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16. ABSTRACT

This study evaluates the open-graded friction course (OGFC) mix design proposed by the National Center for Asphalt Technology (NCAT) in order to suggest revisions to California Test 368, Standard Method for Determining Optimum Binder Content (OBC) for Open-Graded Asphalt Concrete. Three asphalt types (PG 64-10, PG 64-28 PM, and asphalt rubber [AR]), three aggregate types (Sacramento, Watsonville, and San Gabriel) and three gradations (coarse, fine, and middle) that comply with Caltrans specifications of binder and the 1/2 in. OGFC gradation and aggregate quality were used in this study. The NCAT approach includes selection of optimum gradation, selection of optimum asphalt binder content, and evaluation of moisture susceptibility using a modified Lottman method in accordance with AASHTO T 283 with one freeze-thaw cycle.

This study proposes a volumetric-based OGFC mix design (1) to provide a better way to determine the initial binder content rather than basing it on the bulk specific gravity of the aggregate blend as suggested by NCAT; (2) to account for asphalt absorption; and (3) to allow direct selection of trial binder contents to prepare specimens for performance testing.

Accordingly, an OGFC mix design procedure integrated with volumetric design and performance testing is proposed. A moisture susceptibility test in accordance with AASHTO T 283 is known to have considerable within- and between-variations of test results. Thus, the Hamburg Wheel-Track Device test seems to be a better candidate to evaluate moisture susceptibility.

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Evaluation of Open-Graded Friction Course (OGFC) Mix Design: Summary Version

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Part of Partnered Pavement Research Program (PPRC) Strategic Plan Element 4.21:
Subtask 2A: Evaluation of Open-Graded Friction Course (OGFC) Mix Design

PREPARED FOR:	**PREPARED BY:**
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PROJECT OBJECTIVES

The objective of this study is to evaluate the open-graded friction course (OGFC) mix design procedure proposed by the National Center for Asphalt Technology (NCAT) and hence to provide a major revision of California Test 368—*Standard Method for Determining Optimum Binder Content (OBC) for Open-Graded Asphalt Concrete.* This was achieved through the following tasks:

- Verification of the NCAT procedure—that is, the selection of optimum gradation—based on volumetric properties (Phase I) criteria.
- Evaluation of the NCAT procedure—i.e., the selection of optimum asphalt binder content—according to draindown and Cantabro (durability) (Phase II) testing performance criteria.
- Identification of potential problems in the NCAT OGFC mix design procedure (Phase III).
- Evaluation of whether it is possible to incorporate the NCAT OGFC mix design procedure into the CT 368 revision or to develop an appropriate OGFC mix design procedure based on the findings of this study.
- Provide preliminary recommendations for revising CT 368.

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transport Officials
AC	Asphalt content
AR	Asphalt rubber
ASTM	American Society for Testing and Materials
Caltrans	California Department of Transportation
CV	Coefficient of Variation
HMA	Compacted Hot-Mix Asphalt
HWTD	Hamburg Wheel-Track Device
IQR	Inter-Quartile Range
K_c	"K factor" of Coarse Aggregate (CT 303)
MiST	Moisture Induced Sensitivity Test
NCAT	National Center for Asphalt Technology
OBC	Optimum Binder Content
OGFC	Open-graded Friction Course
PAV	Pressure Aging Vessel
RTFO	Rolling Thin Film Oven
SGC	Superpave Gyratory Compaction/Compactor/Compacted
SD	Standard Deviation
TV	Target Value
VCA_{DRC}	Voids in coarse aggregate for the dry-rodded condition
VCA_{MIX}	Voids in coarse aggregate for the compacted mix

LIST OF TEST METHODS AND SPECIFICATIONS

AASHTO T 11	Standard Method of Test for Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing
AASHTO T 19	Standard Method of Test for Bulk Density ("Unit Weight") and Voids in Aggregate
AASHTO T 27	Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates
AASHTO T 85	Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate
AASHTO T 166	Standard Method of Test for Bulk Specific Gravity of Compacted Asphalt Mixtures
AASHTO T 209	Standard Method of Test for Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures
AASHTO T 269	Standard Method of Test for Percent Air Voids in Compacted Dense and Open Asphalt Mixtures
AASHTO T 275	Standard Method of Test for Bulk Specific Gravity of Compacted Hot Mix Asphalt (HMA) Using Paraffin-Coated Specimens
AASHTO T 283	Standard Method of Test for Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage
AASHTO T 305	Standard Method of Test for Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures
AASHTO T 324	Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot-Mix Asphalt (HMA)
AASHTO T 331	Standard Method of Test for Bulk Specific Gravity and Density of Compacted Hot Mix Asphalt (HMA) Using Automatic Vacuum Sealing Method
ASTM D7064	Standard Practice for Open-Graded Friction Course (OGFC) Mix Design; Appendix X2: The Cantabro Abrasion Test
CT 303	Method of Test for Centrifuge Kerosene Equivalent and Approximate Bitumen Ratio (ABR)
CT 368	Standard Method for Determining Optimum Bitumen Content for Open Graded Asphalt Concrete
CT 371	Method of Test for Resistance of Compacted Bituminous Mixture to Moisture Induced Damage

1 INTRODUCTION

1.1 Background

The California Department of Transportation (Caltrans) currently uses California Test 368 (CT 368) (August 2003) – *Standard Method for Determining Optimum Bitumen Content (OBC) for Open Graded Asphalt Concrete* – for Open Graded Friction Course (OGFC) mix design. The OBC determined using this method is expected to provide a mix with an asphalt film thickness that provides good durability and avoids excessive asphalt drainage. The K_c value determined from CT 303 has been used to determine the approximate bitumen ratio to prepare loose mixes for determining the OBC by using a pre-defined maximum drainage as an acceptance criterion. Only conventional (unmodified) asphalts were used in CT 368, but in a recent modification, PG 64-10 asphalt cement replaced AR-4000 material (which was introduced in the 1970s). To determine the OBC for both the polymer-modified asphalts and asphalt rubber binders introduced more recently, a factor is now applied to increase the OBC determined for the design mix with the PG 64-10 asphalt cement.

Among several disadvantages associated with the current CT 368 procedure are these: (1) there is no verification of stone-on-stone contact; (2) there is no determination of volumetric and mechanistic properties of compacted specimens; and (3) there is no performance testing for aging and moisture damage for the state's different climate regions.

Recently, staff members of the National Center of Asphalt Technology (NCAT) (*1*) developed an improved design procedure for OGFC mixes. This methodology includes (1) materials selection, (2) trial gradations, (3) selection of an optimum gradation, (4) selection of an optimum binder content, and (5) moisture susceptibility determination using the modified Lottman method in accordance with AASHTO T 283 with one freeze-thaw cycle.

The Caltrans Hveem Expert Task Group (ETG) of Caltrans has recommended that CT 368 be revised to consider incorporation of the elements contained in the NCAT procedure. This summary report presents an abridged version of the results of a test program—incorporating the recommendation of the Caltrans Hveem ETG and a proposed OGFC mix design procedure—to replace the current CT 368 method based on these results. It is a summary version of the more detailed research source report UCPRC-RR-2012-09, *Evaluation of Open-Graded Friction Course (OGFC) Mix Design*, September 2012 (*2*).

1.2 Objectives

Objectives of this study include the following:

- Verify the NCAT procedure – selection of optimum gradation based on volumetric criteria.
- Evaluate the NCAT procedure – selection of optimum asphalt binder content based on results from the draindown and Cantabro (durability) tests that satisfy the established NCAT performance criteria.
- Identify potential problems in the NCAT OGFC mix design procedure.
- Evaluate the possibility of incorporating the NCAT OGFC mix design procedure into the revision of CT 368 or develop an appropriate OGFC mix design procedure based on the findings of this study.
- Provide recommendations for the revision of CT 368.

To accomplish these objectives, representative OGFC mixes were used. These mixes were prepared using three different binders (PG 64-10, PG 64-28 PM, and an asphalt rubber [AR]), three aggregates obtained from representative sources in California, and three representative gradations within the ½ in. OGFC gradation limits of Section 39 of the California Standard Specifications (CSS) (*3*). The following sections contain the abridged information included in Appendix A.

2 MATERIALS

2.1 Asphalt Binders

Three binders were used in this study: PG 64-10, PG 64-28 PM, and asphalt rubber (AR). The PG 64-10 and PG 64-28 PM binders were supplied by the San Joaquin Refinery in Bakersfield, California. Test properties for these two binders, which met the requirements of Section 92 of the CSS, are summarized in Appendix A, Table A.1 and Table A.2. The AR binder was supplied by International Surfacing Systems of Modesto, California. This binder consisted of 18 percent scrap and high natural crumb rubber modifier (CRM); a blend of 75 percent scrap tire CRM and 25 percent high natural CRM; 82 percent PG 64-22; and 2 percent extender oil. The components for the blend were obtained from the following sources: PG 64-22, VSS Emultech of Redding, California ($G^*/\sin\delta$ at 64°C: 1.12 MPa); extender oil (Raffex 120 ACB), Tricor Refining of Bakersfield, California; and scrap tire CRM and high natural CRM, Golden By-Products of Ballico, California. Properties of the AR binder were determined by the MACTEC Engineering and Consulting Laboratory, Phoenix, Arizona, and are summarized in Appendix A.

Table 2.1 summarizes the mixing and compaction temperatures for the OGFC mixes, based on the suppliers' recommendations:

Table 2.1: Mixing and Compaction Temperatures of Binders

Binder Type	Mixing Temp.	Compaction Temp.
PG 64-10	141 ~ 146°C (286 ~ 295°F)	132 ~ 136°C (270 ~ 277°F)
PG 64-28 PM	166°C (330°F)	143 ~ 154°C (290 ~ 310°F)
Asphalt rubber	170°C (338°F)	163°C (325°F)

2.2 Aggregates

Three different commercially available aggregate samples with different geological origins (alluvial of mixed origins [Sacramento] and granite [from a hard rock mine near Watsonville and from an alluvial deposit near San Gabriel]) were obtained from three different California suppliers.

The Sacramento material was subrounded to subangular compared to the Watsonville and San Gabriel materials, which were predominantly subangular to angular in shape. The Sacramento aggregate had a relatively smooth surface texture although the majority of particles contained at least one crushed face with a rough texture. Both the Watsonville and San Gabriel aggregates consisted of crushed materials with rough surface textures. A summary of the available aggregate test properties reported by the three suppliers is included in Appendix A, Table A.4, and photographs of these aggregates graded by size above the No. 8 sieve are shown in Figure 2.1.

Figure 2.1: The three aggregates graded by size above the No. 8 sieve.

In this figure, the label on each of the aggregates in the photos represents what was retained by a particular sieve, i.e., the material passed the adjacent upper sieve and was retained by next smallest sieve, whose size is indicated. For example, in the photograph showing the No. 8 size, the aggregate represents material that passed the No. 4 sieve and was retained on the No. 8 sieve.

Three trial gradations that fall within the Caltrans one-half inch OGFC limits (*3*) were selected for this study: two are near the lower and upper limits of the gradation band, and the third is in the middle. These gradations, designated G1, G2, and G3 respectively, are listed in Table 2.2 and shown in Figure 2.2.

Table 2.2: Proposed One-Half Inch OGFC Trial Gradations

Sieve Size	Target Value Limits	Allowable Tolerance	G1 (Coarse)	G2 (Fine)	G3 (Middle)
3/4”	100	—	100	100	100
1/2”	95 – 100	TV ± 6	95	100	97
3/8”	78 – 89	TV ± 6	78	89	83
No. 4	28 – 37	TV ± 7	28	37	33
No. 8	7 – 18	TV ± 5	7	18	12
No. 30	0 – 10	TV ± 4	2	10	5
No. 200	0 – 3	TV ± 2	1	3	2

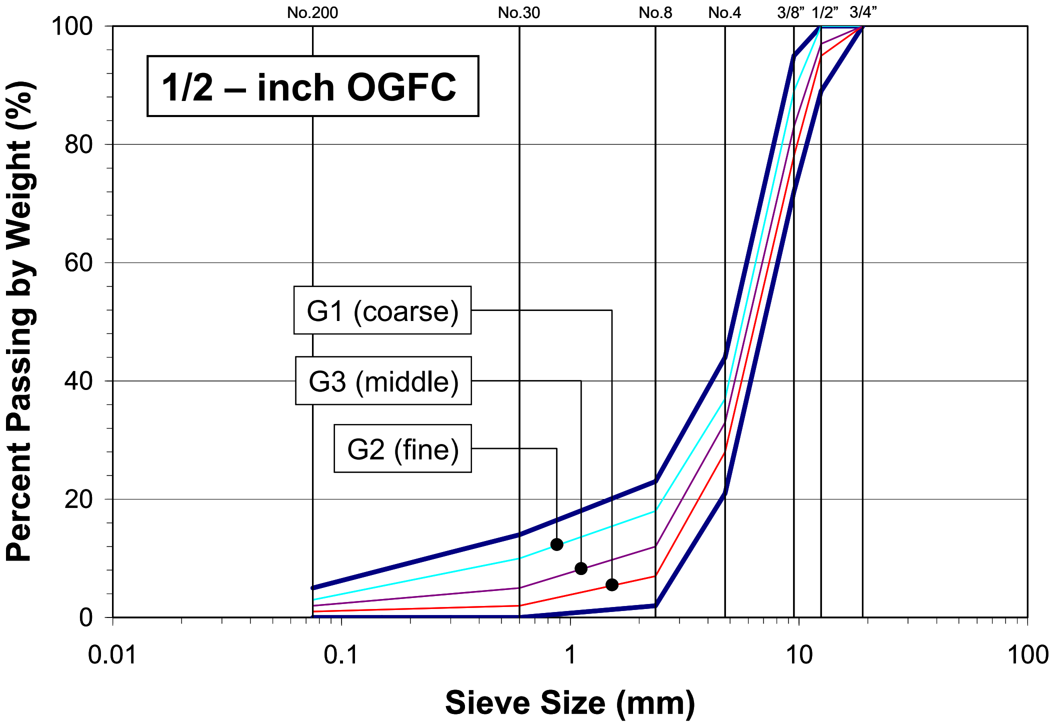


Figure 2.2: Proposed one-half inch OGFC trial gradations.

3 PHASE I: SELECTION OF OPTIMUM GRADATION

In this phase, initial trial binder contents were determined using the current test methods, CT 368 and AASHTO T 305. For each combination of the three aggregates, three binders, and three gradations, one loose mix sample for determining the theoretical maximum specific gravity (G_{mm}) and three Superpave gyratory compacted (SGC) samples with 50 gyrations were prepared. The optimum gradations were determined from volumetric criteria based on determinations of the bulk specific gravities of the compacted asphalt mixes (G_{mb}), the air-void contents (V_a or V_{air}), and the voids in the coarse aggregate of the compacted mixes (VCA_{MIX}).

3.1 Preparation of Trial Gradations

For the three aggregates to meet the aggregate specifications shown in Table 2.2, a wet/dry sieving process was followed. Wet sieving, AASHTO T 11, was used to determine the proportion of material passing the No. 200 sieve; particle size distribution of the oven-dried material retained on the No. 200 sieve was then determined using AASHTO T 27. The results obtained from this process were then used to determine the proper portions of particle sizes to meet the G1, G2, and G3 gradations. The results are shown in Figure 3.1.

3.2 Selection of Trial Binder Contents

According to the NCAT procedure, initial binder content is determined based on the bulk specific gravity (BSG) of the aggregate, as shown in Table 3.1. Also, higher binder contents should be selected for polymer-modified and rubberized asphalts, as in the CT 308 method.

Table 3.1: Minimum Binder Requirements for Aggregates with Varying Bulk Specific Gravity (*1*)

Combined Aggregate Bulk Specific Gravity	Min. Binder Content Based on Mass, %	Combined Aggregate Bulk Specific Gravity	Min. Binder Content Based on Mass, %
2.40	6.8	2.70	6.1
2.45	6.7	2.75	6.0
2.50	6.6	2.80	5.9
2.55	6.5	2.85	5.8
2.60	6.3	2.90	5.7
2.65	6.2	2.95	5.6

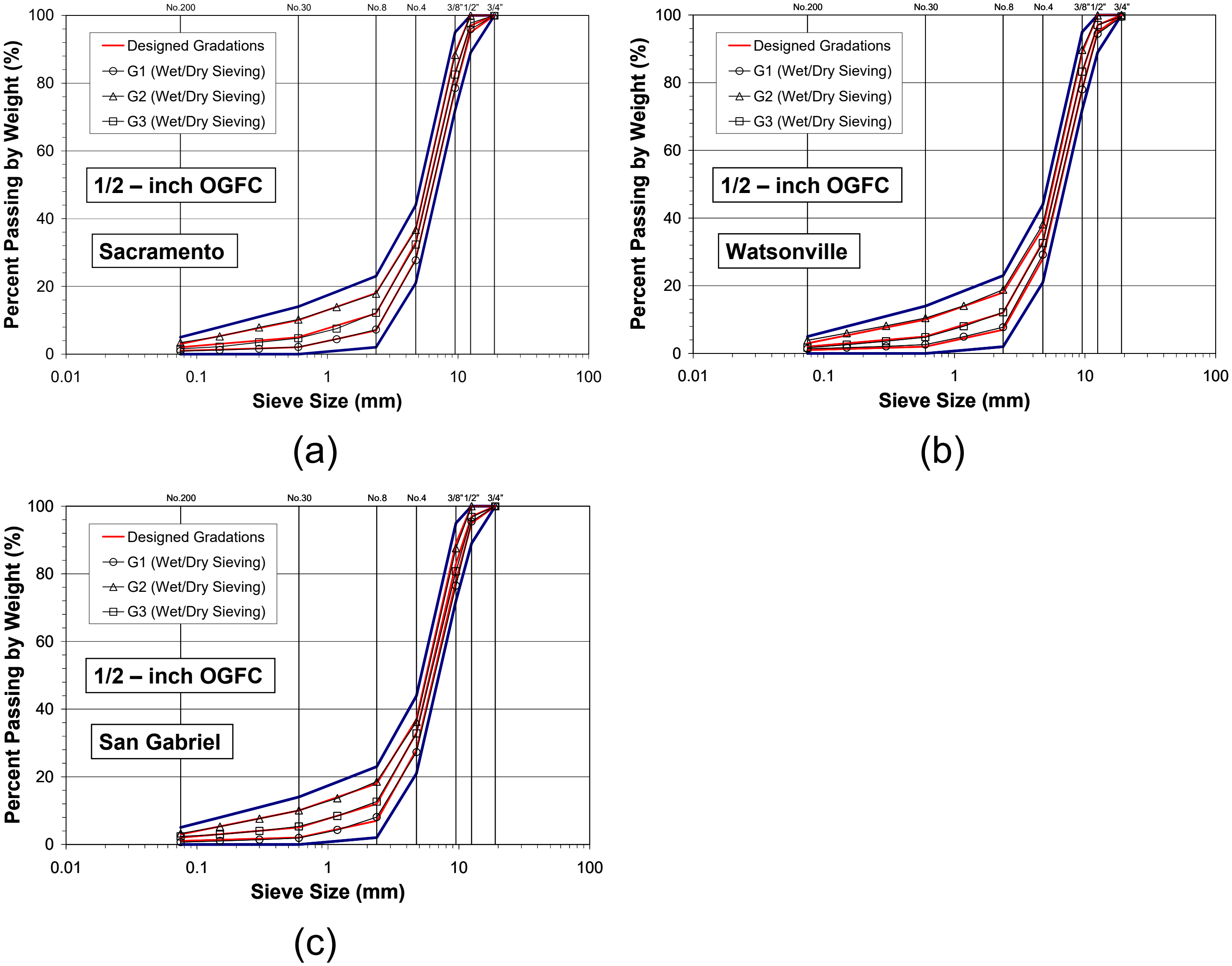


Figure 3.1: Wet/dry sieving test results: (a) Sacramento, (b) Watsonville, and (c) San Gabriel.

Instead of following the NCAT approach for selecting an initial binder content based on the bulk specific gravity of the combined aggregate, the CT 368 and AASHTO T 305 methods were used to determine the initial binder contents. Draindown tests were conducted in accordance with AASHTO T 305 except that a No. 8 (2.36 mm) wire mesh basket was used. Loose mix samples were prepared at five binder contents (5.5, 6.0, 6.5, 7.0, and 7.5 percent by weight of aggregate) using a conventional PG 64-10 binder and Watsonville aggregate with the G3 gradation. At each binder content, two 1,200 gram loose mix samples were prepared for the draindown tests. Figure 3.2 shows the test results in terms of percent draindown versus binder content with an upper limit of draindown set at 0.3 percent. A binder content of 6.0 percent was selected as the initial value for the PG 64-10 mix. An initial binder content of 7.2 percent was determined for the asphalt rubber (AR) by applying a multiplier of 1.2 to the PG 64-10 mix value of 6.0 percent. An initial binder content of 6.5 percent was selected for the PG 64-28 PM mix; this value was set between those of the mixes containing the PG 64-10 and AR binders.

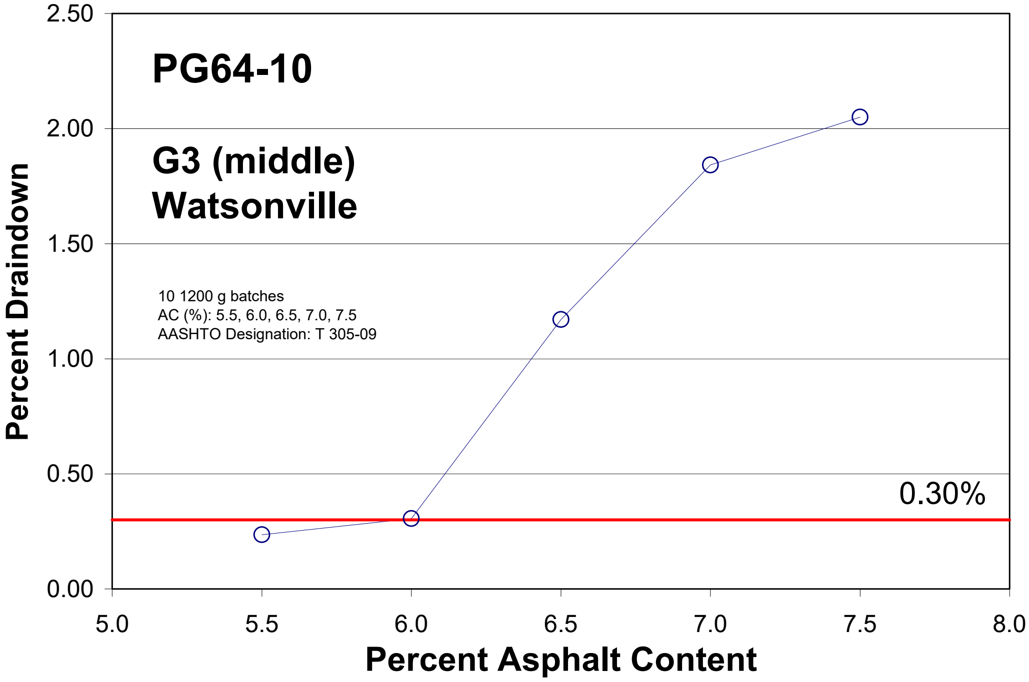


Figure 3.2: Determination of initial binder contents from draindown tests.

3.3 Determination of Voids in Coarse Aggregate

In the NCAT procedure, the first step in determining the voids in coarse aggregate is to establish the coarse fraction of the trial aggregate blend. This fraction is the portion of aggregate coarser than the break point sieve, which is defined as the finest sieve to retain 10 percent or more of the aggregate blend. Accordingly, it can be seen from Table 2.2 and Figure 2.2 that the No. 8 sieve is the break point sieve for all G1, G2, and G3 gradations. The percent passing the No. 8 sieve for the three gradations are 7 percent for the G1, 18 percent for the G2, and 12 percent for the G3. The corresponding fines content (< No. 200 sieve) are 1 percent for the G1, 3 percent for the G2, and 2 percent for the G3. The purpose of determining the voids in coarse aggregate for the coarse aggregate fraction (VCA_{DRC}) is to insure stone-on-stone contact of the aggregate skeleton in the designed OGFC mix.

Following AASHTO T 19, *Standard Method of Test for Bulk Density ("Unit Weight") and Voids in Aggregate*, a dry-rodded density of the coarse aggregate was determined for the three gradings for each of the three aggregates. With this value, VCA_{DRC} was calculated for each of the aggregate gradings (total of nine) using the following equation:

$$VCA_{DRC} = \frac{G_{ca}\gamma_w - \gamma_s}{G_{ca}\gamma_w} \times 100 \tag{3.1}$$

where: VCA_{DRC} is the voids in coarse aggregate, dry-rodded condition,

γ_s is the unit weight of the coarse aggregate fraction in the dry-rodded condition (kg/m^3)

γ_w is the unit weight of water (998 kg/m^3), and

G_{ca} is the bulk specific gravity of the coarse aggregate.

The calculated VCA_{DRC} can then be compared with the voids in the coarse aggregate of the compacted mix (VCA_{MIX}) to estimate the existence of stone-on-stone contact; stone-on-stone contact exists only if $VCA_{MIX} \leq VCA_{DRC}$. The following equation is used to determine VCA_{MIX}:

$$VCA_{MIX} = 100 - \frac{G_{mb}P_{ca}}{G_{ca}} \tag{3.2}$$

where: G_{mb} is the bulk specific gravity of the compacted mix,

P_{ca} is the percent of coarse aggregate in mix, and

G_{ca} is the bulk specific gravity of the coarse aggregate.

Table 3.2 provides a summary of the determination of voids in the coarse aggregate (AASHTO T 19 and T 85) VCA_{DRC}, bulk specific gravity (BSG), and absorption for each aggregate and each gradation. Mean values of VCA_{DRC} for the three aggregates are: Sacramento, 39.4 percent; Watsonville, 36.9 percent; and San Gabriel, 38.6 percent. The data suggest no strong correlation between VCA_{DRC} and gradation type. The aggregates shown in the photographs in Figure 2.2 represent the coarse aggregate fractions (break point sieve, No. 8 sieve) for the three materials.

Table 3.2: Summary of Determination of Voids in Coarse Aggregates (AASHTO T 19 and T 85)

Aggregate Type	Gradation	Bulk Specific Gravity (BSG)	BSG SSD[1]	Apparent Specific Gravity	Absorption (%)	Bulk Density (kg/m^3)	VCA_{DRC} (%)	Mean of VCA_{DRC}	SD[2] of VCA_{DRC}
Sacramento	G1 (coarse)	2.677	2.722	2.804	1.684	1,610.41	39.73	39.41	0.28
	G2 (fine)	2.636	2.690	2.787	2.056	1,595.90	39.33		
	G3 (middle)	2.657	2.713	2.815	2.111	1,612.67	39.18		
Watsonville	G1 (coarse)	2.646	2.716	2.846	2.650	1,680.27	36.38	36.87	0.44
	G2 (fine)	2.652	2.721	2.849	2.608	1,666.40	37.04		
	G3 (middle)	2.667	2.730	2.847	2.371	1,671.25	37.20		
San Gabriel	G1 (coarse)	2.582	2.633	2.720	1.964	1,606.44	37.66	38.58	0.81
	G2 (fine)	2.604	2.648	2.724	1.683	1,581.62	39.15		
	G3 (middle)	2.601	2.642	2.712	1.577	1,584.76	38.95		

Notes:

1. SSD: saturated surface dry.
2. SD: standard deviation.

3.4 Selection of Optimum Gradation

To select optimum gradations, sample preparation included one loose mix sample to determine the theoretical maximum specific gravity (G_{mm}) according to the AASHTO T 209 procedure, and three 102 mm diameter SGC specimens compacted with 50 gyrations to determine the air-void content (V_a) and voids in coarse aggregate (VCA_{MIX}).

$$V_a = 100 \times \left(1 - \frac{G_{mb}}{G_{mm}}\right) \quad \textbf{(3.3)}$$

where: G_{mb} is the bulk specific gravity of the compacted mix

G_{mm} is the theoretical maximum specific gravity of the mix.

Criteria for selecting an optimum gradation for each of the mixes (three aggregates, three gradings, and three binders) were as follows:

Criteria for Selecting Optimum Gradation
1. Highest V_a
2. $VCA_{MIX} \leq VCA_{DRC}$
3. $V_a \geq 18\%$

The AASHTO T 269 Method, *Standard Method of Test for Percent Air Voids in Compacted Dense and Open-Graded Mixes*, was used to determine the air-void content of each compacted mix. In this method, the density of a specimen is calculated based on its dry mass and volume (measured average height and diameter). *N.B., the SSD (AASHTO T 166A), Parafilm (AASHTO T 275A), and Corelock (AASHTO T 331) procedures are not applicable for determining* G_{mb} *for compacted open-graded asphalt mixes.*

3.5 Analysis

The full analyses of the test data that are presented in Reference (*2*) made use of the following: descriptive statistics including measures of mean, standard deviation (SD), and coefficient of variation (CV); boxplots; tree-based models; and correlation matrices. In this shortened version of that document, only the analyses presented in boxplots are included.

Figure 3.3 contains a boxplot summary of percent air-void contents by gradation, binder, and aggregate type. Figure 3.4 and Figure 3.5 illustrate air-void content versus aggregate type and aggregate gradation, respectively.

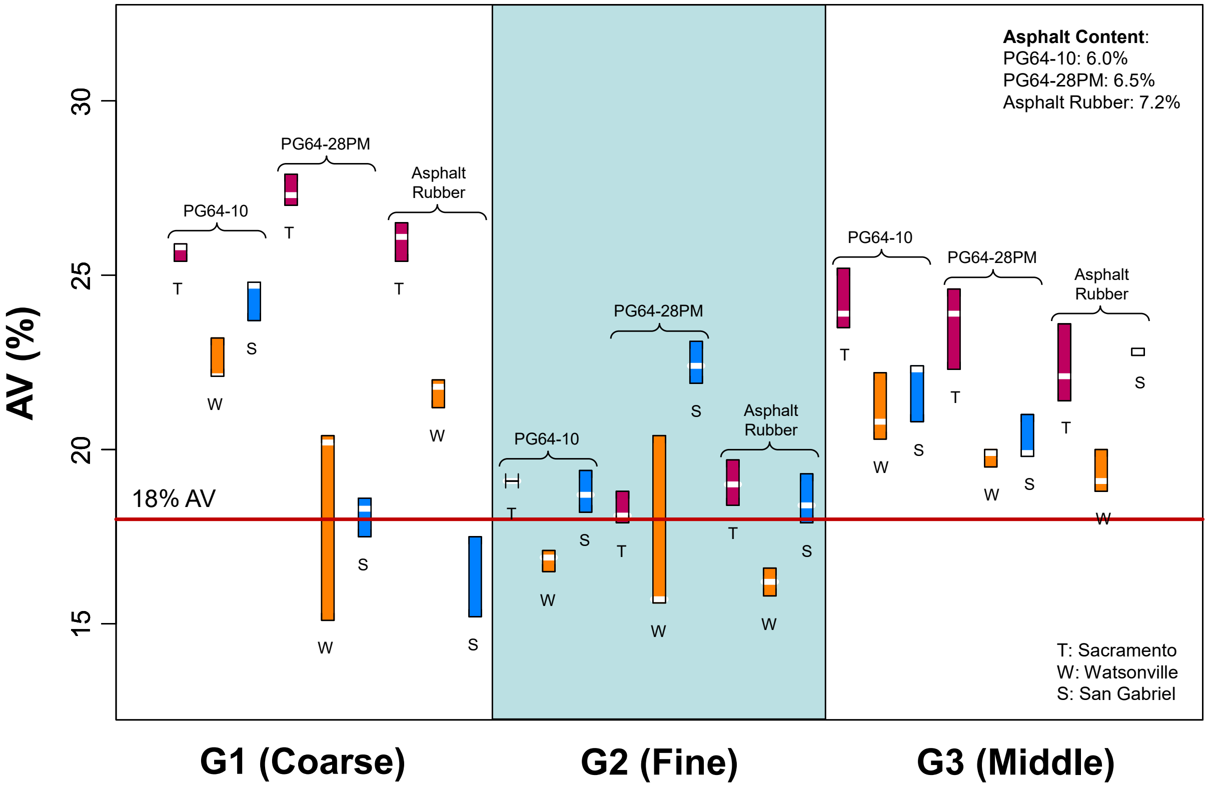


Figure 3.3: Boxplots of air-void content versus gradation, binder, and aggregate type, respectively.

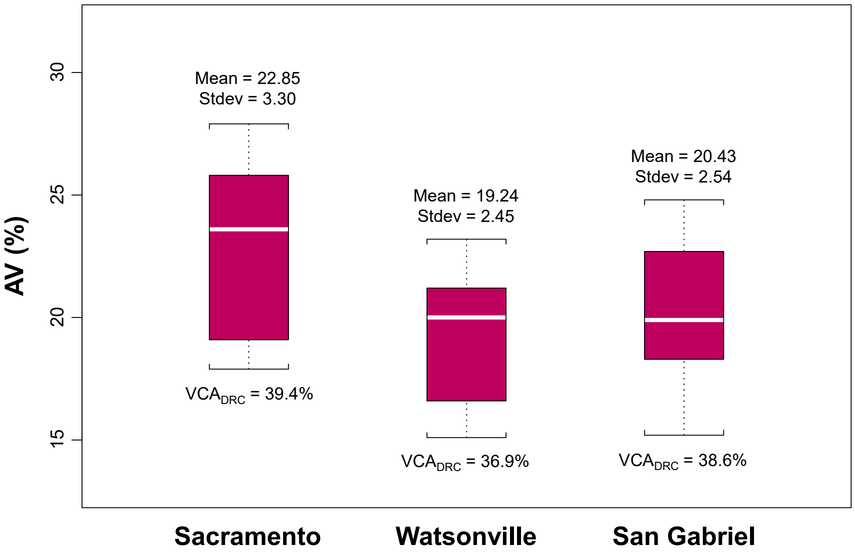


Figure 3.4: Boxplots of air-void content versus aggregate type.

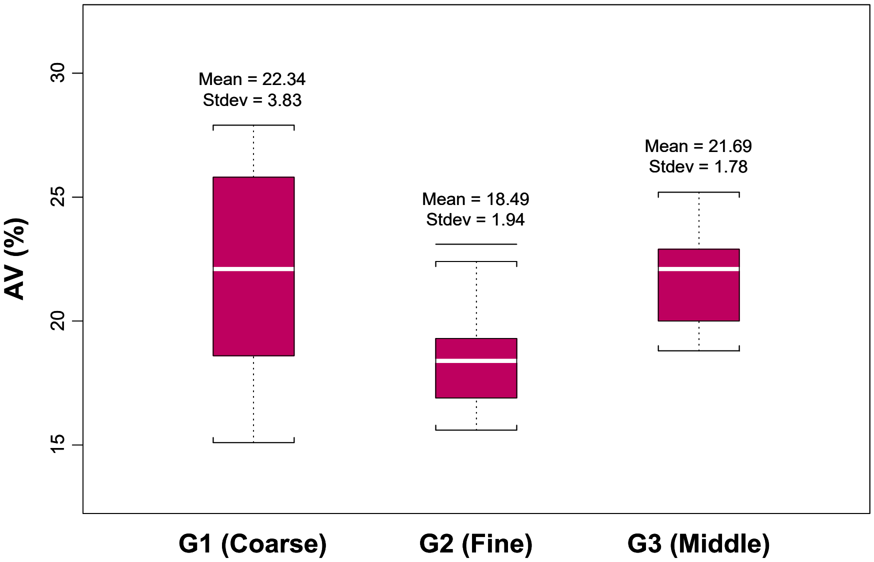


Figure 3.5: Boxplots of air-void content versus gradation.

The results of this first phase of the investigation are as follows.

1. Regardless of gradation and binder type, the ranking of air-void content with respect to aggregate type is Sacramento > San Gabriel > Watsonville, and this reflects the ranking as a function of the VCA_{DRC} of the aggregates (Sacramento [39.4%] > San Gabriel [38.6%] > Watsonville [36.9%]). The two exceptions are the the AR mixes with G1 gradation and PG 64-28 PM with G2 gradation. If the air-void contents are categorized by aggregate type, as illustrated in Figure 3.4, then the ranking of air-void content still follows the same order with means and standard deviations as follows: Sacramento (mean: 22.9%; standard deviation: 3.3%) > San Gabriel (mean: 20.4%; standard deviation: 2.5%) > Watsonville (mean: 19.2%; standard deviation: 2.5%).
2. From Figure 3.5, regardless of aggregate and binder type, the ranking of air-void content with respect to gradation is G1 (coarse) > G3 (middle) > G2 (fine). An unexplained anomaly occurs, however, with the San Gabriel mixes with the PG 64-28 PM and AR binders for the G1 gradation; i.e., the G1 gradation exhibits the lowest air-void contents of the three types. The overall ranking with respect to gradation type (as shown in Figure 3.5) is: G1 (mean: 22.3%; standard deviation: 3.8%) > G3 (mean: 21.7; standard deviation: 1.8%) > G2 (mean: 18.5%; standard deviation: 1.9%).

4 PHASE II: SELECTION OF OPTIMUM BINDER CONTENT

This section describes the methodology used to select optimum binder contents for the optimum gradations for the three aggregates, i.e., the three G1 (coarse) gradations selected in the Phase I study described in Chapter 3.

4.1 Specimen Preparation and Data Analyses

For each combination of three aggregates (Sacramento, Watsonville, and San Gabriel) and three binder types (PG 64-10, PG 64-28 PM, and asphalt rubber [AR]), three trial binder contents in increments of 0.7 percent (target value [TV], TV±0.7 percent) were used to determine mix optimum binder contents. The initial TV binder contents used in this phase were the same target values used for the mixes in Phase I, i.e., PG 64-10 (6.0 percent), PG 64-28 PM (6.5 percent), and asphalt rubber (7.2 percent). The following mixes were prepared for each binder content: two loose mix samples for the draindown tests, one loose sample for G_{mm} determination, and three SGC samples compacted with 50 gyrations to determine air-void contents and for use in Cantabro tests.

Results from the air-void content, draindown, and Cantabro tests were then used to determine optimum binder contents for each of the mixes (a total of 27). Results of these tests are presented in the form of boxplots. Tree-based modeling was used to interpret the results included in the boxplots. Detailed test data and analyses are included in Reference (*2*).

4.2 Test Results for Air-Void Content Determinations

The air-void test data are presented in the form of boxplots in Figure 4.1 for binder type and asphalt content for the three aggregates. It can be seen from this figure that the majority of the Watsonville test specimens exhibited the lowest air-void contents. Also, most of these specimens had test results that lie within the specified range of air-void contents, 18 percent to 22 percent. As might be expected, for the majority of the test specimens, the higher the binder content, the lower the air-void content.

Based on the analyses:

1. The most important factor affecting percent air-void content is the aggregate. In accordance with the printed tree structure (*2*): the Sacramento aggregate exhibited the highest average air-void content, 26.34 percent; the Watsonville aggregate exhibited the lowest, 21.18 percent; and the San Gabriel aggregate, an intermediate value of 23.65 percent. In Chapter 3 the ranking of VCA_{DRC} values for the three aggregates was the same, i.e., Sacramento aggregate, 39.4 percent > San Gabriel aggregate, 38.6 percent > Watsonville aggregate, 36.9 percent *(Note:* only the G1 [coarse)] gradation type was evaluated in Phase I).

2. Regardless of aggregate type and binder type, the smaller the binder content, the larger the percent air-void content.
3. The tree-based modeling (*2*) suggests that there was some effect of binder type on air-void content for the San Gabriel aggregate for a binder content greater than 5.9 percent. (*The ranking of percent air-void content was PG 64-28 PM [24.0 percent] > PG 64-10 [23.2 percent] > AR [21.9 percent].*)
4. Mixes that satisfied the percent air-void content criterion included those for Watsonville aggregate with binder contents greater than 6.25 percent (average percent air-void content 20.6 percent) and mixes with the San Gabriel aggregate AR at binder contents greater than 5.9 percent (average percent air-void content 21.9 percent).

Normal probability and residual analyses (*2*) indicate that the tree-based model developed to interpret the boxplot summary of air-void contents is adequate.

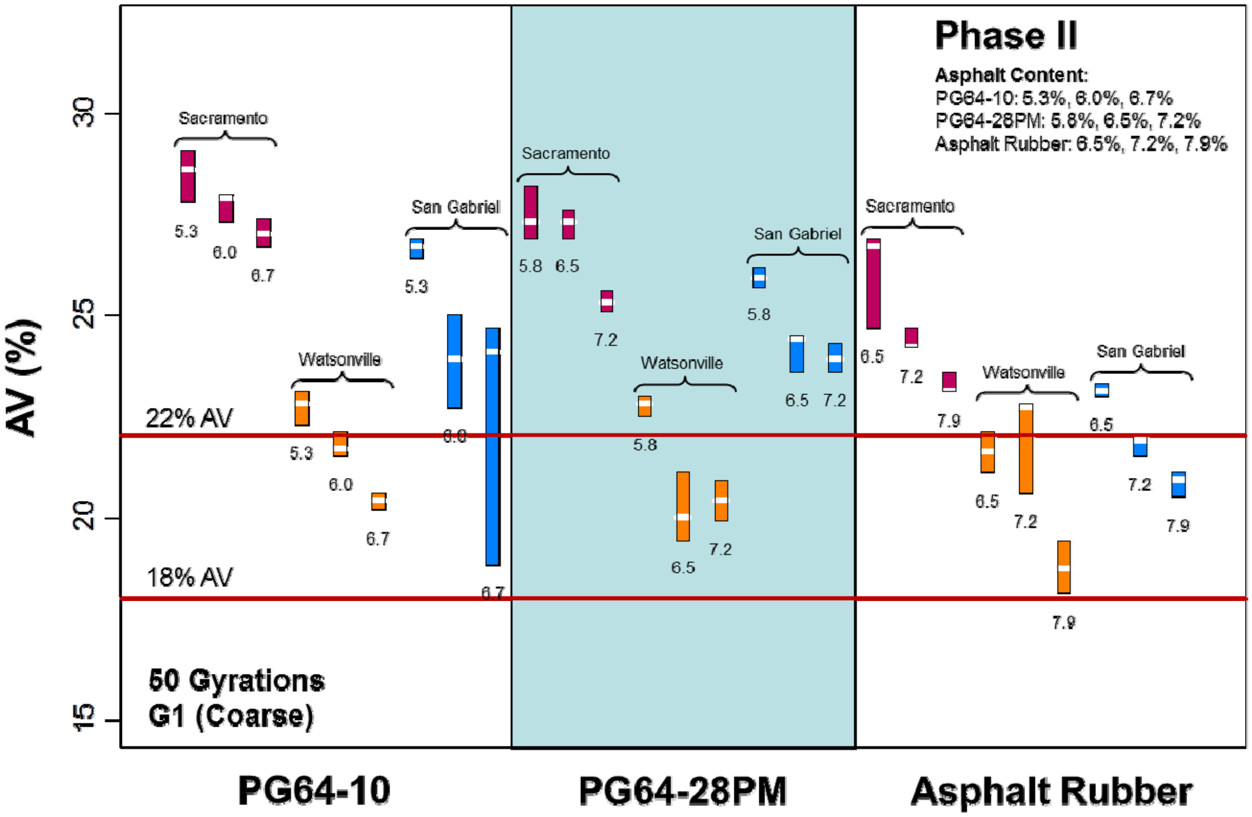


Figure 4.1: Boxplot summary of air-void contents for the three aggregates with three binders and three binder contents for each binder (27 mixes).

4.3 Test Results for Binder Draindown

Binder draindown tests were conducted on two loose mix samples for each of the 27 mixes. The tests were performed at a temperature 15°C (~27°F) higher than the production temperature, in accordance with AASHTO T 305. (*A No. 8 [2.36 mm] wire mesh was used for the basket in lieu of that called for in the test.*)

Results of the draindown tests performed on the 27 loose mixes are summarized in Reference (*2*), and a summary of the data are shown as boxplots in Figure 4.2. It should be noted (a) that all of the mixes containing the AR binder had no draindown (0 percent) and (b) that mixes containing the PG 64-28 PM binder had the highest draindown values. The majority of mixes with the PG 64-10 and PG 64-28 PM binders did not satisfy the required maximum limit of 0.3 percent draindown. Figure 4.2 also shows that the higher the binder content, the larger the percent draindown, regardless of the binder and aggregate types.

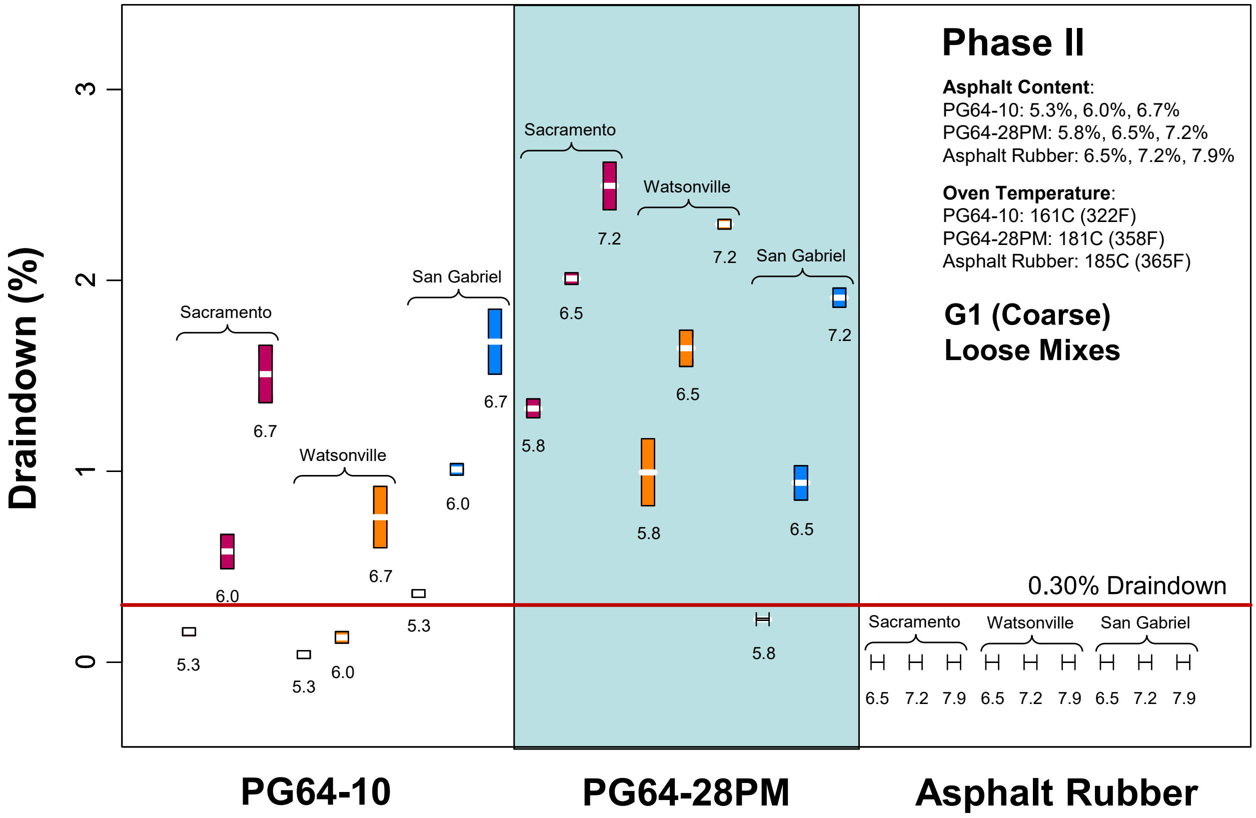


Figure 4.2: Boxplot summary of the draindown test results.

As was done for the percent air-void content analyses discussed in Section 4.2, tree-based modeling was utilized (*2*). Results of that analysis suggest the following results:

1. For these three aggregates, type did not appear to be significant enough to be included in the interpretation of the test data.
2. Binder type was the most important factor that categorized the draindown test results. Regardless of binder content, the average percent draindown was 1.54 percent for mixes containing PG 64-28 PM, 0.69 percent for mixes with PG 64-10, and no draindown (0 percent) for the mixes with AR. With this G1 grading, mixes with PG 64-28PM had a higher percent draindown than those for the mixes with PG 64-10 binder.
3. For mixes with PG 64-10 and PG 64-28 PM binders, the higher the binder content, the larger the percent draindown.
4. According to the tree-based modeling, and as illustrated in Figure 4.2, only mixes with AR and mixes with PG 64-10 and a binder content less than 5.65 percent satisfied the maximum 0.3 percent draindown criterion.

Using the same statistical analyses as in Section 4.2, it is concluded that use of the tree-based model to interpret the boxplot summary of percent draindown is acceptable, although not statistically adequate.

4.4 Test Results for Cantabro Test

As noted earlier, the Cantabro Abrasion Test is used to evaluate the durability (abrasion resistance) of OGFC mixes as part of the mix design process. In general, resistance to abrasion improves with an increase in binder content and/or the use of a stiffer binder. Using Los Angeles Abrasion test equipment, abrasion loss is determined after 300 gyrations at a speed of 30 to 33 rpm at a room temperature of 77±10°F (25±5.6°C). Loss in weight, expressed as a percentage, is calculated according to the following:

$$PL = \frac{P_1 - P_2}{P_1} \times 100 \tag{4.1}$$

where: PL is the percent Cantabro loss,

P_1 is the specimen mass prior to test (grams), and

P_2 is the specimen mass after 300 gyrations (grams).

The average percent loss of three specimens is reported as the Cantabro loss (or Cantabro abrasion loss) for each mix.

Results of the Cantabro tests performed on the 27 loose mixes are tabulated in Reference (*2*) and a summary of the data are shown as boxplots in Figure 4.3. From the Cantabro loss data shown in this figure, it is apparent that Cantabro loss is dependent on binder type. The PG 64-28 PM mixes performed the best, followed by the AR and PG 64-10 mixes in that order. In general, an increase in binder content resulted in a decrease in Cantabro loss. However, for this G1 (coarse) gradation and unit weights obtained using 50 gyrations applied in the gyratory compactor, only two mixes, those with Watsonville aggregate and the PG 64-28 PM at binder contents of 6.5 percent and 7.2 percent, satisfied the maximum 15 percent Cantabro loss criterion. Also, for the same binder type and comparable binder contents, mix specimens with the Watsonville aggregate performed better than those containing the other two aggregates.

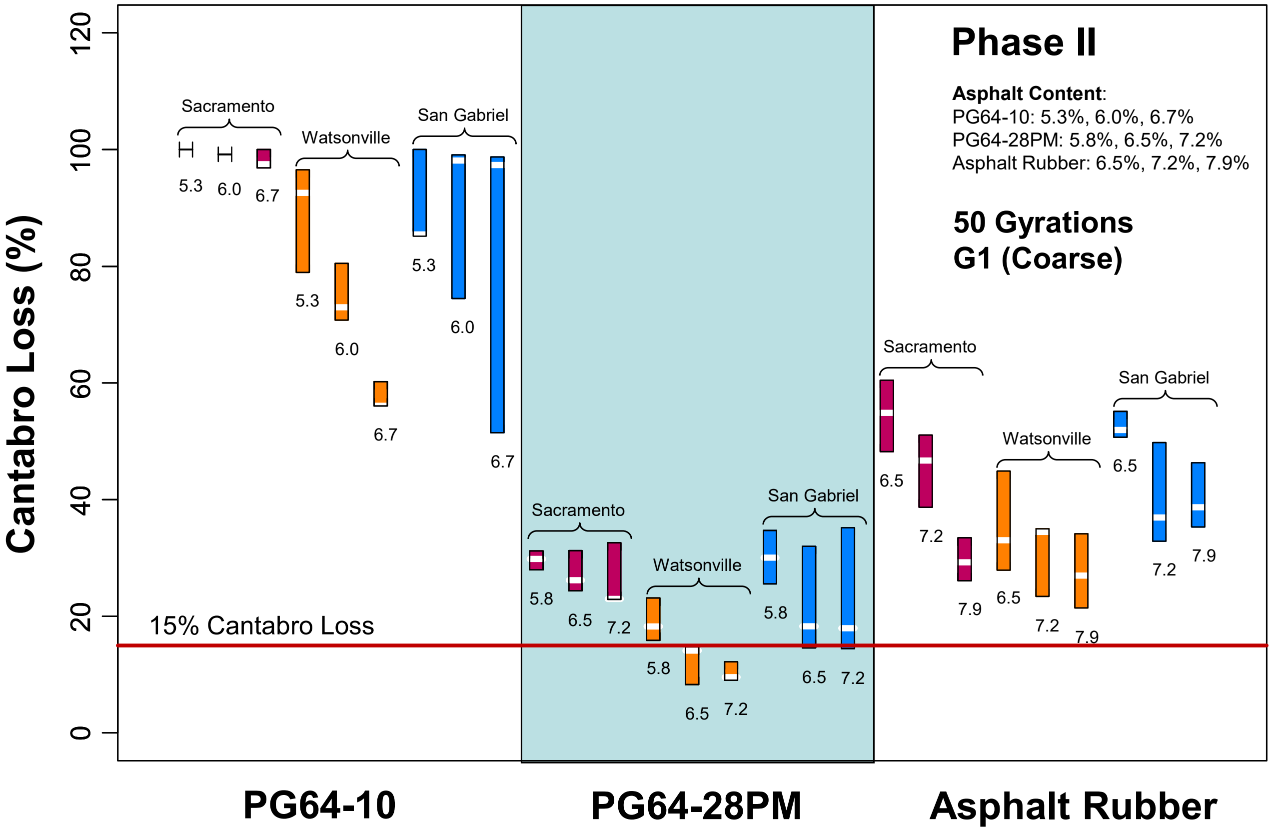


Figure 4.3: Boxplot summary of Cantabro test percent loss results.

Tree-based modeling was included to substantiate the observations of the data shown in Figure 4.3. Results from that analysis (*2*) can be summarized as follows:

1. `Binder` type is far more significant than the other two variables. The average percent Cantabro loss was 86.91 percent for PG 64-10 mixes, 39.54 percent for AR mixes, and 22.11 percent for PG 64-28 PM mixes (*it should be noted again that the test specimens were fabricated with 50 gyrations)*.
2. A`ggregate` type affects Cantabro loss. The losses were smaller for mixes containing the Watsonville aggregate than for the mixes containing the Sacramento and San Gabriel aggregates. However the mixes with the Watsonville aggregate usually had the lowest air-void contents for a given binder type (Figure 4.1).
3. Only the PG 64-28 PM mix with Watsonville aggregate satisfied the maximum 15 percent Cantabro loss criterion.

4.5 Determination of Optimum Binder Content

Using the NCAT approach and the proposed Caltrans OGFC mix design procedure, design criteria for selecting the optimum binder content are as follows:

Criteria for Selecting Optimum Binder Content
1. $18\% \le V_a \le 22\%$
2. Cantabro Abrasion Loss (%), 15% max
3. Draindown at production temperature, 0.30% max.

Table 4.1 summarizes Phase II test results regarding the averages of air-void content, draindown, and Cantabro loss. Mixes that met the specific criteria for selection of the optimum binder content are shaded in the table.

The table shows that 9 of 27 mixes satisfied the criterion for air-void content, 13 mixes satisfied the draindown criterion, and only 2 out of 27 mixes met the Cantabro loss criterion. None of the 27 mixes satisfied all three criteria simultaneously. For this test series, some mixes containing the Watsonville aggregate, with adjustments, might potentially satisfy all three criteria.

The very high Cantabro losses of the mixes used in Phase II may be attributable to the following causes:

1. The G1 (coarse) gradation contains only 7 percent passing the break point sieve and 1 percent fines (< No. 200 sieve). Thus, the lack of fines may result in a matrix of binder and fines that does not provide sufficient cohesion to this coarse aggregate structure.

2. The use of only 50 gyrations to compact specimens in the Superpave gyratory compactor may not have provided a sufficient compactive effort to achieve the desired aggregate interlocking.
3. The selected trial binder contents might not have covered a sufficient range of binder contents to permit section of the optimum value.

It is also possible that the maximum Cantabro loss criterion of 15 percent established by NCAT (and New Zealand) may be too severe.

Table 4.1: Summary of Determination of Optimum Binder Content

Aggregate Type	Binder Type	AC (%)	AV (%)	Draindown (%)	Cantabro Loss (%)	Satisfied? (Y/N)
Sacramento G1 (coarse)	PG 64-10	5.3	28.5	0.16	100.0	N
		6.0	27.7	0.58	99.2	N
		6.7	27.0	1.51	98.11	N
	PG 64-28 PM	5.8	27.5	1.33	29.7	N
		6.5	27.3	2.01	27.3	N
		7.2	25.3	2.50	26.2	N
	Asphalt rubber	6.5	26.1	0.00	54.5	N
		7.2	24.4	0.00	45.6	N
		7.9	23.3	0.00	29.6	N
Watsonville G1 (coarse)	PG 64-10	5.3	22.7	0.04	89.4	N
		6.0	21.8	0.13	74.8	N
		6.7	20.4	0.76	57.5	N
	PG 64-28 PM	5.8	22.8	1.00	19.1	N
		6.5	20.2	1.65	12.4	N
		7.2	20.4	2.30	10.3	N
	Asphalt rubber	6.5	21.6	0.00	35.3	N
		7.2	22.0	0.00	31.0	N
		7.9	18.7	0.00	27.53	N
San Gabriel G1 (coarse)	PG 64-10	5.3	26.7	0.36	90.20	N
		6.0	23.9	1.01	90.57	N
		6.7	22.5	1.68	82.53	N
	PG 64-28 PM	5.8	25.9	0.23	30.09	N
		6.5	24.2	0.94	21.63	N
		7.2	23.9	1.91	22.52	N
	Asphalt rubber	6.5	23.1	0.00	52.58	N
		7.2	21.8	0.00	39.86	N
		7.9	20.8	0.00	40.11	N

4.6 Findings of Phase II

The following provides a summary of the key findings of Phase II: Selection of Optimum Binder Content.

1. Although all the covariates are not included in the tree-based modeling (*2*), residual analyses of the tree-based models indicate that the parameters utilized in boxplots to categorize the resulting test data were sufficient for quantitative interpretation of the test data.
2. Table 4.2 summarizes the first and second levels of the most significant covariates in the tree-based models that affect air-void content, draindown, and Cantabro loss.

Table 4.2: Summary of the First- and Second-Level Covariates (Phase II)

Parameter	First Level	Second Level	Others
Air-void Content	**`Aggregate`** [1]	**`ac`**	**`binder`**
Draindown	**`binder`**	**`ac`**	
Cantabro Loss	**`binder`**	**`aggregate`**	**`ac`**

Note:
1. The covariate `aggregate` is not significant enough to be included in the tree-based model of percent draindown.

3. Aggregate type is the most important factor that affects percent air-void content. The ranking of the average air-void content based on tree-based modeling is: Sacramento (26.3 percent) > San Gabriel (23.7 percent) > Watsonville (21.2 percent). Asphalt content, *ac*, is the next most important factor; in general, the smaller the asphalt content, the larger the air-void content—as would be expected.
4. Binder type is the most important factor that categorizes the draindown test results. Based on the tree-based modeling, the ranking of the average percent draindown is: PG 64-28 PM (1.54 percent) > PG 64-10 (0.69 percent) > AR (0 percent). Also, as would be expected, the higher the asphalt content, the larger the percent draindown.
5. Based on the tree-based modeling, binder type is far more significant for Cantabro loss than the other covariates. The average Cantabro losses were: PG 64-10 mix (86.9 percent), AR mix (39.5 percent), and PG 64-28 PM mix (22.1 percent). Also, relative to the binders used in this study, Cantabro losses for the Watsonville aggregate mixes were smaller than those for mixes with the Sacramento and San Gabriel aggregates.

5 PHASE III: SUPPLEMENTAL TESTS

5.1 Findings from Phase I and Phase II

Results of the investigations from the first two phases suggest the following:

1. In general, for the mixes tested, the coarser the gradation, the larger the air-void content. Higher air-void contents are also associated with larger values of VCA_{DRC}. For the three aggregates investigated, measured VCA_{DRC} depends primarily on aggregate type rather than on aggregate gradation.
2. Although the coarse aggregate gradations produce compacted mixes that satisfy the air-void requirements, this does not guarantee that an OGFC mix will meet the other performance-related test specifications. A lack of fines (defined by either the percent passing the No. 200 sieve or by the percent passing the break point sieve) might contribute to this result.
3. Regardless of the three aggregate and three binder types investigated, the high Cantabro loss results obtained in the Phase II study may be due to the following:
    a. Compaction of the test specimens in the SGC using 50 gyrations did not provide a compactive effort sufficient to retain the integrity of the specimens associated with the aggregate interlocking that occurs in the field.
    b. The G1 (coarse) gradation used in the study accommodates only 7 percent passing the No. 8 break point sieve and 1 percent of fines passing the No. 200 sieve.
    c. The selected range of trial binder contents—in increments of 0.7 percent (TV, TV±0.7 percent), with target values determined from CT 368 and AASHTO T 305—does not necessarily include the optimum binder content, according to the results obtained in this study.
    d. The NCAT mix design procedure's limit of a 15 percent maximum for Cantabro loss may be too strict (too low) for OGFC mixes.
4. Increasing the binder content helps to reduce Cantabro loss but increases mix draindown. The Cantabro loss criterion thus establishes the lower bound and the draindown criterion the upper bound for suitable binder contents.

5.2 Test Plan of Phase III and Specimen Preparation

Based on the findings from Phases I and II, supplemental tests were conducted in Phase III using two mixes selected from the earlier studies. The purpose of this investigation was to provide a preliminary evaluation of the effects of gyratory compactive effort (number of gyrations), aggregate gradation, and specimen conditioning on the performance testing and specifications for OGFC mix design. This phase of the study also investigated the effect of gradation type on Cantabro loss by using a variety of previously untested additional specimens that had been fabricated for Phase I.

These two mixes were selected for Phase III:

1. Mix with PG 64-28 PM binder, Watsonville aggregate (VCA_{DRC} = 36.9 percent), and G2 (fine) gradation; three binder contents (5, 6, and 7 percent): designated *PG64-28PM Watsonville G2*.
2. Mix with AR binder, Sacramento aggregate (VCA_{DRC} = 39.4 percent), and G1 (coarse) gradation; three binder contents (6.5, 7.2, and 7.9 percent): designated *AR Sacramento G1*.

Since the theoretical maximum density (G_{mm}) values were already available from the Phase II testing, the same binder contents were used for the G1 mix with Sacramento aggregate and the AR binder. Specimens were prepared using the SGC compactor at two compactive efforts, 50 and 100 gyrations. Specimens were prepared at two sizes: 4 in. (102 mm) diameter for volumetric properties and Cantabro tests; and 5.91 in. (150 mm) diameter for Hamburg Wheel-Track Device testing. They were also prepared for two conditions: dry, as compacted, and wet, conditioned by Moisture Induced Sensitivity Test (MiST). Table 5.1 summarizes the test plan of Phase III. All test data are summarized in Reference (*2*).

Table 5.1: Summary of Test Plan for Phase III

Mix Type	Gyrations/Conditions	Binder Content	Test Type	Compaction Method	Specimen Size	Total Tests
Asphalt rubber (AR) Sacramento G1 Gradation	2 gyrations: 50, 100 2 conditions: Dry, Wet	6.5, 7.2, 7.9%	VCA_{MIX} & $G_{mb}{}^{1}$	$SGC^{1,\,3}$	4-inch D^{3} x 2.5-inch H^{4}	27
			Cantabro	SGC	4-inch D x 2.5-inch H	27^{2}
	2 gyrations: 50, 100 1 condition: Dry	7.2%	HWTD	SGC	5.9-inch D^{3} x 2.5-inch H	4
PG 64-28PM Watsonville G2 Gradation	2 gyrations: 50, 100 2 Conditions: Dry, Wet	5, 6, 7%	RICE ($G_{mm}{}^{1}$)	Loose mix		3
			VCA_{MIX} & G_{mb}	SGC	4-inch D x 2.5-inch H	30
			Draindown	Loose mix		6
			Cantabro	SGC	4-inch D x 2.5-inch H	30^{2}
	2 gyrations: 50, 100 1 condition: Dry	6.5%	$HWTD^{1}$	SGC	5.9-inch D x 2.5-inch H	4
Phase I: Combinations of three aggregates (Sacramento, Watsonville, San Gabriel), three binders (PG 64-10, PG 64-28 PM, asphalt rubber [AR]), and three gradations (G1, G2, G3)	1 gyration: 50 1 condition: Dry	PG 64-10: 6% PG 64-28 PM: 6.5% AR 7.2%	Cantabro	SGC	4-inch D x 2.5-inch H	81

Notes:

1. VCA_{MIX}: voids in coarse aggregate of the compacted mixture; G_{mb}: bulk specific gravity of the compacted mixture; G_{mm}: the theoretical maximum density of the mixture; HWTD: Hamburg Wheel-Tracking Device Test; SGC: Superpave gyratory compaction.
2. The specimens prepared for VCA_{MIX} and G_{mb} were used for Cantabro tests.
3. Available SGC compaction molds with internal diameters: 4 in. (102 mm) and 150 mm (5.9 inch).
4. The specimen height for the Phase III test plan is 2.5 in. (63.5 mm).

5.3 Test Results and Analyses

5.3.1 Comparison of Percent Air-Void Content

Figure 5.1 compares the air-void contents for the PG64-28PM Watsonville G2 mixes to the AR Sacramento G1 mixes in a boxplot summary showing the air-void contents of the specimens before they were conditioned by the MiST machine or subjected to Cantabro testing. Because of a number of unfortunate circumstances, no specimens were compacted at 50 gyrations for the AR Sacramento G1 mix.

Figure 5.1 reveals a large difference (roughly 11.0 percent) between the air-void contents of the AR Sacramento G1 mix (averaging 23.5 percent) and the PG64-28PM Watsonville G2 mix (averaging 12.5 percent); this difference can be attributed to the fine gradation of the latter mix. (More detailed data are included in Reference [*2*]). As noted earlier, the VCA_{DRC} value is 39.4 percent for the Sacramento aggregate and 36.9 percent for the Watsonville aggregate, and the percent passing the break point sieve is 7 percent for G1 (coarse) gradation and 18 percent for G2 (fine) gradation. From the perspective of volumetric design, a mix with a larger VCA_{DRC} value, a smaller percent passing the break point sieve, and lower asphalt content will have increased air-void content. For these two mixes, the effects of asphalt content and VCA_{DRC} have only small differences. By this logic, the 11 percent difference in average air-void content between these two mixes is primarily the result of the difference in percent passing the break point sieve, i.e., gradation type. This strongly suggests that the air-void content of an OGFC mix is largely influenced by the selection of the aggregate gradation.

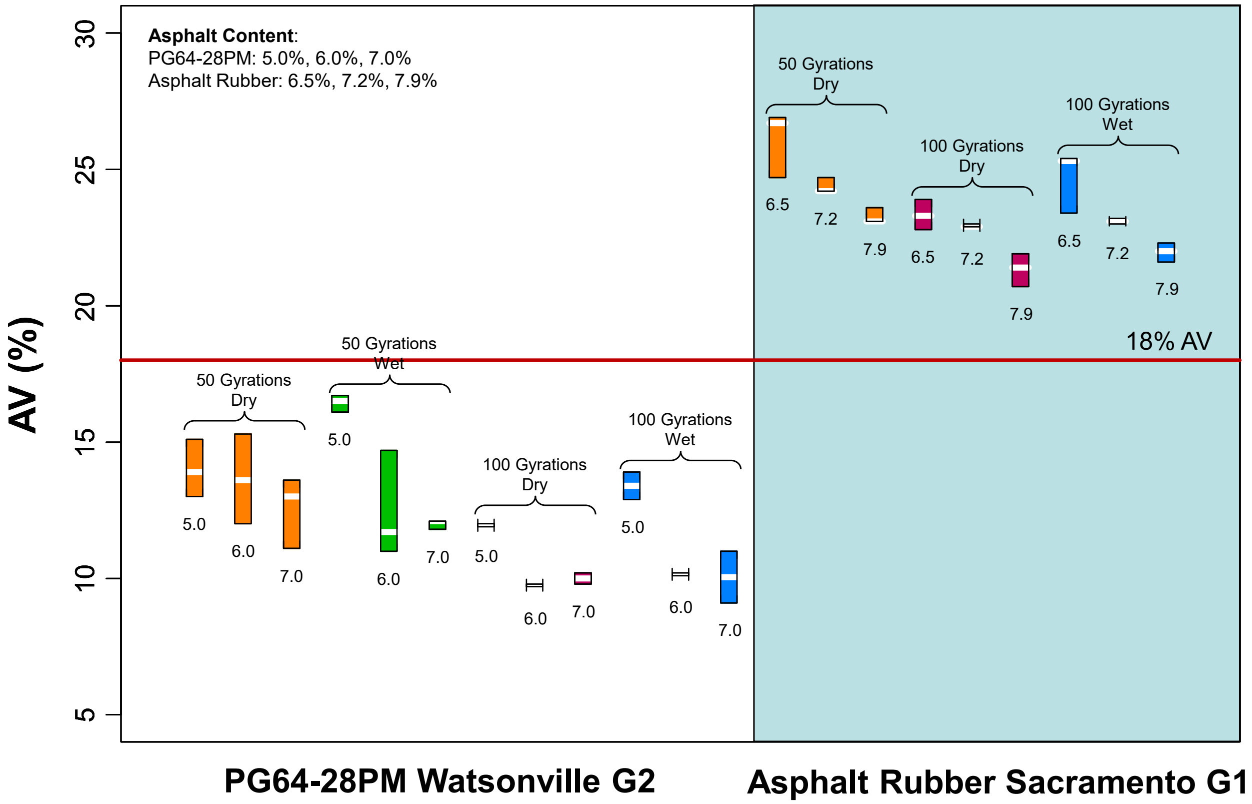


Figure 5.1: Comparison of air-void contents for the PG64-28PM Watsonville G2 and AR Sacramento G1 mixes (Phase III).

5.3.2 Draindown Test Results and Analysis

Figure 5.2 compares the draindown test results for the PG 64-28 PM mixes with Watsonville aggregate from the tests in Phase II and Phase III. As the figure shows, aggregate gradation has a significant influence on the amount of draindown. To prevent draindown during transportation of the mix from the plant to the construction site, the highest allowable asphalt content for the G2 (fine) gradation was roughly 1.5 percent higher than that of the G1 (coarse) gradation based on the maximum 0.3 percent draindown criterion. From the viewpoint of conducting mix durability testing, the greater the asphalt content, the lower the Cantabro loss; in other words, mix durability certainly benefits from the use of fine gradations.

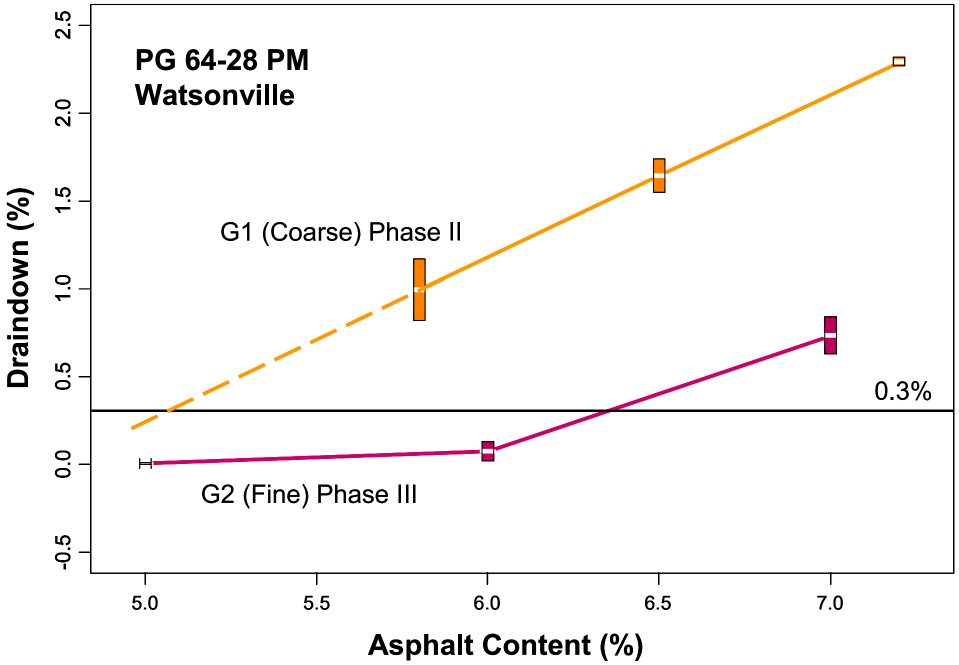


Figure 5.2: Comparison of percent draindown between coarse (Phases II) and fine (Phase III) gradations of PG 64-28 PM mixes containing Watsonville aggregate.

5.3.3 Cantabro Test Results and Analysis of Phase III

In Phase III, the Cantabro test was used to evaluate not only the effects of gradation, binder, and aggregate type, but also the effect of conditioning on mix durability performance. Before the Cantabro testing, the “wet” specimens were conditioned using the MiST machine with test parameters set as follows: 3,000 loading cycles, 40 psi (276 kPa) peak pressure, and 50°C (122°F) water temperature. The MiST machine simulates the pore water pressure built-up due to repeated trafficking during rain.

The Cantabro test data are summarized in Figure 5.3 as boxplots for the AR Sacramento G1 and PG64-28PM Watsonville G2 mixes. Key findings based on the figure are as follows:

1. All of the AR Sacramento G1 mixes failed to meet the Cantabro test criterion of sustaining a maximum loss of 15 percent or less, while most of the PG64-28PM Watsonville G2 mixes passed. It seems that the effect of gradation, i.e., fines content, is a primary factor in passing or failing the Cantabro test.
2. The PG64-28PM Watsonville G2 mixes prepared using 100 gyrations performed slightly better than those specimens fabricated using 50 gyrations. However, for the AR Sacramento G1 mixes, the 100-gyration specimens performed worse than 50-gyration specimens. Crushed aggregates were observed during compaction of the AR Sacramento G1 mix with the 100-gyration compactive effort. Thus, it is possible that the greater Cantabro loss may be due to disintegration of those aggregates. (*This suggests*

that the 50-gyration compaction effort applied to the G1 mixes in the earlier testing may not have been the primary reason those mixes did not pass the Cantabro test.)

3. No effect of MiST conditioning was observed on Cantabro loss for the PG64-28PM Watsonville G2 and AR Sacramento G1 mixes, probably due to the large amount of void spaces in the compacted mix. Those voids can quickly dissipate built-up pore water pressure and mitigate or prevent damage.
4. For the AR Sacramento G1 mixes, it is apparent that regardless of gyration number and conditioning method, the common rule of Cantabro testing—the larger the binder content, the smaller the Cantabro loss—remains unchanged. However, for the PG64-28PM Watsonville G2 mix, the trend was not as noticeable as it was for the AR Sacramento G1 mix, likely due to the improvement in durability due to the fine gradation.

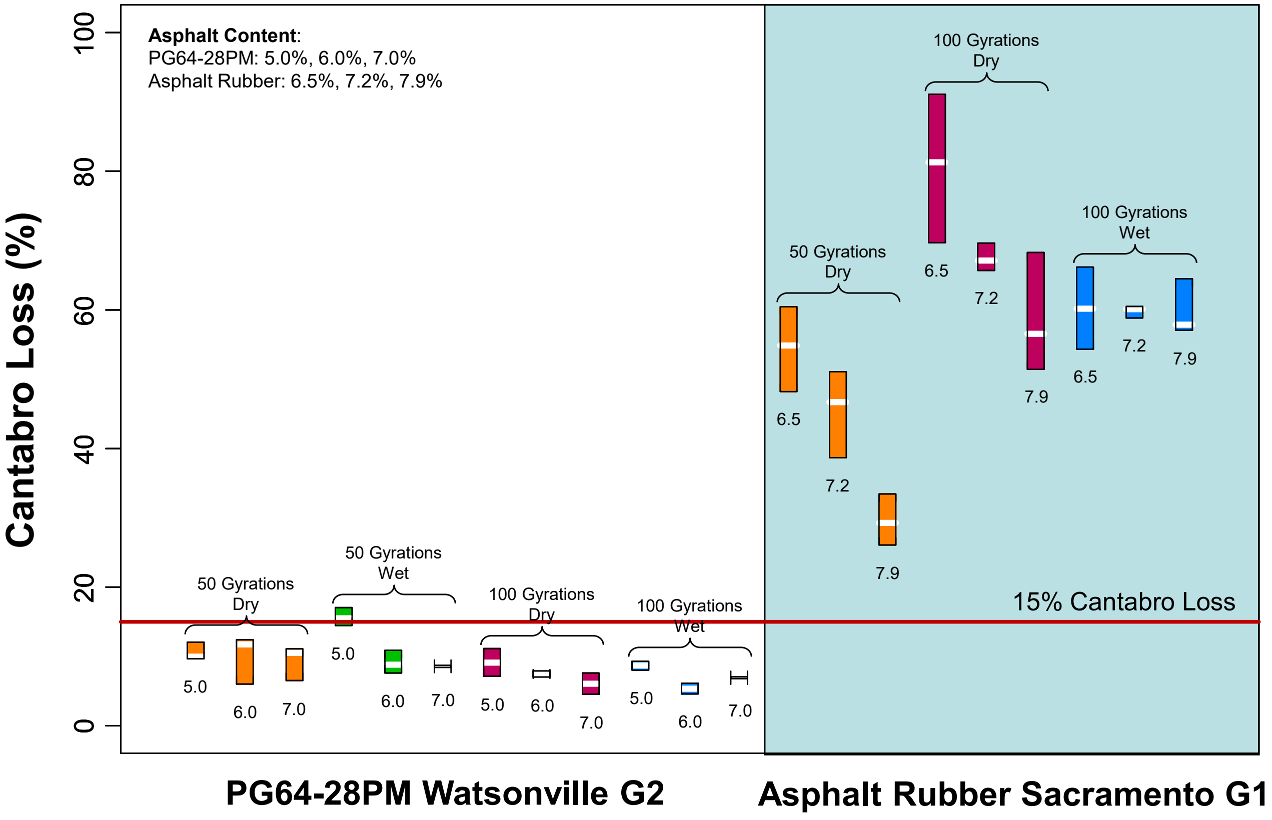


Figure 5.3: Boxplot summary of percent Cantabro loss (Phase III).

5.3.4 Cantabro Test Results and Analysis Using Phase I Specimens

Figure 5.4 provides a summary of Cantabro test results for the mixes used for the Phase I study. The detailed test results are summarized in Reference (*2*). Overall, the ranking of Cantabro loss (from low to high) in terms of binder type is PG 64-28 PM < AR < PG 64-10. Within each binder type, the G2 (fine) gradation generally had the lowest percent Cantabro loss. The figure also shows the effect of aggregate type on Cantabro performance with respect to gradation. For instance, the Watsonville aggregate had the lowest percent Cantabro loss in G1 (coarse) and G2 (fine), whereas San Gabriel performed the best in G3 (middle). In this test series, the mixes with the Sacramento aggregate exhibited the highest Cantabro losses with one exception, the mix with the fine gradation (G2) and PG 64-28 PM binder.

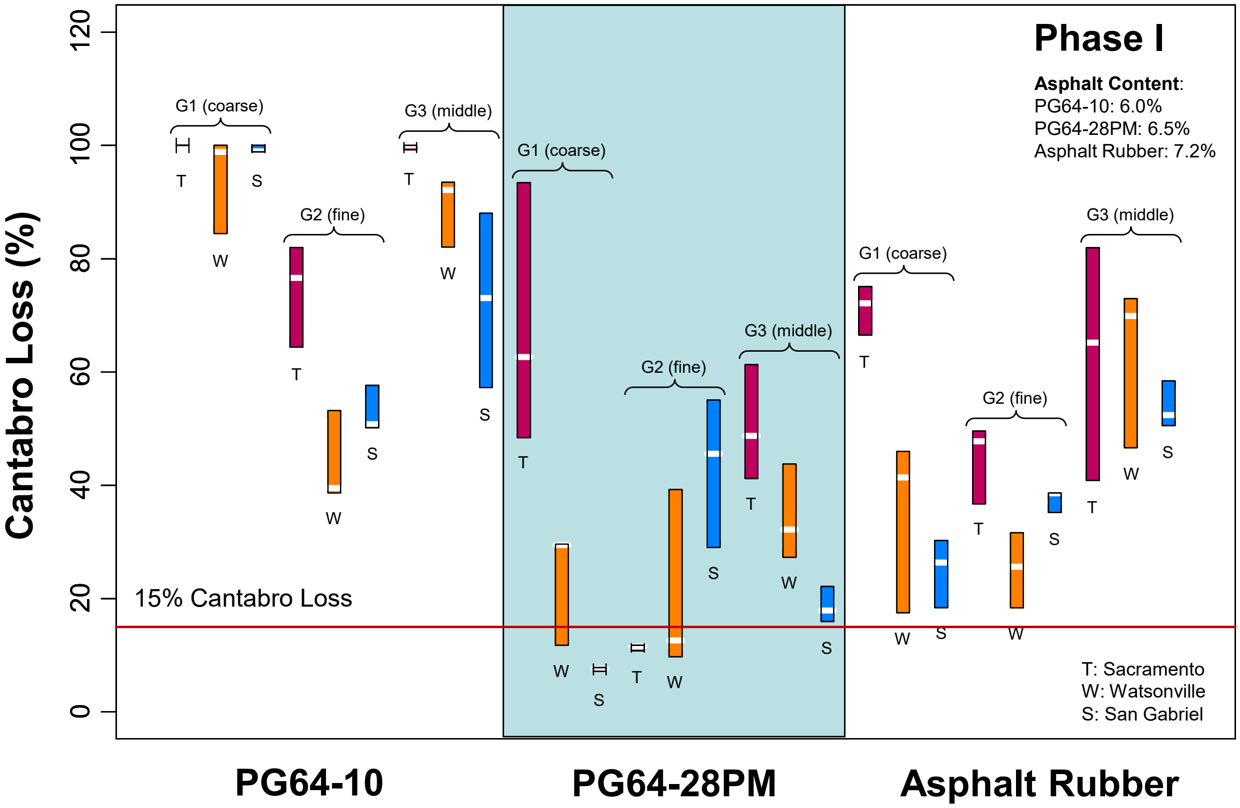


Figure 5.4: Boxplot summary of percent Cantabro loss using Phase I specimens.

Photographs of the test specimens at end of the Cantabro tests are shown in in Figure 5.5 categorized by binder type, aggregate source, and gradation type. Overall, mixes with Watsonville and San Gabriel aggregates had smaller Cantabro losses compared to the mixes with Sacramento aggregate. Mixes with Watsonville aggregate performed slightly better in some instances than mixes with San Gabriel aggregate. Mixes with PG 64-10 binder had higher Cantabro losses than mixes with either PG 64-28 PM or AR binder; some specimens with PG-64-10 binder had losses as high as 100 percent.

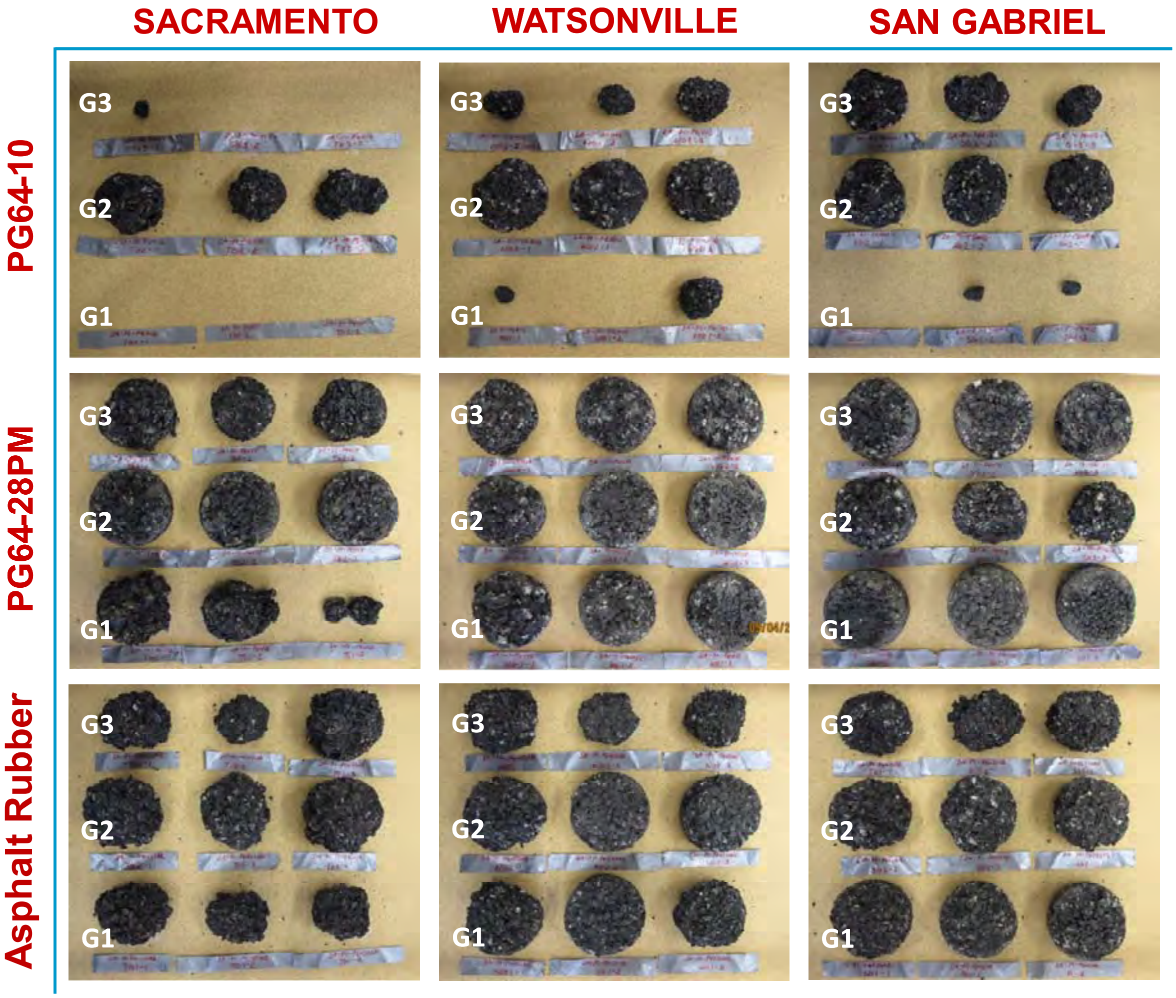


Figure 5.5: Photographic summary of Cantabro tests using Phase I SGC specimens (50 gyrations).

5.3.5 HWTD Test Results and Analysis

Hamburg Wheel-Track Device (HWTD) testing conducted in this study followed AASHTO T 324, *Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)*. The test plan for HWTD is in Table 5.1. One set of HWTD tests was conducted for each mix type and gyration number. Each set included two runs (left and right) of HWTD tests. Each run was conducted with two 5.91 in. (150 mm) diameter gyratory-compacted specimens. The evolution of rutting in the HWTD tests over time (number of passes) and space (profile position) domains were developed using rutting evolution image-and-contour plots. Hence, two rut evolution curves were developed per mix type per gyration number. The development of these curves is described in detail in Reference (*2*). The resulting data are shown in Figure 5.6 and Figure 5.7 for the two mixes.

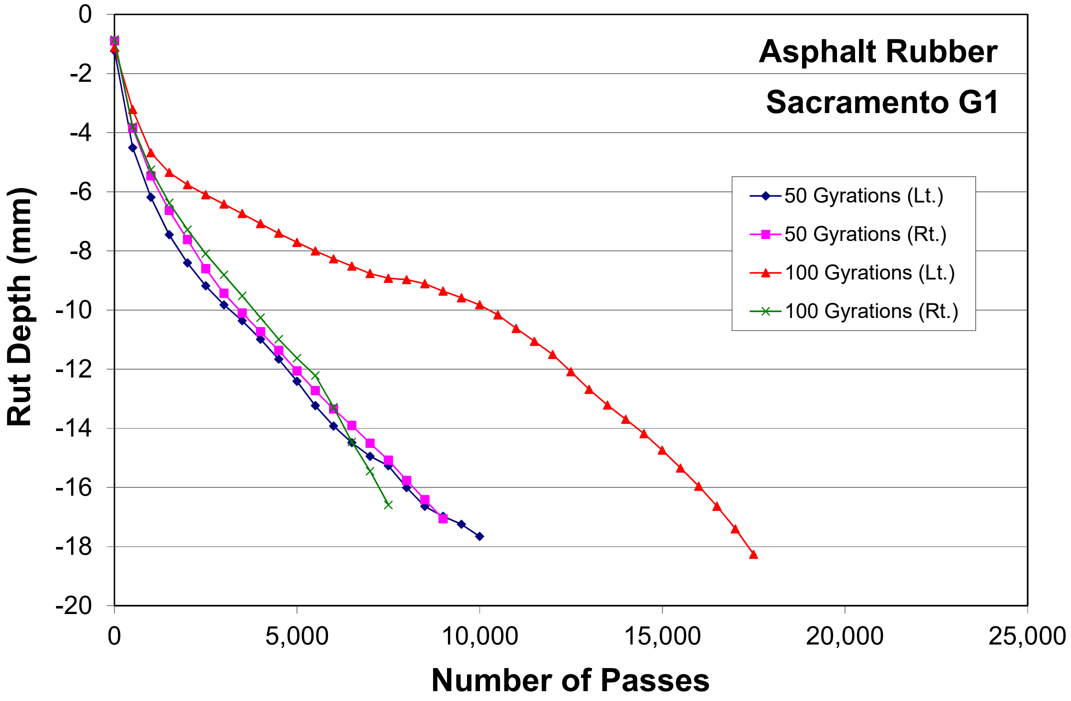


Figure 5.6: HWTD test results for the AR Sacramento G1 mixes.

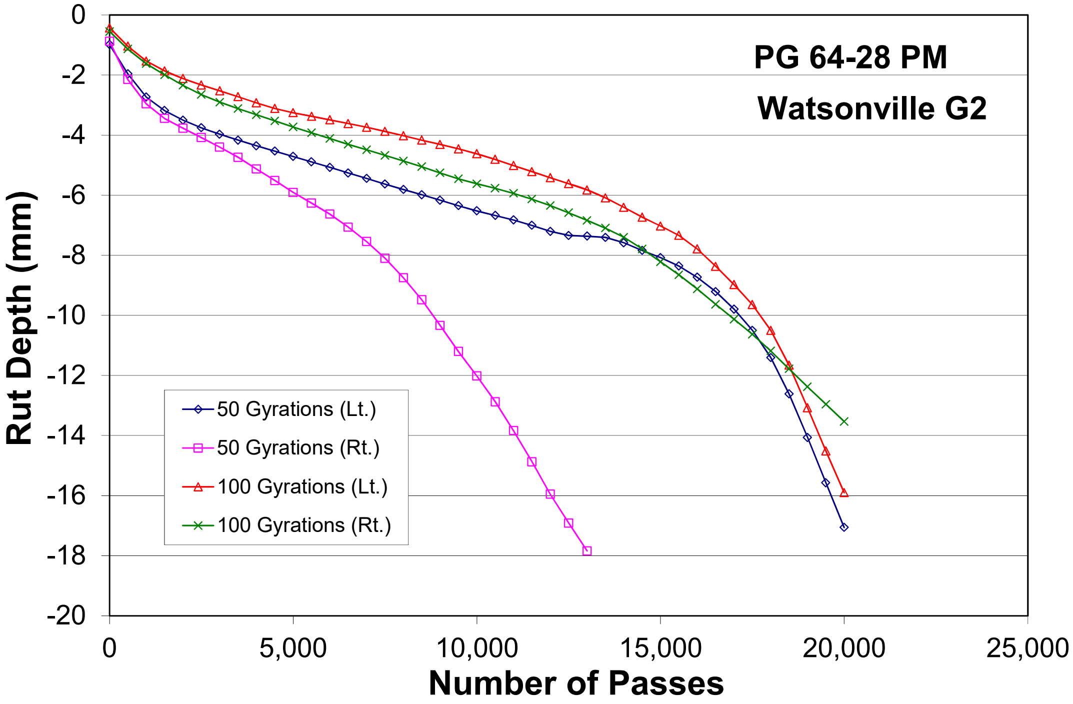


Figure 5.7: HWTD test results for the PG64-28PM Watsonville G2 mixes.

Average rut depths at 10,000 passes and 20,000 passes are used as the performance parameters in the following analyses. In addition, the rut index defined by the following equation provides another performance parameter.

$$Rut\_Index = \frac{20{,}000 - 10{,}000}{|rut@20{,}000| - |rut@10{,}000|} \tag{5.1}$$

where, $|rut@20{,}000|$ stands for the absolute value of the average rut depth (mm) at 20,000 passes.

The rut index represents the average loading passes required to reach a 1 mm rut depth during the loading period from 10,000 to 20,000 passes. The higher the value of the rut index, the better the rutting-resistance capacity of the mix in the presence of water.

Table 5.2 summarizes the HWTD test results for Phase III including the specimen air-void contents, average rut depths at 10,000 and 20,000 passes, rut index, and the number of passes to failure (n_f). The number of passes to failure is determined by a three-stage Weibull approach and described in Reference (*2*). Based on the data summarized in Figure 5.6 and Figure 5.7, key findings are as follows:

1. The PG64-28PM Watsonville G2 mix performed better than the AR Sacramento G1 mix at the densities resulting from both the 50- and 100-gyration compactive efforts.
2. The HWTD test results for mix AR Sacramento G1 are consistent in the 50-gyration tests but quite different for the 100-gyration tests. However, during preparation of the 100-gyration specimens, crushed aggregates were observed and their disintegration may have caused more rutting. Conversely, the test results for PG 64-28PM Watsonville G2 mixes are similar for the 100-gyration tests but rather different for the 50-gyration tests. This may suggest that for mix PG 64-28PM Watsonville G2, the compactive effort of 100 gyrations provided more aggregate interlocking than 50 gyrations.
3. Preliminary HWTD test results for the same mix show that the 100-gyration specimens performed much better than the 50-gyration specimens. Thus, the gyrations applied in Superpave gyratory compaction have an apparent effect on HWTD rutting regardless of mix type. This raises an immediate question: What gyration number should be specified in an OGFC mix design to appropriately judge the mix performance through various performance tests?

Table 5.2: Summary of HWTD Test Results (Phase III)

Mix Type	Test Set Number	Slab Location	Specimen Name	Height (mm)	Diameter (mm)	AV (%)	Last Passes	Average Rut Depth (mm)		Rut Index	Number of Passes to Failure (n_f)
								@10K	@20K	10K - 20K	
PG64-28PM AC = 6.5% Watsonville G2 grading	WG250.12 (50 gyrations)	Rt (C2 & C4)	2A-P3-PM-WG2-50-C2	59.93	149.63	14.5	13,001	12.0	> 17.8	< 1,724	9,903
			2A-P3-PM-WG2-50-C4	58.16	149.36	11.7					
		Lt (C1 & C3)	2A-P3-PM-WG2-50-C1	59.17	149.56	13.3	20,000	6.5	17.1	943	18,171
			2A-P3-PM-WG2-50-C3	59.23	149.32	13.3					
	WG2100.12 (100 gyrations)	Rt (C2 & C3)	2A-P3-PM-WG2-100-C2	57.84	149.46	11.5	20,000	5.6	13.5	1,266	18,344
			2A-P3-PM-WG2-100-C3	57.86	149.58	11.5					
		Lt (C1 & C4)	2A-P3-PM-WG2-100-C1	57.67	149.50	11.1	20,000	4.6	15.9	885	18,523
			2A-P3-PM-WG2-100-C4	60.02	149.78	14.9					
Asphalt rubber (AR) AC = 7.2% Sacramento G1 grading	TG150.12 (50 gyrations)	Rt (C2 & C4)	2A-P3-AR-TG1-50-C2	67.68	150.50	26.0	9,350	> 17.5	NA	NA	6,235
			2A-P3-AR-TG1-50-C4	67.67	150.49	26.2					
		Lt (C1 & C3)	2A-P3-AR-TG1-50-C1	67.70	151.13	27.0	10,051	> 17.7	NA	NA	5,809
			2A-P3-AR-TG1-50-C3	67.60	151.23	26.7					
	TG1100.12 (100 gyrations)	Rt (C2 & C3)	2A-P3-AR-TG1-100-C2	66.11	150.23	24.3	7,800	> 17.3	NA	NA	5,943
			2A-P3-AR-TG1-100-C3	66.49	150.09	24.1					
		Lt (C1 & C4)	2A-P3-AR-TG1-100-C1	66.43	150.57	24.8	17,700	9.8	> 18.6	< 1,136	13,666
			2A-P3-AR-TG1-100-C4	66.88	150.18	24.8					

5.4 Surface Area Versus Equivalent Asphalt Film Thickness Versus Cantabro Loss

5.4.1 Calculations of Surface Area and Equivalent Asphalt Film Thickness

In the Caltrans mix design procedure, estimates of surface area for aggregate gradations are used to determine the percent of asphalt (aggregate basis) for a starting point in mix design. The percentage of asphalt, P_b, is

$$P_b = SA \times t \times \gamma_{asp} \times 100 \tag{5.2}$$

where: SA is the surface area (mm^2 / g),
t is the equivalent asphalt film thickness (mm), and
γ_{asp} is the unit weight of asphalt (g / mm^3).

The surface area is significant because it affects the amount of asphalt needed to coat the aggregate. One of the reasons to estimate the surface area for any given asphalt content is to determine the *equivalent asphalt film thickness* that can provide a measure of the durability of a mix. Although the equivalent asphalt film thickness is an estimated value, it allows systematic comparisons to be made for mixes with various gradations.

For this study, surface area was calculated using a simulation program developed that included two assumptions:

1. *That the aggregate is converted to a spherical equivalent with the same weight.* The spherical aggregates retained between two adjacent sieves are generated based on a uniform distribution under the assumption that the total weight of simulated aggregates is equivalent to the retained weight of an aggregate batching. Thus, the surface area per kilogram of aggregate blend can then be determined for each sieve size.
2. *That the fines that pass the No. 200 sieve together with asphalt will form an asphalt mastic that will coat the aggregates larger than those that pass the No. 200 sieve.* Accordingly, the *asphalt film thickness* is defined as the division of the volume of mastic, which is the sum of the volume of fines (< No. 200 sieve) and volume of asphalt, by the cumulative surface area for aggregates retained above the No. 200 sieve.

The detailed surface area simulations of gradations G1, G2, and G3 are included in Reference (*2*). Table 5.3 provides a summary of the asphalt film thickness calculation based on the cumulative surface areas obtained from 1,000 g of aggregate blend. The ranking of the calculated film thicknesses is G1 (coarse) (127 μm) > G3 (middle) (91 μm) > G2 (fine) (60 μm), whereas the ranking of cumulative surface area is reversed as G1 (0.5 m^2/kg) < G3 (0.7 m^2/kg) < G2 (1.2 m^2/kg).

Figure 5.8 plots cumulative surface area versus sieve size for gradations G1 (coarse), G2 (fine), and G3 (middle) in a logarithm-logarithm scale. It is interesting to note that the curves deviate starting at the No. 30 sieve and the cumulative surface area rapidly diverges thereafter. As expected, the ranking of the surface area accumulation rate is G2 (fine) > G3 (middle) > G1 (coarse).

Table 5.3: Summary of Asphalt Film Thickness Calculation Based on the Cumulative Surface Areas Obtained from 1,000 g of Aggregate Blend

Grading	% Passing No. 200	AC (%)	No.200/AC	(A) Volume of Aggregate (< No. 200) (mm^3)	(B) Volume of Asphalt (mm^3)	(A) + (B) Mastic (mm^3)	Cumulative Surface Area (above No. 200) (mm^2/kg)	Equivalent Asphalt Film Thickness (mm)
G1 (coarse)	1	6	0.166667	3,703.704	60,000	63,703.704	502,785	0.126702
G2 (fine)	3	6	0.500000	11,111.110	60,000	71,111.110	1,177,713	0.060381
G3 (middle)	2	6	0.333333	7,407.407	60,000	67,407.407	742,463	0.090789

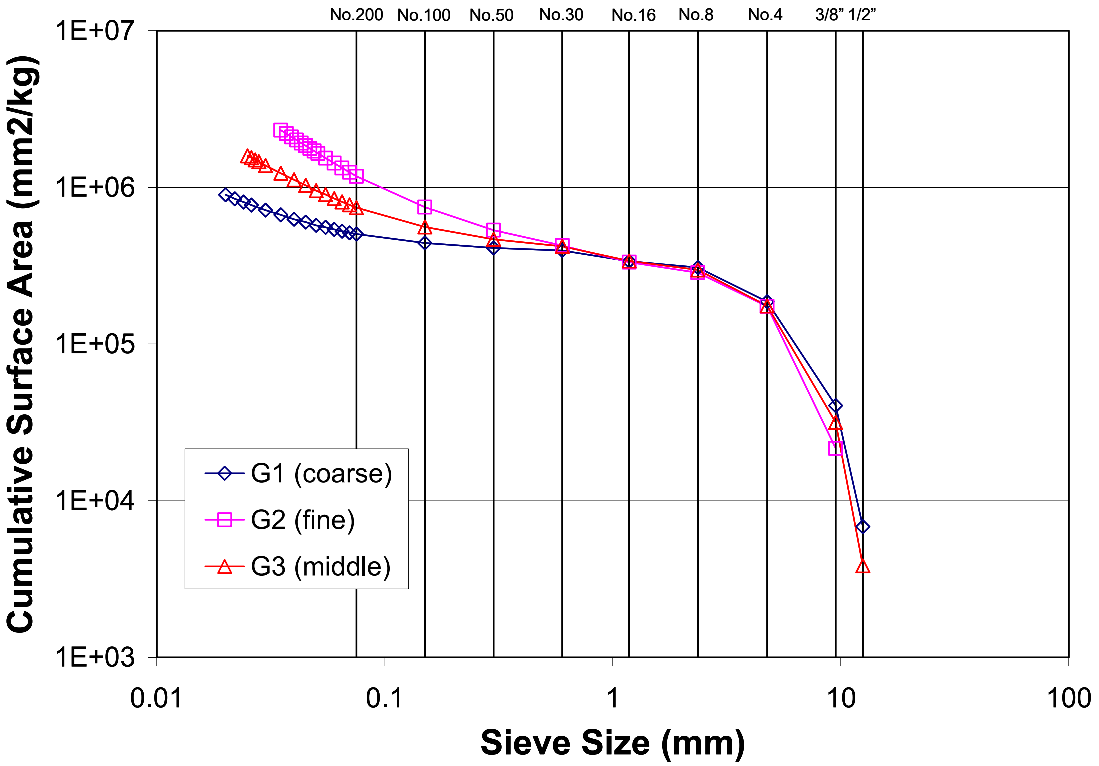


Figure 5.8: Cumulative surface area versus sieve size for various gradation types.

The same calculation procedures for surface area and equivalent asphalt film thickness were applied to the specimens prepared for all three phases (included in Reference [*2*]). Bulk specific gravities used in the surface area calculation for both the coarse and fine aggregates are 2.66 for Sacramento and Watsonville, and 2.60 for the San Gabriel aggregates. The bulk specific gravities used for the binders are 1.03 for the PG 64-10, and 1.01 for both the PG 64-28 PM and AR. Gradations for the simulations are those listed in Table 2.1. A 1,000 gram aggregate blend was used to conduct the simulations. Table 5.4 summarizes the simulation results for the mixes used in Phase I, Phase II, and Phase III; additionally, this table also shows the average Cantabro losses for specimens prepared using 50 gyrations.

Table 5.4: Summary of Calculations of Surface Area and Equivalent Asphalt Film Thickness

Phase	Binder Type	Grading	AC (%)	Aggregate	Percent Passing No. 200	No. 200/AC	(A) Volume of Aggregate (< No. 200) (mm^3)	(B) Volume of Asphalt (mm^3)	(A) + (B) Mastic (mm^3)	Cumulative Surface Area (above No. 200) (mm^2/kg)	Equivalent Asphalt Film Thickness (mm)	Average Cantabro Loss 50 Gyrations (%)
Phase I	PG 64-10	G1	6.0	Sacramento	1	0.17	3,759.4	58,252.4	62,011.8	509,953	0.122	100.00
				Watsonville	1	0.17	3,759.4	58,252.4	62,011.8	508,000	0.122	94.4
				San Gabriel	1	0.17	3,846.2	58,252.4	62,098.6	509,706	0.122	99.3
		G2	6.0	Sacramento	3	0.50	11,278.8	58,252.4	69,530.6	1,194,123	0.058	74.3
				Watsonville	3	0.50	11,278.8	58,252.4	69,530.6	1,193,732	0.058	43.8
				San Gabriel	3	0.50	11,538.5	58,252.4	69,790.9	1,220,901	0.057	52.9
		G3	6.0	Sacramento	2	0.33	7,518.8	58,252.4	65,771.2	754,972	0.087	99.7
				Watsonville	2	0.33	7,518.8	58,252.4	65,771.2	755,509	0.087	89.3
				San Gabriel	2	0.33	7,692.3	58,252.4	65,944.7	771,568	0.085	72.8
	PG 64-28PM	G1	6.5	Sacramento	1	0.15	3,759.4	64,356.4	68,115.8	508,984	0.134	68.2
				Watsonville	1	0.15	3,759.4	64,356.4	68,115.8	509,183	0.134	23.6
				San Gabriel	1	0.15	3,846.2	64,356.4	68,202.6	509,545	0.134	7.5
		G2	6.5	Sacramento	3	0.46	11,278.2	64,356.4	75,634.6	1,193,381	0.063	11.4
				Watsonville	3	0.46	11,278.2	64,356.4	75,634.6	1,193,672	0.063	20.5
				San Gabriel	3	0.46	11,538.5	64,356.4	75,894.9	1,220,869	0.062	43.2
		G3	6.5	Sacramento	2	0.31	7,518.8	64,356.4	71,875.2	755,283	0.095	50.4
				Watsonville	2	0.31	7,518.8	64,356.4	71,875.2	754,872	0.095	34.4
				San Gabriel	2	0.31	7,692.3	64,356.4	72,048.7	772,299	0.093	18.7
	Asphalt rubber (AR)	G1	7.2	Sacramento	1	0.14	3,759.4	71,287.1	75,046.5	510,891	0.147	71.3
				Watsonville	1	0.14	3,759.4	71,287.1	75,046.5	509,753	0.147	35.0
				San Gabriel	1	0.14	3,846.2	71,287.1	75,133.3	510,395	0.147	25.0
		G2	7.2	Sacramento	3	0.42	11,278.2	71,287.1	82,565.3	1,194,504	0.069	44.7
				Watsonville	3	0.42	11,278.2	71,287.1	82,565.3	1,192,033	0.069	25.2
				San Gabriel	3	0.42	11,538.5	71,287.1	82,825.6	1,220,611	0.068	37.5
		G3	7.2	Sacramento	2	0.28	7,518.8	71,287.1	78,805.9	756,434	0.104	62.7
				Watsonville	2	0.28	7,518.8	71,287.1	78,805.9	755,517	0.104	63.2
				San Gabriel	2	0.28	7,692.3	71,287.1	78,979.4	772,984	0.102	53.8

Table 5.4 Summary of Calculations of Surface Area and Equivalent Asphalt Film Thickness *(cont.)*

Phase	Binder Type	Aggregate	Grading	AC (%)	Percent Passing No. 200	No. 200/AC	(A) Volume of Aggregate (< No. 200) (mm^3)	(B) Volume of Asphalt (mm^3)	(A) + (B) Mastic (mm^3)	Cumulative Surface Area (above No. 200) (mm^2/kg)	Equivalent Asphalt Film Thickness (mm)	Average Cantabro Loss 50 Gyrations (%)
Phase II	PG 64-10	Sacramento	G1	5.3	1	0.19	3,759.4	51,456.3	55,215.7	508,903	0.1090	100.00
				6.0	1	0.17	3,759.4	58,252.4	62,011.8	510,286	0.122	99.2
				6.7	1	0.15	3,759.4	65,048.5	68,807.9	510,769	0.135	98.1
		Watsonville	G1	5.3	1	0.19	3,759.4	51,456.3	55,215.7	509,510	0.108	89.4
				6.0	1	0.17	3,759.4	58,252.4	62,011.8	509,669	0.122	74.8
				6.7	1	0.15	3,759.4	65,048.5	68,807.9	511,415	0.135	57.5
		San Gabriel	G1	5.3	1	0.19	3,846.2	51,456.3	55,302.5	521,177	0.106	90.2
				6.0	1	0.17	3,846.2	58,252.4	62,098.6	525,060	0.118	90.6
				6.7	1	0.15	3,846.2	65,048.5	68,894.7	520,934	0.132	82.5
	PG 64-28PM	Sacramento	G1	5.8	1	0.17	3,759.4	57,425.7	61,185.1	511,506	0.120	29.7
				6.5	1	0.15	3,759.4	64,356.4	68,115.8	511,021	0.133	27.3
				7.2	1	0.14	3,759.4	71,287.1	75,046.5	508,228	0.148	26.2
		Watsonville	G1	5.8	1	0.17	3,759.4	57,425.7	61,185.1	510,172	0.120	19.1
				6.5	1	0.15	3,759.4	64,356.4	68,115.8	508,519	0.134	12.4
				7.2	1	0.14	3,759.4	71,287.1	75,046.5	509,496	0.147	10.3
		San Gabriel	G1	5.8	1	0.17	3,846.2	57,425.7	61,271.9	521,593	0.117	30.1
				6.5	1	0.15	3,846.2	64,356.4	68,202.6	522,811	0.130	21.6
				7.2	1	0.14	3,846.2	71,287.1	75,133.3	521,989	0.144	22.5
	Asphalt rubber (AR)	Sacramento	G1	6.5	1	0.15	3,759.4	64,356.46	68,115.8	509,924	0.134	54.5
				7.2	1	0.14	3,759.4	71,287.7	75,046.5	511,048	0.147	45.6
				7.9	1	0.13	3,759.4	78,217.8	81,977.2	510,398	0.161	29.6
		Watsonville	G1	6.5	1	0.15	3,759.4	64,356.4	68,115.8	510,805	0.133	35.3
				7.2	1	0.14	3,759.4	71,287.7	75,046.5	510,555	0.147	31.0
				7.9	1	0.13	3,759.4	78,217.8	81,977.2	507,130	0.162	27.5
		San Gabriel	G1	6.5	1	0.15	3,846.2	64,356.4	68,202.6	521,088	0.131	52.6
				7.2	1	0.14	3,846.2	71,287.1	75,133.3	522,715	0.144	39.9
				7.9	1	0.13	3,846.2	78,217.8	82,064.0	518,304	0.158	40.1
Phase III	Asphalt rubber (AR)	Sacramento	G1	6.5	1	0.15	3,759.4	64,356.4	68,115.8	510,349	0.133	54.5
				7.2	1	0.14	3,759.4	71,287.1	75,046.5	509,798	0.147	45.5
				7.9	1	0.13	3,759.4	78,217.8	81,977.2	510,398	0.161	29.6
	PG 64-28PM	Watsonville	G2	5.0	3	0.60	11,278.2	49,505.0	60,783.1	1,192,725	0.051	10.5
				6.0	3	0.50	11,278.2	59,405.9	70,684.1	1,192,993	0.059	10.1
				7.0	3	0.43	11,278.2	69,306.9	80,585.1	1,193,310	0.068	9.4

5.4.2 *Correlation of Cantabro Loss and Mix Properties*

The purpose of the calculations of surface area and equivalent asphalt film thickness was to find the correlations between Cantabro loss and mix properties, especially for the properties of fine aggregates. The average Cantabro test data used for the analysis together with the surface area calculation data are included in Table 5.4. The parameters considered in the correlation analysis are as follows:

- **Binder**: PG 64-10, AR, and PG 64-28 PM
- **Grading**: G1 (coarse), G2 (fine), and G3 (middle)
- **Pfg**: percent passing break point sieve, G1 (7 percent), G2 (18 percent), and G3 (12 percent)
- **Aggregate**: Sacramento, Watsonville, and San Gabriel
- **No. 200/AC**: the ratio of percent passing at the No. 200 sieve to percent asphalt content (by weight of aggregate)
- **Mastic**: the mastic volume (mm^3) under the assumption that the fines passing the No. 200 sieve together with asphalt form the asphalt mastic that coats the aggregates larger than the No. 200 sieve
- **SA**: cumulative surface area (mm^2/kg) for aggregates retained above the No. 200 sieve
- **EAFT**: an acronym of *Equivalent Asphalt Film Thickness* (mm), which is defined as the division of **Mastic** by **SA**
- **CL50**: percent Cantabro loss for specimens fabricated with 50 gyrations of SGC compaction.

Note that the parameter of average Cantabro loss for specimens prepared using 100 gyrations has been excluded because (1) there were not enough data to provide valid conclusions, and (2) crushed aggregates were observed in the AR Sacramento G1 mix during specimen preparation with 100 gyrations, which might induce higher Cantabro loss than in the specimens prepared using 50 gyrations. Table 5.5 summarizes the correlations matrix among parameters.

Table 5.5: Correlations of Mix Properties and Cantabro Loss

	Binder	Grading	Pfg	Aggregate	No. 200/AC	Mastic	SA	EAFT	CL50
Binder	1.000								
Grading	0.112	1.000							
Pfg	0.114	0.999	1.000						
Aggregate	0.073	0.112	0.114	1.000					
No. 200/AC	0.073	0.977	0.977	0.128	1.000				
Mastic	0.313	0.321	0.320	-0.006	0.143	1.000			
SA	0.116	0.992	0.996	0.097	0.971	0.317	1.000		
EAFT	0.012	-0.923	-0.921	-0.084	-0.957	0.052	-0.912	1.000	
CL50	-0.831	-0.213	-0.222	-0.152	-0.159	-0.490	-0.238	0.004	1.000

It should be noted that **Binder**, **Grading,** and **Aggregate** are category covariates that have to be converted to numbers before correlations can be calculated. These conversions have been labeled numerically starting with the number "1" as follows:

Category Covariates			Conversion Number (When Calculating the Correlation)
Binder	**Grading**	**Aggregate**	
PG 64-10	G1	San Gabriel	1
Asphalt rubber (AR)	G3	Sacramento	2
PG 64-28 PM	G2	Watsonville	3

For example, the correlation, -0.831, between **Binder** and **CL50** indicates: (1) **Binder** is negatively correlated to **CL50** with a high absolute value of correlation; (2) the higher the conversion number, the lower the Cantabro loss, or in other words, the PG 64-28 PM has the best Cantabro-loss–resistant capacity among binder types.

The following key findings are taken from the correlation matrix in Table 5.5:

1. By inspecting the parameters associated with the **CL50**, it was found that the **Binder** is negatively correlated to the **CL50** with a high correlation of -0.831. This indicates that the selection of binder type is extremely important for Cantabro performance in OGFC mix design. The **Mastic** is the next most important parameter that negatively correlates to **CL50** with a correlation of -0.490, implying that the higher the mastic volume, the lower the Cantabro loss. In other words, the Cantabro performance can be improved by increasing mastic volume, i.e., using either more asphalt binder or more fines (< No. 200 sieve), or both. As shown earlier in Table 5.4, a fine gradation generally provides larger mastic volume and surface area.
2. The **Aggregate**, **Grading**, and **Pfg** have very low correlation with **CL50** and other parameters.
3. The **No. 200/AC** is positively correlated to **SA** with a correlation of 0.971 and negatively correlated to **EAFT** with a correlation of -0.957. The higher the ratio of **No. 200/AC,** the larger the **SA**; however, the correlation (-0.159) between **No. 200/AC** and **CL50** is fairly small.

5.5 Findings of Phase III

Key findings from the Phase III test results include the following:

1. The percent air-void content of an OGFC mix is highly dominated by the selection of gradation, as shown conclusively in Figure 5.1.
2. Gradation has a notable effect on draindown performance, as Figure 5.2 shows. The figure also shows that the highest allowable asphalt content for the fine gradation (G2) is higher than that for the coarse gradation (G1). From the viewpoint of conducting the Cantabro test for mix durability, the higher the asphalt content, the lower the Cantabro loss; in other words, mix durability benefits from the use of the fine gradation.

3. The boxplot summary (Figure 5.4) and correlation analysis (Table 5.5) agree that binder type is far more significant than the other factors that affect Cantabro performance. Also, from the correlation analysis, the **Mastic**, which is defined as the volume of fines passing the No. 200 sieve together with asphalt, has a moderate correlation (-0.490) with **CL50,** which indicates that the higher the mastic volume, the lower the Cantabro loss. In other words, the Cantabro performance can be improved by increasing mastic volume, i.e., using either more asphalt binder or more fines (< No. 200 sieve), or both.
4. Increasing the gyration number from 50 to 100 gyrations results in a decrease of measured percent air-void content, a decrease of Cantabro loss (provided that there are no crushed aggregates during specimen preparation), and better rutting-resistance capacity in HWTD tests.

6 DEVELOPMENT OF OGFC MIX DESIGN CHART

6.1 Weight-Volume Relationships

The development of the weight-volume relationships for a compacted asphalt mixture, with consideration of asphalt absorption by the coarse aggregate and any fibers included in the mix, that are used in this chapter are contained in Reference (*2*) and they are based primarily on those contained in *Asphalt Paving Mixtures (4)* and *The Asphalt Handbook (5)*. It should be noted, however, that some of the notations and definitions used here and in (*2*) are slightly different from those other sources.

The break point sieve size defined in an OGFC gradation separates the aggregate into fractions of fine and coarse aggregates, as noted earlier. The total weight of an asphalt mixture is the sum of the weights of the asphalt, fiber, fine aggregate, and coarse aggregate. The total volume is the sum of the volumes of the fiber, the aggregate, and the asphalt not absorbed by the aggregate, plus the air voids. If the total volume is set as "Unit Volume," i.e., 1.0, then the total weight is the unit weight of the compacted asphalt mixture. For an OGFC mix, the VCA_{DRC}, voids in coarse aggregate in dry-rodded condition, is equivalent to the total volume minus the volume of the coarse aggregate. Thus in the OGFC, the VCA_{DRC} is filled with the fine aggregate, fiber, and asphalt not absorbed by the aggregate, plus air voids. That is,

$$\boxed{VCA_{DRC} = V_{air} + V_{fib} + V_{asp} - V_{aasp} + V_{fg}} \qquad \textbf{(6.1)}$$

From the volumetric relationships of asphalt, absorbed asphalt, fiber, and fine aggregate, the VCA_{DRC} (Equation 6.1) is then expressed as (See Reference [*2*] for details):

$$\boxed{VCA_{DRC} = V_{air} + \left(1 - V_{air}\right)\left(\frac{\dfrac{P_{fib}}{G_{fib}} + \dfrac{P_{asp} - P_{aasp}P_{cg}}{G_{asp}} + \dfrac{P_{fg}}{G_{fg}}}{\dfrac{P_{fib}}{G_{fib}} + \dfrac{P_{asp} - P_{aasp}P_{cg}}{G_{asp}} + \dfrac{P_{cg}}{G_{cge}} + \dfrac{P_{fg}}{G_{fg}}}\right)} \qquad \textbf{(6.2)}$$

where,

V_{air} : percent air voids (in decimal form),

P_{fg} : percent passing the break point sieve (in decimal form),

P_{asp} : percent asphalt content by weight of aggregate (in decimal form),

VCA_{DRC} : voids in coarse aggregate in dry-rodded condition (in decimal form),

P_{aasp} : percent absorbed asphalt content by weight of coarse aggregate (in decimal form),

P_{fib} : percent fiber content by weight of aggregate (in decimal form),

G_{cg} : bulk specific gravity of coarse aggregate,

G_{fg} : bulk specific gravity of fine aggregate,

G_{asp} : specific gravity of asphalt, and

G_{fib} : specific gravity of fiber.

Without fiber, Equation 6.2 becomes

$$\boxed{VCA_{DRC} = V_{air} + \left(1 - V_{air}\right)\left(\frac{\dfrac{P_{asp} - P_{aasp}P_{cg}}{G_{asp}} + \dfrac{P_{fg}}{G_{fg}}}{\dfrac{P_{asp} - P_{aasp}P_{cg}}{G_{asp}} + \dfrac{P_{cg}}{G_{cg}} + \dfrac{P_{fg}}{G_{fg}}}\right)} \qquad \textbf{(6.3)}$$

6.2 Sensitivity Study of Weight-Volume Relationship

Equation 6.3 includes three design parameters, V_{air}, P_{fg}, and P_{asp}, and five material parameters, VCA_{DRC}, P_{aasp}, G_{cg}, G_{fg}, and G_{asp}. Note that P_{cg} is not included as a design parameter since $P_{fg} + P_{cg} = 1.0$. The three design parameters are the major considerations in OGFC mix design for ensuring that requirements for drainage, permeability, and durability are satisfied. For a set of given material parameters and any two of the design parameters, the remaining design parameter can be mathematically determined using Equation 6.3. To evaluate how a design parameter is affected by the other two design parameters and the material parameters, design plots and tree-based modeling were developed from the results of 10,000 statistical simulations. The details of tree-based modeling are summarized in Reference (*2*). Each simulation used a set of parameter values that were randomly generated following a uniform distribution in the parameter ranges shown as follows, with the parameter ranges based on available data and experience:

Three design parameters:

- V_{air} : 10 – 30%
- P_{fg} : 2 – 23%
- P_{asp} : 5 –10% (by weight of aggregate)

Five material parameters:

- VCA_{DRC} : 36 – 42%
- P_{aasp} : 0 – 5% (by weight of coarse aggregate)
- G_{cg} : 2.50 – 2.95
- G_{fg} : 2.40 – 2.75
- G_{asp} : 1.00 – 1.03

For instance, if V_{air} is selected as the response variable, then its value will be determined by two other design parameters and five material parameters according to Equation 6.3. A total of 10,000 sets of parameter values were then constructed according to the parameter ranges shown above. Design plots and tree-based modeling summarized the simulation to determine how the response variables were affected by the design and material parameters. These results are included in Reference (*2*).

Conclusions from the sensitivity analysis can be summarized as follows:

1. Table 6.1 summarizes the first and second levels of the most significant covariates that affect the three design parameters, P_{asp} , P_{fg} , and V_{air} . The tree-based models indicated these three design parameters—P_{asp} , P_{fg} , and V_{air} —are mutually and significantly affected by each other.

Table 6.1: Summary of the First- and Second-Level Covariates (Sensitivity Study)

Parameter	First Level	Second Level	Third Level	Fourth Level	Others
P_{asp}	`pfg`	`vair`	`pfg, vair`	`pfg, vair`	`paasp, vcadrc`
P_{fg}	`vair`	`vair`	`pasp`	`paasp, vcadrc`	`paasp, vcadrc`
V_{air}	`pfg`	`pfg`	`pasp`	`paasp, vcadrc`	`paasp, vcadrc`

2. VCA_{DRC}, an aggregate-dependent material parameter, has a moderate effect on the response variables.
3. The effect of asphalt absorbed by coarse aggregate (P_{aasp}) on air-void content (V_{air}) cannot be ignored.
4. The bulk specific gravities, G_{cg}, G_{fg}, and G_{asp}, have very minor effects on the response variables.

6.3 Construction of OGFC Mix Design Chart

According to Equation 6.3 without consideration of fiber addition,

$$VCA_{DRC} = V_{air} + (1 - V_{air}) \left(\frac{\dfrac{P_{asp} - P_{aasp}P_{cg}}{G_{asp}} + \dfrac{P_{fg}}{G_{fg}}}{\dfrac{P_{asp} - P_{aasp}P_{cg}}{G_{asp}} + \dfrac{P_{cg}}{G_{cg}} + \dfrac{P_{fg}}{G_{fg}}} \right),$$

the P_{asp} in this nonlinear equation can be resolved if the values of other parameters are given. Hence, using the design parameter P_{fg} as the *x*-axis and the design parameter V_{air} as the *y*-axis, the calculated P_{asp} values can form a family of contour lines. Figure 6.1 illustrates the OGFC mix design chart for the Sacramento aggregate and P_{aasp} = 1.0 percent that is mapped with the theoretical and measured data from Phase I. In the figure, theoretical data is shown with solid diamond shapes for PG 64-10, solid squares for PG 64-28 PM, and solid circles for AR. The measured data is shown by the empty shapes that correspond to those used for the theoretical data. The figure also shows the air-void content and gradation criteria. As can be seen, under the assumption of P_{aasp} = 1.0 percent, the measured air voids are roughly 2 to 4 percent higher than the theoretical values. For the fine gradation, the difference is even more serious. The interval between the two adjacent asphalt contour lines decreases slightly as the percent asphalt content increases. The difference between the measured and theoretical values shown points to the need to calibrate the mix design chart.

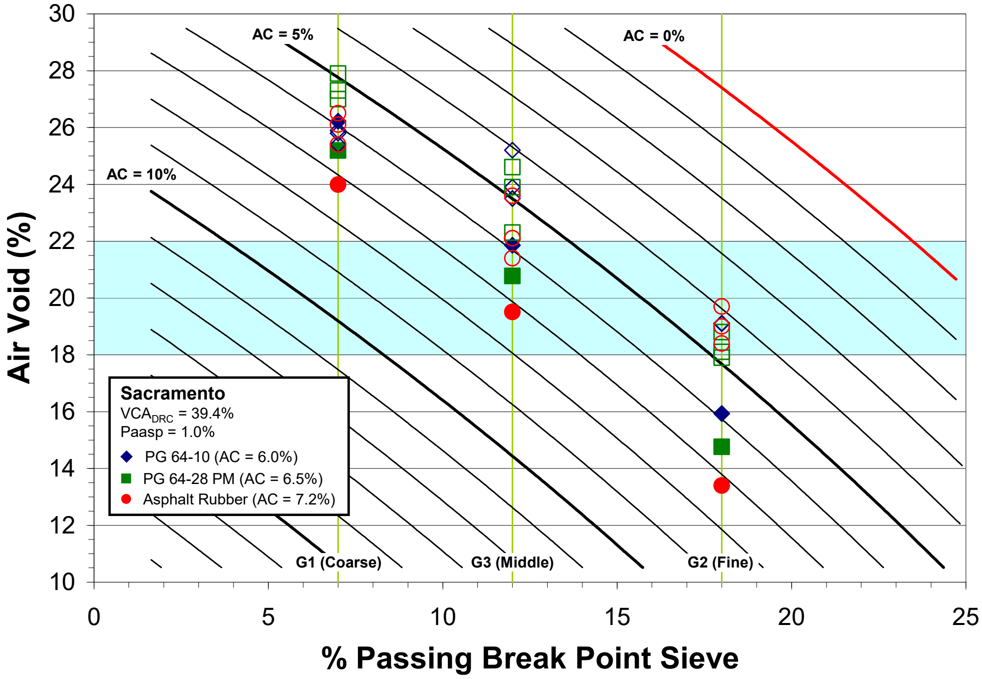


Figure 6.1: OGFC mix design chart (Sacramento, P_{aasp} = 1.0%).

6.3.1 Calibration of Asphalt Absorption Using Phase I Data

As pointed out in the sensitivity study, the effect of P_{aasp} on the three design parameters cannot be ignored. Unfortunately, in this study the tests to determine the asphalt absorption of coarse aggregate (ASTM D4469) were not conducted because it was not expected that the effect would be as significant as it appears to be. To inspect the effect of P_{aasp} on V_{air}, an alternative used in this study was to minimize the residual sum of squares of air-void contents (Equation 6.4) under the assumption that asphalt absorption is a constant function rather than a function of gradation, since it is assumed to only occur in the coarse aggregate. The results of Phase I tests were used to calibrate the effect of asphalt absorption.

$$\min \sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{3}\left(AV_{i,j,k}-AV_{i,j}\right)^{2} \qquad \textbf{(6.4)}$$

where: i is the asphalt type including PG 64-10, PG 64-28 PM, and AR,

j is the gradation type including G1 (coarse), G2 (fine), and G3 (middle),

k is the test replicates,

$AV_{i,j,k}$ is the k^{th} measured percent air-void content for the i^{th} asphalt type and the j^{th} gradation type, and

$AV_{i,j}$ is the theoretical percent air-void content for the i^{th} asphalt type and the j^{th} specified gradation.

Figure 6.2 and Figure 6.3 illustrate the design charts under the assumptions of P_{aasp} = 2.0 percent and P_{aasp} = 3.0 percent for the Sacramento aggregate. As can be seen from these figures, the whole family of asphalt contour lines moves upward due to the increase of P_{aasp}. In other words, increase of P_{aasp} results in an increase of P_{asp} for the given values of V_{air} and P_{fg}. It should be noted that the locations of the measured air-void contents remain unchanged, whereas the locations of the theoretical air-void contents will change due to the change of P_{aasp}. Therefore, the residual sums of squares of percent air-void content can be determined for the given values of P_{aasp}.

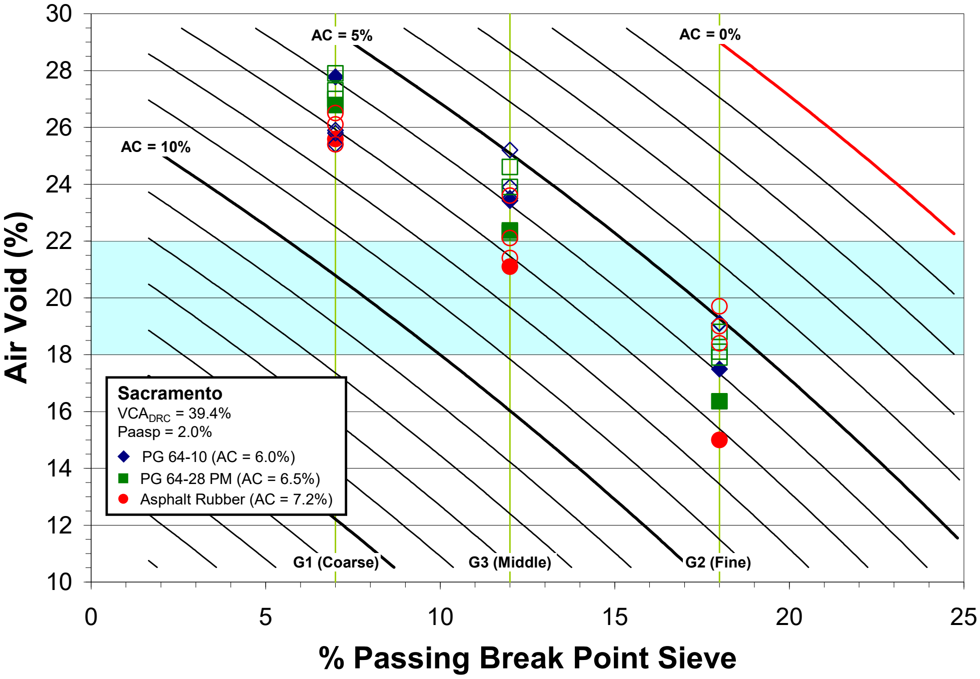


Figure 6.2: OGFC mix design chart (Sacramento, P_{aasp} = 2.0 percent).

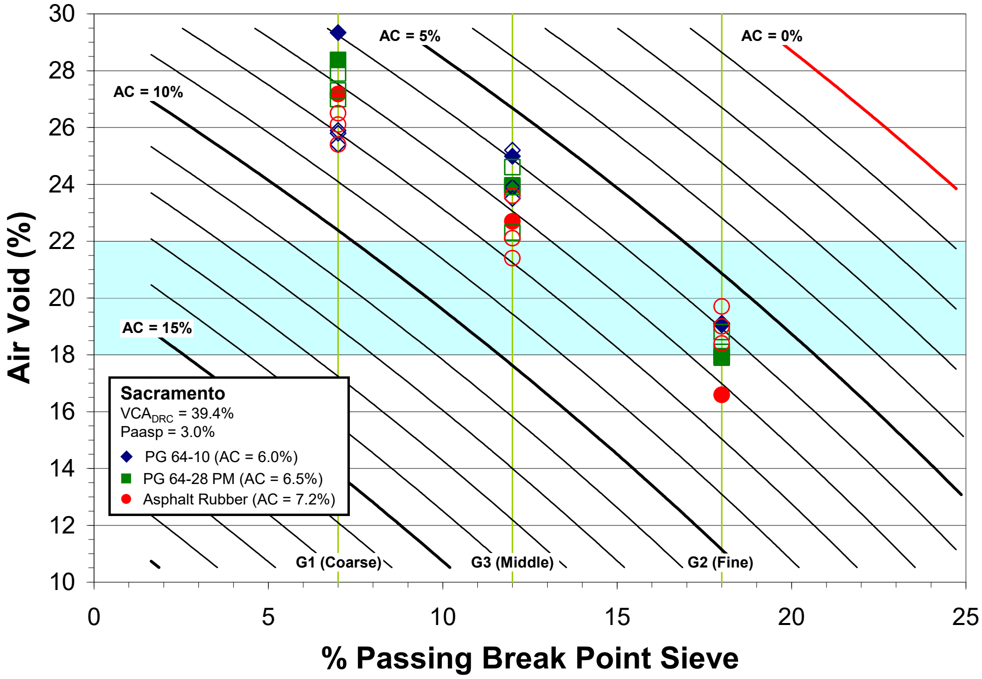
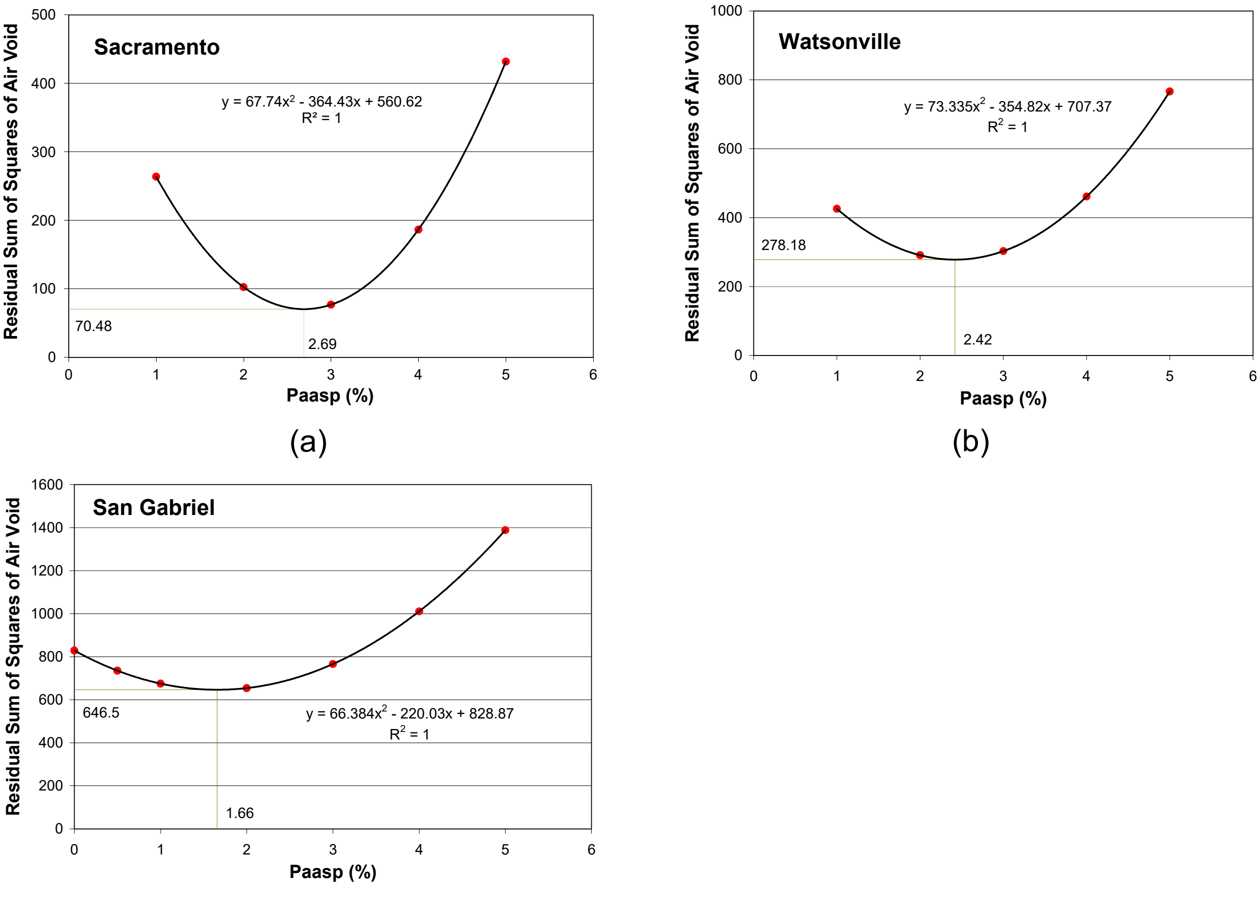


Figure 6.3: OGFC mix design chart (Sacramento, P_{aasp} = 3.0 percent).

Figure 6.4 plots the residual sum of squares versus P_{aasp} for different aggregate types, which can be perfectly represented by a polynomial function with degree two. The nadir of the polynomial curve defines the minimum residual sum of squares. The most likely percentage asphalt absorption obtained is 2.69 percent for Sacramento, 2.42 percent for Watsonville, and 1.66 percent for San Gabriel. As noted earlier, the percentage asphalt absorption is by weight of coarse aggregate. Thus, the sensitivity study indicates that the high sensitivity (1.559) (*2*) of asphalt absorption to air-void content must be considered in developing the OGFC mix design chart. Instead of using the criterion of minimum residual sum of squares of air-void content, the asphalt absorption needs to be measured. The methodology to determine percent asphalt absorption will be included with the work for a following project, Strategic Plan Element 3.25, titled *Improved Methodology for Mix Design of Open-Graded Friction Courses.*



(a) (b)

(c)

Figure 6.4: Determination of percent asphalt absorption based on minimum residual sum of squares of percent air-void content.

Figure 6.5, Figure 6.6, and Figure 6.7 represent the OGFC mix design charts calibrated with P_{aasp} for the Sacramento, Watsonville, and San Gabriel aggregates. These figures also illustrate how the VCA_{DRC} affects the family of asphalt contour lines: an increase in the value of VCA_{DRC} results in upward movement of the whole family of asphalt contour lines, that is, increase of VCA_{DRC} results in the increase of P_{asp} for the given values of V_{air} and P_{fg}. Viewed from these figures, for G2 (fine) gradation it seems that all the measured air-void contents are above the theoretical air-void contents, whereas for the G1 (coarse) gradation all the measured air-void contents are below the theoretical air-void contents. This suggests that the asphalt absorption of coarse aggregate may be a function of the percentage passing the break point sieve rather than just a constant; whether or not this is the case requires further verification. It is unclear why the measured air-void contents of Watsonville and San Gabriel are so scattered. From the viewpoint of volumetric OGFC mix design, it is extremely important to have the measured air-void contents as accurate, consistent, and repeatable as possible. The measured air-void contents of Superpave gyratory specimens prepared using gyration number control seem to vary quite a bit. Control by height may provide a better method.

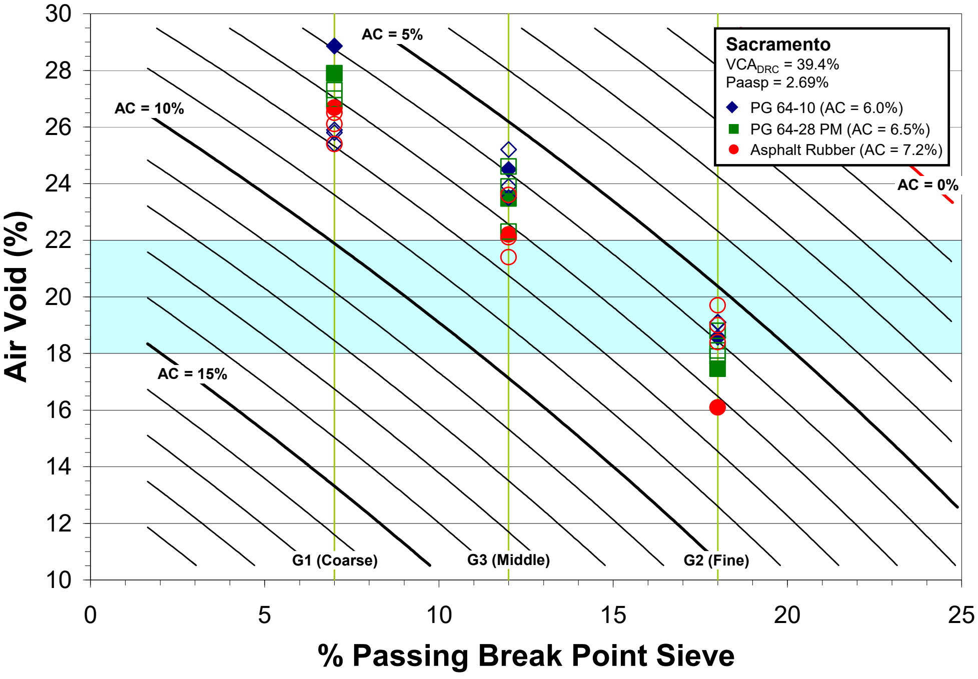


Figure 6.5: OGFC mix design chart calibrated with P_{aasp} = 2.69 percent (Sacramento, Phase I).

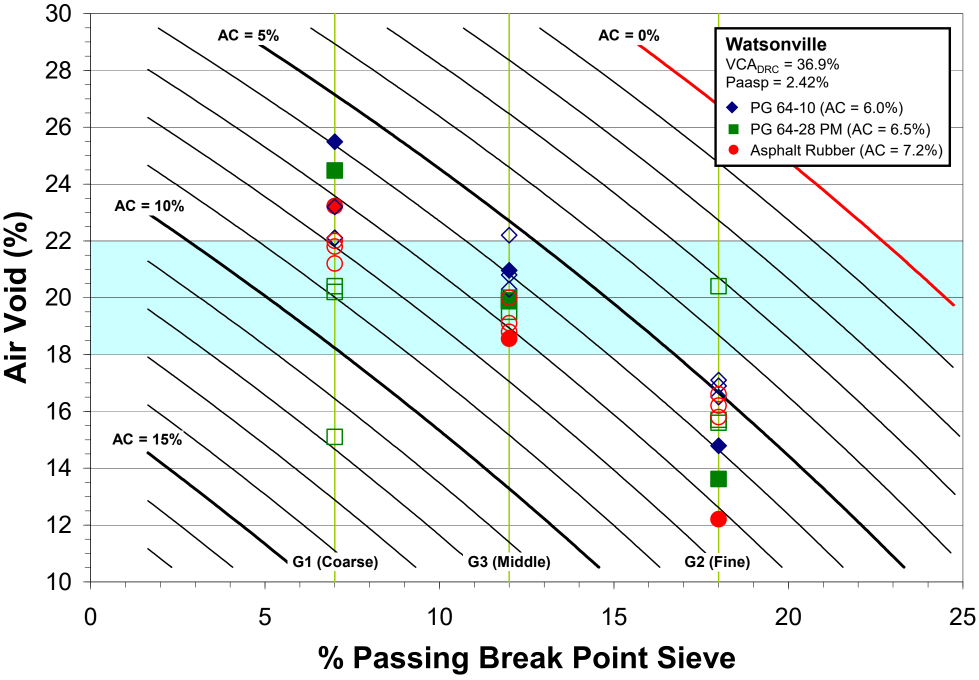


Figure 6.6: OGFC mix design chart calibrated with P_{aasp} = 2.42 percent (Watsonville, Phase I).

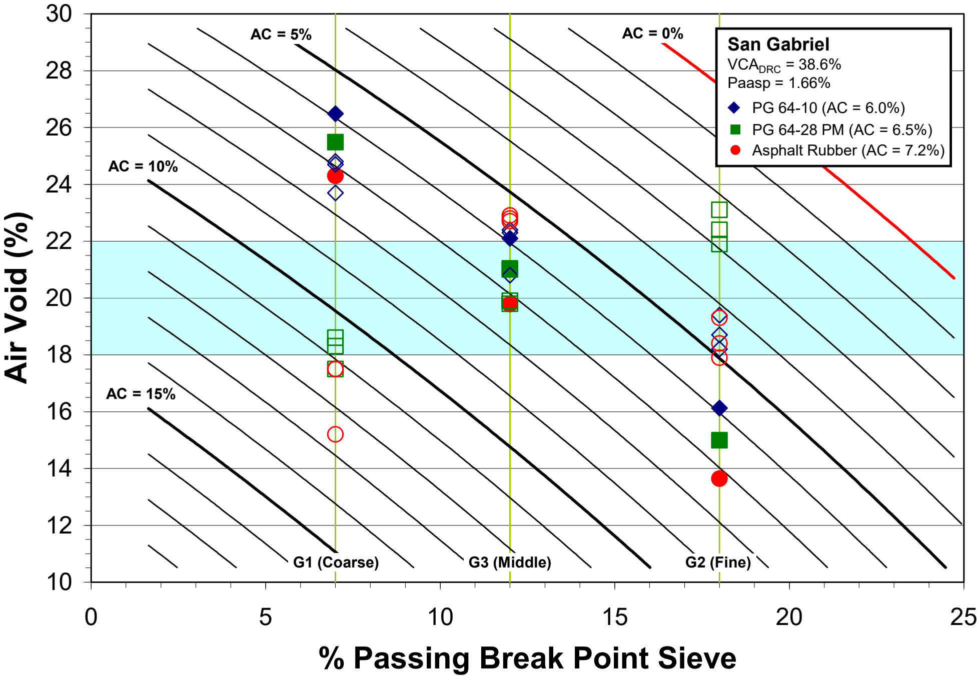


Figure 6.7: OGFC mix design chart calibrated with P_{aasp} = 1.66 percent (San Gabriel, Phase I).

6.4 Advantages of the OGFC Mix Design Chart and Issues to be Resolved

The proposed OGFC mix design chart has the following advantages over the NCAT approach:

1. In contrast to the NCAT approach, which is based on the bulk specific gravity of the aggregate blend, the proposed method provides a more rational volumetric approach for determining the initial binder content required to determine the optimum gradation.
2. The proposed mix design chart takes into consideration the percent asphalt absorption of coarse aggregate, which is not specified in the NCAT approach.
3. The proposed version provides a more rational selection of three trial binder contents, which also comply with requirements for percent air-void content, to prepare specimens for performance testing.

Although the benefits of using this OGFC mix design chart were demonstrated, there are still many improvements that can be made to it. Volumetrically based OGFC mix design cannot identify differences among various binder types, especially polymer-modified and rubberized asphalts which have to be verified through performance tests. However, both CT 368 and the NCAT approach suggest that higher binder content should be used for polymer-modified and rubberized asphalts.

The extent of stone-on-stone contact in a coarse aggregate structure determines how well an OGFC mix design will succeed. The role of fine aggregate in an OGFC mix design is to maintain the stability of the coarse aggregate structure. However, it seems that the use of break point sieve size alone to categorize the aggregate blend into a coarse portion (P_{cg}) and a fine portion (P_{fg}) cannot truly reflect the importance of gradation in OGFC mix performance, especially the fines content (< No. 200 sieve). Test results conducted in Phase III indicate that the fines content significantly affects the performance test results.

Based on these facts, the following steps would need to be taken to make practical use of this OGFC mix design chart:

- First, it must first be better calibrated.
- Second, the performance test results have to be incorporated into the design chart to determine the optimum binder content, particularly for polymer-modified and rubberized asphalt binders.
- Third, and most important, performance specifications must be established in such a way that in-situ performance conforms to expectations based on laboratory testing.

6.5 Proposed OGFC Mix Design Procedure

6.5.1 Volumetric Design and Performance Testing

Advancing the proposed OGFC mix design procedure would include two primary steps:

1. Initiate volumetric design: This includes deciding on material volumetric properties, constructing the OGFC mix design chart, and determining the gradation and the trial binder contents.
2. Conduct performance testing: Primary tests include Cantabro, draindown, and Hamburg Wheel-Track Device (HWTD) testing for three selected binder contents.

Figure 6.8 schematically illustrates the proposed OGFC mix design procedure with the use of a hypothetically calibrated OGFC mix design chart. The steps required to achieve the OGFC mix design are shown in detail as follows:

Volumetric Design:

- *Step 1*: Determine the volumetric properties that are used in constructing the OGFC mix design chart. According to Equation 6.3, the volumetric properties required are VCA_{DRC}, P_{aasp}, G_{cg}, G_{fg}, and G_{asp}. The relationship of P_{aasp} as a function of P_{fg} has to be determined before the OGFC mix design chart is constructed.
- *Step 2*: Construct the OGFC mix design chart based on the volumetric properties obtained from *Step 1*.
- *Step 3*: Select the design gradation so as to meet the air voids requirements.
- *Step 4*: Select the three trial binder contents with consideration of binder type, especially polymer-modified and rubberized asphalts, unless it has been determined that a particular binder should be used. It is suggested that the trial binder range be expanded as much as possible, e.g., target value (TV), TV±1%.

Performance Testing:

- *Step 5*: Conduct Cantabro tests to determine the allowable minimum binder content.
- *Step 6*: Conduct draindown tests to discover the allowable maximum binder content.
- *Step 7*: Conduct HWTD tests to decide the allowable range of binder content based on the rutting performance specification.
- *Step 8*: Determine the allowable optimum binder content (OBC).

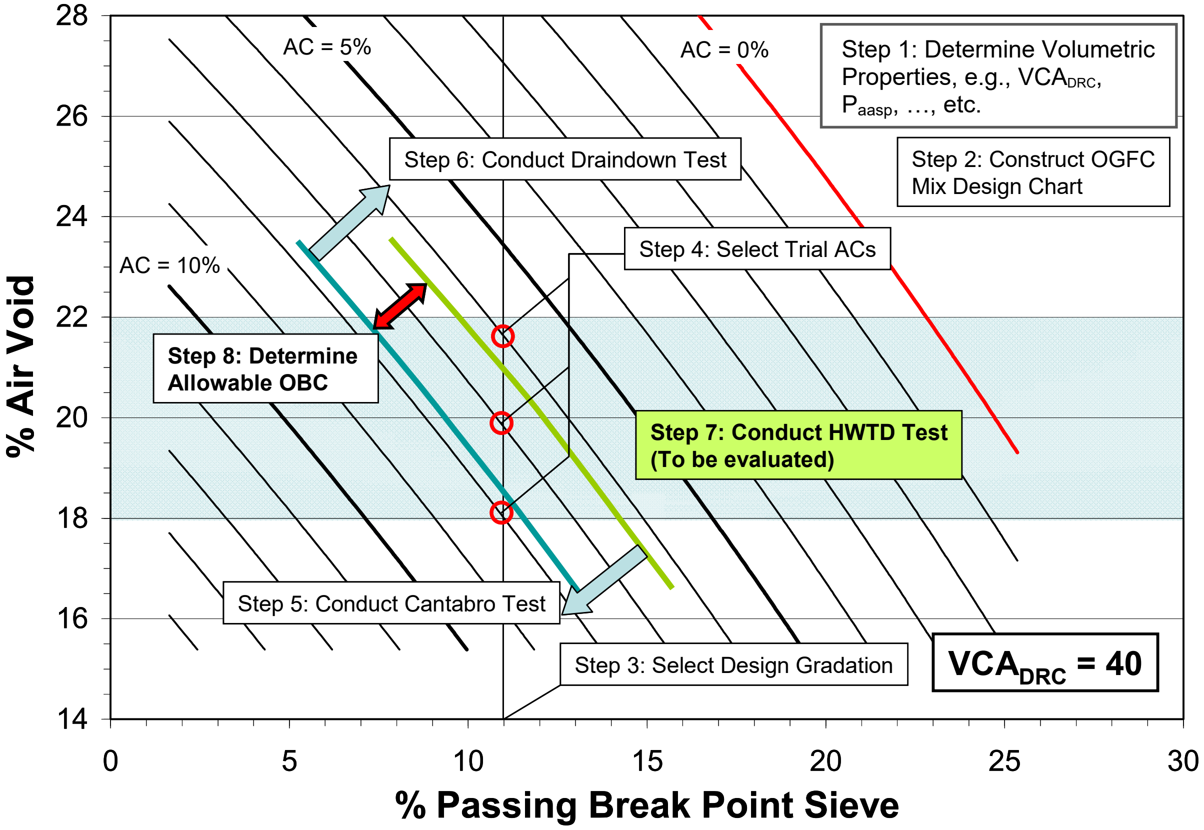


Figure 6.8: Proposed OGFC mix design process.
(Note: Arrows indicate maximum, minimum, and allowable binder ranges.)

It should be noted that development of an *Excel* macro to generate the OGFC mix design chart (steps 1 and 2) based on input design and material parameters is underway, and it will be delivered with the work for a subsequent project, Strategic Plan Element 3.25.

This *Excel* macro has been developed for the selection of three trial binder contents to prepare specimens for performance testing in the OGFC mix design process. For predetermined material properties of the selected aggregate and binder types, the macro provides an improved method for evaluating whether a selected gradation meets the requisite properties. The macro also determines whether volumetric requirements are met with binder sufficient to provide the mix with an asphalt film thickness that will result in adequate durability and rutting resistance without excessive draindown and moisture damage. The proposed mix design chart takes into consideration the percent asphalt absorption of the aggregate blend in addition to the VCA_{DRC}. The design chart does not differentiate among (1) various binder types, especially polymer-modified and rubberized asphalts, (2) various fines contents, and (3) various gradations with different nominal maximum aggregate sizes (NMAS) that form distinct aggregate structures, which have to be verified through performance tests. The *Excel* macro also provides a convenient way to summarize test results and to determine the optimum binder range (OBR).

Table 6.2 summarizes the test methods/specifications used in the proposed OGFC mix design process. To explore the relationship of HWTD performance as a function of binder content, four HWTD tests are suggested for each binder content, i.e., a total of twenty-four 150 mm diameter cylindrical specimens are required. The proposed OGFC mix design procedure is also illustrated in Figure 6.9.

Table 6.2: Summary of Test Methods/Specifications Used in OGFC Mix Design Process

Phase	Parameters/Testing	Caltrans Test Methods	AASHTO Specifications
Volumetric Design	Wet/dry sieving		AASHTO T 11 AASHTO T 27
	VCA_{DRC}		AASHTO T 19 AASHTO T 85
	Asphalt absorption, P_{aasp}		ASTM D4469 – 11
	G_{cg}	CT 206	
	G_{fg}	LP-2	
	G_{asp}		AASHTO T 228
	RICE (G_{mm})	CT 309	AASHTO T 209
	Mix air voids	CT 367	AASHTO T 166A AASHTO T 275A AASHTO T 331
Performance Testing	Draindown Test		AASHTO T 305
	Cantabro Test		ASTM D7064-04 APPENDIX X2
	Hamburg Wheel-Track Device (HWTD) Test		AASHTO T 324

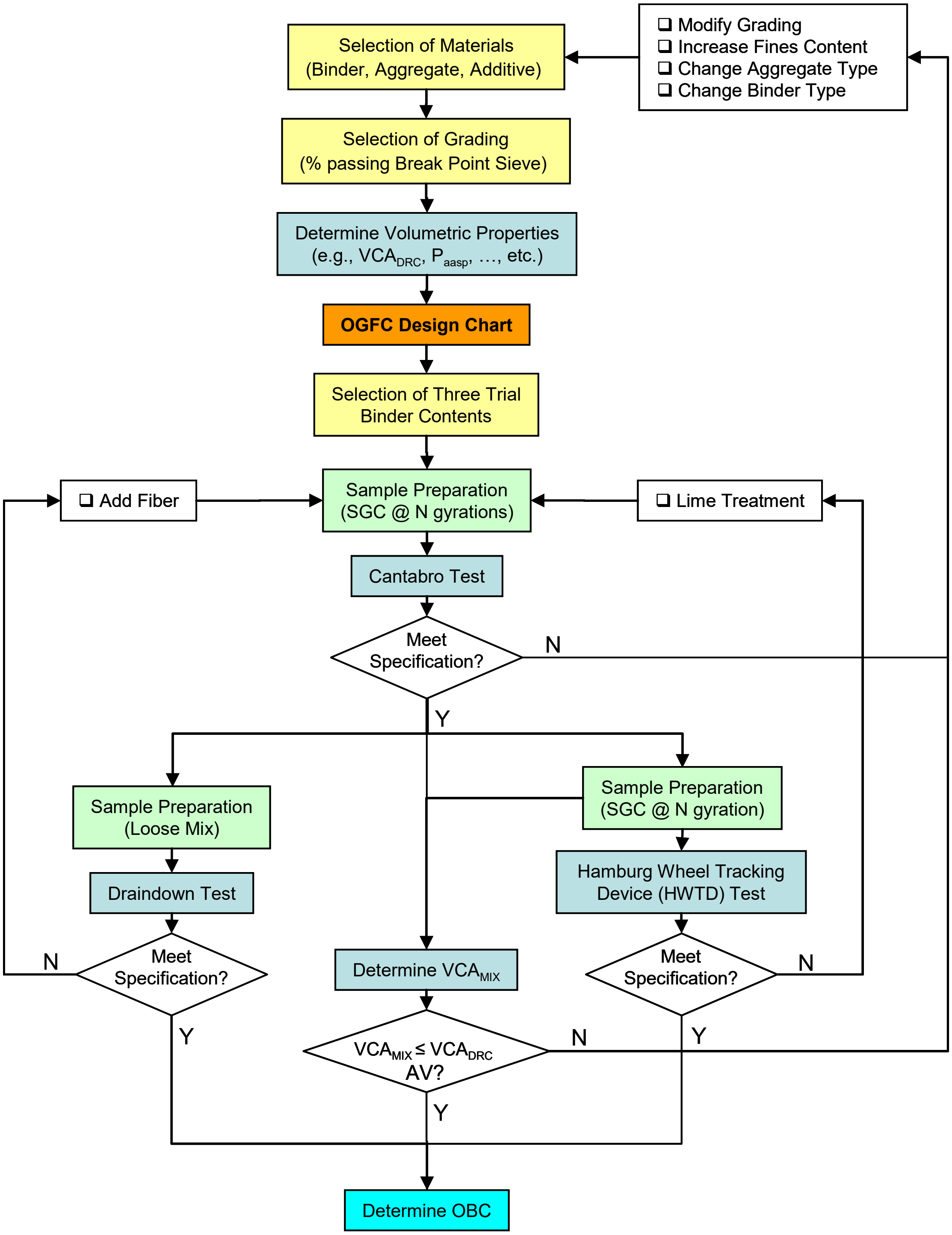


Figure 6.9: Proposed OGFC mix design procedure.

6.5.2 Troubleshooting of OGFC Mix Design

If an OGFC mix design cannot produce a mixture with a given set of materials that meets all requirements in accordance with a calibrated OGFC mix design chart, the following suggestions and remedial actions may improve mixture properties:

- *Air Voids*. The amount of air voids can be adjusted in several ways by changing (1) the aggregate type, (2) the percent passing break point sieve (P_{fg}), and (3) asphalt content (P_{asp}). This study indicates that the aggregate type used in OGFC mix design affects not only the value of VCA_{DRC} but also the value of P_{aasp}, which demonstrates moderately high sensitivity to air-void content, V_{air}. Changes to these two material parameters cause the whole family of asphalt contour lines to shift; as a consequence, the theoretical air-void contents are changed for the given values of P_{asp} and P_{fg}. Decreasing P_{fg} will generally increase the air-void content for a given asphalt content. Finally, for a given P_{fg}, decreasing the asphalt content results in an increase of air-void content; however, this is not recommended because a reduction of asphalt content normally results in higher Cantabro loss.
- *Cantabro Loss*. To reduce Cantabro loss, use higher asphalt content, increase fines content, or select a stiffer binder type.
- VCA_{DRC}. If the VCA_{DRC} is smaller than the VCA_{MIX} (for example, as with the PG 64-28 PM mixes with G2 (fine) gradation and the San Gabriel and Watsonville aggregates in the Phase I test results [*2*]), then modify the mix gradation by decreasing the percent passing break point sieve (P_{fg}).
- *Draindown*. A draindown problem can be easily remedied by changing binder type, selecting and adding a fiber, increasing the dosage of fiber, or using warm mix. Fiber is known to be very effective in reducing draindown.
- *Moisture Susceptibility*. Lime or liquid anti-strip additives are two regular treatments for mixes that fail to meet moisture susceptibility requirements.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This investigation of OGFC mix design used three aggregate types, three binder types, and three trial gradations to prepare specimens using Superpave gyratory compactors for volumetric, draindown, Cantabro, and other performance tests. Based on the analyses of the resulting test data, the following conclusions are offered.

1. *NCAT Approach*. The NCAT approach to OGFC mix design includes a sequential selection process of OGFC materials, trial gradations, optimum gradation, and optimum asphalt binder content, and evaluation of moisture susceptibility using the modified Lottman method in accordance with AASHTO T 283 with one freeze-thaw cycle. In general terms, the NCAT approach can be considered a reasonable OGFC mix design process that can be improved by incorporating the following considerations:
    - The criteria for selecting optimum gradation based on the materials and procedures used in the investigation resulted in the selection of a coarse gradation that did not guarantee a successful OGFC mix design because most of the time the high air-void contents resulting from that choice were accompanied by a lack of the fine aggregates that are believed to improve mix durability.
    - The 50 gyrations used to compact specimens for testing may not provide enough compaction effort to produce aggregate interlocking, which appears to result in particularly high material losses in the Cantabro test for mechanical durability, which is related to raveling.
    - The moisture susceptibility testing in accordance with AASHTO T 283 has been shown to produce highly variable test results (*7*); the Hamburg Wheel-Track Device (HWTD) test would appear to be a better candidate for evaluating moisture susceptibility based on this investigation.
2. *OGFC Mix Design Chart*. Equation 6.3 and the sensitivity study indicate that the three design parameters, P_{asp}, P_{fg}, and V_{air}, are significantly affected by one another. Hence, the OGFC mix design chart is constructed as a family of asphalt contour lines plotted for given values of P_{fg} and V_{air}. The two most important material parameters that affect the OGFC mix design chart are VCA_{DRC} and P_{aasp}. Increases of VCA_{DRC} or P_{aasp} move the whole family of asphalt contour lines upward; in other words, an increase of VCA_{DRC} or P_{aasp} results in an increase of P_{asp} for the given values of V_{air} and P_{fg}. With a fully calibrated OGFC mix design chart, the design chart provides a more rational volumetric approach to determining the initial binder content; the fully calibrated chart takes into consideration the P_{aasp} and allows for direct selection of three trial binder contents to prepare specimens for performance tests.

3. *Balanced OGFC Mix Design*. It can be seen in the OGFC mix design chart that selection of a coarse gradation (i.e., a small percentage passing the break point sieve) will allow more asphalt to be used in the OGFC mix design. This may indicate a decrease of Cantabro loss and an increased risk that draindown and premature rutting might occur. Conversely, when a fine gradation (i.e., large percentage passing the break point sieve) is chosen, the OGFC mix requires less asphalt to meet the air-void criteria. As a consequence, the draindown performance of the OGFC mix is most likely to benefit from the decrease of asphalt. However, decreasing the asphalt content is not beneficial to mix performance with respect to durability and possible rutting. From the test results of Phase III, the use of aggregate gradations with higher fines content tends to reduce Cantabro loss. From this investigation, the primary weakness of the NCAT approach appears to be the selection of optimum gradation. With the materials used in this study, regardless of aggregate and binder types, the selection process always led to selection of a coarse gradation, which does not necessarily guarantee the success of an OGFC mix design. In short, a balanced OGFC mix design has to consider all these elements to meet not only the requirements of mix volumetric properties but also the criteria of mix performance.
4. *Air-Void Content*. In the study of asphalt absorption using Phase I data, the ranking of residual sum of squares at optimum percentage asphalt absorption was Sacramento (70.48) < Watsonville (278.18) < San Gabriel (646.50), which corresponds to the ranking of sample standard deviation of air-void contents, Sacramento (1.65 percent) < Watsonville (3.27 percent) < San Gabriel (4.99 percent). It seems that variation in air-void content between specimens is aggregate-dependent. The specification of specimen compaction in terms of number of gyrations likely contributed to the considerable variation in air-void content among different aggregate types. (Recommendations are presented in Section 7.2.)
5. *Asphalt Absorption*. The sensitivity study indicated a high sensitivity of V_{air} versus P_{aasp}, assuming that asphalt absorption only occurs in the coarse aggregate fraction and absorbed asphalt is a constant regardless of percent passing the break point sieve. The development of the OGFC mix design chart calibrated with computed asphalt absorptions using Phase I data indicated that asphalt absorption appears to be a function of the percentage passing the break point sieve (P_{fg}), and that the higher the P_{fg}, the larger the P_{aasp}.
6. *Draindown and Cantabro Tests*: NCAT identified the reduction of mix temperature during construction to prevent draindown problems as the primary cause of the development of raveling and delamination when OGFC mixes with unmodified asphalt binders were used in the 1970s and 1980s. However, this current study indicates that a mix that satisfies a draindown requirement might not necessarily meet a Cantabro requirement. Today, it is easier to solve a draindown problem by changing the asphalt type (to a polymer-modified, rubberized, or stiffer PG grade) or by using fibers or warm-mix additives. The durability property characterized by the Cantabro test plays a more critical role in OGFC mix design than does the draindown

test because it is easier to fix a draindown problem by adding fiber rather than by changing the mix design when a mix fails the Cantabro test. Hence, as illustrated in Figure 6.9, a higher priority should be given to the Cantabro test in a hierarchy structure of OGFC mix design.

7.2 Recommendations

Based on the results of this study, the following preliminary recommendations are provided for consideration in future efforts to develop a rational OGFC mix design:

1. *Superpave Gyratory Compaction*. The use of 50 gyrations with the Superpave Gyratory Compactor (SGC), recommended by NCAT and utilized in this study for specimen preparation, does not seem to provide enough compactive effort to achieve the aggregate interlock that is normally achieved in the field. The test results of Phase III indicate that an increase of the number of gyrations generally benefits OGFC performance, with less Cantabro loss and greater rutting life, as shown in the HWTD test. However, the crushed aggregates that were observed during gyratory specimen preparation of the AR Sacramento G1 mixes with 100 gyrations may have contributed to greater Cantabro loss due to the disintegration of aggregates. Hence, a gyration number between 50 and 100, on the order of 70, is recommended. In a previous study of the compaction of stabilometer specimens using the SGC (*6*), considerable between- and within-variations were found in the gyration numbers required to compact specimens to the height of 63.5 mm (2.5 in.) for various HMA mixes. Therefore, it is suggested that OGFC compaction be controlled by specimen height rather than by number of gyrations.
2. *Air Void Specification.* Open-graded friction course mixes are primarily designed to have a large number of void spaces in the compacted mix without any sacrifices to durability over their design life. The open void structure helps drain water and preserve surface friction, reducing skid and hydroplaning-related accidents, and thus increasing roadway safety during wet weather. From this perspective, it is not necessary to specify the upper limit of the air-void content if a compacted mix can meet the performance specifications for permeability, Cantabro (measure of durability performance), and Hamburg Wheel Tracking Device testing (HWTD, measure of rutting and moisture sensitivity).
3. *Selection of Binder Type*. The tree-based modeling and correlation analyses completed in this study indicated that binder type is the most significant factor affecting the Cantabro performance of an OGFC mix, and that PG 64-28 PM binder demonstrated superiority over the other two binder types, PG 64-10 and AR. These results are limited to the three binders used in this study but strongly indicate that binder type and/or grade selection is extremely important to balance draindown and durability.
4. *Maximum Cantabro Loss Specification*. The Cantabro test results obtained in this study indicate that it will be difficult for many mixes meet the specification of 15 percent maximum Cantabro loss recommended by the NCAT approach. It is suggested that the specification of 15 percent maximum Cantabro loss be re-

evaluated and coupled with the specification for the value of the dust-to-asphalt ratio (percent passing the No. 200 [0.075 mm] sieve) and/or fines content (percent passing the No. 200 sieve) to ensure that the performance specification calibrated with the in-situ data can satisfy the requirements for OGFC design life.

5. *Further Study—Calibration of Mix Design Chart*. The OGFC mix design chart should be calibrated based on further laboratory testing ensure that it delivers the desired air-void content while also producing mixes that meet the desired properties for the three performance-related tests: draindown, Cantabro (measure of durability performance), and HWTD testing (measure of rutting and moisture sensitivity). The calibration should be done by performing laboratory testing to determine the effects of the percent passing the No. 200 sieve, the dust-to-asphalt ratio, fibers, binder grade, nominal maximum aggregate size (NMAS), percent absorbed asphalt in the aggregate, and percent passing the break point sieve size on air-void content, and on the performance-related test results. Furthermore, an approach should be developed to include the results of performance-related tests in the design chart to determine the allowable range of binder contents that will meet all design requirements.
6. *Further Study—HWTD Performance Specification*. Further study is also required to evaluate the HWTD test as a performance test for OGFC mix design. There are two questions to be answered in this regard. First, will the HWTD testing rank the OGFC mixes correctly and consistently both in the laboratory and in the field, regardless of aggregate type, aggregate size, asphalt type (conventional, polymer-modified, and rubberized), air-void content, and test temperature? Second, how will the laboratory HWTD test performance specification relate to field performance? The work to answer the first question should involve determination of the best Superpave gyratory compaction details, evaluation of the effects of specimen height and wheel size on HWTD performance, and identification of the best performance parameters to be obtained from HWTD tests. As for the second question, calibration of the laboratory HWTD test performance specification to field performance can be achieved using two data sets: field monitoring of initial implementation projects that include field sampling and laboratory testing and analysis, and available Heavy Vehicle Simulator and laboratory HWTD test results to develop a correction factor to relate HWTD rutting to full-scale rutting.

8 REFERENCES

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APPENDIX A

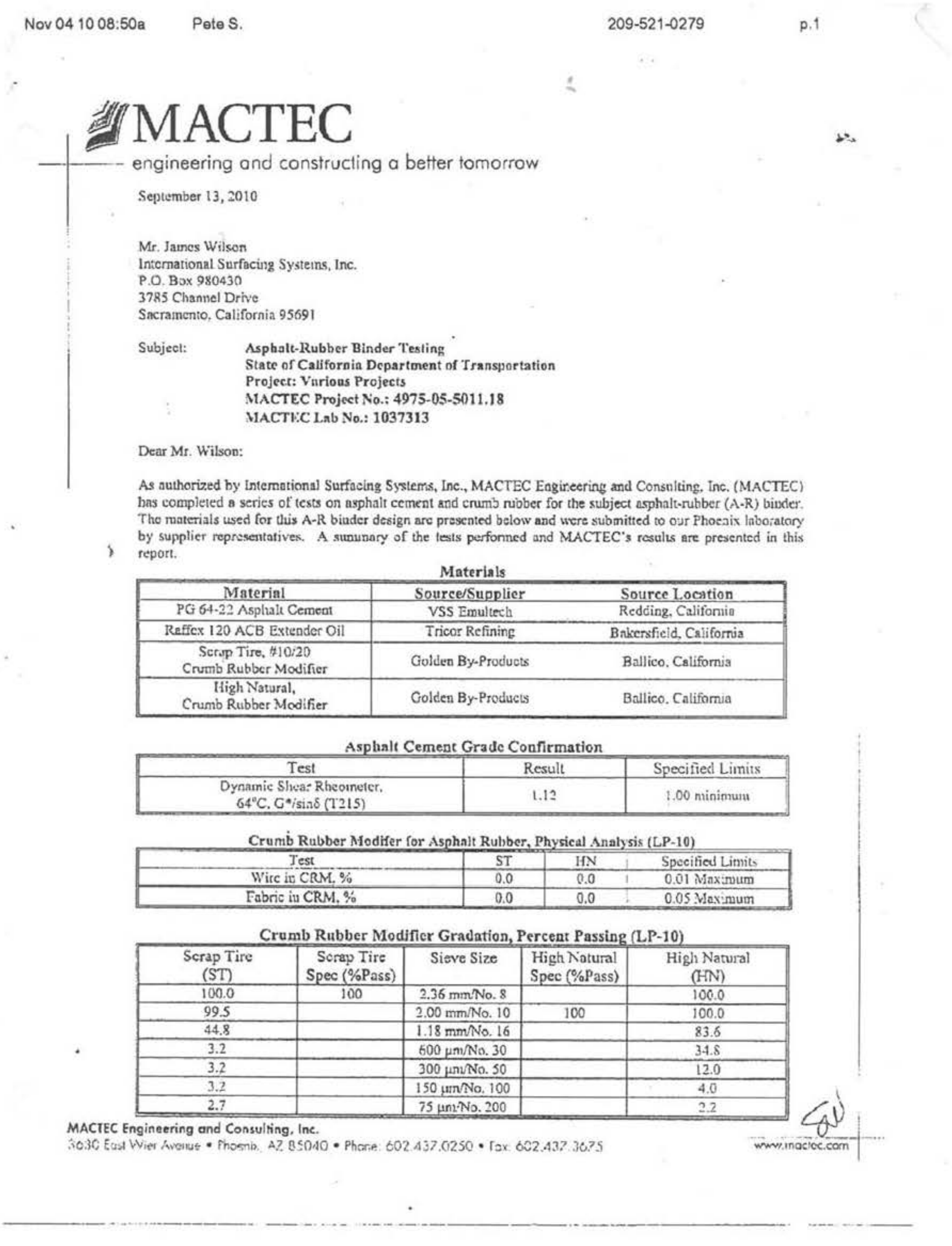
Table A.1: Performance-Graded Asphalt Binder Data, PG 64-10, San Joaquin Refinery

Property	AASHTO Test Method	Specification	Test Result
Original Binder			
Flash Point, Minimum °C	T 48	230	293
Solubility, Minimum %	T 44	99	99.8
Viscosity at 135°C, Maximum, Pa·s	T 316	3.0	0.257
Dynamic Shear	T 315		
Test Temp. at 10 rad/s, °C		64	64
Minimum G*/sin(delta), kPa		1.00	1.293
RTFO Test Aged Binder			
RTFO Test: Mass Loss, Maximum, %	T 240	1.00	-0.241
Dynamic Shear	T 315		
Test Temp. at 10 rad/s, °C		64	64
Minimum G*/sin(delta), kPa		2.2	2.316
Ductility at 25°C, Minimum, cm	T 51	75	150
PAV Aging, Temperature, °C	R 28	100	100
RTFO Test and PAV Aged Binder			
Dynamic Shear	T 315		
Test Temp. at 10 rad/s, °C		31	31
Maximum G*sin(delta), kPa		5,000	4,846
Creep Stiffness	T 313		
Test Temperature, °C		0	0
Maximum S-value, MPa		300	176
Minimum M-value		0.300	0.430
Specific Gravity @ 60°F			1.0253

Table A.2: Performance-Graded Asphalt Binder Per Caltrans Specification: PG 64-28 PM, San Joaquin Refinery

Property	AASHTO Test Method	Specification	Test Result
Original Binder			
Flash Point, Minimum °C	T 48	230	304
Solubility, Minimum %	T 44	99	99.5
Viscosity at 135°C, Maximum, Pa·s	T 316	3.0	1.291
Dynamic Shear	T 315		
Test Temp. at 10 rad/s, °C		64	64
Minimum G*/sinδ, kPa		1.00	1.713
RTFO Test Aged Binder			
RTFO Test: Mass Loss, Maximum, %	T 240	1.00	-0.264
Dynamic Shear	T 315		
Test Temp. at 10 rad/s, °C		64	64
Minimum G*/sinδ, kPa		2.2	2.396
Elastic Recovery at 25°C, Minimum Recovery, %	T 301	75	88
PAV Aging, Temperature, °C	R 28	100	100
RTFO Test and PAV Aged Binder			
Dynamic Shear	T 315		
Test Temp. at 10 rad/s, °C		22	22
Maximum G*sinδ, kPa		5,000	2,833
Creep Stiffness	T 313		
Test Temperature, °C		-18	-18
Maximum S-value, MPa		300	231
Minimum M-value		0.300	0.316
Specific Gravity @ 60°F			1.0082

Table A.3: Asphalt-Rubber Binder Testing Results of Asphalt Rubber (AR) (MACTEC)



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September 13, 2010

Mr. James Wilson
International Surfacing Systems, Inc.
P.O. Box 980430
3785 Channel Drive
Sacramento, California 95691

Subject: **Asphalt-Rubber Binder Testing**
State of California Department of Transportation
Project: Various Projects
MACTEC Project No.: 4975-05-5011.18
MACTEC Lab No.: 1037313

Dear Mr. Wilson:

As authorized by International Surfacing Systems, Inc., MACTEC Engineering and Consulting, Inc. (MACTEC) has completed a series of tests on asphalt cement and crumb rubber for the subject asphalt-rubber (A-R) binder. The materials used for this A-R binder design are presented below and were submitted to our Phoenix laboratory by supplier representatives. A summary of the tests performed and MACTEC's results are presented in this report.

Materials

Material	Source/Supplier	Source Location
PG 64-22 Asphalt Cement	VSS Emultech	Redding, California
Raffex 120 ACB Extender Oil	Tricor Refining	Bakersfield, California
Scrap Tire, #10/20 Crumb Rubber Modifier	Golden By-Products	Ballico, California
High Natural, Crumb Rubber Modifier	Golden By-Products	Ballico, California

Asphalt Cement Grade Confirmation

Test	Result	Specified Limits
Dynamic Shear Rheometer, 64°C, G*/sinδ (T215)	1.12	1.00 minimum

Crumb Rubber Modifer for Asphalt Rubber, Physical Analysis (LP-10)

Test	ST	HN	Specified Limits
Wire in CRM, %	0.0	0.0	0.01 Maximum
Fabric in CRM, %	0.0	0.0	0.05 Maximum

Crumb Rubber Modifier Gradation, Percent Passing (LP-10)

Scrap Tire (ST)	Scrap Tire Spec (%Pass)	Sieve Size	High Natural Spec (%Pass)	High Natural (HN)
100.0	100	2.36 mm/No. 8		100.0
99.5		2.00 mm/No. 10	100	100.0
44.8		1.18 mm/No. 16		83.6
3.2		600 μm/No. 30		34.8
3.2		300 μm/No. 50		12.0
3.2		150 μm/No. 100		4.0
2.7		75 μm/No. 200		2.2

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Table A.4: Aggregate Properties Reported by the Three Suppliers

Test Method	Quality Characteristic/Property	Test Results		
		Sacramento	Watsonville	San Gabriel
CT 205	Crushed particles, coarse aggregate One fractured face (%)	98.2	100	100
	Crushed particles, coarse aggregate Two fractured faces (%)	93.0		97
	Crushed particles, fine aggregate (#4x#8) One fractured face (%)	99.0		97
CT 211	LA Rattler, loss at 100 rev. (%)	4.5	9	9.0
	LA Rattler, loss at 500 rev. (%)	19.5	30	34.4
CT 217	Sand equivalent (avg.)	71	72	72
AASHTO T 304 (Method A)	Fine aggregate angularity (%)	46.5		43
ASTM D4791	Flat and elongated particles % by mass @ 3:1	3.4		0
	Flat and elongated particles % by mass @ 5:1	3.8		0
CT 204	Plasticity index	NP		NP
CT 229	Fine aggregate durability index	93		79
	Coarse aggregate durability index	85		85
CT 303	K_c factor (not mandatory until further notice)		1.0	1.36
	K_f factor (not mandatory until further notice)		1.1	1.00
CT 206	Bulk specific gravity (oven dry), coarse aggregate	2.757	2.80	2.65
	Absorption, coarse aggregate	0.9		0.9
CT 207	Bulk specific Gravity (SSD) of fine aggregate	2.819	2.63	2.67
LP-2	Bulk specific Gravity (oven dry) of fine aggregate	2.776		2.644
CT 207	Absorption of fine aggregate	1.5		1.0
CT 208/LP-2	Apparent specific gravity of supplemental fines			2.68
LP-2	Bulk specific gravity of aggregate blend	2.767	2.71	2.647
CT 208	Specific gravity of fines apparent			