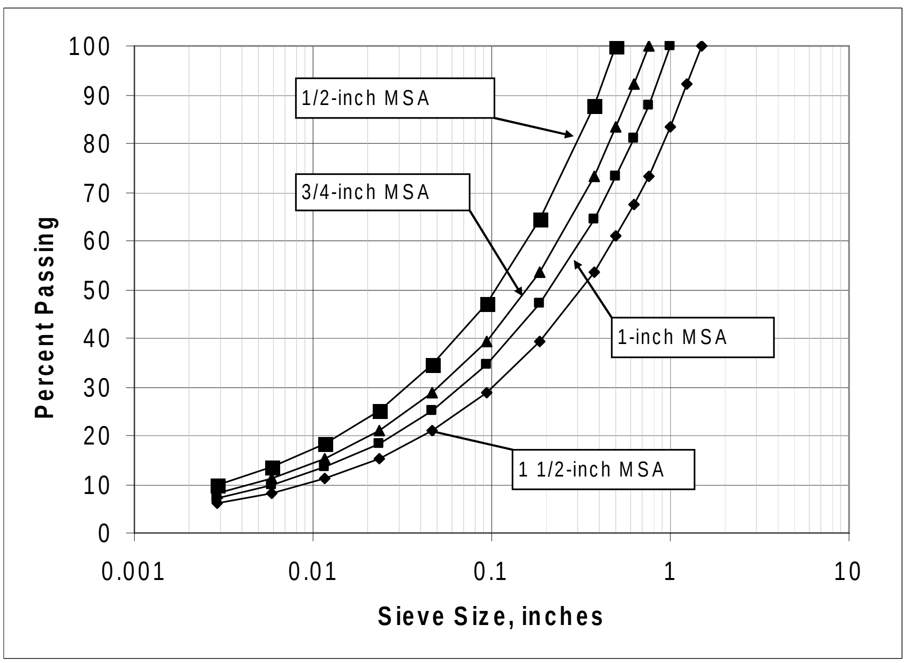
Step 1: Select the target particle-size distribution.

The first step in selecting the proportions for the different aggregate grading classes is to create an aggregate skeleton or grading with a minimum amount of voids after compaction. The modified Fuller-Thompson rule (commonly used to design bituminous concrete mixes) can be used to obtain a target grading curve that yields a dense skeleton:
Where:

d: Sieve size, inches (mm)
D: Aggregate nominal maximum size, inches (mm)
p: Percent passing sieve size *d*

Figure 1 shows typical Fuller-Thompson grading curves for different nominal maximum sizes of aggregate. These curves generally yield a compact aggregate grading when the particles are natural sand and cubic aggregates. The curves indicate that the aggregate grading must contain between 5% and 15% of fine particles passing the No. 200 (75-µm) sieve. This percentage includes fines from the aggregates and cementitious materials (pozzolan) used as mineral filler.

Figure 1 –Modified Fuller-Thompson curves for different aggregate sizes



Fuller-Thompson curves only approximate the ideal grading curve since the volume of voids after compaction depends not only on particle size, but aggregate shape, angularity, surface texture, as well as, the compaction method used. Naturally rounded aggregates (i.e. smooth surface texture) and cubically shaped aggregates yield a denser skeleton, while highly angular aggregates containing a large portion of flat and elongated particles yield a more open skeleton. A change in particle shape and surface texture can significantly influence the degree of compaction of the aggregate skeleton (specifications typically limit the amount of flat and elongated particles in coarse aggregates to no more than 20% by weight).

It is unlikely that commercially available materials for the project will provide the most optimum blend of materials. The goal is to evaluate the available sources and select materials that balance the optimum combination of materials with the cost of acquiring or producing such materials. Large projects are more likely to require a quantity of material where specialized processing can be done to optimize mixtures. The challenge with smaller projects is to make the available materials work.

Step 2: Measure the void volume of the aggregate blend

Once the relative proportions of the coarse and fine aggregates have been calculated to produce a particle-size distribution as close as possible to the target grading (Figure 1), the voids in the compacted aggregate skeleton must be determined (V_v). This volume (expressed in percent of compacted aggregate) is obtained by compacting the blended aggregate in a standard manner. This can be done by using a manual method such as the rodding or jigging procedure as described in ASTM C 29. A mechanical method consisting of vibrating a sample of the aggregate mixture under a surcharge in a cylindrical container attached to a vebe or other vibrating table may be used. It is recommended that compaction be verified to assure that additional rodding, jigging or vibration time does not result in increased density. If density increases, the greater effort for compacting specimens should be used.

The volume of voids after compaction is calculated from the apparent volume of the unit weight bucket or container less the total compacted aggregate volume. The calculation of the apparent volume of the compacted aggregate blend requires the determination of the specific gravity of each of the various coarse and fine aggregate fractions and calculation of the apparent average specific gravity of the blend. The average apparent specific gravity is computed as the weighted average value of the various fractions using the following formula 1.

$$G = (100)/(P_1/G_1 + P_2/G_2 + P_3/G_3 + \ldots.. + P_n/G_n) \quad (1)$$

Where,

G	=	average specific gravity, BSSD
$P_1, P_2, P_3 ... P_n$	=	weight percentage of aggregate fractions 1, 2, 3.......n
$G_1, G_2, G_3 ... G_n$	=	specific gravity for aggregate fractions 1, 2, 3.......n

After the sample is compacted, weigh the sample and container and determine the dry unit weight of the compacted blended aggregate material sample by subtracting the tare weight of the container. The volume of the compacted aggregate sample can be calculated using formula 2. the average specific gravity as blended The volume of voids can then be calculated by subtracting the volume of the constituent materials from the volume of the container (formula 3).

$$V_{sample} = (W_{sample})/((G)(\delta_w)) \quad (2)$$

$$V_v = V_{container} - V_{sample} \quad (3)$$

Where,

V_v = Volume of the blended aggregate voids
$V_{container}$ = Volume of the unit weight bucket or container
V_{sample} = Volume of the blended aggregate sample
W_{sample} = Weight of the blended aggregate sample
G = average specific gravity of the blended aggregate, BSSD
δ_w = unit weight of water, 62.4 lbs/cf

Step 3: Establish the paste volume for a given level of workability

The third step consists of determining the paste volume required to obtain a specific level of workability. The results of many experimental studies have revealed the relationship between the workability of non-air-entrained RCC and the ratio of paste volume to void volume after compaction, where:

V_p: Volume of paste in 1 unit of RCC
V_{vu}: Volume of voids in 1 unit of RCC

The volume of paste V_p for non-air-entrained RCC can be expressed as:

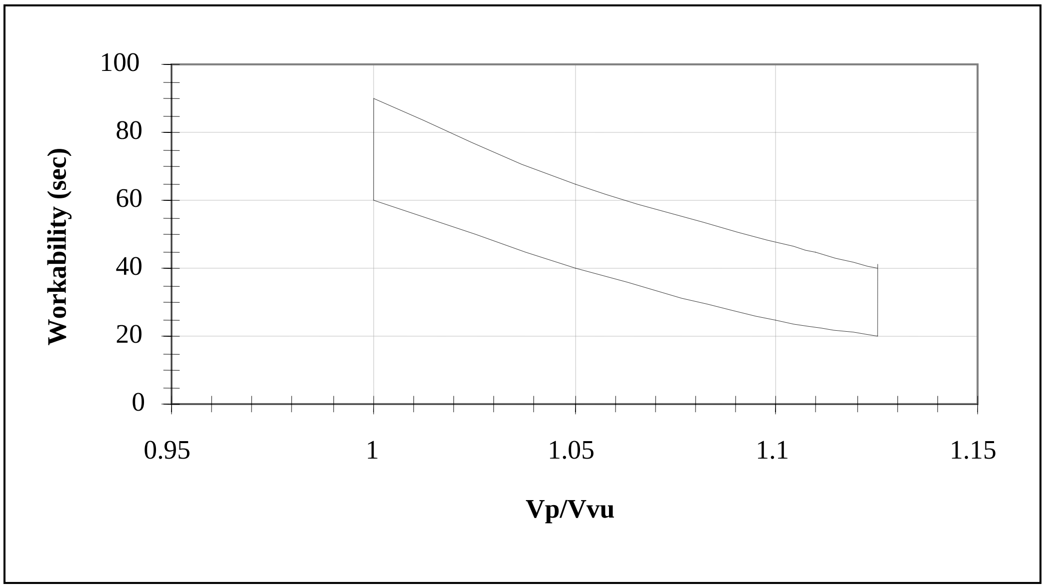
$$V_p = V_{water} + V_{binder} + V_{fines} + V_{entrapped\ air} \qquad (4)$$

Figure 2 illustrates the experimental relationship between workability and the paste-void ratio. This relationship remains approximate since the exact relationship is dependent upon the method used to determine V_{vu} and paste rheological properties. A vebe workability range of 40-60 seconds should be appropriate for most RCC paving applications.

Figure 2 can be used to determine the volume of paste needed to achieve the desired workability. Generally, a paste-void ratio (V_p/V_{vu})ranging from 1.0 to 1.05 yields workability varying from 30 to 80 seconds (CRD-C 53-01, "Test Method for Consistency of No-Slump Concrete Using the Modified Vebe Apparatus). One or two trial batches are required to determine the exact paste volume required to achieve the desired workability.

Paste volume is more than just cementitious materials and water. A certain amount of entrapped air is present in RCC mixtures. The percentage generally ranges from 0.5 to 1.5 percent. The volume of air must be accounted for in the volume tabulations. The aggregate fines smaller than the No. 200 sieve are usually considered part of the paste volume. Likewise these materials must be accounted for in the volume tabulations. The fines are usually considered a percentage of the aggregate group to which they are part and the specific gravity of the fines is assumed to be the same as determined for the aggregate group. While this may not be a strictly accurate treatment of fines, it is satisfactory for the relatively low fraction of fines typically observed in RCC paving aggregates. Fines should be considered separately if the total fines percentage exceeds 10% of the total aggregate.

Figure 2 - Experimental relationships between workability and paste-void ratio for non air-entrained RCC (water-binder ratio < 0.50) [2]



Step 4: Select the water-binder ratio depending on the required compressive strength

Once the paste volume required to obtain the target workability has been established, the next step is to select the water-binder ratio (*w/b*) to achieve the specified mechanical strength. Figure 3 gives the relationships between compressive strength and water-binder ratio for various ages of RCC mixes containing only Portland cement as the binder. The curves in this figure are based on experimental results from technical reports and various publications.

The water-binder ratio that yields the desired mechanical properties depends both on binder physicochemical properties and aggregate properties. Two or three trial batches are nonetheless required in order to determine the optimal water-binder ratio and to measure the concrete's flexural strength, which governs rigid pavement design. Durability criteria may be a significant factor in selecting the water-binder ratio for certain applications.

---

[2] Gagné, R., *High-Performance Roller-Compacted Concrete for Pavement - Mixture Design, Application and Durability*, International Symposium on Engineering Materials for Sustainable Development, Okayama, Japan, 2000, 20-21 November, pp. 74-88.

Figure 3 - Relationship between the water-binder ratio and compressive strength of RCC at different ages

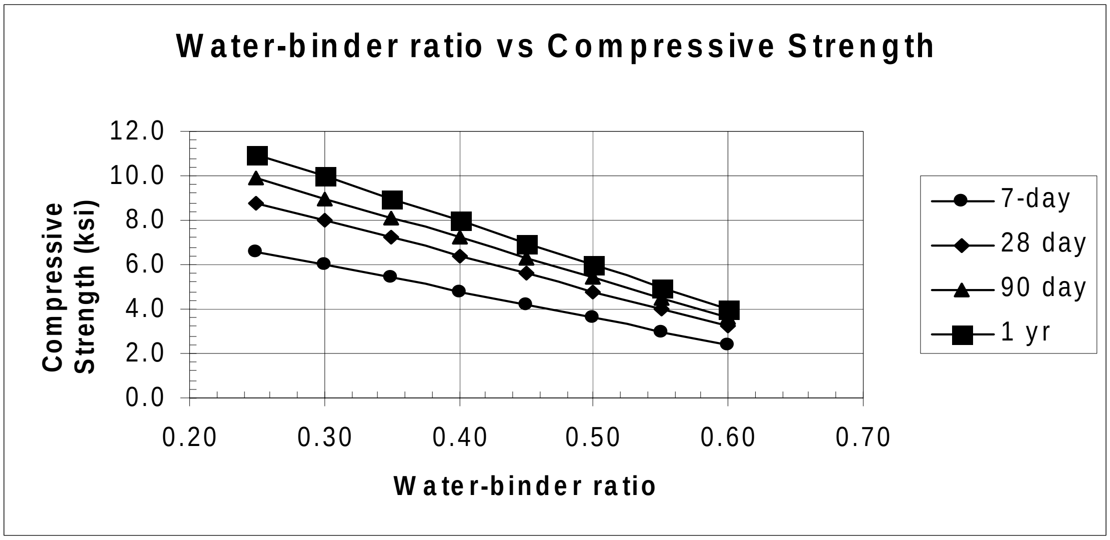
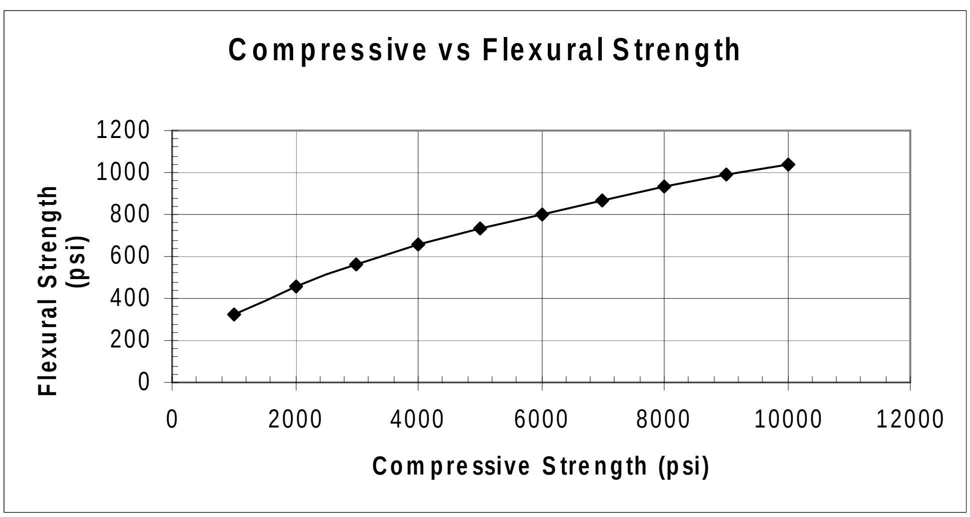


Figure 4 generally describes the relationship between the compressive strength and the flexural strength for RCC mixtures. Since flexural strength is typically specified for RCC pavement applications, figures 3 and 4 can be used to estimate the required water-binder ratio for any given flexural strength.

Figure 4 - Relationship between compressive strength and flexural strength of RCC



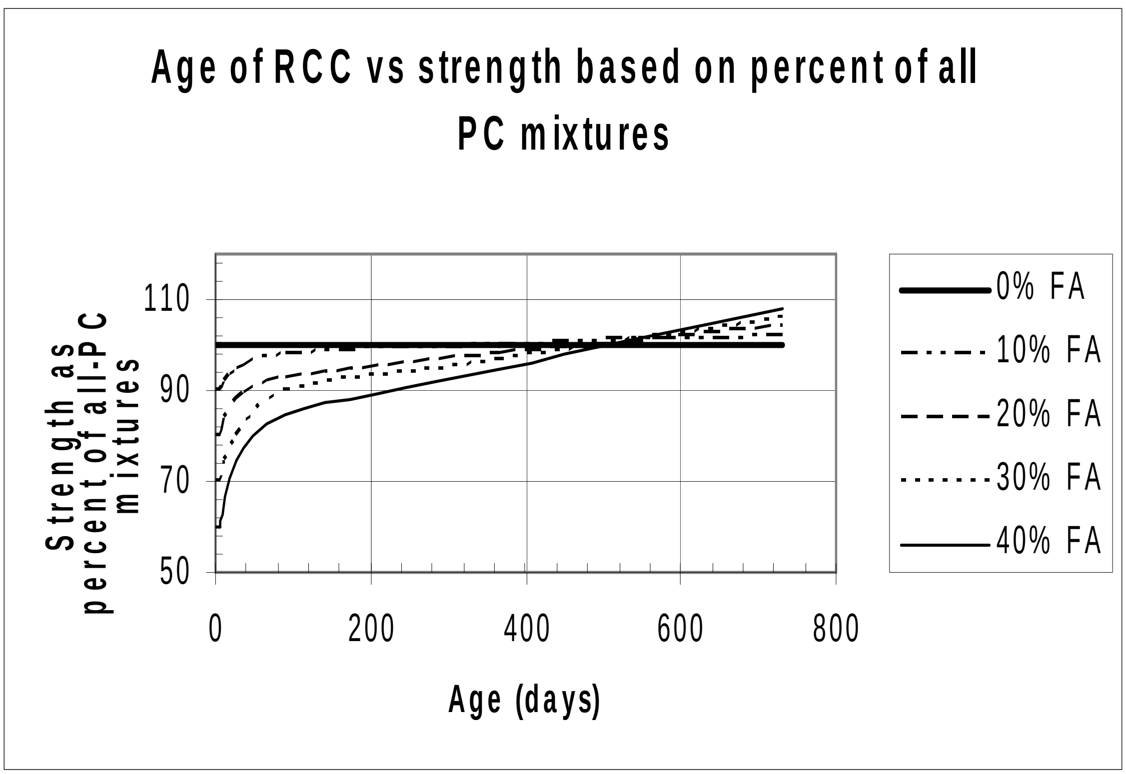
Step 5: Select the proportions of alternate cementitious materials

Numerous alternate cementitious materials are available for use in RCC pavements. They include a range of pozzolans, including flyash, ground granulated blast furnace slag, silica fume, and others. Strength relationships are not available for all possible combinations. More extensive trial batching is required to establish the performance characteristics of specific material blends.

Flyash is the most common alternate cementitious material used with Portland cement. For this mixture proportioning procedure the incorporation of flyash is done by replacing a percentage of the Portland cement volume. Figure 5 provides a general relationship illustrating how the varying percentages of flyash percentage affects strength gain of the mixture. These relationships are provided for the situation where it is desired to use less Portland cement by replacing with flyash.

Required strength plays a determinant role in selecting the water-binder ratio for RCC. Specifically, flexural strength is often used to calculate the thickness of an RCC pavement. Consequently, experimental curves illustrating the relationship between the water-binder ratio and flexural strength of the various RCC mixes should be produced. Compressive strength can also be used to estimate flexural strength.

Figure 5 – Strength variation due to varying percentages of flyash



Example of the optimal paste volume method

The following example illustrates the procedure for determining initial trial mixture proportions to meet the following criteria:

- Non air-entrained RCC mixture with an assumed entrapped air content of 1.0%
- 56-day flexural strength of 600 psi (42MPa).
- Nominal maximum aggregate size of 1 inch (25mm).
- Workability of about 50 sec when placing the RCC (CRD-C 53-01)

Step 1a: Determine aggregate proportions that meet the target grading for the mixture.

Aggregates proposed for use in RCC are submitted to the laboratory and tested to determine physical characteristics. Tests required for the mix design include particle size distribution (ASTM C 136), and specific gravity and absorption (ASTM C 127 and ASTM C 128) on each nominal size aggregate group (mixes are designed based on the saturated surface dry (SSD) condition of the aggregates and therefore, prior to performing trial mix designs, the moisture content of each aggregate size group must also be determined). Given the particle size distribution for each size group, the relative blend proportions of each size fraction that best meets the modified Fuller-Thompson grading is determined. This process is typically done by trial and error and can be easily accomplished using spreadsheet software. For this example, results of the laboratory aggregate tests are shown in Table 1. The aggregate blend by weight of 1” to No. 4, ½” to ¼”, 3/8” to 0 and blend sand that best meets ideal Fuller-Thompson grading is 35-30-10-25 respectively.

Table 1 – Example Sieve analysis and proposed aggregate blend

	Percent Passing					
	Nominal Size, inches					Ideal Blend Fuller Curve
	1” to No. 4	½” to ¼”	3/8” to 0	Blend Sand	35-30-10-25 Blend	
1. Gradation, Size,						
1-inch	100				100	100
3/4-inch	88				96	88
5/8-inch	58	100			85	81
1/2-inch	36	82			72	73
3/8-inch	24	52			59	64
No. 4	4	22	100		43	47
No. 8	1	6	84	100	36	34
No. 16		2	59	82	27	25
No. 30			37	63	20	18
No. 50			17	43	13	14
No. 100			10	28	8	10
No. 200 (washed)	0.2	0.4	4.5	15.1	4.4	7
2. Specific Gravity, BSSD	2.65	2.64	2.62	2.59	2.63	--
3. Absorption, %	0.7	0.8	1.1	1.6	--	--

Step 1b: Evaluate quality and suitability of aggregates for use in RCC.

Concurrently with step 1a, perform other aggregate tests as required to assure suitability for use in RCC. These other tests may include petrographic examination (ASTM C 295 and ASTM C 856), Los Angeles Abrasion (ASTM C 131), organic impurities (ASTM C 40), Soundness (ASTM C 88), flat and elongated particles (ASTM D 4791), etc. For this example, it is assumed that aggregates meet all pertinent quality requirements.

Step 2: Measure the void volume of the aggregate blend.

The void volume is determined on a sample of the aggregate consisting of the individual aggregate size groups mixed and blended in the proportion determined in Step 1a. Binder materials (cement, pozzolan and/or slag) are not included in this blend. The binder fines (minus No. 200 sieve sizes) are considered part of the mixture paste but it is not necessary to include them in the determination of aggregate void volume. The void volume is determined by compacting the aggregate blend in a container of known volume and weight. The aggregate may be compacted by rodding or by vibrating on the vebe table. Once the aggregate is compacted, void volume is calculated using the weight of the compacted aggregate mass and the specific gravity of the aggregates. The steps for determining the void volume are as outlined below:

a. Oven dry the aggregate material.

b. Weigh proportional amounts of each aggregate and blend together until uniform. For this example, the quantity of each size group of aggregate shown is weighed and blended together in the proportion determined in Step 1a.

Aggregate Size Group	Target Blend, %	Proportional Weight for Blending, lbs
1" to No. 4	35	52.5
½" to ¼"	30	45.0
3/8" to 0	10	15.0
Blend Sand	25	37.5
Total	100	150.0

c. Compact the well blended aggregates as specified in ASTM C 29 using the rodding procedure. As an alternative, a mechanical method consisting of vibrating the aggregate sample in the same unit weight container with a surcharge on the vebe table (CRD-C 53) may be used, however, tests should be conducted to verify that additional vibration does not result in increased density.

d. Determine the weight of the compacted aggregate sample and the average specific gravity of the blended aggregate.

Weight of aggr and container = $W_{sample + container}$ = 76.2 lbs
Tare weight of container = $W_{container}$ = 14.1 lbs
Weight of compacted sample = W_{sample}
= $W_{sample + container} - W_{container}$

$= 79.8-13.6 = 66.2$ lbs

Average specific gravity $= G$

$= (100)/(P_1/G_1 + P_2/G_2 + P_3/G_3 + P_4/G_4)$

$= (100)/(35/2.65 + 30/2.64 + 10/2.62 + 25/2.59)$

$= 2.63$

Volume of unit weight container $= V_{container}$

$= 0.502\ ft^3$ (nominal ½ ft^3 bucket)

Volume of compacted sample $= V_{sample}$

$= (W_{sample})/((G)(\delta_w))$

$= (66.2)/((2.63)(62.4))$

$= 0.403\ ft^3$

Volume of apparent aggr voids $= V_{voids}$

$= V_{container} - V_{sample}$

$= 0.502 - 0.403$

$= 0.099\ ft^3$

e. Using the apparent volume of blended aggregate voids determined above in Step 2d, compute the apparent volume of voids based on one cubic yard of RCC.

Apparent void volume per cubic yard

$= V_{vu}$

$= (V_{voids}/V_{container})(27.0\ ft^3/yd^3)$

$= (0.099/0.502)(27.0)$

$= 5.325\ ft^3$

f. Compute the volume of the minus no. 200 aggregate fines and correct the apparent void volume to include the volume of the minus no. 200 aggregate fines (paste includes the volume of the minus no. 200 aggregate fines, the total volume of voids available to be filled with paste is the apparent volume determined in Step 2e plus the volume of the minus no. 200 aggregate fines).

Volume of Total Aggregate $= V_{au}$

$= 27.0 - V_{vu}$

$= 27.0 - 5.325$

$= 21.675\ ft^3$

Volume of minus no. 200 fines $= V_{fu}$

$= (V_{au})$(% passing No. 200 of blend)

$= (21.675)(4.4/100)$

$= 0.954\ ft^3$

Total void volume per cubic yard

$= V_{vu} + V_{fu}$

$= 5.325 + 0.954$

$= 6.279\ ft^3$ (total void volume available to be filled with paste)

Step 3a: Calculate the required paste volume

From Figure 2 in order to obtain a workability (vebe consistency) of approximately 50 seconds, the ratio of V_p/V_{vu} required is approximately 1.07.

$$\begin{aligned}\text{Required paste volume} &= V_p \\ &= (V_{vu})(1.07) \\ &= (6.279)(1.07) \\ &= 6.719 \text{ ft}^3\end{aligned}$$

Step 3b: Calculate the volume of total aggregate volumes, fines and entrapped air

$$\begin{aligned}\text{Plus no. 200 aggregate volume} \\ &= V \\ &= 27.0 - V_p \\ &= 27.0 - 6.719 \\ &= 20.281 \text{ ft}^3\end{aligned}$$

$$\begin{aligned}\text{Minus no. 200 aggregate fines} \\ &= V_{fines} \\ &= [V(100)/(100 - \%\text{ passing No. 200 of blend})] - V \\ &= [20.281(100)/(100 - 4.4)] - 20.281 \\ &= 0.933 \text{ ft}^3\end{aligned}$$

$$\begin{aligned}\text{Total aggregate volume} &= V + V_{fines} \\ &= 20.281 + 0.933 \\ &= 21.214 \text{ ft}^3\end{aligned}$$

$$\begin{aligned}\text{Entrapped Air Volume} &= V_{air} \\ &= (27.0)(\text{Entrapped air content, }\%)/100 \\ &= (27.0)(1.0/100) \\ &= 0.270 \text{ ft}^3\end{aligned}$$

Step 4: Select the water-binder ratio

Figure 3 provides a generalized relationship of compressive strength and water-binder ratio for typical RCC paving mixtures. Figure 4 provides a generalized relationship between compressive strength and flexural strength. Since a flexural strength of 600 psi is desired, Figure 4 indicates that a compressive strength target of 3,500 to 4,000 psi may be appropriate. Figure 3 indicates that a water-binder ratio of 0.55 may result in a compressive strength of 4,000 psi. Therefore a water-binder ratio of 0.55 is selected for use.

Step 5: Calculate the required pozzolan replacement percentage and the volume of the required cementious materials

Since pozzolan provides little strength contribution during early ages, it is critical to determine when strength is required. If strength is necessary at or before 28 days, mixtures should be designed for all Portland cement with no other cementitious materials. If pozzolan is to be used for other reasons such as to mitigate for ASR or to supplement deficient fines in aggregate, the material is considered a mineral admixture and not considered in the w/b ratios for strength evaluation. If strength performance is not required until an age beyond 28 days, the delayed strength contribution of flyash should be considered. Figure 5 provides a generalized relationship for the effect of pozzolan percentages on ultimate strength. Since full strength performance is not required until 56 days, 15.0% of the total equivalent cement volume will be replaced with a class F pozzolan (specific gravity = 2.24).

Water-binder ratio = 0.55 (from Step 3b)

Pozzolan replacement = 15.0 percent (by volume of equivalent cement)

Water + Binder Vol $= V_{water + binder}$
$= V_p - V_{air} - V_{fines}$
$= 6.719 - 0.270 - 0.933 = 5.516$ ft^3

Water Volume $= V_{water}$
$= [(V_{water + binder})(3.15)(\text{w-b ratio})]/[1 + (3.15)(\text{w-b ratio})]$
$= [(5.516)(3.15)(0.55)]/[1 + (3.15)(0.55)] = 3.497$ ft^3

Equivalent Cement Volume
$= V_{eq.\ cem}$
$= V_{water + binder} - V_{water}$
$= 5.516 - 3.497 = 2.019$ ft^3

Cement Volume $= V_{cement}$
$= V_{eq.\ cem}(100 - \%\ \text{Pozzolan Replacement})/100$
$= 2.019\ (100 - 15)/100 = 1.716$ ft^3

Pozzolan Volume $= V_{pozzolan}$
$= V_{eq.\ cem} - V_{cement}$
$= 2.019 - 1.716 = 0.303$ ft^3

Proportions for the resulting RCC mixture are shown in Table 2:

Table 2 – Mixture proportions for first trial mix

Material	Aggregate, percent by vol.	Solid Volume ft^3	Specific Gravity, BSSD	Weight, S.S.D. lbs
1” to No.4	35	7.425	2.65	1228
1/2” to ¼”	30	6.364	2.64	1048
3/8” to 0	10	2.121	2.62	347
Blend Sand	25	5.304	2.59	857
Cement		1.716	3.15	337.3
Pozzolan		0.303	2.24	42.4
Water		3.497	1.00	218.2
Air (1.0%)		0.270		
Totals:	100.0	27.000		4077.9
Theoretical Unit Weight		151.0		

Step 6: Trial Batches and Adjustments

Trial Batch 1:

Unit weight = 151.5 lbs/ft^3
Air content = 0.8 %
Vebe time = 35 seconds

The workability of this first RCC trial batch is low. A little longer Vebe time could be obtained with the same *w/b*, but with an increase in V_p. Increase V_p/V_{vu} from 1.08 to 1.10 and recalculate constituent proportions. Table 3 summarizes the recalculated proportions.

Table 3 – Mixture proportions for second trial mix

Material	Aggregate, percent by vol.	Solid Volume ft^3	Specific Gravity, BSSD	Weight, S.S.D. lbs
1" to No.4	35	7.356	2.65	1216
1/2" to ¼"	30	6.305	2.64	1039
3/8" to 0	10	2.102	2.62	344
Blend Sand	25	5.255	2.59	849
Cement		1.777	3.15	349.3
Pozzolan		0.313	2.24	43.7
Water		3.622	1.00	226.0
Air (1.0%)		0.270		
Totals:	100.0	27.000		4067.0
Theoretical Unit Weight		150.6		

Trial Batch 2:

Unit weight = 150.9
Air content = 0.9 %
Vebe time = 65 seconds
Compressive strength= 1400 psi (99 MPa) at 7 days

Although the second trial batch has the desired workability, it appears that it will fail to meet the 56-day compressive strength requirement of 4000 psi (600 psi flexural strength). A third trial batch must be produced with a lower water-binder ratio while maintaining the same paste volume in order to preserve workability. Therefore maintain the Vp but decrease the w/b from 0.55 to 0.40 and recalculate constituent proportions. Table 4 summarizes the recalculated proportions.

Table 4 – Mixture proportions for third trial mix

Material	Aggregate, percent by vol.	Solid Volume ft^3	Specific Gravity, BSSD	Weight, S.S.D. lbs
1" to No.4	35	7.368	2.65	1218
1/2" to ¼"	30	6.316	2.64	1040
3/8" to 0	10	2.105	2.62	344
Blend Sand	25	5.263	2.59	851
Cement		2.135	3.15	419.7

Pozzolan		0.377	2.24	52.7
Water		3.166	1.00	197.6
Air (1.0%)		0.270		
Totals:	100.0	27.000		4123.0
Theoretical Unit Weight		152.7		

Trial Batch 3:

Unit weight = 152.8
Air content = 1.1 %
Vebe time = 62 seconds
Compressive strength= 1980 psi (140 MPa) at 7 days

In this example, three trial batches were needed to design the mix. Additional batches are required to establish the flexural strength.