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Improved Methodology for Mix Design of Open-Graded Friction Courses

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Partnered Pavement Research Program Strategic Plan Element 3.25:
Improved Methodology for Mix Design of Open-Graded Friction Courses

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Abstract: This study presents an improved methodology for the mix designs of open-graded friction courses (OGFC). The methodology has been enhanced by the development of an *Excel* macro in order to suggest revisions to California Test 368, *Standard Method for Determining Optimum Binder Content (OBC) for Open-Graded Asphalt Concrete*. In addition to the development of the *Excel* macro, one of the primary objectives of this study was to evaluate the effect that fines content has on mix performance, which cannot be identified by the "break point sieve" concept or by volumetric properties.

The proposed OGFC mix design includes two phases: *Phase I: Volumetric OGFC Mix Design* and *Phase II: Performance Testing.* The tasks required to perform Phase I include the determination of material volumetric properties such as specific gravities, voids in coarse aggregate in dry-rodded condition (VCA_{DRC}), and asphalt absorption. These must be performed so it becomes possible to select three trial binder contents for fabricating specimens for performance testing. The main purpose of Phase II is to decide the optimum binder range (OBR) according to the results of draindown, Cantabro, and Hamburg Wheel-Track Device (HWTD) tests.

Two aggregates (Watsonville and Sacramento), three binders (PG 76-22 PM, PG 64-28 TR, and PG 64-10), two gradations (Coarse and Fine) designed to verify the fines content, and three trial binder contents obtained from Phase I were used in the Phase II testing. It was found that an increase of fines content is significant in reducing Cantabro loss, preventing draindown, minimizing the variation of Superpave gyratory compaction curves, and producing more consistent HWTD test results. Hence, it is suggested that the fines content should be part of the OGFC performance specifications. This study also demonstrated the accuracy of the measured air-void contents of Superpave gyratory-compacted specimens that were fabricated with height control rather than gyration control and with binder contents calculated based on the volumetric equation, VCA_{DRC}. A preliminary comparison indicated that the proposed mix design produces similar binder contents for conventional and asphalt rubber binders with similar gradations, and that unreasonably low binder contents it may produce indicate a fines content that is too high.

This improved OGFC mix design together with the *Excel* macro developed provides a rational, accurate, and convenient methodology for determining OBR. However, further studies are required to establish the proper performance specifications that relate to field performance.

Keywords:
OGFC, mix design, performance specification, draindown, Cantabro loss, Hamburg Wheel-Track Device test

Proposals for implementation:
1. Conduct HVS testing on selected mixes designed by the proposed methodology to evaluate performance.
2. Have the Materials Engineering and Testing Services staff implement the revised OGFC methodology on a trial basis together with the current California 368 Test on a series of mixes for mix comparisons and test time requirements.

Related documents:
- Evaluation of Open-Graded Friction Course (OGFC) Mix Design: Summary Version, by B.-W. Tsai, J. T. Harvey, and C. L. Monismith. September 2012. UCPRC-SR-2013-02.
- Evaluation of Open-Graded Friction Course (OGFC) Mix Design, by B.-W. Tsai, J. T. Harvey, and C. L. Monismith. September 2012. UCPRC-RR-2012-09. 2012.

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PROJECT OBJECTIVES

The objective of this report is to present a proposed improved methodology for the mix design of open-graded friction courses (OGFC). This methodology includes an enhancement introduced by the development of an *Excel* macro and provides a major revision of California Test 368 (CT 368), *Standard Method for Determining Optimum Binder Content (OBC) for Open Graded Asphalt Concrete*. This proposed methodology was developed through the following tasks:

- Determine whether break point sieve size provides sufficient information by performing laboratory testing to find the effects of percent passing No. 200 sieve on performance-related test results.
- Verify the accuracy of air-void contents of specimens prepared using height-controlled Superpave gyratory compaction with binder contents obtained from the proposed OGFC mix design chart, which is based on the volumetric equation, VCA_{DRC} .
- Develop an approach that includes the results of performance-related tests in the OGFC mix design chart to determine the allowable range of binder contents that will meet all design requirements.
- Enhance the improved methodology of OGFC mix design with development of an *Excel* macro for selection of the optimum binder range (OBR).
- Provide recommendations for revising CT 368.

EXECUTIVE SUMMARY

The California Department of Transportation (Caltrans) currently uses procedure "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. Over the course of its use, however, several shortcomings in the procedure have been identified. Among these are (1) the procedure does not include verification of whether stone-on-stone contact exists in the mix, (2) it contains no requirement for determining the volumetric and mechanistic properties of compacted specimens, and (3) it does not include performance testing for aging and moisture damage in the state's different climate regions.

The National Center for Asphalt Technology (NCAT) [*1*] recently developed an improved OGFC mix design that 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.

A Caltrans Expert Task Group (ETG) has recommended that CT 368 undergo a major revision and, based on an examination of the NCAT approach, the group recommended that the principles contained in the NCAT approach be considered for use in a revision of CT 368. Caltrans then developed a work plan, *The Development of a Test Method for Open-Graded Friction Courses Used in California* [*2*], that included a proposed OGFC mix design procedure.

The UCPRC used this work plan as part of Strategic Plan Element (SPE) Project 4.21 Subtask 2A that presented a preliminary OGFC design procedure (results of that study appear in Reference [*3*] of this current report). That procedure included a mix design chart that permits selection of trial binder contents that will meet a required air-void content range (in that instance, 18 to 22 percent). The measured parameters required for that proposed procedure include: (1) the percent of aggregate mass in the gradation passing the break point sieve (the finest sieve to retain 10 percent or more of the aggregate blend); (2) the air-void content of the coarse aggregate in the dry-rodded condition (VCA_{DRC}); and (3) the expected absorbed asphalt. This design chart (shown in this report as Figure 1.2) is based on the volumetric concept that VCA_{DRC} is filled with fine aggregate, fiber, and the asphalt not absorbed by the aggregate, plus air voids. The results of the SPE 4.21 project found that, regardless of binder and aggregate types, the optimum gradation selected per the NCAT approach—usually a coarse gradation with fewer fines—did not guarantee the success of an OGFC mix design as measured by draindown testing and a performance-related test for raveling (Cantabro test).

Recently, Caltrans has begun using the Hamburg Wheel-Track Device (HWTD) test to determine the moisture sensitivity of asphalt concrete. This shift has an additional potential benefit for Caltrans because not only do the features of HWTD testing make it useful as a performance test for evaluating moisture sensitivity, but they also give the procedure the potential to evaluate the permanent deformation characteristics of OGFC mixes in the design process.

This report is the follow-on to the research results described in Reference (*3*). The purpose of this investigation has been to use laboratory testing to calibrate the OGFC mix design chart (shown in Figure 1.2) to ascertain that it provides the desired air-void content while it also produces mixes that meet the desired properties from three performance-related tests: draindown, Cantabro (to measure durability performance), and Hamburg Wheel-Track Device testing (HWTD, to measure rutting and moisture sensitivity). Figure 1.3 of this report illustrates a proposed mix design process that includes the results developed in the earlier study plus a process for considering the performance-related tests that are evaluated in this report. In this current investigation, an *Excel* Macro was developed to simplify the preparation of the design chart (developed in Reference [3]) using the specific material properties for the OGFC being evaluated.

The investigation was accomplished by performing laboratory tests to determine the effects that percent passing the No. 200 sieve, binder grade, percent absorbed asphalt in the aggregate, and the percent passing the break-point sieve size have on air-void content and on performance-related test results (draindown, Cantabro, and HWTD tests).

Laboratory Study. Two different commercially available aggregate samples with different geological origins, alluvial and granite, were obtained from different sources, one in northern California and one in central California. The alluvial aggregate was subrounded to subangular in shape with a relatively smooth surface texture although the majority of particles contained at least one crushed face with a rough surface texture. The granite aggregate consisted of crushed materials with rough surface textures.

Three binders were used in this study: PG 64-10 (San Joaquin Refinery), PG 76-22 PM (polymer-modified) and PG 64-28 TR (terminal blend, tire rubber) (Paramount Petroleum Corporation).

From the earlier study (described in Reference [*3*]), it was concluded that the use of a break point sieve alone to categorize the aggregate blend into a coarse portion (P_{cg}) and a fine portion (P_{fg}) could not properly reflect the importance of gradation—and especially of the fines content (< No. 200 sieve)—on OGFC mix performance. Thus this study made use of two OGFC gradations of the same size, 3/8 inch, that complied with the target value (TV) limits of gradation (*4*)] (shown in the table below and in Table 3.2 of the report). The two selected gradations, designated *Coarse* and *Fine,* both retained the No 8 sieve as their break point sieve size (gradations are the same); below this sieve size they deviated (distributions smaller than the No. 8 sieve are also included in the two tables).

Proposed 3/8 in. OGFC Gradations

Sieve Size		Caltrans Specification		Proposed OGFC Gradation	
US	SI (mm)	Target Value Limit	Allowable Tolerance	Coarse	Fine
1/2”	12.5	100	—	100	100
3/8”	9.5	90 – 100	TV ± 6	92	92
No. 4	4.75	29 – 36	TV ± 7	33	33
No. 8	2.36	7 – 18	TV ± 6	17	17
No. 16	1.18			8	14
No. 30	0.60	0 – 10	TV ± 5	4	11
No. 200	0.075	0 – 3	TV ± 2	1	4

After the necessary material properties for the two aggregates and the two gradations (Figure 1.3 of the report) were determined (e.g., stone-on-stone contact as described in Reference [*3*] of the report), three binder contents were selected using the *Excel* macro (Phase I: OGFC Volumetric Mix Design) to prepare specimens for mix testing. These included two loose mix samples for draindown tests and nine height-controlled Superpave gyratory compaction (SGC) specimens—three 4.0 in. diameter (101.6 mm) specimens to be used for Cantabro testing and six 5.91 in. (150 mm) diameter specimens for HWTD testing. The sample mix types were chosen from a factorial that included two aggregates, two gradations, three binders, and three binder contents.

Summary of Test Results and OGFC Mix Design Procedure. After completion of the performance testing, the results were used as the inputs to determine the optimum binder range (OBR) using the *Excel* macro (Phase II: Performance Testing). The performance specifications utilized were the following: maximum 0.3 percent draindown, maximum 30 percent Cantabro loss, and maximum 12.5 mm average rut depth for HWTD testing. It should be noted, however, that although the HWTD performance parameter, number of passes at 12.5 mm average rut depth, was used in this study, it is not recommended because almost two-thirds of the HWTD data were from extrapolations and their use might induce greater uncertainty—in contrast to the use of the average rut depth at 20,000 passes.

Detailed analyses of the mixes tested are described in Chapters 5 and 6 of the report. Based on these analyses, which included the use of the *Excel* macro, three trial binder contents were selected and specimens were prepared for performance testing. This revised OGFC mix design procedure (which is summarized in Table 6.5 of this report) includes the required activities, test methods, and software. A flow chart showing the proposed OGFC mix design procedure appears as Figure 6.7 of this report, replacing the earlier OGFC mix design procedure (shown in Figure 1.3 of the report).

However, before the revised procedure can be used it is important to take the following into account: (1) VCA_{DRC} and P_{aasp} are two critical material properties that affect the construction of the OGFC mix design chart and the accuracy of the percent air-void content; (2) if the trial binder contents obtained using the *Excel* macro are questionable, it is suggested that adjustments be made to the aggregate gradation (based on experience or the results of the performance tests); (3) use of height-controlled Superpave gyratory compaction to prepare specimens for the Cantabro and HWTD tests is strongly recommended.

It should be emphasized that the *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 the predetermined material properties of the selected aggregates and binder types, the macro provides an improved method for evaluating whether a selected gradation meets the requisite properties. It determines whether the mix has sufficient binder to meet the volumetric requirements and whether there is enough binder to yield an asphalt film thickness that results in adequate durability and rutting resistance without excessive draindown and moisture damage. The proposed mix design chart takes into consideration of 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 then 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).

Conclusions

1. The proposed OGFC mix design procedure, with the addition of the *Excel* macro, is very promising. The proposed procedure provides several of the following features: (1) it eliminates the need to determine an optimum gradation, as is required in the NCAT approach; (2) the proposed mix design chart takes into consideration both the percent asphalt absorption of the aggregate blend, which is not specified in the NCAT approach, and the VCA_{DRC}, which insures stone-on-stone contact in the aggregate structure; (3) the *Excel* macro developed in this part of the study provides a convenient way to summarize test results and to determine the optimum binder range; (4) the *Excel* macro can modify each criterion and establish performance specifications that relate to expected performance.
2. An increase in the percent passing the No. 200 sieve not only decreases the variability in the SGC compaction curve, but it also helps to control the amount of draindown and to significantly reduce Cantabro loss. Although tree-based modeling showed only a marginal effect of fines content on HWTD performance, the gradation with more fines reduced variability in the average rut depth curve and yielded more consistent results. Based on this information, it is desirable to include a more specific requirement for fines content in the OGFC mix design procedure than currently exists in the Caltrans specification.

3. The air-void contents of the height-controlled SGC specimens have means very close to the target values, with average standard deviations roughly in the range of 0.3 – 0.5 percent, and, accordingly, have a 95 percent probability within the range of TV±0.6 – 1.0 percent, which is considered acceptable.
4. According to this study, a desirable OGFC mix design would include the following:
   - Selection of an aggregate type that is strong enough to form a solid stone-on-stone contact structure and with a high VCA_{DRC} value so as to accommodate more asphalt that will improve mix durability and to provide greater flexibility in selecting the gradation/NMAS and design air-void content;
   - It would facilitate selection of a binder type that can provide adequate durability, ensure sufficient rutting resistance, minimize moisture damage, and prevent draindown without the addition of fiber.
   - It would enable selection of a gradation with sufficient fines content to minimize draindown and improve Cantabro performance and compactability when placed on hot-mix asphalt (HMA).
5. The proposed procedure to determine asphalt absorption included in the NCAT procedure is practical.
6. The resulting HWTD performance tests indicate that (1) binder type is far more significant than the other covariates, and (2) there is no strong evidence to support the statement that the larger the asphalt content the better the HWTD performance, as demonstrated in Reference (*3*).
7. A preliminary comparison indicates that the proposed procedure tends to produce similar binder contents for conventional and asphalt rubber binders, and that the binder contents from the proposed procedure can be considerably different from those using CT 368, which are based only on draindown.

Recommendations

The following preliminary recommendations are suggested for consideration in future efforts to revise CT 368:

1. Base the SGC procedure for test specimens on height control rather than on a fixed number of gyrations because use of a fixed number of gyrations (for example, the 50 gyrations used in the NCAT procedure) to prepare specimens will result in a large variation in air-void content.
2. Make fines content (i.e., percent passing the No. 200 sieve) a part of the performance specifications, incorporating a criterion based on either the percent passing the No. 200 sieve or the area beneath the gradation curve from the break point sieve size to No. 200 sieve, or both. This is recommended because an increase of fines content is significant in reducing Cantabro loss, preventing draindown, producing more consistent HWTD test results, and in minimizing variations in the SGC curves. *This likely would require a more stringent specification for the percent passing the No. 200 sieve.*
3. Continue use of the maximum 0.3 percent draindown specification suggested by the NCAT approach because it appears to be a reasonable value for use in the specification for the proposed OGFC mix design.

4. It is not necessary to specify the upper limit of air-void content if the compacted mix can meet the performance specifications for draindown, Cantabro, and the Hamburg Wheel-Track Device test. The minimum 18 percent air-void content seems to be adequate.
5. Adopt a maximum percent Cantabro loss specification for OGFC mix design in the range of 20 to 30 percent. The maximum 15 percent Cantabro loss suggested in the NCAT approach seems to be too strict.
6. Continue this study further in order to evaluate the HWTD test as a performance test for OGFC mix design, with the aim of answering the following two questions. First, will the HWTD testing rank the OGFC mixes correctly and consistently both in the laboratory and in the field? Second, how will the laboratory HWTD test performance specification relate to field performance?

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transport Officials
AC	Asphalt content
ASTM	American Society for Testing and Materials
AV	Air-void content
Caltrans	California Department of Transportation
HMA	Compacted hot-mix asphalt
HWTD	Hamburg Wheel-Track Device
NCAT	National Center for Asphalt Technology
OBC	Optimum Bitumen Content
OBR	Optimum Binder Range
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

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 LP-2	Determination of the Voids in Mineral Aggregate
CT LP-4	Determination of Dust Proportion

1 BACKGROUND, GOALS, AND OBJECTIVES

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. Several disadvantages are associated with the current CT 368 procedure, including these: (1) there is no verification of stone-on-stone contact, (2) there is no determination of the 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 for 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 Hveem Expert Task Group (ETG) of Caltrans has agreed that CT 368 needs a major revision. Moreover, the ETG examined the NCAT approach and proposed that the principles contained in it be considered in a revised CT 368. Accordingly, a work plan—*The Development of a Test Method for Open-Graded Friction Courses Used in California*—was proposed by Caltrans on July 21, 2009 (*2*). The University of California Pavement Research Center (UCPRC) used that work plan as part of Strategic Plan Element (SPE) Project 4.21 Subtask 2A, which was completed in late 2011 (*3*). That study produced an evaluation of the proposed mix design procedure by means of laboratory performance testing. Figure 1.1 illustrates the OGFC mix design procedure proposed by Caltrans. The results of the SPE 4.21 project found that, regardless of binder and aggregate types, the optimum gradation selected per the NCAT approach—usually a coarse gradation with fewer fines—did not guarantee the success of an OGFC mix design as measured by draindown testing and a performance-related test for raveling (Cantabro test).

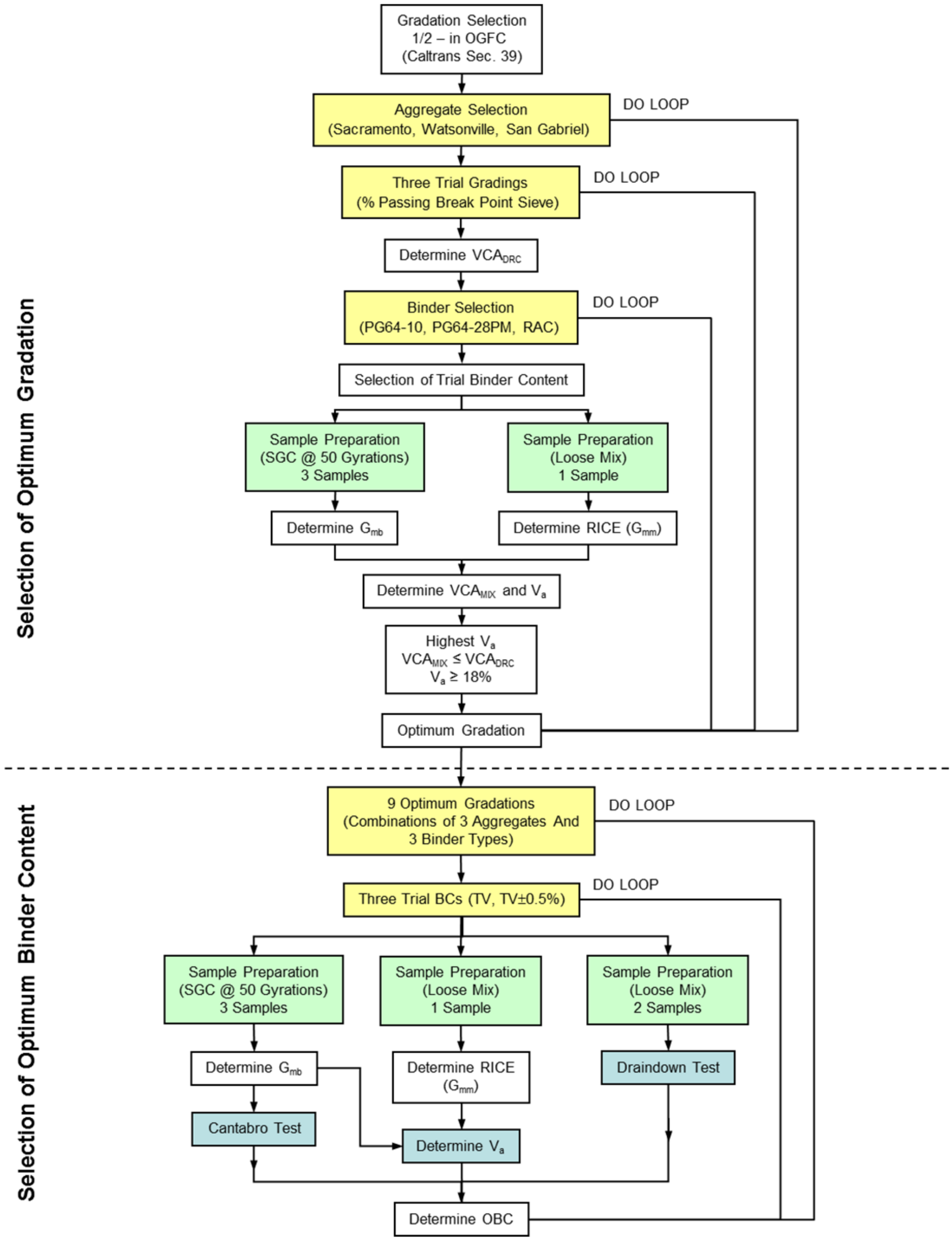


Figure 1.1: OGFC mix design procedure proposed by Caltrans (based on NCAT procedure).

One of the contributions of Project 4.21 Subtask 2A is the OGFC mix design chart shown in Figure 1.2 that supports the OGFC design procedure shown in Figure 1.1. This design chart can help the mix designer select trial binder contents that will meet the required air-void content (in this case 18 to 22 percent) based on the percent of aggregate mass passing the break point sieve in the gradation, the air-void content of the coarse aggregate in the dry-rodded condition (VCA_{DRC}), and the expected absorbed asphalt. The design chart in Figure 1.2 is based on the volumetric concept that VCA_{DRC} is filled with the fine aggregate, fiber, and asphalt not absorbed by the aggregate, plus air voids. Thus far, this design chart has not been calibrated by laboratory testing to insure that a suitable range of binder contents (i.e., optimum binder range [OBR] will be obtained.

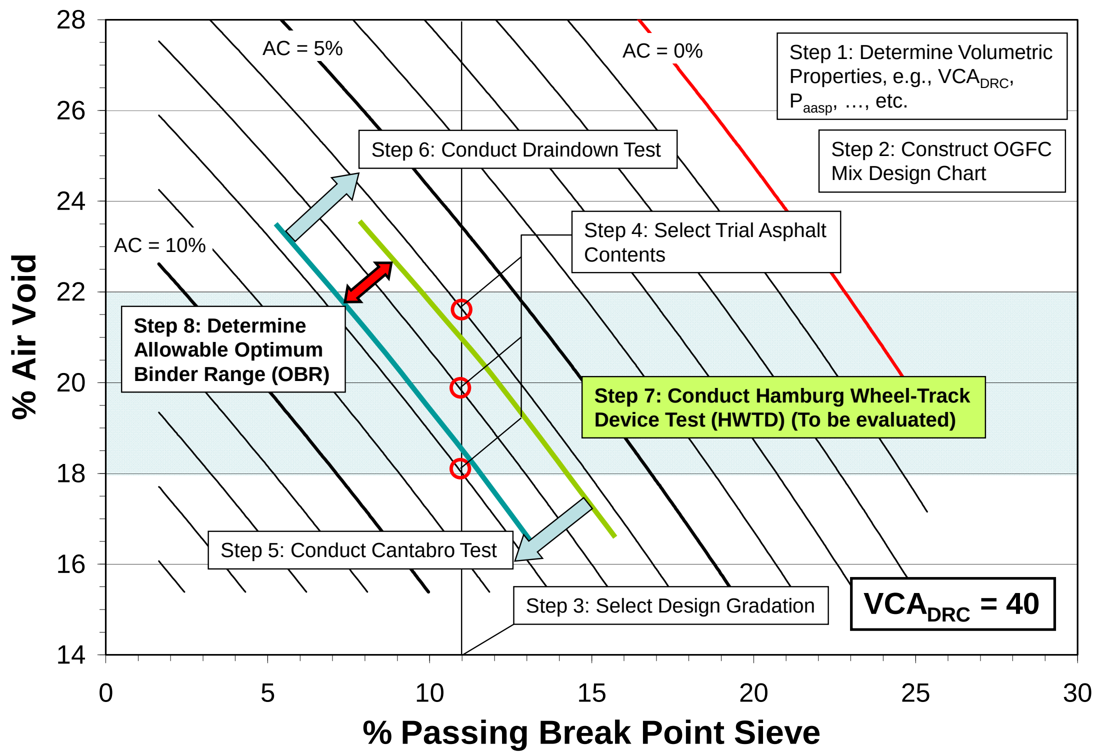


Figure 1.2: Proposed OGFC design chart from Partnered Pavement Research Center Strategic Plan Element Project 4.21 (*3*).

The design chart shown in Figure 1.2 is a critical part of the proposed, recommended OGFC design procedure that resulted from Project 4.21 Subtask 2A. The proposed design procedure shown in Figure 1.3 is based on the Caltrans proposed design procedure shown in Figure 1.1 with changes based on extensive laboratory testing following the process shown in the latter figure. The results of Project 4.21 Subtask 2A showed that many factors, including, percent passing No. 200 sieve, $VCA_{DRC,}$ asphalt absorption, measurement of air-void content, asphalt type, nominal maximum aggregate size (NMAS), and percent passing break point sieve affect the OGFC design chart and not all were considered in the procedure shown in Figure 1.1.

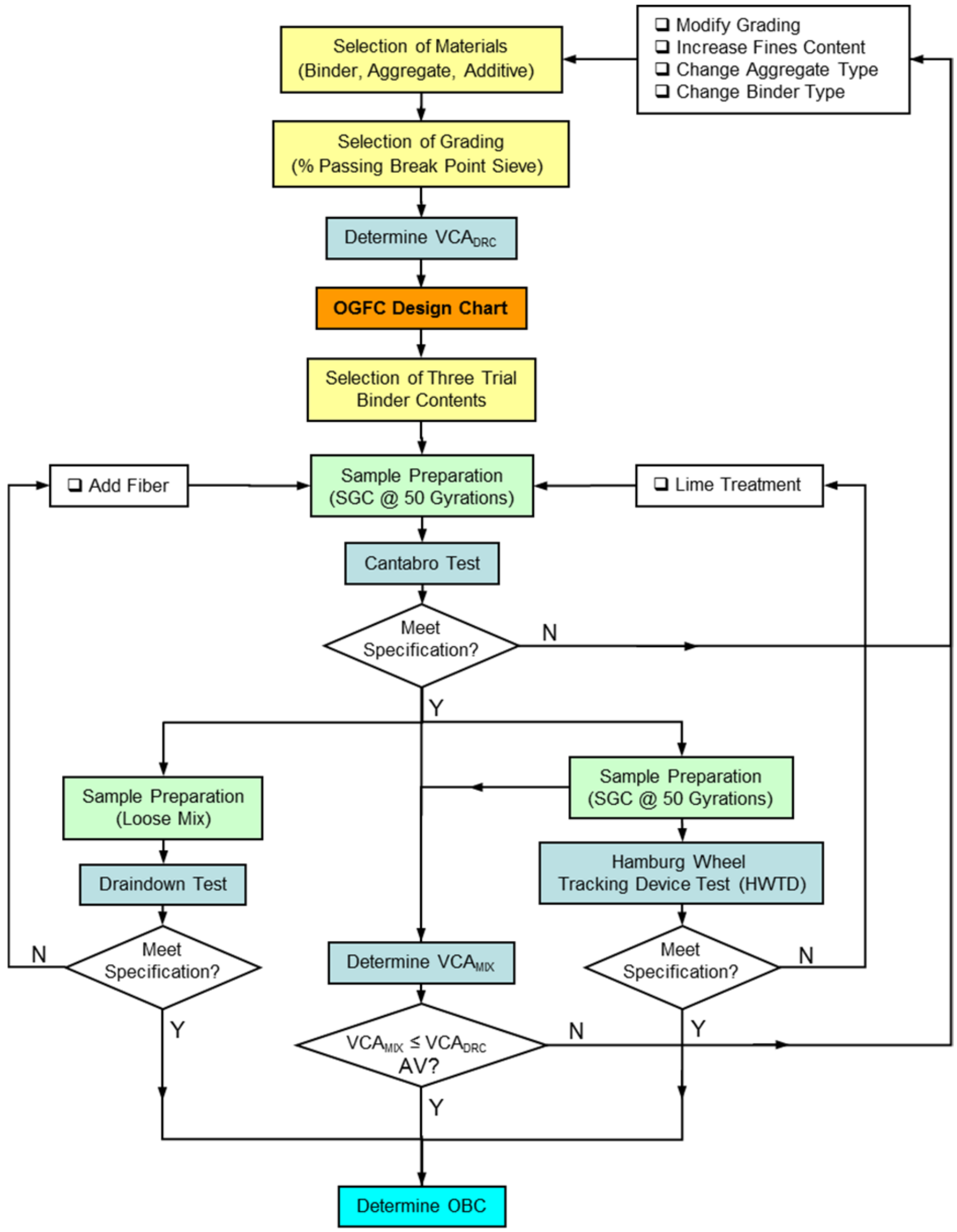


Figure 1.3: Proposed OGFC design procedure from Partnered Pavement Research Center Strategic Plan Element Project 4.21 (*3*) project.

Recently, Caltrans has also begun using HWTD testing to determine the moisture sensitivity of asphalt concrete. The features of this test procedure may also make it a valuable final performance evaluation test for OGFC mix design, as the HWTD test has the potential to serve as a performance test for determining the permanent deformation characteristics of OGFC mixes in the mix design process.

1.2 Goals and Objectives

The goal of Partnered Pavement Research Center Strategic Plan Element 3.25 is to calibrate the OGFC mix design chart shown in Figure 1.2 based on laboratory testing to ensure that it delivers the desired air-void content, while also producing mixes that meet the desired properties for the three performance-related tests in the Figure 1.3 procedure: draindown, Cantabro (measure of durability performance), and Hamburg Wheel-Track Device (HWTD, measure of rutting and moisture sensitivity) testing. These questions are to be answered by the calibration:

1. Can the OGFC mix design chart produce mixes that meet the design requirements?
2. Can the performance-related test results be incorporated into the design chart to arrive at an optimum binder range? (Figure 1.2 currently shows conceptual changes in binder content based on Cantabro [step 5] and draindown [step 6] test results).

To calibrate the OGFC mix design chart and procedure, the following objectives must be met:

1. Determine whether the break point sieve size provides sufficient information about whether the aggregate gradation will meet the design requirements. This will be done by performing laboratory tests to find the effects that percent passing the No. 200 sieve, binder grade, the percent absorbed asphalt in the aggregate, and the percent passing at break-point sieve size have on air-void content and performance-related test results (draindown, Cantabro, and, potentially, HWTD).
2. Develop a new approach for determining an allowable range of binder contents that will meet all design requirements. This approach is to incorporate the results of performance-related testing in the design chart shown in Figure 1.3.

2 MATERIALS

2.1 Aggregates

Two different commercially available aggregate samples with different geological origins were obtained from California suppliers: alluvial aggregates of mixed origins from near Sacramento and granite from a hard rock mine near Watsonville.

The Sacramento material was subrounded to subangular compared to the Watsonville material, which was 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. The Watsonville aggregate consisted of crushed materials with rough surface textures. A summary of the available aggregate test properties reported by the two organizations is included in Appendix A, Table A.1; photographs of these aggregates graded by size above the No. 8 sieve are shown in Figure 2.1.

Figure 2.1: Aggregate comparison above break point sieve size.
(The VCA$_{DRC}$ was based on 3/8 in. OGFC gradation.)

In this figure, the size of the aggregate indicated in each photo represents what was retained by that sieve, i.e., this material passed the adjacent upper sieve and was retained in the next smaller sieve, whose size is shown. For example, in the photograph showing the No. 8 sieve, the aggregate represents the material that passed the No. 4 sieve and was retained on the No. 8 sieve. As will be shown, only a 3/8 inch OGFC gradation was used in this investigation.

2.2 Asphalt Binders

Three binders were used in this study. The San Joaquin Refinery in Bakersfield, California, supplied PG 64-10 and the Paramount Petroleum Corporation provided PG 76-22 PM (polymer-modified) and PG 64-28 TR (terminal blend, tire rubber). Table 2.1 summarizes the properties of these three binders as obtained from their certificates of compliance from the refineries (see also the original test results as illustrated in Figure A.1, Figure A.3, and Figure A.5 in Appendix A, respectively for PG 76-22 PM, PG 64-28 TR, and PG 64-10).

2.3 Mixing and Compaction Temperatures

Table 2.2 summarizes the binder mixing and compaction temperatures used in this study (see also the original test results as illustrated in Figure A.2, Figure A.4, and Figure A.6 in Appendix A, respectively for PG 76-22 PM, PG 64-28 TR, and PG 64-10).

Table 2.1: Performance-Graded Asphalt Binder per Caltrans Specification: PG 64-10 (San Joaquin Refinery), PG 76-22 PM, and PG 64-28 TR (Paramount Petroleum)

Property	AASHTO Test Method	PG 64-10		PG 76-22 PM		PG 64-28 TR	
		Specification	Test Result	Specification	Test Result	Specification	Test Result
Tests on Original Asphalt							
Flash Point, Minimum, °C	T 48	230	293	230	305	230	300
Solubility, Minimum, %	T 44	99	99.8	98.5	99.15	97.5	98.43
Viscosity at 135°C, Maximum, Pa·s	T 316	3.0	0.257	3.0	1.786	3.0	1.528
Viscosity at 165°C, Maximum, Pa·s	T 316				0.589		0.510
Dynamic Shear	T 315						
Test Temp. at 10 rad/s, °C		64	64	76	76	64	64
Minimum G*/sin(delta), kPa		1.00	1.293	1.00	1.89	1.00	1.92
Test on RTFO Residue							
RTFO Test: Mass Loss, Maximum, %	T 240	1.00	-0.241	1.00	0.482	1.00	0.482
Dynamic Shear	T 315						
Test Temp. at 10 rad/s, °C		64	64	76	76	64	64
Minimum G*/sin(delta), kPa		2.20	2.32	2.20	2.71	2.20	3.24
Ductility at 25°C, Minimum, cm	T 51	75	150	65	82	75	82
Tests on PAV Residue							
PAV Aging, Temperature, °C	R 28	100	100	110	110	100	100
Dynamic Shear	T 315						
Test Temp. at 10 rad/s, °C		31	31	31	31	22	22
Maximum G*sin(delta), kPa		5,000	4,846	5,000	678	5,000	3,120
Creep Stiffness	T 313						
Test Temperature, °C		0	0	-12	-12	-18	-18
Maximum S-value, MPa		300	176	300	113	300	275
Minimum M-value		0.300	0.430	0.300	0.365	0.300	0.302
Specific Gravity @ 15°C			1.0253		1.0321		1.0315

Table 2.2: Mixing and Compaction Temperatures of Binders

Binder Type	Mixing	Compaction
PG 64-10	141° – 146°C (286° – 295°F)	132° – 136°C (270° – 277°F)
PG 76-22 PM	197° – 207°C (387° – 404°F)	179° – 187°C (354° – 368°F)
PG 64-28 TR	187° – 197°C (368° – 386°F)	168° – 176°C (335° – 349°F)

3 TEST PLAN, GRADATION, AND METHODOLOGY

3.1 Test Plan

The primary goals of the test plan were to evaluate (1) material volumetric properties (designated as *Phase I: OGFC Volumetric Mix Design* in the *Excel* macro developed for this study), (2) mix performance (designated as *Phase II: Performance Testing* in the *Excel* macro), and (3) the effect of fines content on mix performance.

The Phase I OGFC Volumetric Mix Design procedure consisted of determining the following volumetric properties:

- Voids in coarse aggregate in dry-rodded condition (VCA_{DRC})
- Asphalt absorption by weight of aggregate (P_{aasp})
- Theoretical maximum specific gravity (G_{mm}) and
- Bulk specific gravities of compacted asphalt mix (G_{mb}), coarse aggregate (G_{cg}), fine aggregate (G_{fg}), and asphalt (G_{asp}).

For the Phase II Performance Testing, three preselected performance tests were used to evaluate the compliance of the OGFC mixes with the performance specifications of the following:

- Draindown
- Cantabro (measure of durability performance) and
- Hamburg Wheel-Track Device testing (HWTD, measure of rutting and moisture damage).

As discussed in Chapter 2, three binder types (PG 76-22 PM [PM], PG 64-28 TR [TR], and PG 64-10 [PG]) and two aggregate types (Watsonville [W] and Sacramento [T])[1] were used in this study. Two gradations (Coarse [C] and Fine [F]) that complied with the 3/8 inch OGFC aggregate quality and gradation portion of Section 39 of the Caltrans Standard Specifications were applied to each aggregate type. The coarse and fine gradations were designed to enable evaluation of the effect of fines content on mix performance. A total of 10 mix types out of the full factorial (the combinations of three binder types, two aggregate types, and two gradations) were utilized in this study: PMWC, PMWF, PMTC, PMTF, TRWC, TRWF, TRTC, TRTF, PGWC, and PGWF. Two mixes, PGTC and PGTF, were excluded from this study because of time constraints and reduced budget. For each mix type included, three trial binder contents were determined using the OGFC mix design chart discussed in Chapter 4.

[1] Note that the specimen-naming scheme used in this testing has been carried over from an earlier project.

For each mix type at each of the three trial binder contents, specimen preparation for performance testing included the following:

- Loose mix samples prepared for determining the theoretical maximum specific gravity (G_{mm}) and draindown
- Three 4 in. diameter (101.6 mm) Superpave gyratory-compacted (SGC) cylindrical samples under height control (63.5 mm [2.5 in.]) fabricated for Cantabro testing
- Six 150 mm diameter (5.91 in.) height-controlled SGC samples (also, 63.5 mm [2.5 in.]) for HWTD testing

It should be noted that specimens prepared for Cantabro and HWTD testing were also used to determine the bulk specific gravity of the compacted asphalt mixture (G_{mb}), the air-void content (V_{air}), and the voids in the coarse aggregate of the compacted mix (VCA_{MIX}).

The detailed test plan for PPRC Strategic Plan Element 3.25 is summarized in Table 3.1.

3.2 Selection of Gradation

3.2.1 Break Point Sieve

According to the NCAT approach (*1*), the coarse fraction of an aggregate blend is defined as the portion of aggregate coarser than the break point sieve. The break point sieve is defined as the finest sieve to retain 10 percent or more of the aggregate blend.

3.2.2 Proposed Gradations

From a previous study (SPE 4.21, OGFC Evaluation, Phase 2A [*3*]), it was concluded that the use of a break point sieve 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—and especially of the fines content (< No. 200 sieve)—on OGFC mix performance. Hence, this study used two gradations that complied with the target value (TV) limits of gradation (*4*) shown in Table 3.2. The two selected gradations, designated *Coarse* and *Fine,* retained the No 8. sieve as their break point sieve size, although they deviated below this sieve. The proposed 3/8 inch OGFC gradations are listed in Table 3.2 and illustrated in Figure 3.1. It should be noted that since the Caltrans OGFC specification lists three gradations—1 inch, 1/2 inch, and 3/8 inch—when these studies began it was considered desirable to evaluate all of them. As a step toward accomplishing this, the investigation reported in Reference (*3*) evaluated mixes containing the ½ inch gradation. When the work plan for this current study (UCPRC-WP-2012-01, January 2012) was devised, consideration was then given to investigating the performance of OGFC mixes that include the 1 inch and 3/8 inch OGFC gradations. However, because of funding limitations on this study a decision was made only to evaluate mixes with the 3/8 inch gradation, which is more commonly used.

Table 3.1: Summary of Test Plan for Project 3.25: Improved Methodology for Mix Design of Open-Graded Friction Courses

Tasks	Test Variables and Total Number of Combinations	Test Type	Compaction Method	Specimen Size	Samples Per Combination	Total Samples
Aggregate Gradation Confirmation	2 aggregate types: Sacramento (T), Watsonville (W) 2 trial gradings: 3/8 in. OGFC: Coarse (C), Fine (F) (% passing break point sieve) **2 × 2 = 4**	Wet/Dry Sieving AASHTO T 11 AASHTO T 27	Loose dry aggregate		2	8
Phase I: Volumetric OGFC Mix Design VCA_{DRC}[1]	2 aggregate types: Sacramento (T), Watsonville (W) 1 gradings: (% retained above break point sieve) **2 × 1 = 2**	AASHTO T 19	Loose dry aggregate		3	81
		AASHTO T 85 (G_{cg}[1])	Loose dry aggregate		2	18
Phase I: Volumetric OGFC Mix Design Asphalt Absorption	2 aggregate types: Sacramento (T), Watsonville (W) 2 trial gradings: 3/8 in. OGFC: Coarse (C), Fine (F) (% passing break point sieve) **2 × 2 = 4**	AASHTO T 84 (G_{fg}[1])	Loose dry aggregate		2	8
	3 binder types: PG76-22PM (PM), PG64-28TR (TR) PG64-10 (PG) 2 aggregate types: Watsonville (W) and Sacramento (T) 2 trial gradings: 3/8 in. OGFC: Coarse (C), Fine (F) (% passing break point sieve) 1 trial binder content (2.5% or 3%) **3 × 2 × 2 × 1 = 12 -2 = 10** **(excluding PGTC and PGTF mixes)**	RICE (G_{mm}[1])	Loose mix		2	20
Phase II: Performance Testing	10 mix types as described in determining Asphalt Absorption Plus 3 trial binder contents (TBD[1]) **10 × 3 = 30**	RICE (G_{mm})	Loose mix		1	30
		G_{mb}[1], V_{air}[1], and VCA_{MIX}[1]	SGC @ height control[2]	102 mm D x 63.5 mm H 150 mm D x 63.5 mm H		90 + 180 = 270
		Draindown	Loose mix		2	60
		Cantabro	SGC @ height control	102 mm D x 63.5 mm H	3	90
		HWTD	SGC @ height control	150 mm D x 63.5 mm H	6	180

Notes:

1. VCA_{DRC}: voids in coarse aggregate in dry-rodded condition; G_{cg}: bulk specific gravity of coarse aggregate; G_{fg}: bulk specific gravity of fine aggregate; RICE (G_{mm} : the theoretical maximum specific gravity of the mixture; G_{mb}: bulk specific gravity of the compacted mixture; V_{air}: air-void content; VCA_{MIX}: voids in coarse aggregate of the compacted mixture; HWTD: Hamburg Wheel-Track Device Test; TBD: to be determined.
2. SGC @ height control: specimen prepared using Superpave gyratory compactor with height control.
3. Note that the specimen-naming scheme used in this study has been carried over from an earlier project.

Table 3.2: Proposed 3/8 in. OGFC Gradations

Sieve Size		Caltrans Specification		Proposed OGFC Gradation	
US	SI (mm)	Target Value Limit	Allowable Tolerance	Coarse	Fine
1/2”	12.5	100	—	100	100
3/8”	9.5	90 – 100	TV ± 6	92	92
No. 4	4.75	29 – 36	TV ± 7	33	33
No. 8	2.36	7 – 18	TV ± 6	17	17
No. 16	1.18			8	14
No. 30	0.60	0 – 10	TV ± 5	4	11
No. 200	0.075	0 – 3	TV ± 2	1	4

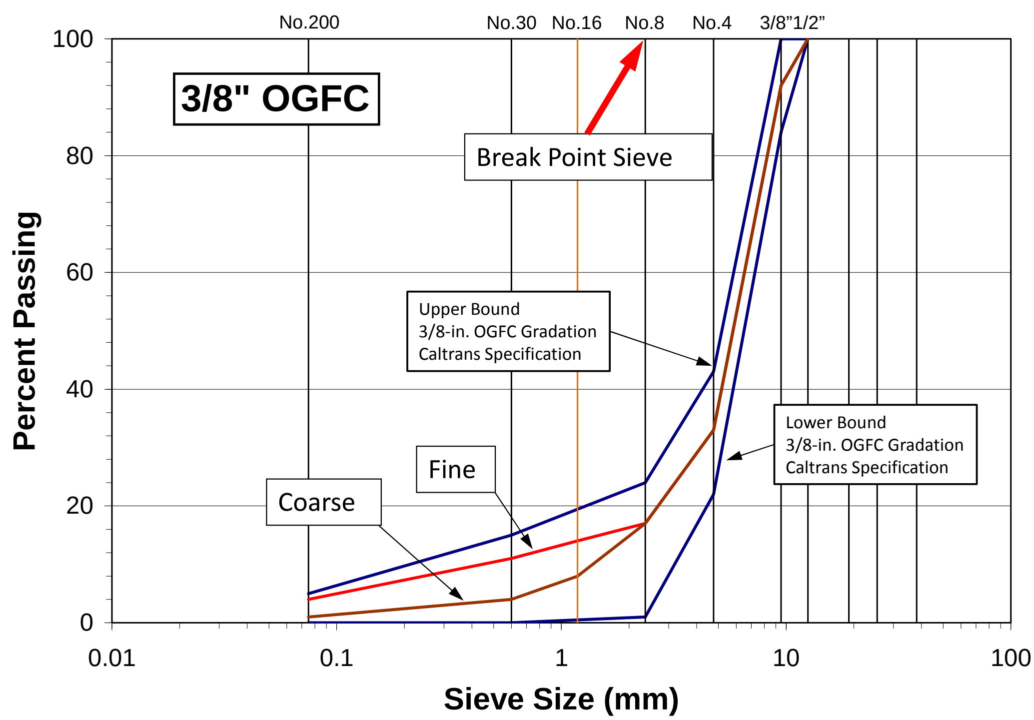


Figure 3.1: Proposed 3/8 inch OGFC trial gradations.

3.2.3 Wet/Dry Sieving

The wet/dry sieving process (AASHTO T 11) and particle size distribution of the fine and coarse aggregates (AASHTO T 27) were used to determine the correct portions of the different particle sizes in an aggregate blend needed to comply with the desired gradations (Table 3.2).

To meet the gradation specification requirements, a trial-and-error procedure of wet/dry sieving was used to adjust the amount of aggregate retained per sieve size. Table 3.3 lists the final results of wet/dry sieving in terms of percent passing by weight, categorizing the results by gradation type and aggregate type. For comparison, Figure 3.2 shows the final wet/dry sieving results together with the proposed gradations of Table 3.2 As can be seen, the results are shown in the figure and compare very favorably with the gradations in the table.

Table 3.3: Test Results of Wet/Dry Sieving (Percent Passing by Weight)

Sieve Size		Coarse Gradation						Fine Gradation					
		Target	Adjusted for Batching[1]	Watsonville		Sacramento		Target	Adjusted for Batching[1]	Watsonville		Sacramento	
U.S.	SI (mm)			Test 1	Test 2	Test 1	Test 2			Test 1	Test 2	Test 1	Test 2
1/2 inch	12.5	100	100	100.00	100.00	100.00	100.00	100	100	100.00	100.00	100.00	100.00
3/8 inch	9.5	92	92	91.59	91.74	91.99	91.64	92	92	92.58	91.89	91.19	91.90
No. 4	4.75	33	31.5	33.49	33.83	31.70	31.73	33	31.5	34.13	33.12	31.61	31.70
No. 8	2.36	17	15.5	16.48	16.36	16.88	17.09	17	15.5	16.64	16.65	16.85	16.98
No. 16	1.18	8	6.6	7.99	7.98	7.56	7.55	14	12.5	13.60	13.54	13.22	13.25
No. 30	0.6	4	2.7	3.73	3.77	3.45	3.42	11	9.5	10.53	10.45	10.21	10.28
No. 50	0.3	3	1.8	2.59	2.61	2.52	2.49	8.7	7.17	8.29	8.16	8.13	8.19
No. 100	0.15	2	0.9	1.76	1.81	1.71	1.71	6.3	4.83	6.56	6.25	6.04	6.09
No. 200	0.075	1	0	0.84	0.90	0.79	0.80	4	2.50	3.87	3.78	3.67	3.69

Note: These gradations allow the various size fractions, when combined, to produce gradations following wet sieving that are close to the proposed gradations of Table 3.2.

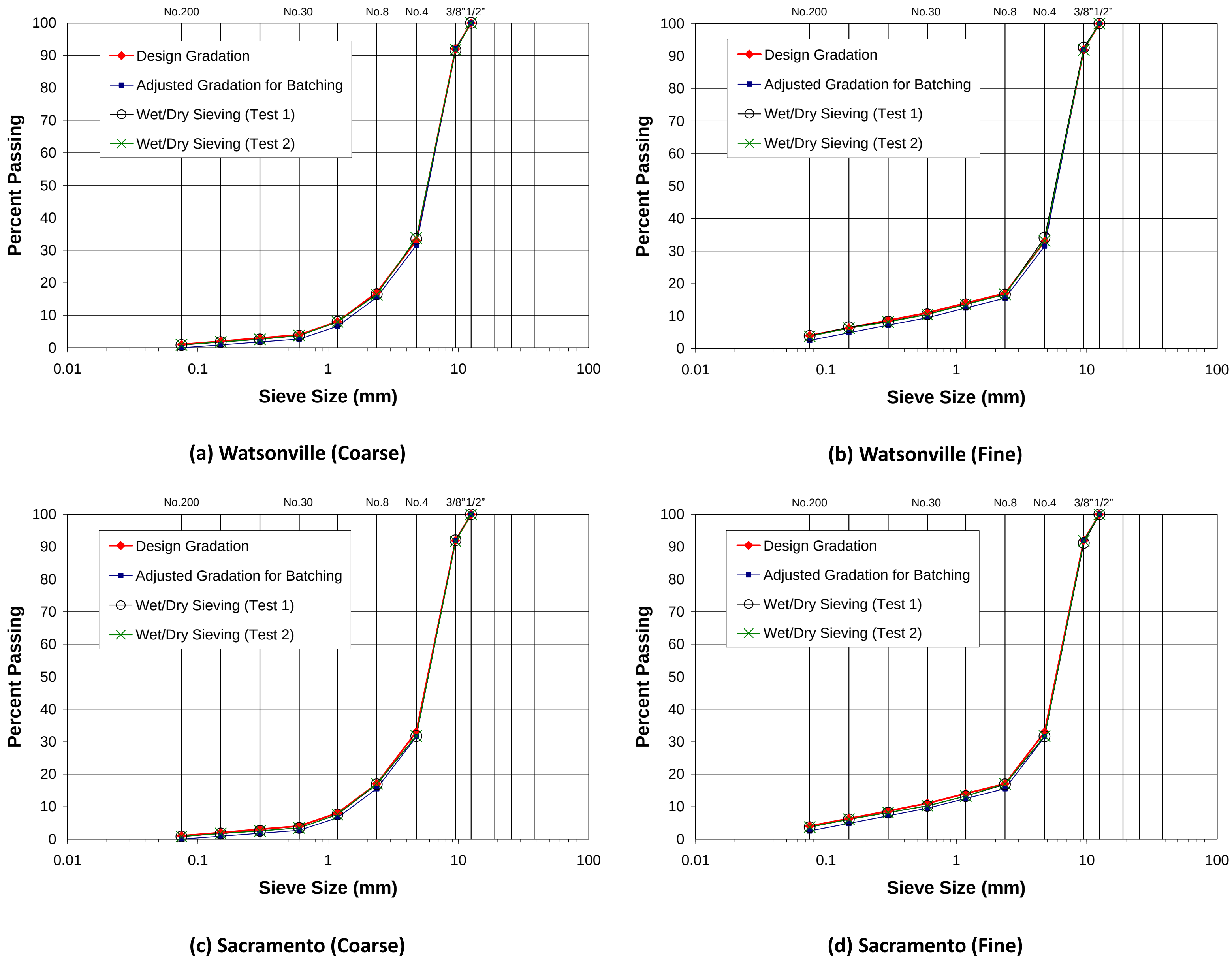


Figure 3.2: Wet/dry sieving test results: (a) Watsonville (Coarse), (b) Watsonville (Fine), (c) Sacramento (Coarse), and (d) Sacramento (Fine).

3.3 Methodologies

3.3.1 Voids in Coarse Aggregate in Dry-Rodded Condition and of Compacted Mix

The purpose of determining the voids in coarse aggregate for the coarse aggregate fraction (VCA_{DRC}) is to ensure stone-on-stone contact of the aggregate skeleton in the designed OGFC mix (*3*). Following AASHTO T 19, the dry-rodded density of the coarse aggregate was determined for the two gradations of the two aggregates. With the dry-rodded density of the coarse aggregate fraction, the VCA_{DRC} can be determined from the following equation:

$$VCA_{DRC} = \frac{G_{ca}\gamma_w - \gamma_s}{G_{ca}\gamma_w} \times 100 \qquad \textbf{(3.1)}$$

where, VCA_{DRC} are the voids in coarse aggregate in dry-rodded condition (percentage),
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 evaluate the existence of stone-on-stone contact. According to the NCAT approach, stone-on-stone contact can occur only if $VCA_{MIX} \le VCA_{DRC}$; the VCA_{MIX} is determined from the following equation:

$$VCA_{MIX} = 100 - \frac{G_{mb}P_{ca}}{G_{ca}} \qquad \textbf{(3.2)}$$

where, G_{mb} is the bulk specific gravity of the compacted mixture,
P_{ca} is the percent of coarse aggregate in the mixture, and
G_{ca} is the bulk specific gravity of the coarse aggregate.

Table 3.4 provides a summary of the calculations for the VCA_{DRC}, bulk specific gravity (BSG), and absorption (percent) for the aggregate and gradation types for the 3/8 inch OGFC gradations. For comparison, the table also includes the values for the 1/2 inch OGFC mixes reported in Reference (*3*). The results show that VCA_{DRC} depends primarily on nominal maximum aggregate size (NMAS) and on aggregate type. The results also indicate that the larger the NMAS, the smaller the VCA_{DRC}. Further, the results also show that for the same NMAS, the VCA_{DRC} of Sacramento aggregate is roughly 2.5 percent higher than that of Watsonville aggregate.

Table 3.4: Summary of Voids in Coarse Aggregate in Dry-Rodded Condition (AASHTO T 19 and T 85)

NMAS	Aggregate Type	Grad.	Oven Dry Mass (g)	SSD[1] Mass (g)	Mass in Water (g)	Bulk Specific Gravity (BSG)	BSG SSD	Apparent Specific Gravity	Absorption (%)	Bulk Density (kg/m³)	VCA$_{DRC}$ (%)	Mean (SD[4])
3/8 in. OGFC[2]	Watsonville	Coarse and Fine	2,550.3	2,588.7	1,655.6	2.733	2.774	2.851	1.506	1,628.20	40.31	40.22 (0.13)
			2,382.7	2,419.4	1,545.0	2.725	2.767	2.844	1.540		40.13	
	Sacramento	Coarse and Fine	2,894.4	2,923.2	1,858.2	2.718	2.745	2.793	0.995	1,564.15	42.33	42.51 (0.25)
			3,032.2	3,061.4	1,952.6	2.735	2.761	2.809	0.963		42.69	
1/2 in. OGFC[3]	Watsonville	G1 (Coarse)	1,981.2	2,033.7	1,285.0	2.646	2.716	2.846	2.650	1,680.27	36.38	36.87 (0.44)
		G2 (Fine)	1,978.4	2,030.0	1,284.0	2.652	2.721	2.849	2.608	1,666.40	37.04	
		G3 (Middle)	1,982.6	2,029.6	1,286.1	2.667	2.730	2.847	2.371	1,671.25	37.20	
	Sacramento	G1 (Coarse)	1,989.5	2,023.0	1,279.9	2.677	2.722	2.804	1.684	1,610.41	39.73	39.41 (0.28)
		G2 (Fine)	1,989.1	2,030.0	1,275.3	2.636	2.690	2.787	2.056	1,595.90	39.33	
		G3 (Middle)	1,990.0	2,032.0	1,283.0	2.657	2.713	2.815	2.111	1,612.67	39.18	

Notes .
1. SSD: saturated surface dry.
2. The OGFC gradation with the 3/8 in. NMAS used in PPRC Strategic Plan Element 3.25.
3. The OGFC gradation with the 1/2 in. NMAS used in Project 4.21 Subtask 2A.
4. SD: standard deviation.

3.3.2 Air-Void Content

The percent air-void content (V_a) can be determined from the following equation:

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

where, G_{mb} is bulk specific gravity of the compacted mixture, and
G_{mm} is the theoretical maximum specific gravity of the mixture.

It should be noted that the procedure to determine the percent air-void content in compacted open-graded asphalt mix follows AASHTO T 269. The specimen density is calculated by its dry mass (in grams) and its volume (in cubic centimeters), which is calculated by the average height and the average diameter of the specimen. This density then can be converted to a bulk specific gravity by it by dividing 0.99707 g/cm^3 (or 997 kg/m^3). The AASHTO T 166A (SSD), AASHTO T 275A (Paraffin), and AASHTO T 331 (CoreLok) methods do not apply for determining G_{mb} for compacted open-graded asphalt mixes.

3.3.3 Determination of Asphalt Absorption

In the previous OGFC study (*3*), a sensitivity analysis indicated that a 1 percent increase (or decrease) in asphalt absorption (by weight of coarse aggregate) will result in roughly a 1.6 percent increase (or decrease) in air-void content. Thus, the determination of asphalt absorption is critical to the accuracy of OGFC volumetric mix design. The methodology used to determine asphalt absorption is primarily based on the NCAT Report No. 91-4 (*5*) and *The Asphalt Handbook MS-4* (*6*); it is assumed that the asphalt is absorbed by both coarse and fine aggregates. Table 3.5 presents a step-by-step procedure with a numerical example to determine asphalt absorption.

Table 3.5: Step-by-Step Procedure to Determine Asphalt Absorption with Example Calculation

Step	Activity	Test Method	Example (Watsonville + PG 64-10 + 3/8 in. OGFC)
1	Determine percent passing break point sieve (P_{fg}, fine aggregate) and percent retained above break point sieve (P_{cg} , coarse aggregate). (Note: $P_{fg} + P_{cg} = 100$.)		$P_{cg} = 83\%$ $P_{fg} = 17\%$
2	Determine bulk specific gravity (oven dry condition) of coarse aggregate (G_{cg}).	AASHTO T 85	$G_{cg} = 2.7291$
3	Determine bulk specific gravity (oven dry condition) of fine aggregate (G_{fg}).	AASHTO T 84	$G_{fg} = 2.6329$
4	Calculate bulk specific gravity of the aggregate blend. $G_{sb} = \dfrac{P_{fg} + P_{cg}}{\dfrac{P_{fg}}{G_{fg}} + \dfrac{P_{cg}}{G_{cg}}}$	CT LP-2	$G_{sb} = \dfrac{17+83}{\dfrac{17}{2.6329}+\dfrac{83}{2.7291}} = 2.7123$
5	Prepare roughly 4 kg of loose mix with 2.5% – 3% binder content (by weight of aggregate), curing for 4 hours at 135°C immediately after completion of mixing.	Reference: NCAT Report No.91-4	2.5 – 3.0% binder content Curing 4 hours at 135°C
6	Determine maximum theoretical specific gravity (G_{mm}) using loose mix prepared in step 5.	AASHTO T 209	$G_{mm} = 2.7022$
7	Calculate effective specific gravity of the aggregate blend. $G_{se} = \dfrac{100}{\dfrac{100 + P_{asp}}{G_{mm}} - \dfrac{P_{asp}}{G_{asp}}}$ P_{asp} is the given percent asphalt content by weight of aggregate blend (in percentage form); G_{asp} is the asphalt specific gravity provided by the refinery.	CT LP-4	$G_{se} = \dfrac{100}{\dfrac{100+2.5}{2.7022} - \dfrac{2.5}{1.0253}} = 2.8174$
8	Calculate asphalt absorption (P_{aasp}), $P_{asp} = 100\left(\dfrac{G_{se} - G_{sb}}{G_{se}G_{sb}}\right) \cdot G_{asp}$ P_{aasp} is the percent absorbed asphalt content by weight of aggregate blend.	Reference: *The Asphalt Handbook MS-4*	$P_{asp} = 100\left(\dfrac{2.8174 - 2.7123}{2.8174 \cdot 2.7123}\right) \cdot 1.0253$ $= 1.4(\%)$

4 DEVELOPMENT OF *EXCEL* MACRO FOR OGFC MIX DESIGN

Development of an *Excel* macro for OGFC mix design (as shown in Figure 4.1) was performed in two phases: *Phase I: OGFC Volumetric Mix Design* and *Phase II: Performance Testing.* The main purpose of Phase I was to determine three trial binder contents based on the design and material parameter inputs so that specimens that met the volumetric requirements for Phase II could be prepared. Accordingly, loose mixes and height-controlled SGC specimens were used to conduct the performance tests—draindown, Cantabro, and HWTD testing—needed to determine the optimum binder range (OBR), the objective of Phase II. Note that the *Excel* macro was developed with the 2010 version of the software program, hence there is no guarantee that it can be run correctly with either old or future versions of *Excel.* Appendix B summarizes the operation details and cautions related to the *Excel* macro.

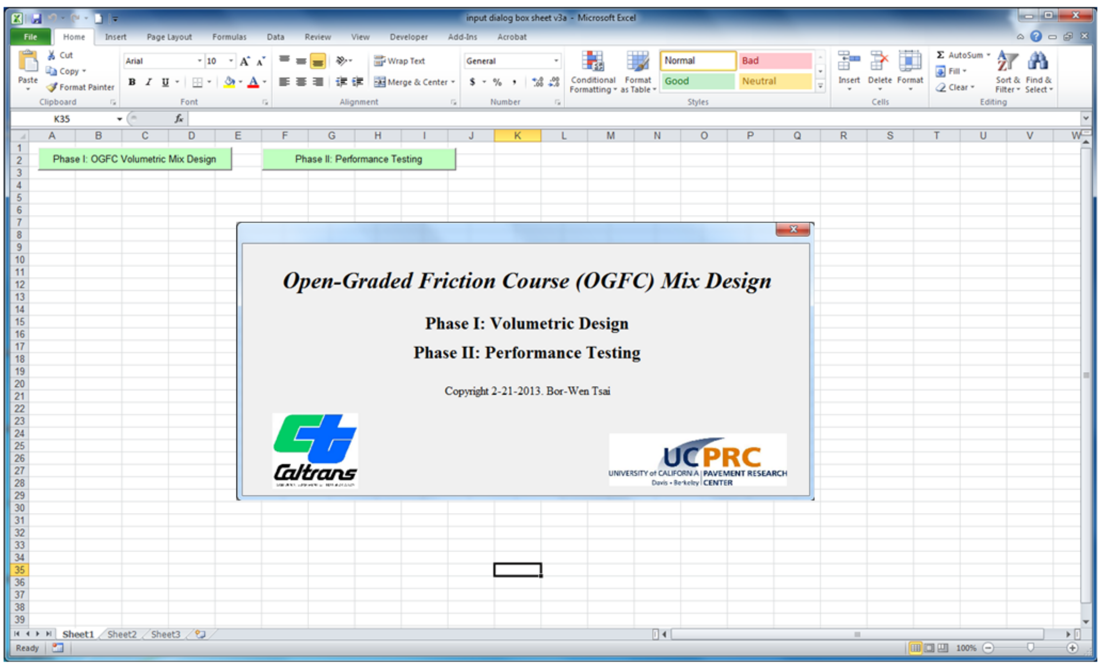


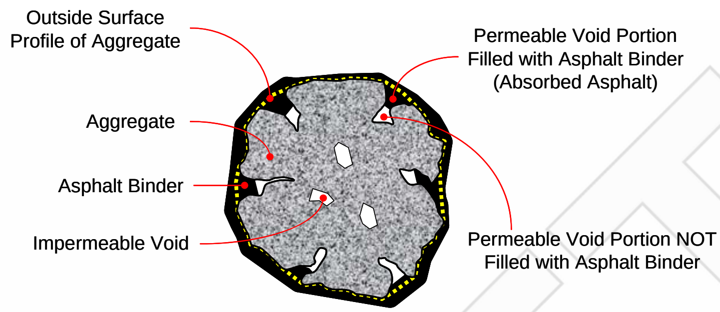
Figure 4.1: *Excel* macro developed for mix design of open-graded friction courses.

4.1 Phase I: OGFC Volumetric Mix Design

The key element in Phase I was the OGFC mix design chart that was developed based on these assumptions: (1) determination of VCA_{DRC}, voids in coarse aggregate in dry-rodded condition, insures stone-on-stone contact in the aggregate skeleton in the OGFC mix design, and (2) VCA_{DRC} is comprised of fibers, the fine aggregate fraction, lime, asphalt not absorbed by the fine and coarse aggregates, and air voids (*3*).

4.1.1 Weight-Volume Relationship with Consideration of Asphalt Absorption

To derive the weight-volume relationship with consideration of asphalt absorption, it is necessary to understand the definitions of the bulk specific gravity and effective specific gravity of an asphalt mixture, as illustrated in Figure 4.2.



	Volumes Considered	Masses Considered
Bulk Specific Gravity	Aggregate Particle + Water Permeable Voids	Aggregate Particle (Oven Dry Condition)
Effective Specific Gravity	Aggregate Particle + Water Permeable Voids – Absorbed Asphalt	Aggregate Particle (Oven Dry Condition)

Figure 4.2: Definitions of bulk specific gravity and effective specific gravity of an asphalt mix.

Figure 4.3 illustrates the weight-volume relationships of a compacted asphalt mixture with consideration of asphalt absorption by the aggregate and fibers included in the mix. The break point sieve size defined in an OGFC gradation separates the aggregate into fractions of fine and coarse aggregates. The total weight of an asphalt mixture is the sum of weight of fiber, asphalt, fine aggregate, and coarse aggregate. The total volume is the sum of the volumes of the aggregate, the asphalt not absorbed by the aggregate, fibers, and, air voids. Setting the total volume as a “Unit Volume,” i.e., 1.0, the total weight is the unit weight of the compacted asphalt mixture. Table 4.1 lists all the notations used in the derivation of the weight-volume relationships in Figure 4.3.

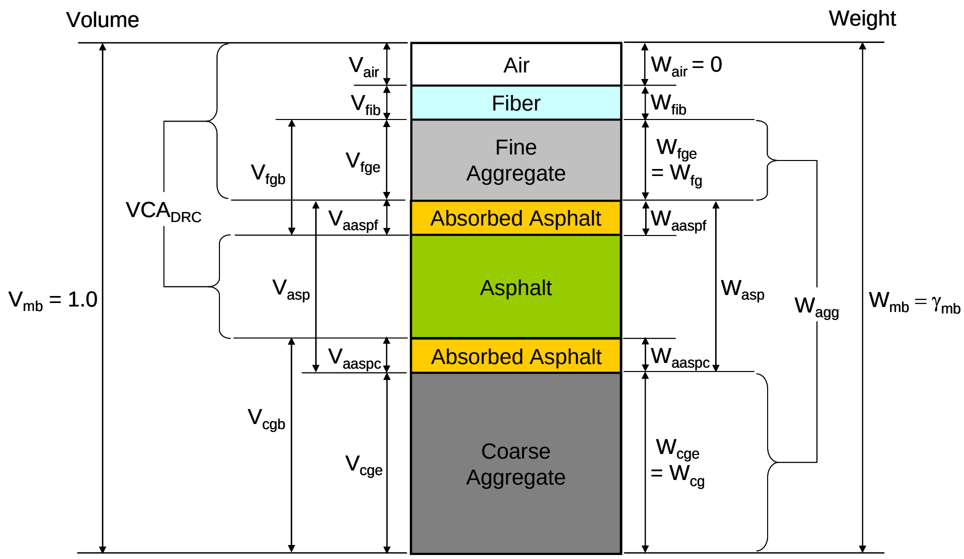


Figure 4.3: Weight-volume relationship with consideration of asphalt absorption by fine and coarse aggregates.

The following development of weight-volume relationships based on Figure 4.3 includes consideration of asphalt absorption by the coarse and fine aggregates, and by any fibers included in the mix. The symbols are based primarily on those contained in *Asphalt Paving Mixtures* (*7*) and *The Asphalt Handbook* (*6*). It should be noted, however, that some of the notations and definitions used here are slightly different from those two sources.

The unit weight of the compacted asphalt mixture can be defined as follows:

$$\gamma_{mb} = \frac{W_{mb}}{V_{mb}} = \frac{W_{mb}}{1.0} = W_{fib} + W_{asp} + W_{cg} + W_{fg} = P_{fib}W_{agg} + P_{asp}W_{agg} + P_{cg}W_{agg} + P_{fg}W_{agg}$$
$$= \left(1 + P_{fib} + P_{asp}\right)W_{agg}$$

Table 4.1: Notations Used in Weight-Volume Relationship Derivations

Notation	Description	Notation	Description
W_{mb}	Weight of compacted asphalt mixture	V_{aaspf}	Volume of asphalt absorbed by fine aggregate
W_{fib}	Weight of fiber	V_{aaspc}	Volume of asphalt absorbed by coarse aggregate
W_{asp}	Weight of asphalt	V_{agg}	Volume of aggregate
W_{aasp}	Weight of absorbed asphalt	V_{fgb}	Volume of fine aggregate passing the break point sieve (by bulk specific gravity)
W_{aaspf}	Weight of asphalt absorbed by fine aggregate	V_{cgb}	Volume of coarse aggregate retained above the break point sieve (by bulk specific gravity)
W_{aaspc}	Weight of asphalt absorbed by coarse aggregate	V_{fge}	Volume of fine aggregate passing the break point sieve (by effective specific gravity)
W_{agg}	Weight of aggregate	V_{cge}	Volume of coarse aggregate retained above the break point sieve (by effective specific gravity)
W_{fg}	Weight of fine aggregate (= W_{fge})	VCA_{DRC}	Voids in coarse aggregate in dry-rodded condition
W_{fge}	Weight of fine aggregate (by effective specific gravity)	V_{mb}	Volume of the compacted asphalt mixture
W_{cg}	Weight of coarse aggregate (= W_{cge})	γ_w	Unit weight of water
W_{cge}	Weight of coarse aggregate (by effective specific gravity)	γ_{mb}	Unit weight of the compacted asphalt mixture
P_{fib}	Percent fiber content by weight of aggregate (in decimal form)	γ_{mm}	Theoretical maximum unit weight of the compacted asphalt mixture
P_{asp}	Percent asphalt content by weight of aggregate (in decimal form)	G_{mb}	Bulk specific gravity of the compacted asphalt mixture
P_{aasp}	Percent absorbed asphalt content by weight of aggregate (in decimal form)	G_{mm}	Theoretical maximum specific gravity
P_{fg}	Percent passing the break point sieve of a gradation curve (in decimal form)	G_{cg}	Bulk specific gravity of coarse aggregate
P_{cg}	Percent retained above the break point sieve of a gradation curve (in decimal form); Note: $P_{fg} + P_{cg} = 1.0$	G_{cge}	Effective specific gravity of coarse aggregate
V_{air}	Volume of air voids (in decimal form)	G_{fg}	Bulk specific gravity of fine aggregate
V_{fib}	Volume of fiber	G_{fge}	Effective specific gravity of fine aggregate
V_{asp}	Volume of asphalt	G_{asp}	Specific gravity of asphalt
V_{aasp}	Volume of absorbed asphalt (= $V_{aaspf} + V_{aaspc}$)	G_{fib}	Specific gravity of fiber

The weights of the mix components are expressed as follows:

$$W_{agg} = \frac{\gamma_{mb}}{1 + P_{fib} + P_{asp}}$$

$$W_{fib} = \frac{P_{fib} \cdot \gamma_{mb}}{1 + P_{fib} + P_{asp}}$$

$$W_{asp} = \frac{P_{asp} \cdot \gamma_{mb}}{1 + P_{fib} + P_{asp}}$$

$$W_{aasp} = W_{aaspc} + W_{aaspf} = P_{aasp} W_{cg} + P_{aasp} W_{fg} = P_{aasp} W_{agg} = \frac{P_{aasp} \cdot \gamma_{mb}}{1 + P_{fib} + P_{asp}}$$

Note that,

$$W_{fge} = W_{fg} = P_{fg} W_{agg} \;,\; W_{cge} = W_{cg} = P_{cg} W_{agg} \;,\; P_{fg} + P_{cg} = 1.0$$

The volumes of mix components are defined in the following:

$$V_{fib} = \frac{W_{fib}}{G_{fib} \cdot \gamma_w} = \frac{G_{mb}}{1 + P_{fib} + P_{asp}} \cdot \frac{P_{fib}}{G_{fib}}$$

$$V_{asp} = \frac{W_{asp}}{G_{asp} \cdot \gamma_w} = \frac{G_{mb}}{1 + P_{fib} + P_{asp}} \cdot \frac{P_{asp}}{G_{asp}}$$

$$V_{aasp} = V_{aaspf} + V_{aaspc} = \frac{W_{aasp}}{G_{asp} \gamma_w} = \frac{G_{mb}}{1 + P_{fib} + P_{asp}} \cdot \frac{P_{aasp}}{G_{asp}}$$

According to the definitions shown in Figure 4.3, the volumes of asphalt-absorbed aggregates can be presented as follows:

$$V_{fge} = \frac{W_{fg}}{G_{fge} \gamma_w} = \frac{G_{mb}}{1 + P_{fib} + P_{asp}} \cdot \frac{P_{fg}}{G_{fge}}$$

$$V_{cge} = \frac{W_{cg}}{G_{cge} \gamma_w} = \frac{G_{mb}}{1 + P_{fib} + P_{asp}} \cdot \frac{P_{cg}}{G_{cge}}$$

$$V_{fgb} = \frac{W_{fg}}{G_{fg} \gamma_w} = \frac{G_{mb}}{1 + P_{fib} + P_{asp}} \cdot \frac{P_{fg}}{G_{fg}}$$

$$V_{cgb} = \frac{W_{cg}}{G_{cg} \gamma_w} = \frac{G_{mb}}{1 + P_{fib} + P_{asp}} \cdot \frac{P_{cg}}{G_{cg}}$$

The volume difference, $V_{asp} - V_{aaspf} - V_{aaspc}$, is expressed as,

$$V_{asp} - V_{aaspf} - V_{aaspc} = V_{asp} - V_{aasp} = \frac{G_{mb}}{1 + P_{fib} + P_{asp}} \cdot \frac{P_{asp} - P_{aasp}}{G_{asp}}$$

From Figure 4.3, the maximum unit weight (γ_{mm}) and the maximum specific gravity (G_{mm}) can then be expressed as follows:

$$\gamma_{mm} = \frac{W_{fib} + W_{asp} + W_{fg} + W_{cg}}{V_{fib} + V_{asp} - V_{aaspf} - V_{aaspc} + V_{fgb} + V_{cgb}}$$

$$= \frac{G_{mb} \gamma_w}{\dfrac{G_{mb}}{1 + P_{fib} + P_{asp}} \cdot \left(\dfrac{P_{fib}}{G_{fib}} + \dfrac{P_{asp} - P_{aasp}}{G_{asp}} + \dfrac{P_{fg}}{G_{fg}} + \dfrac{P_{cg}}{G_{cg}} \right)}$$

$$G_{mm} = \frac{\gamma_{mm}}{\gamma_w} = \frac{1 + P_{fib} + P_{asp}}{\frac{p_{fib}}{G_{fib}} + \frac{P_{asp} - P_{aasp}}{G_{asp}} + \frac{P_{fg}}{G_{fg}} + \frac{P_{cg}}{G_{cg}}}$$

$$\frac{1}{\gamma_{mb}} = \frac{V_{air} + V_{fib} + V_{asp} - V_{aasp} + V_{fgb} + V_{cgb}}{W_{mb}} = \frac{V_{air}}{\gamma_{mb}} + \frac{V_{fib} + V_{asp} - V_{aasp} + V_{fgb} + V_{cgb}}{\gamma_{mb}} = \frac{V_{air}}{\gamma_{mb}} + \frac{1}{\gamma_{mm}} \quad (\because W_{mb} = \gamma_{mb})$$

$$V_{air} = 1 - \frac{\gamma_{mb}}{\gamma_{mm}} = 1 - \frac{G_{mb}}{G_{mm}} \Rightarrow G_{mb} = (1 - V_{air})G_{mm}$$

From Figure 4.3, the VCA_{DRC} is filled with fiber, asphalt not absorbed by the aggregate, fine aggregate, and air voids. That is,

$$VCA_{DRC} = V_{air} + V_{fib} + V_{asp} - V_{aasp} + V_{fge} \quad \textbf{(4.1)}$$

$$\begin{aligned} VCA_{DRC} &= V_{air} + V_{fib} + V_{asp} - V_{aasp} + V_{fge} \\ &= V_{air} + \frac{G_{mb}}{(1 + P_{fib} + P_{asp})}\left(\frac{P_{fib}}{G_{fib}} + \frac{P_{asp} - P_{aasp}}{G_{asp}} + \frac{P_{fg}}{G_{fge}}\right) \\ &= V_{air} + \frac{(1 - V_{air})G_{mm}}{(1 + P_{fib} + P_{asp})}\left(\frac{P_{fib}}{G_{fib}} + \frac{P_{asp} - P_{aasp}}{G_{asp}} + \frac{P_{fg}}{G_{fge}}\right) \\ &= V_{air} + (1 - V_{air})\left(\frac{\frac{P_{fib}}{G_{fib}} + \frac{P_{asp} - P_{aasp}}{G_{asp}} + \frac{P_{fg}}{G_{fge}}}{\frac{P_{fib}}{G_{fib}} + \frac{P_{asp} - P_{aasp}}{G_{asp}} + \frac{P_{cg}}{G_{cg}} + \frac{P_{fg}}{G_{fg}}}\right) \end{aligned}$$

$$VCA_{DRC} = V_{air} + (1 - V_{air})\left(\frac{\frac{P_{fib}}{G_{fib}} + \frac{P_{asp} - P_{aasp}}{G_{asp}} + \frac{P_{fg}}{G_{fge}}}{\frac{P_{fib}}{G_{fib}} + \frac{P_{asp} - P_{aasp}}{G_{asp}} + \frac{P_{cg}}{G_{cg}} + \frac{P_{fg}}{G_{fg}}}\right) \quad \textbf{(4.2)}$$

Without consideration of the addition of fiber and the asphalt absorption of coarse aggregate, Equation 4.2 becomes

$$VCA_{DRC} = V_{air} + (1 - V_{air}) \left(\frac{\frac{P_{asp}}{G_{asp}} + \frac{P_{fg}}{G_{fg}}}{\frac{P_{asp}}{G_{asp}} + \frac{P_{cg}}{G_{cg}} + \frac{P_{fg}}{G_{fg}}} \right) \tag{4.3}$$

If no fiber is added, then Equation 4.2 can be expressed as

$$VCA_{DRC} = V_{air} + (1 - V_{air}) \left(\frac{\frac{P_{asp} - P_{aasp}}{G_{asp}} + \frac{P_{fg}}{G_{fge}}}{\frac{P_{asp} - P_{aasp}}{G_{asp}} + \frac{P_{cg}}{G_{cg}} + \frac{P_{fg}}{G_{fg}}} \right) \tag{4.4}$$

It should be noted that G_{fge} is normally greater than G_{fg}; however, $G_{fge} \cong G_{fg}$ if there is little asphalt absorbed by fine aggregate. Moreover, results from the sensitivity study (*3*) indicate that the specific gravities have very limited influence on the relationship among the three design parameters, (V_{air}, P_{asp}, and P_{fg}); hence, the following equation will be used in the construction of OGFC mix design chart. (This equation corresponds to equation (6.7) in Reference [*3*]).

$$VCA_{DRC} = V_{air} + (1 - V_{air}) \left(\frac{\frac{P_{asp} - P_{aasp}}{G_{asp}} + \frac{P_{fg}}{G_{fg}}}{\frac{P_{asp} - P_{aasp}}{G_{asp}} + \frac{P_{cg}}{G_{cg}} + \frac{P_{fg}}{G_{fg}}} \right) \tag{4.5}$$

4.1.2 Construction of OGFC Mix Design Chart

According to Equation 4.5, without consideration of fiber addition, 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 4.4 is a snapshot from the *Excel* macro (Phase I: OGFC Volumetric Mix Design) using the TRTC mixes as an example. It includes an input dialogue box and an OGFC mix design chart. As can be seen from the OGFC mix design chart, three trial binder contents, 5.5 percent, 6.6 percent, and 7.7 percent, were calculated based on the corresponding percent air-void contents of 22 percent, 20 percent, and 18 percent.

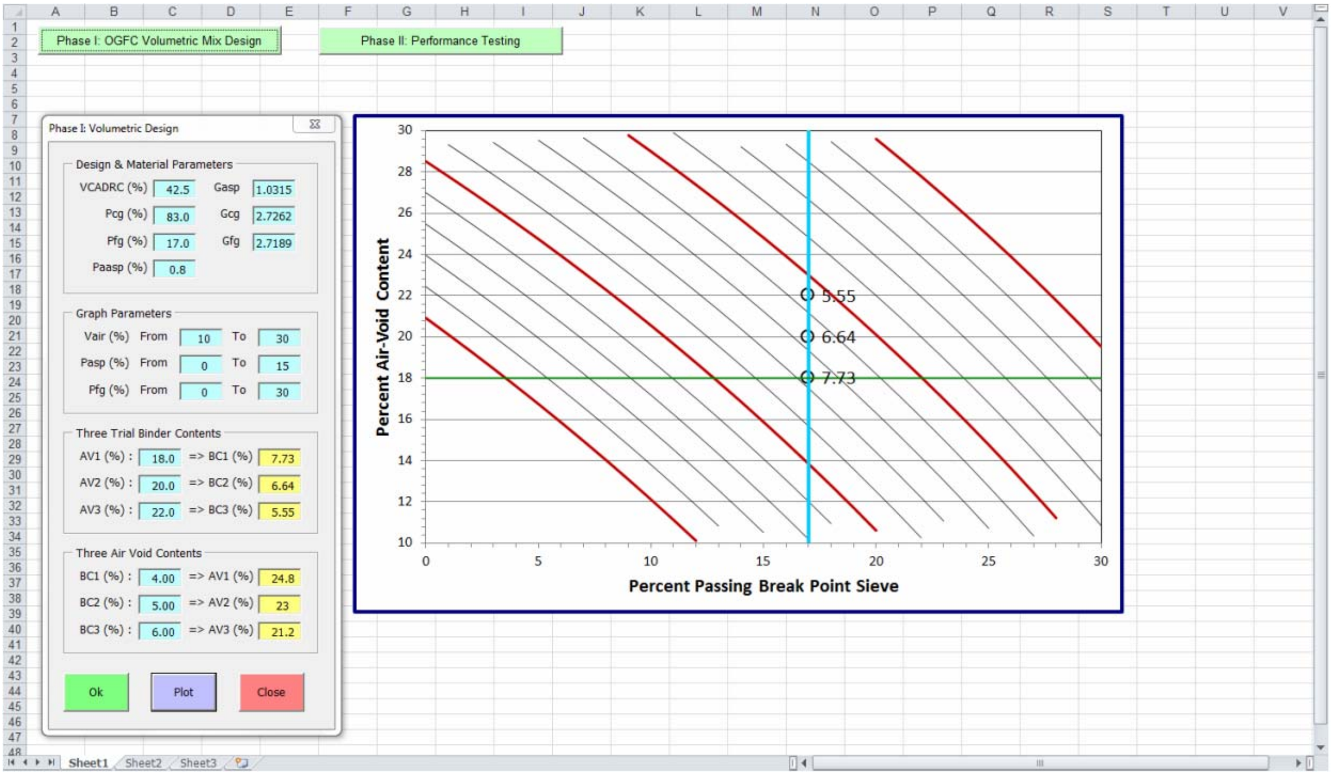


Figure 4.4: Phase I: OGFC Volumetric Mix Design using the TRTC mixes as an example.

4.2 Phase II: Performance Testing

Once three binder contents have been selected using the *Excel* macro (Phase I: OGFC Volumetric Mix Design), the next step for each binder content is to prepare two loose mix samples for draindown tests, and nine height-controlled SGC specimens: three of 4 in. diameter (101.6 mm) for Cantabro testing and six of 150 mm diameter (5.91 in.) for HWTD testing. The objective of the *Excel* macro (Phase II: Performance Testing) was to summarize the performance test results of three trial binder contents and thus to determine whether the OGFC mix design should be rejected or accepted. If it is accepted, selection of the optimum binder range (OBR) can then be determined.

As an example, Figure 4.5 demonstrates the use of the *Excel* macro (Phase II: Performance Testing) to input and summarize the performance test results of the TRTC mixes in three individual charts. The criteria used are a maximum of 0.3 percent draindown, a maximum of 30 percent Cantabro loss (rather than the 15 percent maximum used in the NCAT approach), and a maximum 12.5 mm average rut depth at 20,000 passes of HWTD testing. Viewed from the charts of Figure 4.5, the TRTC mixes easily pass the draindown specification and have allowable minimum binder contents of 6.41 percent for Cantabro test and 6.07 percent for the HWTD testing. Therefore, the OBR was determined to be the intersection of the criteria lines (green sections) shown in Figure 4.5, that is, the OBR is between 6.4 percent and 7.7 percent.

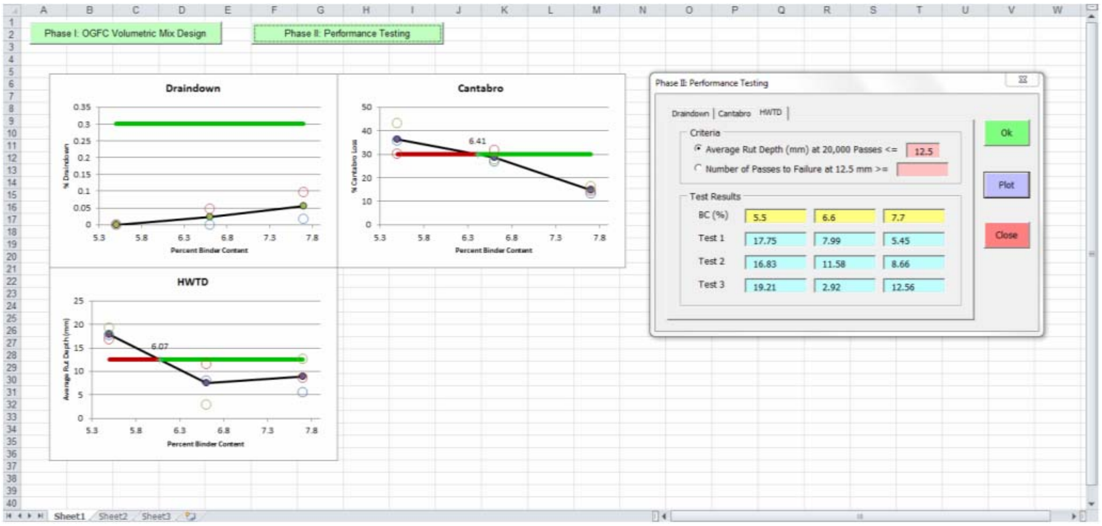


Figure 4.5: Phase II: Performance Testing using the TRTC mixes as an example.
Note: The tabbed dialogue box on the right of the figure allows users to input performance criteria and test results for the draindown, Cantabro, and HWTD tests. The resulting plot for each test appears on the left. OBR is determined by the intersection of the criteria lines (shown in green).

5 PHASE I: OGFC VOLUMETRIC MIX DESIGN

5.1 Summary of OGFC Volumetric Mix Design Parameters

The design and material parameters used for *Phase I: Volumetric OGFC Mix Design* to determine three trial binder contents are summarized in Table 5.1. Based on the table, several observations regarding material parameters can be addressed:

1. For these 3/8 in. nominal maximum aggregate size (NMAS) OGFC gradations, the magnitude of asphalt absorption depends primarily on the aggregate type and gradation. The percent asphalt absorption (by weight of total aggregate) of Sacramento aggregate (with an average of 0.76 percent) is roughly 0.5 percent less than that of Watsonville aggregate (with an average of 1.24 percent). In general, the coarse gradation had slightly higher asphalt absorption than the fine gradation. The deviation due to gradation type (coarse and fine) appears to be noticeable for the Sacramento aggregate.
2. As expected, the VCA_{DRC} is associated with aggregate type and gradation/NMAS. This is demonstrated by comparing the 3/8 in. OGFC gradations of this study with the 1/2 in. OGFC gradations used for the previous OGFC study: the values of VCA_{DRC} for Sacramento aggregate are 42.5 percent versus 39.4 percent (*3*) respectively and 40.2 percent versus 36.9 percent (*3*) respectively for Watsonville aggregate. With the same break point sieves for the 3/8 in. and 1/2 in. OGFC gradations, the smaller the NMAS the larger the value of VCA_{DRC}.
3. A comparison of the bulk specific gravities of the fine aggregates in this study indicates that they are slightly larger than those of the coarse gradations.

According to the previous study of OGFC mix design (*3*), the effects of the bulk specific gravities (including those of both asphalt and aggregate) on the calculation of trial binder contents were limited. To demonstrate the effect of fines content on mix performance, the trial binder contents obtained for the mixes with coarse gradation in this study were also applied to the mixes with fine gradation so as to eliminate the confounding effect on mix performance caused by the difference of binder content. To do so, the percent air-void contents of low, medium, and high trial binder contents of the mixes with fine gradations resulted in slight deviations from the targeted percent air-void contents of 22 percent, 20 percent, and 18 percent respectively. Using the Phase I *Excel* macro (Volumetric Mix Design) and data from Table 5.1 as the inputs, three trial binder contents for each mix type were determined as follows (time limitations precluded preparation of PGTC and PGTF mixes):

Mix Type	Three Trial Binder Contents		
	Low	**Medium**	**High**
PMWC; PMWF; TRWC; TRWF	4.2	5.2	6.3
PMTC; PMTF; TRTC; TRTF	5.5	6.6	7.7
PGWC; PGWF	4.3	5.3	6.4

5.2 Specimen Preparation and Percent Air-Void Content

5.2.1 Specimen Preparation

With the three binder contents selected using the *Excel* macro (Phase I: OGFC Volumetric Mix Design), the following specimen types of each binder content were prepared: two loose mix samples for draindown tests, three 101.6 mm diameter (4 in.) × 63.5 mm height (2.5 in.) SGC specimens for Cantabro tests, and six 150 mm diameter (5.91 in.) × 63.5 mm height (2.5 in.) SGC specimens for HWTD tests.

The SGC specimens were prepared in accordance with AASHTO T 312 using a PINE AGF2 gyratory compactor. Compaction parameters for the gyratory compactor included an internal gyration angle of 1.16°, compaction pressure of 600 kPa (87 psi), height control set at 63.5 mm (2.5 in.), and a maximum gyration number of 300. The compaction curve, including number of gyrations and associated specimen height, was recorded during the compaction process for each specimen. The specimens were extruded immediately after completion of compaction and cooled at normal room temperature on a clean, flat surface prior to measurement of bulk specific gravities and determination of air-void contents.

The weights of the mixes used to produce the 63.5 mm (2.5 in.) high specimens using height control for Superpave gyratory compaction procedure were calculated based on the following equation for both Cantabro and HWTD specimens.

$$W_{mb} = \left(1 - \frac{V_{air}}{100}\right) \cdot G_{mm} \cdot V_{mb} \cdot \gamma_w \qquad \textbf{(5.1)}$$

where: W_{mb} is the amount of mix weight
V_{air} is the design air-void content in percentage
G_{mm} is the maximum theoretical specific gravity in accordance with AASHTO T 209
V_{mb} is the volume of gyratory compaction mold with a height of 63.5 mm, and
γ_w is the unit weight of water.

Table 5.1: Summary of Design and Material Parameters for Volumetric Mix Design to Determine Three Trial Binder Contents

Aggregate Type	Voids in Coarse Aggregate in Dry-Rodded Condition[1]	Binder Type	Grad.	Mix Design[2]	Average Percent Absorbed Asphalt Content		Specific Gravity of Asphalt	Percent Retained Above Break Point Sieve	Percent Passing Break Point Sieve	Bulk Specific Gravity of Coarse Aggregate[3]	Bulk Specific Gravity of Fine Aggregate[4]
					Tests	Average[5]					
Watsonville	40.2	PG 76-22 PM	Coarse	PMWC	1.3 1.3	1.30	1.0321	83	17	2.7291	2.6329
			Fine	PMWF	1.2 1.2	1.20		83	17		2.7239
		PG 64-28 TR	Coarse	TRWC	1.4 1.2	1.30	1.0315	83	17		2.6329
			Fine	TRWF	1.0 1.1	1.05		83	17		2.7239
		PG 64-10	Coarse	PGWC	1.4 1.4	1.40	1.0253	83	17		2.6329
			Fine	PGWF	1.2 1.2	1.20		83	17		2.7239
Sacramento	42.5	PG 76-22 PM	Coarse	PMTC	0.8 0.9	0.85	1.0321	83	17	2.7262	2.6828
			Fine	PMTF	0.6 0.6	0.60		83	17		2.7219
		PG 64-28 TR	Coarse	TRTC	0.9 0.9	0.90	1.0315	83	17		2.6828
			Fine	TRTF	0.8 0.6	0.70		83	17		2.7219

Notes:
1. In accordance with AASHTO T 19 and T 85.
2. Binder type: PG 76-22 PM (PM), PG 64-28 TR (TR), and PG 64-10 (PG); aggregate type: Watsonville (W) and Sacramento (T); gradation type: coarse (C) and fine (F).
3. In accordance with AASHTO T 85.
4. In accordance with AASHTO T 84.
5. The overall average for the each of the two aggregates are for 1.24 and 0.76 for Watsonville, and Sacramento, respectively.

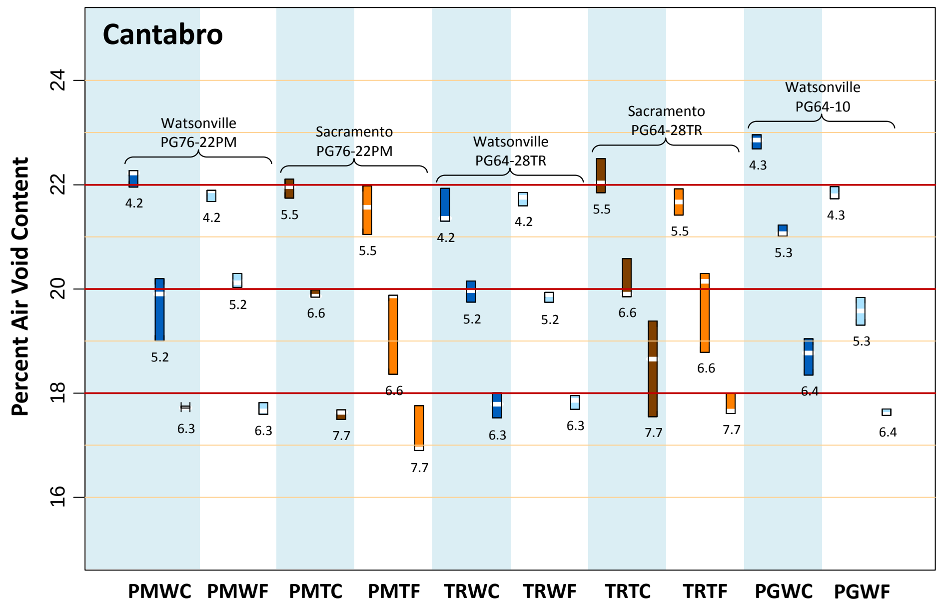
5.2.2 Percent Air-Void Content

The AASHTO T 269 Method, *Standard Method of Test of 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). *Note: the SSD (AASHTO T 166A), Parafilm (AASHTO T 275 A), and CoreLock (AASHTO T 331) procedures are not applicable to determining G_{mb} for compacted open-graded asphalt mixes.*

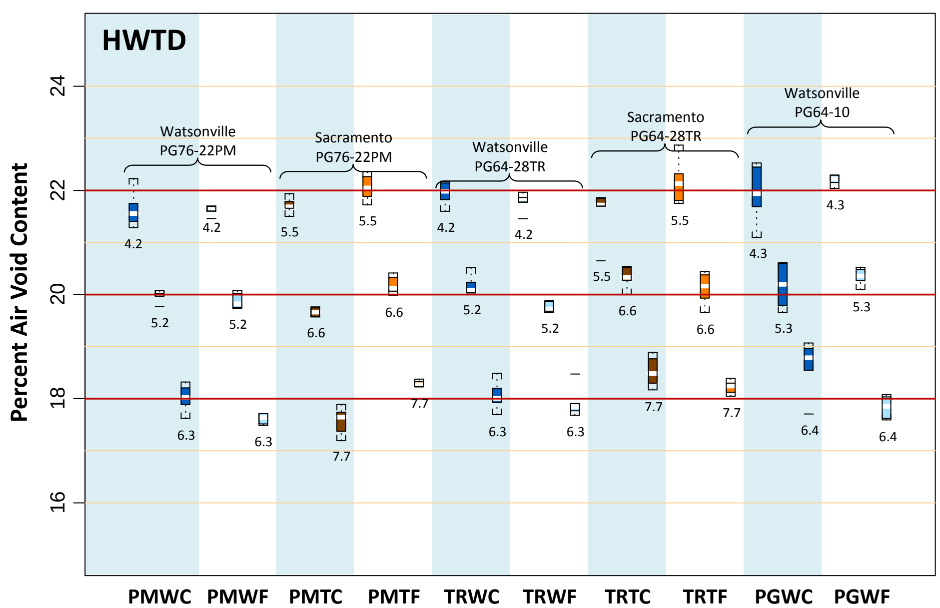
Figure 5.1 and Table 5.2 illustrate and summarize, respectively, the data for the air-void contents of the height-controlled SGC specimens for the Cantabro and HWTD tests. The detailed volumetric properties are listed in Appendix C, Table C.1 through Table C.8.

A few observations regarding the air-void content data are as follows:

1. Gyration-controlled SGC specimens exhibited large variations in air-void contents (*3*). In this study, however, air-void contents of the height-controlled SGC specimens for both the Cantabro and HWTD tests, shown in Figure 5.1(a) and Figure 5.1(b) respectively, are well controlled regardless of the mix type and target air-void content.
2. For the mixes listed in Table 5.2, standard deviations (SD) indicate that
   - When comparing gradation types: The SD of the coarse gradation is usually greater than that of the fine gradation, which suggests that the fine gradation likely produces specimens that are more uniform from a volumetric perspective than the coarse gradations. Also, the SD increases slightly when specimens with high binder contents are prepared versus specimens with corresponding low air-void contents.
   - When categorizing by test type: the HWTD specimens (150 mm diameter) exhibited smaller standard deviations for air-void contents than those for the Cantabro specimens (101.6 mm [4 in.] diameter).
3. As can be seen from Table 5.2, regardless of the test type or gradation type, the means of the air-void contents for the low, medium, and high binder contents are very close to the target values (TV), and the average standard deviations are roughly in the range of 0.3 to 0.5 percent; that is to say, the percent air-void contents of the height-controlled SGC specimens have a 95 percent probability of falling into the range of TV±0.6 to 1.0 percent, which is fully acceptable. Therefore, the use of the proposed OGFC mix design chart, which was constructed mainly based on the volumetric equation of VCA_{DRC} (Equation 4.5), to prepare specimens for performance testing is reasonable and can be considered as the standard procedure for OGFC mix design.



(a) Specimens prepared for Cantabro tests



(b) Specimens prepared for HWTD tests

Figure 5.1: Boxplot summary of percent air-void contents of specimens prepared for (a) Cantabro tests and (b) HWTD tests.
(Note: The number below the box stands for percent binder content.)

Table 5.2: Summary of Percent Air-Void Contents of Specimens Prepared for Cantabro and HWTD Tests

Asphalt Content[1]	Cantabro + HWTD		Cantabro		HWTD		Gradation	Cantabro + HWTD		Cantabro		HWTD	
	Sample Size	%AV Mean (SD[2])	Sample Size	%AV Mean (SD)	Sample Size	%AV Mean (SD)		Sample Size	%AV Mean (SD)	Sample Size	%AV Mean (SD)	Sample Size	%AV Mean (SD)
Low	90	21.88 (0.38)	30	21.92 (0.43)	60	21.87 (0.36)	Coarse	45	21.88 (0.44)	15	22.12 (0.49)	30	21.76 (0.38)
							Fine	45	21.88 (0.31)	15	21.72 (0.24)	30	21.97 (0.32)
Medium	90	20.02 (0.42)	30	19.94 (0.60)	60	20.06 (0.29)	Coarse	45	20.09 (0.42)	15	20.15 (0.59)	30	20.06 (0.31)
							Fine	45	19.95 (0.41)	15	19.74 (0.54)	30	20.05 (0.28)
High	90	17.99 (0.46)	30	17.84 (0.53)	60	18.06 (0.41)	Coarse	45	18.13 (0.53)	15	18.07 (0.61)	30	18.16 (0.49)
							Fine	45	17.85 (0.34)	15	17.62 (0.31)	30	17.97 (0.30)

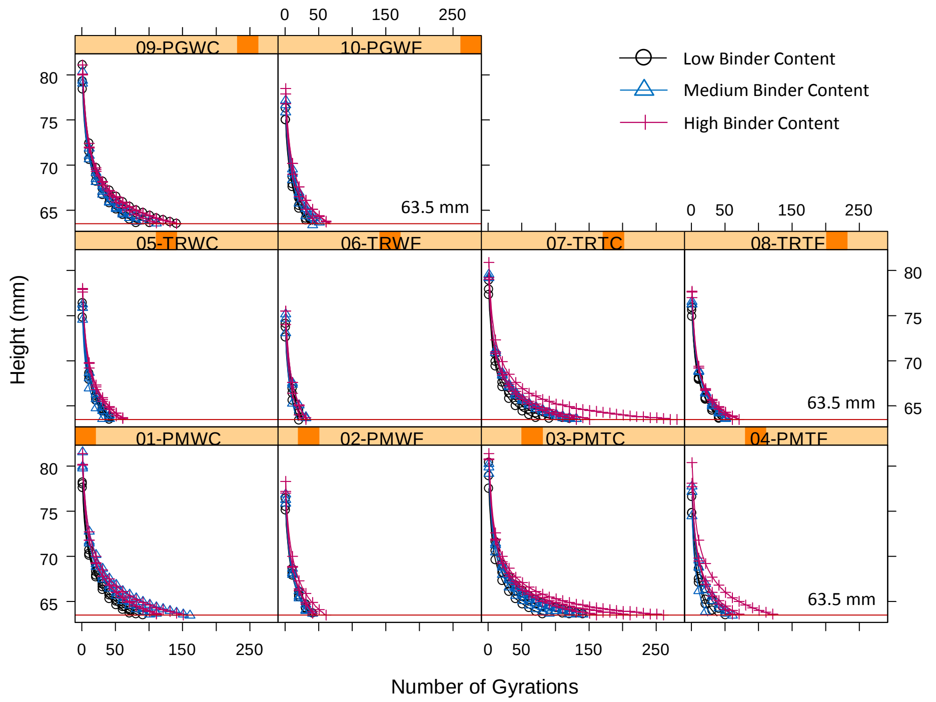
Notes:

1. The low asphalt content obtained from the OGFC mix design chart aimed for 22 percent air-void content; medium asphalt content for 20 percent air-void content, and high asphalt content for 18 percent air-void content.
2. SD = Standard Deviation.

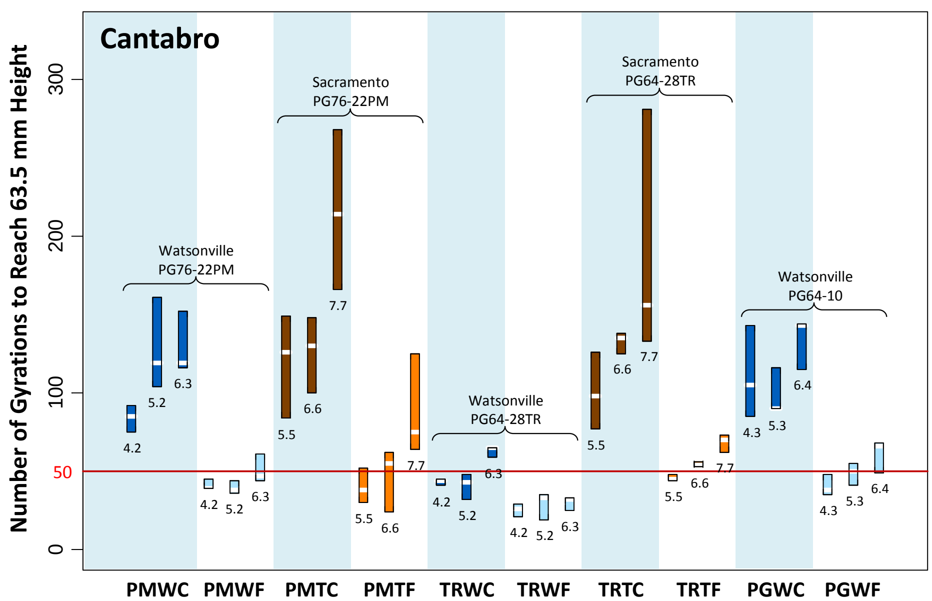
5.2.3 Superpave Gyratory Compaction with Height Control

Figure 5.2(a) and Figure 5.3(a) show Trellis graphs for the Superpave gyratory compaction curves in terms of height versus number of gyrations at a linear-linear scale for the height-controlled SGC Cantabro and HWTD specimens respectively. Figure 5.2(b) and Figure 5.3(b) summarize the number of gyrations to reach 63.5 mm height of various mixes for the height-controlled SGC Cantabro and HWTD specimens separately. The following can be seen from these figures:

1. For both height-controlled SGC Cantabro and HWTD specimens, the compaction curves illustrated in the Trellis graphs of Figure 5.2(a) and Figure 5.3(a) and the number of gyrations shown in the summary boxplots of Figure 5.2(b) and Figure 5.3(b) reach a consensus on the compaction pattern for each mix type. Based on the good agreement of reproducibility (between-variation) and repeatability (within-variation) in the compaction pattern, it can be concluded that the number of gyrations required to fabricate a 63.5 mm high specimen is mix-dependent.
2. Compared to mixes with fine gradation, mixes with coarse gradation generally require more gyrations (more compactive effort) to reach the 63.5 mm height; also, a larger variation in number of gyrations occurs for the coarse gradations (Figure 5.2[b] and Figure 5.3[b]), especially for the PMTC and TRTC mixes.
3. For mixes with the fine gradation, the initial heights of the compaction curves are usually smaller than those for mixes with coarse gradation.
4. Generally, the height-controlled SGC specimens with high binder contents, i.e., low target air-void content, require more gyrations to reach 63.5 mm height.

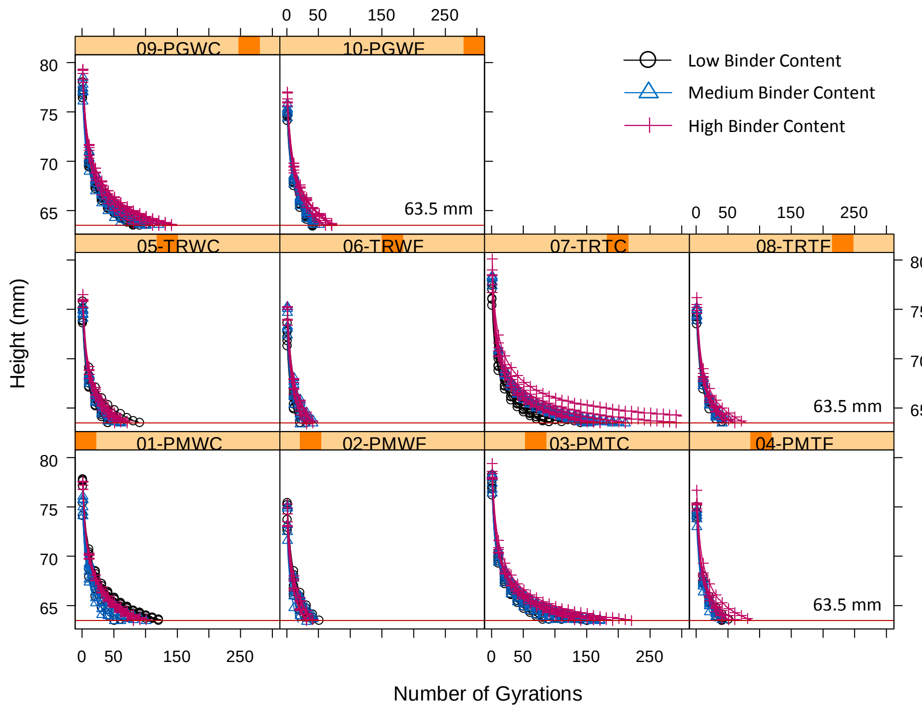


(a) Cantabro compaction curves

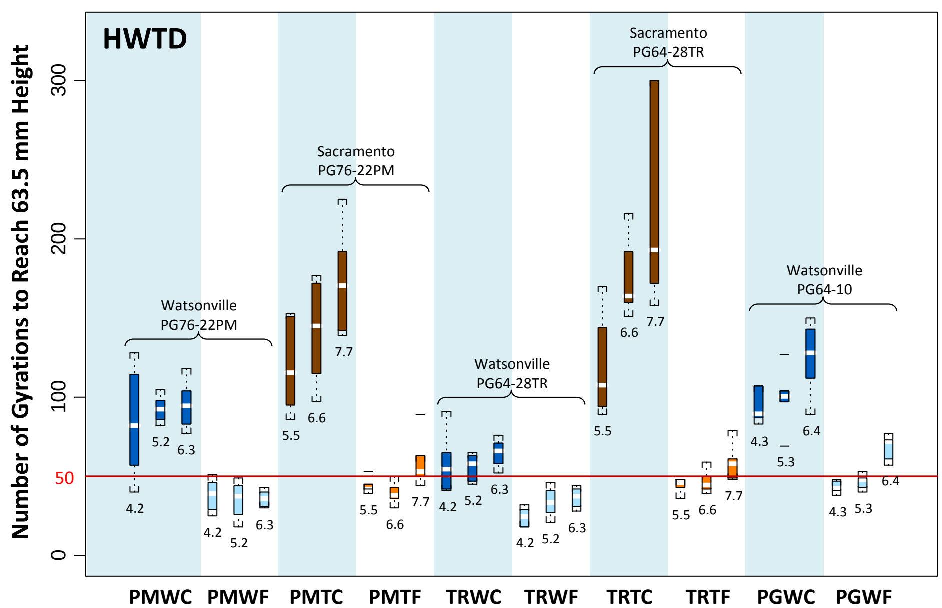


(b) Number of Gyrations

Figure 5.2: Summary of gyratory-compacted specimens for Cantabro tests: (a) Trellis graph of compaction curves and (b) number of gyrations to reach 63.5 mm height.
(Note: the number below the box stands for asphalt content.)



(a) HWTD compaction curves



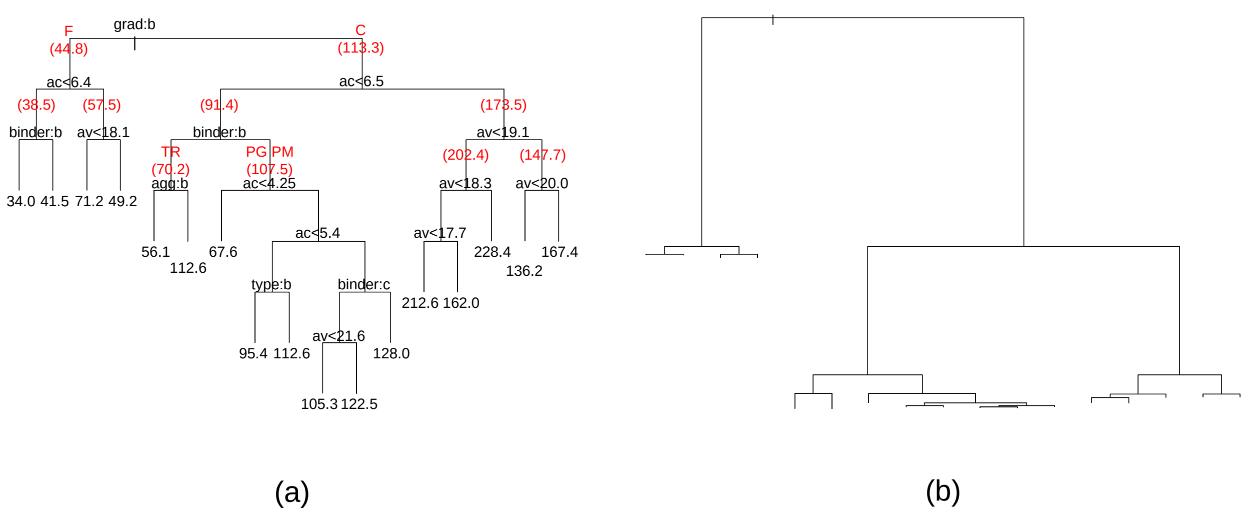
(b) Number of Gyrations

Figure 5.3: Summary of gyratory-compacted specimens for HWTD tests: (a) Trellis graph of compaction curves and (b) number of gyrations to reach 63.5 mm height.
(Note: the number below the box stands for asphalt content.)

Dendrograms resulting from tree-based modeling (*8*), shown in Figure 5.4, were utilized to explore the data structure of number of gyrations to reach the 63.5 mm height, including both the Cantabro and HWTD specimens. The covariates used to develop the tree-based model consist of four category covariates—binder type, gradation type, aggregate type, and test type (specimens for the Cantabro or HWTD testing)—and two numerical covariates, percent air-void content and binder content.

Results of the analysis suggest the following key findings for the mixes used in this study:

1. Gradation type is the most important factor that categorizes the number of gyrations to reach 63.5 mm. Regardless of binder and aggregate type, the average number of gyrations were 45 for the fine gradation mixes and 114 for the coarse gradation mixes.
2. Binder content is the next important factor that separates the fine gradation into two subgroups—with the average number of gyrations 38 if **ac** < 6.4 percent and 57 if **ac** > 6.4 percent—and the coarse gradation into two branches—with the average number of gyrations 91 if **ac** < 6.5 percent and 174 if ac > 6.5 percent. This implies that the higher the binder content, i.e., the lower the percent air-void content, the larger compactive effort is required to reach the 63.5 mm height.
3. The other covariates, binder type, aggregate type, test type and air-void content, have only marginal effects on the number of gyrations to reach 63.5 mm height.



Notes:
1. binder – PG: PG64-10 (a); TR: PG64-28TR (b); PM: PG76-22PM (c)
2. grad – C: coarse gradation (a); F: Fine gradation (b)
3. agg – T: Sacramento aggregate (a); W: Watsonville aggregate (b)
4. type – Cantabro (a); HWTD (b)
5. Number enclosed with parentheses is the average value for the branch.

Figure 5.4: Dendrograms of number of gyrations to reach 63.5 mm height: (a) with split rules and without vertical distance references; and (b) without split rules.

6 PHASE II: PERFORMANCE TESTING

Following determination of the trial binder contents (Phase I), performance testing consisting of draindown, Cantabro, and HWTD tests, at three trial binder contents for each mix type, were conducted. Test results are summarized and evaluated in this section.

The performance test results are summarized in Table 6.1. Performance parameters considered were percent draindown, percent Cantabro loss, average rut depth at 20,000 passes, and number of passes at 12.5 mm average rut depth. Analyses of the test data made use of summary boxplots and tree-based modeling respectively for qualitative and quantitative interpretation. Only the dendrograms of tree-based modeling are presented here. Details of the tree structures and associated residual analyses have not been included.

Figure 6.1 and Figure 6.2, respectively, show summaries of the performance test results in boxplots and dendrograms. In a dendrogram the vertical position of a node pair is a function of the importance of the parent split. But in certain cases, a long-distance dendrogram makes it very difficult to clearly display the split rules on the nodes. Hence, the dendrograms have been presented in two different ways: (1) a dendrogram with the split rule and without a vertical distance reference (Figure 6.2[a], Figure 6.2[c], and Figure 6.2[e]) and (2) a dendrogram without the split rules (Figure 6.2[b], Figure 6.2[d], and Figure 6.2[f]).

Table 6.1: Summary of Performance Test Results of Draindown, Cantabro, and HWTD

Mix Type	Trial BC (%)	Percent Draindown			Percent Cantabro Loss				Average Rut Depth at 20,000 Passes (mm)				Number of Passes at 12.5 mm Average Rut Depth			
		Test 1	Test 2	Mean	Test 1	Test 2	Test 3	Mean [SD]	Test 1	Test 2	Test 3	Mean [SD]	Test 1	Test 2	Test 3	Mean [SD]
PMWC	4.2	0.025	0	0.013	62.8	62.0	69.1	64.6 [3.9]	4.55	3.09	1.99	3.21 [1.28]	69,200	78,070	61,336	69,535 [8,372]
	5.2	0	0	0	60.5	58.0	68.3	62.3 [5.4]	7.21	4.04	4.29	5.18 [1.76]	39,275	62,570	51,789	51,211 [11,658]
	6.3	0	0.039	0.020	57.8	51.0	56.3	55.1 [3.6]	5.31	3.52	1.83	3.55 [1.74]	49,220	74,167	103,250	75,546 [27,041]
PMWF	4.2	0	0	0	61.0	58.0	73.3	64.1 [8.2]	4.22	4.82	6.04	5.03 [0.92]	51,243	51,239	48,271	50,251 [1,715]
	5.2	0	0	0	34.3	44.3	47.3	42.0 [6.8]	4.30	5.13	3.20	4.21 [0.96]	62,985	77,478	99,923	80,129 [18,611]
	6.3	0	0	0	23.4	28.5	33.7	28.5 [5.2]	4.91	3.90	4.06	4.29 [0.54]	67,364	103,798	70,176	80,446 [20,272]
PMTC	5.5	0	0	0	61.3	64.7	70.8	65.6 [4.8]	3.03	2.81	2.17	2.67 [0.45]	106,664	117,279	95,970	106,638 [10,655]
	6.6	0	0	0	51.0	56.9	58.0	55.3 [3.7]	4.30	4.14	1.17	3.20 [1.76]	77,246	80,732	131,809	96,595 [30,545]
	7.7	0.015	0.059	0.037	40.8	38.6	49.2	42.9 [5.6]	2.76	3.00	1.49	2.42 [0.81]	115,138	98,876	137,023	117,012 [19,143]
PMTF	5.5	0.033	0.032	0.032	48.4	42.9	60.0	50.4 [8.8]	2.58	3.70	3.36	3.21 [0.57]	213372	91,716	109,021	138,036 [65,813]
	6.6	0.008	0	0.004	22.6	36.6	52.3	37.2 [14.9]	4.02	3.46	3.58	3.69 [0.29]	98,830	91,455	70,818	87,934 [15,006]
	7.7	0	0.007	0.004	25.9	28.4	45.5	33.3 [10.7]	4.23	3.99	2.61	3.61 [0.88]	87,450	86,066	93,902	89,139 [4,182]
TRWC	4.2	0.050	0	0.025	54.7	63.2	68.2	62.0 [6.8]	10.76	9.27	13.99	11.34 [2.41]	21,679	25,751	19,452	22,294 [3,194]
	5.2	0.038	0.067	0.053	47.7	52.2	57.7	52.5 [5.0]	8.67	16.60	19.02	14.76 [5.42]	28,493	18,628	18,137	21,753 [5,842]
	6.3	0.025	0.114	0.070	44.5	36.1	39.3	40.0 [4.3]	6.96	7.38	5.15	6.50 [1.18]	32,915	35,590	42,503	37,003 [4,948]
TRWF	4.2	0	0	0	43.8	43.5	52.9	46.8 [5.4]	8.98	9.20	9.17	9.12 [0.12]	30,422	28,761	25,747	28,310 [2,370]
	5.2	0	0.057	0.029	27.6	37.8	35.6	33.7 [5.3]	11.97	32.94	8.10	17.67 [13.37]	21,058	14,441	26,907	20,802 [6,237]
	6.3	0.016	0	0.008	19.1	17.0	17.9	18.0 [1.0]	9.31	15.60	6.03	10.32 [4.86]	25,104	17,653	39,983	27,580 [11,369]
TRTC	5.5	0	0	0	35.7	30.2	43.1	36.3 [6.5]	17.75	16.83	19.21	17.93 [1.20]	15,593	18,031	15,838	16,487 [1,342]
	6.6	0	0.047	0.024	26.7	31.8	27.6	28.7 [2.7]	7.99	11.58	2.92	7.50 [4.35]	33,100	21,938	47,109	34,049 [12,612]
	7.7	0.017	0.096	0.056	13.2	14.3	16.4	14.6 [1.6]	5.45	8.66	12.56	8.89 [3.56]	42,081	26,025	20,362	29,489 [11,266]
TRTF	5.5	0.049	0.008	0.029	34.7	30.6	28.4	31.2 [3.2]	7.44	6.59	5.00	6.34 [1.24]	40,304	39,156	41,951	40,470 [1,405]
	6.6	0.032	1.555	0.794	18.5	19.8	18.1	18.8 [0.9]	12.17	12.52	10.11	11.60 [1.30]	20,506	19,929	24,692	21,709 [2,599]
	7.7	0	0	0	12.6	9.5	17.7	13.3 [4.1]	10.51	16.21	10.68	12.47 [3.24]	25,218	16,153	24,487	21,952 [5,036]
PGWC	4.3	0	0	0	70.7	77.9	76.2	74.9 [3.8]	63.43	63.44	63.61	63.49 [0.10]	9,033	6,306	7,870	7,736 [1,368]
	5.3	0.022	0	0.011	87.4	76.1	67.7	77.1 [9.9]	25.74	63.35	30.08	39.72 [20.58]	15,474	8,393	13,600	12,489 [3,669]
	6.4	0.050	0.070	0.06	60.7	63.8	60.5	61.7 [1.8]	54.03	54.70	32.00	46.91 [12.92]	11,117	13,497	14,801	13,138 [1,868]
PGWF	4.3	0	0	0	62.2	58.2	63.7	61.4 [2.8]	55.31	63.14	62.21	60.22 [4.28]	9,146	9,338	9,491	9,325 [173]
	5.3	0	0	0	55.2	50.2	48.6	51.3 [3.4]	43.07	47.89	58.22	49.73 [7.74]	12,601	13,252	11,048	12,300 [1,132]
	6.4	0.016	0	0.008	33.7	40.4	44.2	39.4 [5.3]	62.05	63.26	63.09	62.80 [0.65]	8,807	10,053	12,023	10,294 [1,622]

Notes: The data in the highlighted cells were obtained by extrapolation using three-stage Weibull HWTD curves.
BC = binder content and SD = Standard Deviation

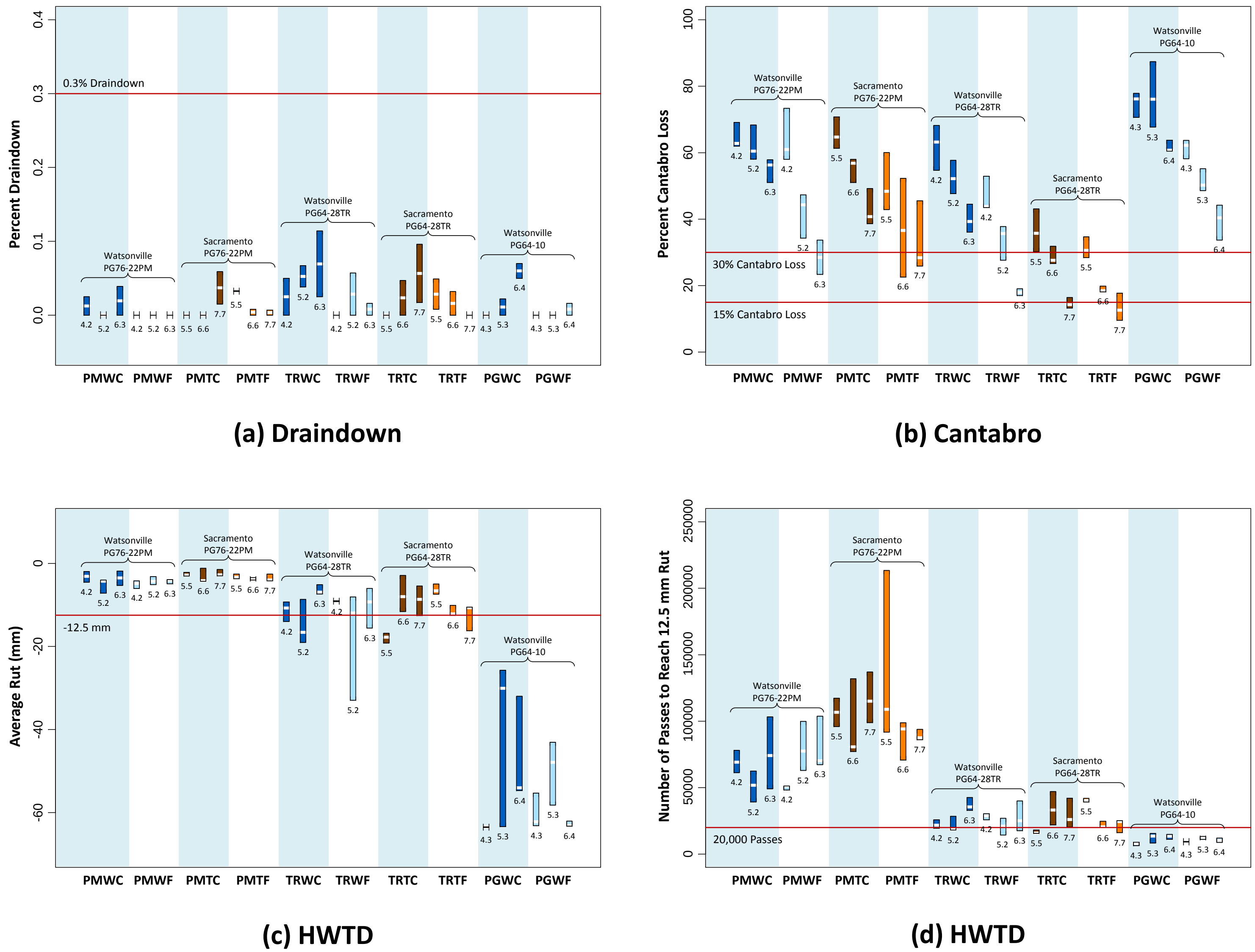
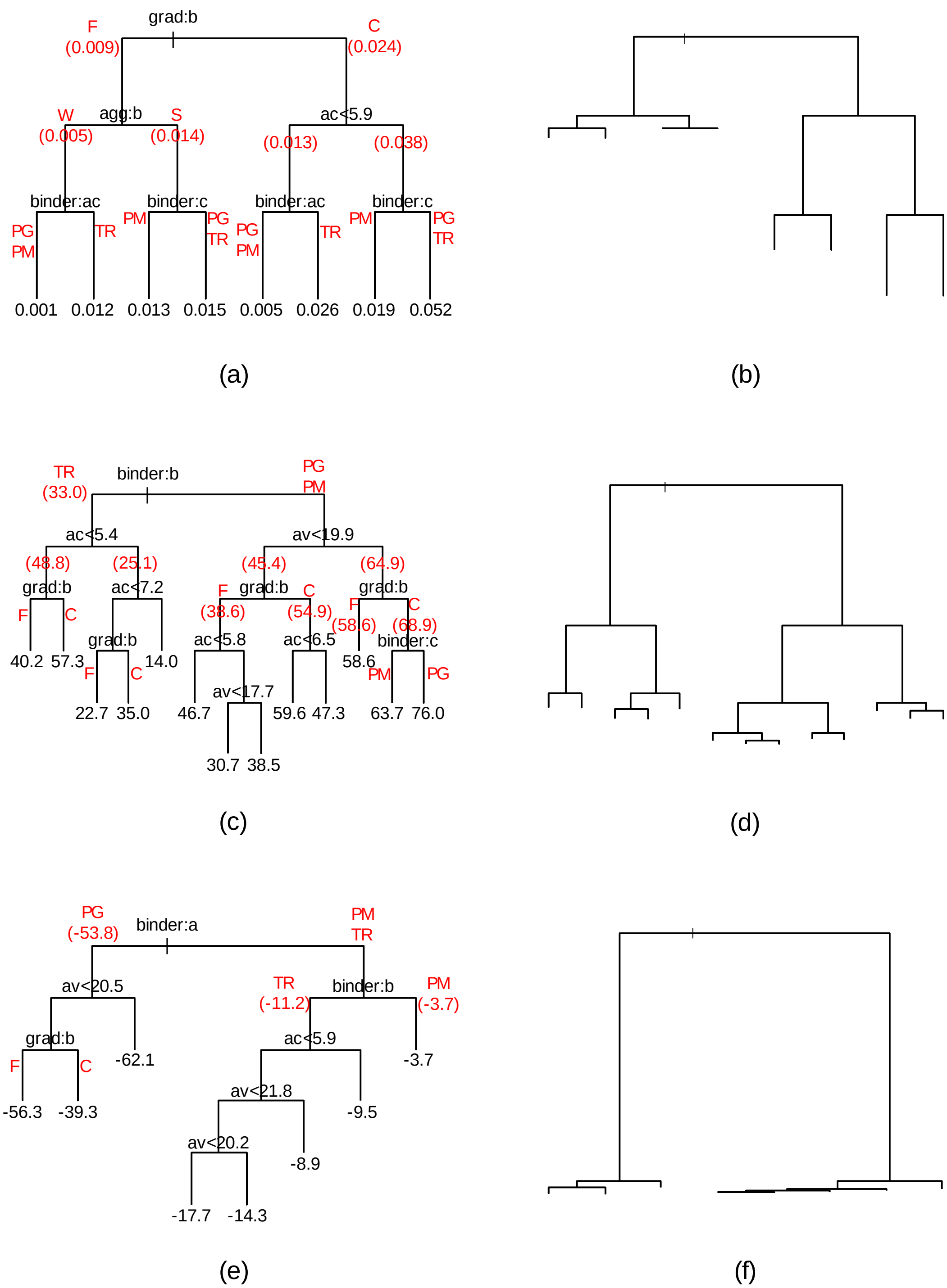


Figure 6.1: Boxplot summary of (a) percent draindown, (b) percent Cantabro loss, (c) average rut depth at 20,000 passes, and (d) number of passes to failure at 12.5 mm rut.
(Note: The number below the box represents the percent asphalt content.)



Notes:
1. binder – PG: PG64-10 (a); TR: PG64-28TR (b); PM: PG76-22PM (c)
2. grad – C: Coarse gradation (a); F: Fine gradation (b)
3. agg – T: Sacramento aggregate (a); W: Watsonville aggregate (b)
4. Number enclosed with parentheses is the average value for the branch.

Figure 6.2: Dendrograms of percent draindown, percent Cantabro loss, and HWTD average rut depth: (a), (c), and (e) with split rules and without vertical distance references; and (b), (d), and (f) without split rules.

6.1 Draindown Tests

The draindown tests were conducted in accordance with AASHTO T 305, *Standard Method of Test for Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures,* except that a No. 8 (2.36 mm) wire mesh basket was used rather than the standard 6.3 mm (0.25 in.) sieve cloth. Only two loose samples were tested at a temperature that was 15°C (27°F) above the anticipated plant production temperature, that is, the laboratory mixing temperature plus 15°C (27°F)

Based on the boxplot summary (Figure 6.1[a]) and tree-based models (Figure 6.2[a] and [b]), findings from the draindown test results are summarized as follows:

1. As seen in Figure 6.1(a), all 10 mixes met the maximum 0.3 percent draindown specification. Although the mixes used in this study presented relatively small percent draindown values compared to the maximum of 0.3 percent, the figure clearly indicates, as expected, that the higher the binder content the larger the percent draindown regardless of binder, aggregate, and gradation types.
2. The dendrograms in Figure 6.2(a) and Figure 6.2(b), indicate that gradation type is the most important factor for categorizing the data into two groups: coarse (C) and fine (F).
   - Mixes with the coarse gradation have an average draindown greater than mixes with the fine gradation.
   - For mixes with the coarse gradation, asphalt content is the most important factor followed by binder type. As expected, mixes with high asphalt content are likely to increase the probability of draindown. The influence of binder type is demonstrated by the mixes with PG 76-22 PM binder, which exhibited lower draindown than those with the PG 64-28 TR binder over the range of asphalt contents.
   - The effect of aggregate type on percent draindown is only significant in mixes with the fine gradation. Mixes with the Watsonville aggregate performed better than those with the Sacramento aggregate, which may be associated with the fact that the asphalt absorption (by weight of aggregate) for the Sacramento aggregate was 0.76 percent and 1.24 percent for the Watsonville aggregate (Table 5.1), i.e., the Watsonville aggregate absorbed more asphalt than the Sacramento aggregate.

6.2 Cantabro Tests

The Cantabro Abrasion Test was performed following ASTM D7064, *Standard Practice for Open-graded Friction Courses (OGFC) Mix Design; Appendix X2.* In OGFC mix design this test is used as an indicator to evaluate mixture durability. In general, resistance to abrasion improves with an increase in binder content and/or the use of stiff binder. The Los Angeles abrasion test apparatus is operated for 300 revolutions at a speed of roughly 30 to 33 revolutions per minute (rpm) and a room temperature around 77±10°F (25±5.6°C). The average percent loss of three replicates is reported as the percent Cantabro loss for each mix.

Figure 6.1(b) summarizes the results of Cantabro tests performed on the 4 in. diameter (101.6 mm) height-controlled SGC specimens. The dendrograms shown in Figure 6.2(c) and Figure 6.2(d) explore quantitatively the data structure of the test results using tree-based modeling. Photographs of the test specimens at end of the Cantabro tests, shown in Figure 6.3, are categorized by binder type, aggregate source, and gradation type.

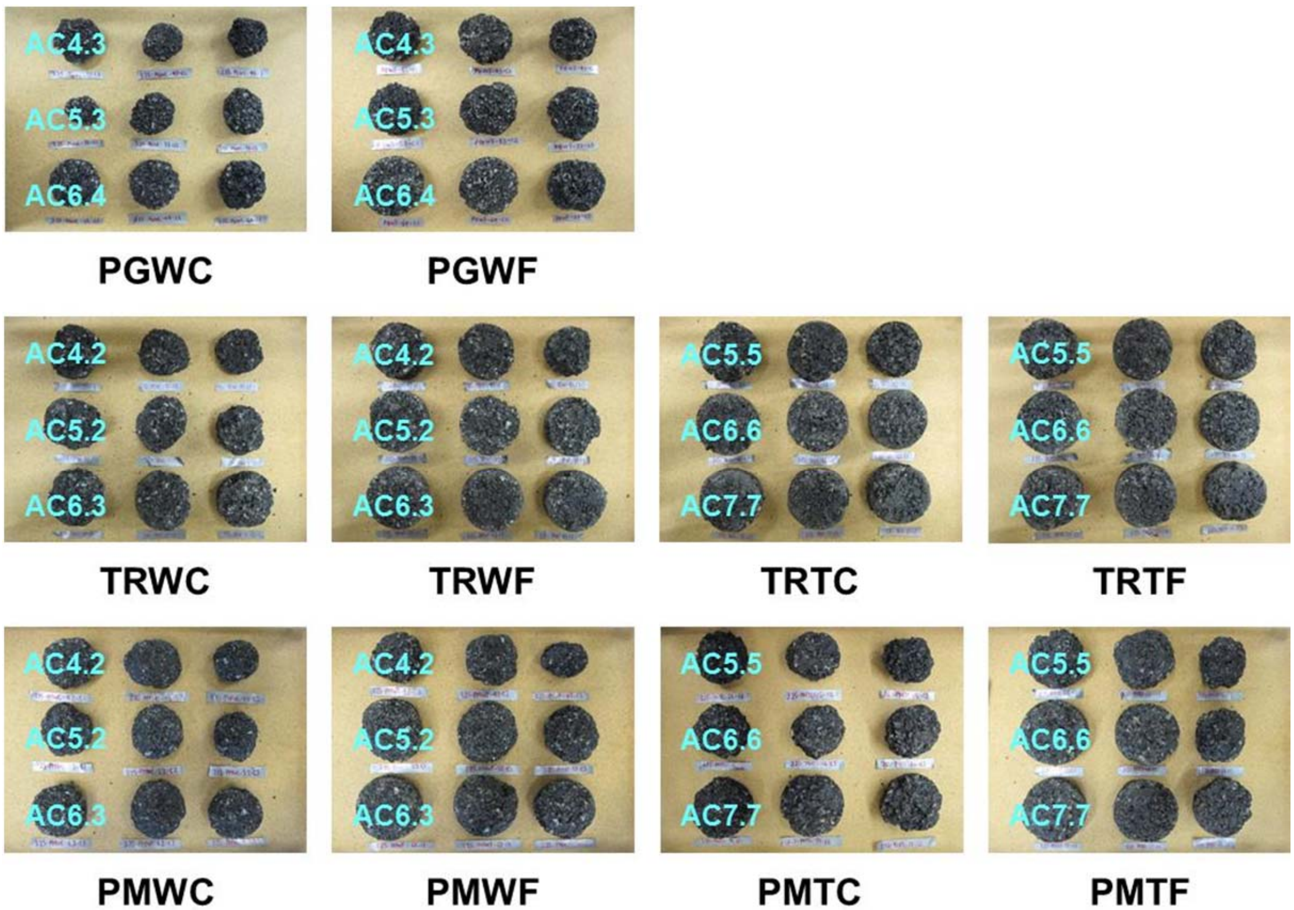


Figure 6.3: Photographic summary of Cantabro test results.

From an analysis of the summary boxplots (Figure 6.1[b]) and the dendrograms (Figure 6.2[c] and [d]), the results may be summarized as follows:

1. The tree-based modeling used to develop the data structure of Cantabro loss consists of three category covariates (binder `[binder]`, aggregate `[agg]`, gradation types `[grad]`) and two numeric variables (percent asphalt content `[ac]` and percent air-void content `[av]`). Interestingly, for this set of data the aggregate type is not significant enough to be included in the model. Viewed from the vertical distance between the nodes of the dendrograms shown in Figure 6.2(c) and Figure 6.2(d), it is apparent that binder type is the most critical factor that affects percent Cantabro loss. Air-void content and/or asphalt

content are the next most important factors followed by gradation type. It should be noted that, for a given gradation, a one percent increase in asphalt content results in a roughly two percent decrease in air-void content, according to the volumetric OGFC mix design chart. That is to say, air-void content and asphalt content are correlated and should be regarded as the same factor. The average percent Cantabro loss for PG 64-28 TR is 33.0 percent whereas the average for PG 64-10 and PG 76-22 PM is 57.3 percent.

2. From the summary boxplots shown in Figure 6.1(b), it is visually clear that an increase of fines content helps to reduce percent Cantabro loss. The Trellis graph shown in Figure 6.4 illustrates that the effect of gradation on average Cantabro loss for the different mixes (categorized by binder and aggregate types) at various binder contents is noticeable.
3. Regardless of binder, gradation, and aggregate type, there is a very clear trend showing that an increase in binder content results in a decrease in Cantabro loss.

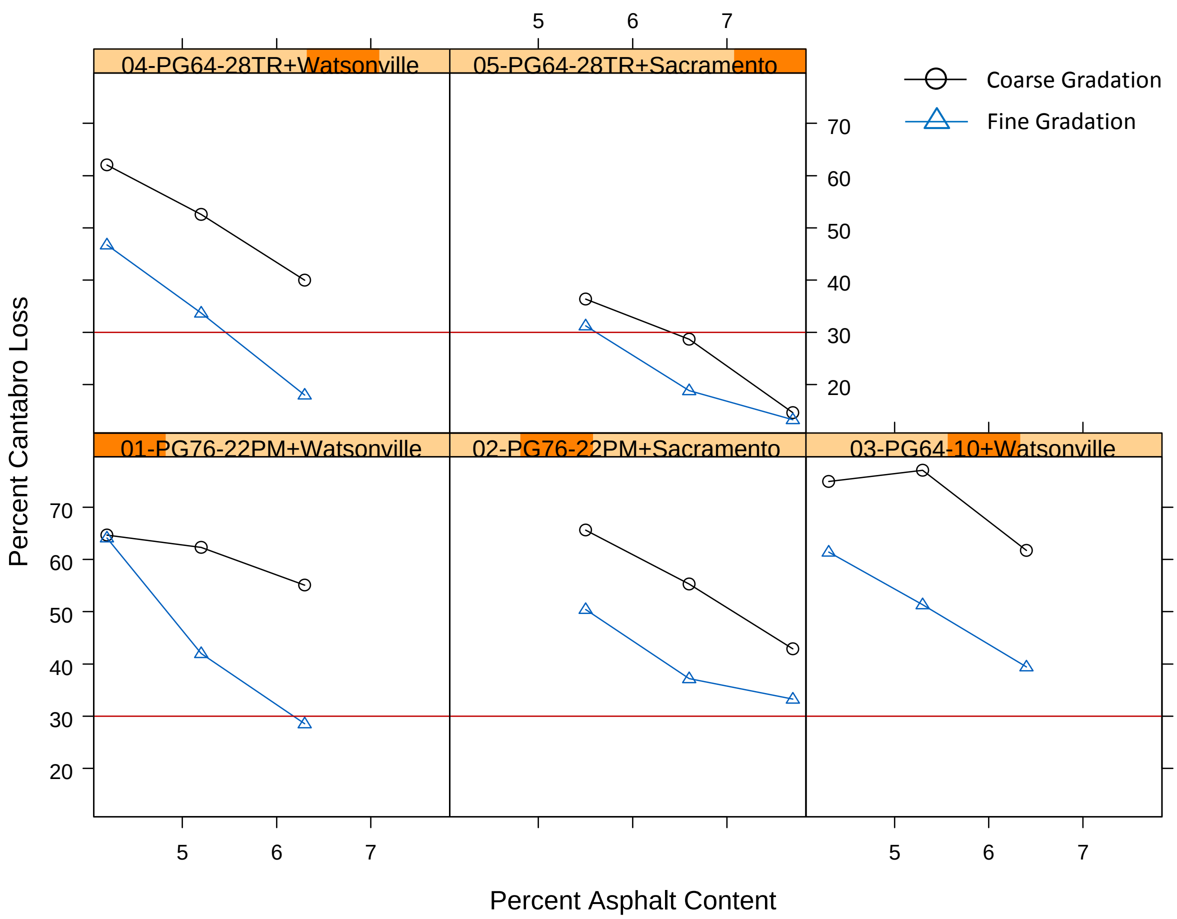


Figure 6.4: Effect of gradation on percent Cantabro loss.

6.3 Hamburg Wheel-Track Device (HWTD) Tests

The Hamburg Wheel-Track Device (HWTD) test conducted in this study follows AASHTO T 324, *Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot-Mix Asphalt (HMA).* This test provides a measure of the rutting and moisture-susceptibility of HMA material. Results were obtained with a water bath temperature of 50°C and test duration of 20,000 passes, or the number of passes to reach the limiting rut depth of the equipment.

The HWTD test plan included three trial binder contents, 10 mix types, and three replicates, i.e., a total of 90 HWTD tests or 180 height-controlled SGC specimens with 150 mm diameter (5.91 in.). The rutting of an HWTD test over the time (number of passes) and space (profile position) domains is better presented by a smoothed rutting evolution image-and-contour plot like the one shown in Figure 6.5 for PMWC mixes. A smoothed algorithm was applied along the time domain, i.e., the *x*-axis of "Number of Passes," to eliminate high-pitched noise due to vibration. The rest of smoothed image-and-contour plots can be found in Appendix D, Figure D.1 to Figure D.9. The detailed test results are listed in Appendix D, Table D.1 to Table D.3. Also, it should be recognized that the worst rutting did not necessarily occur at the middle profile position (position 6). The *average rut depth* used in this study is defined as the average rut depth of middle three profile positions (positions 5, 6, and 7) of a smoothed image-and-contour plot. Note that the color scales in the plots were set between -8 mm and 0 mm for the PMWC, PMWF, PMTC, and PMTF mixes. The color scales of the TRWC, TRWF, TRTC, TRTF, PGWC, and PGWF mixes were set between -21 mm and 0 mm.

The Trellis graph shown in Figure 6.6 summarizes the evolution of average rut depth for the various mixes and binder contents. The average rut depth evolution curve can be fit by a three-stage Weibull equation (*3*), thus it is useful for those tests requiring extrapolation to the average rut depth at 20,000 passes or the number of passes to failure at 12.5 mm average rut depth.

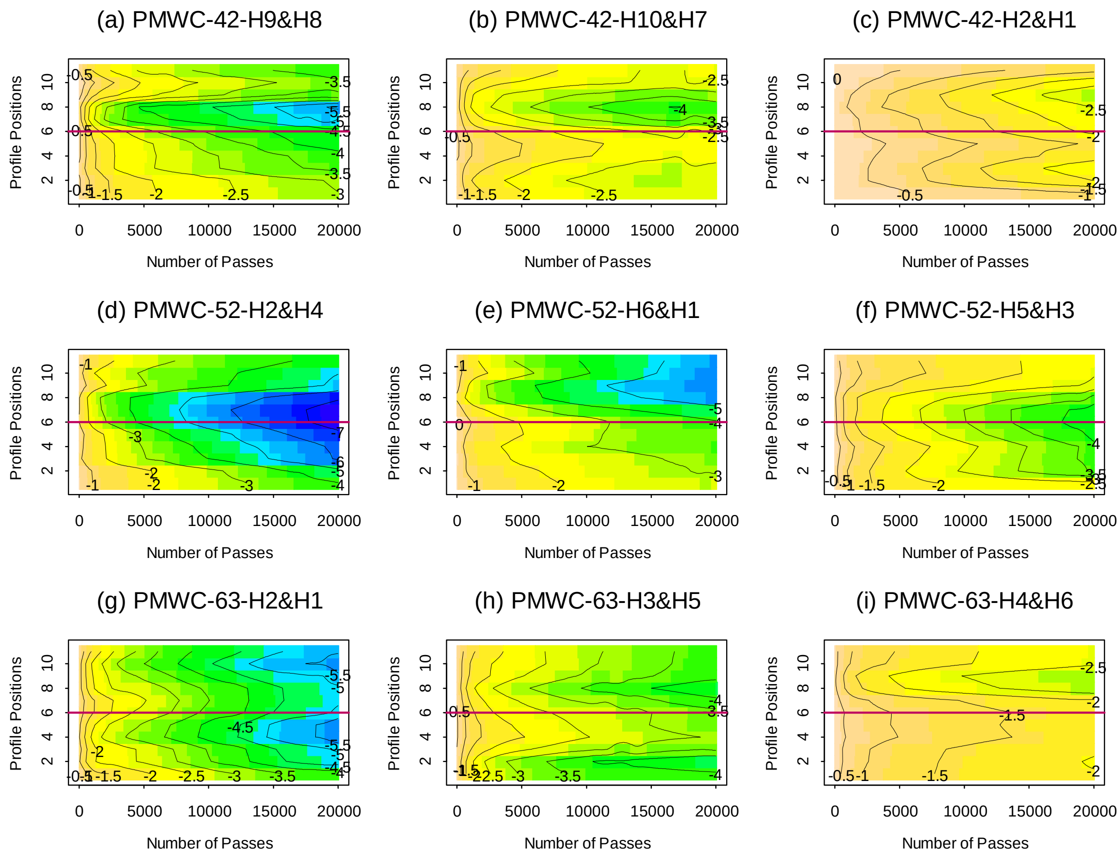


Figure 6.5: Rutting evolution image-and-contour plots for the PMWC mixes (PG 76-22 PM, Watsonville aggregate, and coarse gradation) at three binder contents: 4.2 percent [(a), (b), and (c)]; 5.2 percent [(d), (e), and (f)]; and 6.3 percent [(g), (h), and (i)]. (Note: color scale was set between -8 and 0 mm of the average rut depth.)

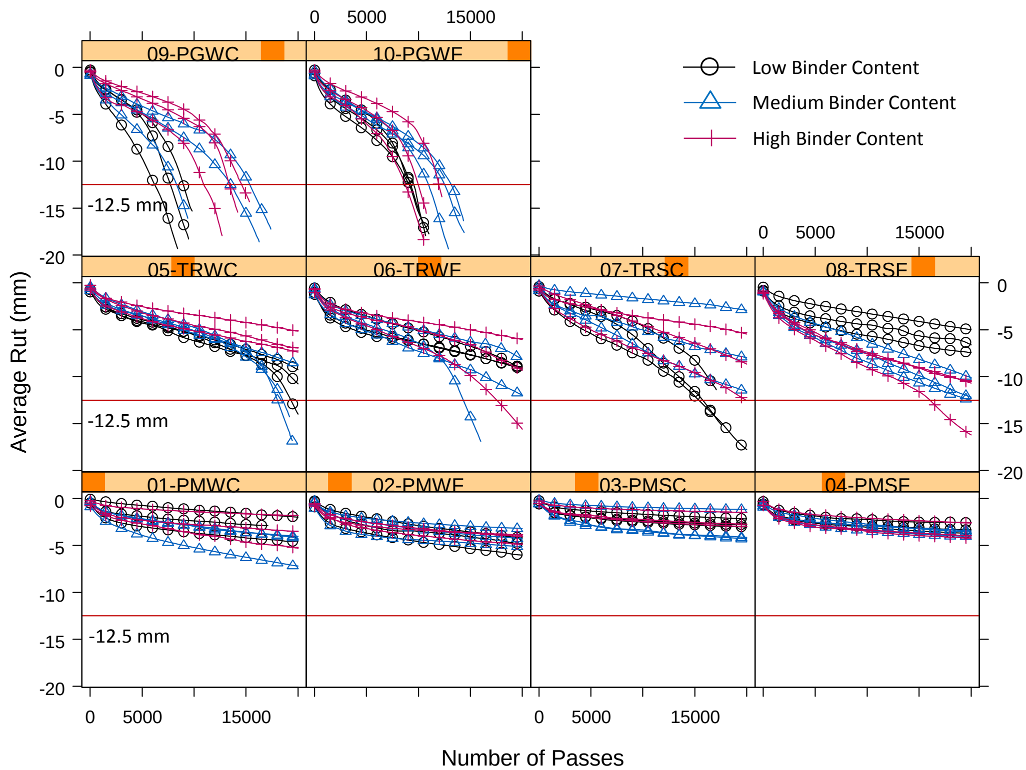


Figure 6.6: Evolution curves of average rut depth for various mix types and binder contents.

From the boxplots shown in Figure 6.1(c) and (d), the dendrograms illustrated in Figure 6.2(e) and (f), and the Trellis graph displayed in Figure 6.6, the findings can be summarized as follows:

1. Analysis of the dendrograms indicates that binder type is far more significant than the other covariates; interestingly, aggregate type is not important enough to be included in the tree-based model. The average rut depth at 20,000 passes for the PG 76-22 PM mixes was 3.7 mm, 11.2 mm for the PG 64-28 TR mixes, and 53.8 mm for the PG 64-10 mixes. The average rut depths at 20,000 passes for the PG 64-10 mixes were extrapolated using three-stage Weibull approach (Table 6.1).
2. The tree-based model indicates that rutting performance is marginally improved with the fine gradation and an increase of binder content.
3. No clear trends are apparent from the data shown in Figure 6.1(c) and Figure 6.6, indicating that an increase in binder content will reduce the rut depth.
4. Compared to mixes with the coarse gradation, the variation of rutting evolution curves for mixes with the fine gradation is smaller and the rutting evolution curves are more consistent.

6.4 Summary of Performance Test Results

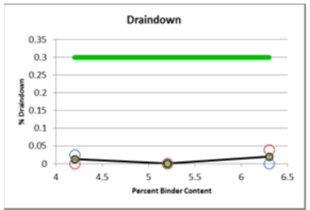
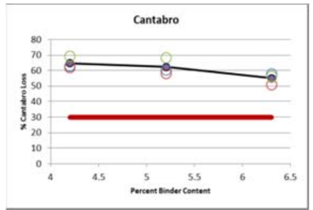
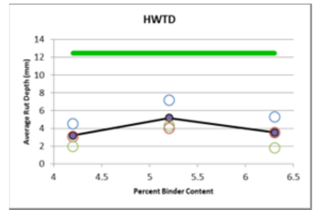
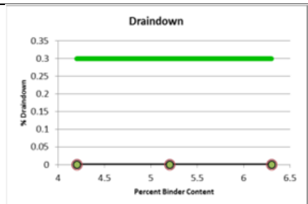
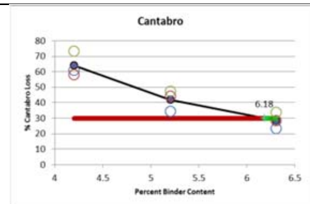
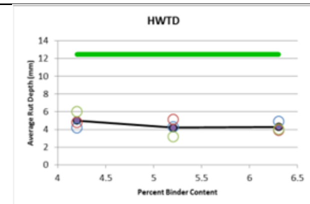
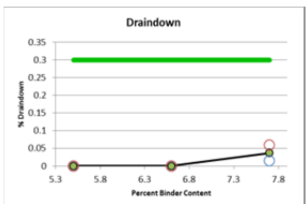
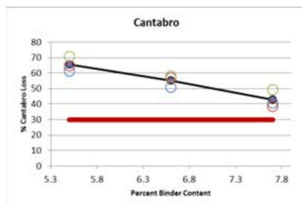
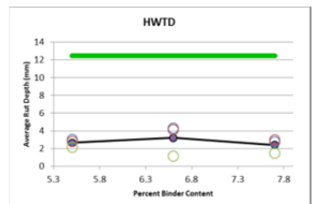
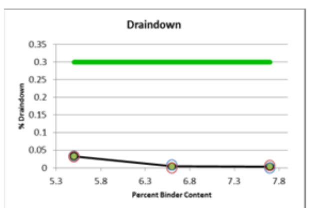
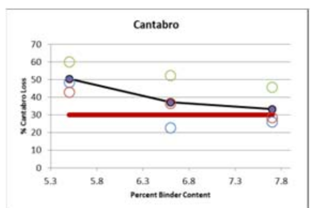
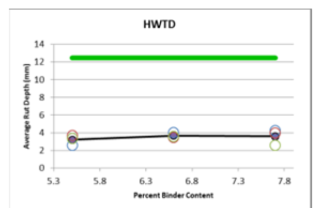
The performance test results summarized in Table 6.1 were used as the inputs to determine the optimum binder range (OBR) using the Phase II *Excel* macro (Performance Testing). Table 6.2, Table 6.3, and Table 6.4 tabulate the graphic results from the *Excel* macro for draindown, Cantabro, and HWTD tests respectively for the mixes with PG 76-22 PM, PG 64-28 TR, and PG 64-10 binders. In addition, suggestions and remedial actions for each mix type are also included in the tables. The performance specifications utilized were the following: maximum 0.3 percent draindown, maximum 30 percent Cantabro loss, and maximum 12.5 mm average rut depth for HWTD testing. It should be noted, however, that although the HWTD performance parameter, number of passes at 12.5 mm average rut depth, was used in this study, it is not recommended because almost two-thirds of the HWTD data were extrapolated and their use might induce greater uncertainty—in contrast to the use of the average rut depth at 20,000 passes.

Mixes with PG 76-22 PM binder very easily met the draindown and HWTD specifications; however, they did not perform as well in meeting the Cantabro requirement, even with the specification of a maximum 30 percent Cantabro loss; they fared even less well in meeting the more strict maximum 15 percent loss specification suggested in the NCAT approach. It can be seen that the greater the asphalt content the smaller the Cantabro loss. Hence, the major remedial actions taken for the PG 76-22 PM mixes are (1) to reduce the percent passing the break point sieve to accommodate more asphalt, i.e., change the gradation type; (2) to change to an aggregate type with a high VCA_{DRC} value so as to increase asphalt content; and (3) to increase the fines content (percent passing No. 200 sieve).

As for mixes with PG 64-28 TR binder, most of them complied with the performance specification except for the TRWC mixes that failed in Cantabro testing. As can be seen from the HWTD test results, there is a recognizable trend in the HWTD performance curves that supports the statement "the greater the binder content the better the HWTD performance." Interestingly, the TRWC and TRWF mixes performed worst at medium binder content.

For mixes with PG 64-10 binder, while they meet the 0.3 percent draindown specification, they did not meet the Cantabro and HWTD requirements. It is suggested that the following remedial actions be adopted for the OGFC mix design with PG 64-10 binder: (1) change the binder type as to improve the HWTD performance; and (2) increase the binder content by selecting a different gradation or aggregate type in order to enhance the Cantabro performance.

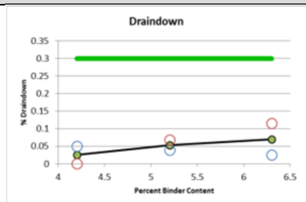
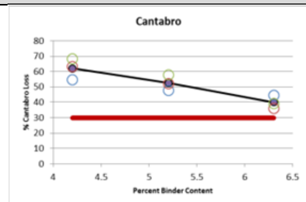
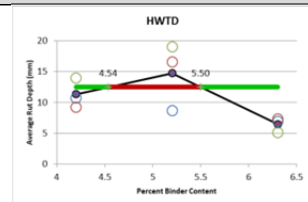
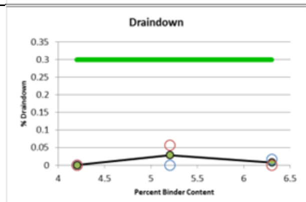
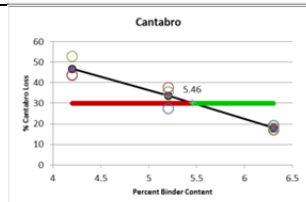
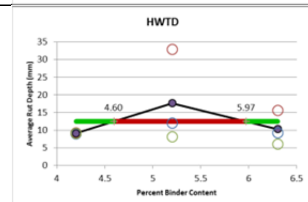
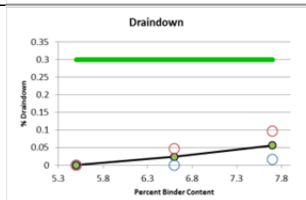
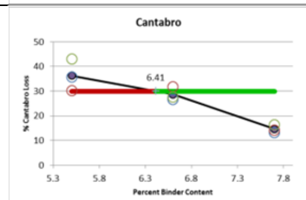
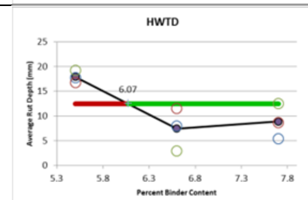
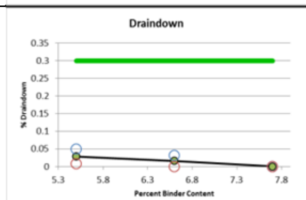
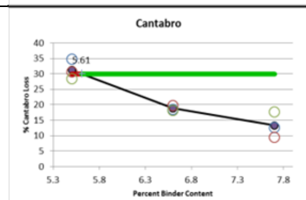
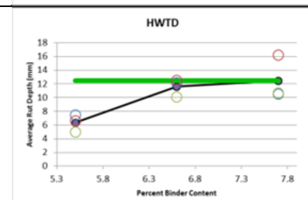
Table 6.2: Summary of Performance Test Results and Associated Suggestions and Remedial Actions for Mixes with PG 76-22 PM Binder

Mix Type	Draindown[1]	Cantabro[2]	HWTD[3]	Optimum Binder Range	Suggestions and Remedial Actions
PMWC				Failed	• Reduce the percent passing the break point sieve to accommodate more asphalt. • Change to aggregate type with high VCA_{DRC} value to increase asphalt content. • Increase fines content (percent passing No. 200 sieve).
PMWF				6.2 – 6.3	No activities required.
PMTC				Failed	• Reduce the percent passing the break point sieve to accommodate more asphalt. • Change to aggregate type with high VCA_{DRC} value to increase asphalt content. • Increase fines content (percent passing No. 200 sieve).
PMTF				Failed	• Reduce the percent passing the break point sieve to accommodate more asphalt. • Change to aggregate type with high VCA_{DRC} value to increase asphalt content. • Increase fines content (percent passing No. 200 sieve).

Notes:

1. The performance specification of percent draindown is maximum 0.3 percent.
2. The performance specification of percent Cantabro loss is maximum 30 percent.
3. The performance specification of the Hamburg Wheel-Track Device (HWTD) test in terms of average rut depth is maximum 12.5 mm at 20,000 passes.

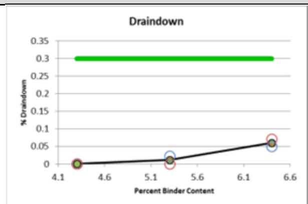
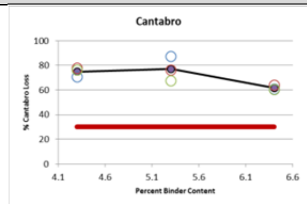
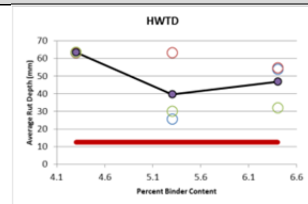
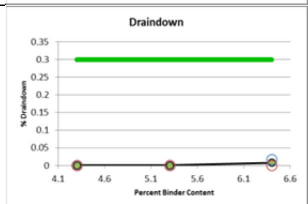
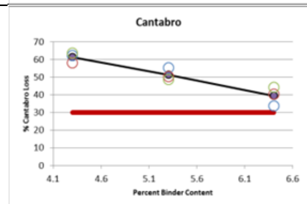
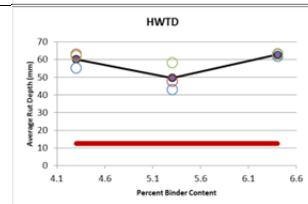
Table 6.3: Summary of Performance Test Results and Associated Suggestions and Remedial Actions for Mixes with PG 64-28 TR Binder

Mix Type	Draindown	Cantabro	HWTD	Optimum Binder Range	Suggestions and Remedial Actions
TRWC				Failed	• Increase fines content (percent passing No. 200 sieve). • Change to aggregate type with high VCA_{DRC} value to increase asphalt content.
TRWF				6.0 – 6.2	No activities required.
TRTC				6.4 – 7.7	No activities required.
TRTF				5.6 – 7.7	No activities required.

Notes:

1. The performance specification of percent draindown is maximum 0.3 percent.
2. The performance specification of percent Cantabro loss is maximum 30 percent.
3. The performance specification of the Hamburg Wheel-Track Device (HWTD) test in terms of average rut depth is maximum 12.5 mm at 20,000 passes.

Table 6.4: Summary of Performance Test Results and Associated Suggestions and Remedial Actions for Mixes with PG 64-10 Binder

Mix Type	Draindown	Cantabro	HWTD	Optimum Binder Range	Suggestions and Remedial Actions
PGWC				Failed	• Change binder type. • Change gradation.
PGWF				Failed	• Change binder type. • Change gradation.

Notes:

1. The performance specification of percent draindown is maximum 0.3 percent.
2. The performance specification of percent Cantabro loss is maximum 30 percent.
3. The performance specification of the Hamburg Wheel-Track Device (HWTD) test in terms of average rut depth is maximum 12.5 mm at 20,000 passes.

6.5 Proposed OGFC Mix Design Procedure

A proposed OGFC mix design procedure appears in summary form in Table 6.5. Laying out the procedure stepwise, the table also shows the required activities and test methods/software. Before using the procedure, it is important to take into account the following:

- VCA_{DRC} and P_{aasp} are two critical material properties that affect the construction of the OGFC mix design chart and the accuracy of the percent air-void content.
- If the trial binder contents obtained with the selected gradation are questionable in terms of engineering judgment when step 4 is reached, it is advisable to repeat step 2 and step 3.
- Use of height-controlled Superpave gyratory-compacted specimens for Cantabro and HWTD tests is highly recommended.

The flow chart of the proposed OGFC mix design procedure that appears in Figure 6.7 is to replace the OGFC mix design procedure from the earlier study, which is shown in Figure 1.3 (*3*).

In the proposed mix design procedure outlined in Table 6.5, the *Excel* macro developed comes into use in steps 4 and 9. After steps 1 through 3 have been performed, use of the macro in step 4 enables selection of three trial binder contents for specimens to be used in the performance testing portion of the OGFC mix design process. *(As discussed in Reference [3], the Excel macro is constructed using the aggregate properties obtained in Steps 1 through 3.)*

Using inputs for the predetermined material properties of the selected aggregate and binder types, the macro provides an improved method for evaluating whether a selected gradation has the requisite properties. The macro determines whether there is sufficient binder in the mix to meet its volumetric requirements and to ensure an asphalt film thickness that will provide adequate durability and rutting resistance and prevent excessive draindown and moisture damage. The proposed mix design chart takes into consideration the percent asphalt absorption of aggregate blend in addition to the VCA_{DRC}. However, the resulting design chart will 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 then have to be verified through performance tests. Once specimens are prepared—following steps 5 through 8 of the procedure shown in Table 6.5—according to the design chart generated by the macro, it again comes into use in step 9, providing a convenient way to summarize the test results and to determine the optimum binder range (OBR).

Table 6.5: Proposed OGFC Mix Design Procedure

Phase	Step	Activity	Item	Test Method/Software
Phase I: Volumetric OGFC Mix Design	1	Select materials.		
	2	Select gradation to determine percent passing the break point sieve size.	Percent passing break point sieve (P_{fg} , fine aggregate)	
			Percent retained above break point sieve (P_{cg} , coarse aggregate)	
	3	Determine the materials' volumetric properties.	Bulk specific gravity of coarse aggregate (G_{cg})	AASHTO T 85
			Bulk specific gravity of fine aggregate (G_{fg})	AASHTO T 84
			Bulk specific gravity of asphalt (G_{asp})	Supplied by refinery
			Voids in coarse aggregate in dry-rodded condition (VCA_{DRC})	AASHTO T 19 and T 85
			Asphalt absorption (P_{aasp})	Refer to Table 3.4 of this report for test methods and procedure.
	4	Construct the OGFC mix design chart and determine three trial binder contents that meet the air void requirements.		*Excel* macro (Phase I: Volumetric OGFC Mix Design)
Phase II: Performance Testing	5	Fabricate specimens for performance tests.	Height-controlled SGC specimens	AASHTO T 321
			RICE (G_{mm})	AASHTO T 209
			Bulk specific gravity of the compacted asphalt mixture (G_{mb})	AASHTO T 269
			Air-void content (V_a)and the voids in coarse aggregate of the compacted mixture (VCA_{MIX})	Equations 3.2 and 3.3 of this report
	6	Conduct Cantabro tests to determine the allowable minimum binder content.		ASTM D7064 Appendix X2
	7	Conduct draindown tests to discover the allowable maximum binder content.		AASHTO T 305
	8	Conduct HWTD tests to decide the allowable binder range.		AASHTO T 324
	9	Determine the optimum binder range (OBR).		*Excel* macro (Phase II: Performance Testing)

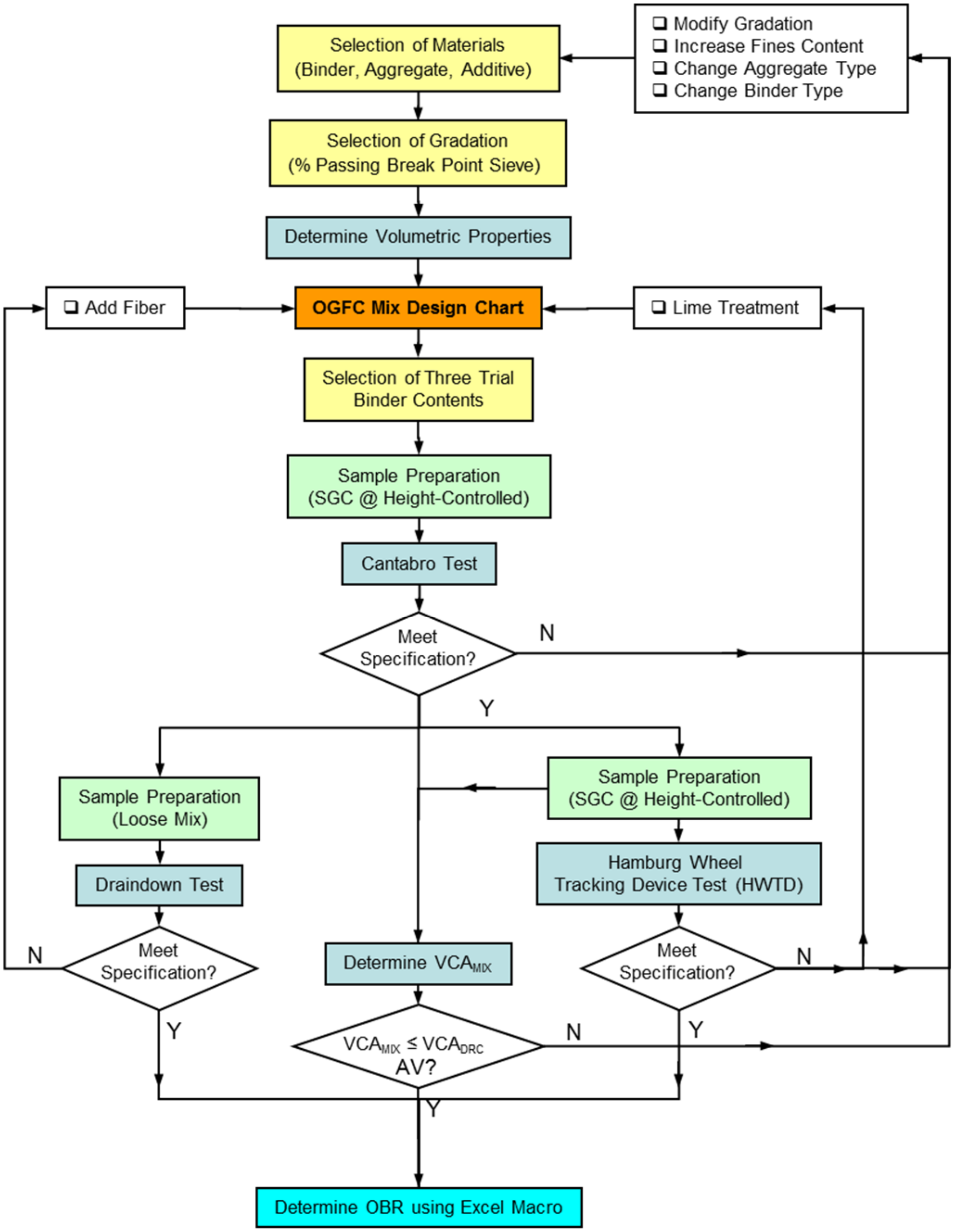


Figure 6.7: Flow chart of the proposed OGFC mix design procedure.

6.6 Comparison of Mix Designs Using Current Caltrans and Proposed Methods

The current Caltrans OGFC mix design procedure shown in Reference (*3*) selects the trial binder content based on the results obtained from CT 368 (2003). CT 368 uses a conventional binder mix to determine the OBC and then applies a safety factor of 1.1 or 1.2 to calculate the OBC for the polymer-modified or asphalt rubber binder content. To compare the OGFC design procedure proposed in this report to the CT 368 (2003) procedure, four mixes were used, made from two aggregate sources (Watsonville and Sacramento) and two gradations for each aggregate source. A direct comparison would have involved the use of the same aggregates, binders, and gradations. However, the original experimental plan for this project did not include a comparison and sufficient materials were not available to make a direct comparison after the testing described in the rest of this report was completed.

Instead, an approximate comparison was made, for asphalt rubber binder, using the information from similar mixes in the SPE 4.21 subtask 2A project and this project. The mixes have the same aggregate sources and conventional and asphalt rubber (AR) binders. However, some of the parameters needed to run the *Excel* macro developed in the proposed OGFC design procedure for comparison with the CT 368 (2003) were unavailable. Instead, the missing parameters—fine aggregate specific gravity and the asphalt absorption—were estimated using values from mixes with the same aggregate source and similar gradations. Table 6.6 shows the two similar gradations for the Watsonville aggregate source in CT 368 (2003) and in the proposed method. Table 6.7 shows the two similar gradations for the Sacramento aggregate source in CT 368 (2003) and the proposed method.

Table 6.6: Comparable Watsonville Aggregate Gradation Used for Comparison Between CT 368 and Proposed Method Results

	CT 368 (2003)	Proposed Method			CT 368 (2003)	Proposed Method
U.S.	Watsonville G3 (Middle, Used in 4.21 Project)	Watsonville Coarse Gradation (Used in This 3.25 Project)		U.S.	Watsonville G2 (Fine, Used in 4.21 Project)	Watsonville Fine Gradation (Used in This 3.25 Project)
¾-inch	99.6			¾-inch	100.0	
½-inch	97.0	100.0		½-inch	99.9	100.0
3/8-inch	83.2	91.7		3/8-inch	89.7	92.2
No. 4	32.6	33.7		No. 4	38.1	33.6
No. 8	12.2	16.4		No. 8	18.8	16.6
No. 16	8.0	8.0		No. 16	14.1	13.6
No. 30	4.8	3.8		No. 30	10.5	10.5
No. 50	3.6	2.6		No. 50	8.1	8.2
No. 100	2.6	1.8		No. 100	6.0	6.4
No. 200	1.7	0.9		No. 200	3.9	3.8

Table 6.7: Comparable Sacramento Aggregate Gradations Used for Comparison Between CT 368 and Proposed Method

	CT 368 (2003)	Proposed			CT 368 (2003)	Proposed
U.S.	Sacramento G3 (Middle, Used in 4.21 Project)	Sacramento Coarse Gradation (Used in This 3.25 Project)		U.S.	Sacramento G2 (Fine, Used in 4.21 Project)	Sacramento Fine Gradation (Used in This 3.25 Project)
¾-inch	100.0			¾-inch	100.0	
½-inch	97.8	100.0		½-inch	100.0	100.0
3/8-inch	82.5	91.8		3/8-inch	88.3	91.5
No. 4	32.4	31.7		No. 4	36.7	31.7
No. 8	12.2	17.0		No. 8	17.8	16.9
No. 16	7.5	7.6		No. 16	13.9	13.2
No. 30	4.7	3.4		No. 30	10.2	10.2
No. 50	3.5	2.5		No. 50	7.9	8.2
No. 100	2.2	1.7		No. 100	5.2	6.1
No. 200	1.6	0.8		No. 200	3.4	3.7

Table 6.8 and Table 6.9 shows the values input into the *Excel* macro to calculate the conventional and AR optimum binder content for the four mixes.

Table 6.8: Input Values of Conventional Binder for the Proposed Method *Excel* Macro

Required Inputs	Watsonville G3	Watsonville G2	Sacramento G3	Sacramento G2	Project Information
VCA_{DRC}	37.2	37.04	39.18	39.33	Measured
P_{cg}	87.8	81.2	87.8	82.2	
P_{fg}	12.2	18.8	12.2	17.8	
G_{asp}	1.0253	1.0253	1.0253	1.0253	
G_{cg}	2.667	2.652	2.657	2.636	
G_{fg}	2.674	2.741	2.719	2.731	Estimated*
P_{aasp}	1.3	1.2	0.7	0.7	

* Specific Gravity of Fine Aggregates (G_{fg}) and Asphalt Absorption (P_{aasp}) are estimated from mixes with the same aggregate type and similar gradations

Table 6.9: Input Values for Asphalt Rubber Binder for the Proposed Method *Excel* Macro

Input Into spreadsheet	Watsonville G3	Watsonville G2	Sacramento G3	Sacramento G2	Project Information
VCA_{DRC}	37.2	37.04	39.18	39.33	Measured
P_{cg}	87.8	81.2	87.8	82.2	
P_{fg}	12.2	18.8	12.2	17.8	
G_{asp}	1.04	1.04	1.04	1.04	
G_{cg}	2.667	2.652	2.657	2.636	
G_{fg}	2.674	2.741	2.719	2.731	Estimated*
P_{aasp}	1.2	1.2	0.8	0.7	

* Specific Gravity of Fine Aggregates (G_{fg}) and Asphalt Absorption (P_{aasp}) are estimated from mixes with the same aggregate type and similar gradations.

Table 6.10 and Table 6.11 present the calculated binder contents using the *Excel* macro for the mixes. The three target air voids are input parameters in the proposed method *Excel* spreadsheet.

Table 6.10: Results of Initial Conventional Binder Content Using Proposed Method Excel Macro

Target Air-Void Content (%)	Watsonville G3 Binder Content (%)	Watsonville G2 Binder Content (%)	Sacramento G3 Binder Content (%)	Sacramento G2 Binder Content (%)
18	6.9	3.7	7.9	5.3
20	5.9	2.7	6.8	4.2
22	4.8	1.7	5.7	3.2

Table 6.11: Results of Initial Asphalt Rubber Binder Content Using Proposed Method Excel Macro

Target Air-Void Content (%)	Watsonville G3 Binder Content (%)	Watsonville G2 Binder Content (%)	Sacramento G3 Binder Content (%)	Sacramento G2 Binder Content (%)
18	6.9	3.7	8.1	5.3
20	5.8	2.7	7.0	4.3
22	4.7	1.7	5.8	3.2

Table 6.12 shows the comparison of the trial binder content using CT 368 (2003) and the proposed method for the conventional and AR mixes.

Table 6.12: Comparison Trial Binder Content Between Current Method and Proposed Method

Mixes	Conventional PG 64-10		Asphalt Rubber PG 64-22AR	
	Current Method Optimum Binder Content (CT 368 2003)	Proposed Method Optimum Binder Content*	Current Method Optimum Binder Content (CT 368 2003)	Proposed Method Optimum Binder Content*
Watsonville G3	6.0	6.9	7.2	6.9
Watsonville G2		3.7		3.7
Teichert G3		7.9		8.1
Teichert G2		5.3		5.3

*Note: for target air-void content of 18 percent shown in Table 6.10 and Table 6.11.

This comparison of design binder contents between both methods is limited because of the differences in gradations used in both methods. The SPE 4.21 project mixes had lower Cantabro losses than the SPE 3.25 project mixes that they are compared with here. This may be due to specimen production differences and gradations. The SPE 4.21 project mixes used gyration control for specimen production, while the SPE 3.25 project mixes used height control for specimen production. Height control may result in specimens of lower density that have higher Cantabro loss. Additionally, as noted previously and can be seen in Table 6.6 and Table 6.7, the 3.25 project mixes had somewhat coarser aggregate gradations than the 4.21 project mixes, which increases the durability of the mix.

A major difference between the current CT 368 procedure and the proposed method is that CT 368 only considers draindown and does not consider the voids in the coarse aggregate (VCA_{DRC}). The VCA_{DRC} can dramatically change the binder content. For instance, mixes Watsonville G2 and Sacramento G2 have a binder content of 6.0 percent according to CT 368 (Table 6.12), but have what may be unreasonably low binder contents based on the new procedure (Table 6.10, Table 6.11 and Table 6.12). This is because both of those mixes have low VCA_{DRC} and a high percentage of fines (P_{fg}, Table 6.8 and Table 6.9). These parameters indicate that these gradations have little void space, which lowers the binder content required to reach the target air-void content for the proposed design procedure. In order to increase the binder content, the aggregate gradation has to be adjusted to obtain a higher VCA_{DRC}.

The difference between the CT 368 (2003) and proposed method binder contents shown in Table 6.12 is that the proposed method focuses on binder material properties, like specific gravity and absorption, while CT 368 takes the draindown test results and applies a safety factor of 1.2 to calculate the binder content for asphalt rubber binder. It can be seen in Table 6.12 that the proposed method calculated nearly the same binder content for both the conventional and asphalt rubber binders, with a maximum difference of 0.2 percent difference in the binder content for a minimum target value of 18 percent air voids.

It can also be seen that the spreadsheet for the new method predicts that about a one percent change in binder content will adjust the air-void content up or down by about two percent. Mix designers can consider reducing the air-void content and increasing the durability by increasing the binder content where traffic and climate conditions warrant. Guidelines regarding target air-void content should be prepared if the proposed method is implemented.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This study is the second phase of development of an OGFC mix design procedure to replace the current procedure, California Test 368. The study's purpose has been to refine the optimum binder range (OBR) developed in Phase I based on volumetric properties using the draindown, Cantabro, and HWTD tests. This phase included performance tests on three binder types, two aggregate types, two gradations, and three trial binder contents obtained from the proposed OGFC mix design chart. Based on information developed in Reference (*3*), specimens were prepared using a height-controlled Superpave gyratory compaction (SGC) procedure to determine the volumetric properties and then obtain results of draindown, Cantabro, and HWTD tests. The following conclusions are offered based on the analyses of the resulting test data:

1. *Promising OGFC Mix Design Procedure.* The proposed OGFC mix design procedure with the addition of the *Excel* macro is very promising, and provides several of the following features:
    - The proposed procedure eliminates the need to determine an optimum gradation as is required in the NCAT approach. The proposed process provides a more rational and direct volumetric approach for selecting three trial binder contents to use for preparing performance test specimens that also comply with the requirements for percent air-void content. With the aid of the *Excel* macro developed, for the given material properties of the selected aggregate and binder types, the process provides an improved method for evaluating whether a selected gradation meets the requisite properties. Essentially, the procedure determines whether or not volumetric requirements are met with sufficient binder to provide the mix with an asphalt film thickness that result will in adequate durability and rutting resistance and without excessive draindown and moisture damage. *(Excel* macro *[Phase I: OGFC Volumetric Mix Design])*
    - The proposed mix design chart takes into consideration the percent asphalt absorption of the aggregate blend, which is not specified in the NCAT approach, in addition to the VCA_{DRC}, which insures stone-on-stone contact in the aggregate structure (the equation for defining stone-on-stone contact was included in Reference [*3*] and incorporated in the *Excel* macro). *(Excel* macro *[Phase I: OGFC Volumetric Mix Design])*
    - The volumetric-based OGFC mix design chart cannot identify the differences 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 must then be verified through performance testing. The *Excel* macro developed in this part of the study provides a convenient way to summarize test results and to determine the optimum binder range (OBR). *(Excel macro [Phase II: Performance Testing])*

- To make practical use of this OGFC mix design chart, the performance specifications must be established in such a way that they relate to the expected in-situ performance. While it requires additional performance criteria adjustments for the three performance tests, the *Excel* macro is able to modify the criterion so as to serve this purpose. *(Excel* macro *[Phase II: Performance Testing])*

2. *Effect of Percent Passing No. 200 Sieve on Performance Tests*. As demonstrated in this study, an increase in percent passing the No. 200 sieve (fines content) not only decreases the variability in the SGC compaction curve, but it also helps to control the amount of draindown and to significantly reduce the Cantabro loss. Although the tree-based modeling showed only a marginal effect of fines content on HWTD performance, the gradation with more fines provided reduced variability in the average rut depth curve and yielded more consistent results. Based on this information, it is desirable to include a requirement for fines content in the OGFC mix design procedure. A measure of the required fines content may be obtained by determining the area beneath the gradation curve from the break point sieve to the No. 200 sieve. In this study, the area for the fine gradation is 15.11 which is almost twice the magnitude of the coarse gradation, 7.78. It should be noted that this area is calculated based on the percent passing the break point sieve versus the *Log*(sieve size [mm]) plot.
3. *Superpave Gyratory-Compacted Specimen with Height Control*. In this study, the specimens for Cantabro and HWTD testing were fabricated using Superpave gyratory compaction with height control rather than by the number of gyrations. The target values (TV) of percent air-void contents for low, medium, and high asphalt contents for each mix type obtained from the proposed OGFC mix design chart were 22 percent, 20 percent, and 18 percent respectively. With the use of this chart the means of the air-void contents for low, medium, and high binder contents were very close to the target values and the average standard deviations are roughly in the range of 0.3 to 0.5 percent. Accordingly, the air-void contents of the height-controlled SGC specimens have a 95 percent probability within the range of TV±0.6 to 1.0 percent, which is considered acceptable. Thus the proposed OGFC mix design chart, based on the volumetric equation for VCA_{DRC} , is a valuable addition to the procedure for specimen preparation for performance testing.
4. *Ideal OGFC Mix Design*. According to this study, a desirable OGFC mix design would include the following:
   - Selection of an aggregate type that is strong enough to form a solid stone-on-stone contact structure and with a high VCA_{DRC} value so as to accommodate more asphalt that will improve mix durability. Moreover, a higher VCA_{DRC} value provides greater flexibility in selecting the gradation/NMAS and design air-void content.
   - Selection of a binder type that can provide adequate durability, insure sufficient rutting resistance, minimize moisture damage, and prevent draindown without fiber addition.

- Selection of a gradation with sufficient fines content to improve Cantabro performance and compactability when placed on hot-mix asphalt (HMA), and that minimizes draindown.

5. *Asphalt Absorption*. The proposed procedure to determine asphalt absorption included in the NCAT procedure is practical. In this study, the asphalt absorption of Watsonville aggregate was determined to be 1.24 percent by weight of aggregate, which is about 0.5 percent greater than that of Sacramento aggregate (0.76 percent).
6. *Discussion of HWTD Test Results*. Results of the HWTD performance tests included herein indicate that: (1) binder type is far more significant than the other covariates, and (2) there is no strong evidence to support the statement that the larger the asphalt content the better the HWTD performance. These HWTD test results with poor performance show that it may not be necessary to remedy mixes using lime treatment. For example, in this study the HWTD performance of PGWC and PGWF mixes could be improved by just changing the binder type.
7. *Comparison of binder contents from CT 368 and proposed procedure.* A preliminary comparison indicates that the proposed procedure tends to produce similar binder contents for conventional and asphalt rubber binders, and the binder contents from the proposed procedure can be considerably different from those using CT 368 and based only on draindown. The proposed procedure can also produce unreasonably low binder contents that indicate that changes may need to be made in the gradation.

7.2 Recommendations

Based on the testing results of this study, the following preliminary recommendations are suggested for consideration in future efforts to revise CT 368:

1. *Specimen Preparation Using the Superpave Gyratory Compactor with Height Control*. As demonstrated in this study, the number of gyrations required to fabricate a 63.5 mm high specimen is mix-dependent. Hence, the use of a fixed number of gyrations (for example, the 50 gyrations used in the NCAT procedure) to prepare specimens will result in a large variation in air-void content. Accordingly, it is recommended that the SGC procedure for test specimens be based on height control rather than on a fixed number of gyrations.
2. *Specification of Percent Passing No. 200 Sieve (fines content).* This study indicates that an increase of fines content is significant in reducing Cantabro loss, preventing draindown, producing more consistent HWTD test results, and minimizing variations in the SGC curves. Hence, it is recommended that fines content should be part of the performance specifications (determined by wet sieving), incorporating a criterion based on percent passing the No. 200 sieve or the area beneath the gradation curve from break point sieve size to No. 200 sieve, or both. *This likely would require a more stringent requirement for the percent passing the No. 200 sieve.*

3. *Maximum Draindown Specification*. The draindown problem can be easily remedied by changing binder type, adding fiber, increasing fines content, or using warm mix. The maximum 0.3 percent draindown specification suggested by the NCAT approach appears to be a reasonable value for use in the specification for OGFC mix design.
4. *Minimum 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 in durability through their design life. Their 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 the compacted mix can meet the performance specifications for permeability, Cantabro (measure of durability performance), and Hamburg Wheel-Track Device testing (HWTD, measure of rutting and moisture sensitivity). Thus, the minimum 18 percent air-void content seems to be adequate.
5. *Maximum Cantabro Loss Specification.* In this study, only mixes TRTC and TRTF with 7.7 percent binder content met the maximum 15 percent Cantabro loss suggested by the NCAT approach. If a maximum of 30 percent Cantabro loss is specified, two more mixes with 6.3 percent binder content, PMWF and TRWF were included. Thus it is suggested that the maximum percent Cantabro loss specification for OGFC mix design be in the range of 20 to 30 percent.
6. *Specification of HWTD Average Rut Depth.* Compared to the performance parameter of the number of passes at 12.5 mm rut depth, the average rut depth at 20,000 passes used to measure the HWTD performance is more intuitive. As can be seen from this study, for the PG 76-22 PM and PG 64-28 TR mixes, extrapolation was usually required to determine the number of passes; as a consequence, uncertainties and variations may be easily introduced to the interpretation of test results. The use of 12.5 mm average rut depth as the HWTD specification seems to be appropriate; however, further verification is required through monitoring the interaction between performance specification and field performance.
7. *Further Study — HWTD Performance Specifications Related to Field Performance.* Further study is desirable to evaluate the HWTD test as a performance test for OGFC mix design. Two questions need to be answered. 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 investigation to answer the first question should involve determination of the best Superpave gyratory compaction details, evaluation of the effects of specimen height, configuration of the HWTD test setup (cylindrical cores versus slab), evaluation of the dimensions of the wheel 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: AGGREGATES AND ASPHALT BINDERS

Table A.1: Aggregate Properties Reported by the Two Suppliers

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

3.25
Qty=5

RCVD UCB PRC
9/12/12 O MALONEY

PARAMOUNT PETROLEUM ALON USA

10090 Waterman Rd.
Elk Grove, CA 95624
Phone: (916) 685-9253

D.S. 09-07-12

PRODUCT: PG 76-22 PM ASPHALT CEMENT
CODE No: 13121
DATE:
TANK No.: 5004

Purchaser: ______
Destination: ______
Transporter: ______
Truck No.: ______
Bill of Lading No.: ______
Contract No.: ______
Purchase Order No.: ______

Meets Specifications: ASTM D 6373 Mod., AASHTO M 320 Mod., Caltrans Section 92.

CERTIFICATE OF COMPLIANCE

TESTS	ASTM No.	AASHTO No.	SPECIFICATION	RESULT
Tests on Original Asphalt:				
Dynamic Shear, 76°C, G/Sinδ, kPa*	D 7175	T 315	1.00 min	1.80
Viscosity, 135°C, 21 Spindle, 20 RPM, Pa·s	D 4402	T 316	3 max	1.755
Viscosity, 165°C, 21 Spindle, 20 RPM, Pa·s	D 4402	T 316		0.558
Flash Point, C.O.C., °C	D 92	T 48	230 min	305
Density, 15°C, Kg/m³	D 70	T 228	- -	1.0321
Solubility in Trichloroethylene, wt.%	D 2042	T 44	98.5 min	99.15
Tests on R.T.F.O. Residue:	D 2872	T 240		
Dynamic Shear, 76°C, G/Sinδ, kPa*	D 7175	T 315	2.20 min	2.71
Dynamic Shear Phase Angle @ 2.2 kPa, °	D 7175	T 315	80 max	58.5
Mass Loss, %	D 2872	T 240	1.00 max	0.482
Elastic Recovery, 25°C, %	D 6084B	T 301	65 min	82
Tests on P.A.V. Residue @ 110°C:	D 6521	R 28		
Dynamic Shear, 31°C, G·Sinδ, kPa*	D 7175	T 315	5000 max	678
Creep Stiffness, -12°C, S, MPa	D 6648	T 313	300 max	113
m-Value, -12°C	D 6648	T 313	0.300 min	0.355

Paramount Petroleum Corporation hereby certifies that the asphalt product accompanying this certificate was produced in accordance with an accepted certification program for suppliers of asphalt, and the above test data is representative of the shipment.

Data Compiled By: ______
QC Lab

Released By: ______
Refinery Shift Supervisor

FILED 9/19/12
OM

Figure A.1: Performance-graded asphalt binder testing results of PG 76-22 PM (Paramount).

3.25
Qty=5
D.S. 09-07-12

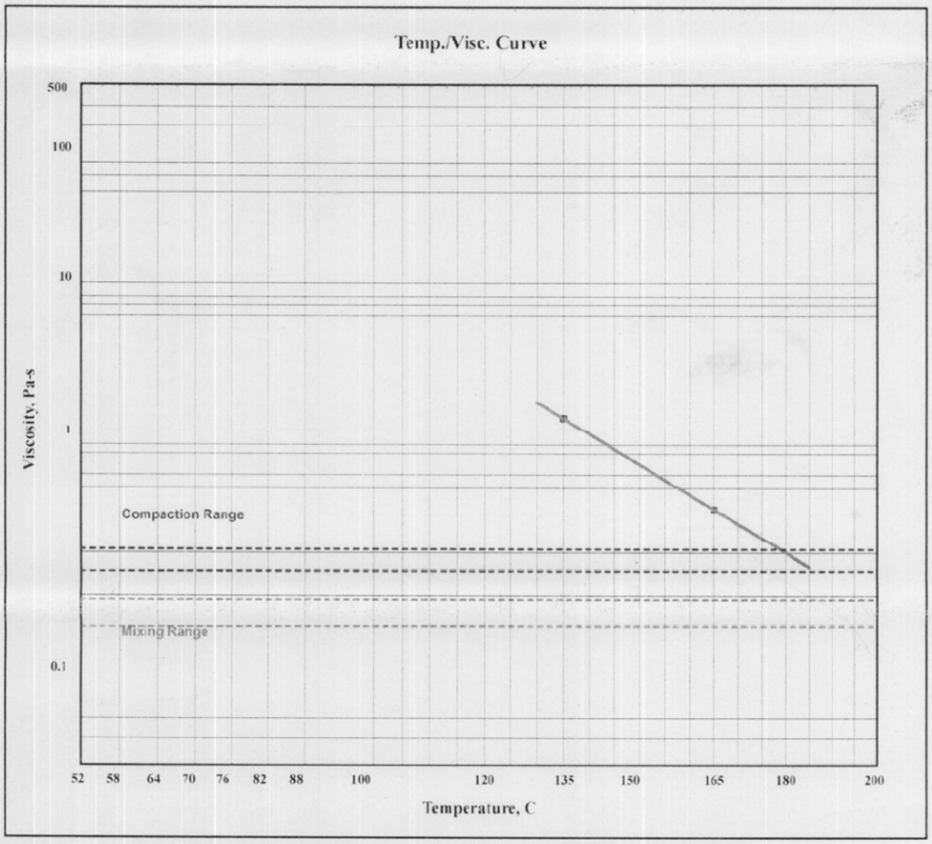
ASPHALT
a subsidiary of ALON USA

RCVD UCB PRC
9/12/12
D. MALONEY

PRODUCT INFORMATION	
PRODUCT SOURCE	PARAMOUNT-ELK GROVE
PRODUCT GRADE	PG76-22PM
CHART TITLE	Temp./Visc. Curve
DATE	September 7, 2012

CALCULATED CONSTRUCTION TEMPERATURES*	
Mixing Temperature Range, °C	197°C - 207°C
Compaction Temperature Range, °C	179°C - 187°C
Mixing Temperature Range, °F	387°F - 404°F
Compaction Temperature Range, °F	354°F - 368°F

Note: This data is for informational purposes. Actual mixing and compaction temperatures may require adjustments to meet field conditions. A compaction test strip is recommended.



Mixing temperature range is where the binder viscosity is 0.17 +/- 0.02 Pa-s.
Compaction temperature range is where the binder viscosity is 0.28 +/- 0.03 Pa-s.

Note: Mixing temperatures are relative to the binder properties for mix design purposes,these may not reflect the actual mixing and compaction experienced in the field and may need to be adjusted to within 25°F

Figure A.2: Suggested mixing and compacting temperatures for PG 76-22 PM (Paramount).

3,25
Qty=5

Rcvd UCB PRC
9/12/12 O. MALONEY

PARAMOUNT PETROLEUM

ALON USA

10090 Waterman Rd.
Elk Grove, CA 95624
Phone: (916) 685-9253

PRODUCT: PG 64-28TR ASPHALT CEMENT
CODE No: 13701
DATE:
TANK No.: 5003

D.S. 09-07-12

Purchaser: ______
Destination: ______
Transporter: ______
Truck No.: ______
Bill of Lading No.: ______
Contract No.: ______
Purchase Order No.: ______

Meets Specifications: Caltrans.

CERTIFICATE OF COMPLIANCE

TESTS	ASTM No.	AASHTO No.	SPECIFICATION	RESULT
Tests on Original Asphalt:				
Dynamic Shear, 64°C, G/Sinδ, kPa*	D 7175	T 315	1.00 min	1.92
Viscosity, 135°C, 21 Spindle, 20 RPM, Pa·s	D 4402	T 316	3 max	1.528
Viscosity, 165°C, 21 Spindle, 20 RPM, Pa·s	D 4402	T 316		0.510
Flash Point, C.O.C., °C	D 92	T 48	230 min	300
Density, 15°C, Kg/m³	D 70	T 228	- -	1.0315
Solubility in Trichloroethylene, wt.%	D 2042	T 44	97.5 min	98.43
Tire Rubber Content, wt.%			15 min	18.3
Tests on R.T.F.O. Residue:	D 2872	T 240		
Dynamic Shear, 64°C, G/Sinδ, kPa*	D 7175	T 315	2.20 min	3.24
Dynamic Shear Phase Angle @ 2.2 kPa, °	D 7175	T 315	80 max	73.7
Mass Loss, %	D 2872	T 240	1.00 max	0.482
Elastic Recovery, 25°C, %	D 6084B	T 301	75 min	82
Tests on P.A.V. Residue @ 100°C:	D 6521	R 28		
Dynamic Shear, 22°C, G·Sinδ, kPa*	D 7175	T 315	5000 max	3120
Creep Stiffness, -18°C, S, MPa	D 6648	T 313	300 max	275
m-Value, -18°C	D 6648	T 313	0.300 min	0.302

Paramount Petroleum Corporation hereby certifies that the asphalt product accompanying this certificate was produced in accordance with an accepted certification program for suppliers of asphalt, and the above test data is representative of the shipment.

Data Compiled By: ______
QC Lab

Released By: ______
Refinery Shift Supervisor

AAP
AASHTO R18

Filed 9/19/12
OM

Figure A.3: Performance-graded asphalt binder testing results of PG 64-28 TR (Paramount).

3.25
Qty=5
D.S. 09-07-12

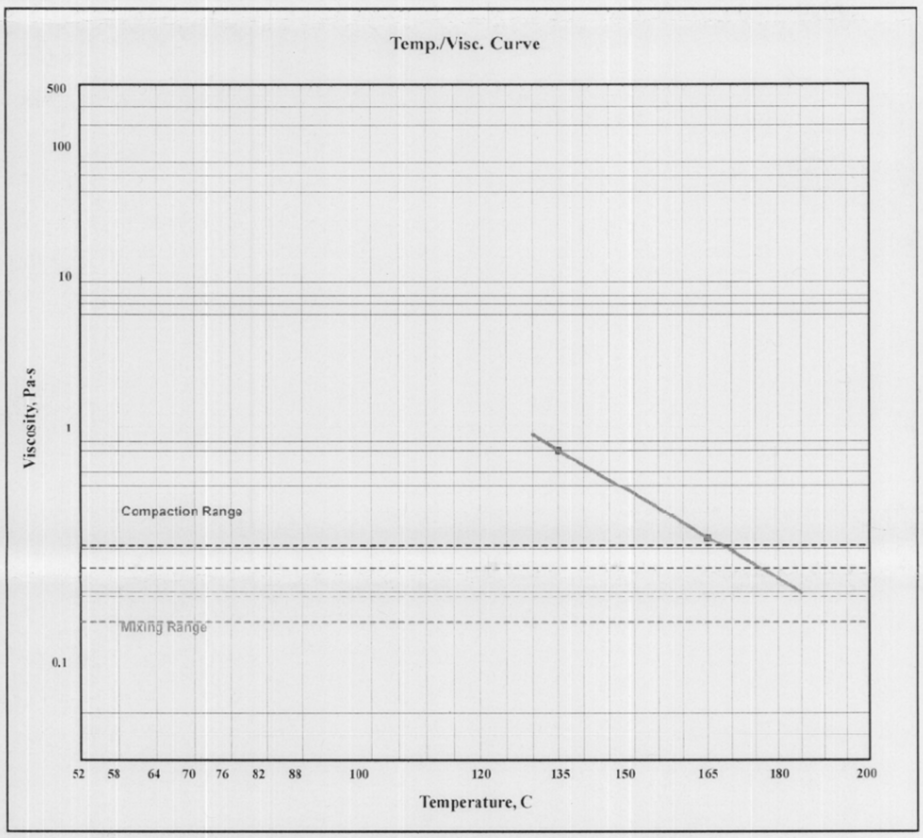
RCVD UCB PRC
9/12/12 O. MALONEY

ASPHALT
a subsidiary of ALON USA

PRODUCT INFORMATION	
PRODUCT SOURCE	PARAMOUNT-ELK GROVE
PRODUCT GRADE	PG64-28TR
CHART TITLE	Temp./Visc. Curve
DATE	September 7, 2012

CALCULATED CONSTRUCTION TEMPERATURES*	
Mixing Temperature Range, °C	187°C - 197°C
Compaction Temperature Range, °C	168°C - 176°C
Mixing Temperature Range, °F	368°F - 386°F
Compaction Temperature Range, °F	335°F - 349°F

Note: This data is for informational purposes. Actual mixing and compaction temperatures may require adjustments to meet field conditions. A compaction test strip is recommended.



Mixing temperature range is where the binder viscosity is 0.17 +/- 0.02 Pa-s.
Compaction temperature range is where the binder viscosity is 0.28 +/- 0.03 Pa-s.

Note: Mixing temperatures are relative to the binder properties for mix design purposes,these may not reflect the actual mixing and compaction experienced in the field and may need to be adjusted to within 25°F

Figure A.4: Suggested mixing and compacting temperatures for PG 64-28 TR (Paramount).

RCVD UCB RFS 10/13/10

SAN JOAQUIN REFINING CO., INC

CERTIFICATE OF ANALYSIS

LABORATORY REPORT- ASPHALT PRODUCTS

Performance Graded Asphalt Binder per CALTRANS Specification

PRODUCT: **PAVING ASPHALT PG64-10** PRODUCT NO: **2185**

PROPERTY	AASHTO Test Method	SPECIFICATION GRADE PG 64-10 SPEC	PG 64-10 TEST
ORIGINAL BINDER			
Flash Point, Minimum C	T-48	230	**293**
Solubility, Minimum %	T-44	99	**99.8**
Viscosity at 135 C,	T-316		
Maximum, Pa ' s		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	T-240		
Mass Loss, Maximum, %		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	T-51		
Minimum, cm		75	**150**
PAV Aging,	R-28		
Temperature, C		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		5000	**4846**
Creep Stiffness,	T-313		
Test Temperature, C		0	**0**
Maximum S-value, Mpa		300	**176**
Minimum M-value		0.300	**0.430**

Tank No.: **20004** Carrier:________ Quantity: (Gal)______(Tons)______

Batch No: 10641035 Specific Gravity @ 60 F: **1.0253**

Buyer:________ Loading Temp, F:________ Shipment Date:________

We hereby certify that the above determinations were performed in accordance with AASHTO, ASTM or other applicable test methods and that the product designated hereon conforms to the Caltrans specification for the product indicated: **PG 64-10**

Tester: [signature]

Date: **9/13/2010**

Figure A.5: Performance-graded asphalt binder testing results of PG 64-10 (San Joaquin).

RCVD UCB KAS 10/13/10

Binder	**SJR PG 64-10 Paving Asphalt**		
Temp (C)	Viscosity (cp)	Mixing Temperature Range, C	141 - 146
135	**257**	Compaction Temperature Range, C	132 - 136

Specific Gravity **1.0253**

DSR (*Do not enter if using two RV measurements*)
Temperature, C **64**
G*/sin δ (kPa) **1.293**

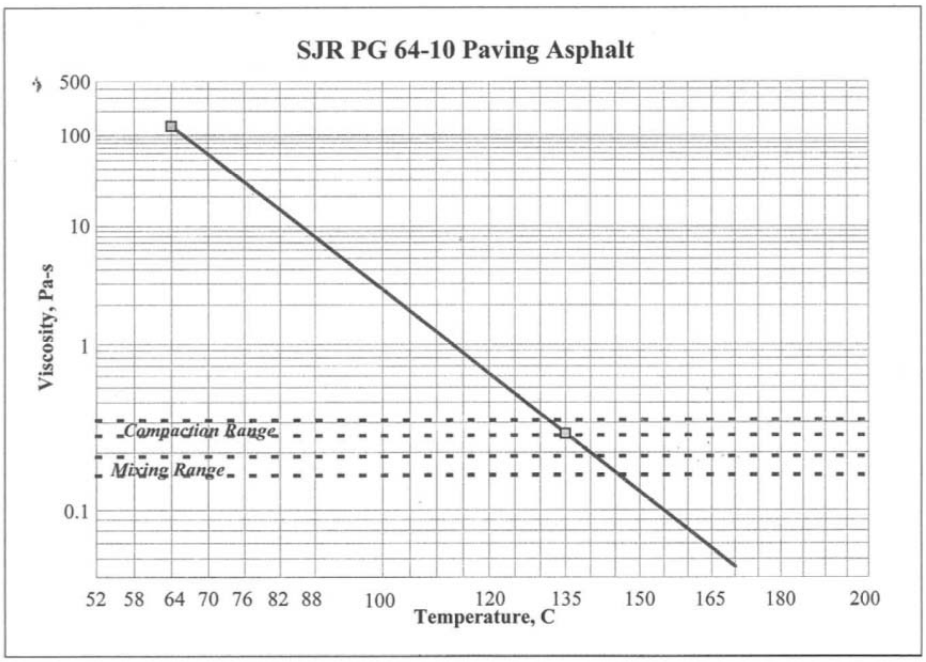


Figure A.6: Suggested mixing and compacting temperatures for PG 64-10 (San Joaquin).

APPENDIX B: *EXCEL* MACRO FOR OGFC MIX DESIGN

Table B.1: Operations of Phase I: OGFC Volumetric Mix Design

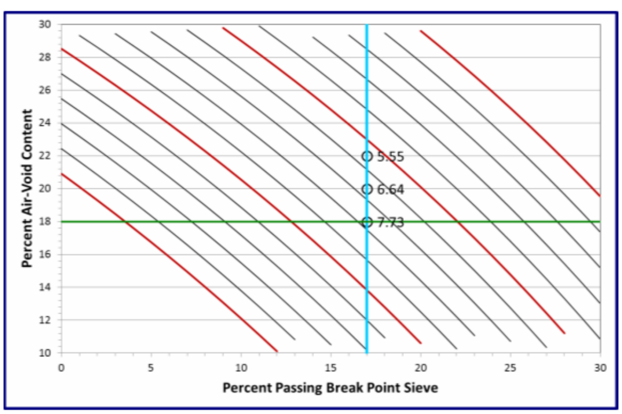
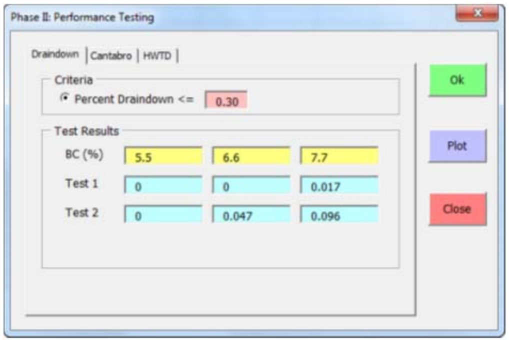
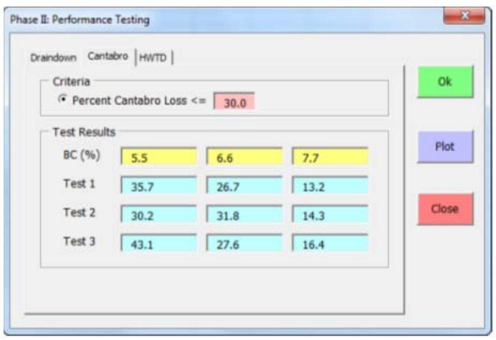
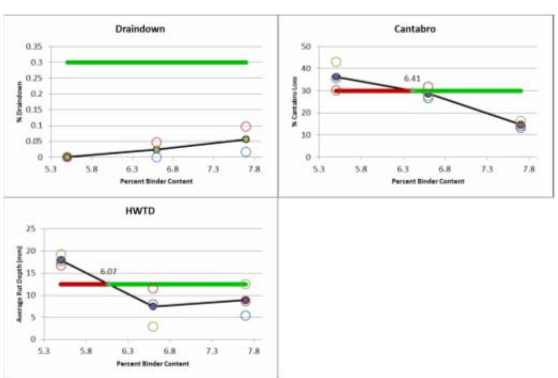
Phase I: OGFC Volumetric Mix Design	
	1. Input the design and material parameters. Design parameters include P_{cg} and P_{fg}; material parameters consist of VCA_{DRC}, P_{aasp}, G_{asp}, G_{cg}, and G_{fg}. 2. Input the ranges of the graph parameters for V_{air}, P_{asp}, and P_{fg}. 3. In order to obtain three trial binder contents, input three air-void content values that meet the specification. For the three given binder contents, the program will calculate three air-void contents based on the input design and material parameters. 4. Click the “Ok” button to generate/update the data on a new worksheet, “Sheet2.” 5. Click the “Close” button to close the input window.
	1. Complete/verify the input data, then click the “Plot” button to generate the OGFC mix design chart with the three trial binder contents.

Table B.2: Operations of Phase II: Performance Testing

Phase II: Performance Testing	
	1. Input the percent draindown criterion. (The default value is set at 0.3 percent.) 2. Enter the three trial binder contents and the resulting percent draindown values for each from their two draindown tests.
	1. Input the percent Cantabro loss criterion. (The default value is set at 30.0 percent.) 2. Enter the three trial binder contents and the percent Cantabro loss values resulting from their associated tests.
	1. Select the HWTD performance specification criterion. Select one of two criteria: (1) average rut depth at 20,000 passes or (2) number of passes to failure at 12.5 mm rut. (Note: the rut depth uses a positive value.) 2. Enter the three trial binder contents and their associated HWTD test results based on the selected criterion. 3. Click the "Ok" button to generate/update the data, which will appear on "Sheet3." 4. Click the "Close" button to close the input window.
	1. Complete/verify the input data, then click the "Plot" button to generate three charts titled, Draindown, Cantabro, and HWTD. The empty circles represent the test results, and the means connected with solid lines are used to determine whether the selected binder contents meet the criterion. 2. The green section of the specification line stands for the binder range that complies with the specification; the red section of the line represents the binder range that fails to meet the specification. The optimum binder range can be determined accordingly.

APPENDIX C: VOLUMETRIC AND CANTABRO RESULTS

Notes for the Appendix C tables:

1. Grad.: gradation
2. G_{ca}: the bulk specific gravity of the coarse aggregate
3. P_{ca}: the percent of coarse aggregate in the mixture
4. AC: the asphalt content
5. RICE: the theoretical maximum specific gravity of the mixture
6. V_a: the percent air-void content
7. VCA_{MIX}: the voids in the coarse aggregate of the compacted mix
8. SD: Standard Deviation
9. The specimen-naming scheme used in this study has been carried over from an earlier project.

Table C.1: Volumetric Properties and Cantabro Test Results of PMWC, PMWF, PMTC, and PMTF Mixes (Cantabro Specimens)

Aggregate Type	Grad.	G_{ca}	P_{ca} (%)	AC (%)	RICE	Specimen Name	Mass (g)	Avg. Height (mm)	Avg. Diameter (mm)	Volume (cm^3)	Bulk Specific Gravity	V_a (%)	VCA_{MIX} (%)	Percent Cantabro Loss	Mean (SD)
Watsonville	Coarse	2.7291	83	4.2	2.6171	3.25-PMWC-42-C1	1,049.2	63.67	101.50	515.18	2.0425	22.0	37.9	62.8	64.6 (3.9)
						3.25-PMWC-42-C2	1,049.1	63.71	101.64	516.91	2.0355	22.2	38.1	62.0	
						3.25-PMWC-42-C3	1,048.8	63.84	101.55	517.09	2.0342	22.3	38.1	69.1	
				5.2	2.5851	3.25-PMWC-52-C1	1,063.0	63.83	101.53	516.77	2.0630	20.2	37.3	60.5	62.3 (5.4)
						3.25-PMWC-52-C2	1,063.3	63.61	101.53	515.02	2.0707	19.9	37.0	58.0	
						3.25-PMWC-52-C3	1,076.1	63.66	101.54	515.41	2.0940	19.0	36.3	68.3	
				6.3	2.5504	3.25-PMWC-63-C1	1,076.2	63.55	101.51	514.31	2.0987	17.7	36.2	57.8	55.1 (3.6)
						3.25-PMWC-63-C2	1,075.8	63.53	101.51	514.13	2.0986	17.7	36.2	51.0	
						3.25-PMWC-63-C3	1,075.5	63.55	101.50	514.21	2.0977	17.8	36.2	56.3	
	Fine	2.7291	83	4.2	2.6193	3.25-PMWF-42-C1	1,051.0	63.51	101.49	513.80	2.0515	21.7	37.6	61.0	64.1 (8.2)
						3.25-PMWF-42-C2	1,050.2	63.56	101.54	514.75	2.0462	21.9	37.8	58.0	
						3.25-PMWF-42-C3	1,050.0	63.60	101.52	514.74	2.0459	21.9	37.8	73.3	
				5.2	2.5920	3.25-PMWF-52-C1	1,061.6	63.55	101.50	514.24	2.0705	20.1	37.0	34.3	42.0 (6.8)
						3.25-PMWF-52-C2	1,060.8	63.67	101.49	515.00	2.0658	20.3	37.2	44.3	
						3.25-PMWF-52-C3	1,062.5	63.56	101.48	514.11	2.0728	20.0	37.0	47.3	
				6.3	2.5492	3.25-PMWF-63-C1	1,075.9	63.55	101.49	514.08	2.0990	17.7	36.2	23.4	28.5 (5.2)
						3.25-PMWF-63-C2	1,075.9	63.49	101.50	513.67	2.1007	17.6	36.1	28.5	
						3.25-PMWF-63-C3	1,074.5	63.60	101.48	514.40	2.0950	17.8	36.3	33.7	
Sacramento	Coarse	2.7262	83	5.5	2.5549	3.25-PMTC-55-C1	1,025.2	63.81	101.54	516.67	1.9901	22.1	39.4	61.3	65.6 (4.8)
						3.25-PMTC-55-C2	1,024.3	63.69	101.50	515.27	1.9937	22.0	39.3	64.7	
						3.25-PMTC-55-C3	1,025.9	63.66	101.46	514.62	1.9994	21.7	39.1	70.8	
				6.6	2.5253	3.25-PMTC-66-C1	1,038.8	63.62	101.49	514.67	2.0243	19.8	38.4	51.0	55.3 (3.7)
						3.25-PMTC-66-C2	1,041.4	63.78	101.51	516.08	2.0238	19.9	38.4	56.9	
						3.25-PMTC-66-C3	1,035.8	63.63	101.43	514.10	2.0207	20.0	38.5	58.0	
				7.7	2.4964	3.25-PMTC-77-C1	1,055.1	63.66	101.48	514.92	2.0551	17.7	37.4	40.8	42.9 (5.6)
						3.25-PMTC-77-C2	1,057.6	63.63	101.52	515.01	2.0596	17.5	37.3	38.6	
						3.25-PMTC-77-C3	1,053.4	63.50	101.50	513.80	2.0562	17.6	37.4	49.2	
	Fine	2.7262	83	5.5	2.5596	3.25-PMTF-55-C1	1,026.4	63.32	101.21	509.37	2.0210	21.0	38.5	48.4	50.4 (8.8)
						3.25-PMTF-55-C2	1,026.4	63.48	101.42	512.76	2.0076	21.6	38.9	42.9	
						3.25-PMTF-55-C3	1,027.6	63.87	101.43	516.08	1.9970	22.0	39.2	60.0	
				6.6	2.5212	3.25-PMTF-66-C1	1,035.5	63.77	101.31	514.06	2.0203	19.9	38.5	22.6	37.2 (14.9)
						3.25-PMTF-66-C2	1,035.1	63.78	101.29	513.92	2.0200	19.9	38.5	36.6	
						3.25-PMTF-66-C3	1,037.8	63.57	101.10	510.31	2.0397	18.4	37.9	52.3	
				7.7	2.4984	3.25-PMTF-77-C1	1,061.4	63.69	101.24	512.73	2.0762	16.9	36.8	25.9	33.3 (10.7)
						3.25-PMTF-77-C2	1,056.0	63.26	101.34	510.30	2.0754	16.9	36.8	28.4	
						3.25-PMTF-77-C3	1,054.5	63.64	101.48	514.73	2.0547	17.8	37.4	45.5	

Table C.2: Volumetric Properties and Cantabro Test Results of TRWC, TRWF, TRTC, and TRTF Mixes (Cantabro Specimens)

Aggregate Type	Grad.	G_{ca}	P_{ca} (%)	AC (%)	RICE	Specimen Name	Mass (g)	Avg. Height (mm)	Avg. Diameter (mm)	Volume (cm^3)	Bulk Specific Gravity	V_a (%)	VCA_{MIX} (%)	Percent Cantabro Loss	Mean (SD)
Watsonville	Coarse	2.7291	83	4.2	2.6123	3.25-TRWC-42-C1	1,047.7	63.26	101.42	511.10	2.0559	21.3	37.5	54.7	62.0 (6.8)
						3.25-TRWC-42-C2	1,048.9	63.62	101.23	512.04	2.0545	21.4	37.5	63.2	
						3.25-TRWC-42-C3	1,047.0	63.74	101.41	514.88	2.0395	21.9	38.0	68.2	
				5.2	2.5744	3.25-TRWC-52-C1	1,058.3	63.99	101.36	516.34	2.0556	20.2	37.5	47.7	52.5 (5.0)
						3.25-TRWC-52-C2	1,059.4	63.62	101.46	514.28	2.0660	19.7	37.2	52.2	
						3.25-TRWC-52-C3	1,056.8	63.68	101.42	514.43	2.0604	20.0	37.3	57.7	
				6.3	2.5485	3.25-TRWC-63-C1	1,074.0	63.55	101.23	512.48	2.1018	17.5	36.1	44.5	40.0 (4.3)
						3.25-TRWC-63-C2	1,073.2	63.82	101.24	513.71	2.0953	17.8	36.3	36.1	
						3.25-TRWC-63-C3	1,073.8	63.70	101.50	515.37	2.0897	18.0	36.4	39.3	
	Fine	2.7291	83	4.2	2.6356	3.25-TRWF-42-C1	1,057.9	63.51	101.56	514.51	2.0622	21.8	37.3	43.8	46.8 (5.4)
						3.25-TRWF-42-C2	1,057.9	63.67	101.50	515.13	2.0597	21.9	37.4	43.5	
						3.25-TRWF-42-C3	1,058.0	63.51	101.47	513.49	2.0665	21.6	37.2	52.9	
				5.2	2.5971	3.25-TRWF-52-C1	1,068.1	63.50	101.52	513.95	2.0843	19.7	36.6	27.6	33.7 (5.3)
						3.25-TRWF-52-C2	1,068.1	63.64	101.50	514.88	2.0805	19.9	36.7	37.8	
						3.25-TRWF-52-C3	1,067.8	63.64	101.51	515.04	2.0793	19.9	36.8	35.6	
				6.3	2.5588	3.25-TRWF-63-C1	1,078.0	63.64	101.50	514.98	2.0994	18.0	36.1	19.1	18.0 (1.0)
						3.25-TRWF-63-C2	1,078.4	63.61	101.49	514.59	2.1018	17.9	36.1	17.0	
						3.25-TRWF-63-C3	1,079.1	63.51	101.50	513.85	2.1062	17.7	35.9	17.9	
Sacramento	Coarse	2.7262	83	5.5	2.5518	3.25-TRTC-55-C1	1,022.3	63.77	101.44	515.33	1.9896	22.0	39.4	35.7	36.3 (6.5)
						3.25-TRTC-55-C2	1,024.2	63.74	101.43	515.08	1.9943	21.8	39.3	30.2	
						3.25-TRTC-55-C3	1,021.6	64.17	101.39	518.09	1.9776	22.5	39.8	43.1	
				6.6	2.5394	3.25-TRTC-66-C1	1,042.2	64.03	101.52	518.28	2.0168	20.6	38.6	26.7	28.7 (2.7)
						3.25-TRTC-66-C2	1,043.5	63.87	101.28	514.51	2.0341	19.9	38.1	31.8	
						3.25-TRTC-66-C3	1,043.9	63.78	101.34	514.42	2.0353	19.9	38.0	27.6	
				7.7	2.5095	3.25-TRTC-77-C1	1,053.0	64.23	101.73	522.03	2.0231	19.4	38.4	13.2	14.6 (1.6)
						3.25-TRTC-77-C2	1,054.7	64.06	101.49	518.20	2.0413	18.7	37.9	14.3	
						3.25-TRTC-77-C3	1,063.6	63.78	101.45	515.53	2.0693	17.5	37.0	16.4	
	Fine	2.7262	83	5.5	2.5560	3.25-TRTF-55-C1	1,027.5	63.83	101.33	514.70	2.0022	21.7	39.0	34.7	31.2 (3.2)
						3.25-TRTF-55-C2	1,026.2	63.75	101.49	515.71	1.9957	21.9	39.2	30.6	
						3.25-TRTF-55-C3	1,027.8	63.72	101.27	513.22	2.0085	21.4	38.8	28.4	
				6.6	2.5238	3.25-TRTF-66-C1	1,038.4	64.01	101.49	517.70	2.0116	20.3	38.8	18.5	18.8 (0.9)
						3.25-TRTF-66-C2	1,039.8	63.90	101.54	517.50	2.0154	20.1	38.6	19.8	
						3.25-TRTF-66-C3	1,040.8	63.63	101.47	514.60	2.0285	18.8	38.2	18.1	
				7.7	2.4976	3.25-TRTF-77-C1	1,058.7	63.75	101.54	516.28	2.0567	17.7	37.4	12.6	13.3 (4.1)
						3.25-TRTF-77-C2	1,061.5	64.06	101.41	517.35	2.0578	17.6	37.3	9.5	
						3.25-TRTF-77-C3	1,051.5	63.65	101.49	514.89	2.0482	18.0	37.6	17.7	

Table C.3: Volumetric Properties and Cantabro Test Results of PGWC and PGWF Mixes (Cantabro Specimens)

Aggregate Type	Grad.	G_{ca}	P_{ca} (%)	AC (%)	RICE	Specimen Name	Mass (g)	Avg. Height (mm)	Avg. Diameter (mm)	Volume (cm^3)	Bulk Specific Gravity	V_a (%)	VCA_{MIX} (%)	Percent Cantabro Loss	Mean (SD)
Watsonville	Coarse	2.7291	83	4.3	2.6275	3.25-PGWC-43-C1	1,052.2	64.20	101.68	521.34	2.0242	23.0	38.4	70.7	74.9 (3.8)
						3.25-PGWC-43-C2	1,053.9	64.06	101.81	521.48	2.0269	22.9	38.4	77.9	
						3.25-PGWC-43-C3	1,053.7	63.95	101.78	520.24	2.0314	22.7	38.2	76.2	
				5.3	2.6081	3.25-PGWC-53-C1	1,069.7	64.21	101.62	520.77	2.0601	21.0	37.3	87.4	77.1 (9.9)
						3.25-PGWC-53-C2	1,069.0	64.28	101.56	520.75	2.0588	21.1	37.4	76.1	
						3.25-PGWC-53-C3	1,069.5	64.11	101.83	522.10	2.0545	21.2	37.5	67.7	
				6.4	2.5655	3.25-PGWC-64-C1	1,079.0	63.91	101.72	519.30	2.0839	18.8	36.6	60.7	61.7 (1.8)
						3.25-PGWC-64-C2	1,081.2	64.35	101.64	522.10	2.0770	19.0	36.8	63.8	
						3.25-PGWC-64-C3	1,082.1	63.77	101.71	518.05	2.0949	18.3	36.3	60.5	
	Fine	2.7291	83	4.3	2.6275	3.25-PGWF-43-C1	1,058.0	63.66	101.58	515.95	2.0566	21.7	37.5	62.2	61.4 (2.8)
						3.25-PGWF-43-C2	1,056.4	63.57	101.62	515.55	2.0551	21.8	37.5	58.2	
						3.25-PGWF-43-C3	1,057.8	63.93	101.51	517.41	5.0504	22.0	37.6	63.7	
				5.3	2.5989	3.25-PGWF-53-C1	1,073.1	63.46	101.47	513.19	2.0972	19.3	36.2	55.2	51.3 (3.4)
						3.25-PGWF-53-C2	1,073.1	63.97	101.24	514.93	2.0901	19.6	36.4	50.2	
						3.25-PGWF-53-C3	1,071.4	63.73	101.51	515.76	2.0834	19.8	36.6	48.6	
				6.4	2.5804	3.25-PGWF-64-C1	1,095.1	63.73	101.58	516.50	2.1265	17.6	35.3	33.7	39.4 (5.3)
						3.25-PGWF-64-C2	1,093.9	63.72	101.60	516.55	2.1239	17.7	35.4	40.4	
						3.25-PGWF-64-C3	1,092.7	63.61	101.56	515.25	2.1270	17.6	35.3	44.2	

Table C.4: Volumetric Properties of PMWC and PMWF Mixes (HWTD Specimens)

Aggregate Type	Grad.	G_{ca}	P_{ca} (%)	AC (%)	RICE	Specimen Name	Mass (g)	Avg. Height (mm)	Avg. Diameter (mm)	Volume (cm^3)	Bulk Specific Gravity	V_a (%)	VCA_{MIX} (%)
Watsonville	Coarse	2.7291	83	4.2	2.6171	3.25-PMWC-42-H1	2,286.8	63.52	149.84	1,119.98	2.0478	21.8	37.7
						3.25-PMWC-42-H2	2,287.2	63.82	149.95	1,127.01	2.0354	22.2	38.1
						3.25-PMWC-42-H7	2,290.6	63.50	149.78	1,118.80	2.0534	21.5	37.5
						3.25-PMWC-42-H8	2,287.2	63.45	149.60	1,115.25	2.0569	21.4	37.4
						3.25-PMWC-42-H9	2,288.0	63.45	149.51	1,113.85	2.0602	21.3	37.3
						3.25-PMWC-42-H10	2,285.4	63.27	149.92	1,116.76	2.0525	21.6	37.6
				5.2	2.5851	3.25-PMWC-52-H1	2,316.9	63.48	150.09	1,123.17	2.0689	20.0	37.1
						3.25-PMWC-52-H2	2,317.6	63.46	150.17	1,123.94	2.0681	20.0	37.1
						3.25-PMWC-52-H3	2,315.6	63.52	150.05	1,123.24	2.0676	20.0	37.1
						3.25-PMWC-52-H4	2,317.7	63.68	149.99	1,125.08	2.0661	20.1	37.2
						3.25-PMWC-52-H5	2,319.0	63.60	150.05	1,124.60	2.0681	20.0	37.1
						3.25-PMWC-52-H6	2,316.1	63.42	149.96	1,120.00	2.0740	19.8	36.9
				6.3	2.5504	3.25-PMWC-63-H1	2,340.2	63.60	150.08	1,125.07	2.0862	18.2	36.6
						3.25-PMWC-63-H2	2,341.1	63.63	150.18	1,127.14	2.0831	18.3	36.6
						3.25-PMWC-63-H3	2,344.0	63.60	150.00	1,123.83	2.0919	18.0	36.4
						3.25-PMWC-63-H4	2,348.4	63.62	150.03	1,124.63	2.0943	17.9	36.3
						3.25-PMWC-63-H5	2,341.2	63.57	150.02	1,123.67	2.0897	18.1	36.4
						3.25-PMWC-63-H6	2,346.9	63.50	149.88	1,120.31	2.1010	17.6	36.1
	Fine	2.7291	83	4.2	2.6193	3.25-PMWC-42-H1	2,290.4	63.38	150.00	1,120.02	2.0510	21.7	37.6
						3.25-PMWC-42-H2	2,289.1	63.41	149.83	1,118.00	2.0535	21.6	37.5
						3.25-PMWC-42-H3	2,291.5	63.46	149.91	1,120.09	2.0518	21.7	37.6
						3.25-PMWC-42-H4	2,290.9	63.45	149.93	1,120.20	2.0511	21.7	37.6
						3.25-PMWC-42-H5	2,292.0	63.31	149.91	1,117.39	2.0572	21.5	37.4
						3.25-PMWC-42-H6	2,292.6	63.47	149.94	1,120.55	2.0520	21.7	37.6
				5.2	2.5920	3.25-PMWC-52-H1	2,311.9	63.42	149.91	1,119.26	2.0716	20.1	37.0
						3.25-PMWC-52-H2	2,311.1	63.36	149.72	1,115.36	2.0782	19.8	36.8
						3.25-PMWC-52-H3	2,313.4	63.47	149.66	1,116.44	2.0782	19.8	36.8
						3.25-PMWC-52-H4	2,312.8	63.52	149.77	1,118.96	2.0730	20.0	37.0
						3.25-PMWC-52-H5	2,314.3	63.46	149.62	1,115.63	2.0805	19.7	36.7
						3.25-PMWC-52-H6	2,313.7	63.40	149.68	1,115.64	2.0800	19.8	36.7
				6.3	2.5492	3.25-PMWC-63-H1	2,339.5	63.40	149.81	1,117.46	2.0997	17.6	36.1
						3.25-PMWC-63-H2	2,341.1	63.36	149.81	1,116.67	2.1027	17.5	36.1
						3.25-PMWC-63-H3	2,341.7	63.46	149.89	1,119.62	2.0977	17.7	36.2
						3.25-PMWC-63-H4	2,339.1	63.32	149.76	1,115.30	2.1034	17.5	36.0
						3.25-PMWC-63-H5	2,339.6	63.43	149.85	1,118.62	2.0977	17.7	36.2
						3.25-PMWC-63-H6	2,344.9	63.61	149.74	1,120.19	2.0994	17.6	36.1

Table C.5: Volumetric Properties of PMTC and PMTF Mixes (HWTD Specimens)

Aggregate Type	Grad.	G_{ca}	P_{ca} (%)	AC (%)	RICE	Specimen Name	Mass (g)	Avg. Height (mm)	Avg. Diameter (mm)	Volume (cm^3)	Bulk Specific Gravity	V_a (%)	VCA_{MIX} (%)
Sacramento	Coarse	2.7291	83	5.5	2.5549	3.25-PMTC-55-H1	2,233.3	63.59	149.81	1,120.85	1.9984	21.8	39.2
						3.25-PMTC-55-H2	2,232.8	63.42	149.87	1,118.79	2.0016	21.7	39.1
						3.25-PMTC-55-H3	2,234.2	63.54	150.05	1,123.47	1.9945	21.9	39.3
						3.25-PMTC-55-H4	2,234.6	63.34	149.88	1,117.48	2.0056	21.5	38.9
						3.25-PMTC-55-H5	2,230.3	63.41	149.81	1,117.63	2.0014	21.7	39.1
						3.25-PMTC-55-H6	2,232.5	63.54	149.77	1,119.35	2.0003	21.7	39.1
				6.6	2.5253	3.25-PMTC-66-H1	2,261.2	63.56	149.72	1,118.97	2.0267	19.7	38.3
						3.25-PMTC-66-H2	2,258.9	63.53	149.65	1,117.48	2.0274	19.7	38.3
						3.25-PMTC-66-H3	2,264.4	63.41	149.85	1,118.22	2.0310	19.6	38.2
						3.25-PMTC-66-H4	2,265.1	63.47	149.83	1,118.99	2.0302	19.6	38.2
						3.25-PMTC-66-H5	2,263.9	63.35	150.07	1,120.53	2.0263	19.8	38.3
						3.25-PMTC-66-H6	2,265.3	63.45	149.82	1,118.53	2.0312	19.6	38.2
				7.7	2.4964	3.25-PMTC-77-H1	2,292.8	63.50	149.84	1,119.78	2.0536	17.7	37.5
						3.25-PMTC-77-H2	2,299.3	63.45	149.79	1,118.04	2.0626	17.4	37.2
						3.25-PMTC-77-H3	2,293.7	63.42	149.94	1,119.86	2.0542	17.7	37.5
						3.25-PMTC-77-H4	2,293.9	63.48	150.04	1,122.39	2.0498	17.9	37.6
						3.25-PMTC-77-H5	2,293.5	63.29	149.62	1,112.73	2.0672	17.2	37.1
						3.25-PMTC-77-H6	2,295.0	63.51	149.76	1,118.60	2.0577	17.6	37.4
	Fine	2.7262	83	5.5	2.5596	3.25-PMTF-55-H1	2,238.4	63.73	150.14	1,128.22	1.9898	22.3	39.4
						3.25-PMTF-55-H2	2,238.3	63.76	150.19	1,128.59	1.9873	22.4	39.5
						3.25-PMTF-55-H3	2,240.4	63.42	150.05	1,121.46	2.0036	21.7	39.0
						3.25-PMTF-55-H4	2,238.4	63.71	150.10	1,127.19	1.9917	22.2	39.4
						3.25-PMTF-55-H5	2,240.0	63.50	150.12	1,123.97	1.9988	21.9	39.1
						3.25-PMTF-55-H6	2,239.8	63.46	150.14	1,123.49	1.9995	21.9	39.1
				6.6	2.5212	3.25-PMTF-66-H1	2,256.0	63.64	150.20	1,127.62	2.0066	20.4	38.9
						3.25-PMTF-66-H2	2,260.2	63.48	150.14	1,123.72	2.0173	20.0	38.6
						3.25-PMTF-66-H3	2,260.9	63.60	150.17	1,126.29	2.0133	20.1	38.7
						3.25-PMTF-66-H4	2,258.8	63.69	150.16	1,127.82	2.0087	20.3	38.8
						3.25-PMTF-66-H5	2,260.5	63.56	150.15	1,125.36	2.0146	20.1	38.7
						3.25-PMTF-66-H6	2,259.6	63.58	150.07	1,124.51	2.0153	20.1	38.6
				7.7	2.4984	3.25-PMTF-77-H1	2,289.4	63.57	150.18	1,125.95	2.0393	18.4	37.9
						3.25-PMTF-77-H2	2,296.0	63.63	150.18	1,127.14	2.0430	18.2	37.8
						3.25-PMTF-77-H3	2,295.6	63.73	150.14	1,128.31	2.0405	18.3	37.9
						3.25-PMTF-77-H4	2,294.5	63.65	150.14	1,126.89	2.0421	18.3	37.8
						3.25-PMTF-77-H5	2,302.1	63.62	150.18	1,126.92	2.0488	18.0	37.6
						3.25-PMTF-77-H6	2,306.6	63.92	150.23	1,132.95	2.0419	18.3	37.8

Table C.6: Volumetric Properties of TRWC and TRWF Mixes (HWTD Specimens)

Aggregate Type	Grad.	G_{ca}	P_{ca} (%)	AC (%)	RICE	Specimen Name	Mass (g)	Avg. Height (mm)	Avg. Diameter (mm)	Volume (cm^3)	Bulk Specific Gravity	V_a (%)	VCA_{MIX} (%)
Watsonville	Coarse	2.7291	83	4.2	2.6123	3.25-TRWC-42-H1	2,284.5	63.73	149.93	1,125.07	2.0365	22.0	38.1
						3.25-TRWC-42-H2	2,284.3	63.56	149.91	1,121.84	2.0422	21.8	37.9
						3.25-TRWC-42-H3	2,284.7	63.72	150.04	1,126.63	2.0339	22.1	38.1
						3.25-TRWC-42-H4	2,284.6	63.46	149.82	1,118.79	2.0480	21.6	37.7
						3.25-TRWC-42-H5	2,285.1	63.65	149.92	1,123.60	2.0397	21.9	38.0
						3.25-TRWC-42-H6	2,284.6	63.75	150.04	1,127.08	2.0330	22.2	38.2
				5.2	2.5744	3.25-TRWC-52-H1	2,307.5	63.61	150.01	1,124.15	2.0587	20.0	37.4
						3.25-TRWC-52-H2	2,308.5	64.06	149.97	1,131.46	2.0463	20.5	37.8
						3.25-TRWC-52-H3	2,306.0	63.71	150.04	1,126.29	2.0535	20.2	37.5
						3.25-TRWC-52-H4	2,307.8	63.72	149.95	1,125.11	2.0572	20.1	37.4
						3.25-TRWC-52-H5	2,311.6	63.71	150.02	1,126.12	2.0587	20.0	37.4
						3.25-TRWC-52-H6	2,306.1	63.56	150.05	1,123.95	2.0578	20.1	37.4
				6.3	2.5485	3.25-TRWC-63-H1	2,341.1	64.02	149.93	1,130.26	2.0774	18.5	36.8
						3.25-TRWC-63-H2	2,339.5	63.56	149.98	1,122.78	2.0898	18.0	36.4
						3.25-TRWC-63-H3	2,340.0	63.52	150.05	1,123.16	2.0895	18.0	36.5
						3.25-TRWC-63-H4	2,341.3	63.58	149.94	1,122.62	2.0917	17.9	36.4
						3.25-TRWC-63-H5	2,340.8	63.46	149.85	1,119.23	2.0976	17.7	36.2
						3.25-TRWC-63-H6	2,338.7	63.69	149.97	1,125.09	2.0848	18.2	36.6
	Fine	2.7291	83	4.2	2.6356	3.25-TRWF-42-H1	2,302.2	63.51	149.91	1,120.89	2.0599	21.8	37.3
						3.25-TRWF-42-H2	2,304.8	63.60	150.00	1,123.87	2.0568	22.0	37.4
						3.25-TRWF-42-H3	2,303.5	63.53	149.94	1,121.81	2.0594	21.9	37.4
						3.25-TRWF-42-H4	2,302.8	63.48	149.95	1,121.12	2.0601	21.8	37.3
						3.25-TRWF-42-H5	2,300.5	63.38	149.93	1,119.05	2.0618	21.8	37.3
						3.25-TRWF-42-H6	2,305.0	63.21	149.98	1,116.72	2.0702	21.5	37.0
				5.2	2.5971	3.25-TRWF-52-H1	2,328.9	63.38	150.06	1,120.92	2.0838	19.8	36.6
						3.25-TRWF-52-H2	2,328.0	63.38	149.96	1,119.41	2.0858	19.7	36.6
						3.25-TRWF-52-H3	2,329.6	63.37	150.02	1,120.09	2.0859	19.7	36.6
						3.25-TRWF-52-H4	2,330.5	63.40	149.99	1,120.14	2.0867	19.7	36.5
						3.25-TRWF-52-H5	2,329.9	63.47	150.08	1,122.81	2.0812	19.9	36.7
						3.25-TRWF-52-H6	2,330.0	63.47	150.10	1,123.05	2.0808	19.9	36.7
				6.3	2.5588	3.25-TRWF-63-H1	2,350.2	63.54	149.95	1,122.09	2.1006	17.9	36.1
						3.25-TRWF-63-H2	2,349.1	63.37	150.05	1,120.54	2.1026	17.8	36.1
						3.25-TRWF-63-H3	2,351.5	63.44	149.98	1,120.79	2.1042	17.8	36.0
						3.25-TRWF-63-H4	2,352.0	63.43	149.93	1,119.90	2.1064	17.7	35.9
						3.25-TRWF-63-H5	2,351.2	63.57	149.92	1,122.06	2.1016	17.9	36.1
						3.25-TRWF-63-H6	2,330.5	63.50	149.88	1,120.42	2.0861	18.5	36.6

Table C.7: Volumetric Properties of TRTC and TRTF Mixes (HWTD Specimens)

Aggregate Type	Grad.	G_{ca}	P_{ca} (%)	AC (%)	RICE	Specimen Name	Mass (g)	Avg. Height (mm)	Avg. Diameter (mm)	Volume (cm^3)	Bulk Specific Gravity	V_a (%)	VCA_{MIX} (%)
Sacramento	Coarse	2.7262	83	5.5	2.5518	3.25-TRTC-55-H1	2,231.3	63.62	149.87	1,122.30	1.9940	21.9	39.3
						3.25-TRTC-55-H2	2,232.9	63.50	149.94	1,121.20	1.9974	21.7	39.2
						3.25-TRTC-55-H3	2,230.5	63.44	150.04	1,121.68	1.9944	21.8	39.3
						3.25-TRTC-55-H4	2,265.9	63.52	149.98	1,122.27	2.0250	20.6	38.3
						3.25-TRTC-55-H5	2,231.8	63.50	149.88	1,120.42	1.9978	21.7	39.2
						3.25-TRTC-55-H6	2,229.1	63.40	149.90	1,118.83	1.9982	21.7	39.2
				6.6	2.5394	3.25-TRTC-66-H1	2,277.4	63.90	150.03	1,129.54	2.0221	20.4	38.4
						3.25-TRTC-66-H2	2,269.5	63.73	150.13	1,128.07	2.0178	20.5	38.6
						3.25-TRTC-66-H3	2,279.7	63.68	150.27	1,129.33	2.0246	20.3	38.4
						3.25-TRTC-66-H4	2,271.0	63.78	150.09	1,128.48	2.0184	20.5	38.6
						3.25-TRTC-66-H5	2,271.7	63.60	150.12	1,125.66	2.0240	20.3	38.4
						3.25-TRTC-66-H6	2,277.9	63.74	149.88	1,124.57	2.0315	20.0	38.1
				7.7	2.5095	3.25-TRTC-77-H1	2,297.6	63.86	149.99	1,128.27	2.0424	18.6	37.8
						3.25-TRTC-77-H2	2,297.5	63.68	150.34	1,130.37	2.0385	18.8	37.9
						3.25-TRTC-77-H3	2,291.8	63.42	150.08	1,121.88	2.0488	18.4	37.6
						3.25-TRTC-77-H4	2,302.5	64.00	150.24	1,134.47	2.0355	18.9	38.0
						3.25-TRTC-77-H5	2,301.4	63.68	150.03	1,125.78	2.0503	18.3	37.6
						3.25-TRTC-77-H6	2,305.4	63.59	150.15	1,125.98	2.0535	18.2	37.5
	Fine	2.7262	83	5.5	2.5560	3.25-TRTF-55-H1	2,239.6	63.93	149.97	1,129.33	1.9890	22.2	39.4
						3.25-TRTF-55-H2	2,239.8	63.66	150.19	1,127.81	1.9918	22.1	39.4
						3.25-TRTF-55-H3	2,236.8	63.37	150.13	1,121.66	2.0001	21.8	39.1
						3.25-TRTF-55-H4	2,236.1	63.87	150.06	1,129.45	1.9856	22.3	39.5
						3.25-TRTF-55-H5	2,238.1	63.68	150.88	1,138.57	1.9715	22.9	40.0
						3.25-TRTF-55-H6	2,237.3	63.47	150.07	1,122.69	1.9987	21.8	39.2
				6.6	2.5238	3.25-TRTF-66-H1	2,261.8	63.84	150.06	1,128.88	2.0095	20.4	38.8
						3.25-TRTF-66-H2	2,259.1	63.64	150.26	1,128.44	2.0079	20.4	38.9
						3.25-TRTF-66-H3	2,256.4	63.36	150.13	1,121.69	2.0175	20.1	38.6
						3.25-TRTF-66-H4	2,28.04	63.73	150.11	1,127.94	2.0277	19.7	38.3
						3.25-TRTF-66-H5	2,264.5	63.79	150.09	1,128.56	2.0124	20.3	38.7
						3.25-TRTF-66-H6	2,265.8	63.68	149.96	1,124.60	2.0207	19.9	38.5
				7.7	2.4976	3.25-TRTF-77-H1	2,296.4	63.71	150.19	1,128.66	2.0406	18.3	37.9
						3.25-TRTF-77-H2	2,294.0	63.68	150.23	1,128.77	2.0383	18.4	37.9
						3.25-TRTF-77-H3	2,298.1	63.64	150.27	1,128.58	2.0423	18.2	37.8
						3.25-TRTF-77-H4	2,295.5	63.63	150.10	1,125.85	2.0449	18.1	37.7
						3.25-TRTF-77-H5	2,294.1	63.43	150.41	1,127.04	2.0415	18.3	37.8
						3.25-TRTF-77-H6	2,299.2	63.49	150.31	1,126.60	2.0468	18.0	37.7

Table C.8: Volumetric Properties of PGWC and PGWF Mixes (HWTD Specimens)

Aggregate Type	Grad.	G_{ca}	P_{ca} (%)	AC (%)	RICE	Specimen Name	Mass (g)	Avg. Height (mm)	Avg. Diameter (mm)	Volume (cm^3)	Bulk Specific Gravity	V_a (%)	VCA_{MIX} (%)
Watsonville	Coarse	2.7291	83	4.3	2.6275	3.25-PGWC-43-H1	2,292.9	63.38	149.96	1,119.41	2.0543	21.8	37.5
						3.25-PGWC-43-H2	2,297.4	63.59	150.10	1,125.15	2.0479	22.1	37.7
						3.25-PGWC-43-H3	2,298.1	63.86	150.18	1,131.09	2.0377	22.4	38.0
						3.25-PGWC-43-H4	2,296.1	63.78	150.17	1,129.69	2.0356	22.5	38.1
						3.25-PGWC-43-H5	2,292.9	63.45	150.26	1,125.09	2.0577	21.7	37.4
						3.25-PGWC-43-H6	2,308.3	63.73	150.05	1,127.03	2.0732	21.1	36.9
				5.3	2.6081	3.25-PGWC-53-H1	2,329.7	63.61	150.14	1,126.13	2.0921	19.8	36.4
						3.25-PGWC-53-H2	2,349.1	63.79	150.13	1,129.26	2.0710	20.6	37.0
						3.25-PGWC-53-H3	2,331.8	63.81	150.21	1,130.69	2.0706	20.6	37.0
						3.25-PGWC-53-H4	2,334.3	63.61	150.18	1,126.82	2.0803	20.2	36.7
						3.25-PGWC-53-H5	2,337.3	63.66	150.06	1,125.83	2.0824	20.2	36.7
						3.25-PGWC-53-H6	2,337.5	63.83	149.95	1,127.21	2.0955	19.7	36.3
				6.4	2.5655	3.25-PGWC-64-H1	2,355.1	63.81	150.18	1,130.28	2.0898	18.5	36.4
						3.25-PGWC-64-H2	2,354.4	63.85	150.49	1,135.75	2.0791	19.0	36.8
						3.25-PGWC-64-H3	2,360.3	64.08	150.32	1,137.14	2.0817	18.9	36.7
						3.25-PGWC-64-H4	2,351.0	63.81	150.21	1,130.66	2.0854	18.7	36.6
						3.25-PGWC-64-H5	2,370.3	63.66	150.07	1,125.98	2.1113	17.7	35.8
						3.25-PGWC-64-H6	2,351.6	64.10	150.21	1,135.91	2.0763	19.1	36.9
	Fine	2.7291	83	4.3	2.6275	3.25-PGWF-43-H1	2,301.1	63.73	150.29	1,130.54	2.0414	22.3	37.9
						3.25-PGWF-43-H2	2,301.5	63.72	150.16	1,128.47	2.0455	22.2	37.8
						3.25-PGWF-43-H3	2,300.6	63.78	150.15	1,129.21	2.0433	22.2	37.9
						3.25-PGWF-43-H4	2,299.9	63.65	150.08	1,125.99	2.0486	22.0	37.7
						3.25-PGWF-43-H5	2,301.0	63.83	150.15	1,130.23	2.0418	22.3	37.9
						3.25-PGWF-43-H6	2,301.6	63.85	150.06	1,129.27	2.0441	22.2	37.8
				5.3	2.5989	3.25-PGWF-53-H1	2,332.9	63.86	150.09	1,129.80	2.0709	20.3	37.0
						3.25-PGWF-53-H2	2,332.8	63.94	150.19	1,132.70	2.0656	20.5	37.2
						3.25-PGWF-53-H3	2,331.7	63.82	150.06	1,128.57	2.0721	20.3	37.0
						3.25-PGWF-53-H4	2,331.3	63.86	150.19	1,131.33	2.0667	20.5	37.1
						3.25-PGWF-53-H5	2,331.7	63.80	150.20	1,130.40	2.0688	20.4	37.1
						3.25-PGWF-53-H6	2,333.9	63.69	150.12	1,127.13	2.0767	20.1	36.8
				6.4	2.5804	3.25-PGWF-64-H1	2,378.6	63.71	150.18	1,128.47	2.1140	18.1	35.7
						3.25-PGWF-64-H2	2,375.5	63.65	150.11	1,126.45	2.1150	18.0	35.7
						3.25-PGWF-64-H3	2,378.9	63.61	150.16	1,126.56	2.1179	17.9	35.6
						3.25-PGWF-64-H4	2,383.6	63.61	150.18	1,126.73	2.1217	17.8	35.5
						3.25-PGWF-64-H5	2,382.5	63.50	150.13	1,124.05	2.1258	17.6	35.3
						3.25-PGWF-64-H6	2,389.3	63.64	150.15	1,126.90	2.1265	17.6	35.3

APPENDIX D: HWTD TEST RESULTS

Table D.1: Summary of HWTD Test Results for PMWC, PMWF, PMTC, and PMTF Mixes

Aggregate Type	Grad.	AC (%)	Specimen Name	AV (%)	Average Rut @ 20,000 Passes		Number of Passes to Failure @ 12.5 mm	
					Average Rut (mm)	Mean (SD)	Number of Passes (N_f)	Mean (SD)
Watsonville	Coarse	4.2	PMWC-42-H9 & H8	21.3	4.55	3.21 (1.28)	69,200	69,536 (8,372)
			PMWC-42-H10 & H7	21.6	3.09		78,070	
			PMWC-42-H2 & H1	22.0	1.99		61,336	
		5.2	PMWC-52-H2 & H4	20.0	7.21	5.18 (1.76)	39,275	51,211 (11,658)
			PMWC-52-H6 & H1	19.9	4.04		62,570	
			PMWC-52-H5 & H3	20.0	4.29		51,789	
		6.3	PMWC-63-H2 & H1	18.3	5.31	3.55 (1.74)	49,220	75,546 (27,041)
			PMWC-63-H3 & H5	18.0	3.52		74,167	
			PMWC-63-H4 & H6	17.8	1.83		103,250	
	Fine	4.2	PMWF-42-H4 & H5	21.6	4.22	5.03 (0.92)	51,243	50,251 (1,715)
			PMWF-42-H3 & H1	21.7	4.82		51,239	
			PMWF-42-H2 & H6	21.6	6.04		48,271	
		5.2	PMWF-52-H5 & H6	19.7	4.30	4.21 (0.96)	62,985	80,129 (18,611)
			PMWF-52-H2 & H4	19.9	5.13		77,478	
			PMWF-52-H3 & H1	19.9	3.20		99,923	
		6.3	PMWF-63-H5 & H1	17.7	4.91	4.29 (0.54)	67,364	80,446 (20,272)
			PMWF-63-H2 & H6	17.6	3.90		103,798	
			PMWF-63-H3 & H4	17.6	4.06		70,176	
Sacramento	Coarse	5.5	PMTC-55-H5 & H4	21.6	3.03	2.67 (0.45)	106,664	106,638 (10,655)
			PMTC-55-H2 & H3	21.8	2.81		117,279	
			PMTC-55-H6 & H1	21.7	2.17		95,970	
		6.6	PMTC-66-H5 & H3	19.7	4.30	3.20 (1.76)	77,246	96,595 (30,545)
			PMTC-66-H4 & H1	19.7	4.14		80,732	
			PMTC-66-H2 & H6	19.6	1.17		131,809	
		7.7	PMTC-77-H6 & H5	17.4	2.76	2.42 (0.81)	115,138	117,012 (19,143)
			PMTC-77-H3 & H2	17.5	3.00		98,876	
			PMTC-77-H4 & H1	17.8	1.49		137,023	
	Fine	5.5	PMTF-55-H5 & H6	21.9	2.58	3.21 (0.57)	213,372	138,036 (65,813)
			PMTF-55-H1 & H2	22.3	3.70		91,716	
			PMTF-55-H3 & H4	22.0	3.36		109,021	
		6.6	PMTF-66-H1 & H6	20.2	4.02	3.69 (0.29)	98,830	87,934 (15,006)
			PMTF-66-H5 & H2	20.0	3.46		94,155	
			PMTF-66-H4 & H3	20.2	3.58		70,818	
		7.7	PMTF-77-H4 & H6	18.3	4.23	3.61 (0.88)	87,450	89,139 (4,182)
			PMTF-77-H1 & H2	18.3	3.99		86,066	
			PMTF-77-H3 & H5	18.2	2.61		93,902	

Note: The highlighted cells have been extrapolated using three-stage Weibull HWTD curves.

Table D.2: Summary of HWTD Test Results for TRWC, TRWF, TRTC, and TRTF Mixes

Aggregate Type	Grad.	AC (%)	Specimen Name	AV (%)	Average Rut @ 20,000 Passes		Number of Passes to Failure @ 12.5 mm	
					Average Rut (mm)	Mean (SD)	Number of Passes (N_f)	Mean (SD)
Watsonville	Coarse	4.2	TRWC-42-H2 & H3	22.0	10.76	11.34 (2.41)	21,679	22,294 (3,194)
			TRWC-42-H6 & H4	21.9	9.27		25,751	
			TRWC-42-H1 & H5	22.0	13.99		19,452	
		5.2	TRWC-52-H6 & H2	20.3	8.67	14.76 (5.42)	28,493	21,753 (5,842)
			TRWC-52-H3 & H4	20.2	16.60		18,628	
			TRWC-52-H1 & H5	20.0	19.02		18,137	
		6.3	TRWC-63-H3 & H5	17.9	6.96	6.50 (1.18)	32,915	37,003 (4,948)
			TRWC-63-H4 & H1	18.2	7.38		35,590	
			TRWC-63-H2 & H6	18.1	5.15		42,503	
	Fine	4.2	TRWF-42-H5 & H1	21.8	8.98	9.12 (0.12)	30,422	28,310 (2,370)
			TRWF-42-H3 & H2	21.9	9.20		28,761	
			TRWF-42-H6 & H4	21.6	9.17		25,747	
		5.2	TRWF-52-H1 & H2	19.7	11.97	17.67 (13.37)	21,058	20,802 (6,237)
			TRWF-52-H4 & H5	19.8	32.94		14,441	
			TRWF-52-H6 & H3	19.8	8.10		26,907	
		6.3	TRWF-63-H3 & H2	17.8	9.31	10.32 (4.86)	25,104	27,580 (11,369)
			TRWF-63-H5 & H4	17.8	15.60		17.653	
			TRWF-63-H1 & H6	18.2	6.03		39,983	
Sacramento	Coarse	5.5	TRTC-55-H1 & H4	21.3	17.75	17.93 (1.20)	15,593	16,487 (1,342)
			TRTC-55-H2 & H6	21.7	16.83		18,031	
			TRTC-55-H3 & H5	21.8	19.21		15,838	
		6.6	TRTC-66-H3 & H6	20.1	7.99	7.50 (4.35)	33,100	34,049 (12,612)
			TRTC-66-H1 & H4	20.4	11.58		21,938	
			TRTC-66-H2 & H5	20.4	2.92		47,109	
		7.7	TRTC-77-H6 & H5	18.2	5.45	8.89 (3.56)	42,081	29,489 (11,266)
			TRTC-77-H4 & H3	18.6	8.66		26,025	
			TRTC-77-H2 & H1	18.7	12.56		20,362	
	Fine	5.5	TRTF-55-H4 & H5	22.6	7.44	6.34 (1.24)	40,304	40,470 (1,405)
			TRTF-55-H1 & H6	22.0	6.59		39,156	
			TRTF-55-H3 & H2	21.9	5.00		41,951	
		6.6	TRTF-66-H3 & H5	20.2	12.17	11.60 (1.30)	20,506	21,709 (2,599)
			TRTF-66-H2 & H4	20.0	12.52		19,929	
			TRTF-66-H1 & H6	20.2	10.11		24,692	
		7.7	TRTF-77-H5 & H4	18.2	10.51	12.47 (3.24)	25,218	21,952 (5,036)
			TRTF-77-H1 & H2	18.3	16.21		16,153	
			TRTF-77-H6 & H3	18.1	10.68		24,487	

Note: The highlighted cells have been extrapolated using three-stage Weibull HWTD curves.

Table D.3: Summary of HWTD Test Results for TRWC, TRWF, TRTC, and TRTF Mixes

Aggregate Type	Grad.	AC (%)	Specimen Name	AV (%)	Average Rut @ 20,000 Passes: Average Rut (mm)	Average Rut @ 20,000 Passes: Mean (SD)	Number of Passes to Failure @ 12.5 mm: Number of Passes (N_f)	Number of Passes to Failure @ 12.5 mm: Mean (SD)
Watsonville	Coarse	4.3	PGWC-43-H6 & H5	21.4	63.43	63.49 (0.10)	9,033	7,736 (1,368)
			PGWC-43-H1 & H4	22.2	63.44		6,306	
			PGWC-43-H3 & H2	22.3	63.61		7,870	
		5.3	PGWC-53-H5 & H4	20.2	25.74	39.72 (20.58)	15,474	12,489 (3,669)
			PGWC-53-H3 & H2	20.6	63.35		8,393	
			PGWC-53-H1 & H6	19.7	30.08		13,600	
		6.4	PGWC-64-H4 & H2	18.8	54.03	46.91 (12.92)	11,117	13,138 (1,868)
			PGWC-64-H3 & H5	18.3	54.70		13,497	
			PGWC-64-H6 & H1	18.8	32.00		14,801	
	Fine	4.3	PGWF-43-H3 & H2	22.2	55.31	60.22 (4.28)	9,146	9,325 (173)
			PGWF-43-H5 & H6	22.2	63.14		9,338	
			PGWF-43-H4 & H1	22.0	62.21		9,491	
		5.3	PGWF-53-H4 & H3	20.4	43.07	49.73 (7.74)	12,601	12,300 (1,132)
			PGWF-53-H6 & H2	20.3	47.89		13,252	
			PGWF-53-H5 & H1	20.4	58.22		11,048	
		6.4	PGWF-64-H1 & H5	17.8	62.05	62.80 (0.65)	8,807	10,294 (1,622)
			PGWF-64-H6 & H4	17.7	63.26		10,053	
			PGWF-64-H3 & H2	18.0	63.09		12,023	

Note: The highlighted cells have been extrapolated using three-stage Weibull HWTD curves.

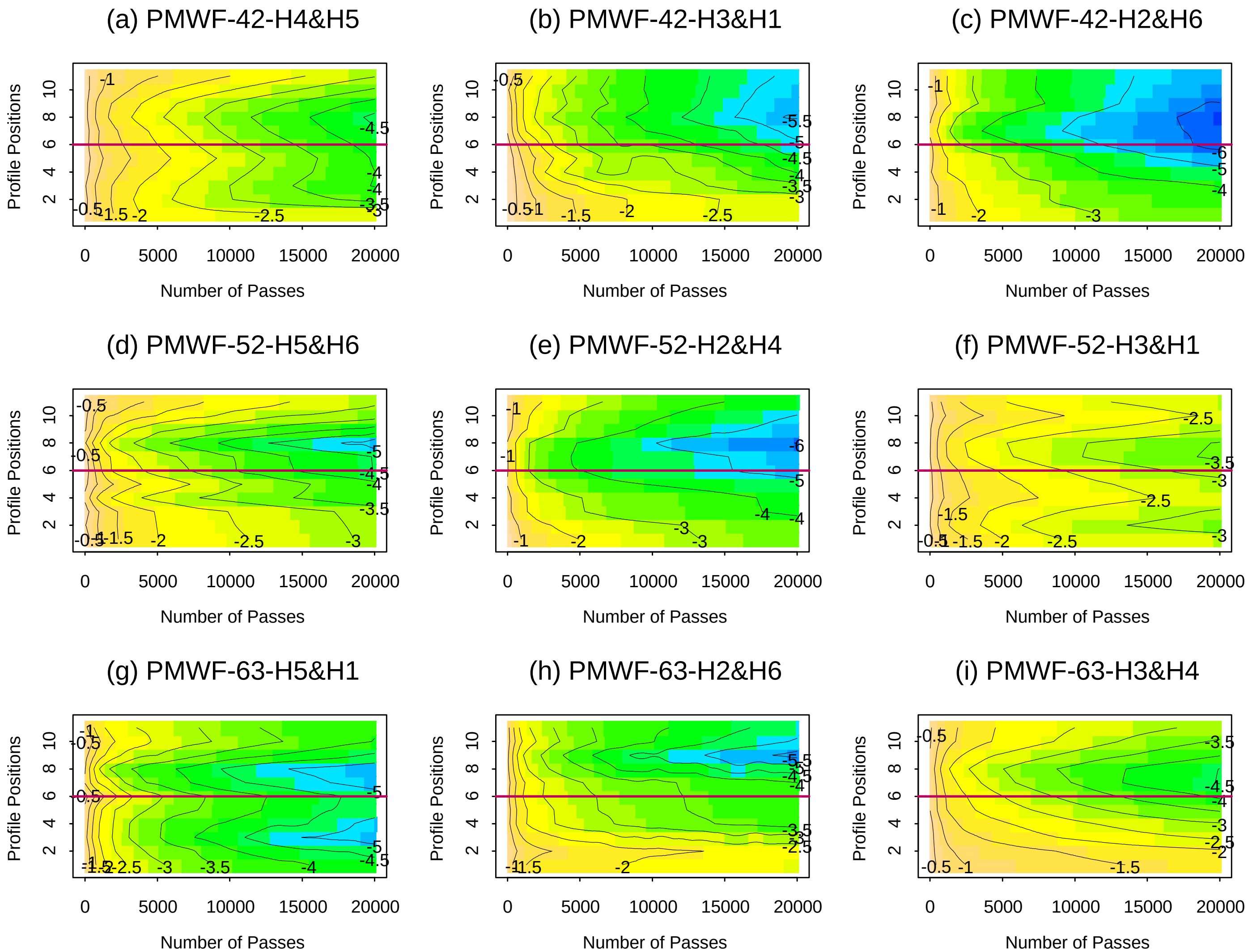


Figure D.1: Rutting evolution image-and-contour plots for PMWF mixes (PG 76-22 PM, Watsonville aggregate, and Fine gradation) at three binder contents: 4.2 percent [(a), (b), and (c)], 5.2 percent [(d), (e), and (f)], and 6.3 percent [(g), (h), and (i)].
(Note: Color scale is set between -8 and 0 mm of the average rut depth.)

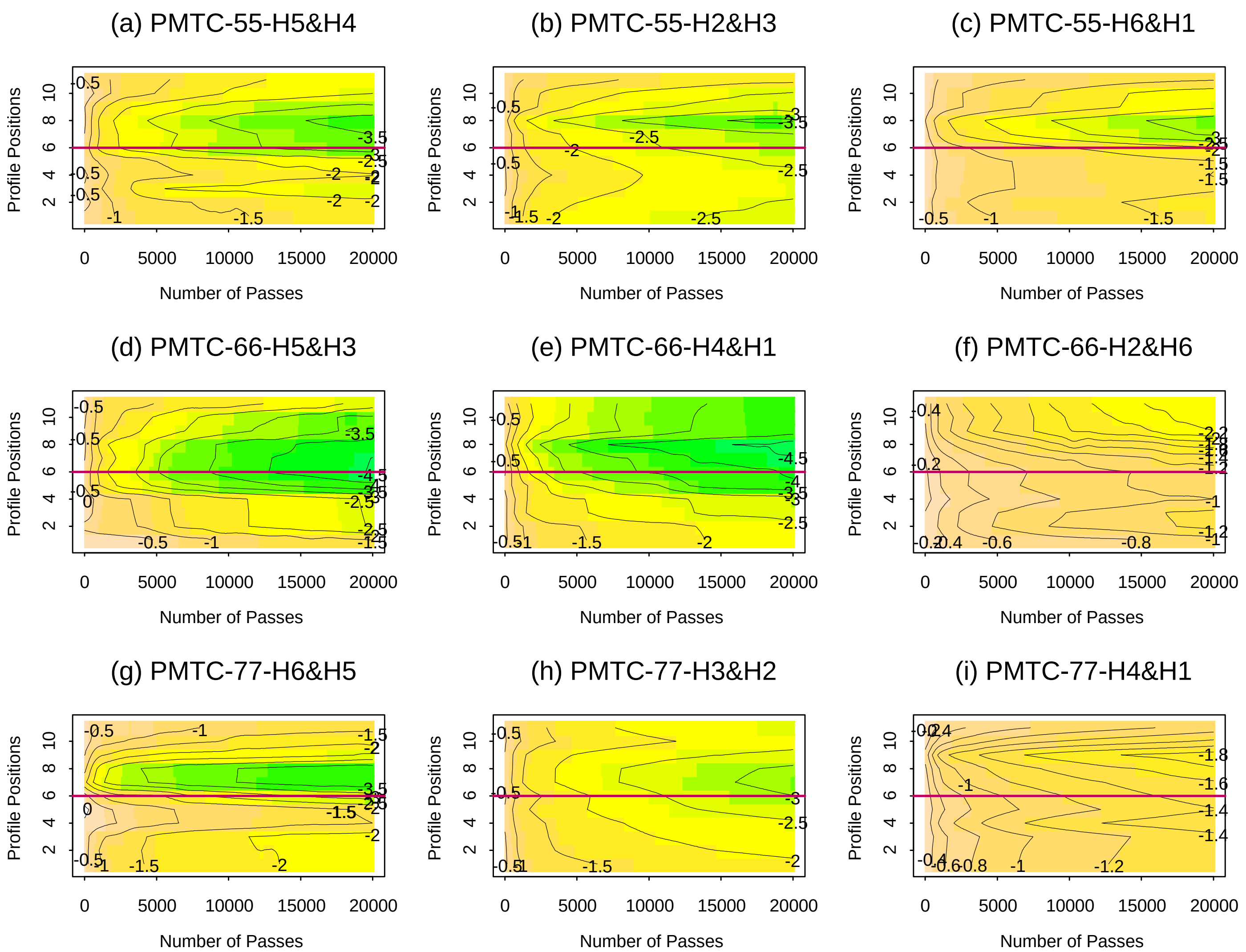


Figure D.2: Rutting evolution image-and-contour plots for PMTC mixes (PG 76-22 PM, Sacramento aggregate, and Coarse gradation) at three binder contents: 5.5 percent [(a), (b), and (c)], 6.6 percent [(d), (e), and (f)], and 7.7 percent [(g), (h), and (i)]. (Note: Color scale is set between -8 and 0 mm of the average rut depth.)

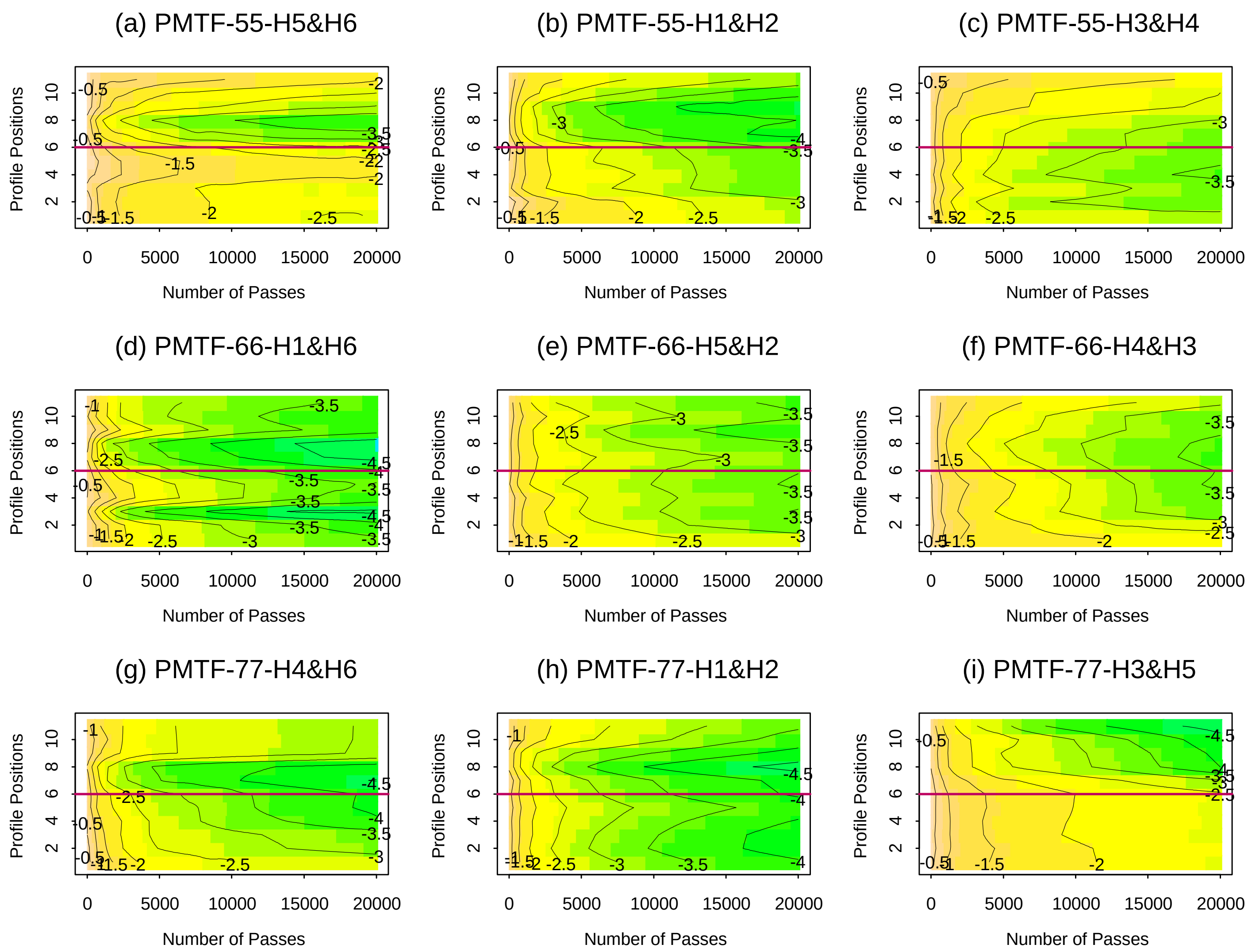


Figure D.3: Rutting evolution image-and-contour plots for PMTF mixes (PG 76-22 PM, Sacramento aggregate, and Fine gradation) at three binder contents: 5.5 percent [(a), (b), and (c)], 6.6 percent [(d), (e), and (f)], and 7.7 percent [(g), (h), and (i)].
(Note: Color scale is set between -8 and 0 mm of the average rut depth.)

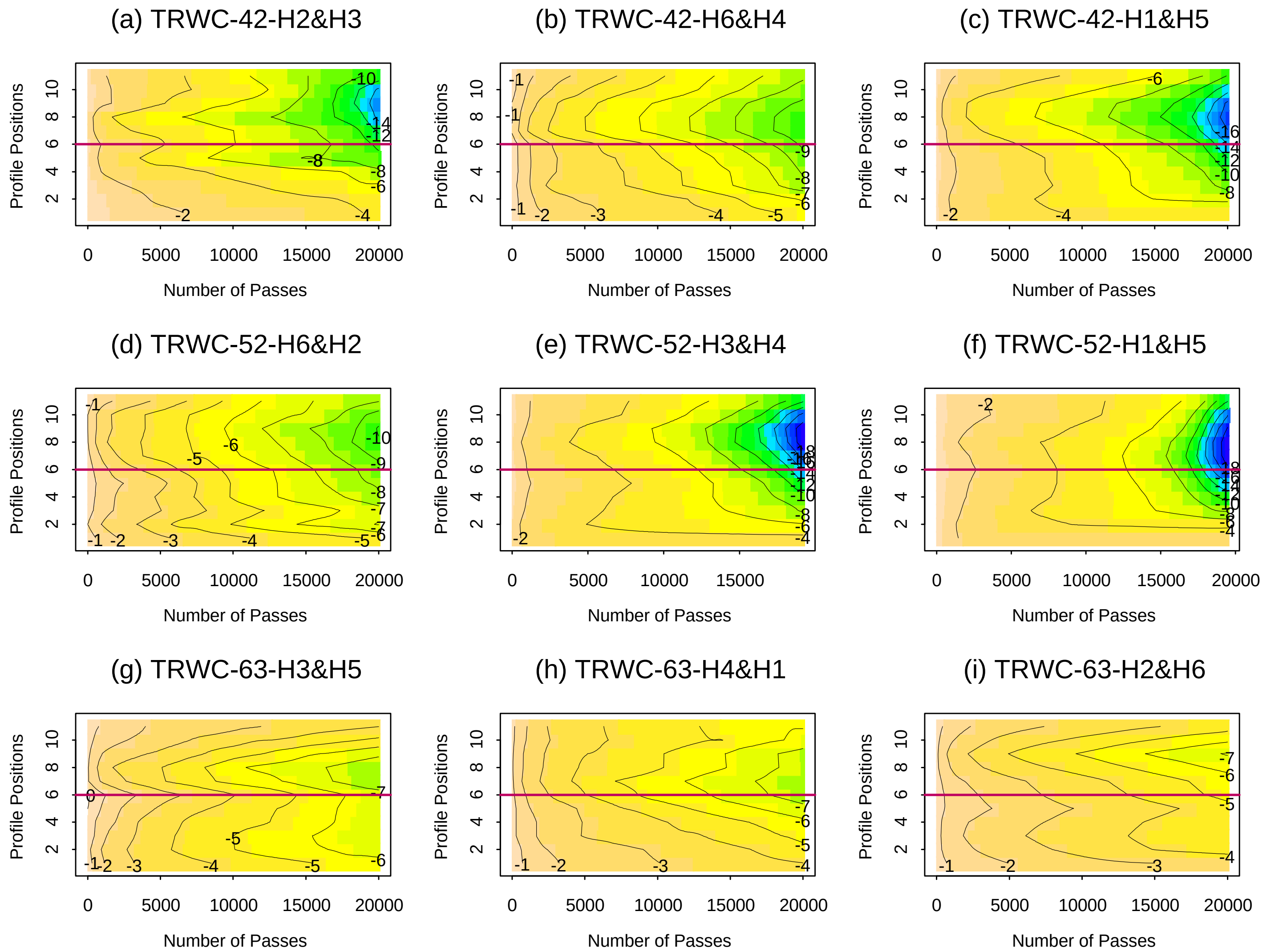


Figure D.4: Rutting evolution image-and-contour plots for TRWC mixes (PG 64-28 TR, Watsonville aggregate, and coarse gradation) at three binder contents: 4.2 percent [(a), (b), and (c)], 5.2 percent [(d), (e), and (f)], and 6.3 percent [(g), (h), and (i)]. (Note: Color scale is set between -21 and 0 mm of the average rut depth.)

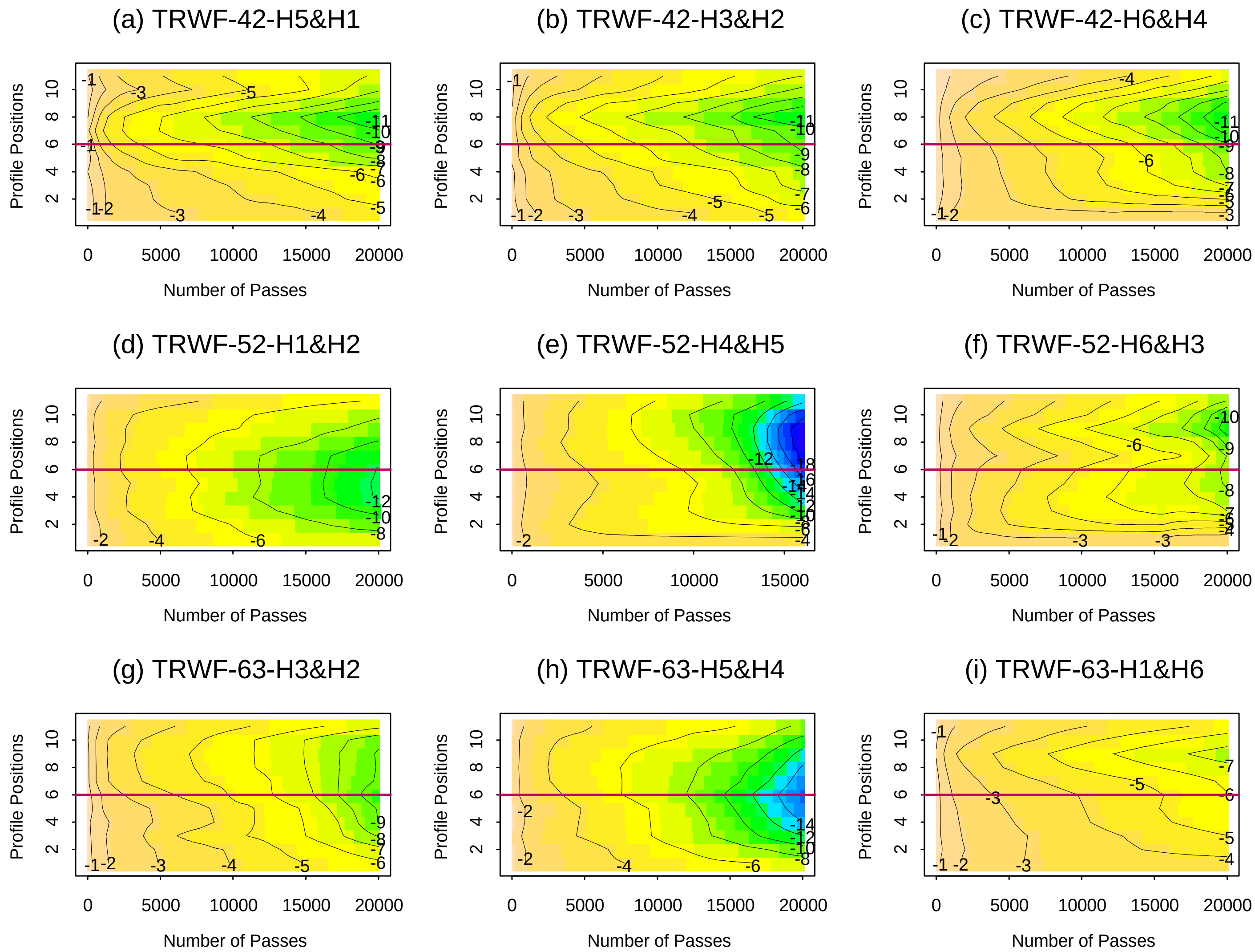


Figure D.5: Rutting evolution image-and-contour plots for TRWF mixes (PG 64-28 TR, Watsonville aggregate, and fine gradation) at three binder contents: 4.2 percent [(a), (b), and (c)], 5.2 percent [(d), (e), and (f)], and 6.3 percent [(g), (h), and (i)].
(Note: Color scale is set between -21 and 0 mm of the average rut depth.)

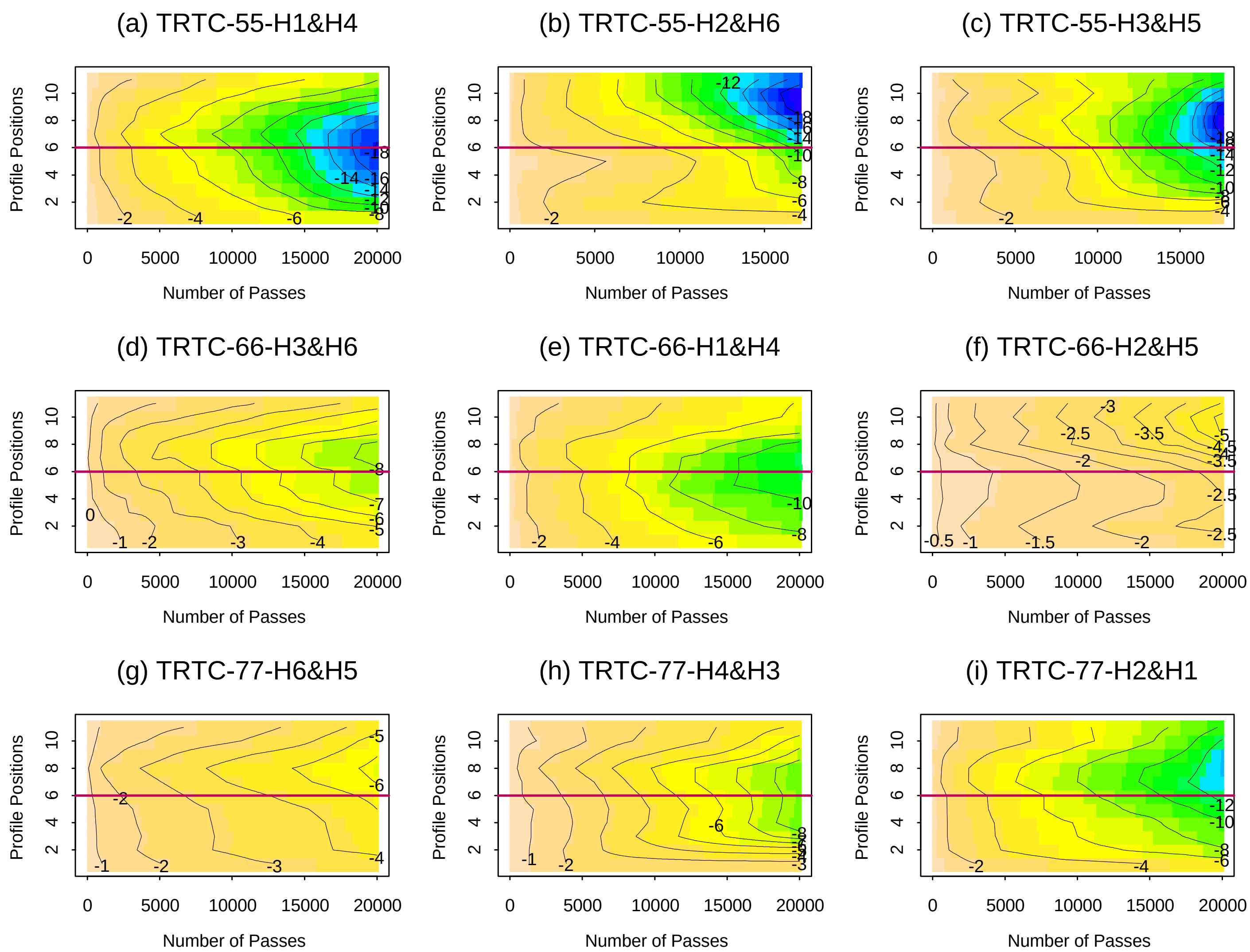


Figure D.6: Rutting evolution image-and-contour plots for TRTC mixes (PG 64-28 TR, Sacramento aggregate, and Coarse gradation) at three binder contents: 5.5 percent [(a), (b), and (c)], 6.6 percent [(d), (e), and (f)], and 7.7 percent [(g), (h), and (i)].
(Note: Color scale is set between -21 and 0 mm of average rut depth.)

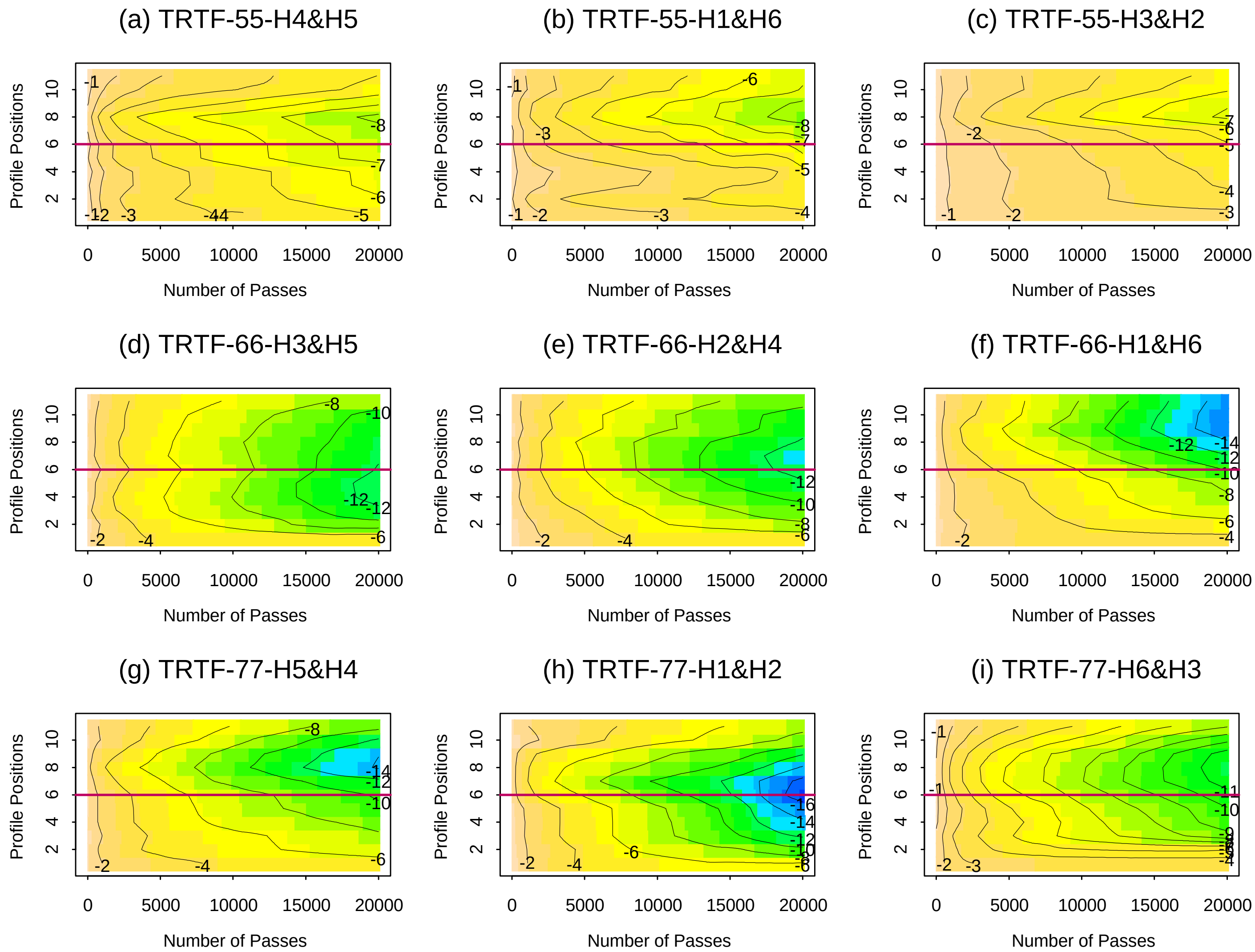


Figure D.7: Rutting evolution image-and-contour plots for TRTF mixes (PG 64-28 TR, Sacramento aggregate, and Fine gradation) at three binder contents: 5.5 percent [(a), (b), and (c)], 6.6 percent [(d), (e), and (f)], and 7.7 percent [(g), (h), and (i)]. (Note: Color scale is set between -21 and 0 mm of the average rut depth.)

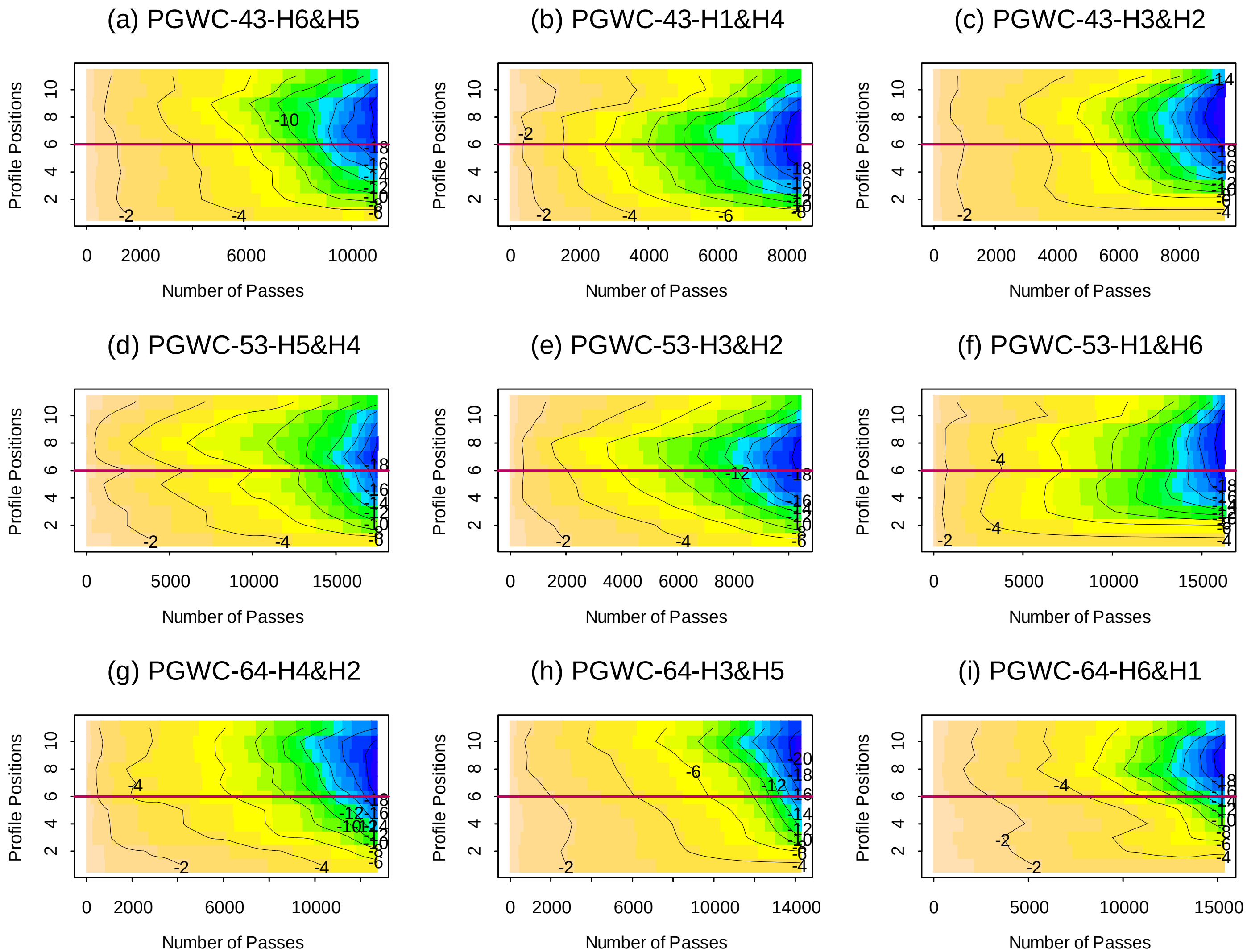


Figure D.8: Rutting evolution image-and-contour plots for PGWC mixes (PG 64-10, Watsonville aggregate, and Coarse gradation) at three binder contents: 4.3 percent [(a), (b), and (c)], 5.3 percent [(d), (e), and (f)], and 6.4 percent [(g), (h), and (i)].
(Note: Color scale is set between -21 and 0 mm of the average rut depth.)

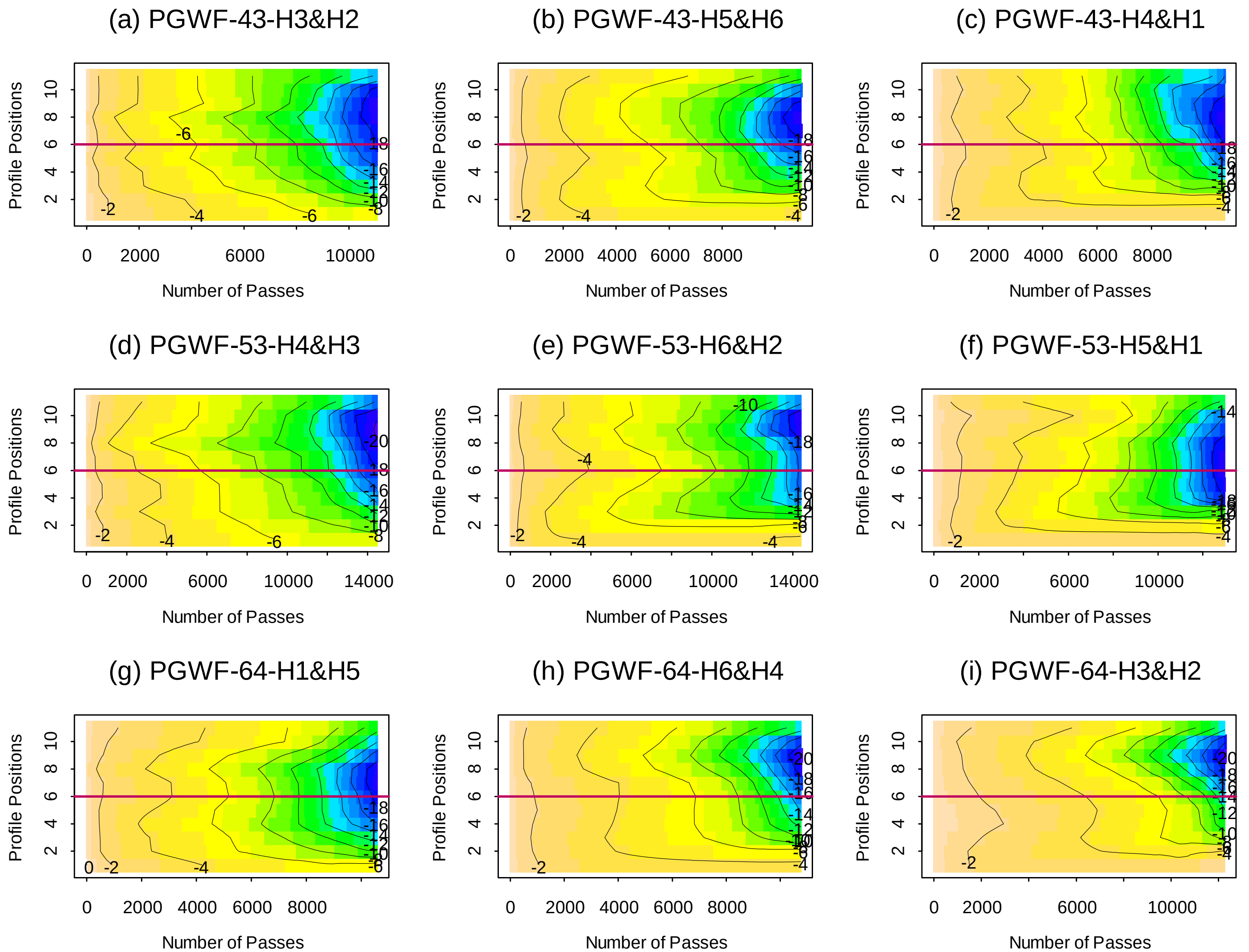


Figure D.9: Rutting evolution image-and-contour plots for PGWF mixes (PG 64-10, Watsonville aggregate, and Fine gradation) at three binder contents: 4.3 percent [(a), (b), and (c)], 5.3 percent [(d), (e), and (f)], and 6.4 percent [(g), (h), and (i)].
(Note: Color scale is set between -21 and 0 mm of the average rut depth.)