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Superpave Implementation Phase I: Determining Optimum Binder Content

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Abstract:
This research study was conducted as part of Partnered Pavement Research Center (PPRC) Strategic Plan Element 3.18.3. This technical memorandum summarizes the first phase of a research study on the implementation of Superpave mix design for Caltrans. Fifteen Hveem mix designs selected from around the state that are often used in their region were used as the basis of this study. The 15 selected mix designs vary in binder PG-grade, binder type (unmodified, rubber, and polymer), aggregate gradation and mineralogy, and RAP percentage. Based on the Hveem mix designs, Superpave volumetric mix designs were developed for each mix and comparisons were made between mixes developed from both methods. Specifically, these mixes were evaluated to meet the draft Caltrans Superpave volumetric mix design specification which includes the design air-void content, percent VMA, percent VFA and dust proportion as major design components. Details regarding adjustments to and strategies in determining the Superpave optimal binder content for each mix are discussed. A summary of changes and adjustments to Hveem mixes needed to meet Superpave specifications is presented. Recommendations for specimen preparation using Superpave mix design procedures are given.

Keywords: Superpave, optimum binder content (OBC), volumetrics, gyratory, compaction, binder content, RAP, Hveem

Proposals for implementation:

Related documents:

Signatures

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PROJECT OBJECTIVES

The goal of this project is to support development and implementation of a new mix design procedure for hot/warm mix asphalt for California using AASHTO "Superpave" mix design principles. This will be achieved through completion of the following objectives:

1. A literature review on recent national Superpave mix design and mix design test equipment–related research, including rutting and cracking performance, and moisture sensitivity.
2. Creation of a laboratory testing matrix considering key variables identified in the literature review.
3. Collection of aggregates, binders, and current Hveem or rubberized mix designs for them.
4. Development of Superpave volumetric mix designs and comparison with current mix designs.
5. Preparation and laboratory testing of RSCH and RLT specimens and analysis of the results:
    a. To compare expected rutting resistance of Superpave and Hveem mix designs;
    b. To compare results of RSCH and RLT testing.
6. Recommendations for changes in preliminary new mix design procedure.
7. Evaluation of comparison of RSCH and RLT results and required changes in *CalME* to use RLT testing to produce design inputs.
8. Preparation and laboratory testing for different performance-related tests for rutting, cracking, and moisture sensitivity for possible use in a new mix design method.
9. Recommendations for performance-related tests for use in a new mix design procedure.
10. Preparation of reports documenting the study and study results.

This technical memorandum documents the results of Objectives 1, 2, 3, and 4, and recommendations for volumetric mix design as part of Objective 6.

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AASHTO T 27 (dry sieve)	Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates
AASHTO T 166	Standard Method of Test for Bulk Specific Gravity (G_{mb}) of Compacted Hot Mix Asphalt (HMA) Using Saturated Surface-Dry Specimens
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AASHTO T 324 (Modified)	Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)
CT 371	Method of Test for Resistance of Compacted Bituminous Mixture to Moisture Induced Damage

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AMPT	Asphalt Mixture Performance Tester
CT	Caltrans Test Method
DME	District Materials Engineer
DP	Dust Proportion
DWA	Dry Weight of Aggregate
FHWA	Federal Highway Administration
%Gmm	Percent Mixture Density
HMA	Hot-mix Asphalt
HV	Hveem Design Method
HWTT	Hamburg Wheel-Track Test
JMF	Job Mix Formula
OBC	Optimal Binder Content
PPRC SPE	Partnered Pavement Research Center Strategic Plan Element
RAP	Recycled Asphalt Pavement
RHMA	Rubberized Hot-Mix Asphalt
RLT	Repeated Load Triaxial
RSCH	Repeated Shear Constant Height
SHRP	Strategic Highway Research Program
SP	Superpave Design Method
SPOBC	Superpave Optimal Binder Content
STOA	Short-term Oven Aging
Superpave	SUperior PERforming asphalt PAVEment
TSR	Tensile Strength Ratio
TWM	Total Weight of Mixture
VFA	Voids Filled with Asphalt
VMA	Voids in Mineral Aggregate
UCPRC	University of California Pavement Research Center

1 INTRODUCTION

1.1 Background

Since the Hveem mix design procedure was developed in the 1950s, the California Department of Transportation (Caltrans) has used it, and its associated aggregate gradations, to determine optimum binder content (OBC) for conventional dense-graded asphalt mixes. Over the years, refinements and adjustments have been made to the basic Hveem procedure for determining OBC, which is based on the stability determined with a Hveem stabilometer and measurement of laboratory compacted air-void content. Other changes to the basic Hveem method extended its capabilities to polymer-modified mixes, and a modified version was developed so it could be used for gap-graded rubberized mixes. A retained tensile strength test CT 371 (which is similar to AASHTO T 283) is currently used to assess moisture sensitivity, another specified part of mix design. However, few other U.S. states currently use the Hveem procedure and as a consequence the equipment used in the tests has become increasingly difficult to acquire and maintain—specifically the kneading compactor and the Hveem stabilometer.

The Superpave (SUperior PERforming Asphalt PAVEments) mix design procedure was developed as part of the first Strategic Highway Research Program (SHRP) in the early 1990s to "give highway engineers and contractors the tools they need to design asphalt pavements that will perform better under extremes of temperature and heavy traffic loads." (*1*)

The Superpave procedure developed during SHRP included a binder specification (for conventional and polymer-modified binders, but not for rubberized asphalt binder), a volumetric mix design method, and a set of performance-related tests to be performed on the mix resulting from the volumetric design. The performance-related testing included flexural fatigue and frequency sweep tests (both of which became AASHTO T 321), repeated simple shear tests (AASHTO T 320), a low-temperature cracking test, short-term and long-term aging procedures, and a moisture sensitivity test that was later replaced by AASHTO T 283. Between the end of SHRP and the year 2005, most U.S. state highway agencies had adopted either all or part of the Superpave volumetric mix design procedure, nearly always with refinements to suit local conditions, practices, and requirements.

The current Superpave system consists of three interrelated elements:

- An asphalt binder specification (implemented by Caltrans in 2005).
- A volumetric mix design and analysis system that is based on gyratory compaction.

- Performance-related mix analysis tests and a performance prediction system that includes environmental and performance models. (This last element has been implemented inconsistently on the national scale, with different states using a variety of tests and performance-prediction methods. Several states have chosen not to use any performance-related testing other than a moisture sensitivity test (AASHTO T 283); however, interest has grown in a switch from that test to the Hamburg Wheel Track Test (HWTT) for assessing both moisture sensitivity and rutting. Additionally, many states are using *both* AASHTO T 324 and T 283 or their own versions of those tests.

Between 1992 and 2005, a number of major changes were made to the Superpave volumetric mix design procedure, most significantly the elimination of the "restricted zone" in aggregate gradations. Another important change was the simplification of the N_{design} tables. The original implementation of Superpave volumetric design generally recommended use of Superpave Coarse gradations (that is, those passing below the restricted zone) for locations with increased risk of rutting. However, results from the WesTrack project (1995 to 1999) and experience in several states showed potential risks for rutting, compaction, and permeability with Superpave Coarse gradations, and as a result their use has decreased in some states. When the original Superpave method was developed, one determination with special significance for California was that nearly all the Hveem aggregate gradations that Caltrans had been using successfully were able to pass through the original Superpave specification's restricted zone.

As part of its current effort to implement Superpave mix design, Caltrans is interested in evaluating the changes in OBC and gradation that result from redesigning current Caltrans-approved Hveem-designed mixes with the Superpave method, and in determining the best approach for performance-related testing. To accomplish this, in summer of 2011 Caltrans asked the University of California Pavement Research Center (UCPRC) for assistance in evaluating the Superpave volumetric mix design for Caltrans mixes and performance-related tests. This work is being performed as Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 3.18.3, "Implementation of the Superpave Asphalt Mix Design Procedure in California."

It is anticipated that none of these items will change significantly in the transition from Hveem to Superpave mix designs:

- The current aggregate gradations for dense- and gap-graded mixes
- The current binder performance grade (PG) usage map
- The rubber binder specification.

It is anticipated that the new mix design procedure will need to consider these:

- Mix designs including up to 25 percent RAP
- The use of warm-mix additives and the effect of lower mixing temperatures.

It is assumed that low-temperature cracking is sufficiently addressed using the California PG binder specification and that no further considerations are needed in the mix design procedure.

1.2 Project Goal and Objectives

The goal of this project is to support development of a new mix design procedure for hot/warm-mix asphalt for California using AASHTO Superpave mix design principles. This will be achieved through completion of the following objectives, which are intended to answer four key questions. The objectives will be completed in two project phases. Phase I of the project has been divided into parts A and B. Phase IA will include comparison of the Hveem and Superpave mix designs, and Phase IB will assess the relative rutting performance of the two mix designs and compare Repeated Shear Constant Height (RSCH) and Asphalt Mix Performance Test/Repeated Load Triaxial (AMPT/RLT) results. Phase II will compare other performance-related tests.

Objectives of Phase IA

1. A literature review of recent national Superpave mix design and mix design test equipment–related research, including rutting and cracking performance, and moisture sensitivity.
2. Creation of a laboratory testing matrix that considers key variables identified in the literature review.
3. Collection of aggregates, binders, and current Hveem or rubberized mix designs for them.
4. Development of Superpave volumetric mix designs and comparison with current mix designs.

Objectives of Phase IB

5. Preparation and laboratory testing of RSCH and RLT specimens and analysis of the results:
    a. To compare the expected rutting resistance of the Superpave and Hveem mix designs;
    b. To compare the results of RSCH and RLT testing.
6. Recommendations for changes in preliminary new mix design procedure.
7. Evaluation of a comparison of RSCH and RLT results and of required changes in *CalME* to allow use of RLT testing to produce design inputs.

Objectives of Phase II

8. Preparation and laboratory testing of different performance-related tests for rutting, cracking, and moisture sensitivity for possible use in a new mix design method.
9. Recommendations for performance-related tests to use in a new mix design procedure.
10. Preparation of reports documenting the study and study results.

This technical memorandum documents the work completed for Phase IA and the volumetric mix design part of Objective 6, and answers the following key questions:

1. What are the main questions that Caltrans faces based on the literature review?
2. What are the changes in OBC and gradation required for revising existing Hveem mix gradations to meet Caltrans draft Superpave specifications?
3. What are the appropriate the numbers of gyrations and pressure levels for Caltrans mixes with different binder types (conventional, rubberized, and polymer-modified), aggregate types, and gradations?
4. What are any potential adjustments required to the draft specifications?

1.3 Structure and Content of this Technical Memorandum

This technical memorandum documents the evaluation of changes in job mix formula (JMF) required for 15 Hveem mix designs to meet draft Caltrans Superpave volumetric mix design specifications, and adjustments to those specifications. The 15 mix designs were taken from throughout the state and include a variety of binder types, binder sources, and aggregate sources. This memo contains the detailed results of optimum binder content (OBC) determination by the Superpave mix designs and comparisons with the original Hveem mixes. These results are based on laboratory tests to produce JMFs that meet the draft Superpave specifications and the adjustments needed to both the mix designs and specifications.

- Chapter 2 provides a summary of the key questions found from the literature review, a summary of the Superpave mix design procedure used, a summary experimental factorial, and a description of materials selected and acquired to allow comparison between Hveem OBC versus Superpave OBC.
- Chapter 3 describes the specimen fabrication and testing processes for the HMA and RHMA specimens for each mix.
- Chapter 4 provides test results for all 15 mixes and shows each of the adjusted mix designs and the adjustments made.
- Chapter 5 summarizes changes to the Hveem OBC and gradation to meet Superpave specifications, final recommended specimen preparation and testing procedures, and other recommendations for changes to the draft Superpave specifications.

2 MIX SELECTION AND DESIGN METHOD

2.1 Selection of Mixes

To ensure that representative mix designs were tested in this research, Caltrans district materials engineers (DMEs) throughout California were contacted by the Caltrans Division of Pavement Management, which asked them to select mixes used widely in their districts and to recommend which mixes should be evaluated as part of Superpave implementation. After input from the DMEs was received and analyzed, 15 Hveem HMA designs were selected for this project. Among the selections were PG-graded and rubber-modified mixes, including ones from different climate regions and with different aggregate types (mineralogy and source). Table 2.1 presents the materials details of the 15 mixes chosen for the Phase I experiment. (Note: The table also shows the five mixes selected for Phase II of the experiment.)

Table 2.1: Superpave Implementation Phase 1: List of 15 Selected Mixes with Aggregate and Binder Information

Asphalt Binder Type	Mix Name	NMAS	RAP	Agg. Type	Quarry Location	Agg. Sampled Date	Binder	Binder Sampled Date
Unmodified	**A**[a]	3/4 in.		Alluvial	Northern California	Dec. 2011	Refinery 1 PG 64-16	Dec. 2011
	B[a]	3/4 in.		Basalt	Central California	Apr. 2012	Refinery 2 PG 64-16	Apr. 2012
	C	3/4 in.		Granite	Central California	Nov. 2011	Refinery 2 PG 64-16	Nov. 2011
	D	3/4 in.		Alluvial	Northern California	Dec. 2011	Refinery 2 PG 64-16	Dec. 2011
	E	3/4 in.		Alluvial	Northern California	Dec. 2011	Refinery 1 PG 64-16	Dec. 2011
	F	3/4 in.	15%	Alluvial	Northern California	Dec. 2011	Refinery 1 PG 64-16	Dec. 2011
	G	1/2 in.		Basalt	Central California	Apr. 2012	Refinery 2 PG 64-16	Apr. 2012
	H	3/4 in.		Granite	Central California	Aug. 2012	Refinery 1 PG 70-10	Jul. 2012
Rubber-modified	**I**[a]	1/2 in		Basalt	Central California	Apr. 2012	Refinery 2 PG 64-16 Rubber	Jul. 2012
	J[a]	3/4 in.		Granite	Southern California	Jun. 2012	Refinery 3 PG 64-16 Rubber	Jun. 2012
	K	3/4 in.		Alluv. Fan	Southern California	Aug. 2012	Refinery 3 PG 70-10 Rubber	Jul. 2012
	L	1/2 in.		Granite	Central California	Nov. 2011	Refinery 2 PG 64-16 Rubber	Nov. 2011
	M	3/4 in.		Granite	Central California	May 2012	Refinery 3 PG 64-16 Rubber	Jul. 2012
Polymer-modified	**N**[a]	1 in.		Granite	Southern California	Jun. 2012	Refinery 3 PG 64-28 PM	Jun. 2012
	O	1 in.	15%	Alluv. Fan	Southern California	Aug. 2012	Refinery 3 PG 64-28 PM	Jun. 2012

a Selected by Chief, Office of Roadway Materials Testing, Co-Chair, Superpave Task Group for Phase II Testing.

2.2 Materials Acquisition

The two steps that followed mix selection were to obtain the Hveem mix JMFs for each of the selected mixes and to acquire the necessary materials. The Caltrans-approved JMFs (Caltrans CEM-3511 and 3512 forms) obtained from contractors were updated in 2011 or 2012 for the most current paving projects. Calculations were made to determine the amount of material needed for each mix. Suppliers were contacted and the aggregates and binders shown in each of the JMFs were acquired via common carrier or by UCPRC staff plant pickup. Aggregates were either sampled hot from mixer screens or sampled cold from stockpiles. Aggregates were loaded in drums and buckets sorted by bin size and delivered to UCPRC for processing. All the binders obtained were stored in a 25°C temperature-controlled room until laboratory mixing and testing. The sample dates appear in Table 2.1.

2.3 Superpave Mix Design

Caltrans plans to implement use of the Superpave mix design process by July 2014, with modifications made through research and early pilot projects. A brief overview of the Superpave mix design process is presented below, followed by the modified process utilized by UCPRC for Caltrans implementation.

2.3.1 Overview of Superpave Mix Design Process

As noted earlier, the Superpave mix design was developed by SHRP to replace the older Hveem and Marshall design methods. Superpave primarily addresses two pavement distresses: permanent deformation (rutting), which results from inadequate shear strength in the asphalt mix, and low temperature cracking, which occurs when an asphalt layer shrinks and the tensile stress exceeds the tensile strength. The Superpave system consists of three interrelated elements:

1) An asphalt binder specification (implemented by Caltrans in 2005).
2) A volumetric mix design and analysis system based on gyratory compaction.
3) Performance-related mix analysis tests and a performance prediction system that includes environmental and performance models. (There has been no national consistency of implementation of this last element, with a variety of tests and performance prediction methods being used by different states, and a number of states not using this element at all except for a moisture sensitivity test [AASHTO T 283]).

Like the Hveem method, the Superpave mix design method considers density and volumetric analysis, but unlike the Hveem method Superpave also considers regional climate and traffic volume in the aggregate and binder selection processes. Superpave uses the SHRP gyratory compactor for production of cylindrical test specimens. Its compaction load is applied on the sample's top while the sample is inclined at 1.25 degrees. This orientation is aimed at mimicking the compaction achieved in the field using a rolling wheel compactor.

A typical Superpave mix design consists of the following general steps. Caltrans may or may not utilize all these steps upon introduction of the Superpave process in 2014 (see Section 2.3.2):

(1) PG Binder Selection

A binder grade is first selected by geographic area, pavement temperature, or air temperature. Caltrans has published a map designating PG binder grades for different climate regions in California, with boundaries on each route in the state defined by post mile. If traffic volume is heavy, an adjustment is made to a higher binder grade.

(2) Aggregate Selection

An acceptable aggregate structure has to first meet the so-called "consensus properties" (those originally developed based on a consensus of experts involved in the SHRP project and later revised by the FHWA Mix Expert Task Group) including coarse aggregate angularity, flat and elongated particle percentage, fine aggregate angularity, and clay content. A trial compaction is then performed to estimate volumetric properties and dust proportion to check against the criteria. An estimate of binder content is also calculated for specimen preparation.

(3) Specimen Preparation and Compaction

A minimum of two specimens are prepared at each of these four binder contents (by total weight of mixture [TWM]): estimated binder content, estimated binder content ±0.5%, and estimated binder content +1.0%. These specimens are compacted to N_{max}.

(4) Data Analysis

Compaction densities at different levels of gyration are backcalculated from the measured bulk specific gravity. Volumetric properties (%VMA and %VFA) and dust proportion are calculated at N_{des} and plotted versus the four binder contents tested.

(5) Optimal Binder Content Selection

The binder content at 4 percent air-void content is selected as the OBC. Volumetric properties, dust proportion, and compaction density at N_{ini} and N_{max} are determined and then verified regarding whether they are met at the OBC.

(6) Moisture Susceptibility

Specimens are compacted to 7 percent air-void content to be tested for indirect tensile strengths and rutting according to AASHTO T 283 and AASHTO T 324, respectively.

2.3.2 Modified Superpave Process

Caltrans is interested implementing the Superpave mix design method but also in keeping aggregate gradation specifications similar to those in the current Hveem mix design process. In this project, some Hveem aggregate gradations did not have enough dust content to meet the dust proportion specification of the Superpave process. Thus dust contents for these mixes were increased to meet the specification. The modification was kept to a minimum so the modified gradation curve stayed close to the original curve and wherever possible within the existing upper and lower band limits. This process is presented for each mix individually in Chapter 4. Moisture susceptibility testing was not included in the Phase I experiment, but will be conducted in Phase II.

This modified Superpave process focused primarily on determining the OBC using the new gyratory compactor and achieving associated density and volumetric requirements. The Superpave design method was originally developed for HMA using unmodified binders. Several mixes using polymer-modified and rubber-modified binders were included in this project in an attempt to check the feasibility of adapting the Superpave mix design to these materials, which are commonly used in California but which are not necessarily used extensively in other states (particularly rubber-modified binders and gap gradations).

3 SPECIMEN FABRICATION AND TESTING

3.1 Specimen Fabrication Process

3.1.1 Preparation of Aggregates

Aggregates were dried in the laboratory oven overnight at 110°C upon receiving and sampling (AASHTO T 2). Then the aggregates were loaded into barrels or buckets by bin size for storage in the warehouse. Some barrels were held outdoors and covered with tarps to keep their contents dry. The aggregates not put into storage were sieved on bulk sieve shakers (Gilson TS-1) with standard size screens from 25 mm (1 in.) to 0.075 mm (#200), then collected in buckets by individual screen size. Laboratory aggregate “batches” were produced by recombining the aggregates according to JMF size requirements. This individual-size batching method ensured greater accuracy and tighter gradation control compared to bin batching. Aggregates from the same source and of the same type (rock or rock dust) were then combined in sieving and batching. A small portion of sand from the sand bin was added to some of the mixes; this sand had been bin-batched and did not significantly alter the gradation and mixing interaction due to the small quantities (<10%) present. Individual aggregate batches were placed in plastic cylinders until use.

Prior to producing batches for mixing, a sieve analysis was performed according to AASHTO T 11A (wet sieve) and T 27 (dry sieve). Two 2,500-gram samples were prepared according to the JMF combined gradation. For some mixes, the dust content was increased from the JMF gradation in order to meet Superpave dust proportion specification (see the individual mix results in Chapter 4). A comparison of the original JMF gradation and a sieve analysis gradation is presented for each individual mix in Chapter 4. For compacted specimens that were used for the Superpave mix design, the standard size of 150 mm diameter and 115±5 mm height required approximately 4,600 to 4,700 grams of aggregate (*2*).

3.1.2 Mixing and Compaction Process

HMA mixing was conducted in a Cutler Hammer rotary mixer. Mixing and compaction temperature were determined from the temperature-viscosity charts provided by the binder supplier depending upon the binder grade and type. A list of mixing, aging, and compaction temperatures is shown in Table 3.1.

The aggregate temperature for each mix was set 15°C higher than the binder mixing temperature (*2*) for unmodified binders. For polymer-modified and rubber-modified mixes, the aggregate was heated up to the temperature previously determined based on binder viscosity. During the mixing process, bowls, spoons, and spatulas were heated to maintain temperature. After mixing, all mixtures were short-term aged at 135°C for four hours (*2*) to simulate mixing, compaction, and the first several years of field aging.

Each mix was prepared at four binder contents to determine the Superpave OBC (*2*). For each binder content, one mix batch was prepared to determine the maximum specific gravity (AASHTO T 209). Two mix batches were prepared for gyratory compaction (AASHTO T 312).

For unmodified and polymer-modified binder mixes, the standard gyratory compaction used a compaction pressure of 600 kPa and compaction internal angle 1.16 degrees. Although Caltrans will be testing with 85 gyrations for N design (N_{des}), all specimens were compacted to 195 gyrations. This was performed to retrieve sufficient data points to evaluate specimen densities at all levels, including high levels of gyration.

For rubber-modified binder mixes, a gyratory compaction pressure of 825 kPa was used to facilitate the compaction of these stiffer binders. The compaction internal angle was 1.16 degrees and specimens were also compacted to 195 gyrations.

Specimens mixed with unmodified and polymer-modified binder were cooled by an external fan for five minutes before extraction to prevent undue distortion. Specimens mixed with rubber-modified binder were squared (held at a constant height) by the gyratory compactor for 1 hour and 30 minutes. This was to prevent possible expansion due to the elasticity of rubber-modified binder at high temperature.

3.2 Data Analysis Process

After specimens were extracted, bulk specific gravities were measured per AASHTO T 166. The densities for any gyration level were then backcalculated (Chapter 5 in Reference [*2*]). Percent voids in mineral aggregate (VMA), percent voids filled with asphalt (VFA), and dust proportion (DP) were also calculated for all four binder contents. Table 3.2 shows the HMA mix design requirement specified by Caltrans in SP Section 39 – SSP 12-29-11 (*4*). The requirement for unmodified binder mixes is well established while the requirement for rubber-modified binder mixes is still in development. Due to the different specification requirements for unmodified binder mixes and rubber-binder mixes, the process of determining OBC is presented in two separate sections.

Table 3.1: Mixing and Compaction Temperature and Compaction Pressure Settings

Binder Type	Mix Name	Binder	Mixing Temp. (°C) (Binder/ Agg.)	STOA Temp. (°C)[b]	Compaction Temp. (°C)	Compaction Pressure	Height Squaring Time
Unmodified	A[a]	Refinery 1 PG 64-16	145/160	135	140	600 kPa	n/a
	B[a]	Refinery 2 PG 64-16	145/160	135	140	600 kPa	n/a
	C	Refinery 2 PG 64-16	145/160	135	140	600 kPa	n/a
	D	Refinery 2 PG 64-16	145/160	135	140	600 kPa	n/a
	E	Refinery 1 PG 64-16	145/160	135	140	600 kPa	n/a
	F	Refinery 1 PG 64-16	145/160	135	140	600 kPa	n/a
	G	Refinery 2 PG 64-16	145/160	135	140	600 kPa	n/a
	H	Refinery 1 PG 70-10	160/175	135	150	600 kPa	n/a
Rubber-Modified	I[a]	Refinery 2 PG 64-16 Rubber	170/170	135	163	825 kPa	1 hr 30 min
	J[a]	Refinery 3 PG 64-16 Rubber	170/170	135	163	825 kPa	1 hr 30 min
	K	Refinery 3 PG 70-10 Rubber	170/170	135	163	825 kPa	1 hr 30 min
	L	Refinery 2 PG 64-16 Rubber	170/170	135	163	825 kPa	1 hr 30 min
	M	Refinery 3 PG 64-16 Rubber	170/170	135	163	825 kPa	1 hr 30 min
Polymer-Modified	N[a]	Refinery 3 PG 64-28 PM	166/166	135	150	600 kPa	n/a
	O	Refinery 3 PG 64-28 PM	166/166	135	150	600 kPa	n/a

a Selected by Chief, Office of Roadway Materials Testing, Co-Chair, Superpave Task Group for Phase II Testing.

b STOA: Short-term oven aging

Table 3.2: Hot Mix Asphalt Mix Design Requirements from Section 39 (Page 3, SP Section 39-SSP 11-01-12)

Quality Characteristic	Test Method	HMA-SP	
		Type A	RHMA-SP-G
Air voids content (%)	AASHTO T 269[a]	$N_{initial}$ 8.0 N_{design} 4.0 N_{max} 2.0	N_{design} N_{design} Specification
Gyration Compaction (number of gyrations)	AASHTO T 312	$N_{initial}$ 8 N_{design} 85 N_{max} 130	N_{design} 50 – 150
Voids in mineral aggregate (% min.) 1/4" grading 3/8" grading 1/2" grading 3/4" grading	SP-2 Asphalt Mixtures Volumetrics[c]	 18.0 16.0 14.5 13.5	 -- -- 19.0–24.0[b] 19.0–24.0[b]
Voids filled with asphalt (%) 1/4" grading 3/8" grading 1/2" grading 3/4" grading	SP-2 Asphalt Mixtures Volumetrics[c]	 65.0 – 75.0 65.0 – 75.0 65.0 – 75.0 65.0 – 75.0	Report Only
Dust proportion 1/4" and 3/8" gradings 1/2" and 3/4" gradings	SP-2 Asphalt Mixtures Volumetrics[c]	 0.9 – 2.0 0.6 – 1.3	Report Only
Hamburg wheel track (minimum number of passes at 0.5 inch average rut depth) PG 58 PG 64 PG-70 PG-76 or higher	AASHTO T 324 (Modified)[d, e]	 10,000 15,000 20,000 25,000	 15,000 20,000 25,000
Hamburg wheel track (inflection point minimum number of passes)[f] PG 58 PG 64 PG-70 PG-76 or higher	AASHTO T 324 (Modified)[d, e]	 10,000 10,000 12,500 15,000	 10,000 10,000 12,500
Moisture susceptibility (minimum dry strength, psi)	AASHTO T 283[d]	120	120
Moisture susceptibility (tensile strength ration, %)	AASHTO T 283[df]	70	70

[a] Calculate the air-void content of each specimen using AASHTO T 275 to determine bulk specific gravity AASHTO T 209 Method A to determine theoretical maximum specific gravity. Under AASHTO T 209 use a digital monometer and pycnometer when performing AASHTO T 209.
[b] Voids in mineral aggregate for RHMA-G-SP-G must be within this range.
[c] Measure bulk specific gravity using AASHTO T 275.
[d] Test plant produced HMA.
[e] Test as specified in Section 39-1.01D(1).
[f] Freeze thaw is not required.

3.2.1 Determining Superpave OBC for Unmodified and Polymer-Modified Mixes

For the unmodified binder and polymer-modified mixes, the method for determining OBC followed the typical Superpave mix design. At N_{des} of 85 gyrations, air-void contents were backcalculated and plotted versus binder content. The percent VMA, percent VFA, and dust proportions were also plotted versus binder content. From a best-fit curve, the binder content at four percent air-void content was selected as the Superpave OBC. Mixes at this Superpave OBC then needed to meet several density, volumetric, and dust proportion requirements as shown below:

(1) Compaction density less than 92 percent at N_{ini} of 8 gyrations
(2) Compaction density greater than 98 percent at N_{max} of 130 gyrations
(3) Percent VMA greater than 13.5 (for ¾ inch or larger size mixes)
(4) Percent VFA in between 65 to 75 (for ¾ inch or larger size mixes)
(5) Dust proportion between 0.6 to 1.3 (for ¾ inch or larger size mixes)

If the mix did not pass all five criteria, it was modified.

3.2.2 Determining Superpave OBC for Rubber-Modified Mixes

Caltrans has established a testing range of 50 to 150 gyrations to compact rubberized mixes to four percent target air-void content. To determine the Superpave OBC, specimen densification data was plotted versus the number of gyrations. Four curves were created representing the four tested binder contents to show compaction densities at different levels of gyration. The following steps were used as a general guideline to determine Superpave OBC for rubber-modified binder mixes.

(1) Determine whether binder content at 50 gyrations is less than 94 percent, and invalidate mixes that exceed that percentage.
(2) Determine whether binder content at 150 gyrations is greater than 96 percent, and invalidate mixes with density lower than that percentage.
(3) Based on steps (1) and (2), determine the OBC range using the upper and lower values of binder content that can be compacted to 4 percent air-void content at or before 150 gyrations.
(4) Within the OBC range determined from step (3), verify that the percent VMA is between 19 and 24. This may further narrow the OBC range.
(5) Evaluate the percent VFA and dust proportion, which are reported values rather than specified values.
(6) Select a desired Superpave OBC based on the density, volumetric, and dust proportion properties.

4 RESULTS FROM SUPERPAVE OBC DETERMINATION

This chapter shows detailed findings for all 15 mixes prepared using modified Superpave methods to determine OBC. Table 4.1 summarizes the test results for all 15 mixes. The chapter sections and subsections that follow the table describe each mix and any repeated mix designs, and the changes made in each iteration of the mix design. Unmodified binder mixes are presented in Section 4.1, rubber-modified binder mixes in Section 4.2, and polymer-modified binder mixes in Section 4.3. Detailed results for each individual mix are presented following the order shown in Table 4.1.

Table 4.1: Summary of Design Properties: Hveem Design Versus Superpave Design

			Hveem Mix Design Properties					Superpave Mix Design Properties				
Binder Type	**Mix Name**	**Binder Type**	**HV OBC (TWM)[c]**	**Design % Air Void**	**%VMA**	**%VFA**	**DP**	**SP OBC (TMW)[c]**	**Design % Air Void**	**%VMA**	**%VFA**	**DP**
Design Specification for Unmodified Binder				**4.0±0.5**	**>13**	**65-75**	**Report**		**4.0±0.5**	**>13.5**	**65-75**	**0.6-1.3**
Unmodified	**A[a]**	Refinery 1 PG 64-16	4.8	4.0	15.5	73.0	1.2	5.2	4.0	15.5	74.4	1.1
	B[a]	Refinery 2 PG 64-16	4.9	4.0	13.6	70.9	1.0	5.9	4.5	18.5	74.9	0.8
	C	Refinery 2 PG 64-16	5.2	4.0	14.2	72.8	0.8	6.1	4.0	15.4	74.0	0.5
	D	Refinery 2 PG 64-16	4.6	4.0	13.1	69.0	1.0	5.2	4.0	14.0	71.2	1.4
	E	Refinery 1 PG 64-16	4.6	4.0	13.1	69.0	1.0	5.2	4.0	13.5	71.2	1.5
	F	Refinery 1 PG 64-16	4.8	4.0	13.0	69.0	0.9	5.8	4.5	18.6	74.6	0.7
	G	Refinery 2 PG 64-16	5.8	4.2	16.5	74.9	0.9	6.5	4.3	16.9	74.6	1.0
	H	Refinery 1 PG 70-10	4.9	4.0	16.0	76.0	1.1	5.5	4.0	18.1	73.9	0.9
Design Specification for Rubberized Binder				**-**	**18-23**	**Report**	**Report**		**4.0±0.5**	**19-23**	**Report**	**Report**
Rubber-Modified	**I[a]**	Refinery 2 PG 64-16 Rubber	7.4	4.5	19.1	76.0	0.5	7.7	4.0	19.1	79.5	1.0
	J[a]	Refinery 3 PG 64-16 Rubber	6.7	5.4	18.8	71.3	0.5	8.1	4.0	16.7	74.9	1.0
	K	Refinery 3 PG 70-10 Rubber	6.9	4.9	18.4	73.3	0.3	7.5	4.0	18.9	79.4	0.9
	L	Refinery 2 PG 64-16 Rubber	7.2	4.2	18.9	77.8	0.3	7.4	4.0	19.3	78.5	0.2
	M	Refinery 3 PG 64-16 Rubber	6.5	5.0	20.1	75.0	0.3	9.2[b]	4.0	21.0[b]	80.3[b]	0.1
Design Specification for PM Binder				**4.0±0.5**	**>13**	**65-75**	**Report**		**4.0±0.5**	**>13.5**	**65-75**	**0.6-1.3**
Polymer-Modified	**N[a]**	Refinery 3 PG 64-28 PM	4.8	5.3	15.1	64.5	0.7	6.0	4.3	17.6	74.9	1.0
	O	Refinery 3 PG 64-28 PM	4.7	4.9	14.9	67.2	1.1	4.6	4.0	13.8	71.3	1.4

a Selected by Chief, Office of Roadway Materials Testing, Co-Chair, Superpave Task Group for Phase II Testing.
b These values were calculated by linear extrapolation and are not reliable recommendations.
c Optimum Binder Content (OBC) is calculated by Total Weight of Mixture (TWM).

4.1 Test Results for Unmodified Binder Mixes

4.1.1 Mix A

Table 4.2 shows the basic aggregate and binder information for Mix A. Table 4.3 presents the aggregate gradation used for both the Hveem and Superpave mix designs. Figure 4.1 presents the same information on the 0.45 power gradation chart.

Table 4.2: Aggregate and Binder Type for Mix A

Mix ID	Mix A
NMAS	3/4 inch
RAP %	0
Aggregate Type	Alluvial
Quarry Location	Northern California
Binder Supplier	Refinery 1
Binder Grade	PG 64-16

Table 4.3: Aggregate Gradation Table for Mix A

Gradation of Aggregate Blend (Cumulative Percent Passing)				
Sieve Size		Contractor Test Result JMF Combined Gradation	Operating Range	UCPRC Lab Test Result Sieve Analysis
(mm)	(in.)			
25	1	**100.0**	100	**100.0**
19	3/4	**99.0**	94 – 100	**99.4**
12.5	1/2	**85.0**	79 – 91	**86.1**
9.5	3/8	**71.0**		**71.0**
4.75	#4	**50.0**	43 – 57	**49.2**
2.36	#8	**36.0**	31 – 41	**33.5**
1.18	#16	**27.0**		**24.8**
0.6	#30	**20.0**	16 – 24	**18.5**
0.3	#50	**14.0**		**12.6**
0.15	#100	**10.0**		**8.2**
0.075	#200	**6.0**	4.0 – 8.0	**5.3**

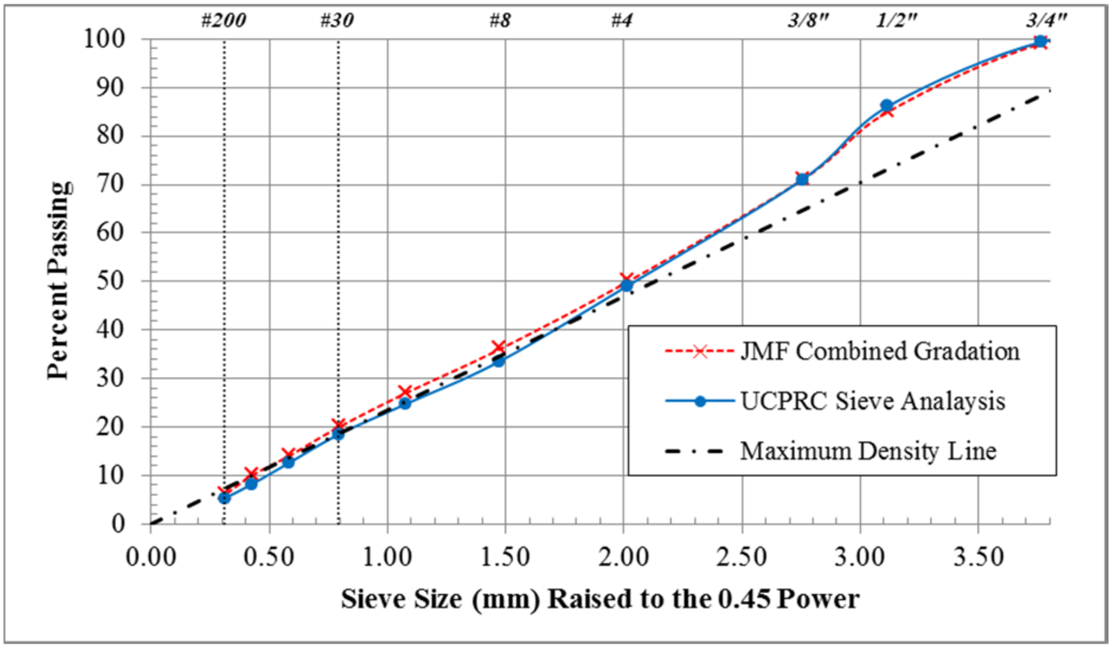

Figure 4.1: Aggregate gradation chart for Mix A.

Table 4.4 shows a comparison of design properties for the Hveem versus the Superpave mix design. For Superpave mix design, mixture properties are evaluated for four asphalt binder contents by using the densification data at N_{ini} (8 gyrations), N_{des} (85 gyrations), and N_{max} (130 gyrations). Table 4.5 shows the mixture's compaction and volumetric properties. Figure 4.2 illustrates the specimen densification versus number of gyrations. Graphs of air-void content, percent VMA, percent VFA, and dust proportion are shown in Figure 4.3 to Figure 4.6. The Superpave OBC was found to be 5.2 percent by total weight of mixture (TWM). The value of each of these properties at the Superpave OBC is indicated by the arrow in each of the figures for this mix, and all other mixes.

Table 4.4: Summary of Design Properties for Mix A

Mix Design Properties	Contractor JMF Hveem Design OBC Properties	UCPRC Lab Testing Superpave Design OBC Properties	Superpave Design Specification
Hveem %OBC (DWA)	5.0	5.5	
Hveem %OBC (TWM)	4.8	5.2	
% Air Void Content	4.0	4.0	4.0
% VMA	15.5	15.5	>13.5
% VFA	73.0	74.4	65–75
Dust Proportion	1.2	1.1	0.6 – 1.3
%Gmm @ N_{ini}=8	n/a	87.4	<92
%Gmm @ N_{max}=130	n/a	97.2	<98

Table 4.5: Compaction and Volumetric Properties for Superpave OBC for Mix A

%AC (TWM)	Compaction Properties			Volumetric Properties @ N_{des} = 85			Dust Proportion
	$\%G_{mm}$ @ N=8	$\%G_{mm}$ @ N=85	$\%G_{mm}$ @ N=130	%AirVoids	%VMA	%VFA	
Criteria	<92	96	<98	4.0	>13.5	65-75	0.6 – 1.3
4.3	85.8	93.7	94.9	6.3	15.9	60.6	1.3
4.8	86.4	94.7	95.9	5.3	15.8	66.4	1.2
5.2	87.8	96.3	97.5	3.7	15.2	75.5	1.1
5.7	88.1	97.0	98.2	3.0	15.8	80.9	1.0

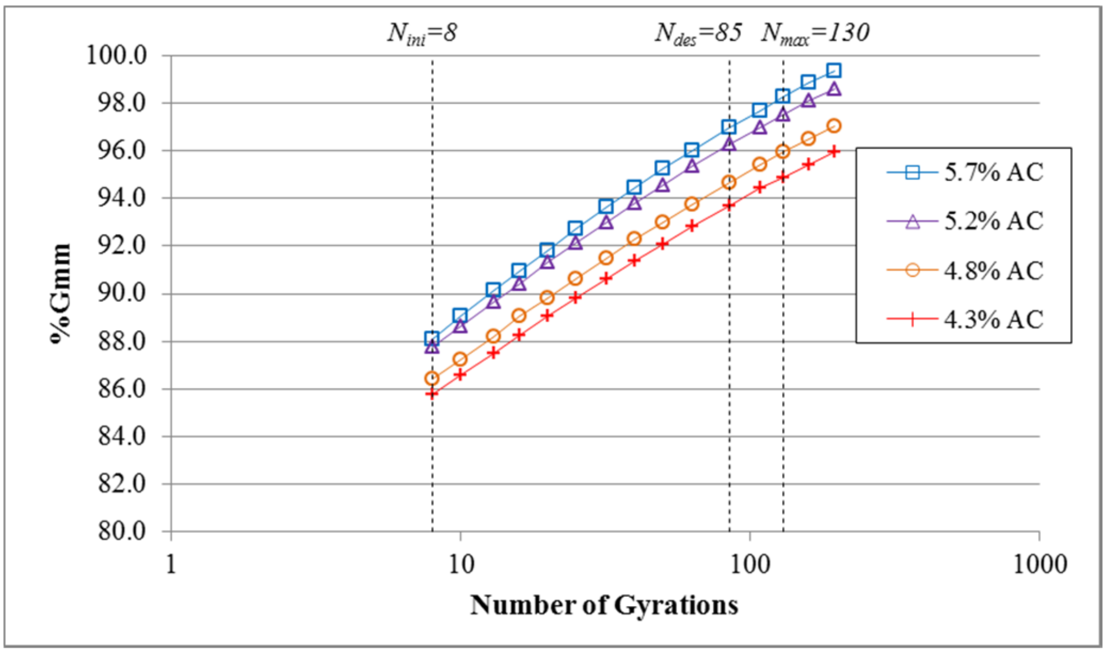

Figure 4.2: Mixture density versus number of gyrations for Mix A.

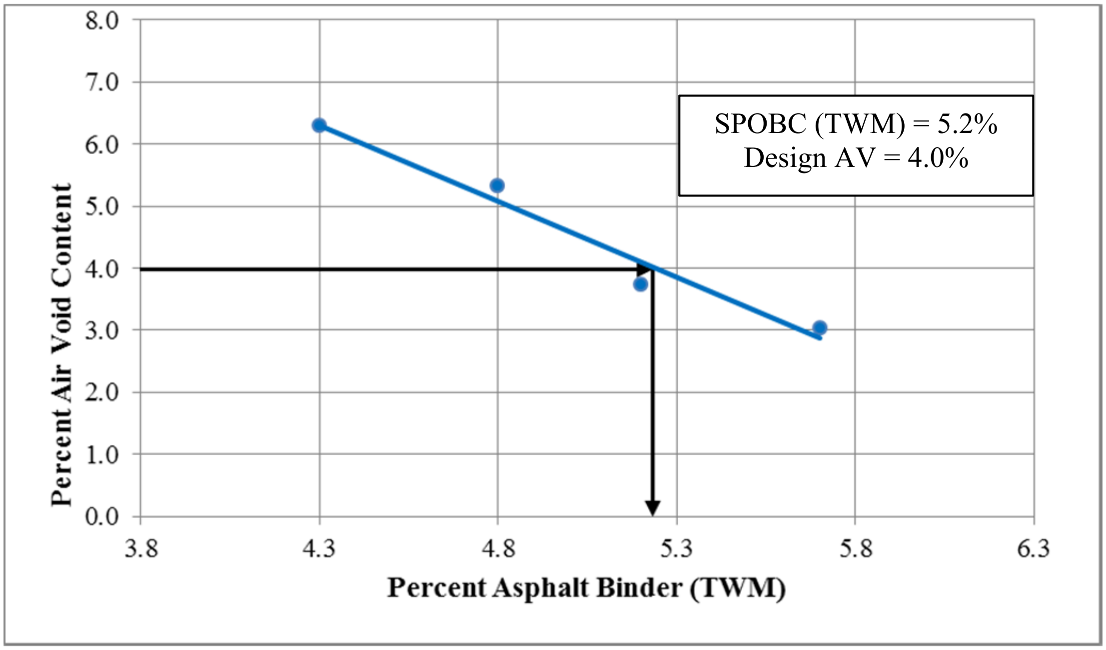

Figure 4.3: Selection of Superpave OBC based on percent air-void content versus percent asphalt binder for Mix A. (Note: The arrow in the figure shows the Superpave OBC selected based on the 4 percent air-void content criterion.)

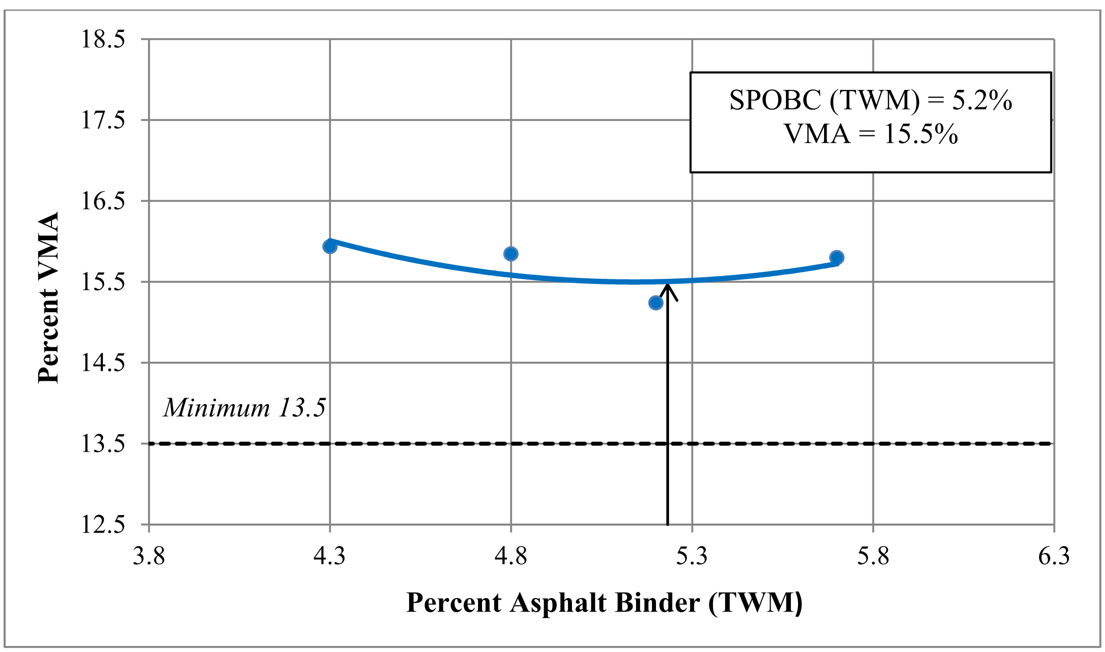

Figure 4.4: Percent VMA versus percent asphalt binder for Mix A. (Note: The arrow in the figure indicates the value of percent VMA at the Superpave OBC.)

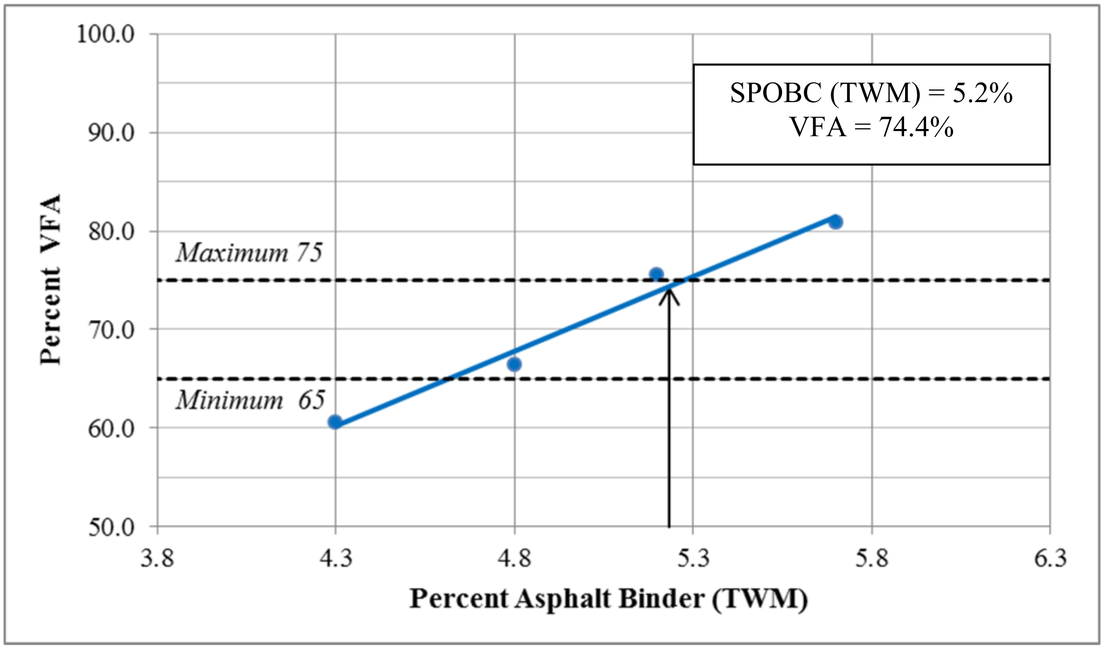

Figure 4.5: Percent VFA versus percent asphalt binder for Mix A.
(Note: The arrow in the figure indicates the value of percent VFA at the Superpave OBC.)

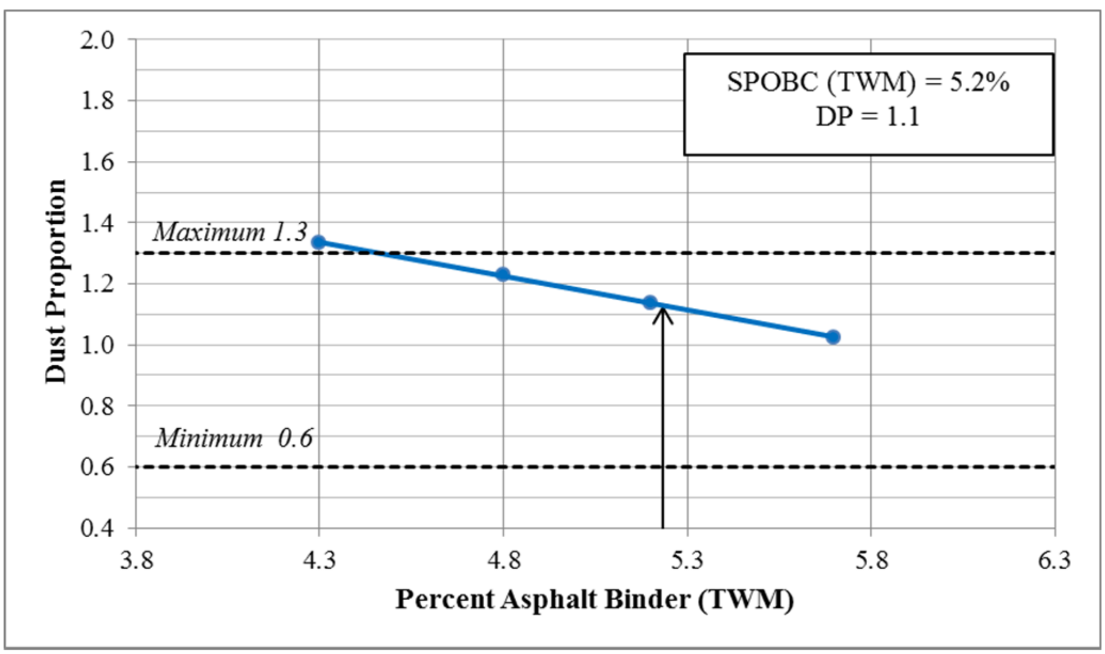

Figure 4.6: Dust proportion versus percent asphalt binder for Mix A.
(Note: The arrow in the figure indicates the dust proportion value at the Superpave OBC.)

4.1.2 Mix B

Table 4.6 shows the basic aggregate and binder information for Mix B. Table 4.7 presents the aggregate gradation used for both the Hveem and Superpave mix designs. Figure 4.7 presents the same information on the 0.45 power gradation chart.

Table 4.6: Aggregate and Binder Type for Mix B

Mix ID	**Mix B**
NMAS	3/4 inch
RAP %	0
Aggregate Type	Basalt
Quarry Location	Central California
Binder Supplier	Refinery 2
Binder Grade	PG 64-16

Table 4.7: Aggregate Gradation Table for Mix B

Gradation of Aggregate Blend (Cumulative Percent Passing)				
Sieve Size		**Contractor Test Result JMF Combined Gradation**	**Operating Range**	**UCPRC Lab Test Result Sieve Analysis**
(mm)	**(in.)**			
25	1	**100.0**	100	**100.0**
19	3/4	**98.0**	93 – 100	**96.9**
12.5	1/2	**82.0**	76 – 88	**82.1**
9.5	3/8	**71.0**		**70.9**
4.75	#4	**50.0**	43 – 57	**49.3**
2.36	#8	**34.0**	29 – 39	**34.0**
1.18	#16	**23.0**		**22.8**
0.6	#30	**17.0**	13 – 21	**16.8**
0.3	#50	**12.0**		**12.7**
0.15	#100	**6.0**		**6.6**
0.075	#200	**4.2**	2.2 – 6.2	**5.1**

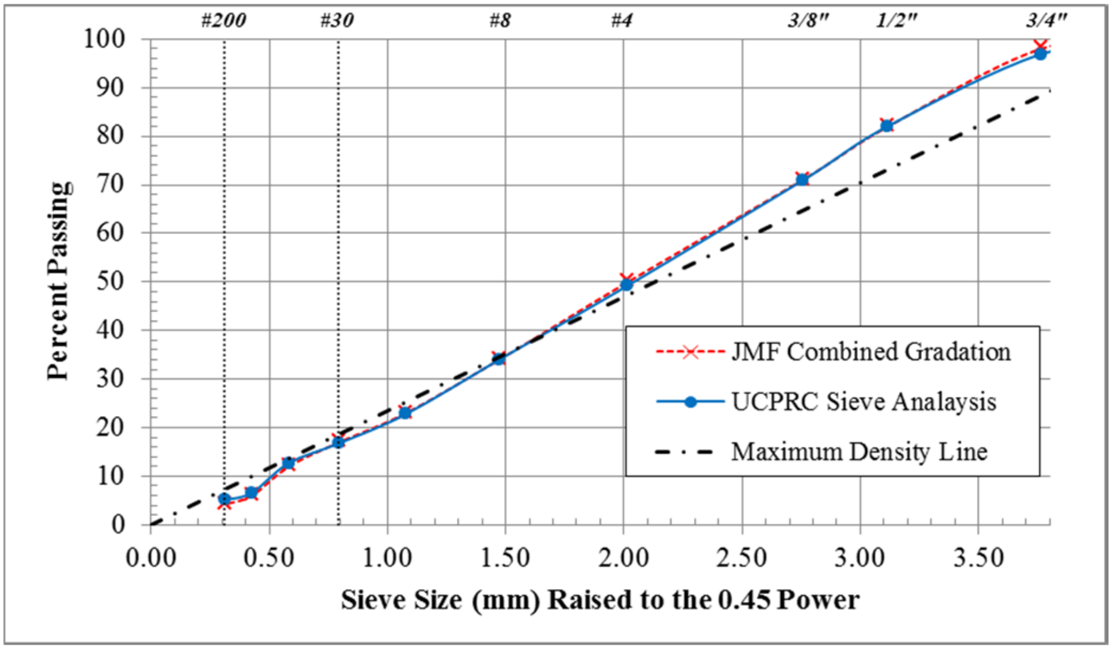

Figure 4.7: Aggregate gradation chart for Mix B.

Table 4.8 shows a comparison of design properties for the Hveem versus the Superpave mix design. For Superpave mix design, mixture properties are evaluated for four asphalt binder contents by using the densification data at N_{ini} (8 gyrations), N_{des} (85 gyrations), and N_{max} (130 gyrations). Table 4.9 shows the mixture's compaction and volumetric properties. Figure 4.8 illustrates specimen densification versus number of gyrations. Graphs of air-void content, percent VMA, percent VFA, and dust proportion are shown in Figure 4.9 to Figure 4.12. The Superpave OBC was found to be 5.9 percent by TWM. The value of each of these properties at the Superpave OBC is indicated by the arrow in each of the figures for this mix,

At design air-void content of four percent, percent VFA was above 75. With a ±0.5 percent tolerance for a laboratory mixed and compacted specimen, the Superpave OBC of 5.9 percent was found at a design air-void content of 4.5 percent to meet the specification.

Table 4.8: Summary of Design Properties for Mix B

Mix Design Properties	Contractor JMF Hveem Design OBC Properties	UCPRC Lab Testing Superpave Design OBC Properties	Superpave Design Specification
Hveem %OBC (DWA)	5.2	6.3	
Hveem %OBC (TWM)	4.9	5.9	
% Air-void Content	4.0	4.5	4.0
% VMA	13.6	18.5	>13.5
% VFA	70.9	74.9	65 – 75
Dust Proportion	1.0	0.8	0.6 – 1.3
%Gmm @ N_{ini} = 8	n/a	85.9	<92
%Gmm @ N_{max} = 130	n/a	96.7	<98

Table 4.9: Compaction and Volumetric Properties for Mix B

%AC (TWM)	Compaction Properties			Volumetric Properties @ N_{des} = 85			Dust Proportion
	%G_{mm} @ N=8	%G_{mm} @ N=85	%G_{mm} @ N=130	%AirVoids	%VMA	%VFA	
Criteria	<92	96	<98	4.0	>13.5	65 – 75	0.6 – 1.3
4.5	82.1	90.2	91.4	9.8	19.0	48.4	1.3
4.9	82.7	91.1	92.3	8.9	19.2	53.6	1.1
5.4	84.0	92.8	94.1	7.2	18.7	61.5	1.0
5.8	86.0	95.4	96.7	4.6	18.6	75.5	0.8

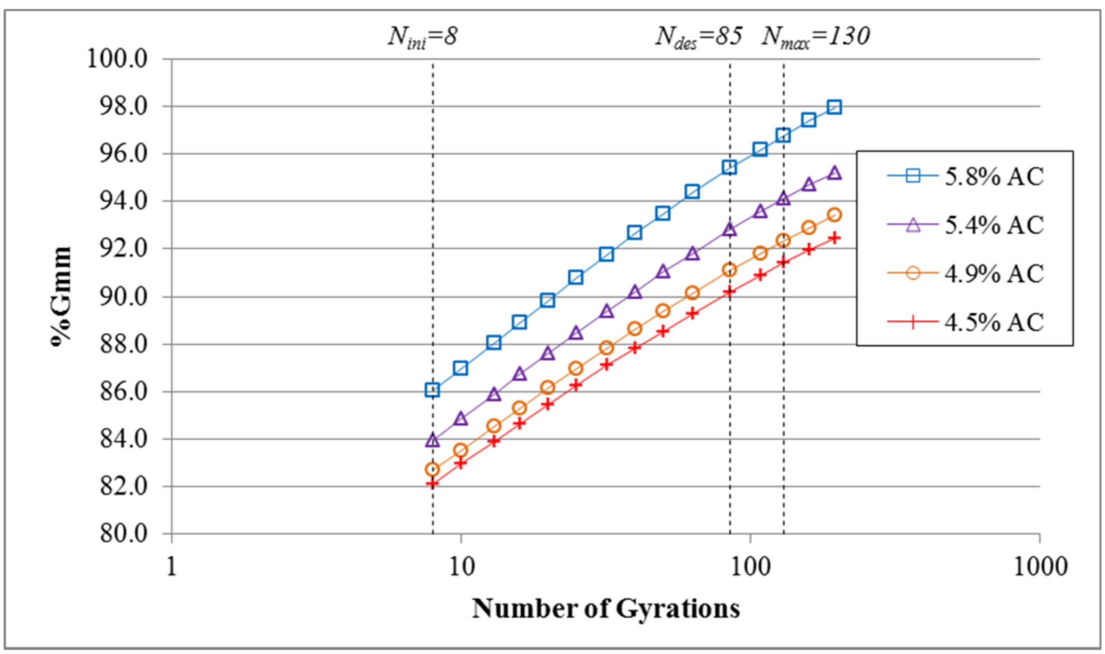

Figure 4.8: Mixture density versus number of gyrations for Mix B.

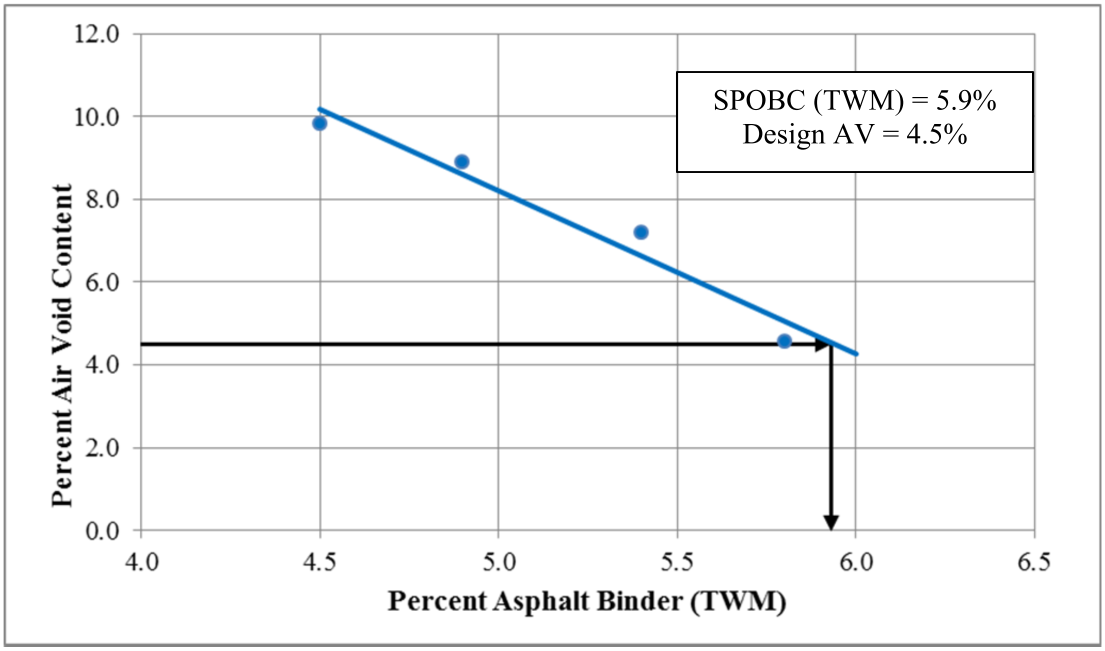

Figure 4.9: Selection of Superpave OBC based on percent air-void versus percent asphalt binder for Mix B. (Note: The arrow in the figure shows the Superpave OBC selected based on the 4.5 percent air-void content criterion.)

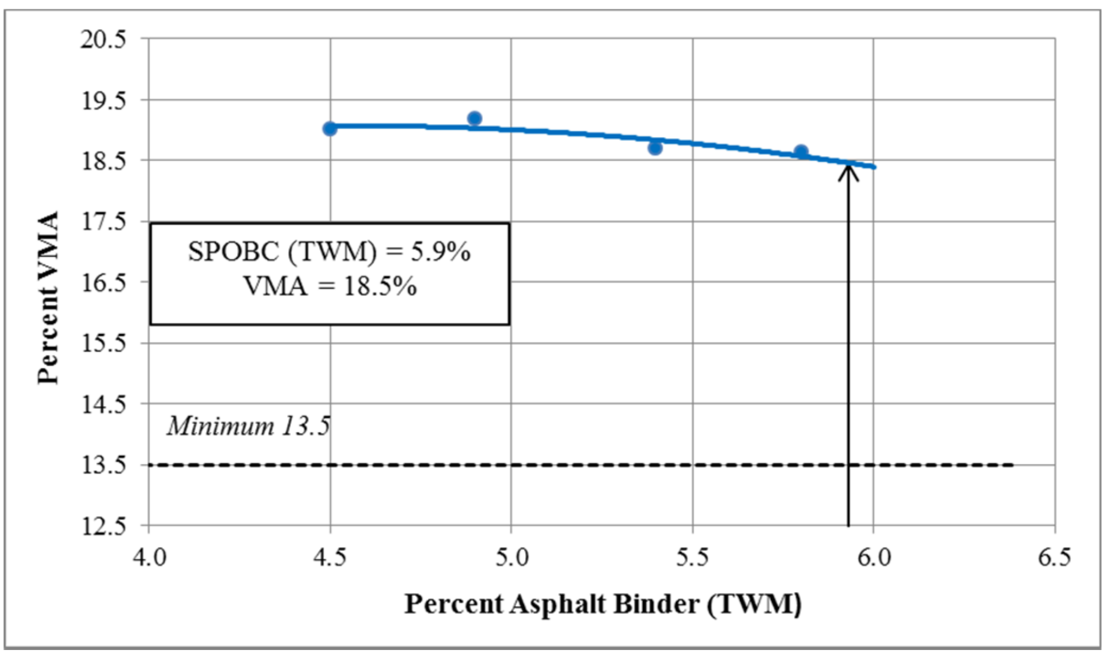

Figure 4.10: Percent VMA versus percent asphalt binder for Mix B.
(Note: The arrow in the figure indicates the value of percent VMA at the Superpave OBC.)

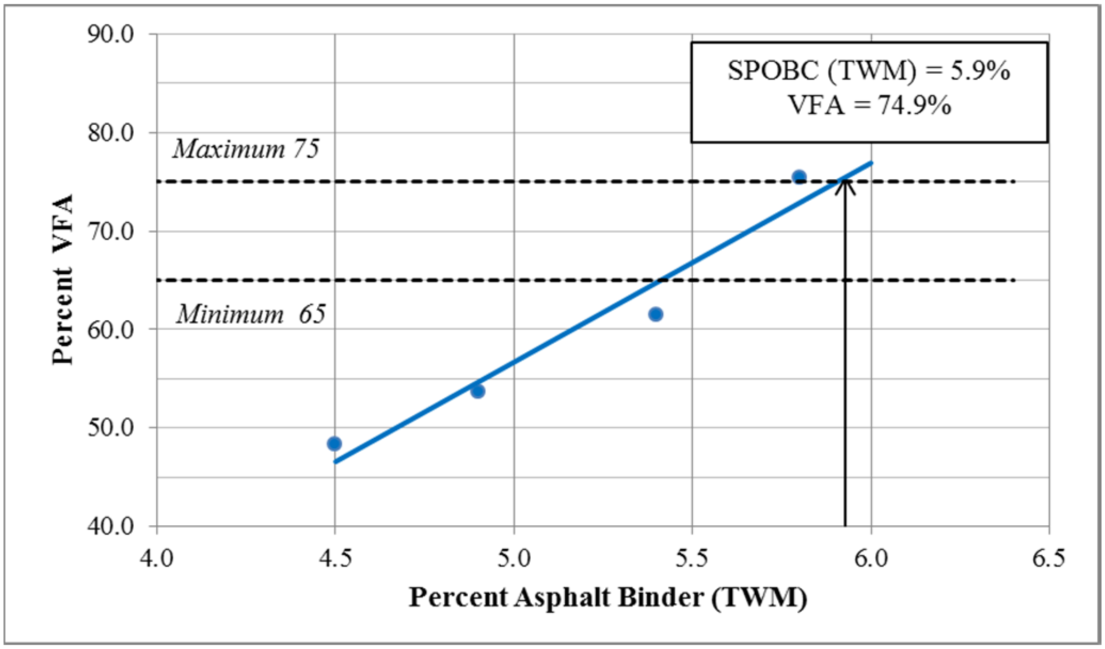

Figure 4.11: Percent VFA versus percent asphalt binder for Mix B.
(Note: The arrow in the figure indicates the value of percent VFA at the Superpave OBC.)

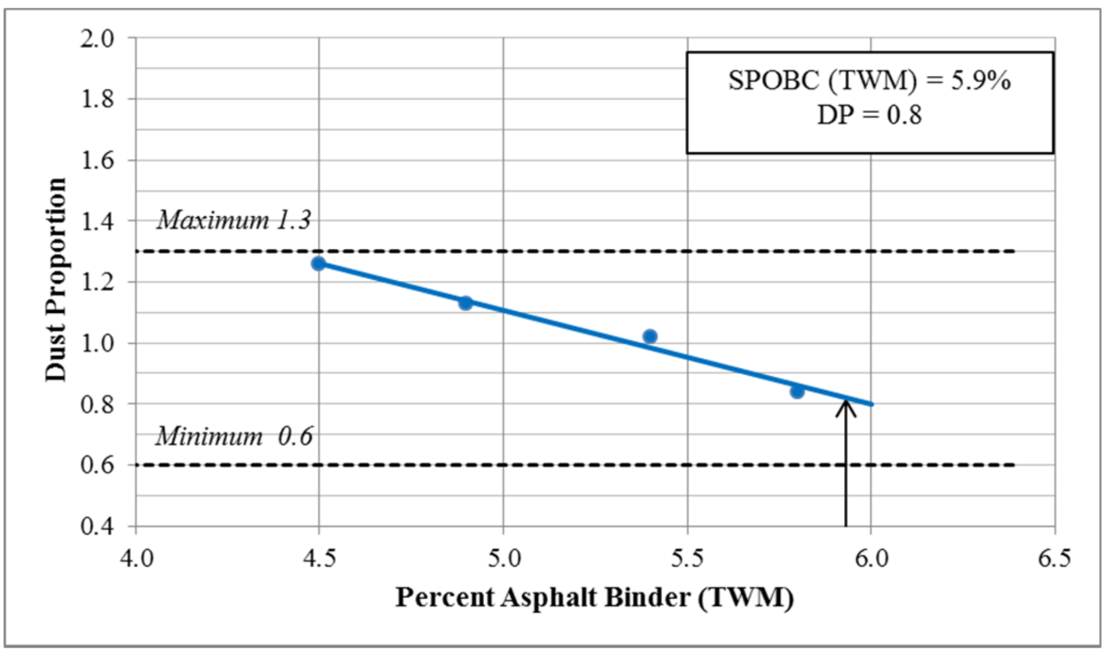

Figure 4.12: Dust proportion versus percent asphalt binder for Mix B.
(Note: The arrow in the figure indicates the dust proportion value at the Superpave OBC.)

4.1.3 Mix C

Table 4.10 shows the basic aggregate and binder information for Mix C. Table 4.11 presents the aggregate gradation used for both the Hveem and Superpave mix designs. Figure 4.13 presents the same information on the 0.45 power gradation chart.

Table 4.10: Aggregate and Binder Type for Mix C

Mix ID	**Mix C**
NMAS	3/4 inch
RAP %	0
Aggregate Type	Granite
Quarry Location	Central California
Binder Supplier	Refinery 2
Binder Grade	PG 64-10

Table 4.11: Aggregate Gradation Table for Mix C

Gradation of Aggregate Blend (Cumulative Percent Passing)				
Sieve Size		**Contractor Test Result JMF Combined Gradation**	**Operating Range**	**UCPRC Lab Test Result Sieve Analysis**
(mm)	**(in.)**			
25	1	**100.0**		**100.0**
19	3/4	**98.0**		**97.9**
12.5	1/2	**89.0**		**88.9**
9.5	3/8	**79.0**		**79.1**
4.75	#4	**55.0**		**55.8**
2.36	#8	**40.0**		**38.5**
1.18	#16	**28.0**		**26.9**
0.6	#30	**19.0**		**18.1**
0.3	#50	**10.0**		**10.1**
0.15	#100	**5.0**		**4.5**
0.075	#200	**3.5**		**2.2**

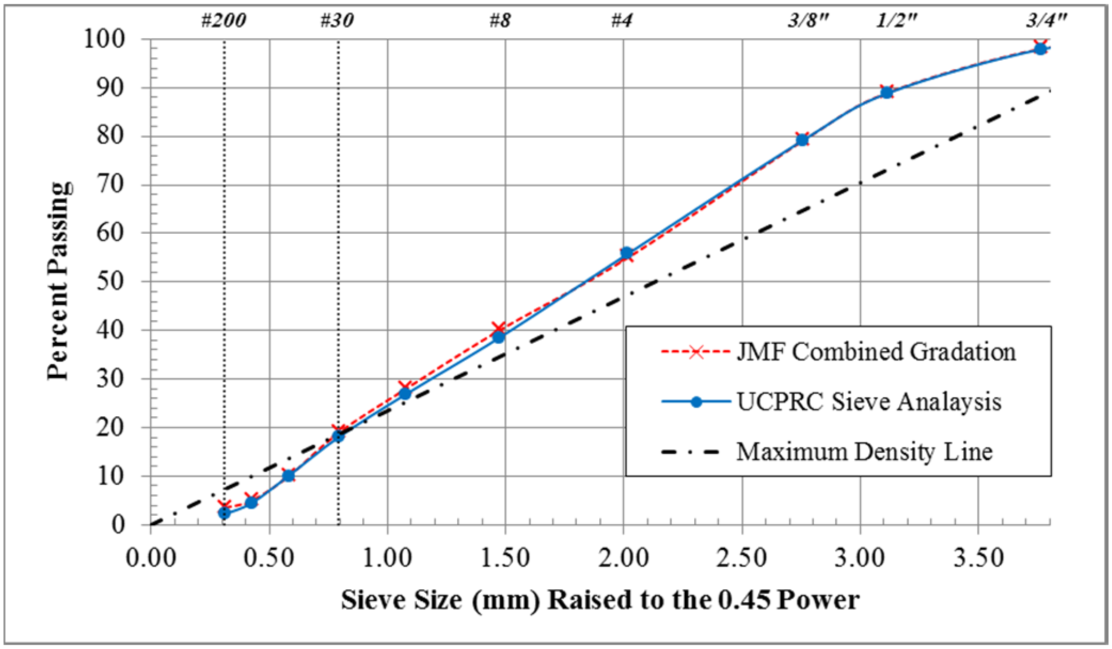

Figure 4.13: Aggregate gradation chart for Mix C.

Table 4.12 shows a comparison of design properties for the Hveem versus the Superpave mix design. For Superpave mix design, mixture properties are evaluated for four asphalt binder contents by using the densification data at N_{ini} (8 gyrations), N_{des} (85 gyrations), and N_{max} (130 gyrations). Table 4.13 shows the mixture's compaction and volumetric properties. Figure 4.14 illustrates specimen densification versus number of gyrations. Graphs of air-void, percent VMA, percent VFA, and dust proportion are shown in Figure 4.15 to Figure 4.18. The Superpave OBC was found to be 6.1 percent by TWM. The value of each of these properties at the Superpave OBC is indicated by the arrow in each of the figures for this mix.

Table 4.12: Summary of Design Properties for Mix C

Mix Design Properties	Contractor JMF Hveem Design OBC Properties	UCPRC Lab Testing Superpave Design OBC Properties	Superpave Design Specification
Hveem %OBC (DWA)	5.5	6.5	
Hveem %OBC (TWM)	5.2	6.1	
% Air Void Content	4.0	4.0	4.0
% VMA	14.2	15.4	>13.5
% VFA	72.8	74.0	65-75
Dust Proportion	0.8	0.5	0.6-1.3
%Gmm @ N_{ini}=8	n/a	87.7	<92
%Gmm @ N_{max}=130	n/a	97.2	<98

Table 4.13: Compaction and Volumetric Properties for Superpave OBC for Mix C

%AC (TWM)	Compaction Properties			Volumetric Properties @ N_{des} = 85			Dust Proportion
	$\%G_{mm}$ @ N=8	$\%G_{mm}$ @ N=85	$\%G_{mm}$ @ N=130	%AirVoids	%VMA	%VFA	
Criteria	<92	96	<98	4.0	>13.5	65 – 75	0.6 – 1.3
4.8	85.1	92.7	93.9	7.3	15.6	53.5	0.6
5.2	86.5	94.3	95.5	5.7	15.4	63.2	0.5
5.7	86.7	94.7	95.9	5.3	15.7	66.2	0.5
6.1	87.8	96.1	97.4	3.9	15.4	74.6	0.5

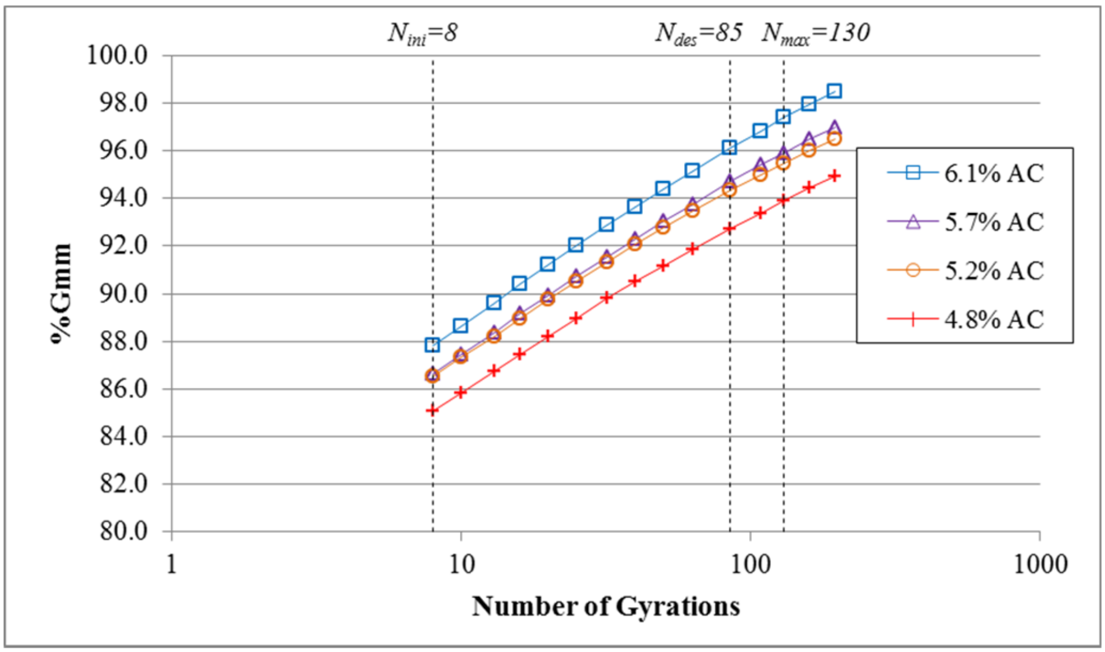

Figure 4.14: Mixture density versus number of gyrations for Mix C.

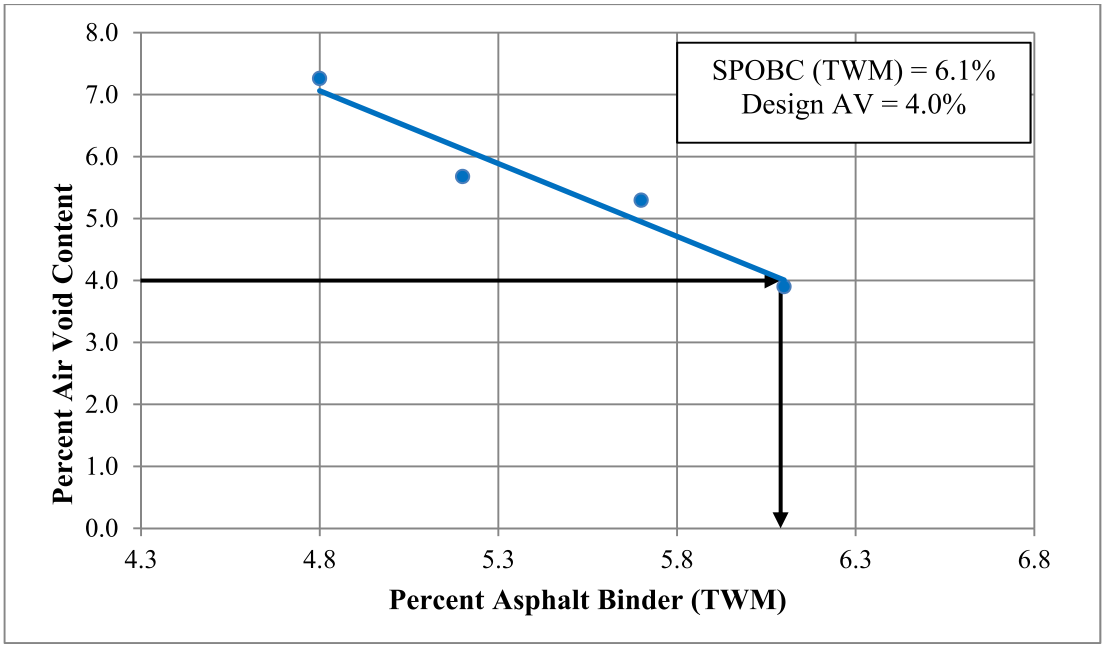

Figure 4.15: Selection of Superpave OBC based on percent air-void content versus percent asphalt binder for Mix C.
(Note: The arrow in the figure shows the Superpave OBC selected based on the 4 percent air-void content criterion.)

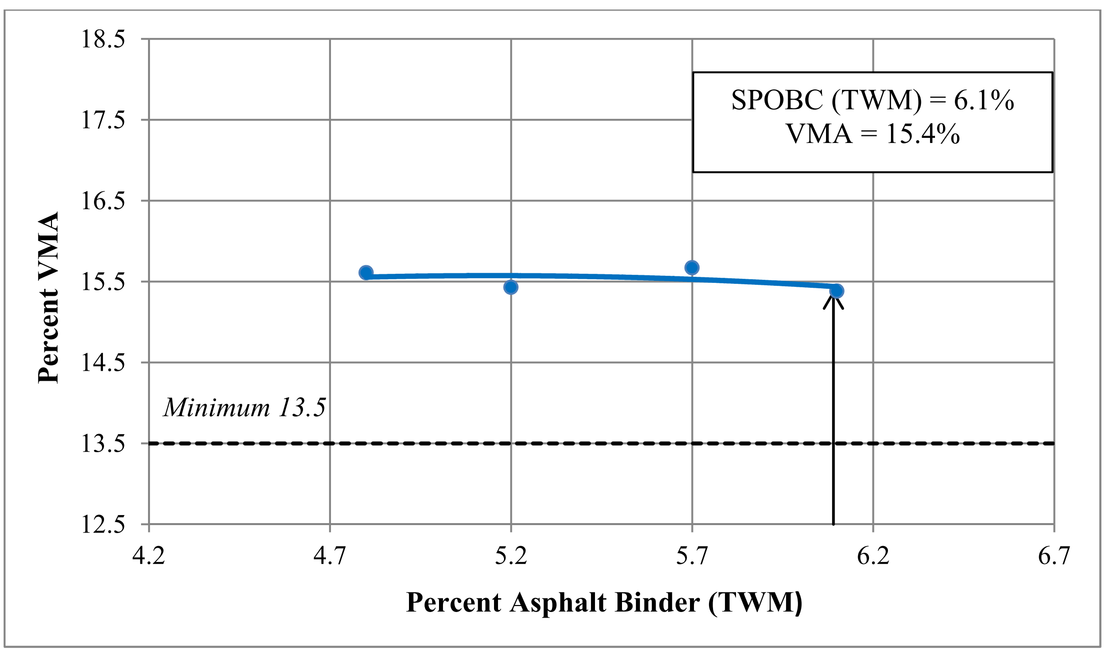

Figure 4.16: Percent VMA versus percent asphalt binder for Mix C.
(Note: The arrow in the figure indicates the value of percent VMA at the Superpave OBC.)

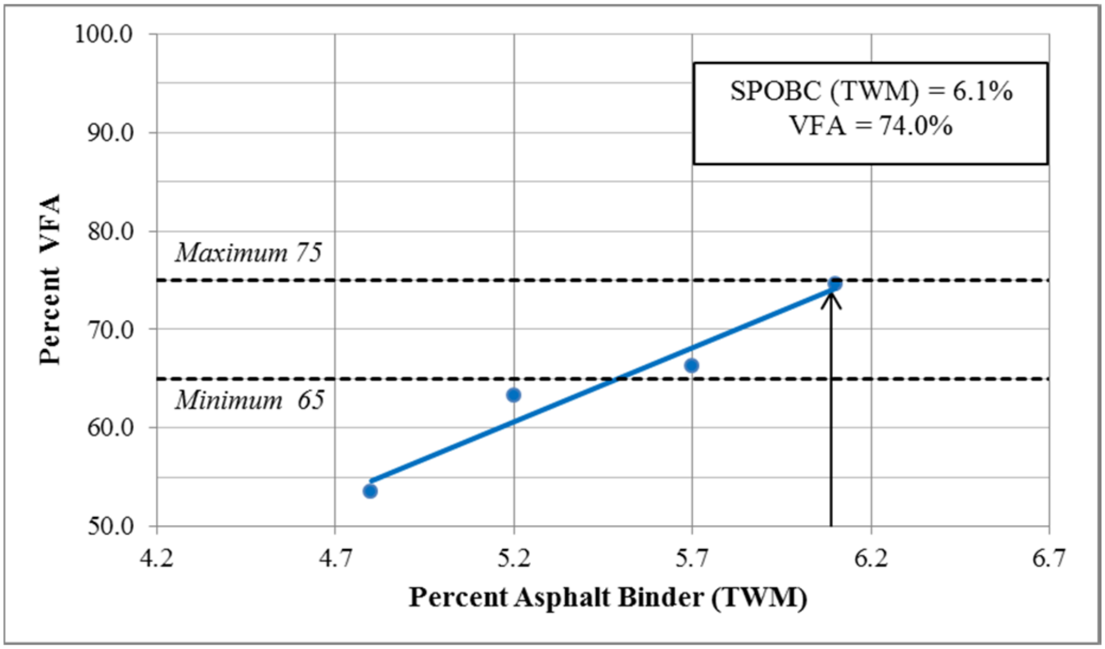

Figure 4.17: Percent VFA versus percent asphalt binder for Mix C.
(Note: The arrow in the figure indicates the value of percent VFA at the Superpave OBC.)

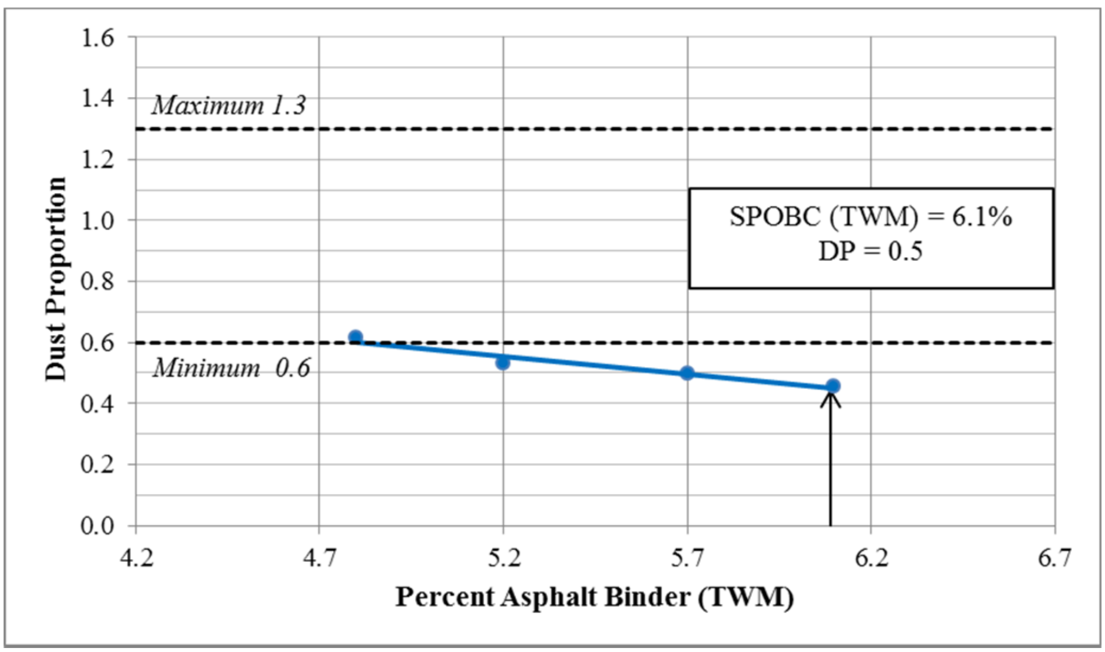

Figure 4.18: Dust proportion versus percent asphalt binder for Mix C.
(Note: The arrow in the figure indicates the dust proportion value at the Superpave OBC.)

4.1.4 Mix D

Table 4.14 shows the basic aggregate and binder information for the Mix D. Table 4.15 presents the aggregate gradation used for both the Hveem and Superpave mix designs. Figure 4.19 presents the same information on the 0.45 power gradation chart.

Table 4.14: Aggregate and Binder Type for Mix D

Mix ID	**Mix D**
NMAS	3/4 inch
RAP %	0
Aggregate Type	Alluvial
Quarry Location	Northern California
Binder Supplier	Refinery 2
Binder Grade	PG 64-16

Table 4.15: Aggregate Gradation Table for Mix D

Gradation of Aggregate Blend (Cumulative Percent Passing)				
Sieve Size		**Contractor Test Result JMF Combined Gradation**	**Operating Range**	**UCPRC Lab Test Result Sieve Analysis**
(mm)	**(in.)**			
25	1	**100.0**	100	**100.0**
19	3/4	**99.0**	94 – 100	**97.7**
12.5	1/2	**82.0**	76 – 88	**83.5**
9.5	3/8	**71.0**		**70.1**
4.75	#4	**47.0**	40 – 54	**46.2**
2.36	#8	**34.0**	29 – 39	**32.5**
1.18	#16	**24.0**		**23.0**
0.6	#30	**18.0**	14 – 22	**16.6**
0.3	#50	**12.0**		**11.1**
0.15	#100	**8.0**		**7.3**
0.075	#200	**5.8**	3.8 – 7.8	**5.8**

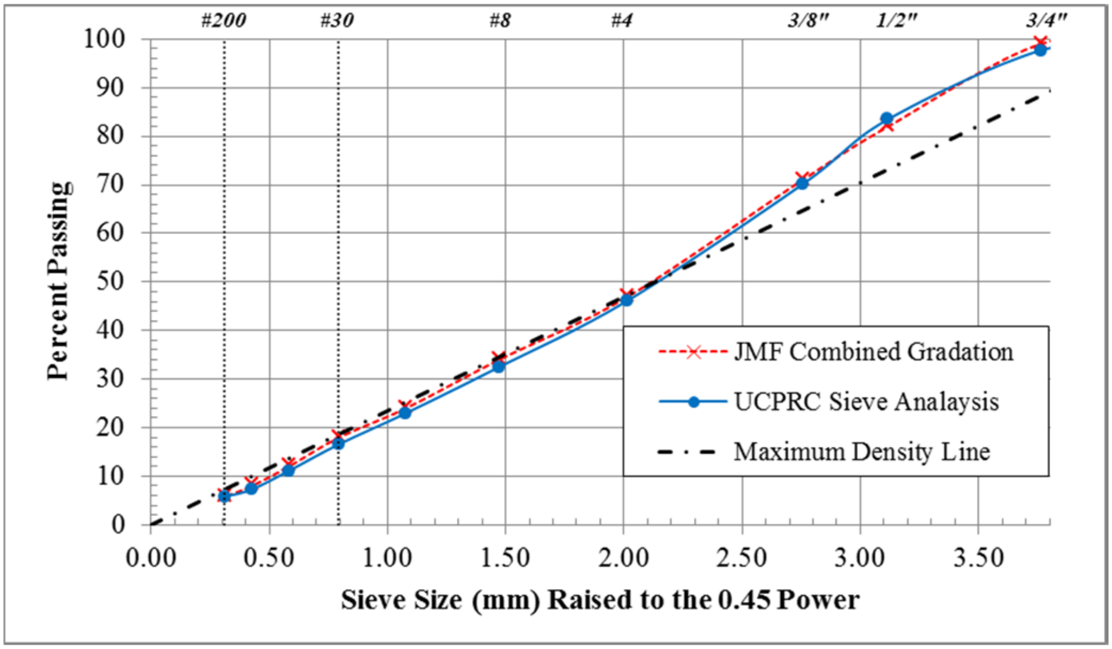

Figure 4.19: Aggregate gradation chart for Mix D.

Table 4.16 shows a comparison of design properties for the Hveem versus the Superpave mix design. For Superpave mix design, mixture properties are evaluated for four asphalt binder contents by using the densification data at N_{ini} (8 gyrations), N_{des} (85 gyrations), and N_{max} (130 gyrations). Table 4.17 shows the mixture's compaction and volumetric properties. Figure 4.20 illustrates specimen densification versus number of gyrations. Graphs of air-void content, percent VMA, percent VFA, and dust proportion are shown in Figure 4.21 to Figure 4.24. The Superpave OBC was found to be 5.2 percent by TWM. The value of each of these properties at the Superpave OBC is indicated by the arrow in each of the figures for this mix.

Table 4.16: Summary of Design Properties for Mix D

Mix Design Properties	Contractor JMF Hveem Design OBC Properties	UCPRC Lab Testing Superpave Design OBC Properties	Superpave Design Specification
Hveem %OBC (DWA)	4.8	5.5	
Hveem %OBC (TWM)	4.6	5.2	
% Air Void Content	4.0	4.0	4.0
% VMA	13.1	14.0	>13.5
% VFA	69.0	71.2	65 – 75
Dust Proportion	1.0	1.4	0.6 – 1.3
%Gmm @ N_{ini}=8	n/a	87.2	<92
%Gmm @ N_{max}=130	n/a	97.2	<98

Table 4.17: Compaction and Volumetric Properties for Superpave OBC for Mix D

%AC (TWM)	Compaction Properties			Volumetric Properties @ N_{des} = 85			Dust Proportion
	%G_{mm} @ N=8	%G_{mm} @ N=85	%G_{mm} @ N=130	%AirVoids	%VMA	%VFA	
Criteria	<92	96	<98	4.0	>13.5	65 – 75	0.6 – 1.3
4.1	85.2	93.1	94.3	6.9	14.3	51.5	1.9
4.6	85.4	93.8	95.1	6.2	14.2	56.6	1.7
5.0	86.9	95.5	96.8	4.5	14.0	67.9	1.5
5.5	87.7	96.7	97.9	3.3	14.0	76.3	1.3

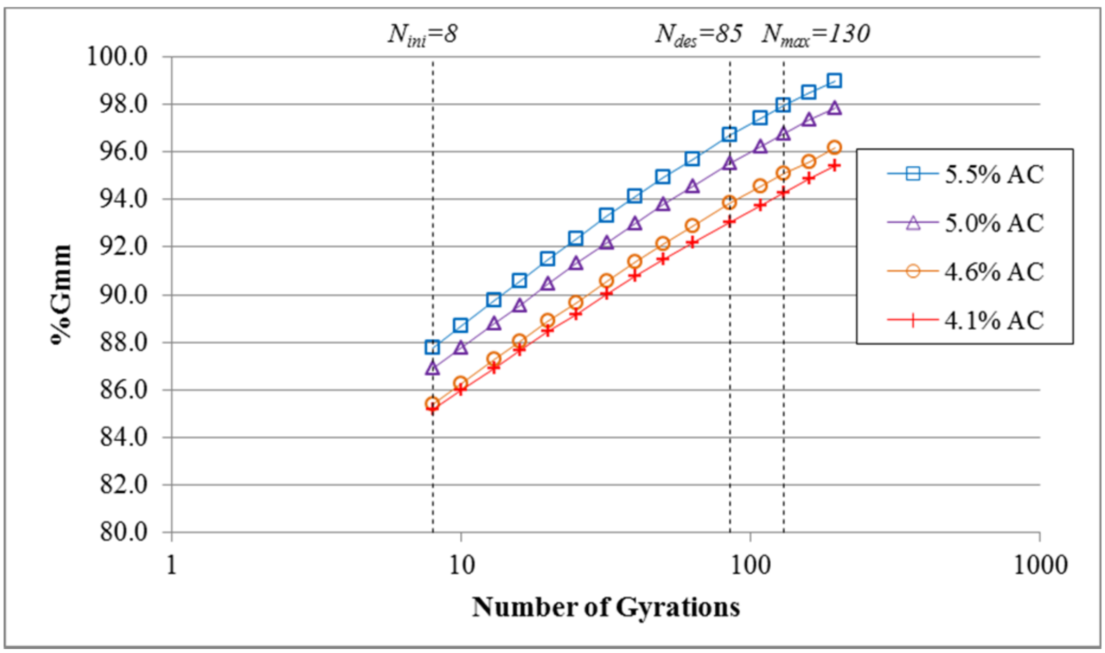

Figure 4.20: Mixture density versus number of gyrations for Mix D.

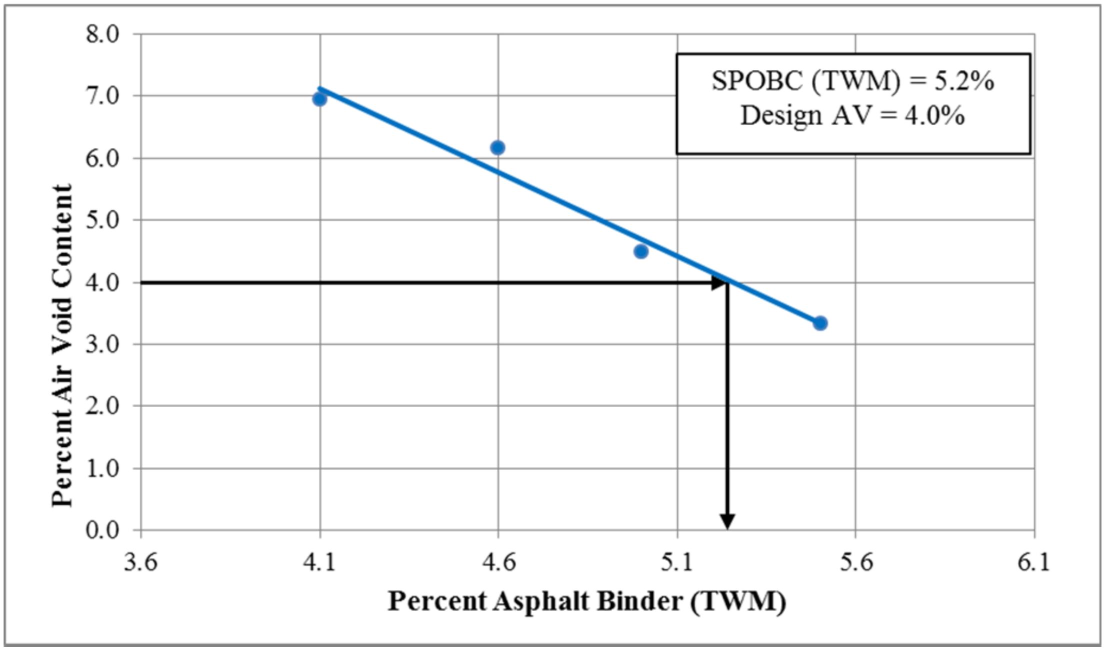

Figure 4.21: Selection of Superpave OBC based on percent air-void content versus percent asphalt binder for Mix D.
(Note: The arrow in the figure shows the Superpave OBC selected based on the 4 percent air-void content criterion.)

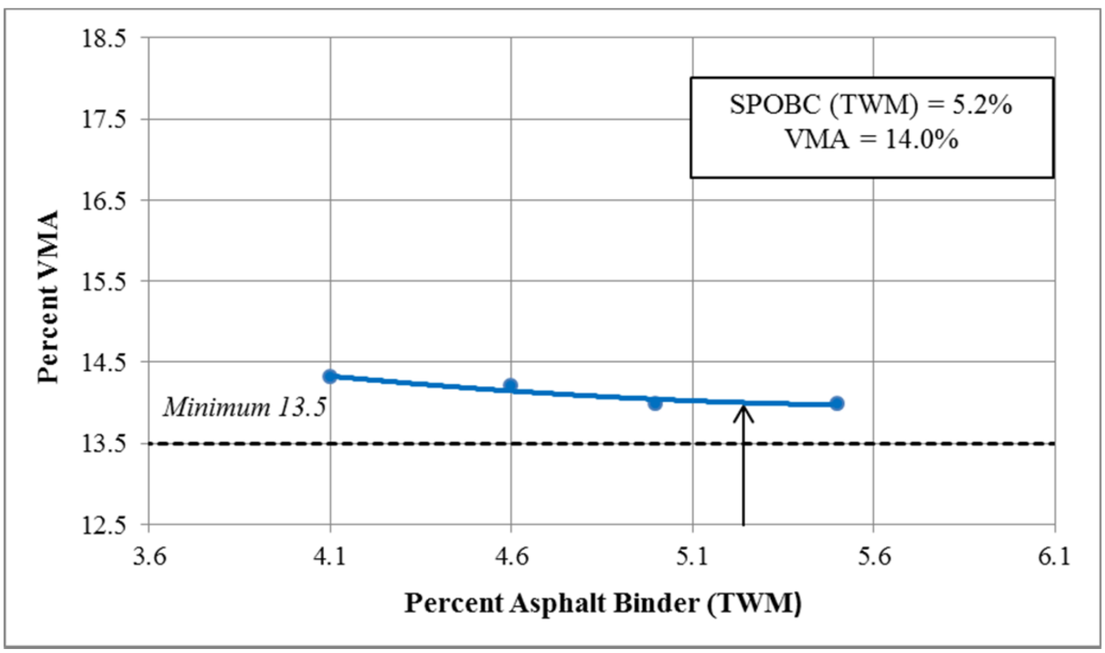

Figure 4.22: Percent VMA versus percent asphalt binder for Mix D.
(Note: The arrow in the figure indicates the value of percent VMA at the Superpave OBC.)

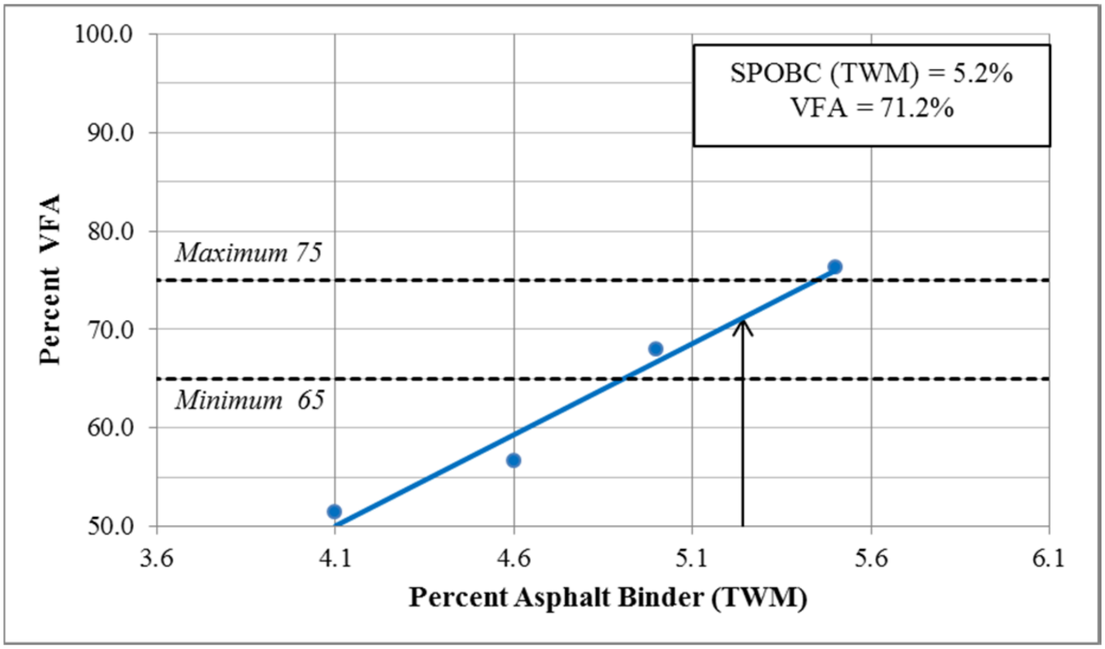

Figure 4.23: Percent VFA versus percent asphalt binder for Mix D.
(Note: The arrow in the figure indicates the value of percent VFA at the Superpave OBC.)

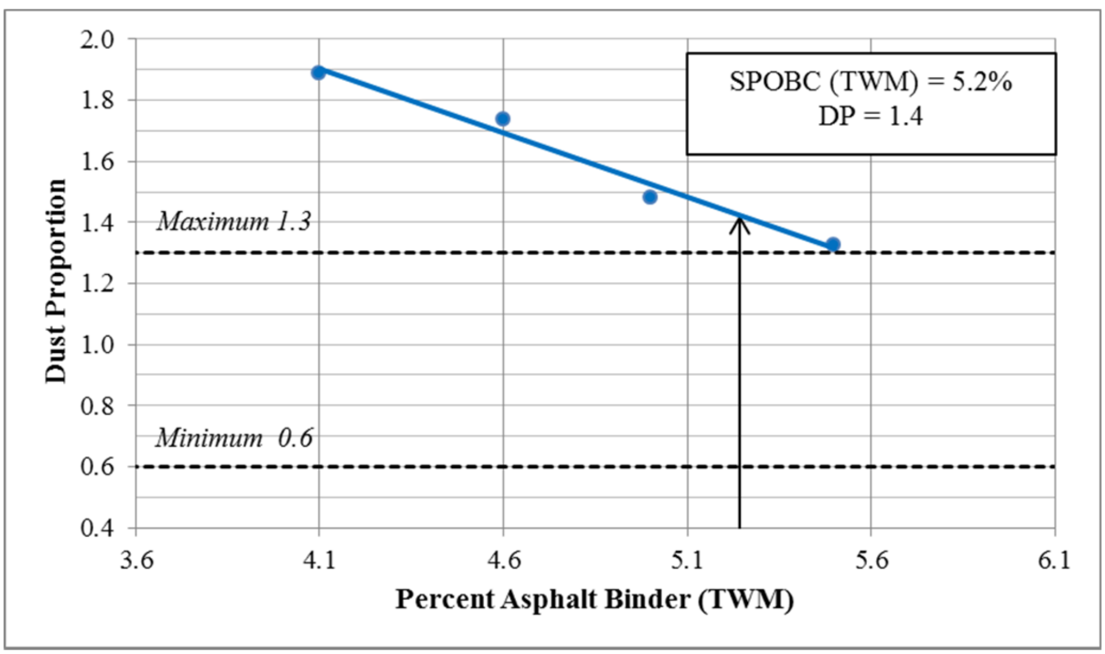

Figure 4.24: Dust proportion versus percent asphalt binder for Mix D.
(Note: The arrow in the figure indicates the dust proportion value at the Superpave OBC.)

4.1.5 Mix E

Table 4.18 shows the basic aggregate and binder information for the Mix E. Table 4.19 presents the aggregate gradation used for both the Hveem and Superpave mix designs. Figure 4.25 presents the same information on the 0.45 power gradation chart.

Table 4.18: Aggregate and Binder Type for Mix E

Mix ID	**Mix E**
NMAS	3/4 inch
RAP %	0
Aggregate Type	Alluvial
Quarry Location	Northern California
Binder Supplier	Refinery 1
Binder Grade	PG 64-16

Table 4.19: Aggregate Gradation Table for Mix E

Gradation of Aggregate Blend (Cumulative Percent Passing)				
Sieve Size		**Contractor Test Result JMF Combined Gradation**	**Operating Range**	**UCPRC Lab Test Result Sieve Analysis**
(mm)	**(in.)**			
25	1	**100.0**	100	**100.0**
19	3/4	**99.0**	94 – 100	**97.7**
12.5	1/2	**82.0**	76 – 88	**83.5**
9.5	3/8	**71.0**		**70.1**
4.75	#4	**47.0**	40 – 54	**46.2**
2.36	#8	**34.0**	29 – 39	**23.5**
1.18	#16	**24.0**		**23.0**
0.6	#30	**18.0**	14 – 22	**16.6**
0.3	#50	**12.0**		**11.1**
0.15	#100	**8.0**		**7.3**
0.075	#200	**5.8**	3.8 – 7.8	**5.8**

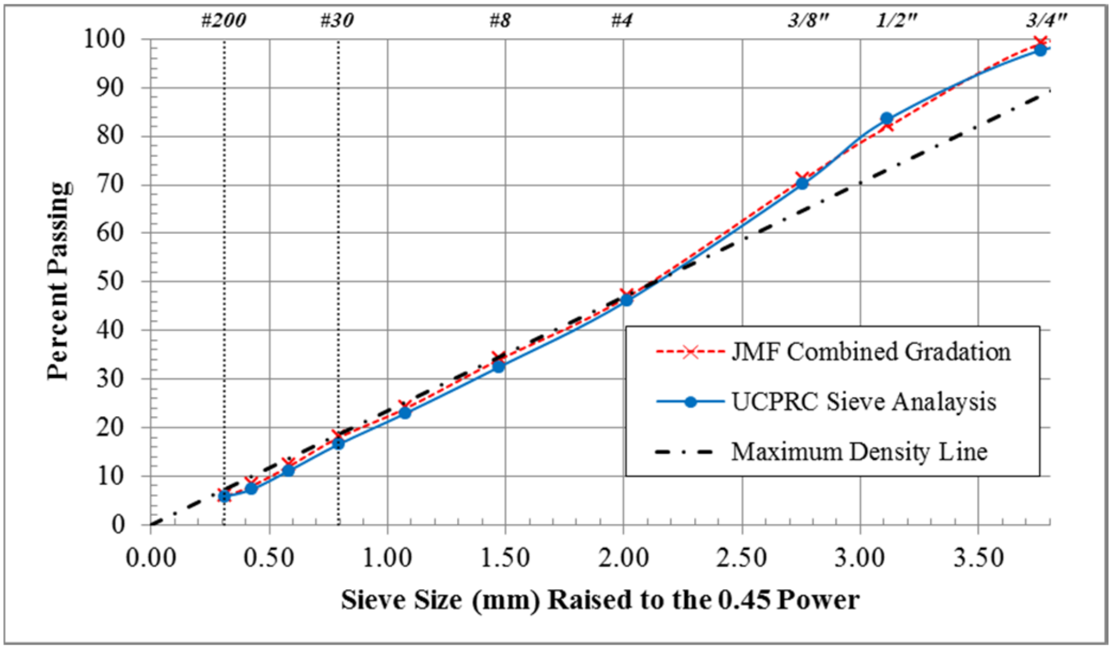

Figure 4.25: Aggregate gradation chart for Mix E.

Table 4.20 shows a comparison of design properties for the Hveem versus the Superpave mix design. For Superpave mix design, mixture properties are evaluated for four asphalt binder contents by using the densification data at N_{ini} (8 gyrations), N_{des} (85 gyrations), and N_{max} (130 gyrations). Table 4.21 shows the mixture's compaction and volumetric properties. Figure 4.26 illustrates specimen densification versus number of gyrations. Graphs of air-void content, percent VMA, percent VFA, and dust proportion are shown in Figure 4.27 to Figure 4.30. The Superpave OBC was found to be 5.2 percent by TWM. The value of each of these properties at the Superpave OBC is indicated by the arrow in each of the figures for this mix.

Table 4.20: Summary of Design Properties for Mix E

Mix Design Properties	Contractor JMF Hveem Design OBC Properties	UCPRC Lab Testing Superpave Design OBC Properties	Superpave Design Specification
Hveem %OBC (DWA)	4.8	5.5	
Hveem %OBC (TWM)	4.6	5.2	
% Air Void Content	4.0	4.0	4.0
% VMA	13.1	13.5	>13.5
% VFA	69.0	71.2	65 – 75
Dust Proportion	1.0	1.5	0.6 – 1.3
%Gmm @ N_{ini}=8	n/a	87.3	<92
%Gmm @ N_{max}=130	n/a	97.3	<98

Table 4.21: Compaction and Volumetric Properties for Superpave OBC for Mix E

%AC (TWM)	Compaction Properties			Volumetric Properties @ N_{des} = 85			Dust Proportion
	%G_{mm} @ N=8	%G_{mm} @ N=85	%G_{mm} @ N=130	%AirVoids	%VMA	%VFA	
Criteria	<92	96	<98	4.0	>13.5	65 – 75	0.6 – 1.3
4.1	85.4	93.1	94.3	6.9	14.4	51.7	1.9
4.6	86.7	95.2	96.4	4.8	13.6	64.7	1.6
5.0	87.5	96.2	97.5	3.8	13.4	71.7	1.5
5.5	87.5	96.4	97.7	3.6	13.9	74.1	1.4

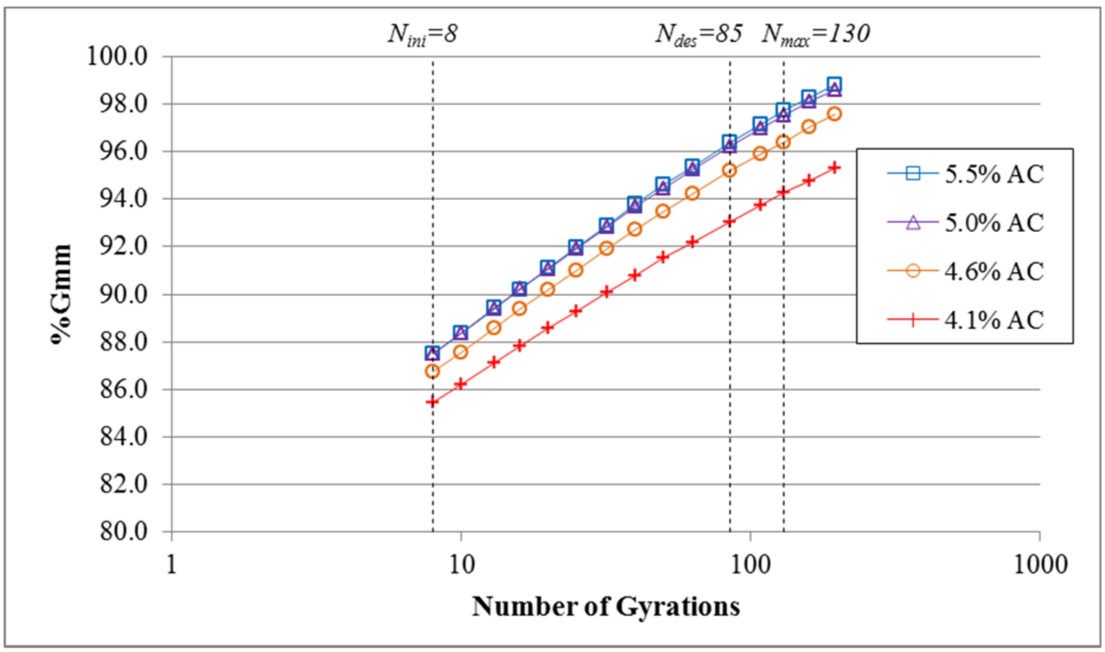

Figure 4.26: Mixture density versus number of gyrations for Mix E.

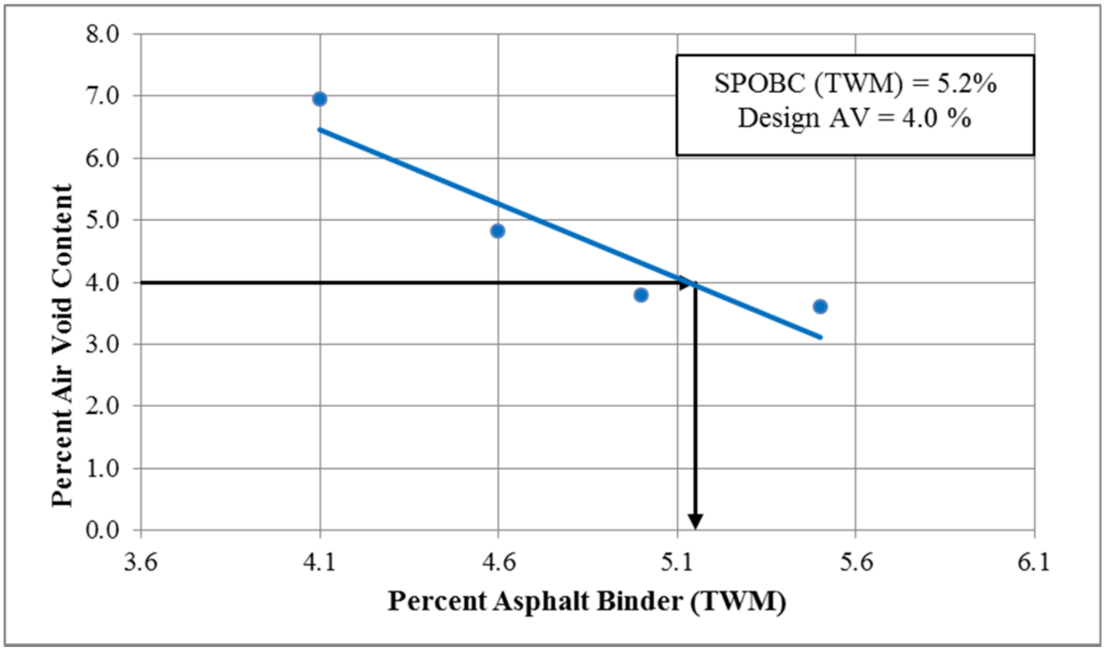

Figure 4.27: Selection of Superpave OBC based on percent air-void content versus percent asphalt binder for Mix E.
(Note: The arrow in the figure shows the Superpave OBC selected based on the 4 percent air-void content criterion.)

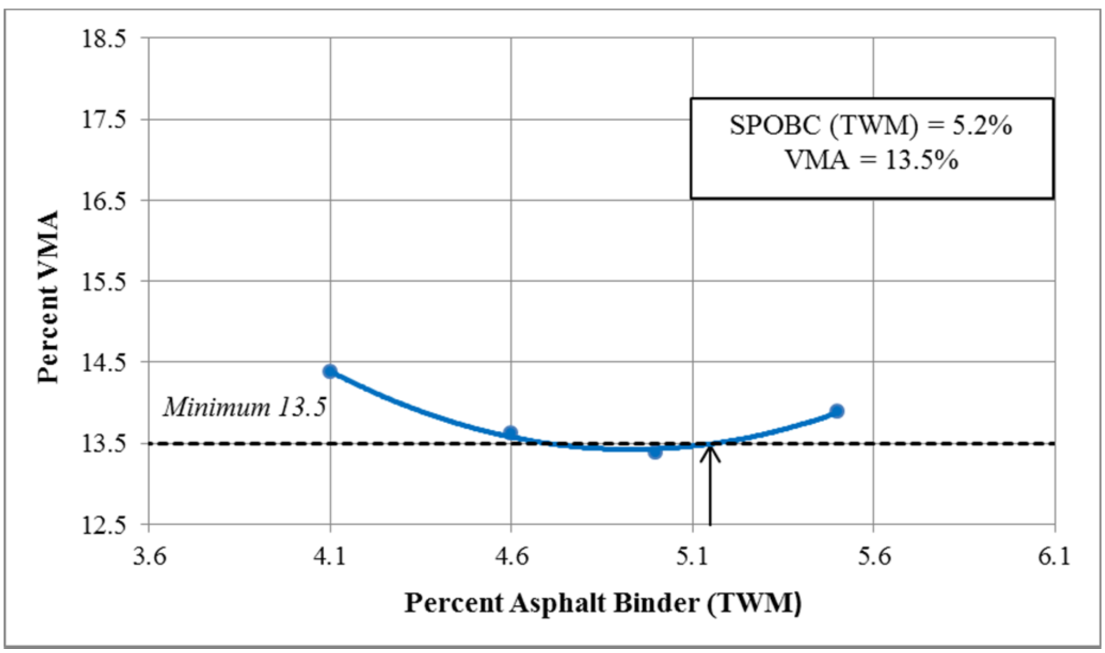

Figure 4.28: Percent VMA versus percent asphalt binder for Mix E.
(Note: The arrow in the figure indicates the value of percent VMA at the Superpave OBC.)

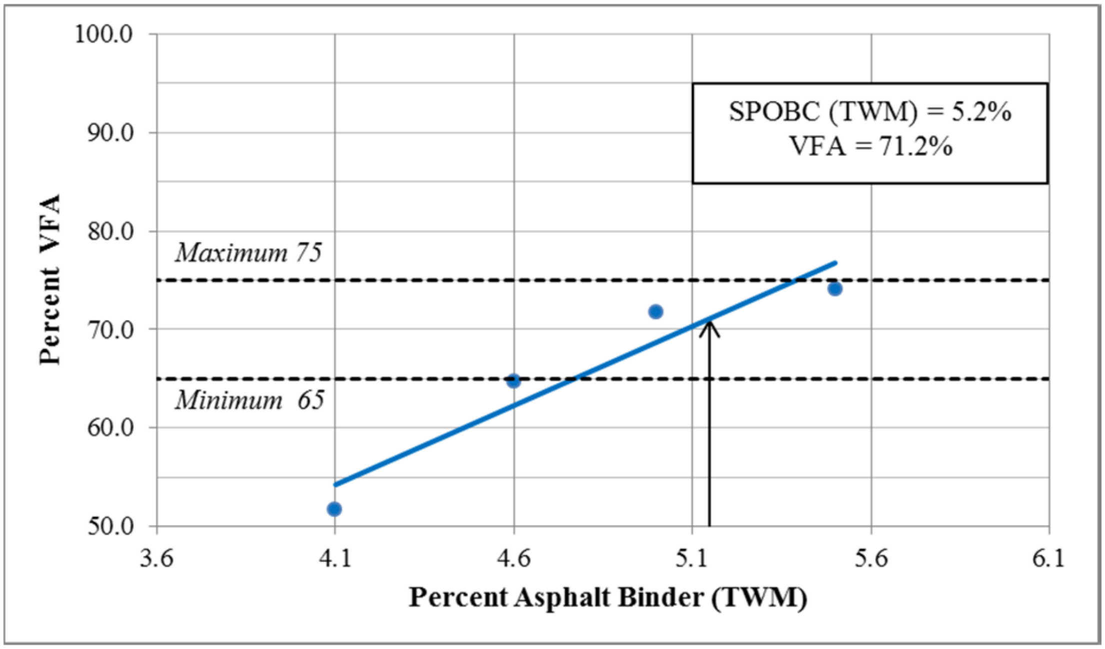

Figure 4.29: Percent VFA versus percent asphalt binder for Mix E.
(Note: The arrow in the figure indicates the value of percent VFA at the Superpave OBC.)

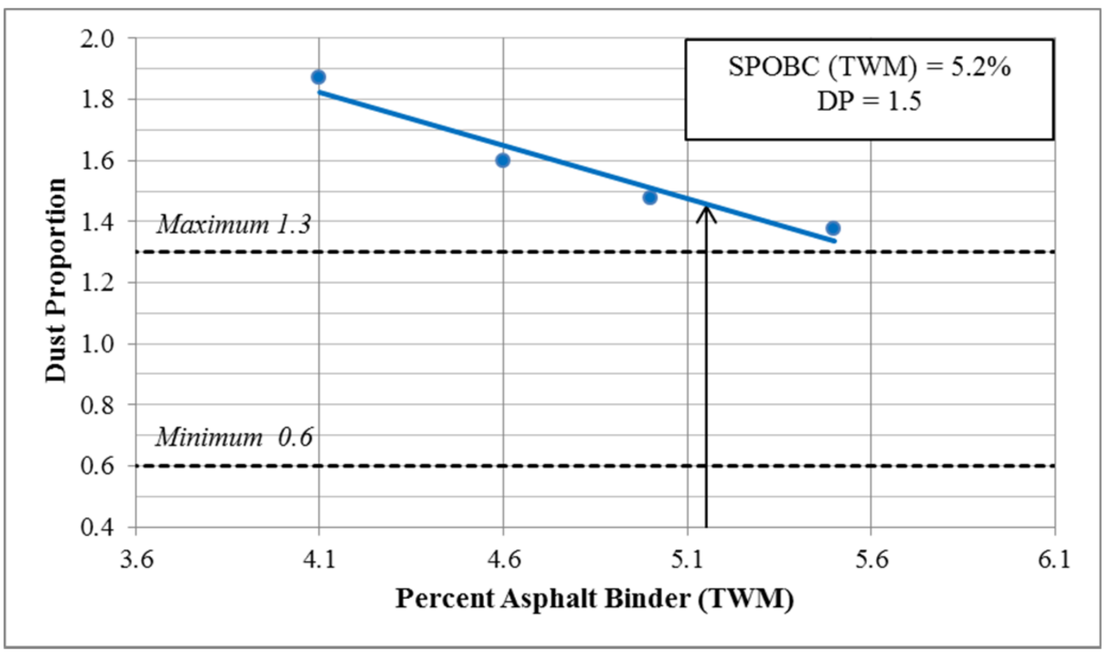

Figure 4.30: Dust proportion versus percent asphalt binder for Mix E.
(Note: The arrow in the figure indicates the dust proportion value at the Superpave OBC.)

4.1.6 Mix F

Table 4.22 shows the basic aggregate and binder information for the Mix F. Table 4.23 presents the aggregate gradation used for both the Hveem and Superpave mix designs. Figure 4.31 presents the same information on the 0.45 power gradation chart.

Table 4.22: Aggregate and Binder Type for Mix F

Mix ID	Mix F
NMAS	3/4 inch
RAP %	15
Aggregate Type	Alluvial
Quarry Location	Northern California
Binder Supplier	Refinery 1
Binder Grade	PG 64-16

Table 4.23: Aggregate Gradation Table for Mix F

Gradation of Aggregate Blend (Cumulative Percent Passing)				
Sieve Size		Contractor Test Result JMF Combined Gradation	Operating Range	UCPRC Lab Test Result Sieve Analysis
(mm)	(in.)			
25	1	**100.0**	100	**100.0**
19	3/4	**98.0**	93 – 100	**98.2**
12.5	1/2	**84.0**	78 – 90	**86.4**
9.5	3/8	**75.0**		**73.9**
4.75	#4	**52.0**	45 – 59	**51.8**
2.36	#8	**34.0**	29 – 39	**33.7**
1.18	#16	**22.0**		**22.9**
0.6	#30	**15.0**	11 – 19	**15.0**
0.3	#50	**9.0**		**9.8**
0.15	#100	**6.0**		**6.5**
0.075	#200	**3.8**	1.8 – 5.8	**4.1**

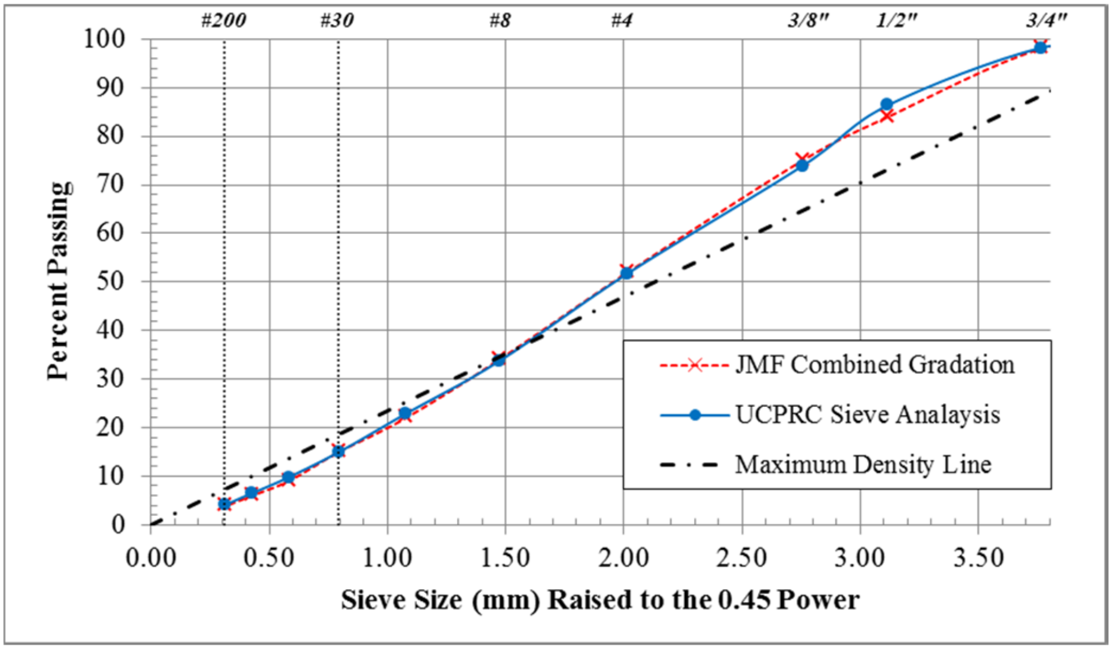

Figure 4.31: Aggregate gradation chart for Mix F.

Table 4.24 shows a comparison of design properties for the Hveem versus the Superpave mix design. For Superpave mix design, mixture properties are evaluated for four asphalt binder contents by using the densification data at N_{ini} (8 gyrations), N_{des} (85 gyrations), and N_{max} (130 gyrations). Table 4.25 shows the mixture's compaction and volumetric properties. Figure 4.32 illustrates the specimen densification versus number of gyrations. Graphs of air-void content, percent VMA, percent VFA, and dust proportion are shown in Figure 4.33 to Figure 4.36. The Superpave OBC was found to be 5.8 percent by TWM. The value of each of these properties at the Superpave OBC is indicated by the arrow in each of the figures for this mix.

At design air-void content of four percent, percent VFA was above 75. With a ±0.5 percent tolerance for a laboratory mixed and compacted specimen, the Superpave OBC of 5.8 percent was found at a design air-void content of 4.5 percent to meet the specification.

Table 4.24: Summary of Design Properties for Mix F

Mix Design Properties	Contractor JMF Hveem Design OBC Properties	UCPRC Lab Testing Superpave Design OBC Properties	Superpave Design Specification
Hveem %OBC (DWA)	5.0	6.2	
Hveem %OBC (TWM)	4.8	5.8	
% Air Void Content	4.0	4.5	4.0
% VMA	13.0	18.6	>13.5
% VFA	69.0	74.6	65-75
Dust Proportion	0.9	0.7	0.6-1.3
%Gmm @ N_{ini}=8	n/a	86.3	<92
%Gmm @ N_{max}=130	n/a	96.7	<98

Table 4.25: Compaction and Volumetric Properties for Superpave OBC for Mix F

%AC (TWM)	Compaction Properties			Volumetric Properties @ N_{des} = 85			Dust Proportion
	$\%G_{mm}$ @ N=8	$\%G_{mm}$ @ N=85	$\%G_{mm}$ @ N=130	%AirVoids	%VMA	%VFA	
Criteria	<92	96	<98	4.0	>13.5	65 – 75	0.6 – 1.3
4.3	82.4	90.7	92.0	9.3	19.2	51.7	0.9
4.8	83.6	92.0	93.3	8.0	19.0	58.0	0.8
5.2	85.5	94.2	95.5	5.8	18.5	68.6	0.7
5.7	85.7	94.8	96.1	5.2	18.6	71.9	0.7

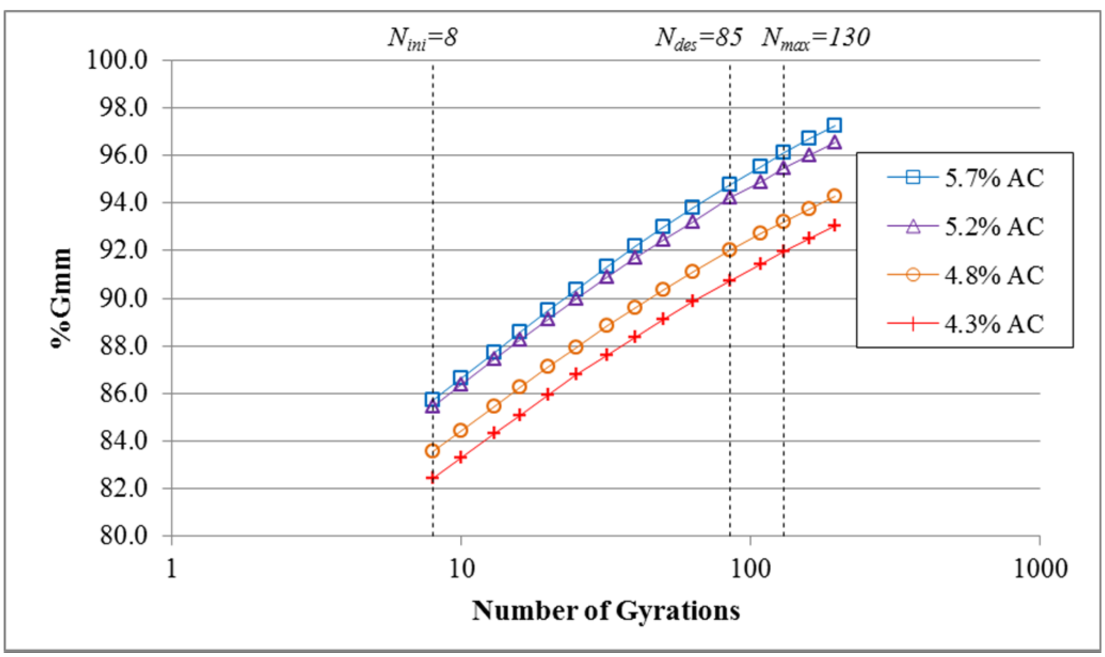

Figure 4.32: Mixture density versus number of gyrations for Mix F.

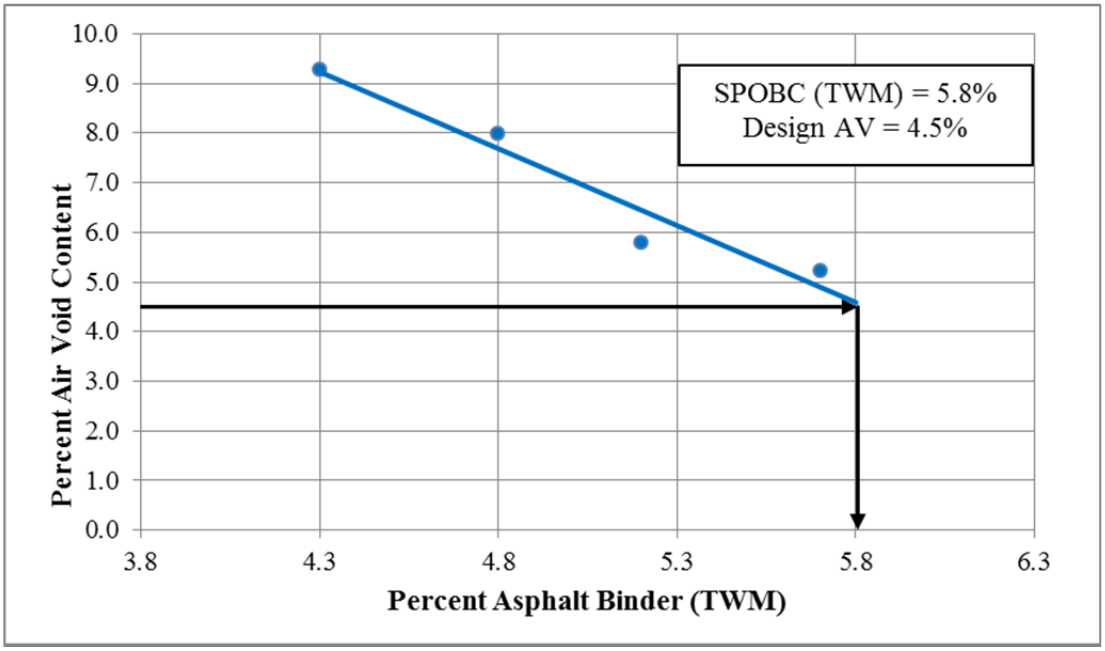

Figure 4.33: Selection of Superpave OBC based on percent air-void content versus percent asphalt binder for Mix F. (Note: The arrow in the figure shows the Superpave OBC selected based on the 4.5 percent air-void content criterion.)

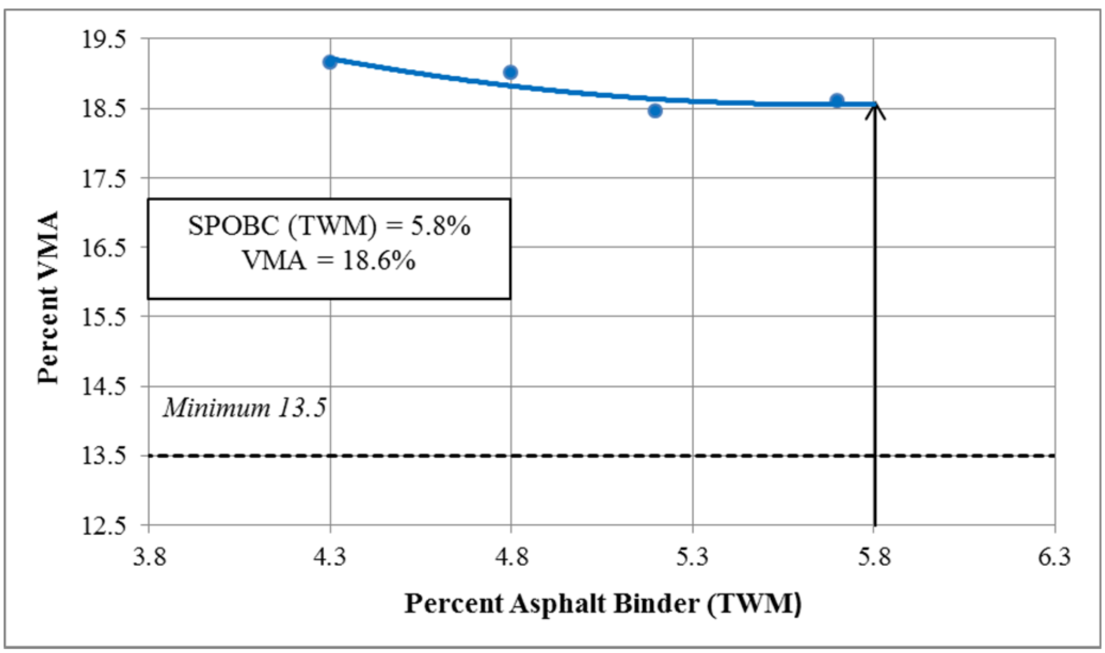

Figure 4.34: Percent VMA versus percent asphalt content for Mix F. (Note: The arrow in the figure indicates the value of percent VMA at the Superpave OBC.)

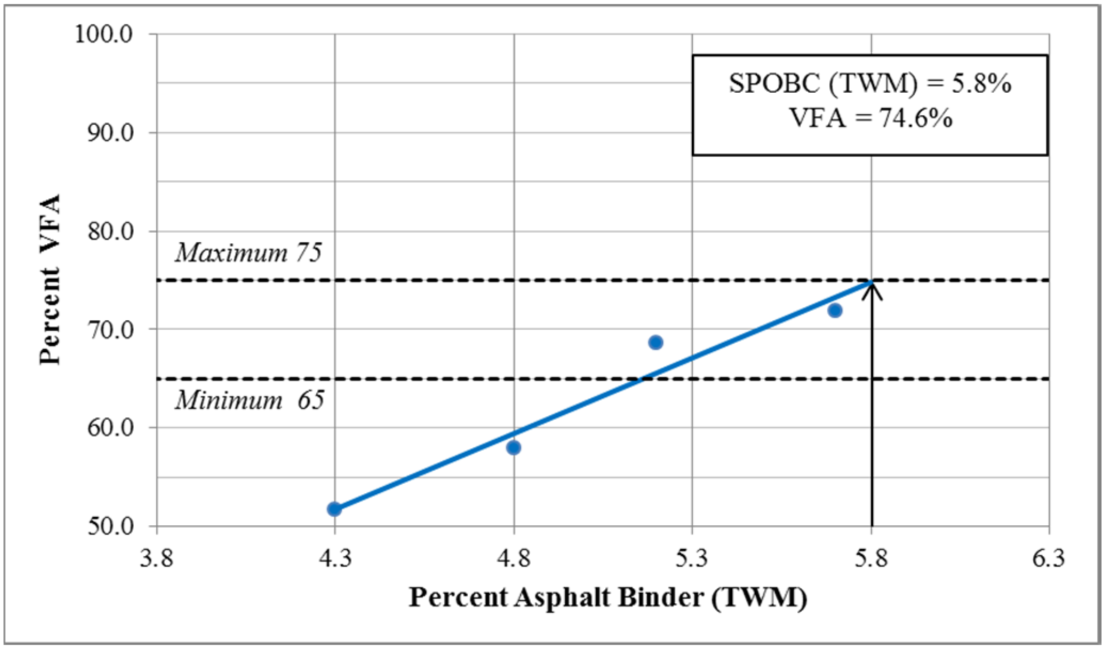

Figure 4.35: Percent VFA versus percent asphalt binder for Mix F.
(Note: The arrow in the figure indicates the value of percent VFA at the Superpave OBC.)

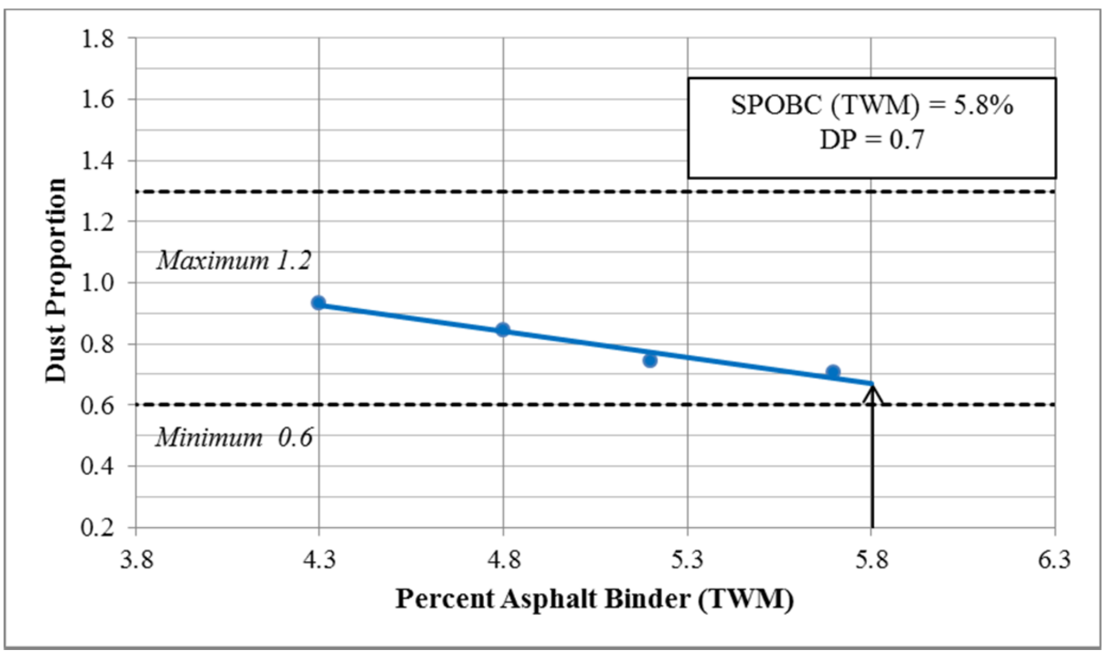

Figure 4.36: Dust proportion versus percent asphalt binder for Mix F.
(Note: The arrow in the figure indicates the dust proportion value at the Superpave OBC.)

4.1.7 Mix G

Table 4.26 shows the basic aggregate and binder information for the Mix G. Table 4.27 presents the aggregate gradation used for both the Hveem and Superpave mix designs. Figure 4.37 presents the same information on the 0.45 power gradation chart.

Table 4.26: Aggregate and Binder Type for Mix G

Mix ID	**Mix G**
NMAS	1/2 inch
RAP %	0
Aggregate Type	Basalt
Quarry Location	Central California
Binder Supplier	Refinery 2
Binder Grade	PG 64-16

Table 4.27: Aggregate Gradation Table for Mix G

Gradation of Aggregate Blend (Cumulative Percent Passing)				
Sieve Size		**Contractor Test Result JMF Combined Gradation**	**Operating Range**	**UCPRC Lab Test Result Sieve Analysis**
(mm)	**(in.)**			
25	1	**100.0**	100	**100.0**
19	3/4	**100.0**	100	**100.0**
12.5	1/2	**99.0**	93 – 100	**99.0**
9.5	3/8	**90.0**	84 – 96	**90.1**
4.75	#4	**59.0**	52 – 66	**60.0**
2.36	#8	**45.0**	40 – 50	**44.4**
1.18	#16	**31.0**		**30.4**
0.6	#30	**22.0**	18 – 26	**22.0**
0.3	#50	**14.0**		**16.3**
0.15	#100	**7.0**		**7.8**
0.075	#200	**5.1**	3.1 – 7.1	**5.4**

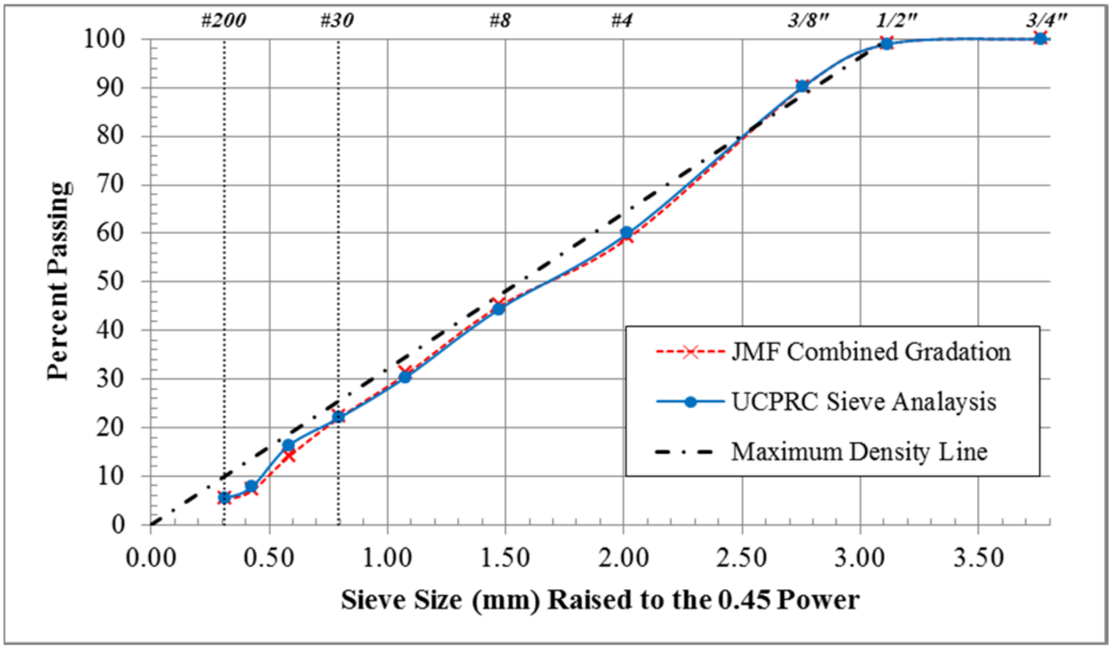

Figure 4.37: Aggregate gradation chart for Mix G.

Table 4.28 shows a comparison of design properties for the Hveem versus the Superpave mix design. For Superpave mix design, mixture properties are evaluated for four asphalt binder contents by using the densification data at N_{ini} (8 gyrations), N_{des} (85 gyrations), and N_{max} (130 gyrations). Table 4.29 shows the mixture's compaction and volumetric properties. Figure 4.38 illustrates the specimen densification versus number of gyrations. Graphs of air-void content, percent VMA, percent VFA, and dust proportion are shown in Figure 4.39 to Figure 4.42. The Superpave OBC was found to be 6.5 percent by TWM. The value of each of these properties at the Superpave OBC is indicated by the arrow in each of the figures for this mix.

At design air-void content of four percent, percent VFA was above 75. With a ±0.5 percent tolerance for a laboratory mixed and compacted specimen, the Superpave OBC of 6.5 percent was found at a design air-void content of 4.3 percent to meet the specification.

Table 4.28: Summary of Design Properties for Mix G

Mix Design Properties	Contractor JMF Hveem Design OBC Properties	UCPRC Lab Testing Superpave Design OBC Properties	Superpave Design Specification
Hveem %OBC (DWA)	6.2	6.8	
Hveem %OBC (TWM)	5.8	6.4	
% Air Void Content	4.15	4.3	4.0
% VMA	16.5	16.9	>13.5
% VFA	74.9	74.6	65 – 75
Dust Proportion	0.9	1.0	0.6 – 1.3
%Gmm @ N_{ini}=8	n/a	86.6	<92
%Gmm @ N_{max}=130	n/a	97.0	<98

Table 4.29: Compaction and Volumetric Properties for Superpave OBC for Mix G

%AC (TWM)	Compaction Properties			Volumetric Properties @ N_{des} = 85			Dust Proportion
	$\%G_{mm}$ @ N=8	$\%G_{mm}$ @ N=85	$\%G_{mm}$ @ N=130	%AirVoids	%VMA	%VFA	
Criteria	<92	96	<98	4.0	>13.5	65 – 75	0.6 –1.3
5.4	84.6	92.9	94.0	7.1	17.0	58.0	1.3
5.8	85.5	94.2	95.4	5.8	17.0	65.7	1.1
6.3	86.5	95.4	96.7	4.6	16.9	73.1	1.0
6.7	87.0	96.3	97.6	3.7	16.9	78.2	1.0

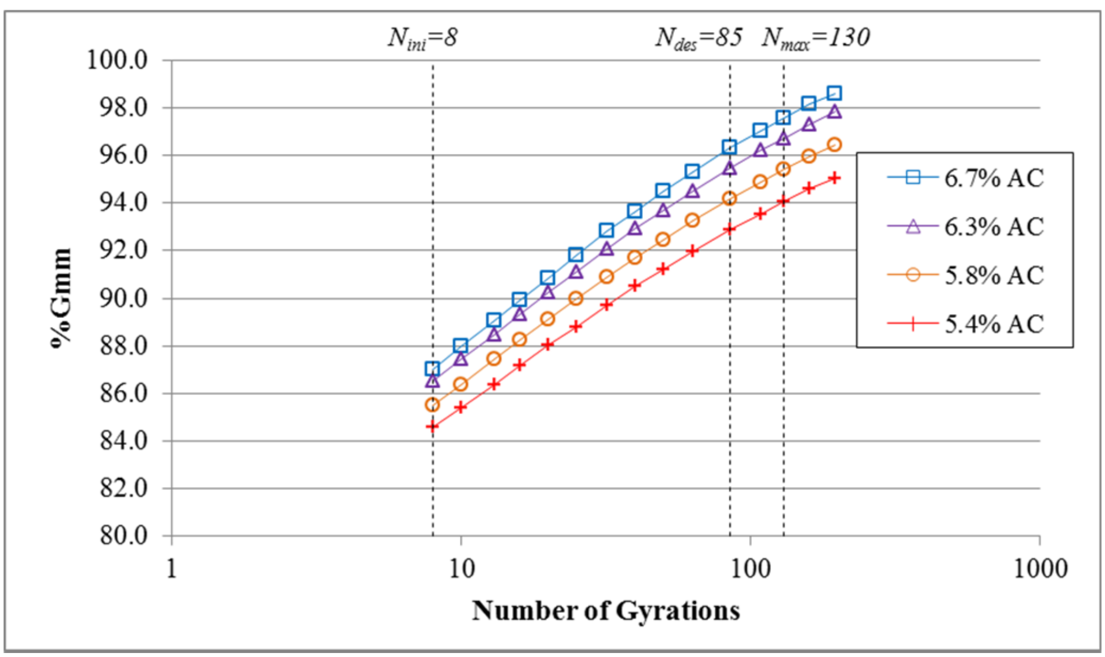

Figure 4.38: Mixture density versus number of gyrations for Mix G.

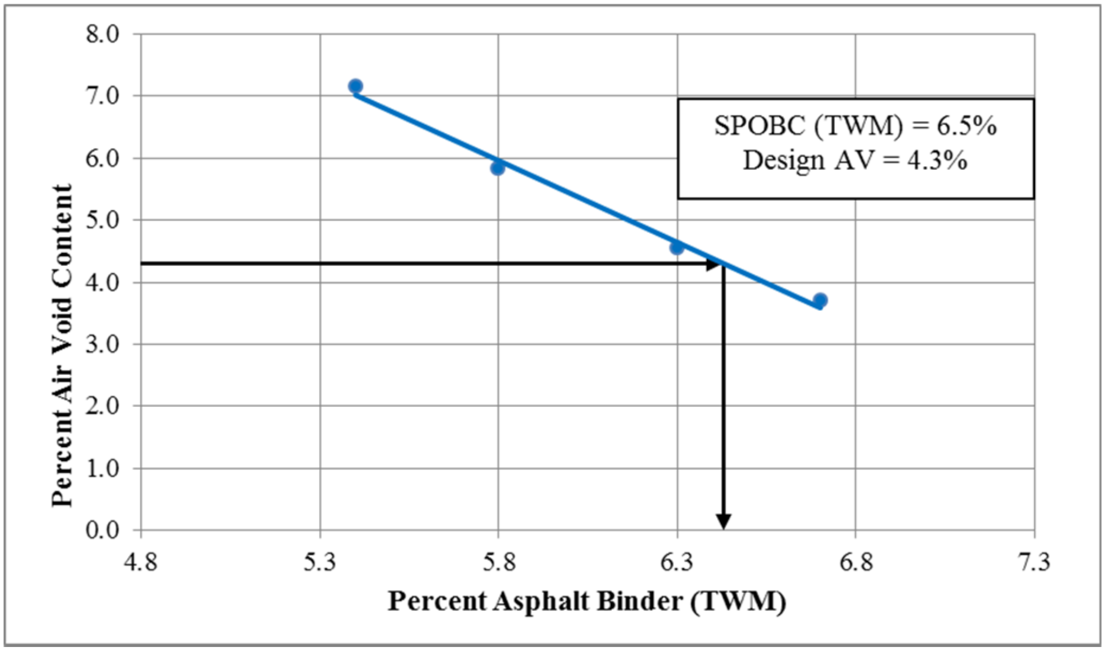

Figure 4.39: Selection of Superpave OBC based percent air-void content versus percent asphalt binder for Mix G. (Note: The arrow in the figure shows the Superpave OBC selected based on the 4.3 percent air-void content criterion.)

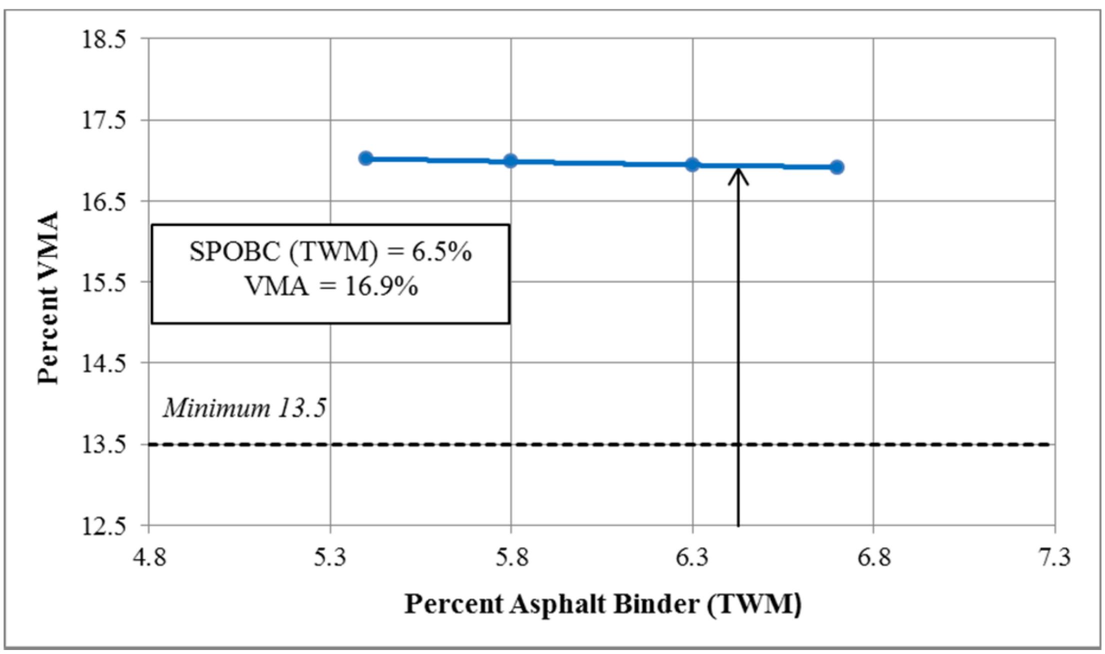

Figure 4.40: Percent VMA versus percent asphalt binder for Mix G.
(Note: The arrow in the figure indicates the value of percent VMA at the Superpave OBC.)

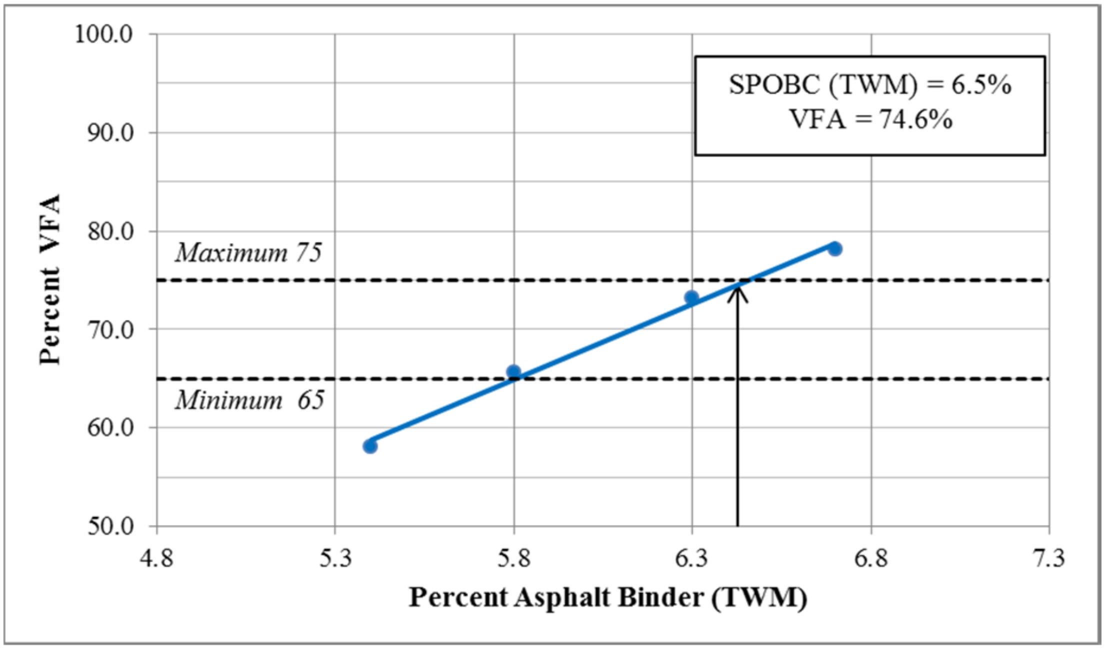

Figure 4.41: Percent VFA versus percent asphalt binder for Mix G.
(Note: The arrow in the figure indicates the value of percent VFA at the Superpave OBC.)

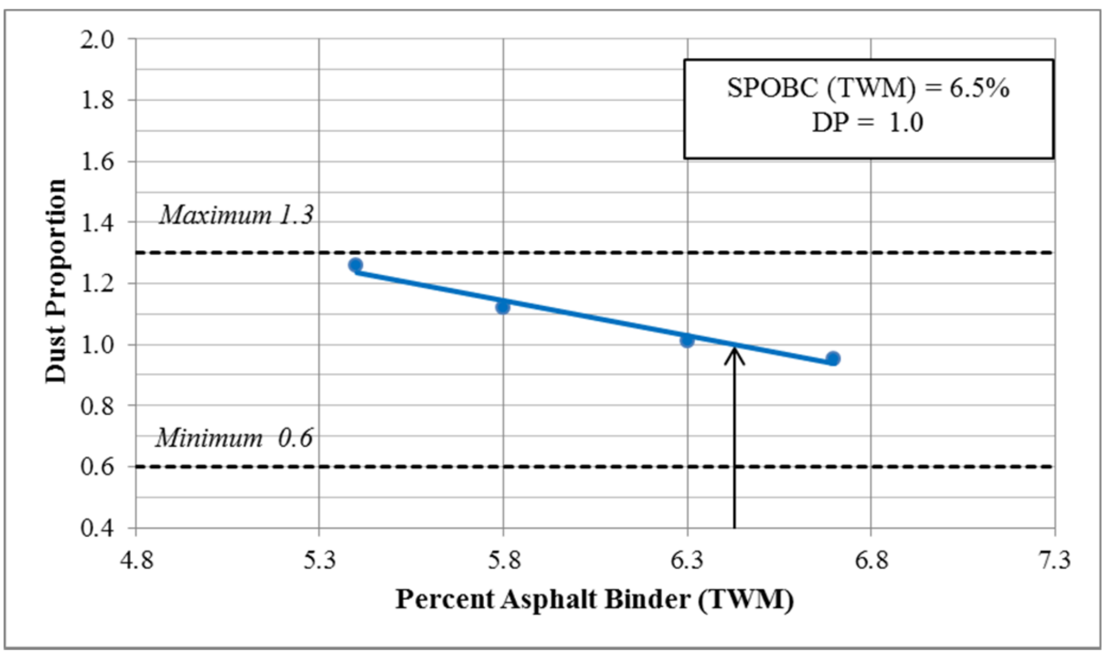

Figure 4.42: Dust proportion versus percent asphalt binder for Mix G.
(Note: The arrow in the figure indicates the dust proportion value at the Superpave OBC.)

4.1.8 Mix H

Table 4.30 shows the basic aggregate and binder information for Mix H. Table 4.31 presents the aggregate gradation used for both the Hveem and Superpave mix designs. Figure 4.43 presents the same information on the 0.45 power gradation chart.

Table 4.30: Aggregate and Binder Type for Mix H

Mix ID	**Mix H**
NMAS	3/4 inch
RAP %	0
Aggregate Type	Granite
Quarry Location	Central California
Binder Supplier	Refinery 1
Binder Grade	PG 70-10

Table 4.31: Aggregate Gradation Table for Mix H

Gradation of Aggregate Blend (Cumulative Percent Passing)				
Sieve Size		**Contractor Test Result JMF Combined Gradation**	**Operating Range**	**UCPRC Lab Test Result Sieve Analysis**
(mm)	**(in.)**			
25	1	**100.0**		**100.0**
19	3/4	**100.0**		**99.3**
12.5	1/2	**87.0**		**85.9**
9.5	3/8	**70.0**		**70.1**
4.75	#4	**50.0**		**50.3**
2.36	#8	**38.0**		**37.9**
1.18	#16	**28.0**		**26.1**
0.6	#30	**18.0**		**18.0**
0.3	#50	**12.0**		**12.2**
0.15	#100	**8.0**		**8.3**
0.075	#200	**5.0**		**5.0**

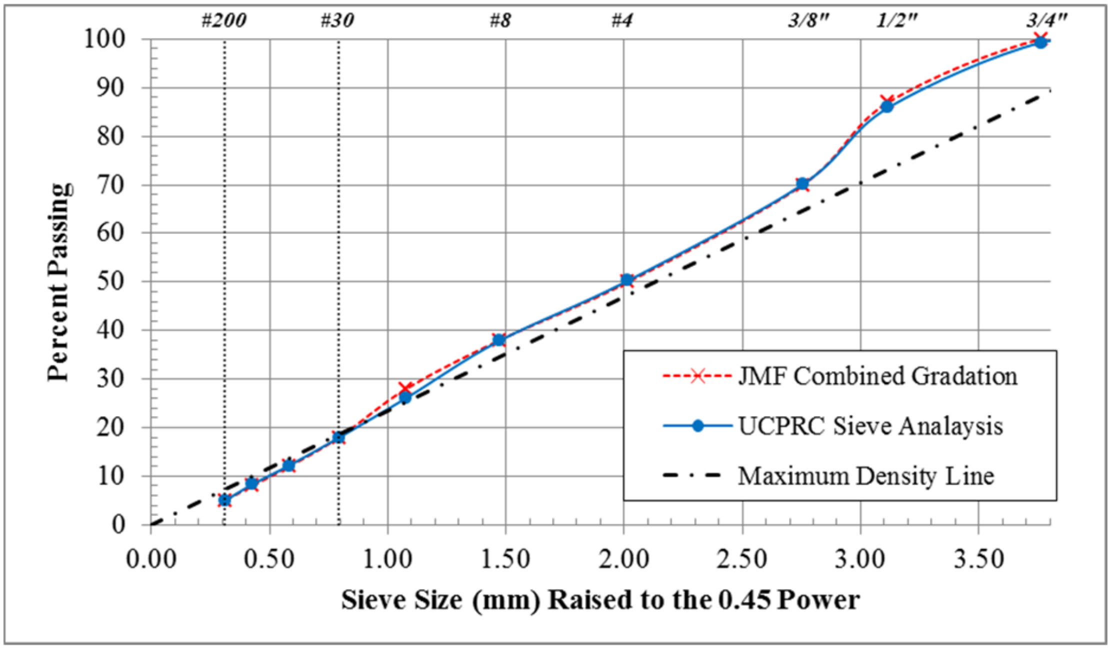

Figure 4.43: Aggregate gradation chart for Mix H.

Table 4.32 shows a comparison of design properties for the Hveem versus the Superpave mix design. For Superpave mix design, mixture properties are evaluated for four asphalt binder contents by using the densification data at N_{ini} (8 gyrations), N_{des} (85 gyrations), and N_{max} (130 gyrations). Table 4.33 shows the mixture's compaction and volumetric properties. Figure 4.44 illustrates the specimen densification versus number of gyrations. Graphs of air-void content, percent VMA, percent VFA, and dust proportion are shown in Figure 4.45 to Figure 4.48. The Superpave OBC was found to be 5.5 percent by TWM. The value of each of these properties at the Superpave OBC is indicated by the arrow in each of the figures for this mix.

Table 4.32: Summary of Design Properties for Mix H

Mix Design Properties	Contractor JMF Hveem Design OBC Properties	UCPRC Lab Testing Superpave Design OBC Properties	Superpave Design Specification
Hveem %OBC (DWA)	5.1	5.9	
Hveem %OBC (TWM)	4.9	5.5	
% Air Void Content	4.0	4.0	4.0
% VMA	16.0	18.1	>13.5
% VFA	76.0	73.9	65 – 75
Dust Proportion	1.1	0.9	0.6 – 1.3
%Gmm @ N_{ini}=8	n/a	87.0	<92
%Gmm @ N_{max}=130	n/a	97.2	<98

Table 4.33: Compaction and Volumetric Properties for Mix H

%AC (TWM)	Compaction Properties			Volumetric Properties @ N_{des} = 85			Dust Proportion
	$\%G_{mm}$ @ N=8	$\%G_{mm}$ @ N=85	$\%G_{mm}$ @ N=130	%AirVoids	%VMA	%VFA	
Criteria	<92	96	<98	4.0	>13.5	65 – 75	0.6 – 1.3
4.4	83.6	91.6	92.8	8.4	18.8	54.5	1.2
4.9	85.1	93.5	94.8	6.5	18.7	59.6	1.1
5.3	86.2	95.0	96.3	5.0	18.3	68.7	0.9
5.7	87.3	96.4	97.6	3.6	17.9	77.1	0.9

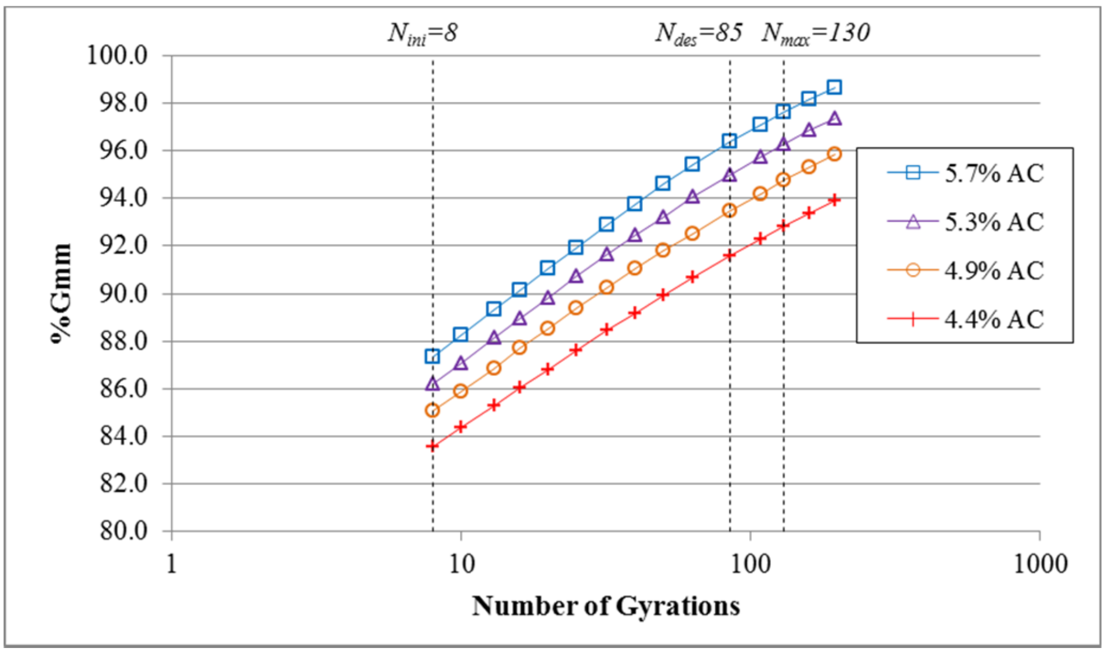

Figure 4.44: Mixture density versus number of gyrations for Mix H.

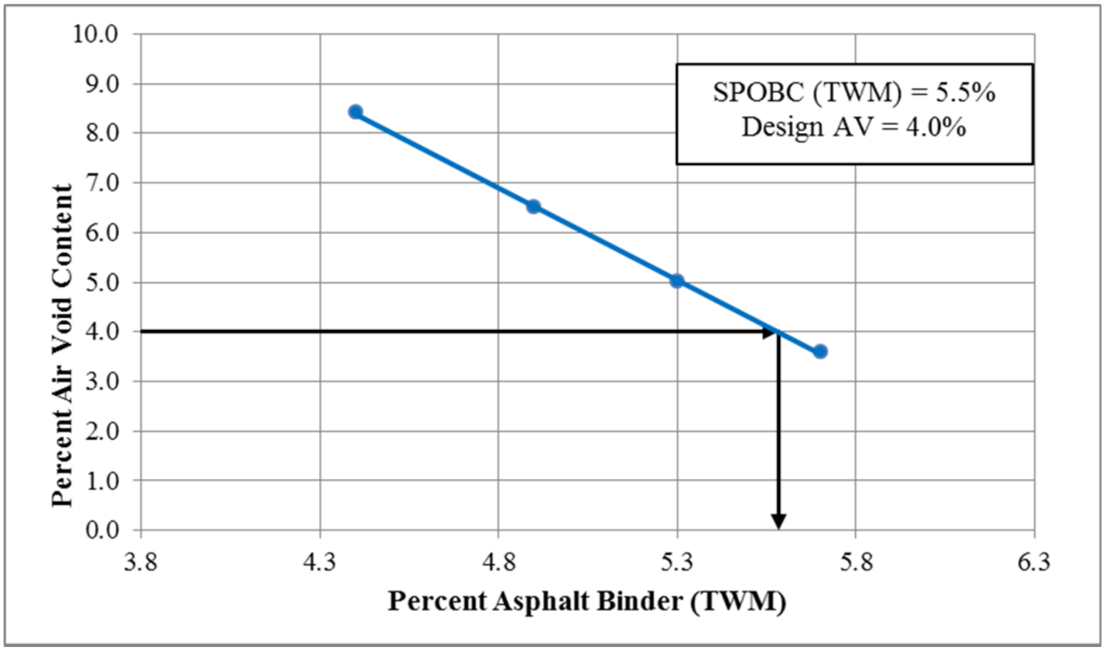

Figure 4.45: Selection of Superpave OBC based percent air-void content versus percent asphalt binder for Mix H. (Note: The arrow in the figure shows the Superpave OBC selected based on the 4 percent air-void content criterion.)

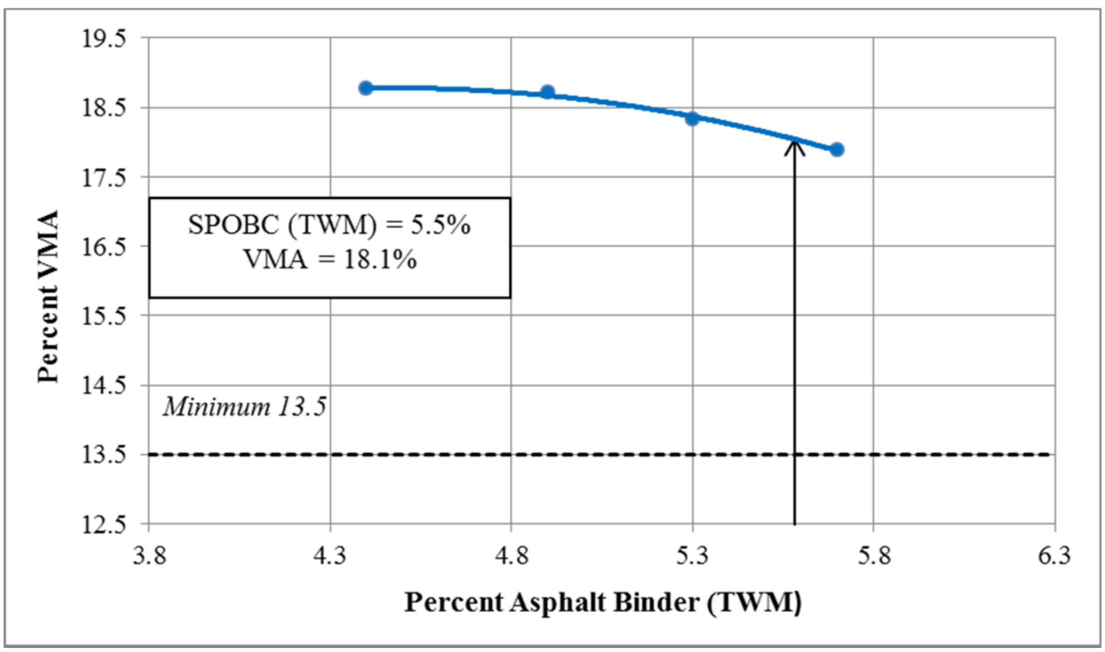

Figure 4.46: Percent VMA versus percent asphalt binder for Mix H. (Note: The arrow in the figure indicates the value of percent VMA at the Superpave OBC.)

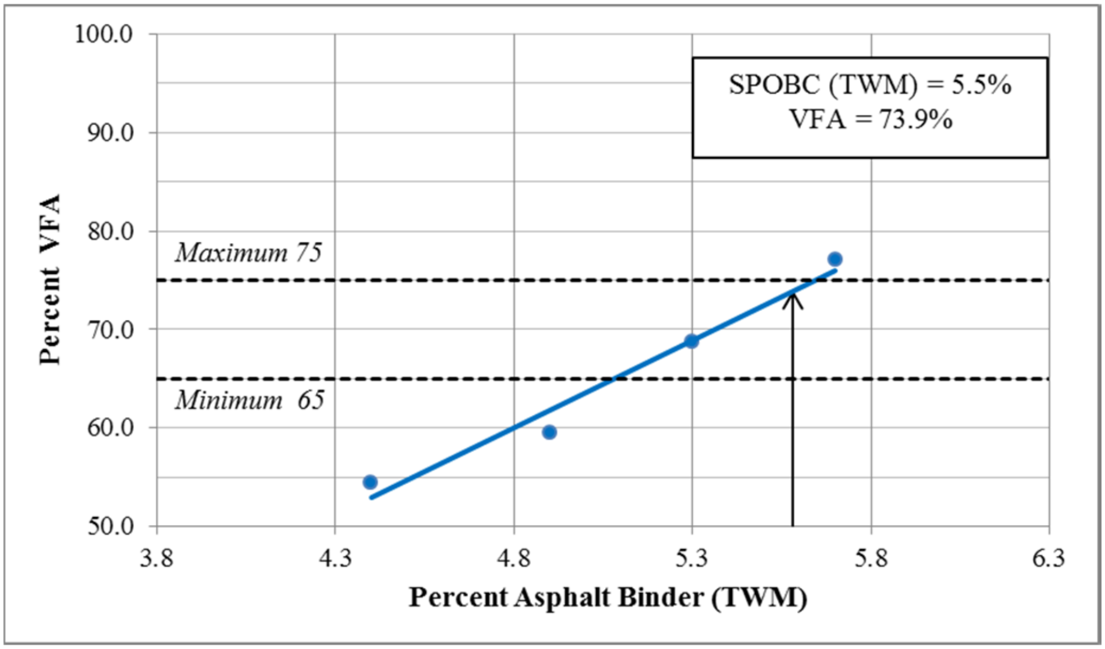

Figure 4.47: Percent VFA versus percent asphalt binder for Mix H.
(Note: The arrow in the figure indicates the value of percent VFA at the Superpave OBC.)

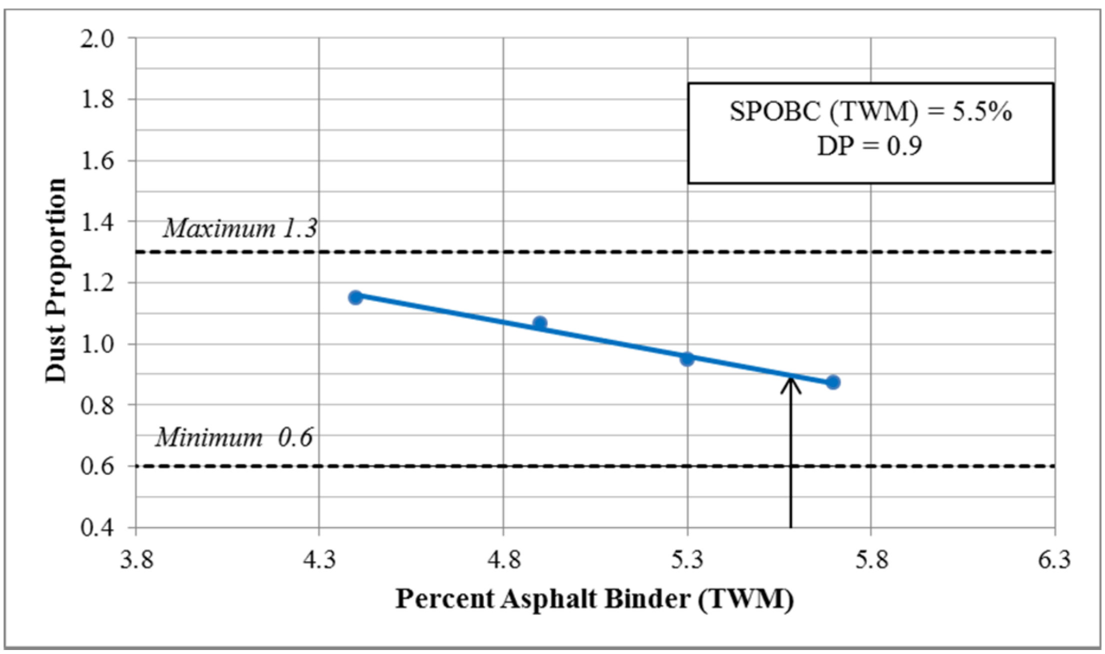

Figure 4.48: Dust proportion versus percent asphalt binder for Mix H.
(Note: The arrow in the figure indicates the dust proportion value at the Superpave OBC.)

4.2 Test Result for Rubber-Modified Binder Mixes

4.2.1 Mix I

Table 4.34 shows the basic aggregate and binder information for Mix I. Table 4.35 presents the aggregate gradation used for both the Hveem and Superpave mix designs. Figure 4.49 presents the same information on the 0.45 power gradation chart. The gradation for the Superpave mix design was intentionally made with a higher dust content (percent passing #200 sieve). The purpose of this increase was to reach a four percent target air-void content for a rubberized mix and to generate a higher dust proportion for a future study of specifications.

Table 4.34: Aggregate and Binder Type for Mix I

Mix ID	**Mix I**
NMAS	1/2 inch
RAP %	0
Aggregate Type	Basalt
Quarry Location	Central California
Binder Supplier	Refinery 2
Binder Grade	PG 64-16 Rubber-Modified

Table 4.35: Aggregate Gradation Table for Mix I

Gradation of Aggregate Blend (Cumulative Percent Passing)				
Sieve Size		**Contractor Test Result JMF Combined Gradation**	**Operating Range**	**UCPRC Lab Test Result Sieve Analysis**
(mm)	**(in.)**			
25	1	**100.0**	100	**100.0**
19	3/4	**100.0**	100	**100.0**
12.5	1/2	**98.0**	92 – 100	**97.5**
9.5	3/8	**84.0**	78 – 90	**84.5**
4.75	#4	**38.0**	31 – 45	**39.9**
2.36	#8	**21.0**	16 – 26	**23.2**
1.18	#16	**15.0**		**17.8**
0.6	#30	**12.0**		**15.0**
0.3	#50	**9.0**		**12.4**
0.15	#100	**4.0**		**7.6**
0.075	#200	**3.0**	1 – 5	**6.6**

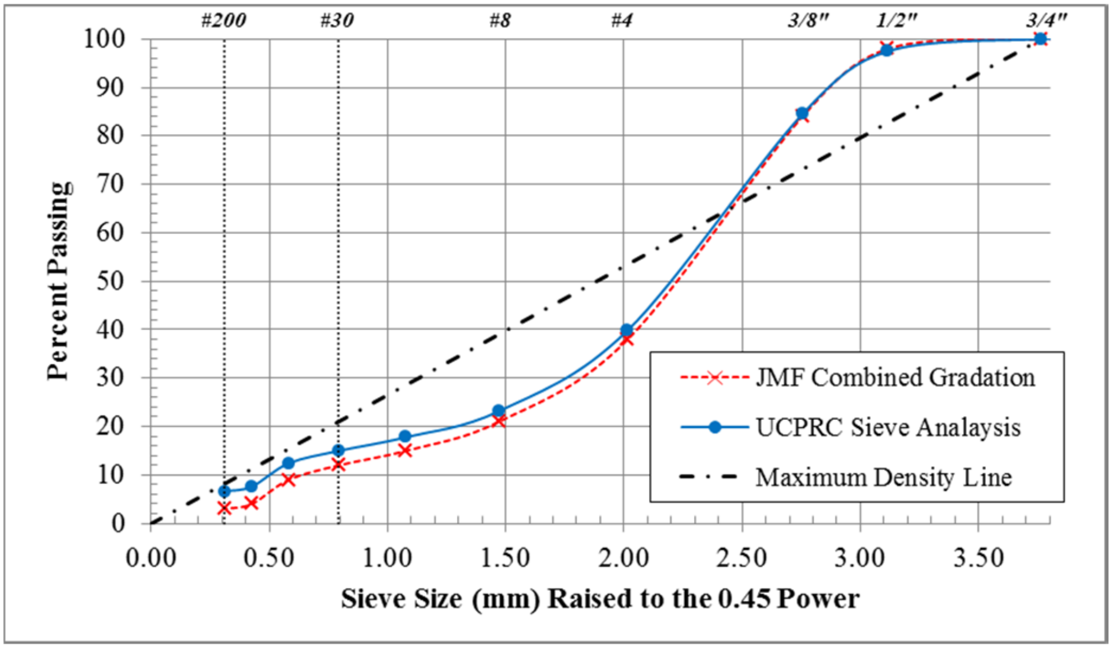

Figure 4.49: Aggregate gradation chart for Mix I.

Table 4.36 shows a summary of the Hveem and Superpave mix design properties. OBC was selected following the steps laid out in Section 3.2.2. Table 4.37 shows the compaction and volumetric properties at different levels of gyration. These data generated Figure 4.50 to Figure 4.54, which show mixture density versus number of gyrations, and air-void content, percent VMA, percent VFA, and dust proportion versus binder content, respectively. Caltrans initially established a design gyration range of 50 to 150 to compact rubberized mixes to a four percent target air-void content. To meet this requirement, a range of OBC from 6.8 percent to 8.0 percent was also determined from step 3 in Section 3.2.2. A spreadsheet was then set up using this range to linearly interpolate percent Gmm, percent VMA, and percent VFA from binder content to the nearest 0.1 percent, as shown in Table 4.38. The Superpave OBC was found to be 7.5 percent, as illustrated by the plus signs ("+") shown in Figure 4.51 to Figure 4.54.

For this mix, OBC selection was based on meeting the percent VMA requirement of 19 percent. OBC of 7.5 percent was selected because any binder content lower than that would render a percent VMA value lower than the specification minimum. However, since there is no required VFA specification, it would be possible to select a higher OBC to increase percent VFA. In the end, a 7.7 percent Superpave OBC was selected, the minimum that would result in a mix that met all volumetric requirements.

Table 4.36: Summary of Design Properties for Mix I

Mix Design Properties	Contractor JMF Hveem Design OBC Properties	UCPRC Lab Testing Superpave Design OBC Properties	Superpave Design Specification
Hveem %OBC (DWA)	8.0	8.3	
Hveem %OBC (TWM)	7.4	7.7	
% Air Void Content	4.5	4.0	4.0
% VMA	19.1	19.1	19 – 23
% VFA	76.0	79.5	Report only
Dust Proportion	0.5	1.0	Report only
Gyrations needed to compact to 4%	n/a	101	50 – 150
%Gmm @ N=50	n/a	93.5	<94
%Gmm @ N=150	n/a	97.4	>96

Table 4.37: Compaction and Volumetric Properties at Different Gyrations for Mix I

	%Gmm					%Air Void					
	N=50	N=65	N=85	N=115	N=150	N=50	N=65	N=85	N=115	N=150	
7.0% AC	92.3	93.3	94.3	95.3	96.2	7.7	6.7	5.7	4.7	3.8	
7.4% AC	93.6	94.7	95.7	96.8	97.6	6.4	5.3	4.3	3.2	2.4	
7.8% AC	93.6	94.7	95.7	96.8	97.7	6.4	5.3	4.3	3.2	2.3	
8.3% AC	94.0	95.0	96.1	97.0	97.8	6.0	5.0	3.9	3.0	2.2	
	%VMA					%VFA					Dust Proportion
	N=50	N=65	N=85	N=115	N=150	N=50	N=65	N=85	N=115	N=150	
7.0% AC	20.8	20.0	19.1	18.2	17.5	62.9	66.4	70.2	74.3	78.3	1.1
7.4% AC	20.5	19.6	18.8	17.9	17.2	69.0	72.9	77.2	81.9	85.9	1.0
7.8% AC	21.5	20.6	19.8	18.9	18.2	70.5	74.4	78.4	82.9	87.1	1.0
8.3% AC	21.8	21.0	20.1	19.3	18.6	72.6	76.4	80.4	84.5	88.3	0.9

Table 4.38: Calculation Sheet for SPOBC[a], Compaction and Volumetric Properties for Mix I

Enter Des. values		SP Design Spec		50 – 150	19 – 23	Report	Report	<94	>96
Des. %AV	OBC	Properties	LN(N)	N	VMA	VFA	DP	G_{mm}N50	G_{mm}N150
4.0	7.7	Calculated Values	4.61	101	19.1	79.5	1.0	93.5	97.4
Calculation of %Gmm, %VMA and %VFA at different gyrations									
N	8	13	20	32	50	65	85	115	150	195
LN(N)	2.08	2.56	3.00	3.47	3.91	4.17	4.44	4.74	5.01	5.27
%Gmm	85.4	87.6	89.5	91.6	93.5	94.5	95.5	96.6	97.4	98.1
%VMA	28.1	26.2	24.6	22.8	21.2	20.4	19.5	18.7	17.9	17.3
%VFA	47.9	52.5	57.3	63.2	69.3	73.1	77.1	81.5	85.4	89.1

[a] SPOBC = Superpave Optimum Binder Content

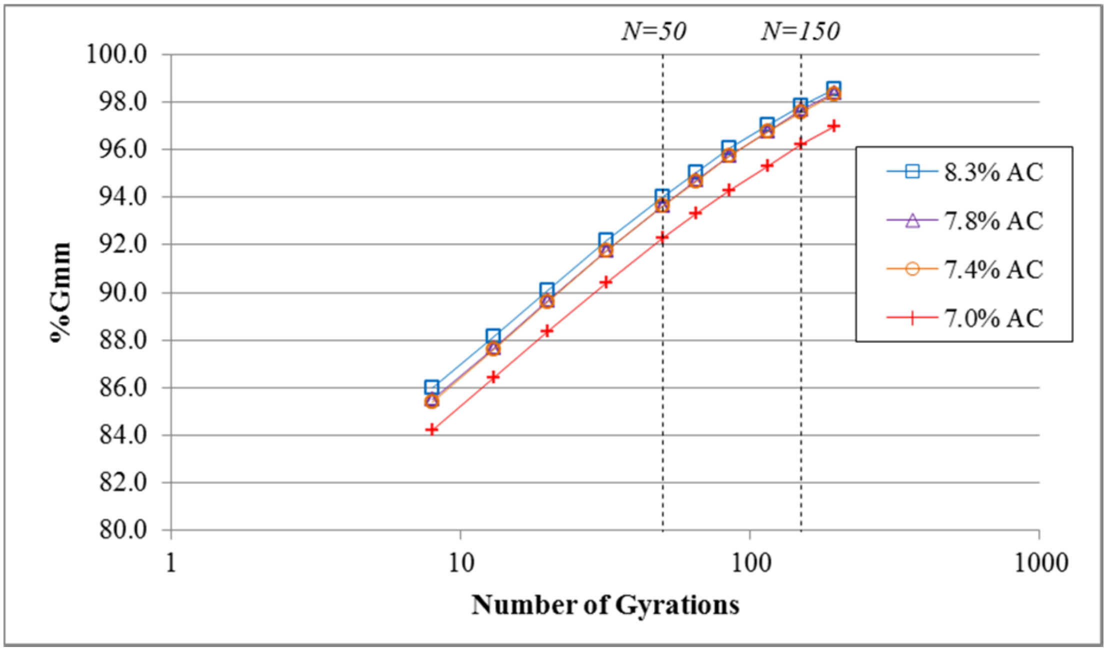

Figure 4.50: Mixture density versus number of gyrations for Mix I.

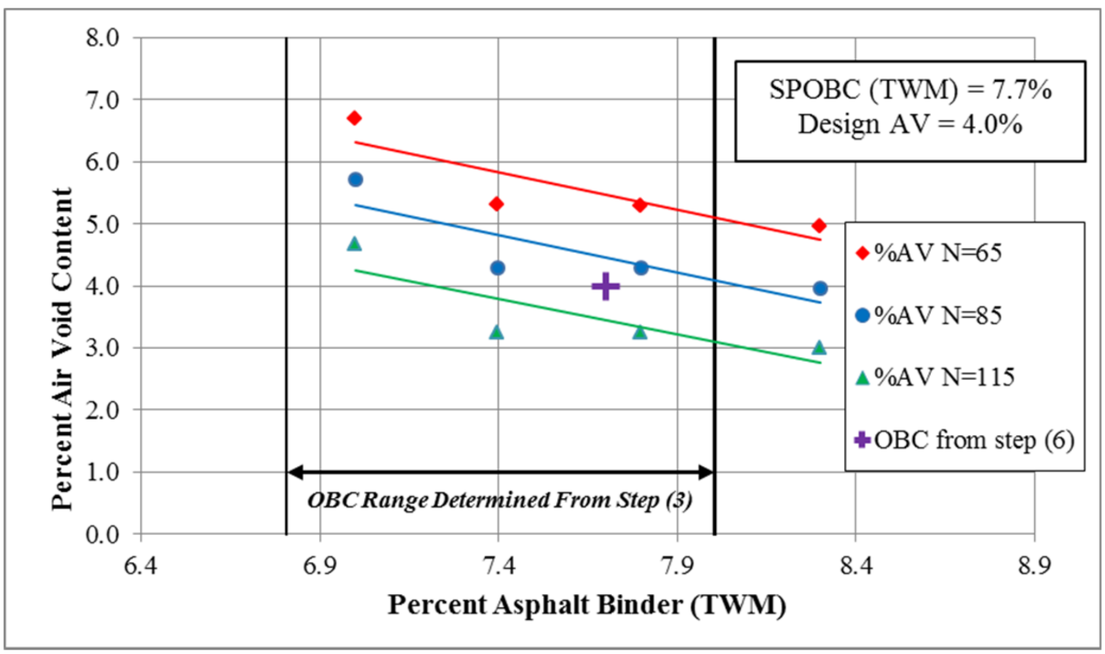

Figure 4.51: Percent air-void content versus percent asphalt binder for Mix I.
(Note: The "+" sign indicates the Superpave OBC selected based on the criterion of the minimum binder content that meets all volumetric requirements.)

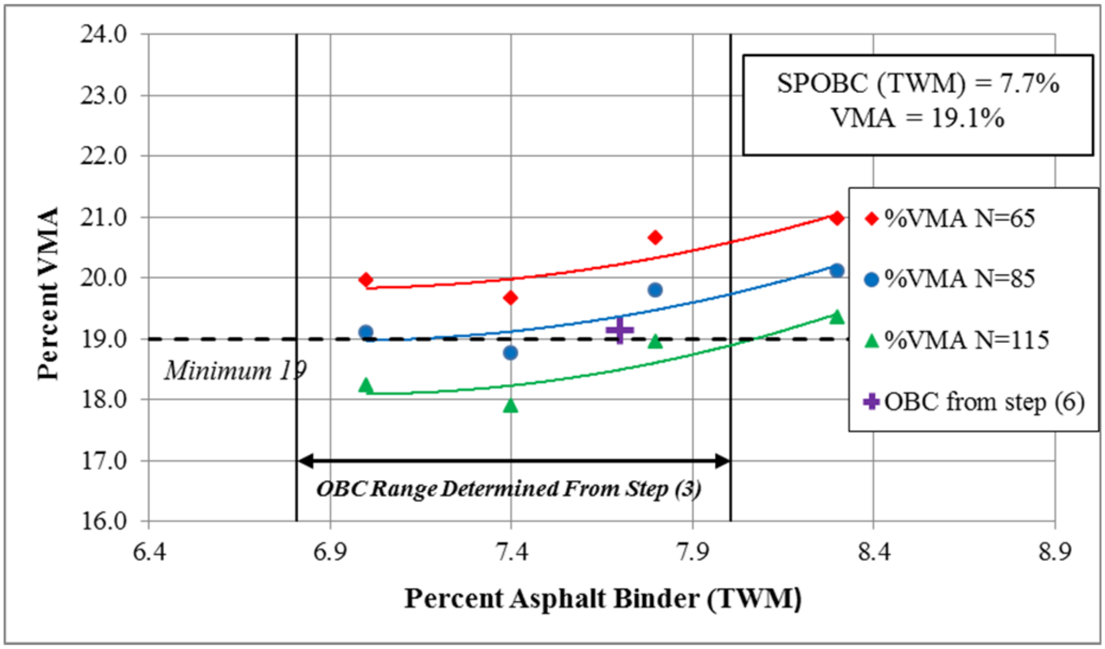

Figure 4.52: Percent VMA versus percent asphalt binder for Mix I.
(Note: The "+" sign indicates the Superpave OBC selected based on the criterion of the minimum binder content that meets all volumetric requirements.)

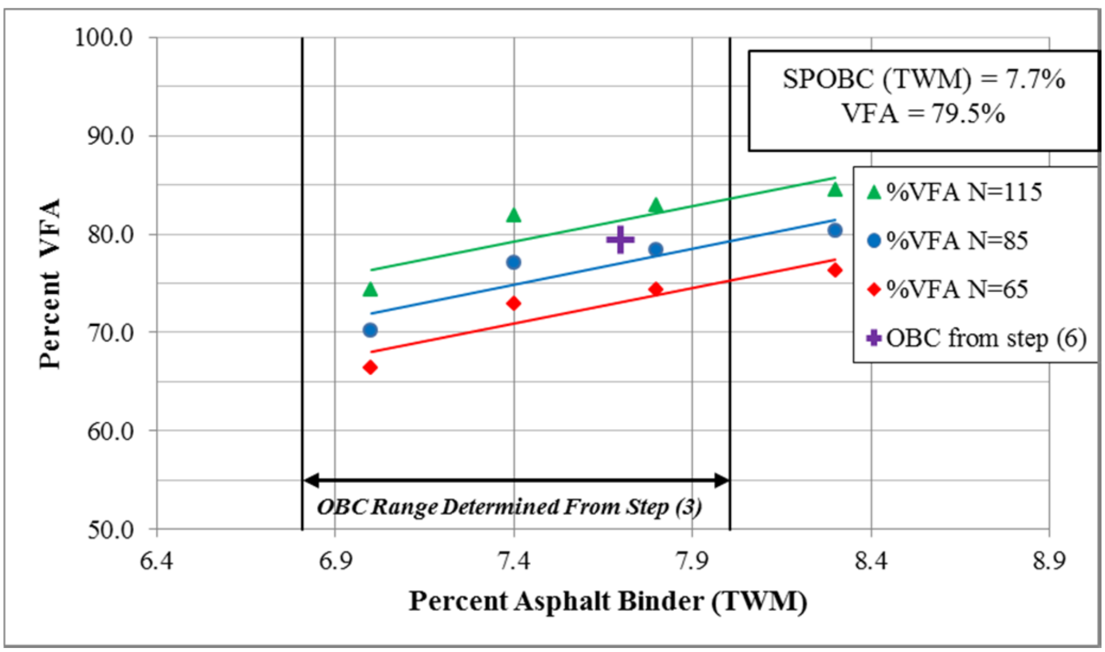

Figure 4.53: Percent VFA versus percent asphalt binder for Mix I.
(Note: The "+" sign indicates the Superpave OBC selected based on the criterion of the minimum binder content that meets all volumetric requirements.)

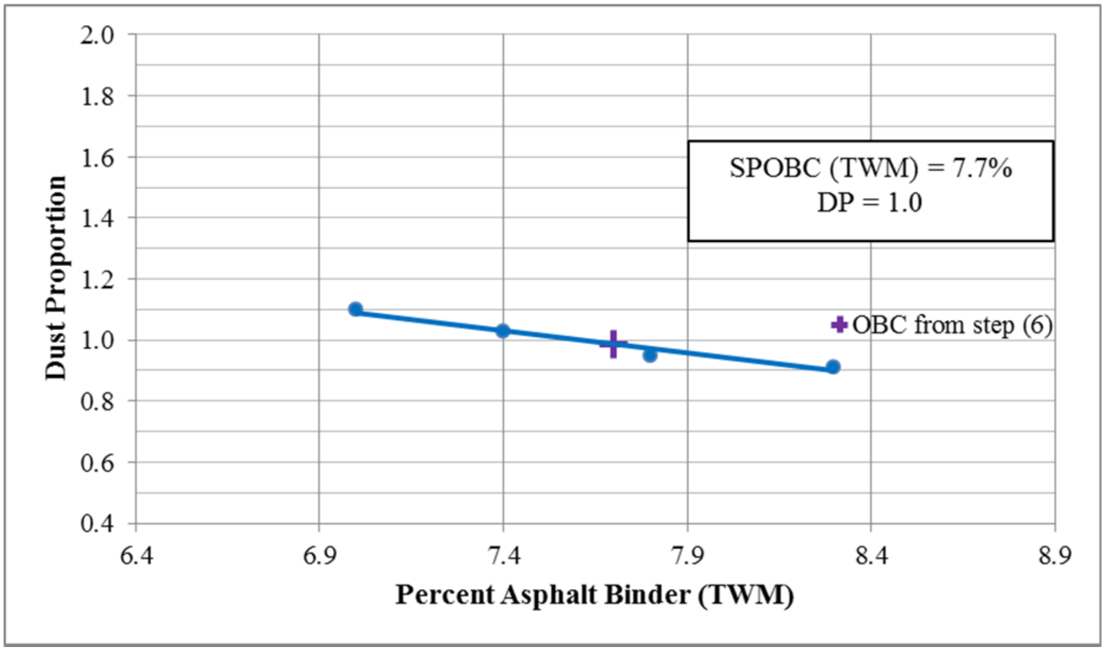

Figure 4.54: Dust proportion versus percent asphalt binder for Mix I.
(Note: The "+" sign indicates the Superpave OBC selected based
on the criterion of the minimum binder content that meets all volumetric requirements.)

4.2.2 Mix J

Table 4.39 shows the basic aggregate and binder information for Mix J. Table 4.40 presents the aggregate gradation used for both the Hveem and Superpave mix designs. Figure 4.55 presents the same information on the 0.45 power gradation chart. The gradation for the Superpave mix design was intentionally made with a higher dust content (percent passing #200 sieve) than the original Hveem mix design. The purpose of this increase was to reach a four percent target air-void content for a rubberized mix and to generate a higher dust proportion for a future study of specifications.

Table 4.39: Aggregate and Binder Type for Mix J

Mix ID	Mix J
NMAS	1/2 inch
RAP %	0
Aggregate Type	Granite
Quarry Location	Southern California
Binder Supplier	Refinery 3
Binder Grade	PG 64-16 Rubber-Modified

Table 4.40: Aggregate Gradation Table for Mix J

Gradation of Aggregate Blend (Cumulative Percent Passing)				
Sieve Size		Contractor Test Result JMF Combined Gradation	Operating Range	UCPRC Lab Test Result Sieve Analysis
(mm)	(in.)			
25	1	**100.0**		**100.0**
19	3/4	**97.0**		**97.0**
12.5	1/2	**83.0**		**86.0**
9.5	3/8	**69.0**		**73.1**
4.75	#4	**37.0**		**40.3**
2.36	#8	**18.0**		**19.0**
1.18	#16	**11.0**		**12.4**
0.6	#30	**8.0**		**9.3**
0.3	#50	**5.0**		**7.3**
0.15	#100	**4.0**		**6.2**
0.075	#200	**3.0**		**5.6**

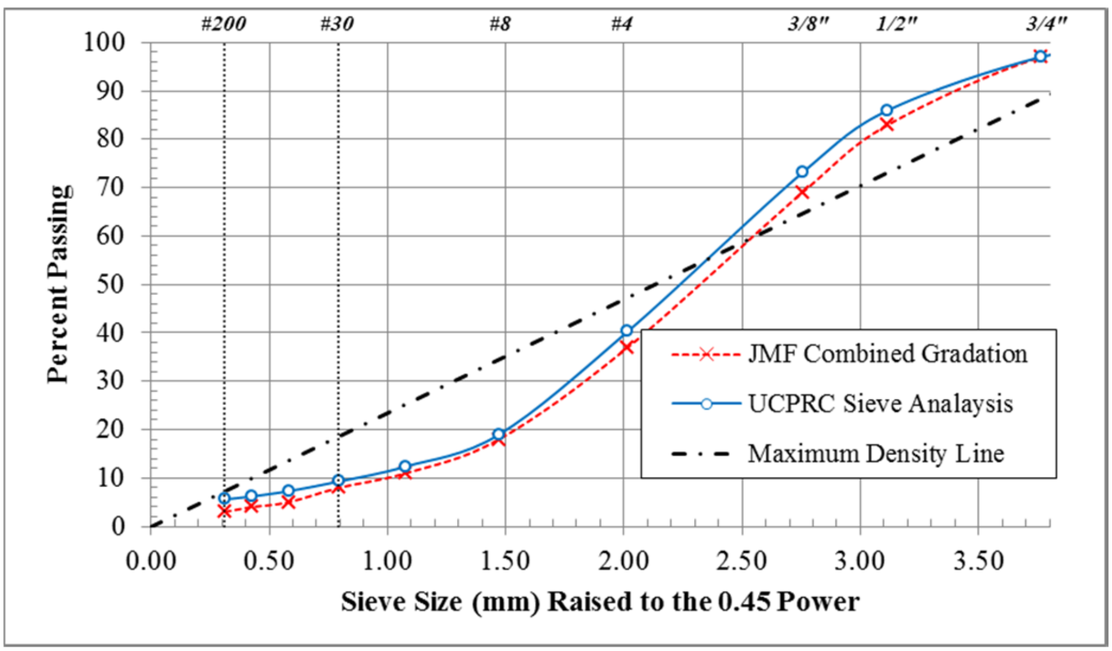

Figure 4.55: Aggregate gradation chart for Mix J.

Table 4.41 shows a summary of the Hveem and Superpave mix design properties. OBC was selected following the steps laid out in Section 3.2.2. Table 4.42 shows the compaction and volumetric properties at different levels of gyration. These data generated Figure 4.56 to Figure 4.60, which show mixture density versus number of gyrations, and air-void content, percent VMA, percent VFA, and dust proportion versus binder content. Caltrans initially established a design gyration range of 50 to 150 to compact rubberized mixes to a four percent target air-void content. To meet this requirement, a range of OBC from 8.1 percent to 8.7 percent was also determined from step 3 in Section 3.2.2. A spreadsheet was then set up using this range to linearly interpolate percent Gmm, percent VMA, and percent VFA from binder content to the nearest 0.1 percent, as shown in Table 4.43. The Superpave OBC was found to be 8.1 percent, indicated by the "+" shown in Figure 4.57 through Figure 4.60.

For this mix, the estimated range of OBC fell outside of the testing range of binder content. This indicates the difficulty of compacting to a four percent target air-void content using the gyratory compactor for a cubic, completely crushed granite mix. The existing aggregate structure required a richer binder content to fill in the air-voids that occur with cubic, rough granite aggregates. The binder content's sensitivity to variation in dust proportion was comparable to most of the mixes tested, and was not a major factor in the difficulty in compacting the mix. However, with the selected Superpave OBC of 8.1 percent, percent VMA reached 16.7, which is well under the 19 percent minimum specification.

Table 4.41: Summary of Design Properties for Mix J

Mix Design Properties	Contractor JMF Hveem Design OBC Properties	UCPRC Lab Testing Superpave Design OBC Properties	Superpave Design Specification
Hveem %OBC (DWA)	7.2	8.8	
Hveem %OBC (TWM)	6.7	8.1	
% Air Void Content	5.4	4.0	4.0
% VMA	18.8	16.7	19 – 23
% VFA	71.3	74.9	Report only
Dust Proportion	0.5	1.0	Report only
Gyrations needed to compact to 4%	n/a	140	50 – 150
%Gmm @ N=50	n/a	93.0	<94
%Gmm @ N=150	n/a	96.0	>96

Table 4.42: Compaction and Volumetric Properties at Different Gyrations for Mix J

	%Gmm					%Air Void					
	N=50	N=65	N=85	N=115	N=150	N=50	N=65	N=85	N=115	N=150	
6.7% AC	90.7	91.4	92.3	92.9	93.7	9.3	8.6	7.7	7.1	6.3	
7.1% AC	91.6	92.4	93.3	93.9	94.7	8.4	7.6	6.7	6.1	5.3	
7.6% AC	91.9	92.6	93.5	94.1	94.9	8.1	7.4	6.5	5.9	5.1	
8.0% AC	92.9	93.6	94.5	95.2	95.9	7.1	6.4	5.5	4.8	4.1	
	%VMA					%VFA					Dust Proportion
	N=50	N=65	N=85	N=115	N=150	N=50	N=65	N=85	N=115	N=150	
6.7% AC	18.6	18.0	17.1	16.6	15.9	49.9	52.1	55.1	57.4	60.5	1.3
7.1% AC	18.7	18.1	17.3	16.7	16.0	55.3	57.7	61.0	63.6	67.0	1.2
7.6% AC	19.2	18.6	17.9	17.3	16.6	58.0	60.4	63.4	65.8	69.1	1.1
8.0% AC	19.2	18.6	17.8	17.2	16.5	63.1	65.7	69.3	71.9	75.5	1.0

Table 4.43: Calculation Sheet for SPOBC[a], Compaction and Volumetric Properties for Mix J

Enter Des values		SP Design Spec			50-150	19-23	Report	Report	<94	>96
Des %AV	OBC	Properties		LN(N)	N	VMA	VFA	DP	G_{mm}N50	G_{mm}N150
4.0	8.1	Calculated Values		4.94	140	16.7	74.9	1.0	93.0	96.0
Calculation of %Gmm, %VMA and %VFA at different gyrations										
N	8	13	20	32	50	65	85	115	150	195
LN(N)	2.08	2.56	3.00	3.47	3.91	4.17	4.44	4.74	5.01	5.27
%Gmm	85.9	87.9	89.7	91.4	93.0	93.7	94.6	95.2	96.0	96.5
%VMA	25.5	23.7	22.2	20.6	19.3	18.7	17.9	17.4	16.7	16.2
%VFA	44.6	49.0	53.5	58.6	63.8	66.3	69.8	72.4	76.0	78.8

[a] SPOBC = Superpave Optimum Binder Content

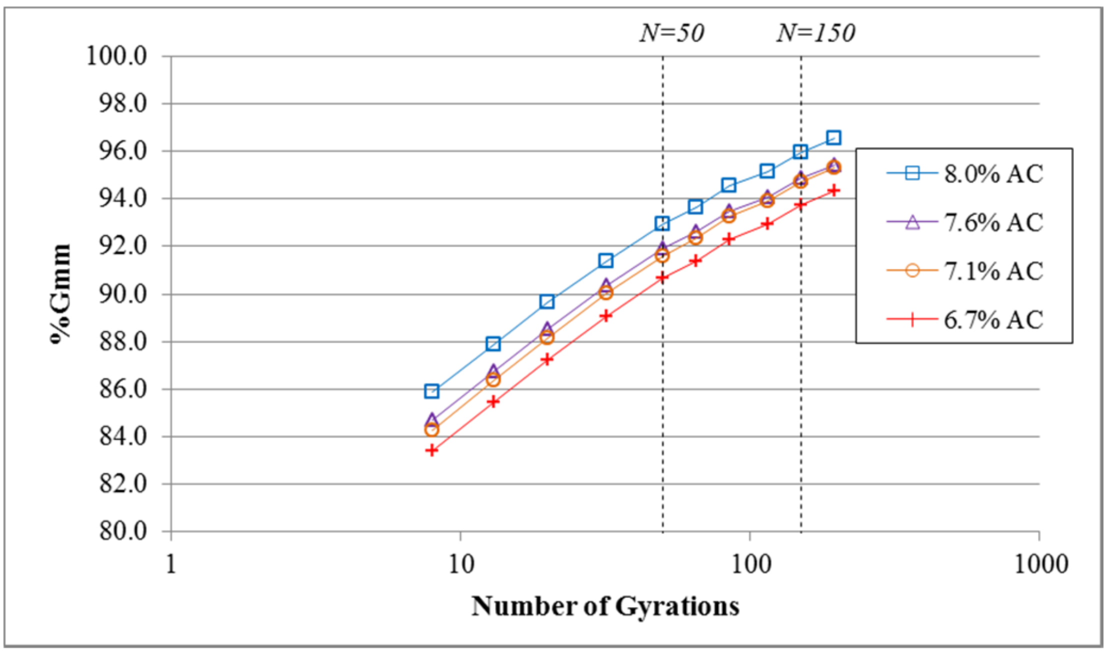

Figure 4.56: Mixture density versus number of gyrations for Mix J.

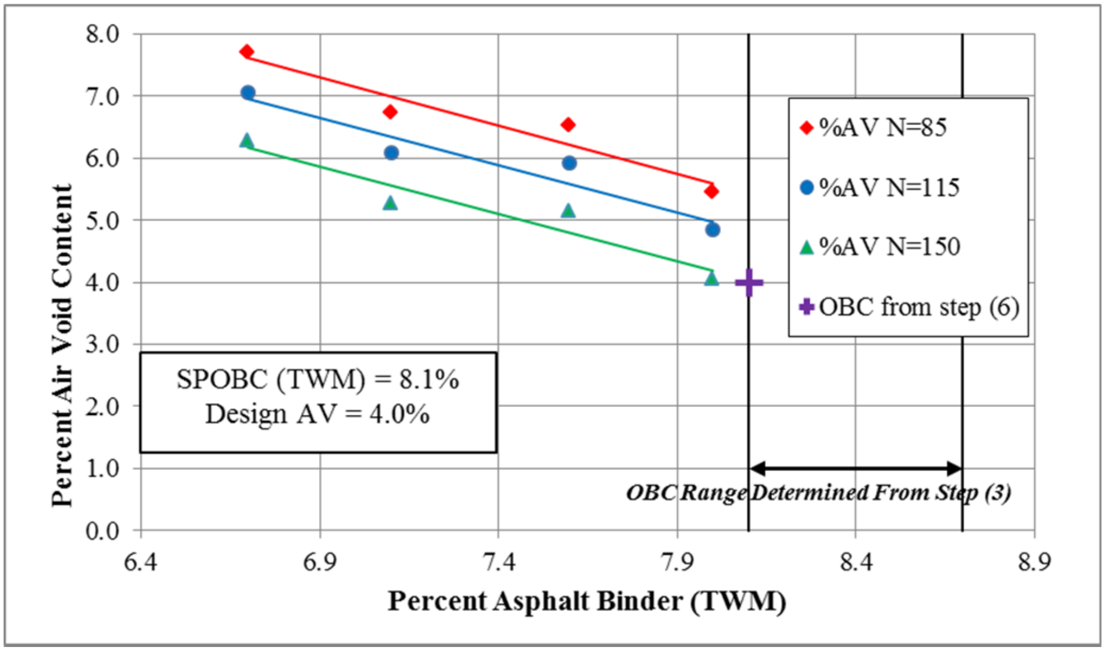

Figure 4.57: Percent air-void content versus percent asphalt binder for Mix J. (Note: the "+" sign indicates the Superpave OBC selected based on the criterion of the minimum binder content that meets all volumetric requirements.)

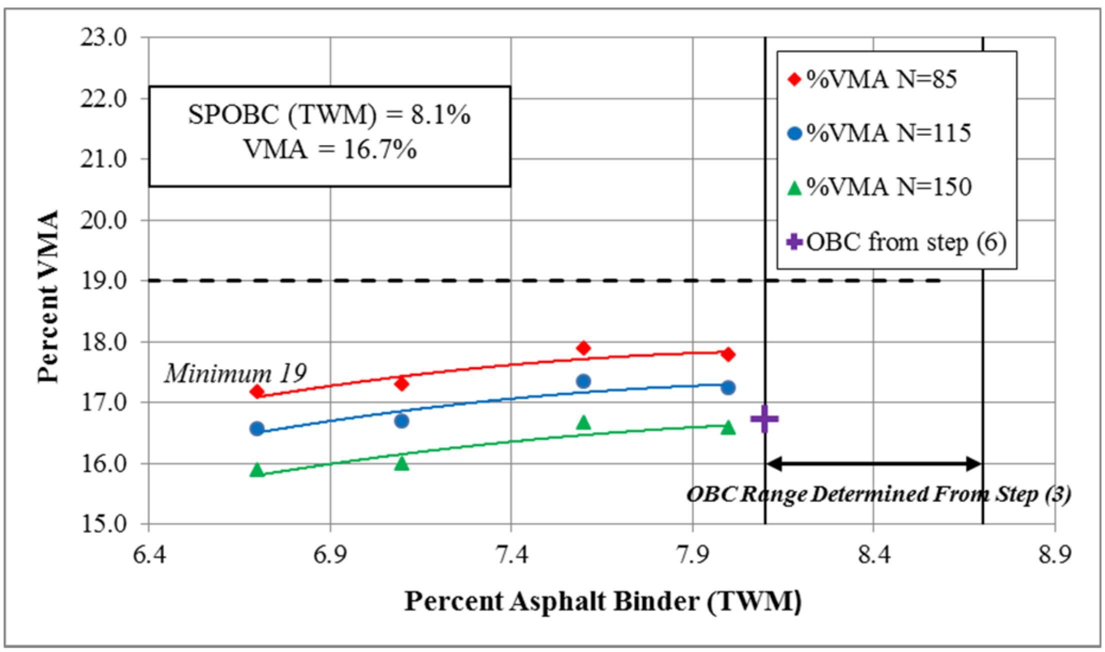

Figure 4.58: Percent VMA versus percent asphalt binder for Mix J. (Note: The "+" sign indicates the Superpave OBC selected based on the criterion of the minimum binder content that meets all volumetric requirements.)

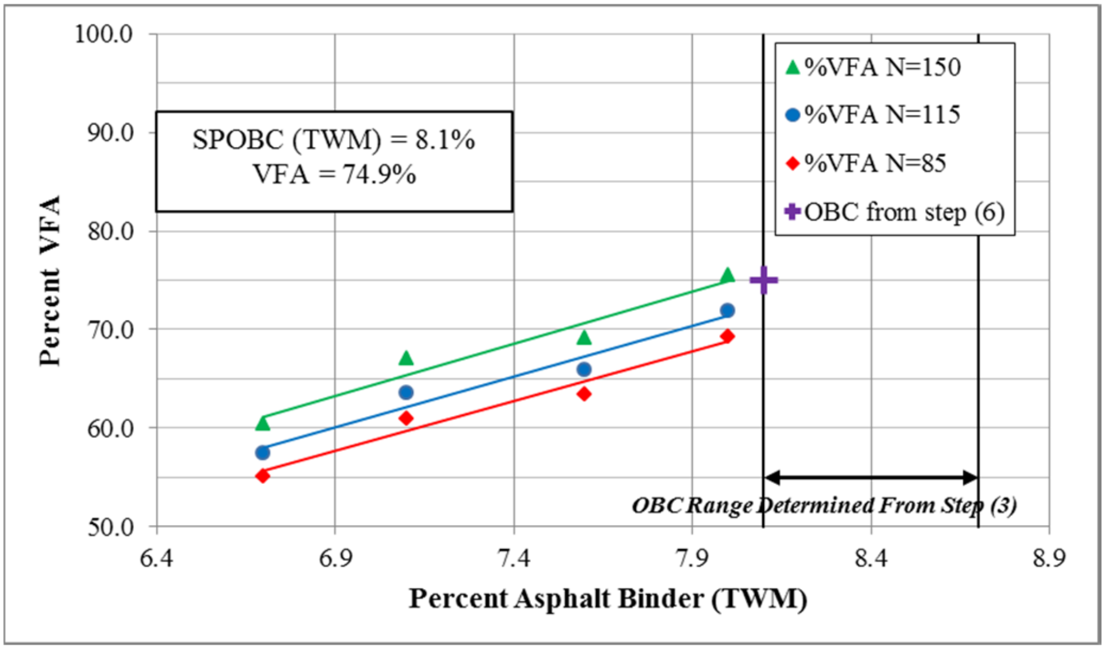

Figure 4.59: Percent VFA versus percent asphalt binder for Mix J.
(Note: The "+" sign indicates the Superpave OBC selected based on the criterion of the minimum binder content that meets all volumetric requirements.)

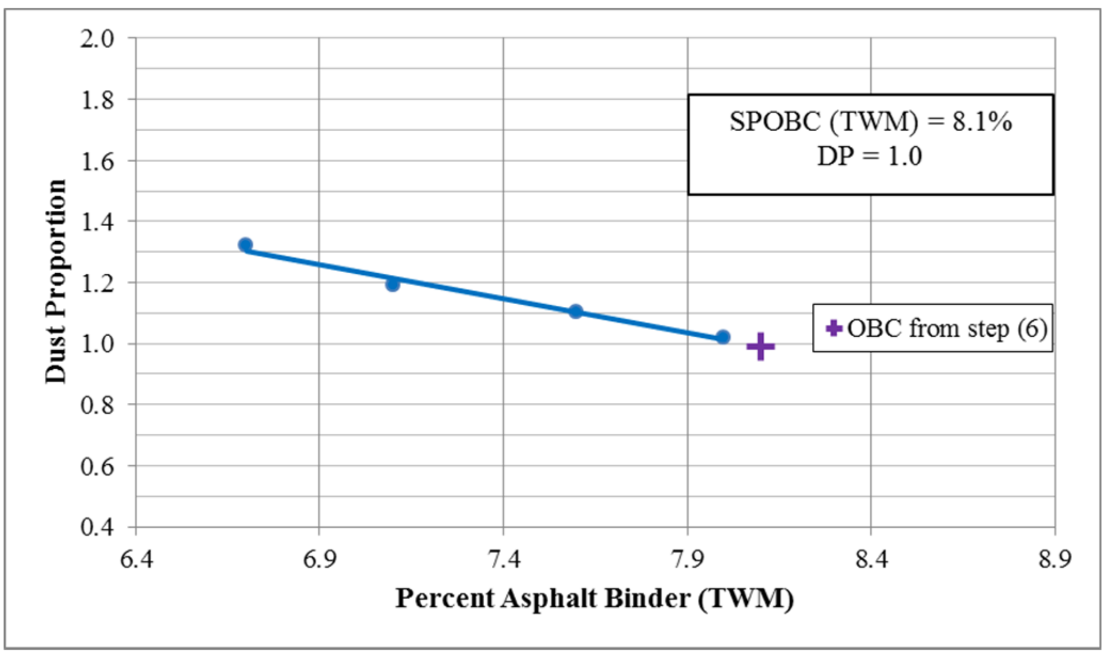

Figure 4.60: Dust proportion versus percent asphalt binder for Mix J.
(Note: The "+" sign indicates the Superpave OBC selected based on the criterion of the minimum binder content that meets all volumetric requirements.)

4.2.3 Mix K

Table 4.44 shows the basic aggregate and binder information for Mix K. Table 4.45 presents the aggregate gradation used for both the Hveem and Superpave mix designs. Figure 4.61 presents the same information on the 0.45 power gradation chart. The gradation for the Superpave mix design was intentionally made with a higher dust content (percent passing #200 sieve). The purpose of this increase was to hit a four percent target air-void content for a rubberized mix and to generate a higher dust proportion for a future study of specifications.

Table 4.44: Aggregate and Binder Type for Mix K

Mix ID	**Mix K**
NMAS	1/2 inch
RAP %	0
Aggregate Type	Alluvial Fan
Quarry Location	Southern California
Binder Supplier	Refinery 3
Binder Grade	PG 64-16 Rubber-Modified

Table 4.45: Aggregate Gradation Table for Mix K

Gradation of Aggregate Blend (Cumulative Percent Passing)				
Sieve Size		**Contractor Test Result JMF Combined Gradation**	**Operating Range**	**UCPRC Lab Test Result Sieve Analysis**
(mm)	**(in)**			
25	1	**100.0**		**100.0**
19	3/4	**100.0**		**100.0**
12.5	1/2	**96.0**		**97.8**
9.5	3/8	**85.0**		**86.7**
4.75	#4	**31.0**		**34.8**
2.36	#8	**15.0**		**19.1**
1.18	#16	**10.0**		**14.0**
0.6	#30	**7.0**		**11.2**
0.3	#50	**5.0**		**8.4**
0.15	#100	**3.0**		**6.9**
0.075	#200	**1.7**		**5.7**

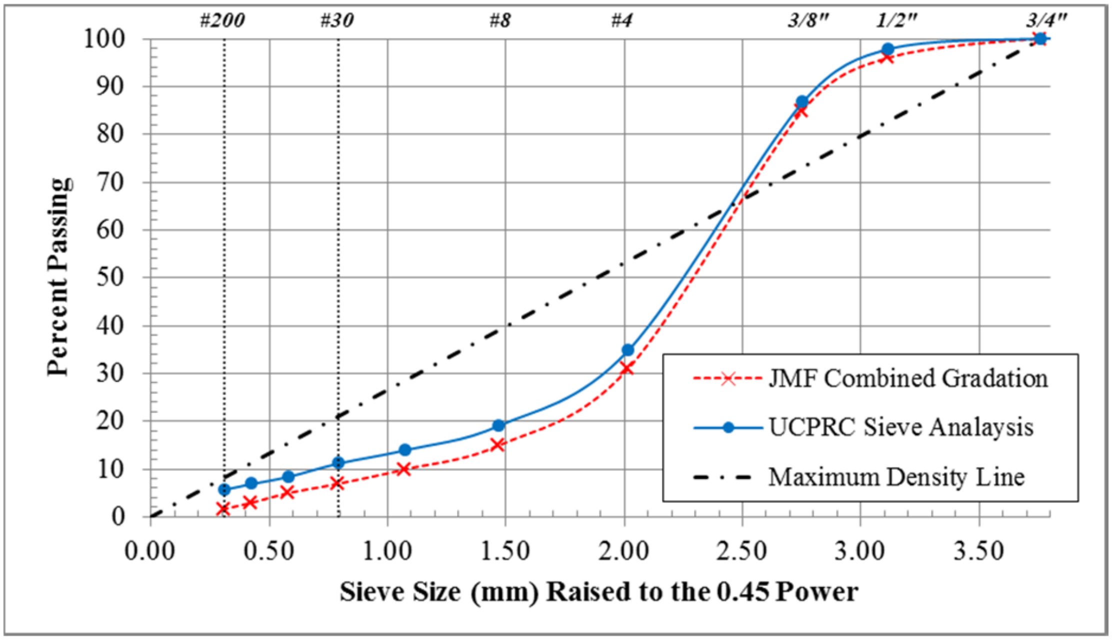

Figure 4.61: Aggregate gradation chart for Mix K.

Table 4.46 shows a summary of the Hveem and Superpave mix design properties. OBC was selected following the steps laid out in Section 3.2.2. Table 4.47 shows the compaction and volumetric properties at different levels of gyration. These data generated Figure 4.62 to Figure 4.66, which show mixture density versus number of gyrations, and air-void content, percent VMA, percent VFA, and dust proportion versus binder content, respectively. Caltrans initially established a design gyration range of 50 to 150 to compact rubberized mixes to a four percent target air-void content. To meet this requirement, a range of OBC from 6.8 percent to 7.5 percent was also determined from step 3 in Section 3.2.2. A spreadsheet was then set up using this range to linearly interpolate percent Gmm, percent VMA, and percent VFA from binder content to the nearest 0.1 percent, as shown in Table 4.48. The Superpave OBC was found to be 7.5 percent, as illustrated by the "+" shown in Figure 4.63 through Figure 4.66.

For this mix, any binder content that lower than 7.5 percent would result in percent VMA falling below the 19 percent minimum specification. A binder content higher than 7.5 percent would result in a percent Gmm @ 50 gyrations increase to above the specification of maximum of 94 percent.

Table 4.46: Summary of Design Properties for Mix K

Mix Design Properties	Contractor JMF Hveem Design OBC Properties	UCPRC Lab Testing Superpave Design OBC Properties	Superpave Design Specification
Hveem %OBC (DWA)	7.4	8.1	
Hveem %OBC (TWM)	6.9	7.5	
% Air Void Content	4.9	4.0	4.0
% VMA	18.4	18.9	19 – 23
% VFA	73.3	79.4	Report only
Dust Proportion	0.3	0.9	Report only
Gyrations needed to compact to 4%	n/a	94	50 – 150
%Gmm @ N=50	n/a	94.0	<94
%Gmm @ N=150	n/a	97.5	>96

Table 4.47: Compaction and Volumetric Properties at Different Gyrations for Mix K

	%Gmm					%Air Void					
	N=50	N=65	N=85	N=115	N=150	N=50	N=65	N=85	N=115	N=150	
6.5% AC	91.5	92.4	93.5	94.3	95.3	8.5	7.6	6.5	5.7	4.7	
6.9% AC	92.3	93.2	94.3	95.1	96.1	7.7	6.8	5.7	4.9	3.9	
7.3% AC	94.0	94.8	95.9	96.6	97.5	6.0	5.2	4.1	3.4	2.5	
7.7% AC	94.3	95.2	96.2	97.0	97.8	5.7	4.8	3.8	3.0	2.2	
	%VMA					%VFA					Dust Proportion
	N=50	N=65	N=85	N=115	N=150	N=50	N=65	N=85	N=115	N=150	
6.5% AC	20.3	19.5	18.6	17.9	17.0	58.2	61.1	65.0	68.1	72.4	1.1
6.9% AC	20.3	19.6	18.7	18.0	17.1	62.4	65.4	69.4	72.7	77.0	1.0
7.3% AC	20.3	19.5	18.6	18.0	17.3	70.2	73.5	77.8	81.2	85.5	0.9
7.7% AC	20.8	20.0	19.2	18.6	17.9	72.8	76.1	80.3	83.7	87.6	0.8

Table 4.48: Calculation Sheet for SPOBC[a], Compaction and Volumetric Properties for Mix K

Enter Des values		SP Design Spec		50-150	19-23	Report	Report	<94	>96
Des %AV	OBC	Properties	LN(N)	N	VMA	VFA	DP	G_{mm}N50	G_{mm}N150
4.0	7.5	Calculated Values	4.54	94	18.9	79.4	0.9	94.0	97.5
Calculation of %Gmm, %VMA and %VFA at different gyrations									
N	8	13	20	32	50	65	85	115	150	195
LN(N)	2.08	2.56	3.00	3.47	3.91	4.17	4.44	4.74	5.01	5.27
%Gmm	86.1	88.3	90.2	92.2	94.0	94.9	95.9	96.7	97.5	98.1
%VMA	27.3	25.5	23.8	22.1	20.6	19.8	19.0	18.3	17.6	17.1
%VFA	48.9	53.8	58.8	64.9	71.0	74.4	78.6	82.0	86.0	89.1

[a] SPOBC = Superpave Optimum Binder Content

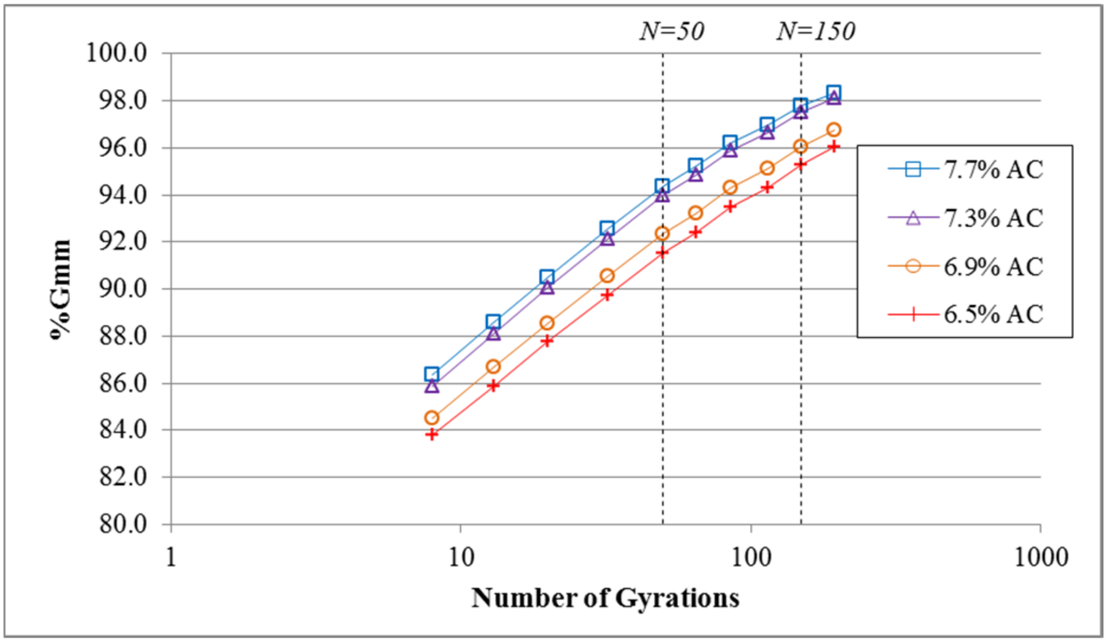

Figure 4.62: Mixture density versus number of gyrations for Mix K.

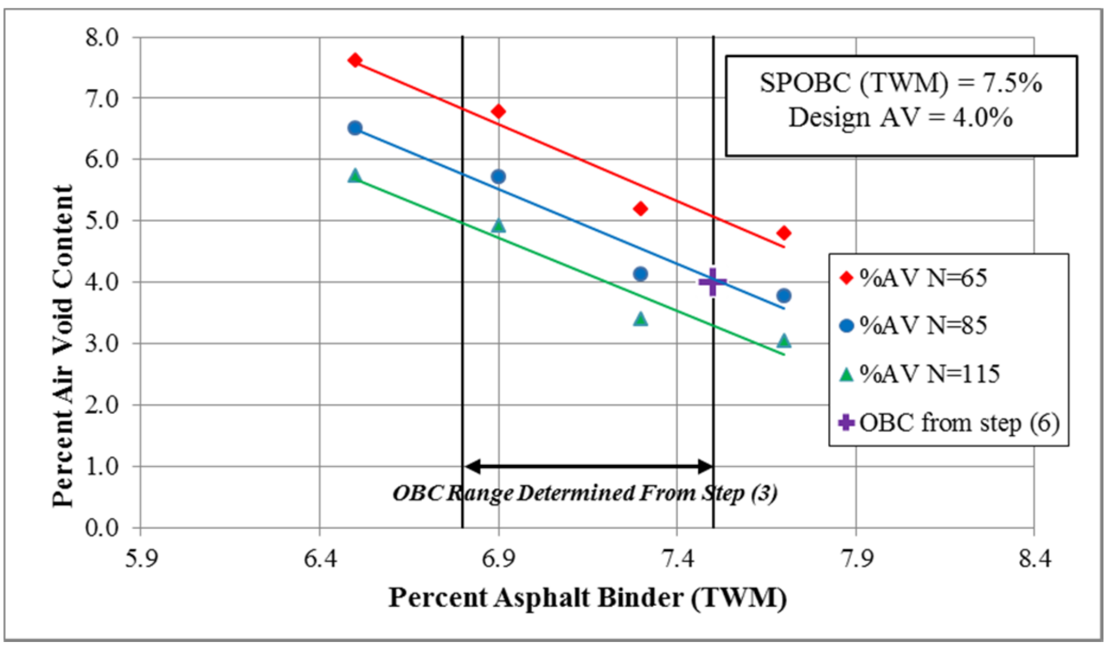

Figure 4.63: Percent air-void content versus percent asphalt binder for Mix K.
(Note: The "+" sign indicates the Superpave OBC selected based on the criterion of the minimum binder content that meets all volumetric requirements.)

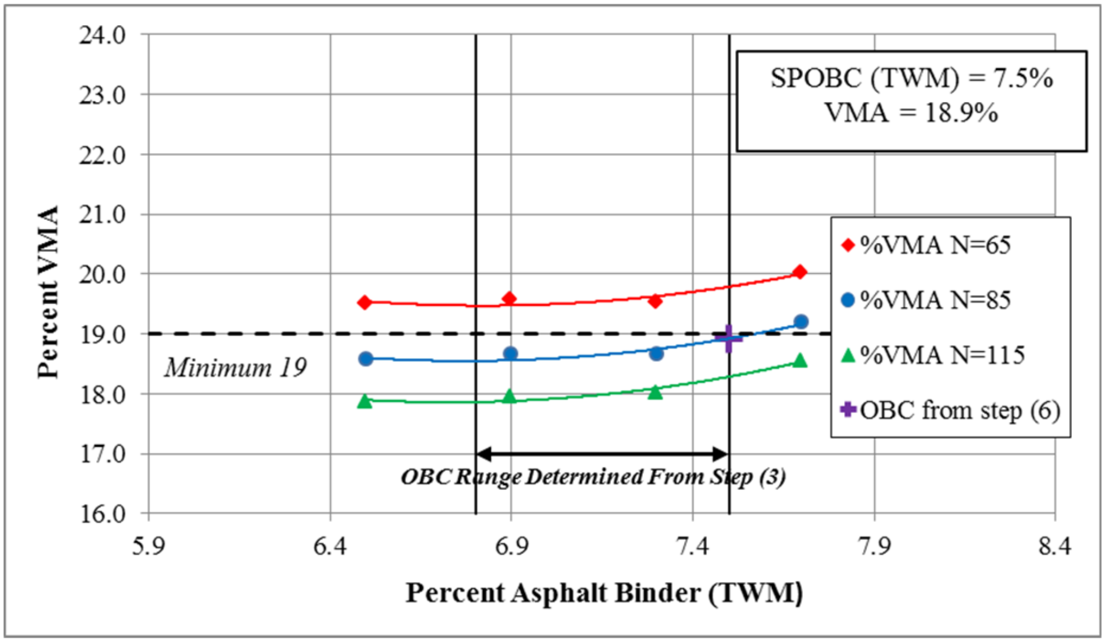

Figure 4.64: Percent VMA versus percent asphalt binder for Mix K.
(Note: The "+" sign indicates the Superpave OBC selected based on the criterion of the minimum binder content that meets all volumetric requirements.)

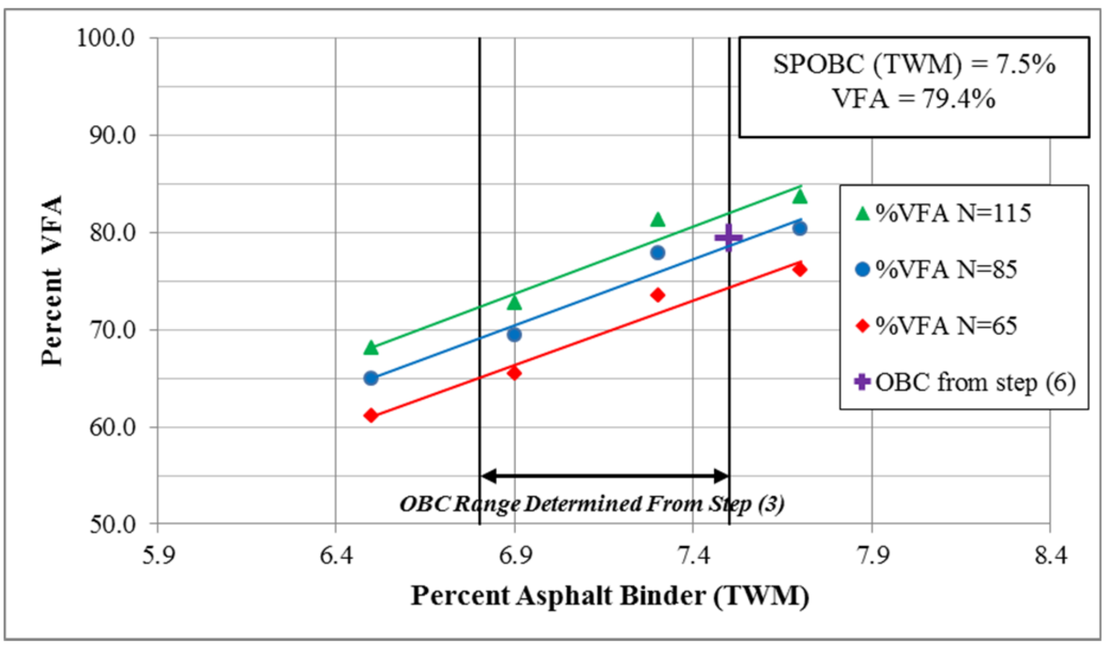

Figure 4.65: Percent VFA versus percent asphalt binder for Mix K.
(Note: The "+" sign indicates the Superpave OBC selected based on the criterion of the minimum binder content that meets all volumetric requirements.)

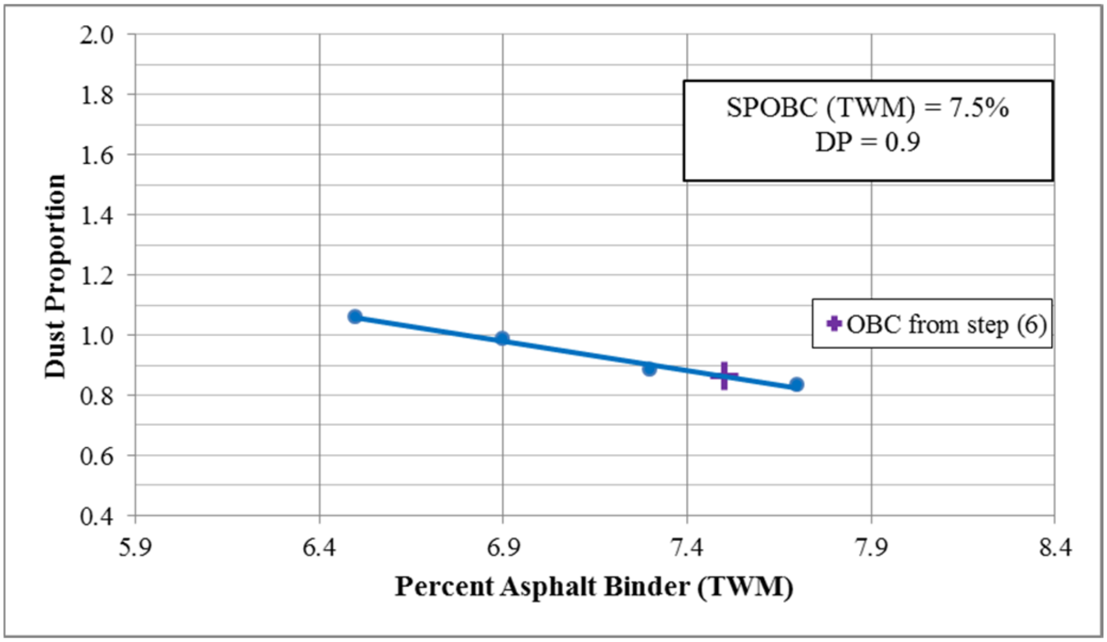

Figure 4.66: Dust proportion versus percent asphalt binder for Mix K.
(Note: The "+" sign indicates the Superpave OBC selected based on the criterion of the minimum binder content that meets all volumetric requirements.)

4.2.4 Mix L

Table 4.49 shows the basic aggregate and binder information for Mix L. Table 4.50 presents the aggregate gradation used for both the Hveem and Superpave mix designs. Figure 4.67 presents the same information on the 0.45 power gradation chart.

Table 4.49: Aggregate and Binder Type for Mix L

Mix ID	Mix L
NMAS	1/2 inch
RAP %	0
Aggregate Type	Granite
Quarry Location	Central California
Binder Supplier	Refinery 2
Binder Grade	PG 64-16 Rubber-Modified

Table 4.50: Aggregate Gradation Table for Mix L

Gradation of Aggregate Blend (Cumulative Percent Passing)				
Sieve Size		Contractor Test Result JMF Combined Gradation	Operating Range	UCPRC Lab Test Result Sieve Analysis
(mm)	(in.)			
25	1	**100.0**	100	**100.0**
19	3/4	**100.0**	100	**100.0**
12.5	1/2	**98.0**	92 – 100	**97.9**
9.5	3/8	**83.0**	77 – 89	**83.6**
4.75	#4	**37.0**	30 – 44	**36.8**
2.36	#8	**16.0**	11 – 21	**14.5**
1.18	#16	**12.0**		**10.1**
0.6	#30	**8.0**		**7.7**
0.3	#50	**5.0**		**5.8**
0.15	#100	**3.0**		**3.1**
0.075	#200	**2.0**	0 – 4	**1.3**

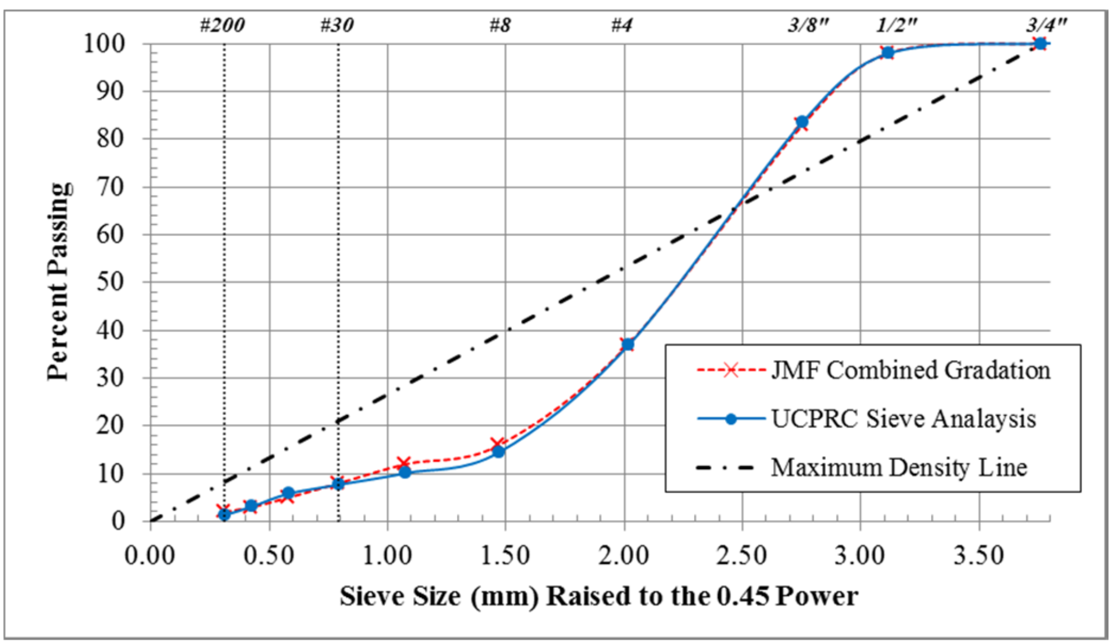

Figure 4.67: Aggregate gradation chart for Mix L.

Table 4.51 shows a summary of the Hveem and Superpave mix design properties. OBC was selected following the steps laid out in Section 3.2.2. Table 4.52 shows the compaction and volumetric properties at different levels of gyration. These data generated Figure 4.68 to Figure 4.72, which show mixture density versus number of gyrations, and air-void content, percent VMA, percent VFA, and dust proportion versus binder content, respectively. Caltrans initially established a design gyration range of 50 to 150 to compact rubberized mixes to a target four percent air-void content. To meet this requirement, a range of OBC from 7.1 percent to 8.3 percent was also determined from step 3 in Section 3.2.2. A spreadsheet was then set up using this range to linearly interpolate percent Gmm, percent VMA, and percent VFA from binder content to the nearest 0.1 percent, as shown in Table 4.53. The Superpave OBC was found to be 7.4 percent, as illustrated by the "+" shown in Figure 4.69 through Figure 4.72.

For this mix, the OBC selection was based on meeting the percent VMA requirement of 19 percent. OBC of 7.4 percent was selected because any binder content lower than that would render a percent VMA lower than the specification minimum. However, since there is no required VFA specification, it would be possible to select a higher OBC that would increase percent VFA. In the end, a 7.4 percent Superpave OBC was selected, the minimum that would result in a mix that met all volumetric requirements.

Table 4.51: Summary of Design Properties for Mix L

Mix Design Properties	Contractor JMF Hveem Design OBC Properties	UCPRC Lab Testing Superpave Design OBC Properties	Superpave Design Specification
Hveem %OBC (DWA)	7.8	8.0	
Hveem %OBC (TWM)	7.2	7.4	
% Air Void Content	4.2	4.0	4.0
% VMA	18.9	19.3	19 – 23
% VFA	77.8	78.5	Report only
Dust Proportion	0.3	0.2	Report only
Gyrations needed to compact to 4%	n/a	130	50 – 150
%Gmm @ N=50	n/a	92.3	<94
%Gmm @ N=150	n/a	96.5	>96

Table 4.52: Compaction and Volumetric Properties for Mix L

	%Gmm					%Air Void					
	N=50	N=65	N=85	N=115	N=150	N=50	N=65	N=85	N=115	N=150	
7.0% AC	91.5	92.4	93.6	94.6	95.8	8.5	7.6	6.4	5.4	4.2	
7.4% AC	92.5	93.4	94.5	95.4	96.5	7.5	6.6	5.5	4.6	3.5	
7.8% AC	93.1	94.0	95.1	96.0	97.1	6.9	6.0	4.9	4.0	2.9	
8.3% AC	93.9	94.9	96.1	96.9	98.0	6.1	5.1	3.9	3.1	2.0	
	%VMA					%VFA					Dust Proportion
	N=50	N=65	N=85	N=115	N=150	N=50	N=65	N=85	N=115	N=150	
7.0% AC	22.4	21.5	20.5	19.7	18.7	61.8	64.9	69.0	72.5	77.5	0.2
7.4% AC	22.2	21.4	20.4	19.7	18.8	66.2	69.3	73.3	76.7	81.5	0.2
7.8% AC	22.5	21.7	20.8	20.1	19.2	69.2	72.4	76.6	80.1	84.8	0.2
8.3% AC	22.8	21.9	21.0	20.3	19.3	73.2	76.7	81.2	84.9	89.9	0.2

Table 4.53: Calculation Sheet for SPOBC[a], Compaction and Volumetric Properties for Mix L

Enter Des values		SP Design Spec			50-150	19-23	Report	Report	<94	>96
Des %AV	OBC	Properties		LN(N)	N	VMA	VFA	DP	G_{mm}N50	G_{mm}N150
4.0	7.4	Calculated Values		4.87	130	19.3	78.5	0.2	92.3	96.5
Calculation of %Gmm, %VMA and %VFA at different gyrations										
N	8	13	20	32	50	65	85	115	150	195
LN(N)	2.08	2.56	3.00	3.47	3.91	4.17	4.44	4.74	5.01	5.27
%Gmm	84.0	86.3	88.3	90.4	92.3	93.3	94.4	95.3	96.5	97.3
%VMA	29.3	27.5	25.8	24.0	22.4	21.6	20.6	19.8	18.9	18.2
%VFA	45.6	50.0	54.5	59.9	65.6	68.8	73.0	76.4	81.3	85.2

[a] SPOBC = Superpave Optimum Binder Content

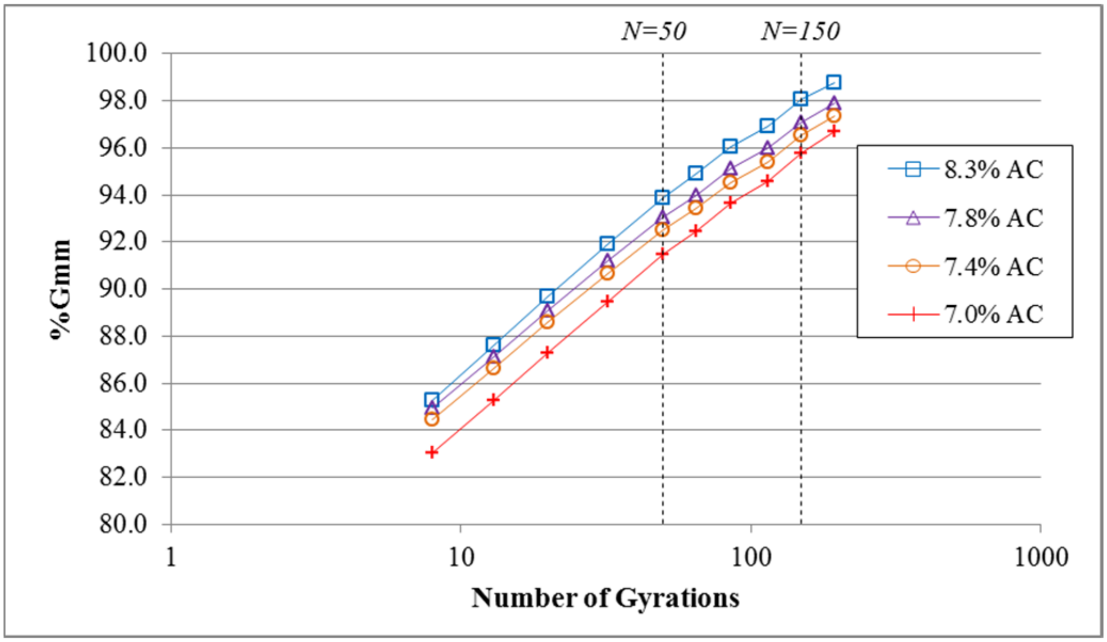

Figure 4.68: Mixture density versus number of gyrations for Mix L.

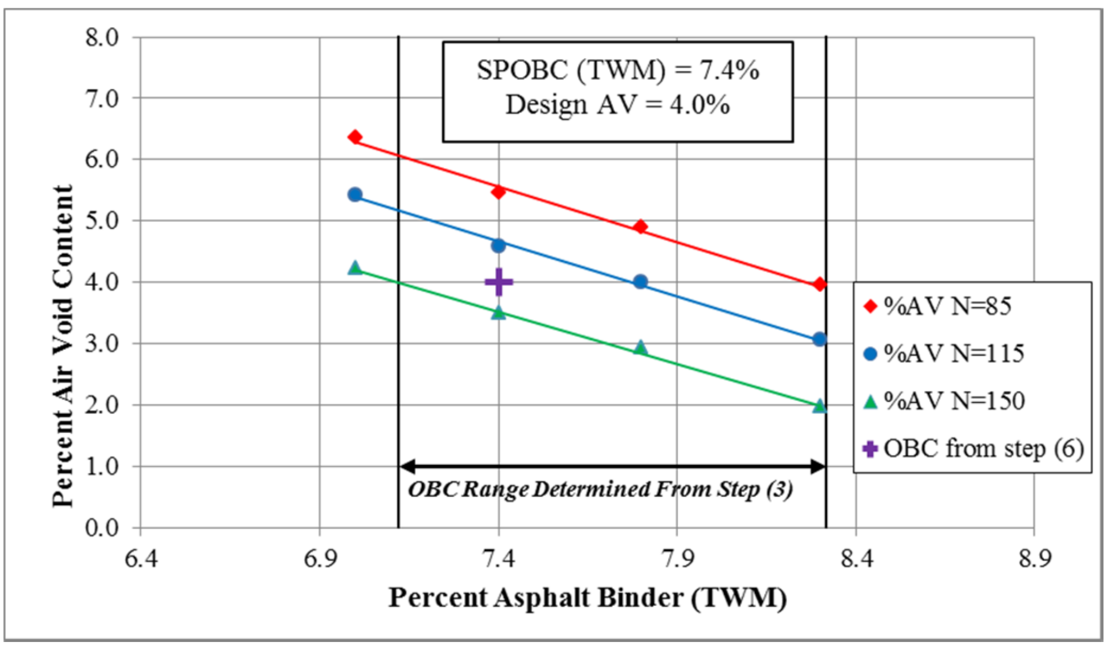

Figure 4.69: Percent air-void content versus percent asphalt binder for Mix L.
(Note: the "+" sign indicates the Superpave OBC selected based on the criterion of the minimum binder content that meets all volumetric requirements.)

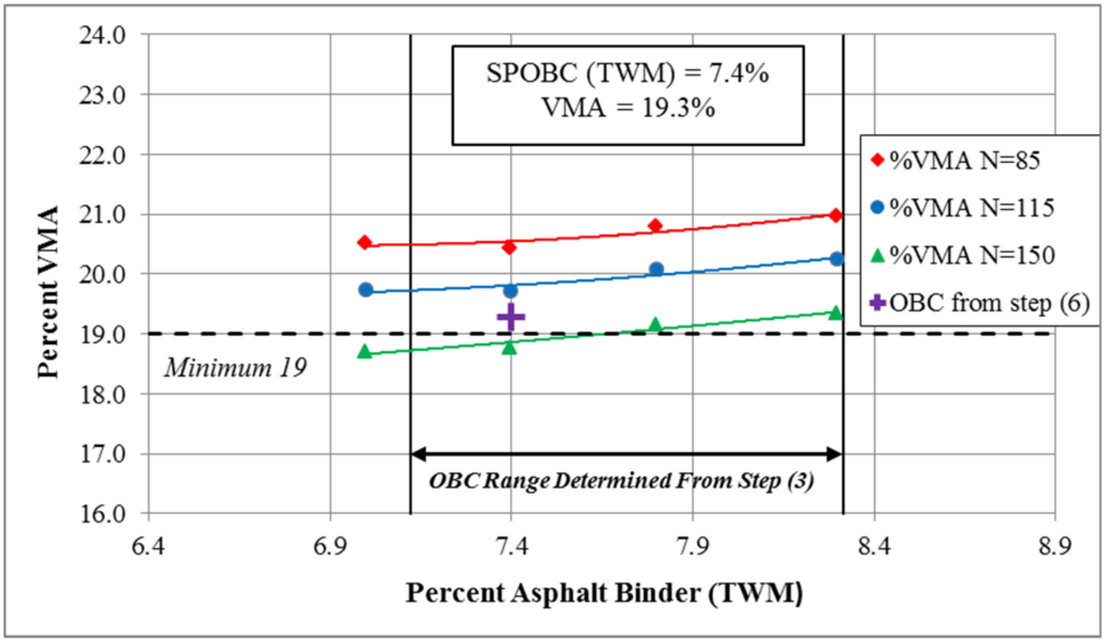

Figure 4.70: Percent VMA versus percent asphalt binder for Mix L.
(Note: The "+" sign indicates the Superpave OBC selected based on the criterion of the minimum binder content that meets all volumetric requirements.)

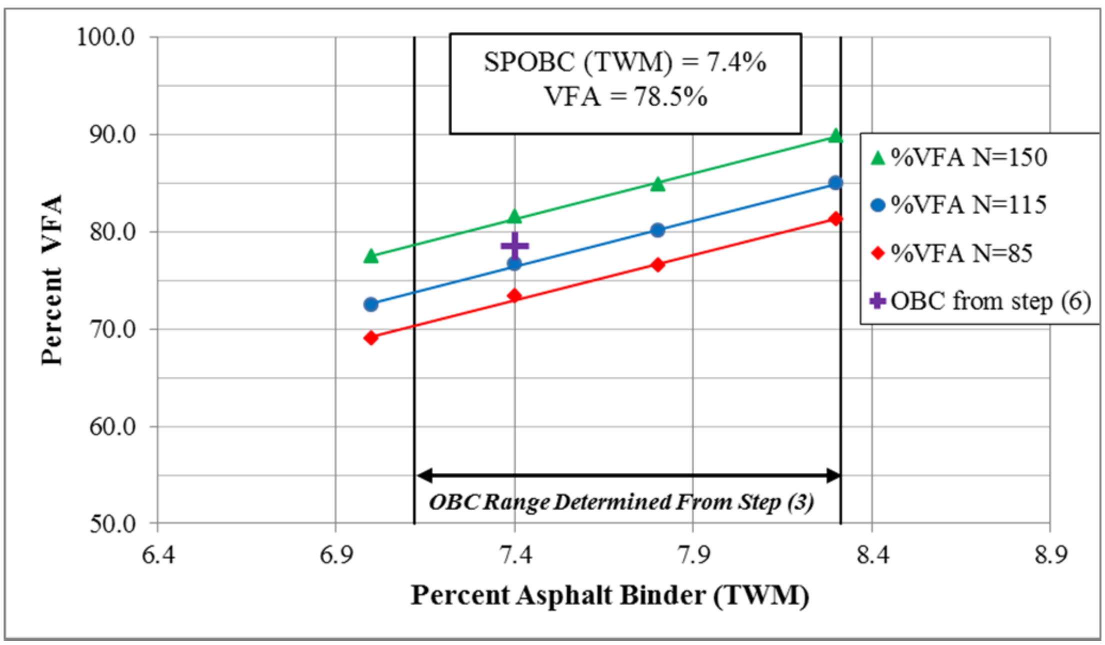

Figure 4.71: Percent VFA versus percent asphalt binder for Mix L.
(Note: The "+" sign indicates the Superpave OBC selected based on the criterion of the minimum binder content that meets all volumetric requirements.)

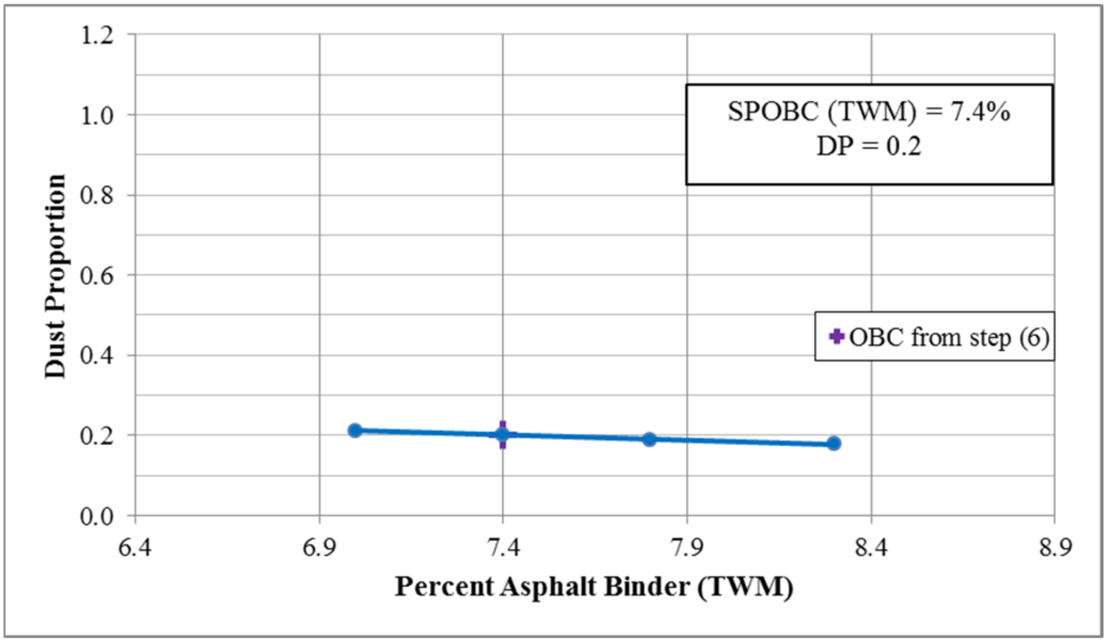

Figure 4.72: Dust proportion versus percent asphalt binder for Mix L.
(Note: The "+" sign indicates the Superpave OBC selected based on the criterion of the minimum binder content that meets all volumetric requirements.)

4.2.5 Mix M

Table 4.54 shows the basic aggregate and binder information for Mix M. Table 4.55 presents the aggregate gradation used for both the Hveem and Superpave mix designs. Figure 4.73 presents the same information on the 0.45 power gradation chart.

Table 4.54: Aggregate and Binder Type for Mix M

Mix ID	Mix M
NMAS	3/4 inch
RAP %	0
Aggregate Type	Granite
Quarry Location	Central California
Binder Supplier	Refinery 3
Binder Grade	PG 64-16 Rubber-Modified

Table 4.55: Aggregate Gradation Table for Mix M

Gradation of Aggregate Blend (Cumulative Percent Passing)				
Sieve Size		Contractor Test Result JMF Combined Gradation	Operating Range	UCPRC Lab Test Result Sieve Analysis
(mm)	(in.)			
25	1	**100.0**	100	**100.0**
19	3/4	**100.0**	95 – 100	**100.0**
12.5	1/2	**84.0**	78 – 90	**86.9**
9.5	3/8	**70.0**	64 – 76	**70.2**
4.75	#4	**28.0**	21 – 35	**27.5**
2.36	#8	**14.0**	9 –19	**13.2**
1.18	#16	**9.0**		**8.4**
0.6	#30	**6.0**		**5.8**
0.3	#50	**4.0**		**3.4**
0.15	#100	**3.0**		**2.0**
0.075	#200	**1.8**	0 – 3.8	**1.1**

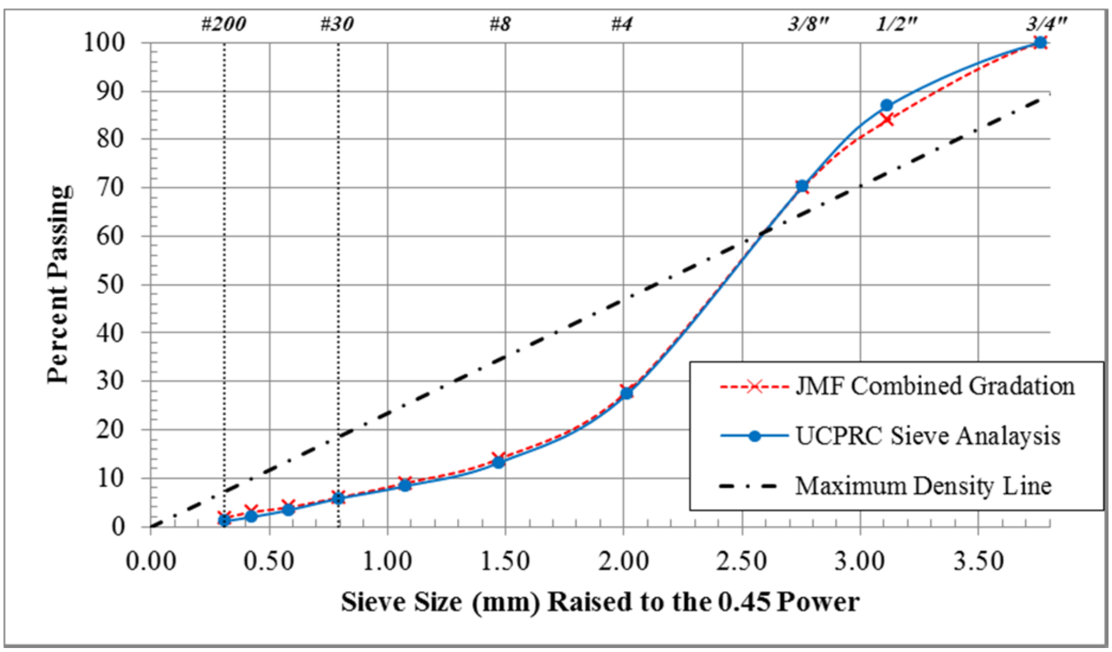

Figure 4.73: Aggregate gradation chart for Mix M.

The Superpave optimum binder content (SPOBC) for this mix could not be reliably determined from the test data since specimens made using the Hveem mix design gradation and the four binder contents tested could not be compacted to the target air-void content. These specimens did not receive sufficient compaction to achieve the appropriate volumetric requirements in Superpave specification. At N=150 the four binder contents compacted yielded air-void contents ranging from 7.1 percent to 9.6 percent, which were much higher than the target air-void content of 4.0 percent. An extrapolation value of OBC was calculated, but it was not recommended. Modifications could have been made to the existing mix design but time constraints prevented this. Table 4.56 shows a summary of the Hveem and Superpave mix design properties.

Table 4.57 shows the compaction and volumetric properties at different levels of gyration. Table 4.58 shows the calculation of the extrapolated mix property values. These data generated Figure 4.74 to Figure 4.78, which show mixture density versus number of gyrations, and air-void content, percent VMA, percent VFA, and dust proportion versus binder content, respectively.

Table 4.56: Summary of Design Properties for Mix M

Mix Design Properties	Contractor JMF Hveem Design OBC Properties	UCPRC Lab Testing Superpave Design OBC Properties	Superpave Specification
Hveem %OBC (DWA)	7.0	10.1	
Hveem %OBC (TWM)	6.5	9.2	
% Air Void Content	5.0	4.0	4.0
% VMA	20.1	21.0	19 – 23
% VFA	75.0	80.3	Report only
Dust Proportion	0.3	0.1	Report only
Gyrations needed to compact to 4%	n/a	151	50 – 150
%Gmm @ N=50	n/a	91.9	<94
%Gmm @ N=150	n/a	96.0	>96

Table 4.57: Compaction and Volumetric Properties at Different Gyrations for Mix M

	%Gmm					%Air Void				
	N=50	N=65	N=85	N=115	N=150	N=50	N=65	N=85	N=115	N=150
7.0% AC	87.0	87.8	88.8	89.5	90.4	13.0	12.2	11.2	10.5	9.6
7.4% AC	88.1	88.9	89.9	90.6	91.6	11.9	11.1	10.1	9.4	8.4
7.8% AC	88.2	89.0	90.0	90.9	91.9	11.8	11.0	10.0	9.1	8.1
8.3% AC	89.3	90.1	91.1	91.9	92.9	10.7	9.9	8.9	8.1	7.1

	%VMA					%VFA					Dust Proportion
	N=50	N=65	N=85	N=115	N=150	N=50	N=65	N=85	N=115	N=150	
7.0% AC	23.4	22.7	21.8	21.2	20.4	44.4	46.2	48.6	50.4	53.0	0.2
7.4% AC	23.2	22.5	21.7	21.0	20.2	48.8	50.7	53.3	55.4	58.5	0.2
7.8% AC	23.7	22.9	22.1	21.3	20.5	50.0	52.1	54.8	57.2	60.3	0.2
8.3% AC	23.7	23.0	22.1	21.5	20.6	54.8	56.9	59.9	62.3	65.7	0.2

Table 4.58: Calculation Sheet for SPOBC[a], Compaction and Volumetric Properties for Mix M

Enter Des values		SP Design Spec		50-150	19-23	Report	Report	<94	>96
Des %AV	OBC	Properties	LN(N)	N	VMA	VFA	DP	G_{mm}N50	G_{mm}N150
4.0	9.2	Calculated Values	5.02	151	21.0	80.3	0.1	91.9	96.0
Calculation of %Gmm, %VMA and %VFA at different gyrations									
N	8	13	20	32	50	65	85	115	150	195
LN(N)	2.08	2.56	3.00	3.47	3.91	4.17	4.44	4.74	5.01	5.27
%Gmm	84.1	86.2	88.0	89.9	91.9	92.8	93.9	94.8	96.0	96.7
%VMA	30.8	29.1	27.6	26.0	24.4	23.6	22.7	21.9	21.0	20.4
%VFA	48.7	52.9	56.9	61.8	67.2	70.0	73.6	76.9	81.3	84.4

[a] SPOBC = Superpave Optimum Binder Content

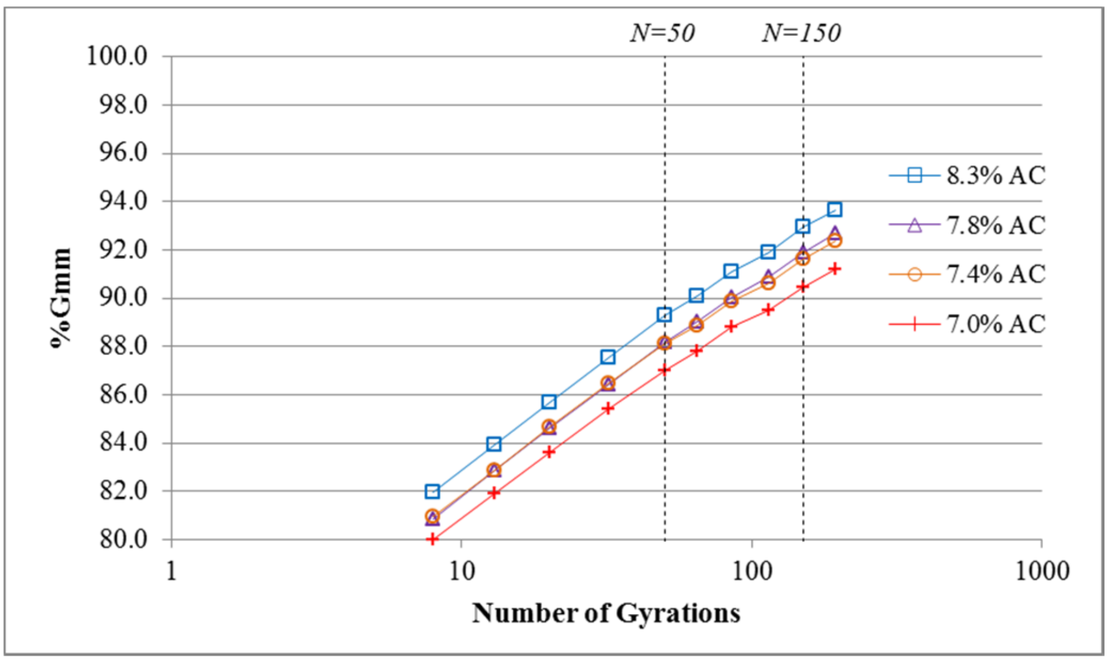

Figure 4.74: Mixture density versus number of gyrations for Mix M.

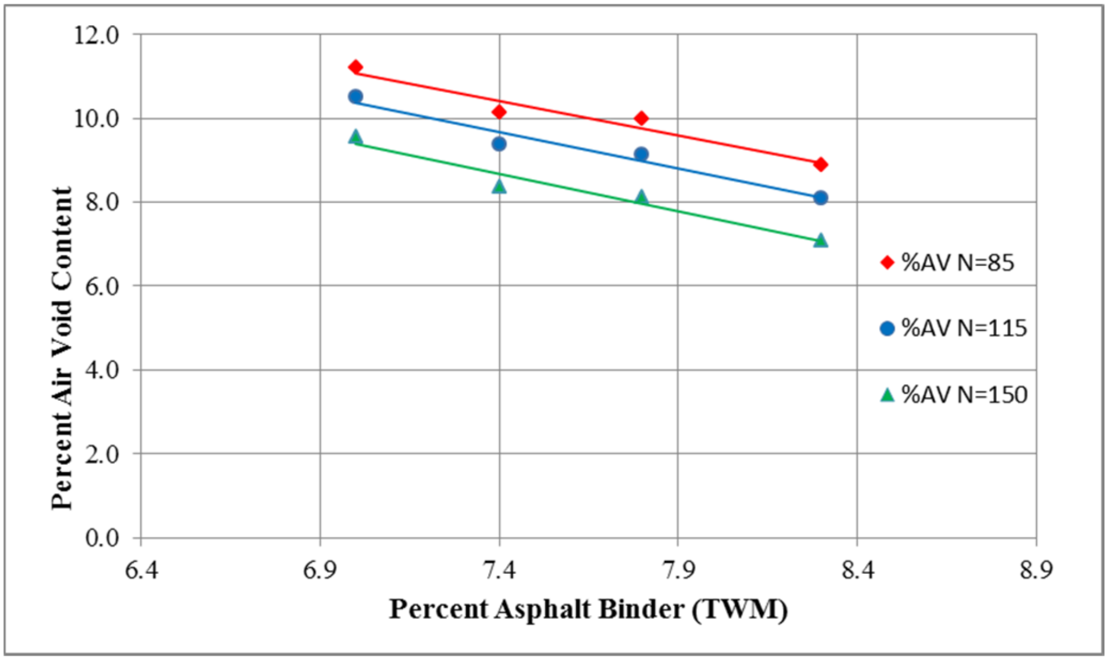

Figure 4.75: Percent air-void content versus percent asphalt content for Mix M.

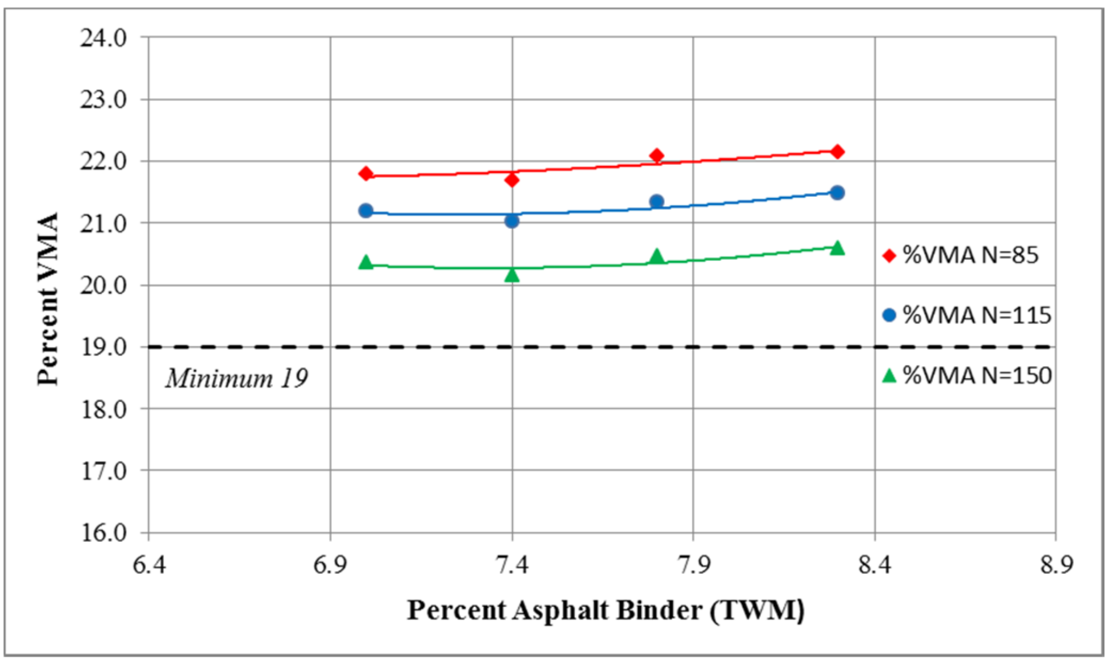

Figure 4.76: Percent VMA versus percent asphalt binder for Mix M.

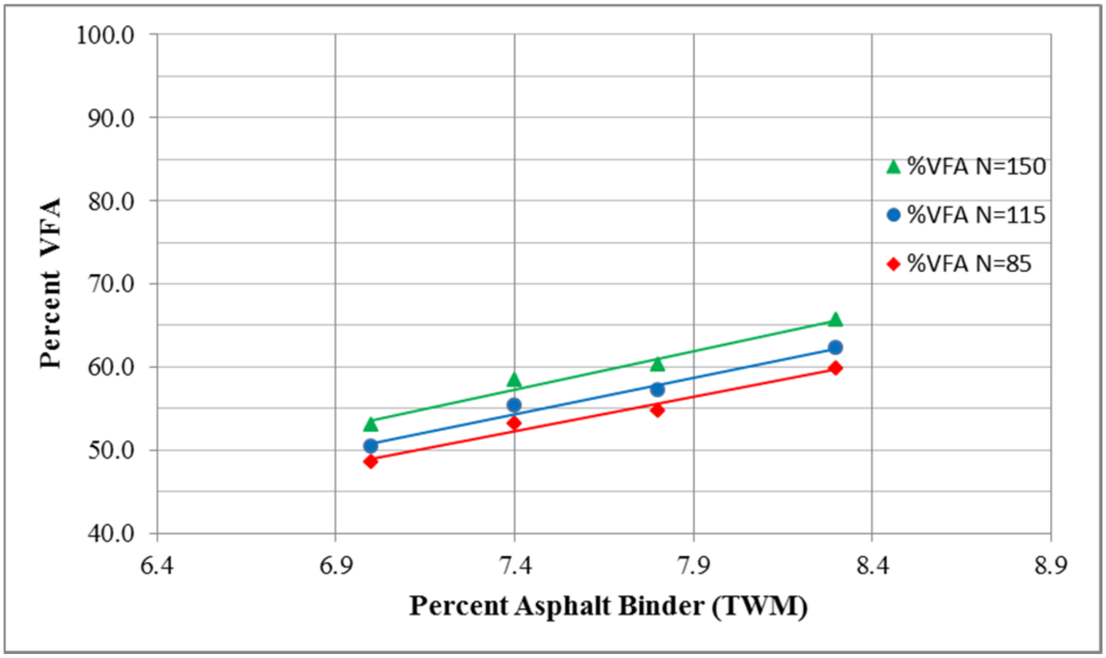

Figure 4.77: Percent VFA versus percent asphalt binder for Mix M.

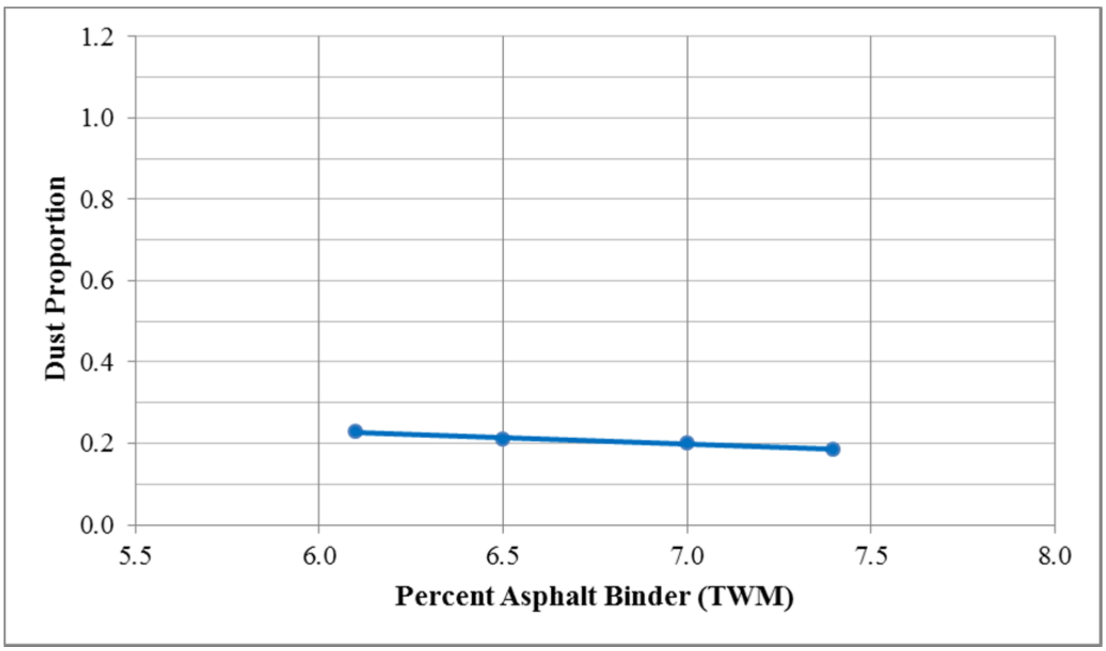

Figure 4.78: Dust proportion versus percent asphalt binder for Mix M.

4.3 Test Results for Polymer-Modified Binder Mixes

4.3.1 Mix N

Table 4.59 shows the basic aggregate and binder information for Mix N. Table 4.60 presents the aggregate gradation used for both the Hveem and Superpave mix designs. Figure 4.79 presents the same information on the 0.45 power gradation chart.

Table 4.59: Aggregate and Binder Type for Mix N

Mix ID	Mix N
NMAS	3/4 inch
RAP %	0
Aggregate Type	Granite
Quarry Location	Southern California
Binder Supplier	Refinery 3
Binder Grade	PG 64-16 Polymer-Modified

Table 4.60: Aggregate Gradation Table for Mix N

Gradation of Aggregate Blend (Cumulative Percent Passing)				
Sieve Size		Contractor Test Result JMF Combined Gradation	Operating Range	UCPRC Lab Test Result Sieve Analysis
(mm)	(in.)			
25	1	**100.0**		**100.0**
19	3/4	**93.0**		**92.5**
12.5	1/2	**75.0**		**75.2**
9.5	3/8	**63.0**		**63.9**
4.75	#4	**38.0**		**39.8**
2.36	#8	**25.0**		**26.3**
1.18	#16	**16.0**		**17.8**
0.6	#30	**10.0**		**11.7**
0.3	#50	**7.0**		**9.1**
0.15	#100	**4.0**		**7.0**
0.075	#200	**3.0**		**5.8**

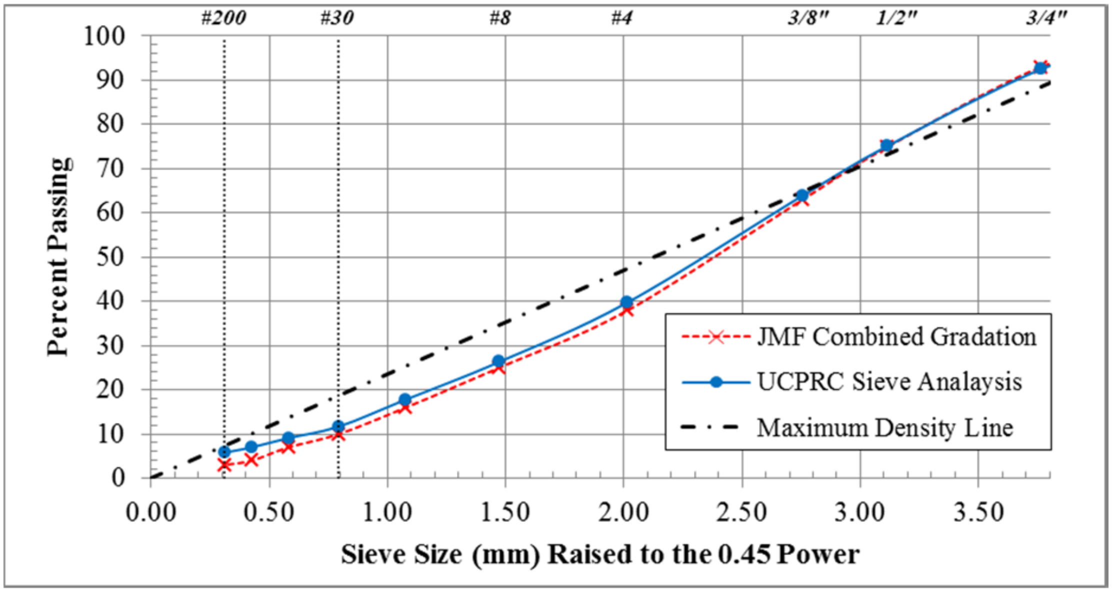

Figure 4.79: Aggregate gradation chart for Mix N.

Table 4.61 shows a comparison of design properties for the Hveem versus Superpave mix designs. For Superpave mix design, mixture properties are evaluated for four asphalt binder contents by using the densification data at N_{ini} (8 gyrations), N_{des} (85 gyrations), and N_{max} (130 gyrations). Table 4.62 shows the mixture's compaction and volumetric properties. Figure 4.80 illustrates specimen densification versus number of gyrations. Graphs of air-void content, percent VMA, percent VFA, and dust proportion are shown in Figure 4.81 to Figure 4.84. The Superpave OBC was found to be 6.0 percent by TWM. The value of each of these properties at the Superpave OBC is indicated by the arrow in each of the figures for this mix.

At a design target air-void content of four percent, percent VFA was above 75 percent. With a ±0.5 percent tolerance for a laboratory mixed and compacted specimen, a Superpave OBC of 6.0 percent was selected with a design air-void content of 4.3 percent to meet the specification.

Table 4.61: Summary of Design Properties for Mix N

Mix Design Properties	Contractor JMF Hveem Design OBC Properties	UCPRC Lab Testing Superpave Design OBC Properties	Superpave Design Specification
Hveem %OBC (DWA)	5.0	6.4	
Hveem %OBC (TWM)	4.8	6.0	
% Air Void Content	5.3	4.3	4.0
% VMA	15.1	17.6	>13.5
% VFA	64.5	74.9	65 – 75
Dust Proportion	0.7	1.0	0.6 – 1.3
%Gmm @ N_{ini}=8	n/a	86.4	<92
%Gmm @ N_{max}=130	n/a	96.9	<98

Table 4.62: Compaction and Volumetric Properties for Mix N

%AC	Compaction Properties			Volumetric Properties @ N_{des} = 85			Dust Proportion
	$\%G_{mm}$ @ N=8	$\%G_{mm}$ @ N=85	$\%G_{mm}$ @ N=130	%Air Voids	%VMA	%VFA	
4.8	83.9	92.7	93.9	7.3	16.7	56.2	1.5
5.2	84.6	93.9	95.1	6.1	16.9	63.6	1.3
5.7	85.1	94.2	95.5	5.8	17.5	67.2	1.2
6.1	87.0	96.2	97.6	3.8	17.6	78.6	1.0

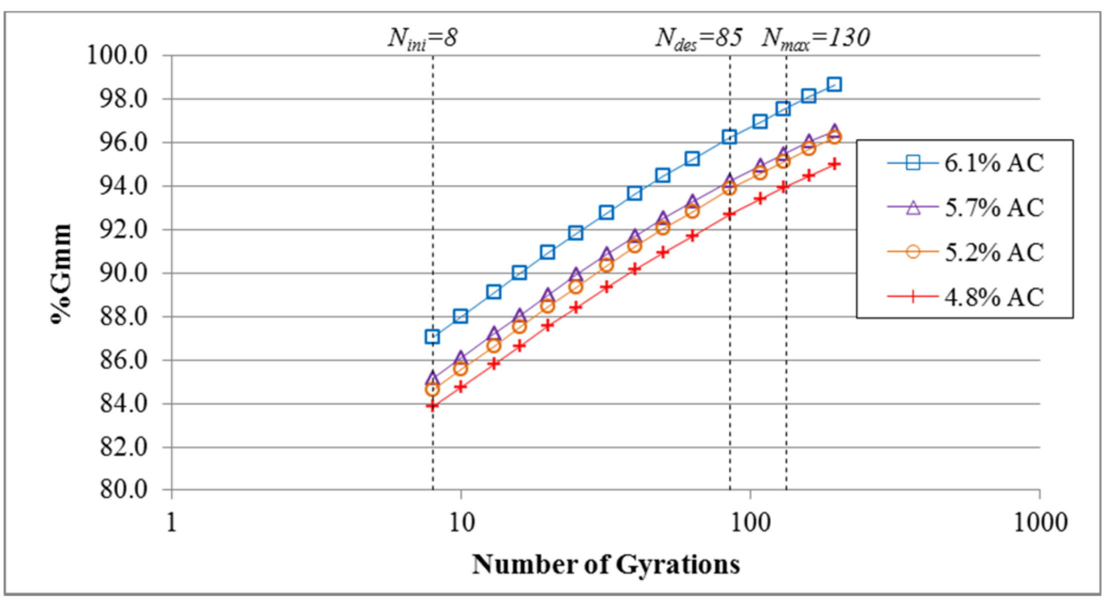

Figure 4.80: Mixture density versus number of gyrations for Mix N.

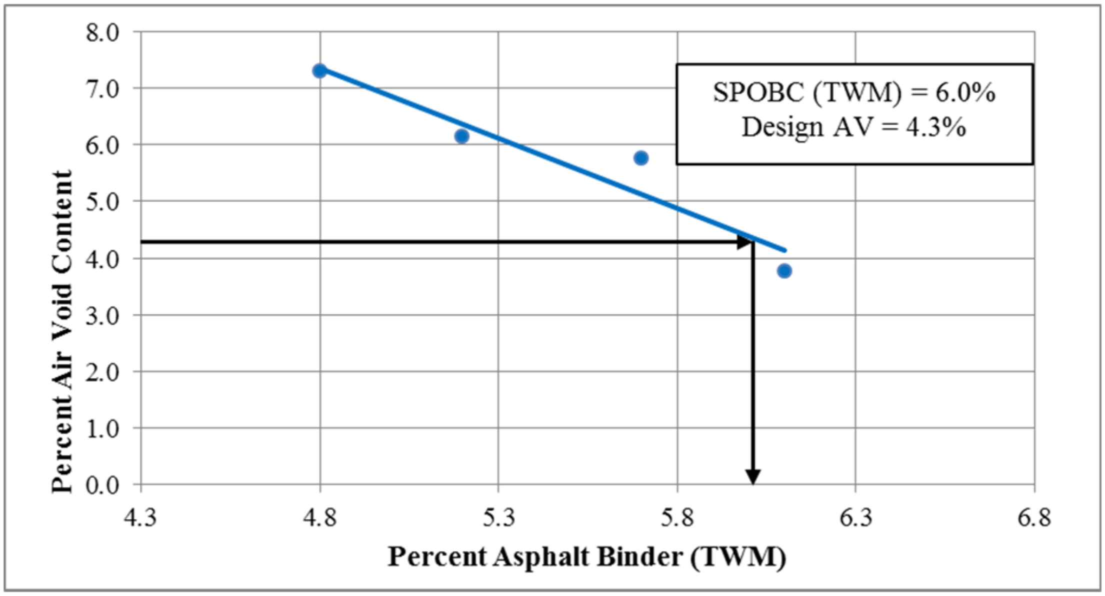

Figure 4.81: Selection of Superpave OBC based on percent air-void content versus percent asphalt binder for Mix N.
(Note: The arrow in the figure shows the Superpave OBC selected based on the 4.3 percent air-void content criterion.)

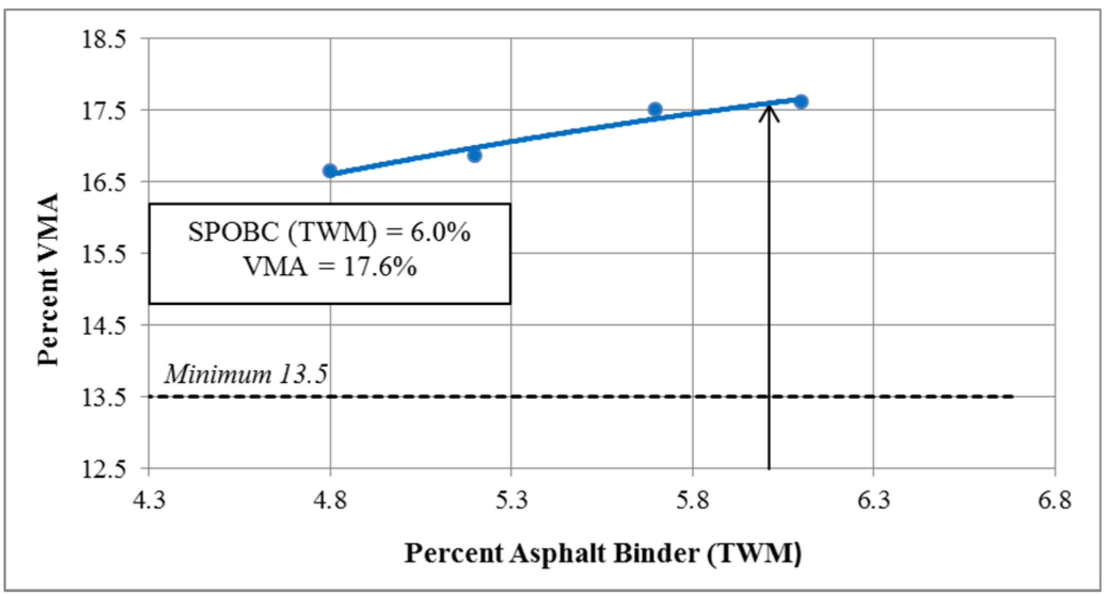

Figure 4.82: Percent VMA versus percent asphalt binder for Mix N.
(Note: The arrow in the figure indicates the value of percent VMA at the Superpave OBC.)

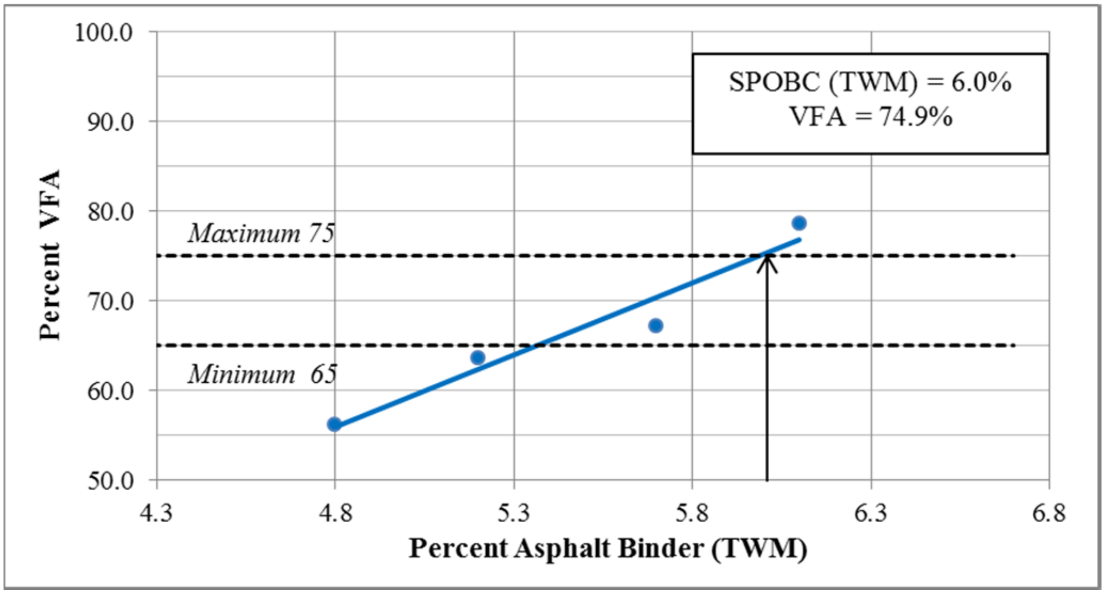

Figure 4.83: Percent VFA versus percent asphalt binder for Mix N.
(Note: The arrow in the figure indicates the value of percent VFA at the Superpave OBC.)

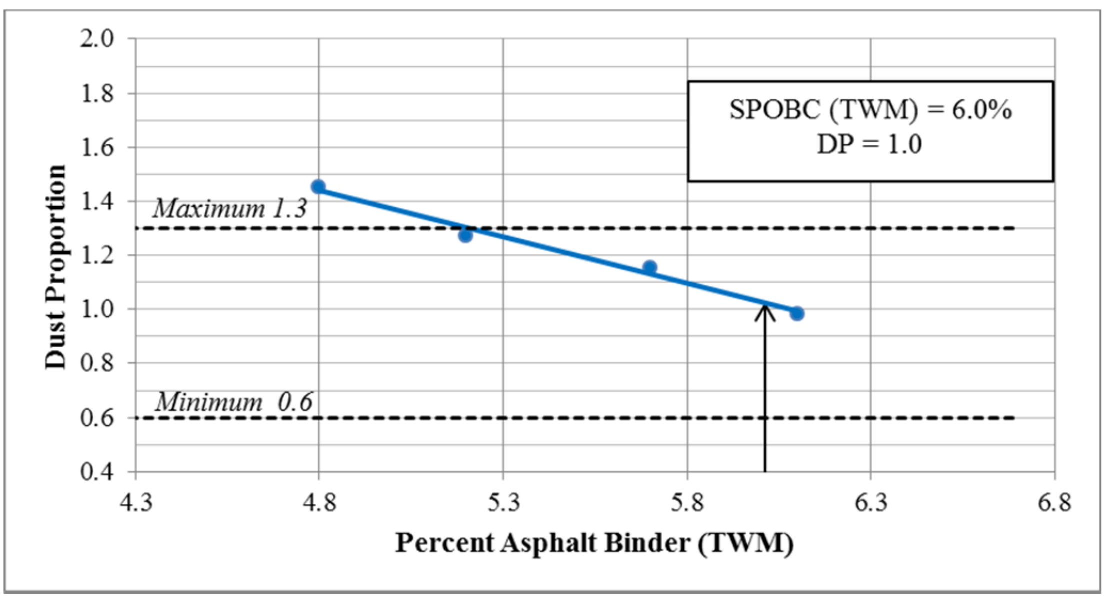

Figure 4.84: Dust proportion versus percent asphalt binder for Mix N.
(Note: The arrow in the figure indicates the dust proportion value at the Superpave OBC.)

4.3.2 Mix O

Table 4.63 shows the basic aggregate and binder information for Mix O. Table 4.64 presents the aggregate gradation used for both the Hveem and Superpave mix designs. Figure 4.85 presents the same information on the 0.45 power gradation chart.

Table 4.63: Aggregate and Binder Type for Mix O

Mix ID	Mix O
NMAS	3/4 inch
RAP %	0
Aggregate Type	Alluvial Fan
Quarry Location	Southern California
Binder Supplier	Refinery 3
Binder Grade	PG 64-28 Polymer-Modified

Table 4.64: Aggregate Gradation Table for Mix O

Gradation of Aggregate Blend (Cumulative Percent Passing)				
Sieve Size		Contractor Test Result JMF Combined Gradation	Operating Range	UCPRC Lab Test Result Sieve Analysis
(mm)	(in.)			
25	1	**100.0**		**97.9**
19	3/4	**89.0**		**92.9**
12.5	1/2	**74.0**		**77.9**
9.5	3/8	**67.0**		**70.3**
4.75	#4	**51.0**		**51.9**
2.36	#8	**38.0**		**38.4**
1.18	#16	**28.0**		**28.5**
0.6	#30	**20.0**		**20.7**
0.3	#50	**13.0**		**15.3**
0.15	#100	**8.0**		**9.7**
0.075	#200	**4.9**		**6.0**

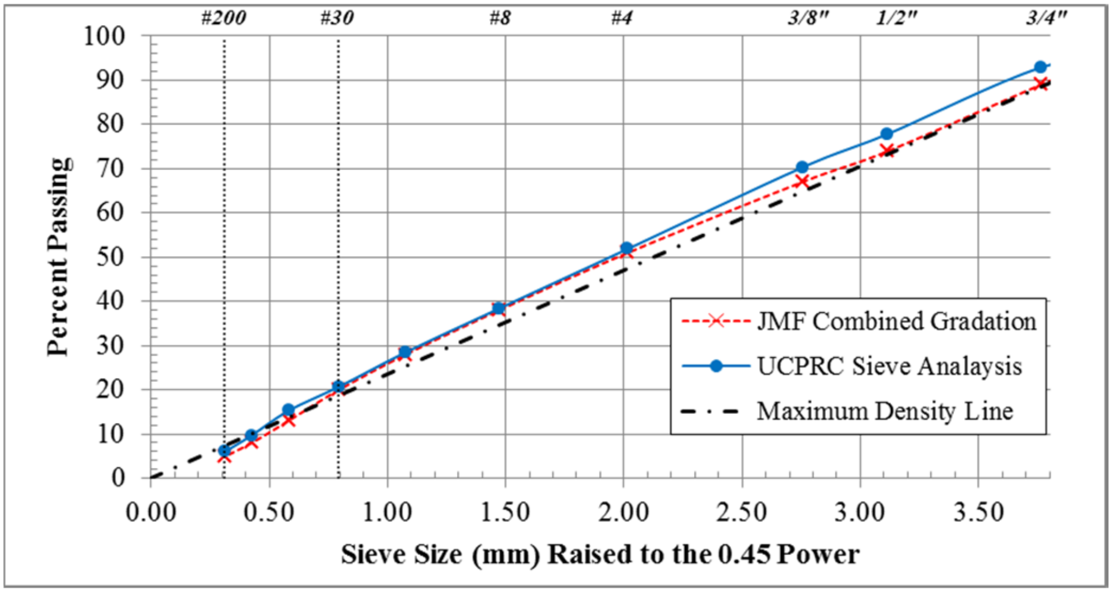

Figure 4.85: Aggregate gradation chart for Mix O.

Table 4.65 shows a comparison of design properties for the Hveem versus Superpave mix design. For Superpave mix design, mixture properties are evaluated for four asphalt binder contents by using the densification data at N_{ini} (8 gyrations), N_{des} (85 gyrations), and N_{max} (130 gyrations). Table 4.66 shows the mixture's compaction and volumetric properties. Figure 4.86 illustrates specimen densification versus number of gyrations. Graphs of air-void content, percent VMA, percent VFA, and dust proportion are shown in Figure 4.87 to Figure 4.90. The Superpave OBC was found to be 4.6 percent by TWM. The value of each of these properties at the Superpave OBC is indicated by the arrow in each of the figures for this mix.

Table 4.65: Summary of Design Properties for Mix O

Mix Design Properties	Contractor JMF Hveem Design OBC Properties	UCPRC Lab Testing Superpave Design OBC Properties	Superpave Design Specification
Hveem %OBC (DWA)	4.9	4.8	
Hveem %OBC (TWM)	4.7	4.6	
% Air Void Content	4.9	4.0	4.0
% VMA	14.9	13.8	>13.5
% VFA	67.2	71.3	65 – 75
Dust Proportion	1.1	1.4	0.6 – 1.3
%Gmm @ N_{ini}=8	n/a	88.8	<92
%Gmm @ N_{max}=130	n/a	97.0	<98

Table 4.66: Compaction and Volumetric Properties for Mix O

%AC	Compaction Properties			Volumetric Properties @ N_{des} = 85			Dust Proportion
	$\%G_{mm}$ @ N=8	$\%G_{mm}$ @ N=85	$\%G_{mm}$ @ N=130	%Air Voids	%VMA	%VFA	
4.5	88.6	95.8	96.8	4.2	13.8	69.5	1.5
4.9	89.8	97.0	97.9	3.0	13.7	78.1	1.3
5.4	90.6	97.8	98.6	2.2	13.9	84.4	1.2
5.8	92.6	99.5	100.1	0.5	14.2	96.7	1.0

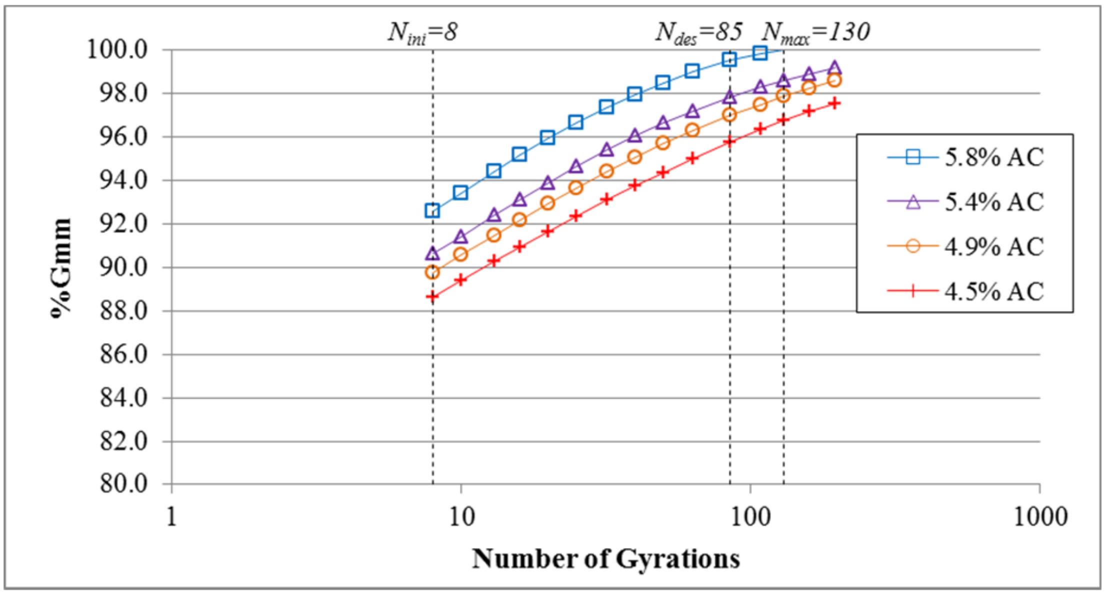

Figure 4.86: Mixture density versus number of gyrations for Mix O.

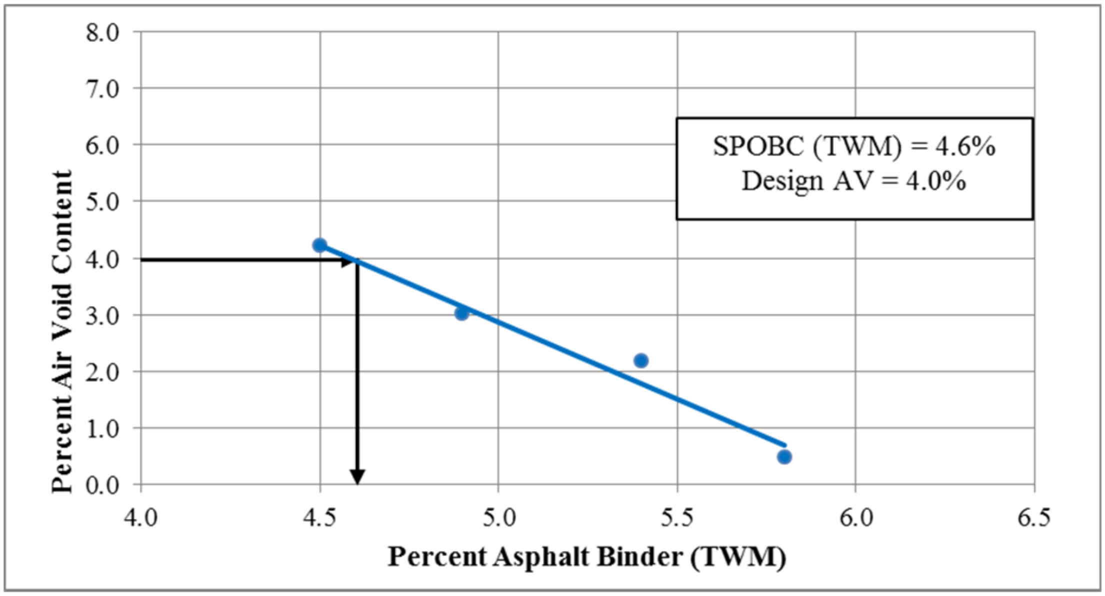

Figure 4.87: Selection of Superpave OBC based on percent air-void content versus percent asphalt binder for Mix O.
(Note: The arrow in the figure shows the Superpave OBC selected based on the four percent air-void content criterion.)

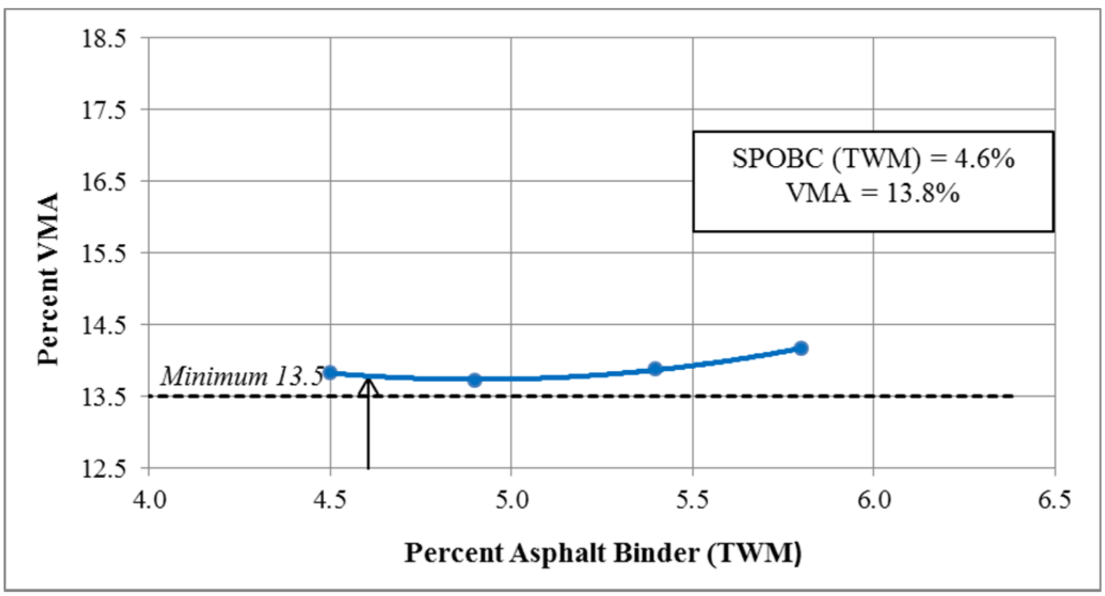

Figure 4.88: Percent VMA versus percent asphalt binder for Mix O.
(Note: The arrow in the figure indicates the value of percent VMA at the Superpave OBC.)

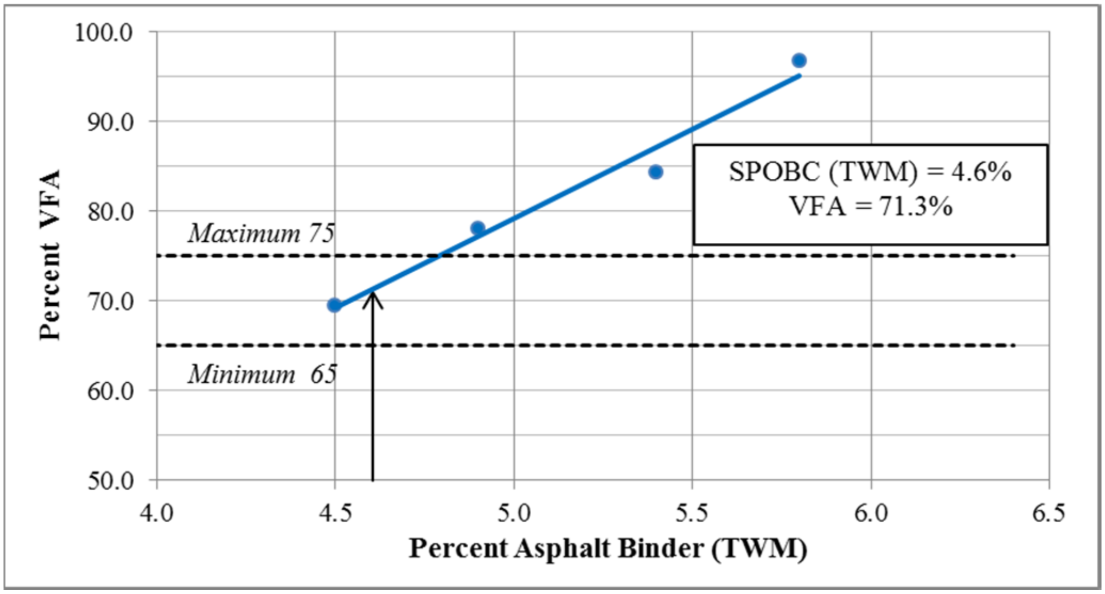

Figure 4.89: Percent VFA versus percent asphalt binder for Mix O.
(Note: The arrow in the figure indicates the value of percent VFA at the Superpave OBC.)

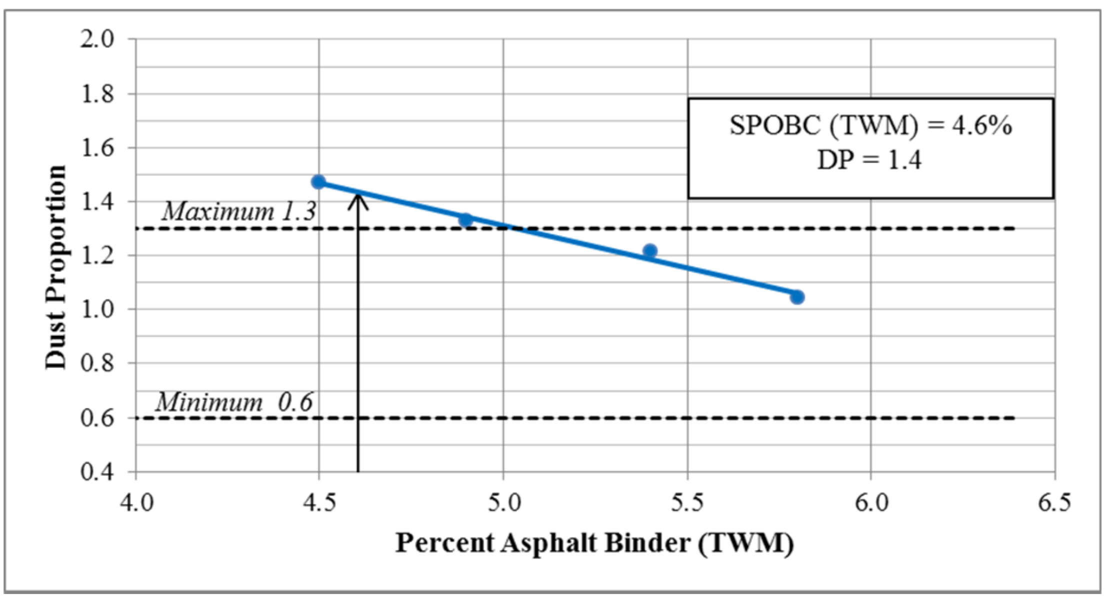

Figure 4.90: Dust proportion versus percent asphalt binder for Mix O.
(Note: The arrow in the figure indicates the dust proportion value at the Superpave OBC.)

5 SUMMARY AND RECOMMENDATIONS

This technical memorandum presents the results of a study in which Superpave mix designs were performed on a select number of Caltrans mixes from different parts of the state. These mixes included a range of aggregate types, as well as conventional, rubberized, and polymer-modified binders. An evaluation compared Superpave and Hveem optimum binder contents (OBCs), gradations, and volumetrics. Table 5.1 contains a summary of these properties and design parameters.

This memorandum also includes a series of recommended specimen preparation and testing procedures based on information gathered during this project.

5.1 Summary of Changes to Hveem OBC and Gradation to Meet Superpave Specifications

In order to meet the Superpave specifications, adjustments were made to each of the initial approved Hveem mix designs. Table 4.1 shows a summary of the contractor-measured Hveem mix OBC (shown as HV) and the UCPRC-measured Superpave mix OBC (shown as SP) for each mix tested in Phase I. The unmodified binder Superpave mix OBC increased on average by 0.7 percent with a range from 0.4 percent to 1.0 percent. Dust proportions for these same Superpave mixes were sometimes higher and sometimes lower than the Hveem mix designs with the same materials. For rubber-modified binder mixes, the Superpave OBC increased on average by 0.6 percent compared with that of the Hveem mix design procedure. Dust proportions for the rubber mixes were typically very low for the Hveem mix designs. Dust proportion is a reported value only in the specification, and dust proportions for several mixes (Mixes I, J, and K) were increased to meet the minimum 0.6 value required for unmodified-binder and polymer-modified binder mixes. Time and budget precluded changing the mix designs for two rubberized-binder Superpave mixes (Mixes L and M) with low dust proportion values. Performance differed within the set of polymer-modified mixes: when moving from Hveem to Superpave, the OBC for Mix J increased 1.3 percent while the OBC for Mix N remained nearly identical. In some cases, the dust contents were increased to maintain the dust proportion (DP) within specification as binder contents increased.

Most of the mixes were able to achieve the design air-void content, typically four percent, and still meet volumetric requirements (VMA, VFA). In 4 of the 15 mixes (Mixes B, F, G, and N) it was necessary to work with the tolerance in design air-void content of ±0.5 percent in order to achieve volumetrics in the laboratory. For these four mixes, percent VFA was slightly higher than the maximum specified value of 75 percent. Increasing the design air-void content to 4.5 percent lowered the OBC determined by up to 0.2 percent and this lowered percent VFA to within the specified range of 65 to 75 percent.

Table 5.1: Mix OBC Summary Comparison Table

			Optimal Binder Content			Dust Proportion	
Binder Type	**Mix Name**	**Binder Type**	**Hveem Design OBC (TWM)**	**SP Design OBC (TMW)**	**OBC Change (TWM)**	**Hveem Design Dust Proportion**	**Superpave Design Dust Proportion**
Unmodified	**A**[a]	Refinery 1 PG 64-16	4.8	5.2	+0.4	1.1	1.2
	B[a]	Refinery 2 PG 64-16	4.9	5.9	+1.0	1.0	0.8
	C	Refinery 2 PG 64-16	5.2	6.1	+0.9	0.8	0.5
	D	Refinery 2 PG 64-16	4.6	5.2	+0.6	1.0	1.4
	E	Refinery 1 PG 64-16	4.6	5.2	+0.6	1.0	1.5
	F	Refinery 1 PG 64-16	4.8	5.8	+1.0	0.9	0.7
	G	Refinery 2 PG 64-16	5.8	6.5	+0.7	0.9	1.0
	H	Refinery 1 PG 70-10	4.9	5.5	+0.6	1.1	0.9
Rubber-modified	**I**[a]	Refinery 2 PG 64-16 Rubber	7.4	7.5	+0.1	0.5	1.0
	J[a]	Refinery 3 PG 64-16 Rubber	6.7	8.1	+1.4	0.5	1.0
	K	Refinery 3 PG 70-10 Rubber	6.9	7.5	+0.6	0.3	0.9
	L	Refinery 2 PG 64-16 Rubber	7.2	7.4	+0.2	0.3	0.2
	M	Refinery 3 PG 64-16 Rubber	6.5	n/a	n/a	0.3	0.1
Polymer-modified	**N**[a]	Refinery 3 PG 64-28 PM	4.8	6.0	+1.2	0.7	1.0
	O	Refinery 3 PG 64-28 PM	4.7	4.6	-0.1	1.1	1.4

[a] Selected by Chief, Office of Roadway Materials Testing, Co-Chair, Superpave Task Group for Phase II Testing.

5.2 Summary of Final Recommended Specimen Preparation and Testing Procedures and Time Estimates

The following recommended general guidelines for preparation of Superpave mix designs specimens are based on the work performed in this investigation, particularly those pertaining to compaction pressures, post-compaction holding (squaring) time, and number and range of gyrations. Table 3.1 details the values used for each mix.

Recommendations for Specimen Preparation

Mixing, short-term oven-aging, and compaction temperature:

Unmodified

- Mix binder temperature as directed by binder viscosity chart or at supplier-recommended temperature.
- Mix aggregate at temperature 15°C higher than binder.
- Short-term oven age for four hours at 135°C.
- Compact mixture at temperature as directed by binder viscosity chart.

Rubber- and polymer-modified

- Mix binder temperature as directed by per binder viscosity chart or at supplier-recommended temperature.
- Mix aggregate at temperature 15°C higher than binder.
- Short-term oven age for four hours at 135°C.
- Compact mixture at temperature as directed by binder viscosity chart.

Compaction pressure varies depending on binder type:

- Unmodified and polymer-modified: 600 kPa (1.16° internal angle)
- Rubber: 825 kPa (1.16° internal angle)

Fan-cooling or holding (squaring) time postcompaction or prior to specimen removal:

- Unmodified and polymer-modified: 5-min. fan cooling, no squaring
- Rubber: 90-min. squaring with constant height control

Number and range of gyrations:

- Unmodified and polymer-modified: N Design = 85, check mixture density at N Initial = 8 and N Maximum = 130.
- Rubber: N Design = 50 to 150, check mixture density at N=50 and N=150.

Unmodified-binder mixes posed few problems during the mix design process and these mixes could consistently be compacted to the desired air-void content. With the small number of polymer-modified mixes, mixing and compacting temperatures were adjusted slightly higher to achieve the desired mixture density. For the polymer-modified mixes, it is recommended that materials and compaction molds be transferred quickly to the gyratory compactor to prevent temperature reduction. Rubber-modified mixes proved the most problematic of the three binder types. These gap-graded mixes were generally difficult to compact to the target four percent air-void content. In addition, because of rebound in the specimens' volumes after removal of the compactor's compressive load, it is recommended that specimens be held ("squared") in the gyratory compactor for 90 minutes with constant height control before they are taken out.

The productivity rates at which Superpave mix designs can be performed vary by binder type because of variations in the specimen preparation process. However, a typical mix design process and the time needed for each step are shown in Table 5.2.

Table 5.2: Steps in Superpave Mix Design, Time Required, Notes and Recommendations for Unmodified Binder Mixes

Major Steps	Notes and Recommendations	Days Needed
1. Mixing	Prepare samples at four binder contents. For each binder content, prepare one mixture for RICE (T 209) and two mixtures for gyratory compaction (T 312).	1 day
	Stagger each mixture by 15 to 20 minutes when mixing to accommodate the time needed for compacting.	
2. Short-term aging	Stir mixture every hour when short-term aging in oven.	
3. Compaction	Requires approximately 15 to 20 minutes to complete the compaction procedure (transferring the mixture into a compacting mold, compacting the mix in the gyratory device, and cooling it for five minutes by fan) for one mixture.	
4. Specimen Extraction	No holding (squaring) needed. Specimens can be removed when cooling is complete.	
5. Air-void Content Measurement	Determine RICE (T 209).	1 to 2 days
	Measure air-void content via concurrent test method from Caltrans (T 166 was used in this project).	1 day
6. Data Analysis	Refer to Chapter 5 in Superpave Series No.2 (SP-2) for data analysis.	

Following compaction, rubber mixes require holding (squaring), an extra step that significantly lengthens the procedure time. Expected productivity rate for mixes with rubber- and polymer-modified binders are shown in Table 5.3.

Table 5.3: Steps in Superpave Mix Design, Time Required, Notes and Recommendations for Rubber and Polymer Binder Mixes

Major Steps	Notes and Recommendations	Days Needed
1. Mixing	Prepare samples at four binder contents. For each binder content, prepare one mixture for RICE (T 209) and two mixtures for gyratory compaction (T 312). Put each mix in individual labeled pans to prepare for short-term aging (curing) and compaction. Reserve two ovens for the aging and compaction processes to be performed the next day. It is recommended that one oven be pre-set to warm up to curing temperature 4 hours before the next workday is to begin. Place first pan of mix to be compacted into this oven.	1 day
2. Short-term aging	Just prior to completion of the 4-hour (preferably overnight) curing, set the second oven to compaction temperature. Once the first text mix pan has completed the curing process, move it to the second oven and heat mix until it reaches compaction temperature.	2 to 3 days
	Stagger the curing and compaction of each remaining mixture by 1 hour-and-45 minutes to 2 hours to accommodate the time needed for compaction and squaring.	
3. Compaction	Compaction of each mixture takes approximately 15 to 20 minutes. The process requires transferring the mixture to a compaction mold, compacting the mix in the gyratory device, and fan-cooling it for 5 minutes.	
4. Specimen Extraction	After compaction is complete, set the gyratory compactor to perform a 90-minute squaring post-compaction with constant height control. Specimens can be removed after squaring.	
5. Air-void Content Measurement	Determine RICE (T 209)	1 to 2 days (can be performed concurrently during the compaction day)
	Measure air-void content via concurrent test method from Caltrans (T 166 was used in this project).	1 day
6. Data Analysis	Refer to Chapter 5 in Superpave Series No.2 (SP-2) for data analysis.	

5.3 Summary of Other Recommendations for Changes to Draft Superpave Specifications

Specimens in this study were produced following draft Superpave specification guidelines (*4*). Based on the results, no changes are recommended to the specification at this time.

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1. North Central Superpave Center. *https://engineering.purdue.edu/ncsc/about/superpave.htm* (Accessed Dec. 19, 2012)
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3. Pavement Interactive. **Superpave Mix Design**. Jan. 26, 2011. *http://www.pavementinteractive.org.*
4. **Standard Specification: Section 39 Hot Mix Asphalt, Superpave**. November 1, 2012. California: State of California Department of Transportation.