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Technical Memorandum

TM-UCB PRC- 99-2

Mix Design and Analysis and Structural Section Design for Full Depth Pavement for Interstate Route 710

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Date:	June, 1999

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1.0 INTRODUCTION

This report summarizes the results of an investigation to design both a suitable asphalt concrete mix and a full-depth asphalt concrete structural section containing the mix, or mixes for a "Long Life Pavement" for a portion of Interstate 710 in Southern California. A companion report (Technical Memorandum, TM UCB PRC-99-3) desribes the asphalt concrete section for use as an overlay on the existing portland cement concrete pavement.

1.1 Pavement Site

Interstate 710 is located in Southern California, in Los Angeles County, Figure 1. Rehabilitation is scheduled for the summer 2000 and the project has been selected for a long-life pavement design, with a design life of 30 to 40 years. The freeway is a heavily trafficked route and carries traffic in and out of the Port of Long Beach. The specific section of Interstate Route 710 selected for this project is between the Pacific Coast Highway and the 405 Freeway, Figure 2. The current maximum number of trucks per day in the design lane is 9,650. An estimate of the design traffic for this period is 100×10^6 to 200×10^6 equivalent single axle loads (ESALs).

The existing pavement structural section consists of 200 mm of portland cement concrete (PCC), 100 mm of cement treated subbase, 100 mm of aggregate base and 200 mm of imported subbase material. Two rehabilitation strategies are planned, one for the majority of the section and the other for under the structures. On the sections where the overhead clearance is not limiting, the existing PCC will be cracked and seated and overlaid with asphalt concrete. Under the structures where minimum clearance requirements do not allow an overlay, full depth asphalt concrete sections are will be utilized.

1.2 Design Concepts

The design methodology is illustrated schematically in Figure 3. For Interstate Route 710 the performance tests and associated analyses have been limited to rutting and fatigue cracking.

For rutting, the Hveem stabilometer has been used to select the range of binder contents required for the initial mix design process shown in Figure 3. To select the final mix design an accelerated performance test, the repeated load simple shear test at constant height (RSST-CH) has been utilized. Figure 4 illustrates the framework for the selection of the design binder content using the RSST-CH.

Essentially the mix design consists of selecting the highest binder content which will permit the mix to accommodate the design traffic at the critical temperature, T_c[1], without exceeding a limiting rut depth, in this case 0.5 inches (12.5 mm).

When the mix design has been selected, fatigue tests are performed on a representative mix at the design binder content. Following the framework of Figure 5, a structural section is selected, in this case a full depth asphalt concrete layer, to insure that the anticipated traffic will be carried for the design period with a level of cracking not expected to exceed about 10 percent in the wheel paths.

In both Figures 4 and 5 it will be noted that reliability is incorporated in the design process through a reliability multiplier, M. For the design recommended herein, a level of

---

[1] The critical temperature is defined as the temperature at a 2-inch depth at which the maximum permanent deformation occurs assuming in this case that the truck traffic is applied at a uniform rate throughout the year.

reliability of 95 percent has been selected. This value reflects the variances in the lives selected from the laboratory tests (N_{supply}) and those for the estimated traffic (N_{demand}).

2.0 MATERIALS

Materials for the project included two asphalts, designated AR-8000 and PBA-6A, supplied by Huntway Refining; and aggregate supplied from a CALMAT / VULCAN source in Southern California termed *San Gabriel* material.

2.1 Asphalt Binders

Two binders have been used in the investigation; one is a conventional AR-8000 paving asphalt and the other a polymer modified material designated as PBA-6A. The Industry Group recommended that the PBA-6A material be used because of its improved long-term durability characteristics and potential for improved permanent deformation resistance that it would impart to the mix.

Available test results for the two binders are summarized in Table 1 together with appropriate specification limits. Results for the AR-8000 are plotted on the Shell Bitumen Test Data Chart in Figure 6. The results indicate a Class S (standard) behavior according to the classification suggested by Heukelom (*1*).

2.2 Aggregate

The aggregate, *San Gabriel* material, was obtained from VULCAN / CALMAT plants in the Los Angeles basin. Initial mix evaluation was performed on mixes prepared from the cold-feed material. A limited series of tests were also performed on mix prepared from the hot bin aggregates and one mix was tested in which sand replaced a portion of the crushed fines.

Table 1 Binder Characteristics

Property	AASHTO Method	AR-8000		PBA-6A	
		Test Result	Spec.	Test Result	Spec.
Tests on Original Asphalt					
Flash Point, C.O.C, ºC	T-48	288	230 min	302	232 min
Solubility in TCE (%)	T-44		99 min	99.8+	Report
Absolute Viscosity, 60ºC, poise	T-202	2113	-	10000+	2000 min
Kinematic Viscosity, 135ºC, cSt	T-201	388	-	673	2000 max
Tests on Residue from RTFO (AASHTO T-240)					
Absolute Viscosity, 60ºC, poise	T-202	8322	6000-10000	10000+	5000 min
Kinematic Viscosity, 135ºC, cSt	T-201	706	400 min	1187	275 min
Viscosity Ratio: residual/original	-		-	1.8	4.0 max
Mass Loss, percent	T-240		-	0.149	0.6 max
Ductility @ 25ºC, cm	T-51		750 min	NA	60 min
Tests on PAV Residue (AASHTO PP-1), 100ºC					
BBR, Creep Stiffness @ -30ºC, MPa			-	236	300 max
BBR, m-value @ -30ºC			-	0.312	0.300 min

Summaries of wash and sieve analyses performed on the various materials are contained in Appendix A. Results of the combined aggregate grading based on a wash and sieve analysis are shown in Figure 7 for the UCB evaluation and for the combined gradation supplied by the industry group for the initial test series. The proportions of each of the fractions used by the two groups are as follows:

Cold Feed Aggregates, Percent

Fraction	¾ inch (19.0 mm)	½ inch (12.5 mm)	3/8 inch (9.5 mm)	Rock Dust
Industry	30	15	20	35
UCB	29	16	15	40

Figure 8 contains the same two combined gradings plotted on the 0.45-grading chart. The control points and the maximum density line according to the Superpave requirements are shown for an aggregate gradation with a ¾ inch (19 mm) nominal maximum size. It should be noted that the gradations pass through the so-called "restricted zone."

Los Angeles abrasion test (AASHTO T-96) results are shown in Table 2 for three of the size fractions. Also shown are aggregate specific gravities for the four fractions (supplied by industry).

Table 2 Aggregate Characteristics

Fraction	**¾ inch (19.0 mm)**	**½ inch (12.5 mm)**	**3/8 inch (9.5 mm)**	**Rock Dust**	**Spec. Limits**
LA Abrasion:					
Loss @ 100 rev. (%)	8.6	11.0	11.0	-	10 max
Loss @ 500 rev. (%)	34.2	37.8	37.8	-	45 max
Specific Gravity	2.69	2.67	2.65	2.67	-

Mixes prepared with this aggregate grading were used to select the preliminary design binder contents using the Hveem stabilometer and to prepare mixes for the performance-based simple shear and fatigue tests.

Subsequent to this test program, additional aggregates were received and limited testing was performed. One series involved preparing mixes for Hveem stabilometer tests using materials from the hot bins (rather than the cold feed) and the AR-8000 asphalt cement with the same range in binder contents as used for the first test series. Another mix was prepared in which a portion of the crushed fines was replaced with sand. Proportions for these mixes are as follows:

Hot Bin Aggregates, Percent

Bin	#5	#4	#3	#2	#1	Filler
Industry and UCB	15	11	9	27	37	1

Cold Feed Aggregate Fractions Including Sand, Percent

Material	¾ inch (19.0 mm)	½ inch (12.5 mm)	3/8 inch (9.5 mm)	Rock Dust	Sand	
					XCS	WCS
Industry and UCB	25	15	20	24	8	8

Gradation data obtained from wash and sieve analyses for these materials are also included in Appendix A. Figures 9 and 10 contain the combined gradings for the material prepared from the hot bins, while Figures 11 and 12 show the grading for the combination of crushed cold bin aggregates and the two sands. The resultant gradings from the hot bin blending pass through the "restricted zone" as seen in Figure 10. On the other hand, the blend of crushed materials from the cold bins and the two sands passes above the restricted zone, Figure 12.

3.0 MIX EVALUATIONS

A series of mix tests were performed for both mix design and analysis purposes. These included: Hveem stabilometer tests at 60ºC; repeated load simple shear tests, constant height at 50ºC and 60ºC; and flexural fatigue tests at 20ºC for the mix with AR-8000 asphalt cement and at 10ºC, 20ºC, and 30ºC for the mix containing the PBA-6A binder. Table 3 contains a summary of the various tests performed together with the intended uses of the resulting data.

3.1 Hveem Stabilometer Test Results

The stabilometer tests were performed at 60ºC following State of California Test Method 366 using specimens prepared by kneading compaction with the Triaxial Institute Kneading Compactor (State of California Test Method 304).

Results from the mixes, which were tested, are summarized in Table 3. The majority of the stabilometer tests were performed on mixes containing the AR-8000 asphalt cement to provide a tie-in with data obtained for such mixes produced for in-service pavements in the Los Angeles basin as well as providing a guide for selecting the range in binder contents for preparing the simple shear test specimens. Results of stabilometer tests on mixes containing the PBA-6A binder were used primarily as a guide to select the range in binder contents for mixes to be subjected to the simple shear tests.

In addition to the regular compactive effort in the kneading compactor, additional specimens at the 5.0 percent binder content were subjected to 500 and 1000 additional tamps. These additional tamps were applied while the specimens were maintained at a temperature of

Table 3 Summary of Mix Tests

Materials: Aggregate Source/Binder	**Binder Content(s)***	**Test**	**Purpose(s)**
Crushed cold feed, AR-8000	4.2 to 5.7	Hveem stabilometer	Mix design–preliminary binder content selection
	4.2 to 5.2	Repeated simple shear test at constant height (RSST-CH)	Mix design–binder content selection
	4.7, 5.2	Controlled strain fatigue test–20ºC	Define relationship between tensile-strain and load repetitions for fatigue cracking analysis and evaluation of "rich-bottom" application
	5.0	500, 1000 tamps in kneading compactor; Hveem stabilometer	Check behavior after heavy trafficking as represented by 500 and 1000 tamps in the kneading compactor
Crushed cold feed, PBA-6A	4.7 to 5.7	Hveem stabilometer	Mix design–preliminary binder content selection
	4.2 to 5.2	Repeated simple shear test at constant height (RSST-CH)	Mix design–binder content selection
	4.7, 5.2	Controlled strain fatigue test–10º, 20º, 30ºC	Define relationship between tensile-strain and load repetitions for fatigue cracking analysis and evaluation of "rich-bottom" application
	5.0	500, 1000 tamps in kneading compactor; Hveem stabilometer	Check behavior after heavy trafficking as represented by 500 and 1000 tamps in the kneading compactor
Hot bins, AR-8000	4.7 to 5.7	Hveem stabilometer	Mix evaluation and comparison with crushed cold feed mix data
Crushed cold feed plus sand, AR-8000	4.7	Hveem stabilometer	Mix evaluation

* binder contents by weight of aggregate

60°C (140°F). The purpose of this study was to ascertain the change in stability with increased trafficking which is likely to be representative of the heavy truck traffic on Interstate Route 710. This procedure was recommended by Vallerga and Zube (*2*) to evaluate the influence of additional heavy traffic. Vallerga has used the procedure to evaluate a mix from a heavily trafficked pavement in Dubai which had rutted (*3*); in addition he has introduced this concept for mixes subjected to the Boeing 747-400 at San Francisco International Airport (*4*) and for pavements subjected to "port-packers" at the Port of Oakland.

3.1.1 AR-8000 Mixes

Stabilometer test results for the mixes containing the AR-8000 binder are shown in Figure 13; detailed data are included in Appendix B. In examining these data, it will be noted that the stabilometer "S" values fall between 30 and 40 for the range of asphalt contents examined.

Based on the initial data, an asphalt content of 5.0 percent was selected for the extended compaction study. The additional compaction was applied at 60ºC (140ºF). In Figure 13, it will be noted that a reduction in stability was obtained. The reduction in the air void content of these specimens, Figure 14, substantiates the reason for this reduction in stability.

From the data it was decided to select an asphalt content range of 4.2 to 5.2 percent (by weight of aggregate) for the RSST-CH test program on mixes containing the AR-8000 asphalt.

Following the meeting of the Industry Group on February 26, 1999, it was agreed that stabilometer tests would be performed on mixes prepared from aggregate samples of the same material obtained from the hot bins rather than the cold feed. The AR-8000 asphalt cement was

selected and the asphalt content range of 4.2 to 5.2 percent (by weight of aggregate) was utilized. Results of these tests are also included in Figure 13.

The stabilometer "S" values for the hot bin combination was about the same as those for the material prepared from the cold feed.[2]

Finally, one mix prepared from the cold feed but with part of the crushed fines replaced with sand, was tested at a binder content of 4.7 percent with the AR-8000 asphalt. Results of the three tests are also shown in Figure 13. An average "S" value of about 36 was obtained.

3.1.2 Mix with PBA-6A Binder

Results of the stabilometer tests at 60ºC (140ºF) on the mix containing the PBA-6A binder are shown in Figure 15. These values are somewhat less than those for the mix with the AR-8000 binder. However, our experience with stabilometer testing of other mixes containing modified binders is similar.

Air-void contents of the compacted PBA-6A mixes, Figure 16, are somewhat lower than those for the mixes containing the AR-8000 asphalt, Figure 14.

As with the mixes with the AR-8000 asphalt, the mixes subjected to the additional compactive effort show a reduction in "S" value at the 5 percent binder content.

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[2] It should be noted in Figures 13 and 14 that reference is made to data attached with the solid follower in the stabilometer test. Some of the data shown in Figure 13 were obtained with the follower used in earlier versions of the stabilometer test method. This may be responsible for the lower values reported for some of the mixes tested.

Based on the results of these tests, the same range in binder contents, 4.2 to 5.2 percent (by weight of aggregate), was selected for specimens to be tested in the RSST-CH

3.2 RSST-CH Test Results

Repeated simple shear tests at constant height (RSST-CH) were performed both at 50ºC and 60ºC (122ºF and 140ºF). The temperature of 50ºC is likely close to the critical temperature T_c, for the portion of Interstate Route 710 under investigation. This section includes a brief discussion of the shear test procedure and a summary of the test results for both mixes.

3.2.1 Brief Description of RSST-CH Test Procedure

Specimens, obtained as 6-inch diameter cores from slabs prepared by rolling wheel compaction, were tested in the simple shear test (*5*) in repeated loading using a haversine stress pulse while the height of specimens was maintained fixed (RSST-CH). A schematic diagram of the test equipment for these tests is shown in Figure 17.

Shear stress is applied to the specimen using the horizontal actuator while the vertical actuator is used to apply sufficient vertical stress to maintain the height constant.[3] For the 6-inch diameter specimens tested, a height of 2 inches is used[4] to insure a reasonable length-to-height ratio (*5*).

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[3] The vertical actuator can also be used to produce a constant ratio of vertical stress to shear stress.

[4] This specimen size is normally used for mixes containing ¾ inch maximum size aggregate. For mixes with larger size aggregate, larger specimens are used; e.g. 8 inches diameter by 3 inches high.

In the tests conducted as a part of this study, a shear stress of 10 psi (69 kPa) was repeatedly applied with a loading time of 0.1 sec and a time interval between load application of 0.6 sec. This stress and time of loading have been used for both mix analysis and design (e.g. *6*, *7*). Experience relating traffic loading and performance has shown these test conditions to be reasonable. The tests are normally conducted for 5000 stress applications or to a permanent shear strain of 5 percent, whichever occurs first.

A typical relationship between permanent shear strain γ_p, and the number of load applications, *N*, is shown in Figure 18. Each curve is adjusted by defining the intercept of γ_p at $N = 0$ and subtracting this value from all measurements of γ_p. An equation of the form:

$$\gamma_p = a\, N^b$$

is then fit to the data, usually for values of $N \geq 100$ repetitions. In this expression, the coefficients *a* and *b* result from regression analysis.

3.2.2 Test Results

Test data for mixes containing both the AR-8000 and PBA-6A binders are summarized in Figures 19 and 20 respectively. In these figures, values of *N* corresponding to $\gamma_p = 5$ percent have been plotted. More detailed test results for the mixes are contained in Appendix C.

In both figures it will be noted that as the air-void content of the mix is decreased from about 6 percent to about 2 percent, the value of *N* at 5 percent first increases then begins to decrease at air-void contents less than about 2.5 percent.

Section 4 will discuss how these data are used to select a design binder content according to the framework of Figure 4.

3.3 Fatigue Test Results

Controlled strain fatigue tests were performed on mixes containing both binders. Specimens for this test program, obtained from slabs prepared by rolling wheel compaction, are 2.5 inches wide by 2.0 inches high and approximately 16 inches long. A schematic of the test equipment is shown in Figure 21. Beams are tested in third-point loading; for this test series the load was applied sinusoidally at a frequency of 10 Hz. Mixes containing the AR-8000 asphalt were tested at 20°C while those with the PBA-6A binder were tested at 10°C, 20°C, and 30°C.

Results of the fatigue tests at 20°C are shown in Figure 22 and summaries of the data for both mixes are contained in Appendix D. As seen in Figure 22, at a given strain the mixes containing the PBA-6A binder exhibit longer fatigue lives than these containing the AR-8000 asphalt. It is also important to note that the mix stiffnesses of the two mixes at 20°C are significantly different as seen in Table 4. The stiffness of the AR-8000 mix is approximately six times that of the mix with the PBA-6A binder. The differences in mix stiffnesses are important to note since stiffness influences the strains developed in the mixes under traffic loads. Thus one must not only look at the laboratory fatigue test results but also the thickness of the pavement structure in which the materials will be used in order to ascertain how well each material will perform relative to fatigue cracking. This point will be illustrated subsequently in the section summarizing the structural section design proposed for Interstate Route 710.

Table 4 Mix Stiffnesses at 20ºC

Mix		V_{air} percent	Mix Stiffness MPa (psi)
Binder	Binder Content, percent		
AR 8000	4.7	5.6	6372 (924,000)
	5.2	3.2	6898 (1,000,000)
PBA-6A	4.7	5.2	1008 (146,000)
	5.2	3.3	918 (133,000)

4.0 MIX DESIGN CONSIDERATIONS

The simple shear test results are used to select the binder content recommended for use in the surface course of the Interstate Route 710 pavement in accordance with the procedure outlined in Figure 4. For the mix design, the ESALs expected during the first five years are used. This number is based on total traffic of 200×10^6 ESALs estimated for a thirty-year period. Considering both existing traffic and different estimated growth rates, a design level of $30\text{x}10^6$ ESALs was selected.

For the equation shown in Figure 4:

$$N_{supply} \geq M \bullet N_{demand}$$

the estimate of 30×10^6 ESALs for N_{supply} was determined from:

$$N_{supply} \geq M \bullet Design\ ESALs \bullet TCF \bullet SF$$

where:

TCF = Temperature conversion factor, 0.11 for site

SF = Shift factor, 0.04

M = Reliability factor; a value of 5 has been used based on test variance and an estimate of the variance in the ln(ESALs) for a reliability level of 95 percent.

With these assumptions, the estimated value of N_{supply} for selection of the binder content from the laboratory test data was determined to be 660,000 repetitions.

Figure 23 contains a plot of the repetitions at γ_p = 5 percent (N_{supply}) versus binder content for mixes containing both the PBA-6A and AR-8000 binders tested at 50°C. It will be noted that the mix containing the PBA-6A will satisfy the design estimate of 660,000 repetitions (shown as the dashed line in Figure 23).

Based on these analyses, a design binder content of 4.7 percent is recommended for the PBA-6A mix to be used as the surface course.

During construction, the AR-8000 mix may carry traffic before the PBA-6A mix is placed. It is important that the AR-8000 mix does not rut at this time. A conservative estimate for the time between placements of the AR-8000 and PBA-6A mix is one year. As estimate of the design ESALs for one year is 6.67×10^6 ESALs. The N_{supply} for these design ESALs is 146,000 repetitions. As shown in Figure 23, the AR-8000 mix will satisfy the design estimate of 146,000 repetitions at the same design binder content as the PBA-6A mix, 4.7 percent. Accordingly, *a design binder content of 4.7 percent is recommended for the AR-8000 mix.*

5.0 PROPOSED STRUCTURAL SECTION DESIGN

The laboratory fatigue test data are used to determine the structural section design for the full-depth replacement section of Interstate 710. The recommended structural section includes the use of a "rich-bottom" layer near the bottom of the pavement to improve the fatigue resistance. A rut resistant mix is used in the upper portion of the pavement.

The analysis procedure for determining the structural section is illustrated in Figure 24. (*8*). The procedure requires the determination of the principal tensile strain at the bottom of the asphalt concrete layer using elastic layer theory and the simulated pavement structure.

Some of the structural sections include a rich bottom layer, which consists of an increase in asphalt content of 0.5 percent and a corresponding 3 percent decrease in air-void content to improve the fatigue resistance of the mix at the bottom of the AC layer. By placing this layer at the bottom of the AC layer, the rutting resistance of the mix at the surface is not affected. Further discussion on "rich-bottom" pavements can be found in Reference 8.

The material properties for the subgrade were determined from falling weight deflectometer readings on the existing pavement. Two subgrade stiffness values are used, 83 MPa and 55 MPa. The first value is a reasonable estimate for the design subgrade stiffness, and the second value is an approximate lower bound of the measured stiffnesses. The stiffness of the AC and the "rich-bottom" layers are shown in Table 4, and are dependent on the assumed air-void contents. A Poisson's ratio of 0.45 is assumed for the subgrade and 0.35 for the AC and "rich-bottom" layers. The principal tensile strain is determined at the bottom of the AC and "rich-bottom" layers using the software CIRCLY (*9*). An ESAL load consisting of an 80 kN

axle load with dual tires is assumed. The vertical compressive strain at the top of the subgrade is also determined as a check for subgrade rutting.

The fatigue test results are used to determine a relationship between tensile strain (ε) and laboratory fatigue life (N) by means of regression analysis. With the strain calculated using elastic layer theory, the corresponding laboratory fatigue life is determined and denoted N. The structural sections designed for Interstate 710 are relatively thick to accommodate the large traffic estimates. Consequently the strains are small and it is necessary to extrapolate the laboratory fatigue data. At strain values of less than 70 microstrain (με) the likelihood of failure in fatigue is small. The following fatigue relationships were used:

AR-8000	Conventional mix	$Nf = 5.14206 \times 10^{-15} \varepsilon_t^{-5.60217}$	$\varepsilon_t > 70\mu\varepsilon$
	Rich bottom mix	$Nf = 5.08326 \times 10^{-11} \varepsilon_t^{-4.6138}$	$\varepsilon_t > 70\mu\varepsilon$
PBA-6A	Conventional mix	$Nf = 2.22908 \times 10^{-4} \varepsilon_t^{-2.98571}$	$\varepsilon_t > 70\mu\varepsilon$
	Rich bottom mix	$Nf = 9.47702 \times 10^{-3} \varepsilon_t^{-2.58721}$	$\varepsilon_t > 70\mu\varepsilon$

The temperature conversion factor (TCF) for fatigue has been calculated for three environments in California; desert, mountain and coastal, as a function of pavement thickness. Interstate Route 710 is considered to be in the coastal environment, and the associated TCF is shown in Figure 24. (*8*)

The fatigue shift factor is given as a function of tensile strain and was calibrated against the Caltrans pavement design procedure. Reliability multipliers, M, were calculated for fatigue distress at different levels of reliability. The number of ESALs that the pavement can carry before fatigue failure is determined by the equation shown in Figure 24. (*8*)

To minimize rutting resulting from permanent deformation in the unbound layers the Asphalt Institute subgrade strain criteria have been used, according to the relationship shown below (*10*), where ε_v is the vertical compressive strain at the top of the subgrade:

$$N = 1.05 \times 10^{-9} \varepsilon_v^{-4.484}$$

An iterative procedure was used to determine the minimum thickness of the AC layer to withstand fatigue failure and limit the subgrade stain. The minimum ESALs for the fatigue analyses are 200×10^6 and to satisfy the subgrade strain requirement 50×10^6.

Pavements are designed with and without a rich bottom layer, and a composite structure consisting of an AR-8000 rich bottom layer, an AR-8000 conventional mix layer, and a 75 mm PBA-6A layer on the surface of the pavement to provide the resistance to rutting. These three pavements are designed for two subgrade stiffnesses and for two air-void contents. Pavements designed with only PBA-6A are substantially thicker than for AR-8000 pavements because the AR-8000 is 6 times stiffer than the PBA-6A. It is therefore recommended that PBA-6A is not used for the entire thickness of the full-depth sections. However, repeated simple shear tests on the two mixes demonstrated the PBA-6A to have greater resistance to rutting than the AR-8000. Based on the information presented, the **composite pavement** is recommended for use on Interstate 710.

5.1 Subgrade Stiffness

The structural sections determined for the two subgrade stiffness values are shown in Figure 25 and in Table 5 for both the AR-8000 and the Composite pavements. The thickness of the Composite pavements are determined for a 3 inch (75 mm) PBA-6A surface layer and for a 5

inch (125 mm) PBA-6A surface layer. The Composite pavements are thicker than the AR-8000 pavements, however they have more resistance to surface rutting.

In these analyses it is assumed that the air-void content in the mix is 6 percent, and 3 percent in the rich-bottom layer. If these air-void contents in the mix are not met in the field, these structural sections may be inadequate. The construction specifications for the project should be written to ensure these air-void contents are obtained.

5.2 Effect Of Increasing Air Voids

Figure 26 and Table 5 illustrate the impact of increasing the air-void content in the asphalt concrete layers. For these analyses, the air-void content was increased to 8 percent in the layer containing the conventional mix, and 5 percent in the rich bottom layer. The effect is to increase the necessary pavement thickness by approximately 10 – 15 mm or ½ inch. The subgrade strain criterion is critical for the pavement with the lower air-void contents, but the fatigue criterion is critical for the higher air-void contents.

If the pavement thickness is not increased to compensate for the increase in air-void content, the fatigue life of the pavement is reduced to approximately 0.37 of the original fatigue life.

Table 5 Structural Section Design

Total Pavement Thickness (mm)			Subgrade Modulus = 83 MPa (12,000 psi)			Subgrade Modulus = 55 MPa (8,000 psi)		
			Fatigue 200 million	Subgrade Strain 50 million	Critical Thickness	Fatigue 200 million	Subgrade Strain 50 million	Critical Thickness
COASTAL AR-4000	3" Rich bottom	6 %, 3 %*	260 (10.2")	315 (12.4")	315 (12.4")	280 (11.0")	345 (13.6")	345 (13.6")
		8 %, 5 %	310 (12.2")	355 (14.0")	355 (14.0")	335 (13.2")	385 (15.2")	385 (15.2")
	No Rich Bottom	6%	345 (13.6")	345 (13.6")	345 (13.6")	365 (14.4")	375 (14.8")	375 (14.8")
		8%	405 (15.9")	385 (15.2")	405 (15.9")	430 (16.9")	420 (16.5")	430 (16.9")
VALLEY AR-4000	3" Rich bottom	6 %, 3 %	335 (13.2")	190 (7.5")	335 (13.2")	350 (13.8")	205 (8.1")	350 (13.8")
		8 %, 5 %	380 (15.0")	200 (7.9")	380 (15.0")	395 (15.6")	220 (8.7")	395 (15.6")
	No Rich Bottom	6%	395 (15.6")	195 (7.7")	395 (15.6")	410 (16.1")	215 (8.5")	410 (16.1")
		8%	445 (17.5")	210 (8.3")	445 (17.5")	465 (18.3")	230 (9.1")	465 (18.3")
AR-8000	3" Rich bottom	6 %, 3 %	195 (7.7")	215 (8.5")	215 (8.5")	210 (8.3")	235 (9.3")	235 (9.3")
		8 %, 5 %	230 (9.1")		230 (9.1")	245 (9.6")		245 (9.6")
	No Rich Bottom	6%	205 (8.1")	220 (8.7")	220 (8.7")	215 (8.5")	240 (9.4")	240 (9.4")
		8%	235 (9.3")		235 (9.3")	245 (9.6")		245 (9.6")
COMPOSITE	3" PBA-6A Surface, 3" Rich bottom	6 %, 3 %	240 (9.4")	260 (10.2")	260 (10.2")	250 (9.8")	280 (11.0")	280 (11.0")
		8 %, 5 %	270 (10.6")		270 (10.6")	285 (11.2")		285 (11.2")
	5" PBA-6A Surface, 3" Rich bottom	6 %, 3 %	255 (10.0")	280 (11.0")	280 (11.0")	270 (10.6")	305 (12.0")	305 (12.0")
		8 %, 5 %	290 (11.4")	-	290 (11.4")	280 (11.0")	-	305 (12.0")
ASPHALT INSTITUTE	3" Rich bottom	4 %, 7%, 2 %**	370 (14.6")	-	370 (14.6")	400 (15.7")	-	400 (15.7")
		4 %, 7%, 2 %						
	No Rich Bottom	4%, 7%	510 (20.1")	-	510 (20.1")	535 (21.0")	-	535 (21.0")
		4%, 7%						

Notes:

* % voids in AC layer, % voids in Rich bottom layer

** Asphalt Institute designs have a 2 inch top layer (4% voids) and a middle layer (7% voids). The rich bottom layer, where applicable, has 2 % voids.

Thickness given is total pavement thickness

5.3 Structural Sections Using Valley and Coastal Asphalts

Structural sections have also been determined for two other binders that are typically used in California. These binders have the AR-4000 designation and are from Coastal and Valley sources. Watsonville aggregate was used in the mixes from which the fatigue relationships were developed.

The stiffness (S_0) and fatigue relationships used in these analyses are as follows:

Coastal Stiffness: $\ln S_0 = 8.5270 - 0.12224\ AV$

Coastal Fatigue Life: $\ln N = -24.362 + 0.83988\ AC - 0.19193\ AV - 4.3606 \ln \varepsilon_t$

Valley Stiffness: $\ln S_0 = 10.282 - 0.172\ AC - 0.076\ AV$

Valley Fatigue Life: $\ln N = -22.001 + 0.57520\ AC - 0.16457\ AV - 3.7176 \ln \varepsilon_t$

where ln N is the natural log of the fatigue life, AC the asphalt content, AV the air-void content and $\ln \varepsilon_t$ the natural log of the tensile strain.

The structural sections are shown in Figure 27 and Table 5. The critical criterion in determining the thickness of the pavements using the Valley binder is the fatigue criterion, whereas for the Coastal binder, especially at the lower air-void contents, the subgrade strain criterion is critical. This is due to the difference in stiffness of these mixes.

5.4 Asphalt Institute

The Asphalt Institute performance criteria (*10*) were used to select structural sections. These results are shown in Table 5. The thickness of these pavements is slightly larger than for the

Valley and Coastal pavements, and significantly larger than the AR-8000 and composite pavements.

5.5 Caltrans Method

Structural sections were determined using the Caltrans design procedure. The recommended thickness is 534 mm (21 inches) which includes a 4 inch rich bottom layer and 2 inch surface layer containing a polymer modified mix. A summary of these results, and various other alternatives are included in Appendix E.

5.6 Staged Construction

The top three-inch layer of the pavement may be constructed some time after the other layers are constructed. It is important that these underlying layers do not fail in fatigue, nor should the total pavement fatigue life be significantly reduced by the traffic carried on the pavement before the final surfacing layer is placed. Analyses were performed to evaluate if the recommended pavement thicknesses are sufficient for this staged construction. Two scenarios were assumed, the first is for a one year delay in the construction of the final layer, and the second for a six month delay. For both conditions, the pavement has adequate thickness to prevent premature fatigue damage. These analyses are included in Appendix F.

5.7 Sacrificial Layer

It is recommended that a porous friction course is placed on the surface of the pavement. This mix should contain an asphalt rubber binder and a recommended specification for the gradation

is shown in Figure 28 and in Table 6. A mix that meets these specifications has been successfully used at the Oakland International Airport for ten years.

The inclusion of this layer will aid in the maintenance of these pavements, and will help to reduce tire splash and noise, which are important safety features.

Table 6 Open Graded Aggregate Gradation Specifications (Porous Friction Course), MOIA, R/W 11-29, B.A. Vallerga

Sieve Size	**Percent Passing**
¾" (19mm)	100
½" (12.5 mm)	70 – 90
3/8" (9.5 mm)	45 – 75
No. 4 (4.75 mm)	15 – 35
No. 8 (2.36 mm)	8 – 15
No. 30 (0.6 mm)	0 – 10
No. 200 (0.075 mm)	0 –5

6.0 REFERENCES

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4. Monismith, C. L., J. T. Harvey, I. Guada, F. Long, and B. A. Vallerga, *Asphalt Mix Studies San Francisco International Airport*, Pavement Research Center, University of California, Berkeley, June 1999.

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10. The Asphalt Institute, 1982, Research and Development of The Asphalt Institute’s Thickness Design Manual (MS-1) Ninth Edition, Research Report No. 82-2.

7.0 FIGURES

Figure 1. Interstate 710 Location

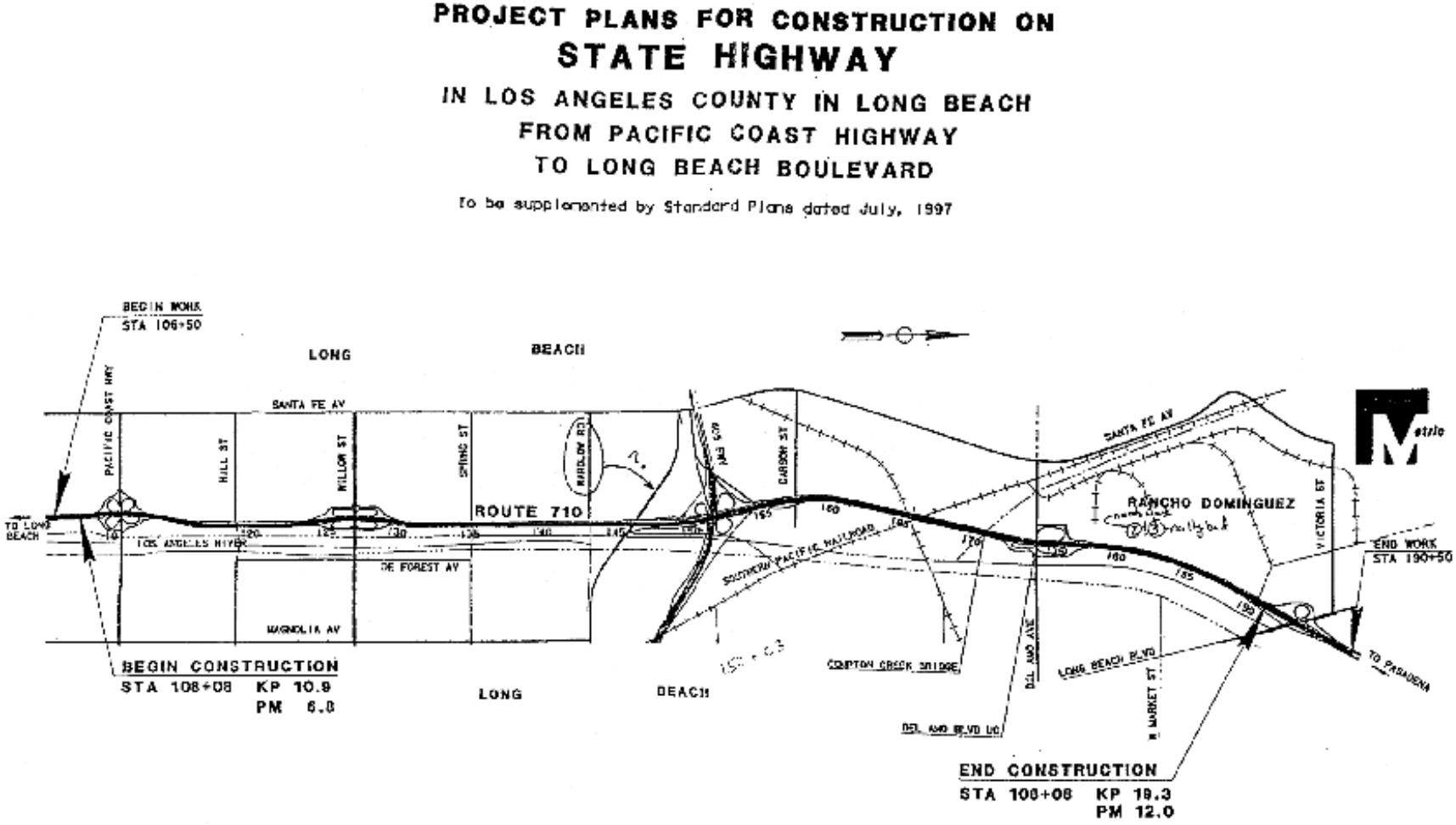

Figure 2. Portion of Interstate 710 Scheduled for Rehabilitation.

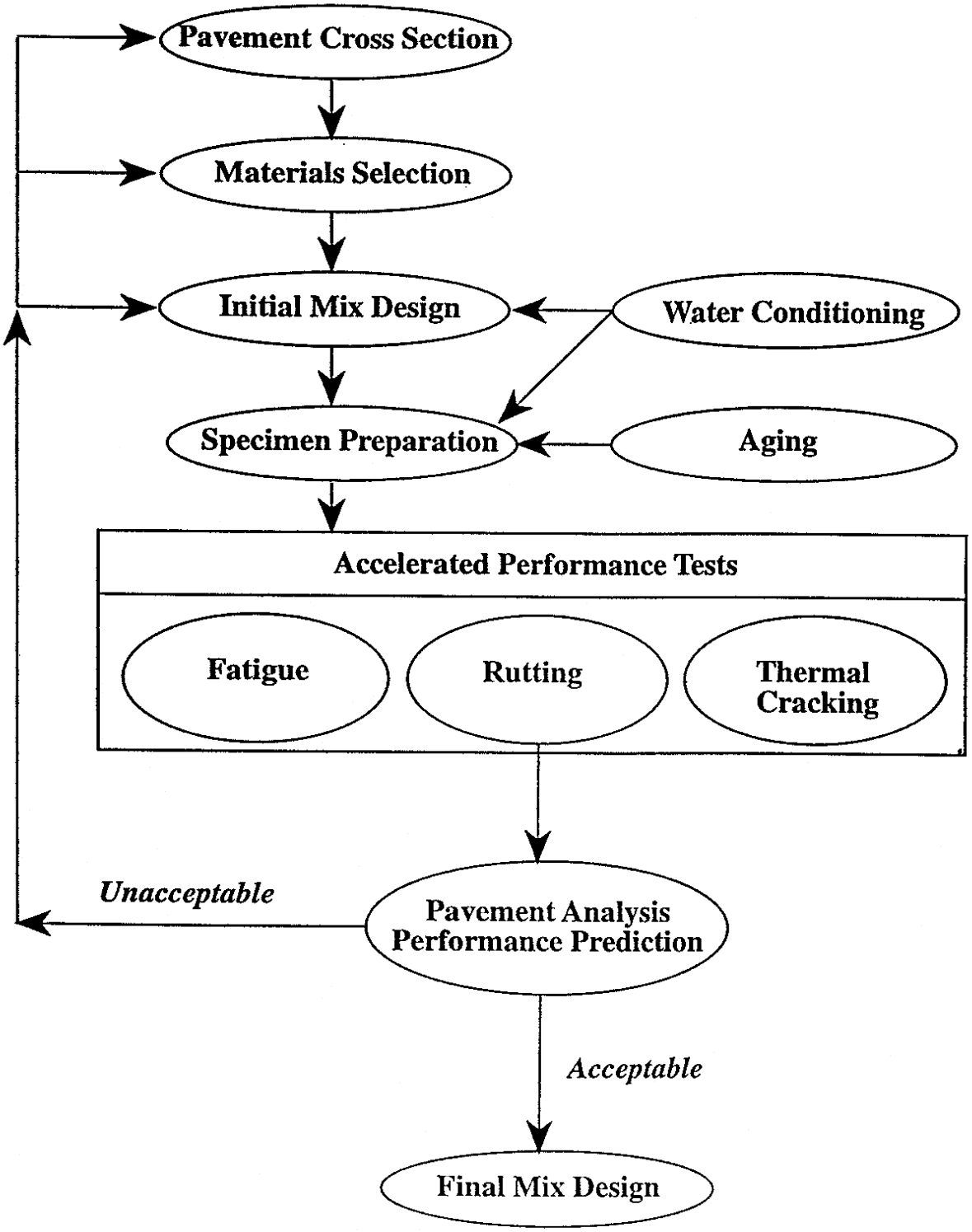

Figure 3. Schematic of Mix Design and Analysis Framework.

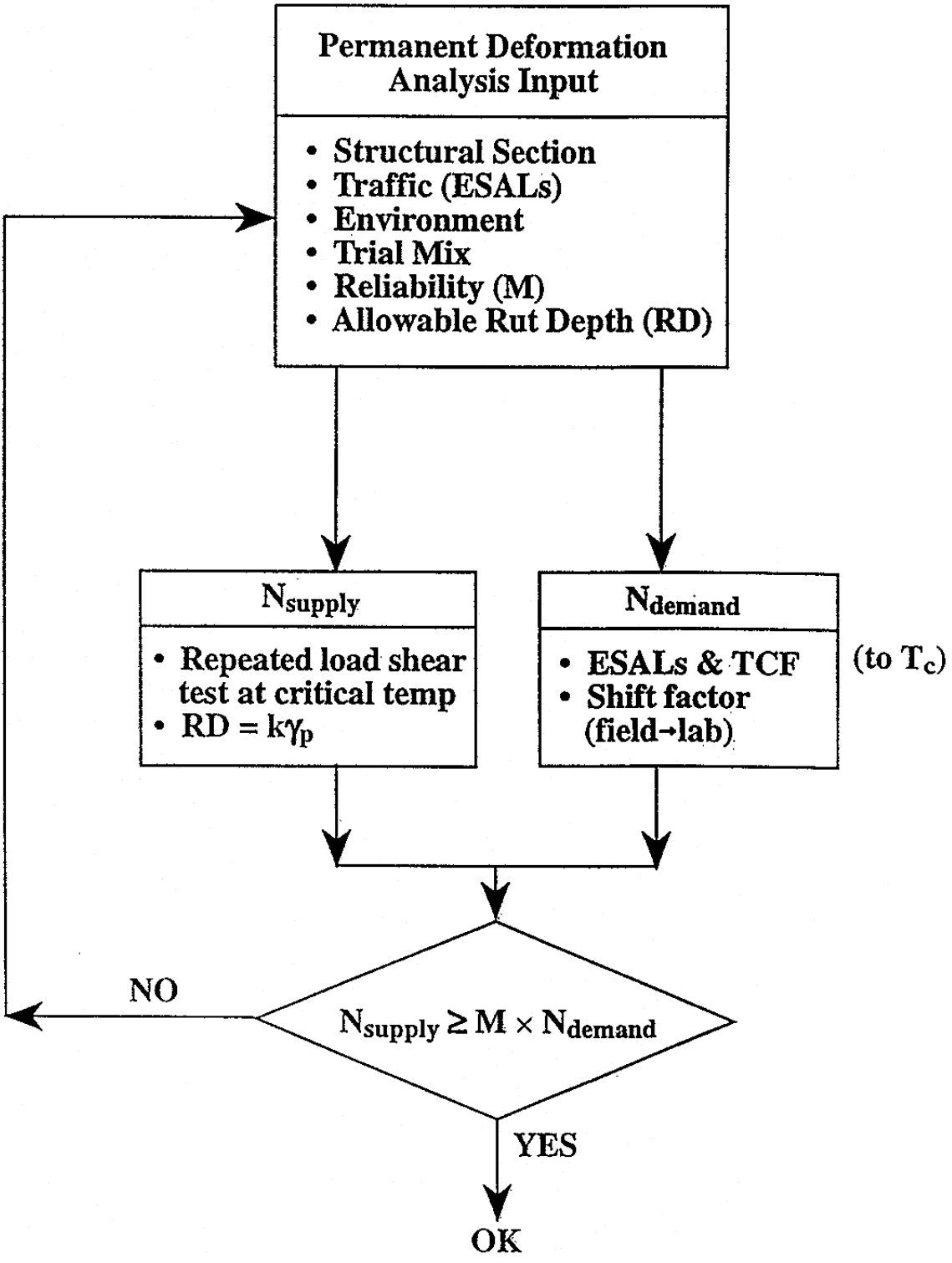

Figure 4. Permanent Deformation System.

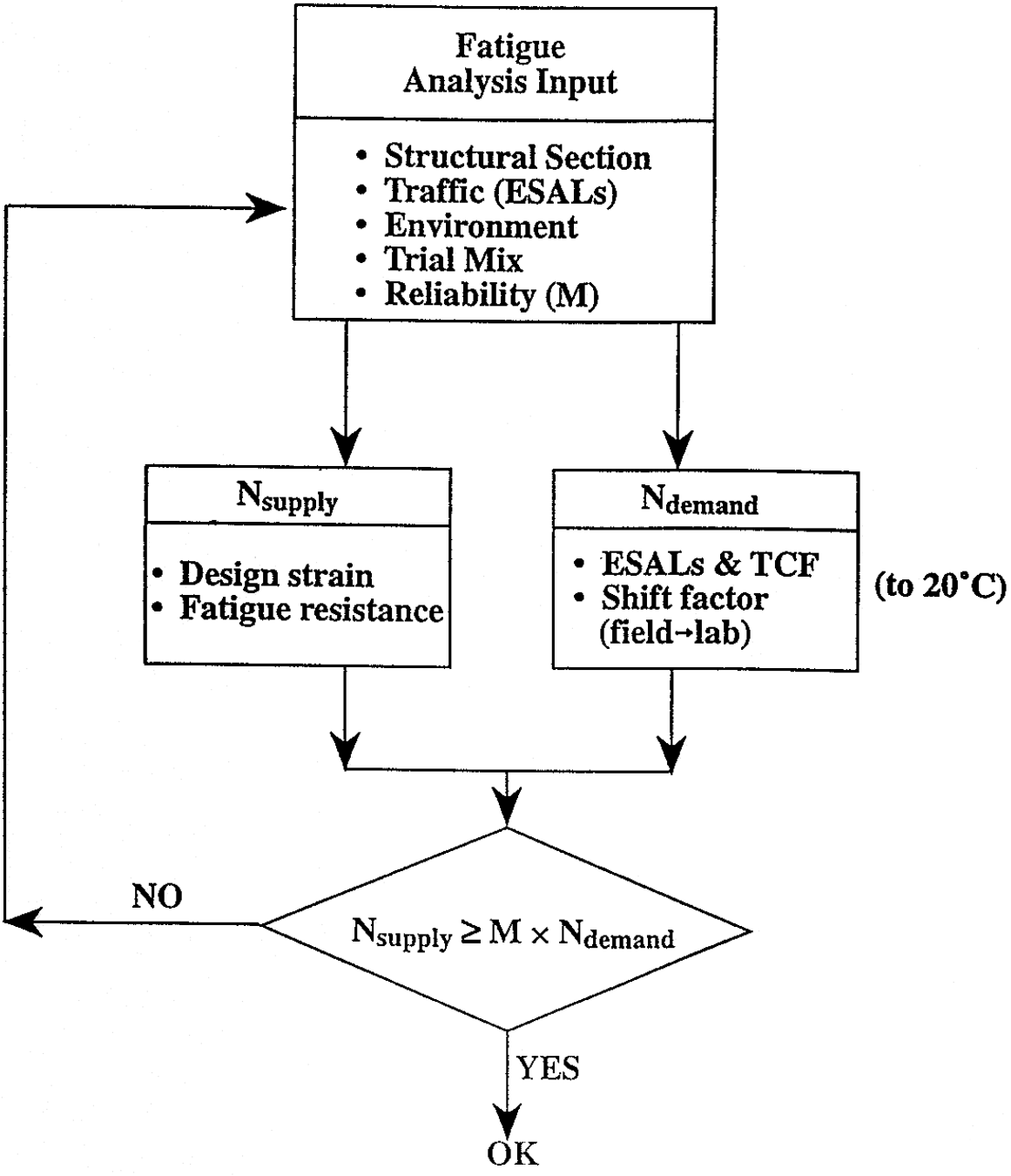

Figure 5. Fatigue System.

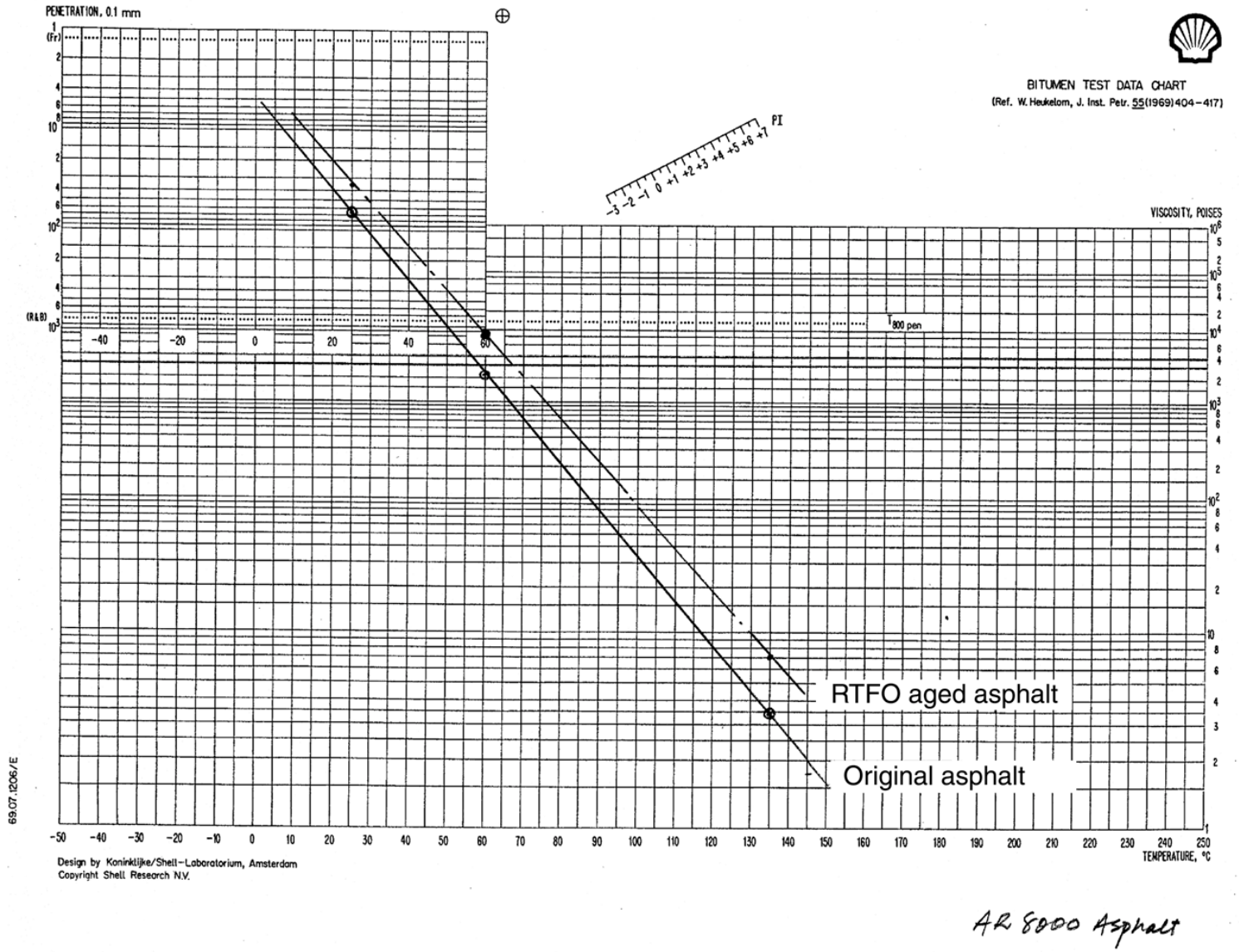

Figure 6. Bitumen Test Data Chart (AR-8000)

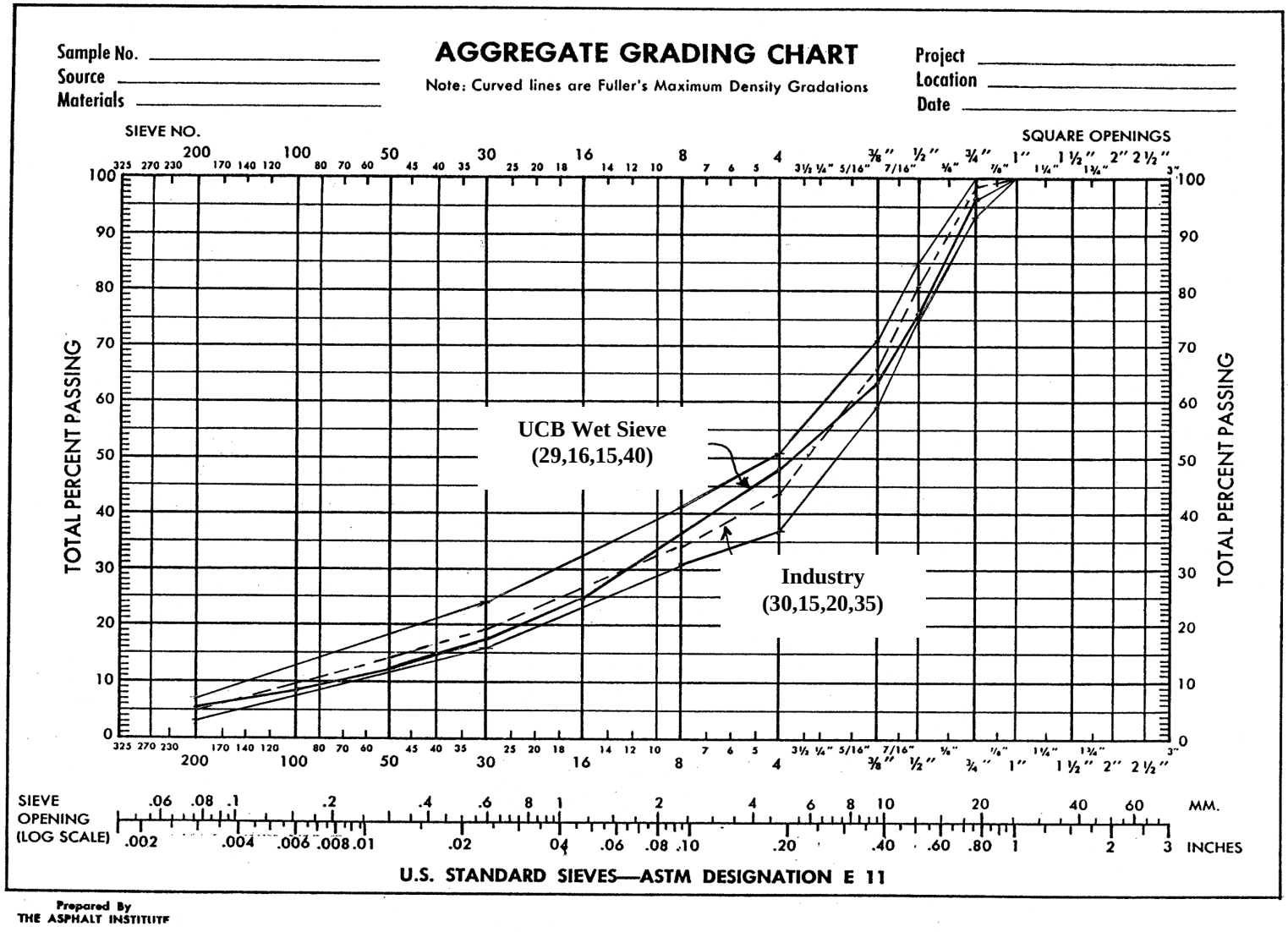

Figure 7. Comparison of UCB Wet Sieve and Industry Gradation.

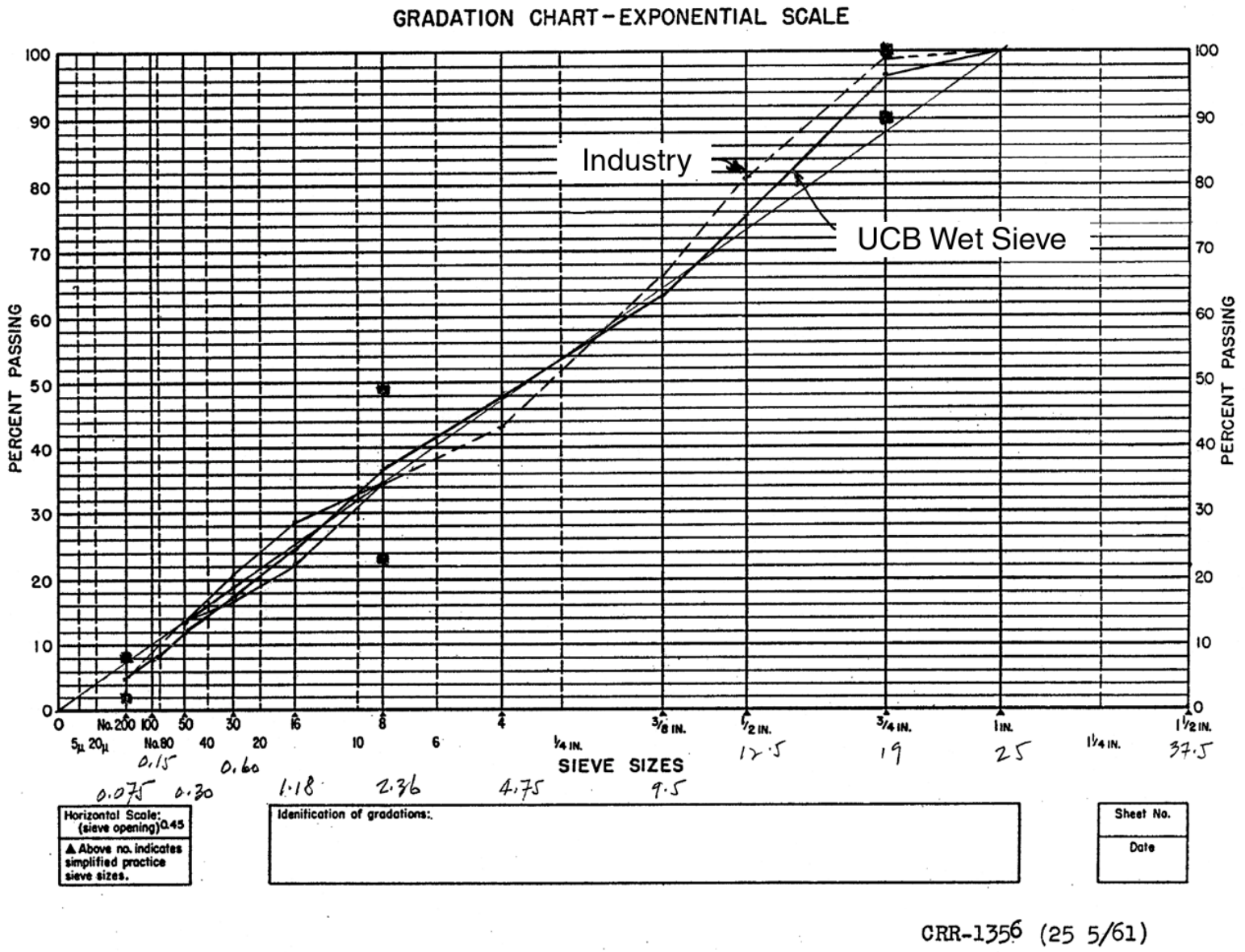

Figure 8. Comparsion of UCB Wet Sieve and Industry Gradations, 0.45 Grading Chart.

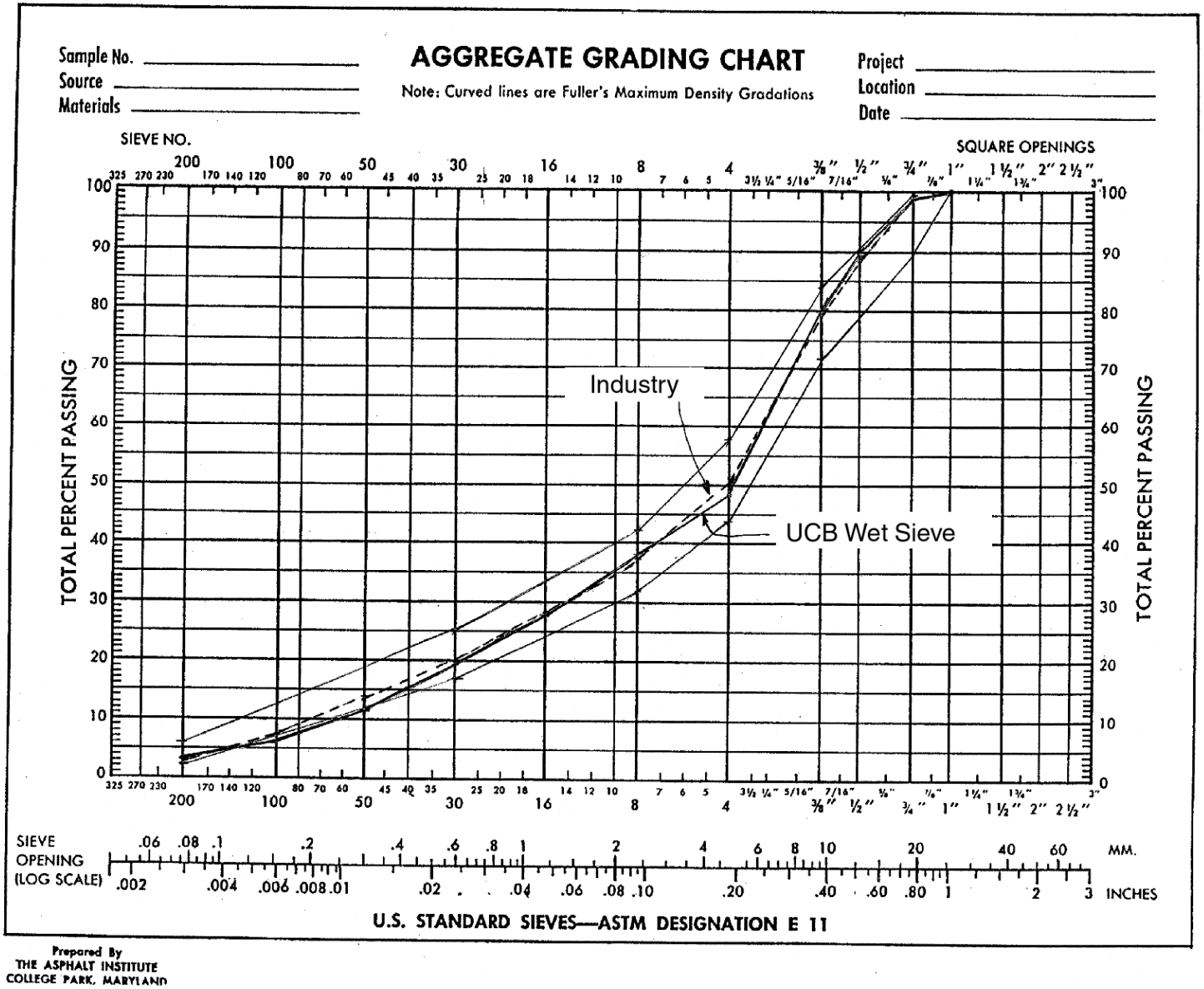

Figure 9. Comparison of UCB and Industry Gradations, Hot Bin Aggregates.

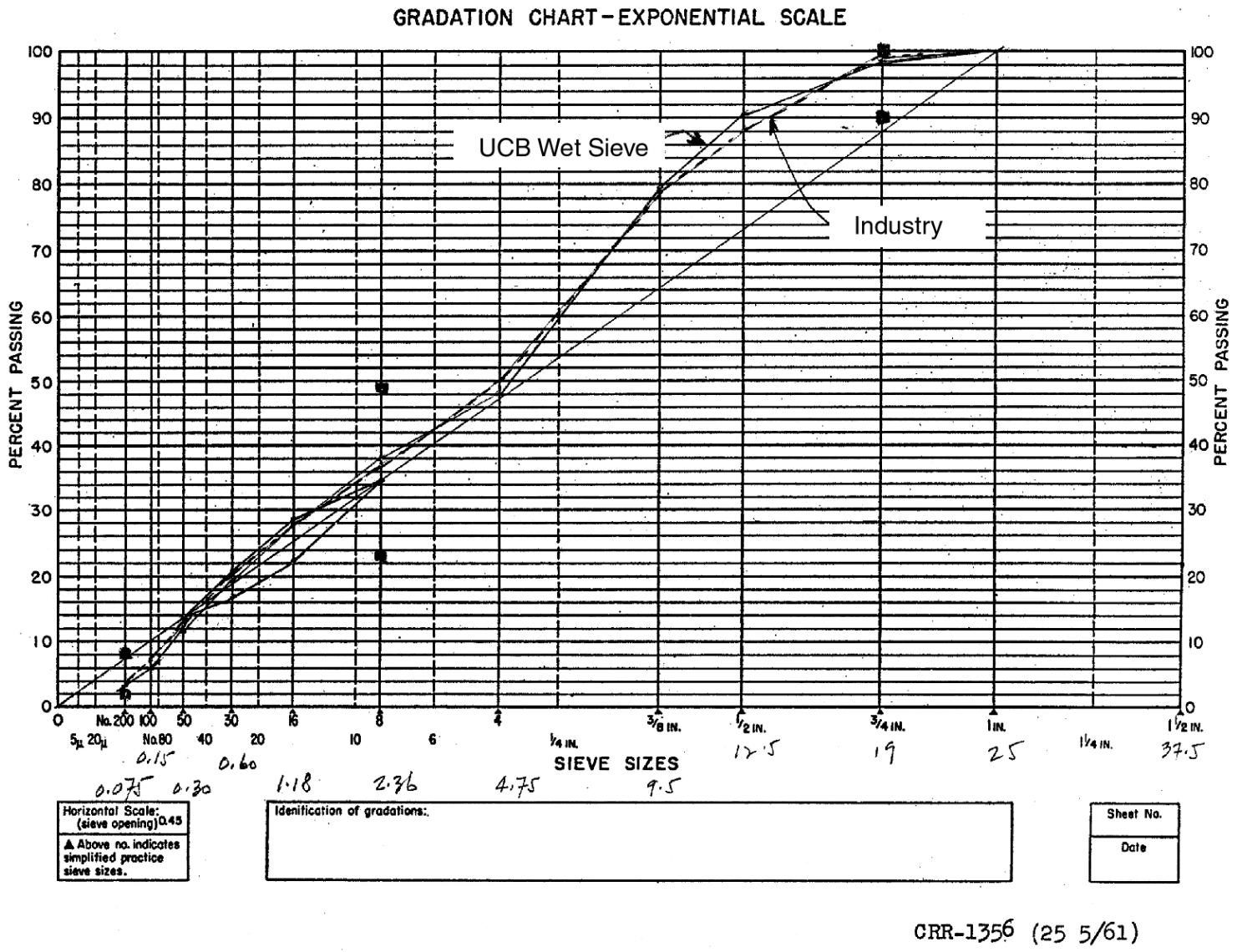

Figure 10. Comparison of UCB and Industry Gradations, Hot Bin Aggregates, 0.45 Grading Chart.

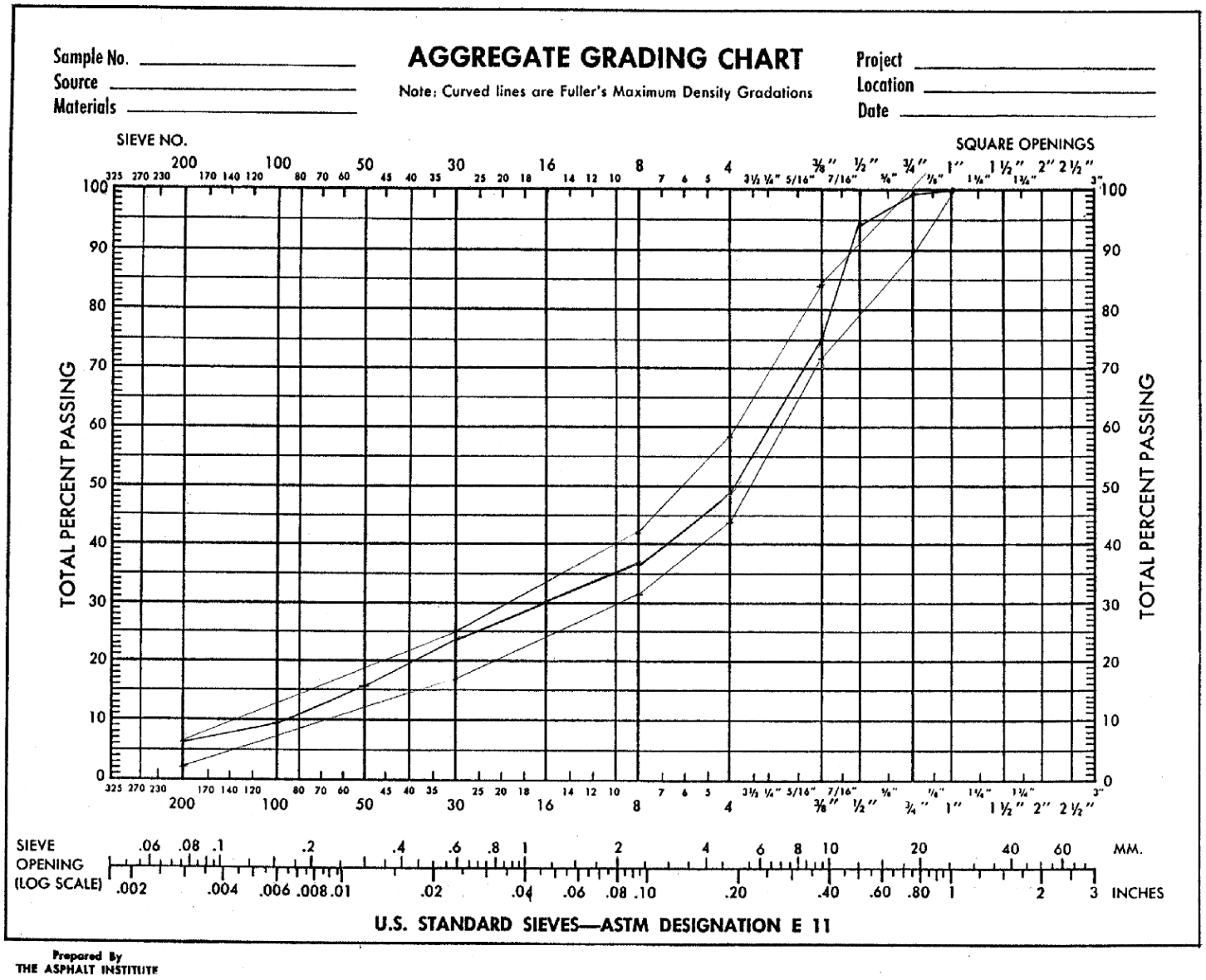

Figure 11. Aggregate Gradation with Crushed Cold Feed and Sands (16 Percent).

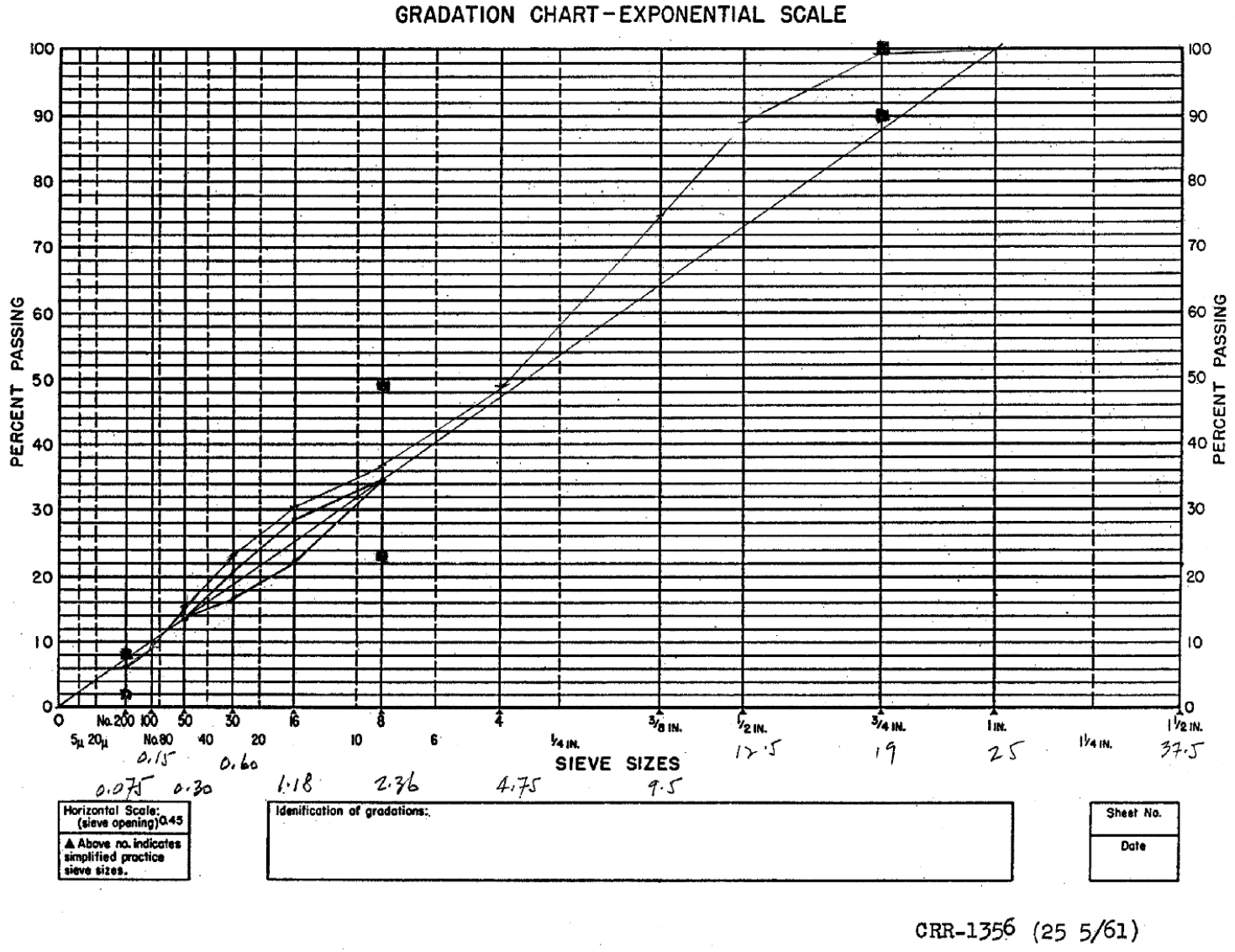

Figure 12. Aggregate Gradation with Crushed Cold Feed and Sand (16 Percent), 0.45 Grading Chart.

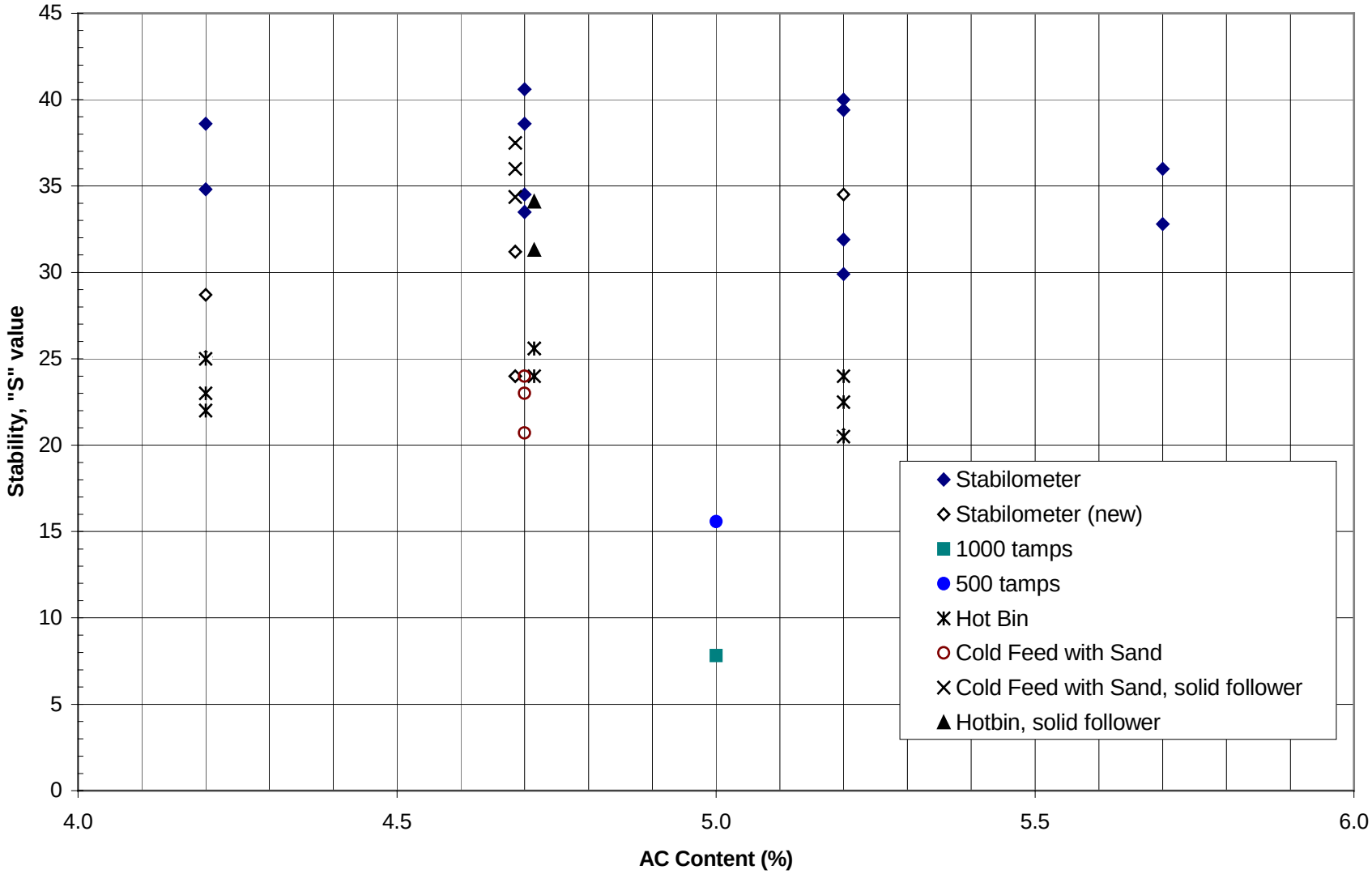

Figure 13. Stabilometer Data Versus Asphalt Content, Conventional AR-8000.

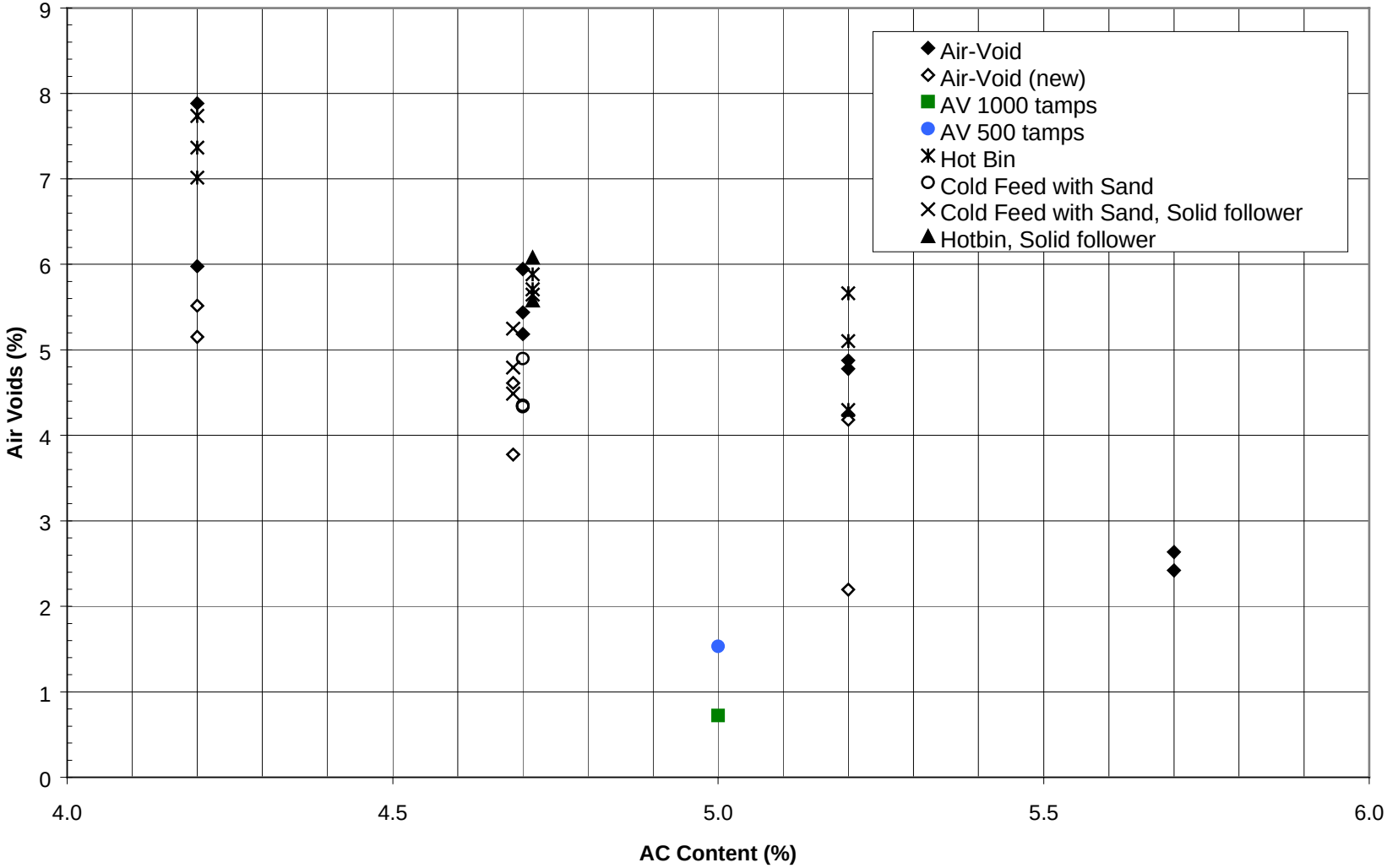

Figure 14. Air-Void Content versus Asphalt Content, Conventional AR-8000.

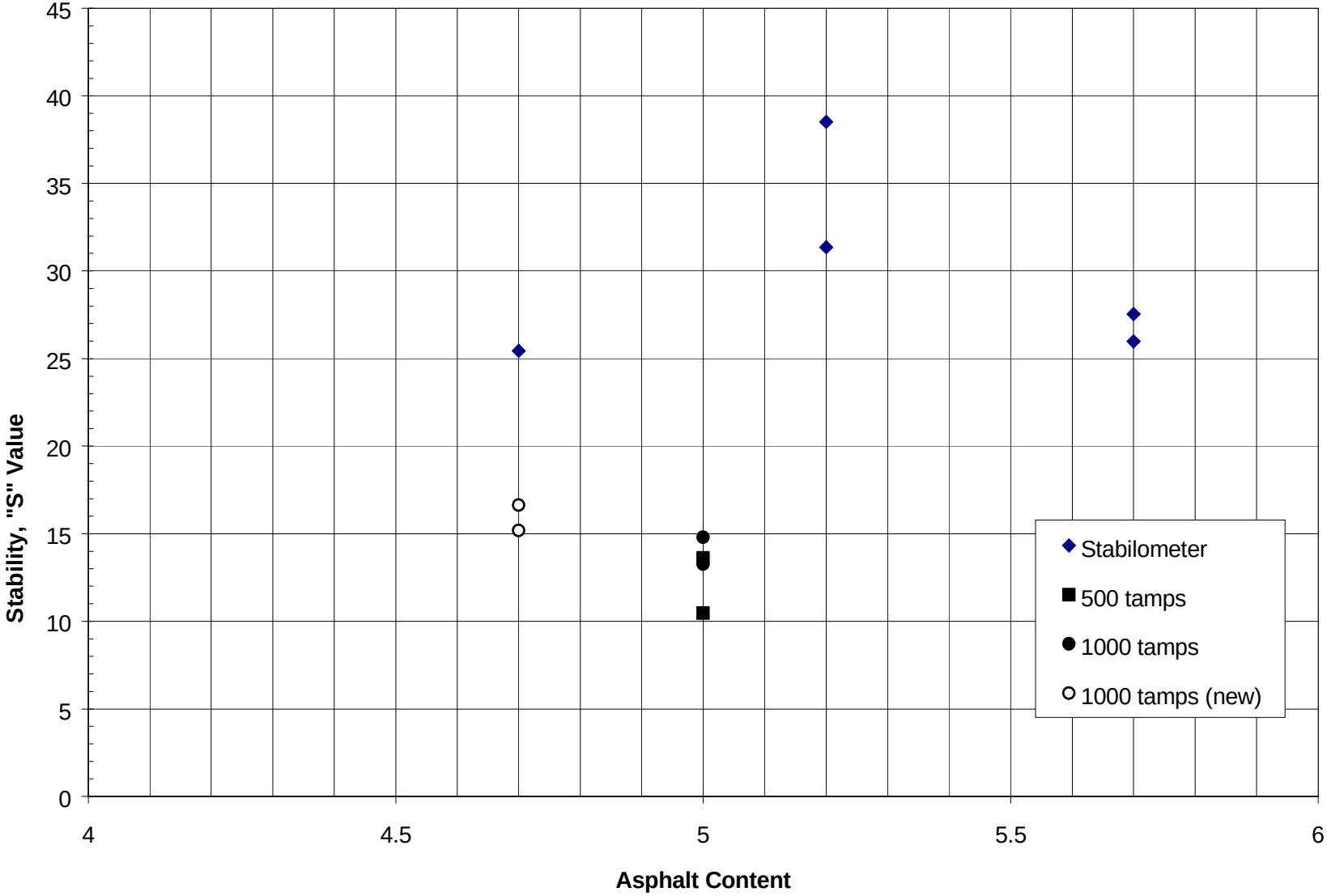

Figure 15. Stabilometer Data versus Asphalt Content, PBA-6A Binder.

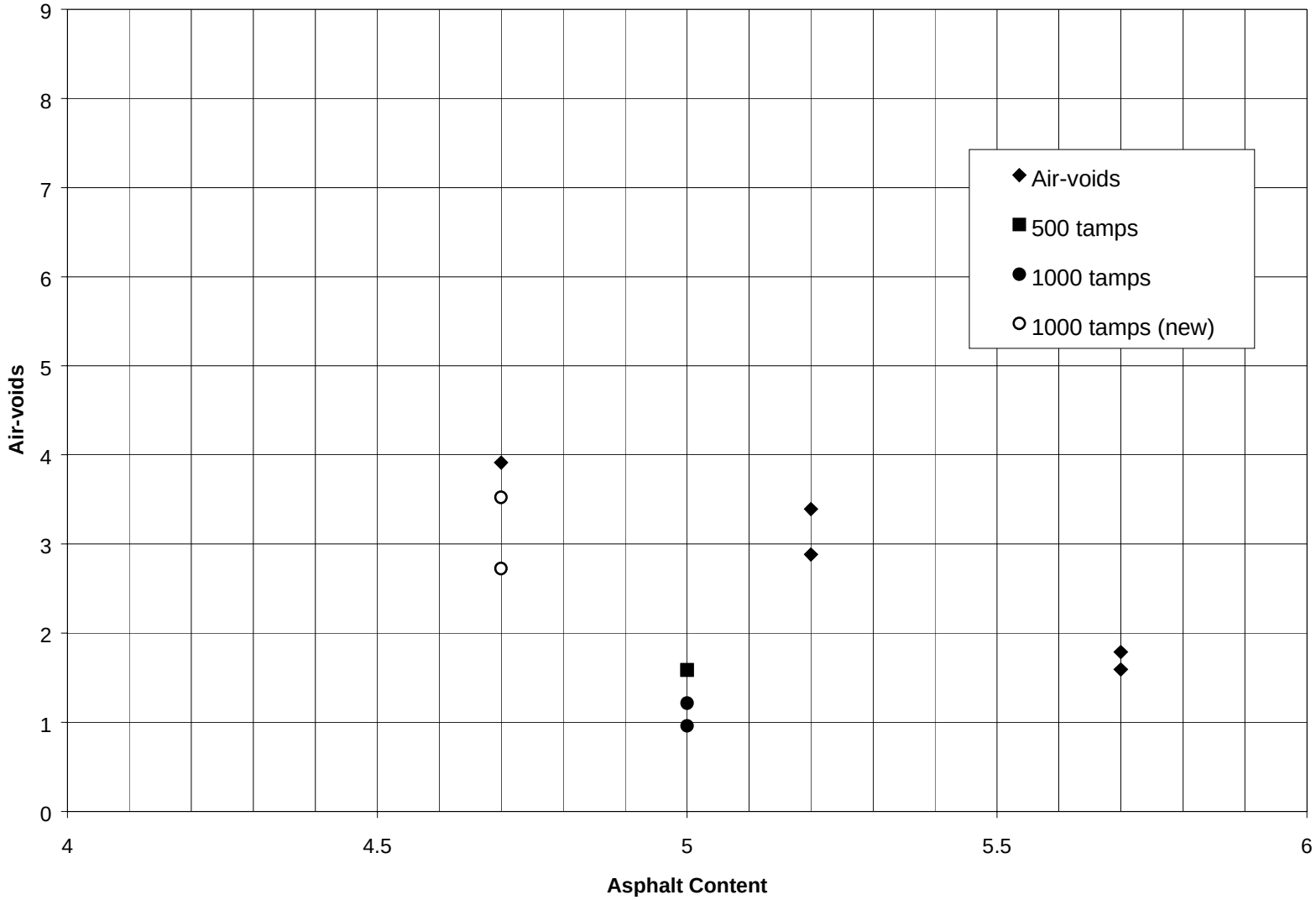

Figure 16. Air-Void Content versus Asphalt Content, PBA-6A Binder.

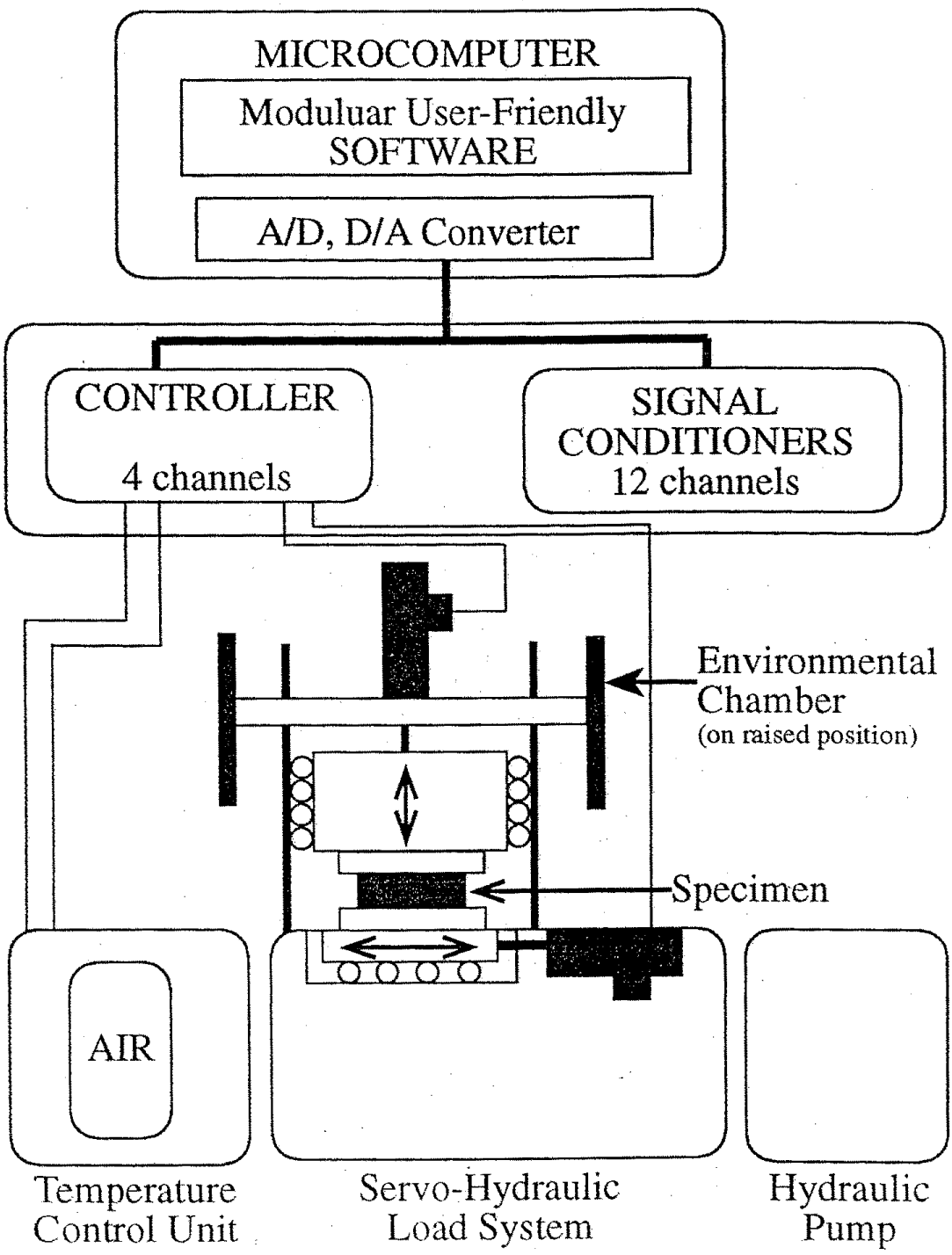

Figure 17. Schematic of Simple Shear Test.

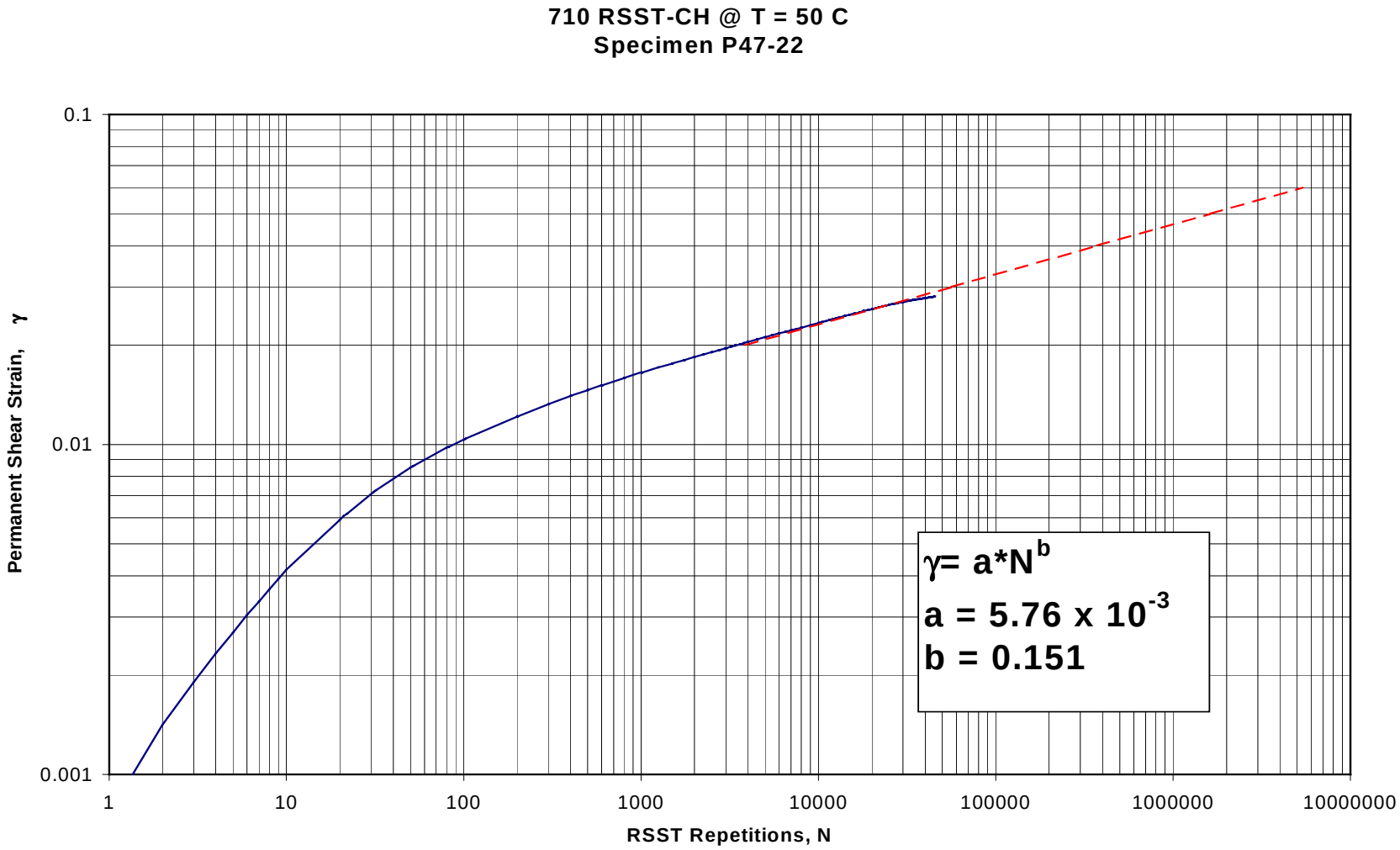

Figure 18. Permanent Shear Strain versus Stress Repetitions in RSST-CH at 50°C; PBA-6A Mix, 4.7 Percent Binder Content.

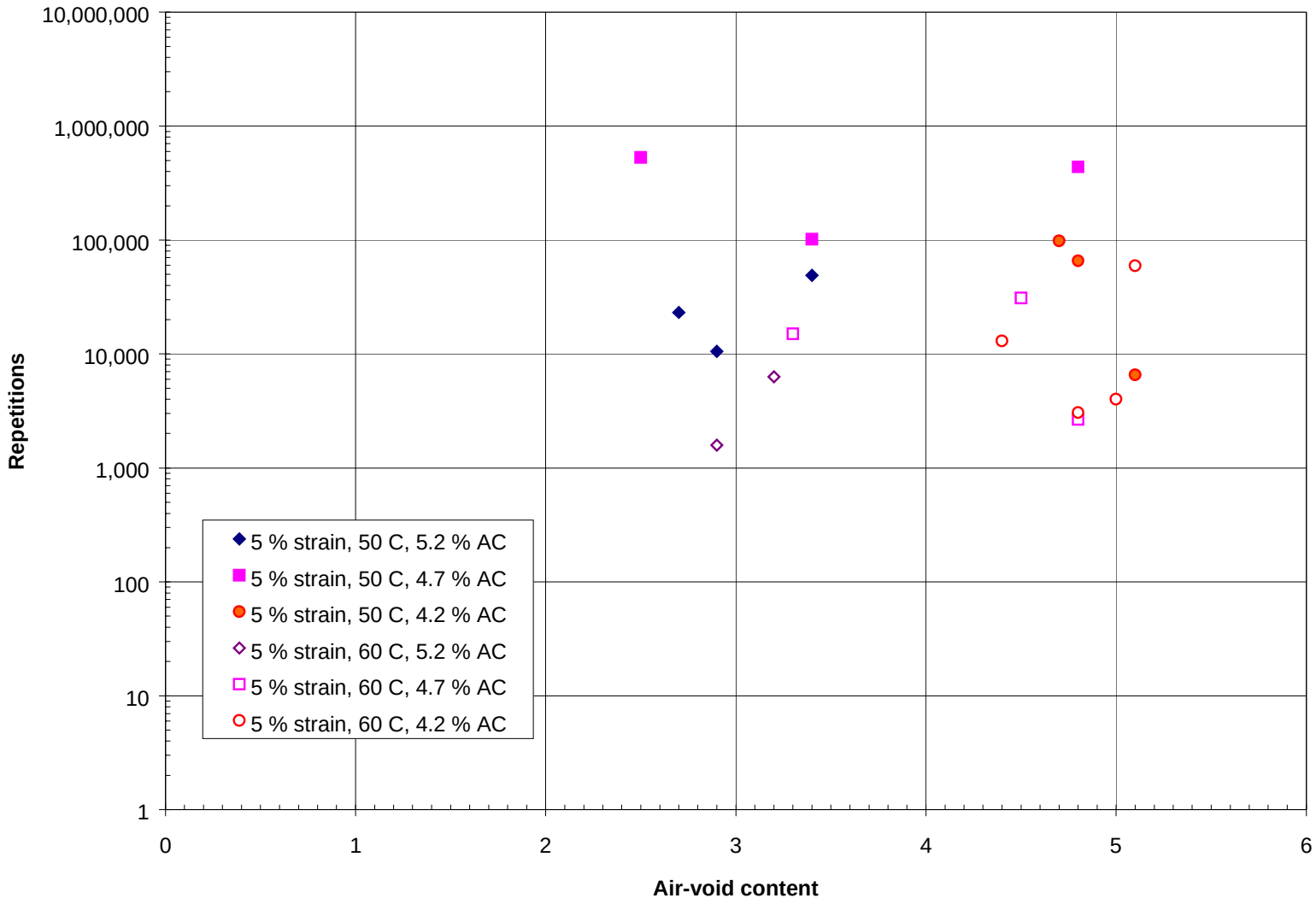

Figure 19. Relationship between Number of Repetitions to 5 Percent Permanent Shear Strain and Air-Void Content, Mixes with AR-8000 Binder.

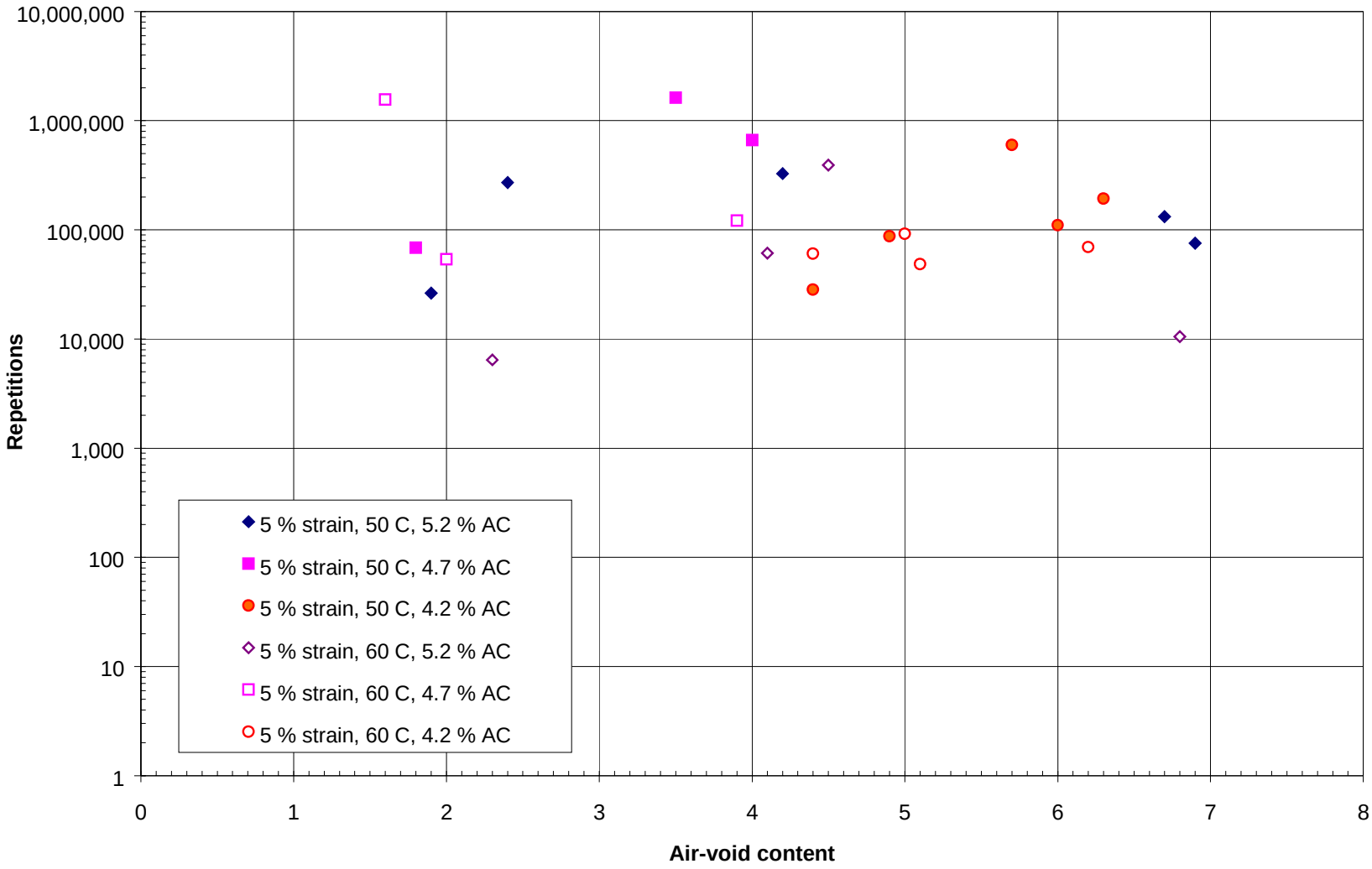

Figure 20. Relationship between Number of Repetitions to 5 Percent Permanent Shear Strain and Air-Void Content, Mixes with PBA-6A Binder.

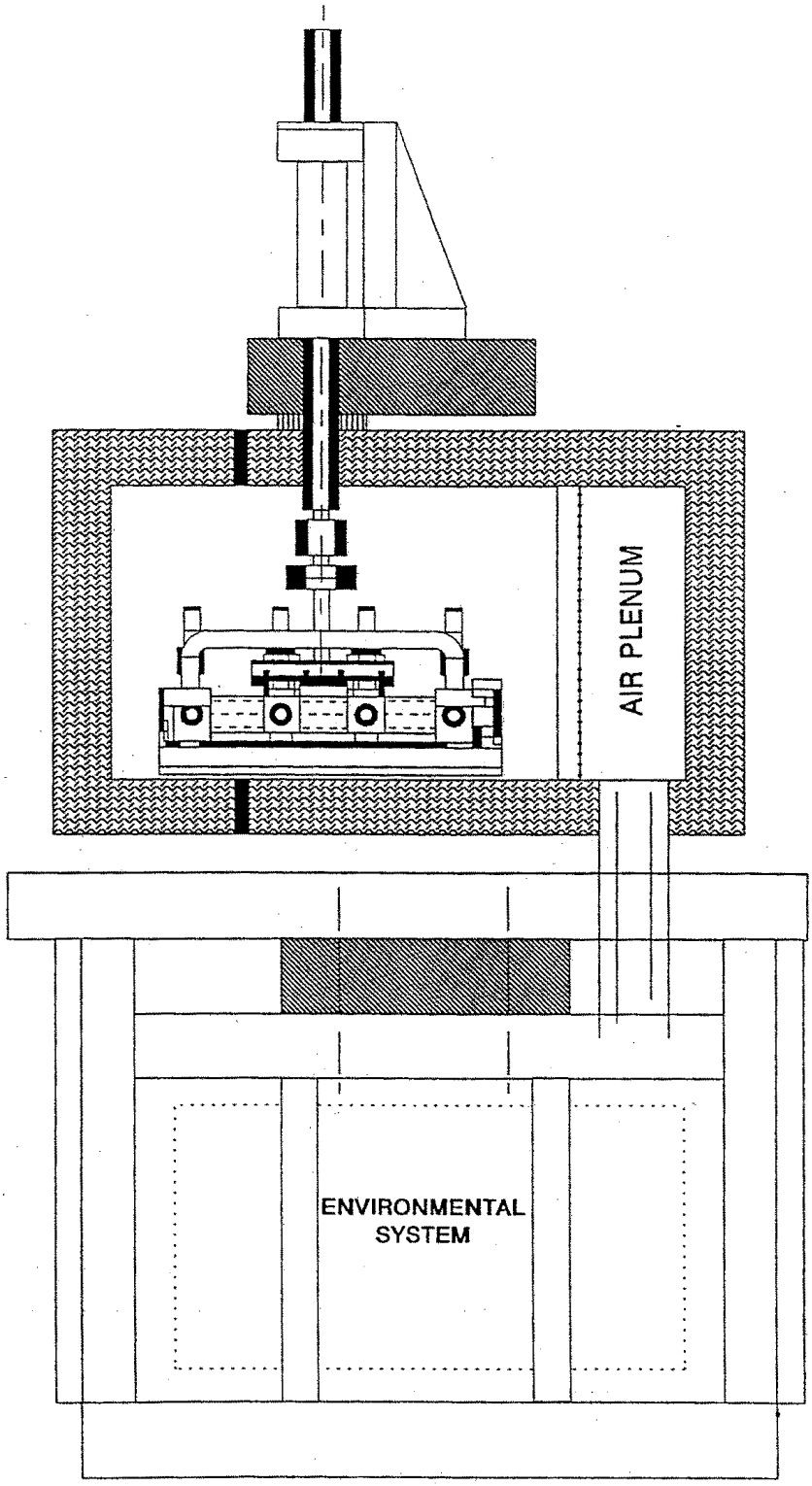

Figure 21. Schematic of Flexural Beam Fatigue Test Apparatus, Side View.

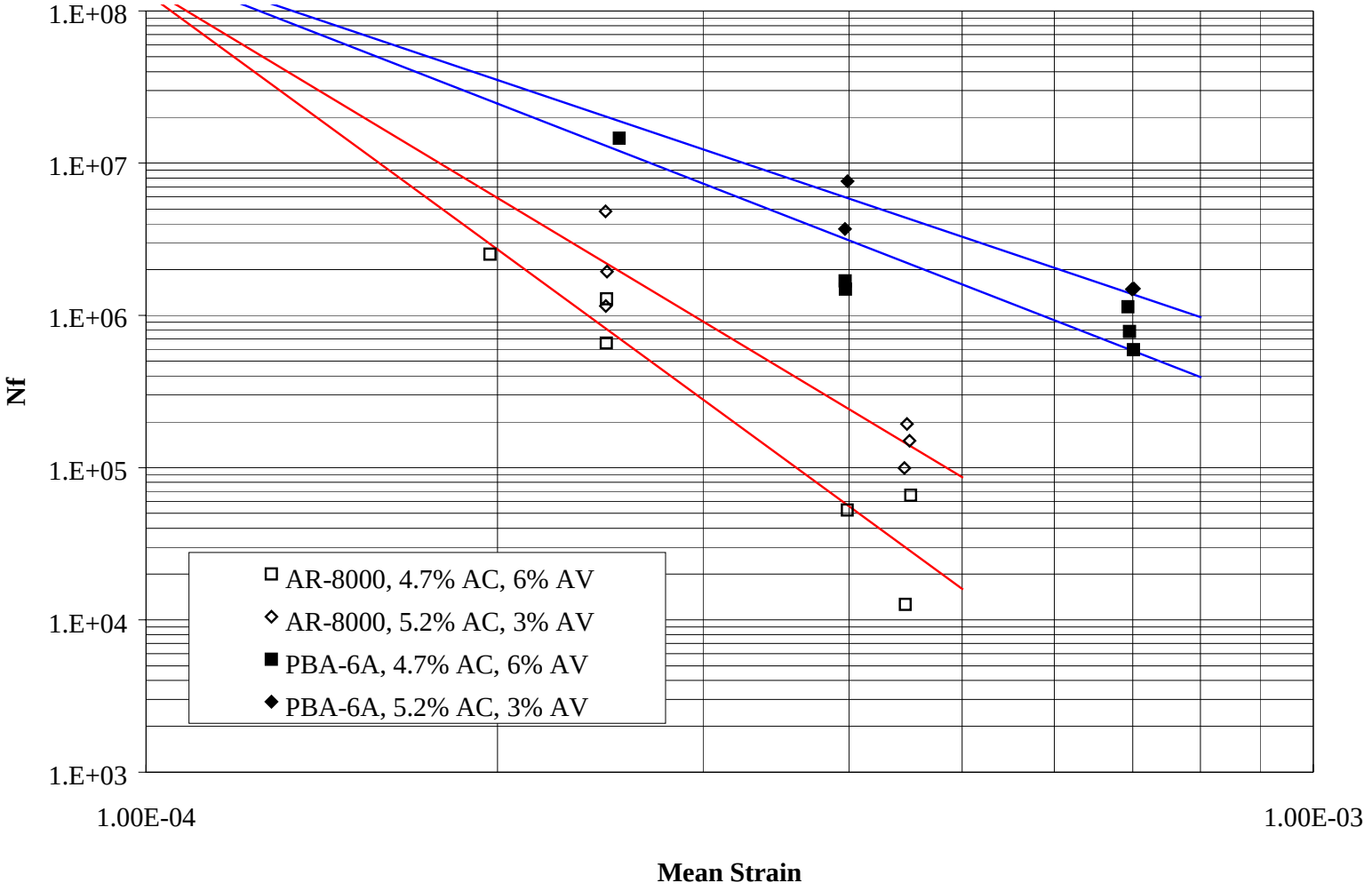

Figure 22. Results of Controlled Strain Fatigue Tests at 20°C, 10 Hertz Frequency.

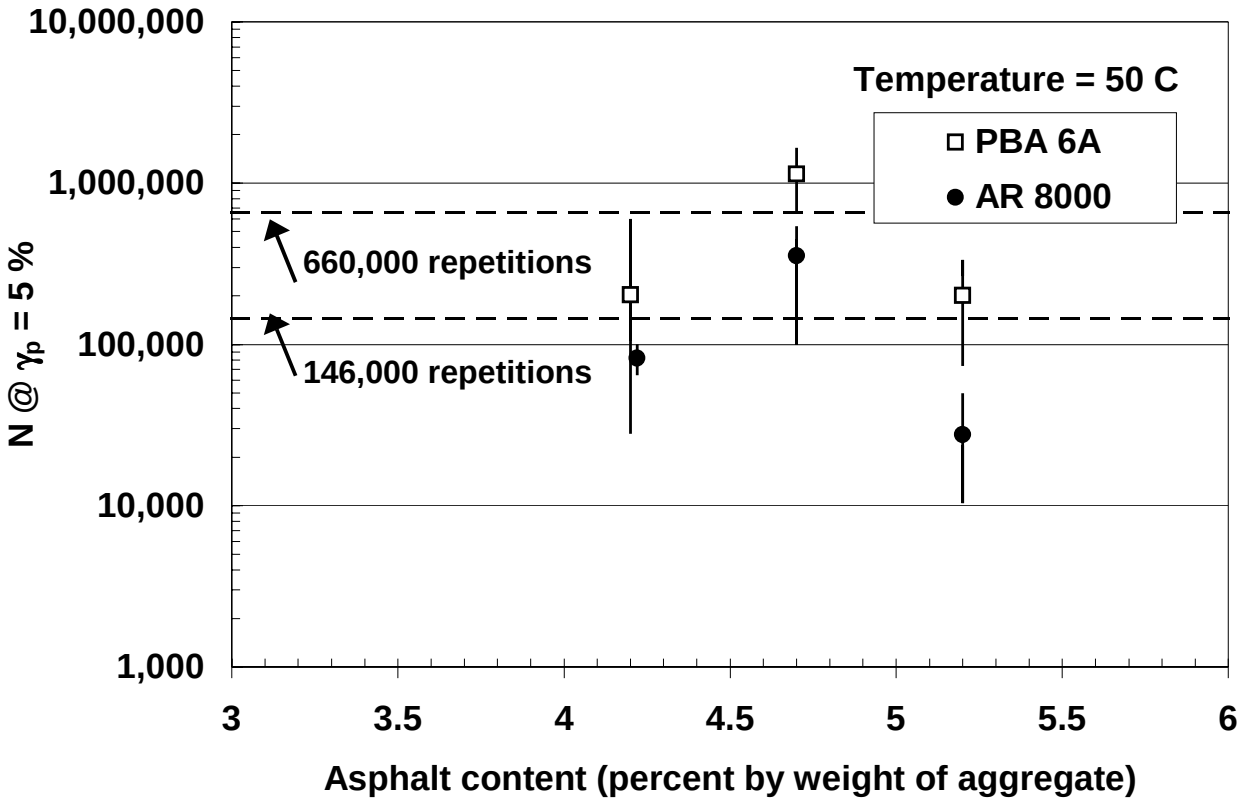

Figure 23. Repetitions to 5 Percent Permanent Shear Strain, N_{supply}, Versus Binder Content; Tests at 50°C.

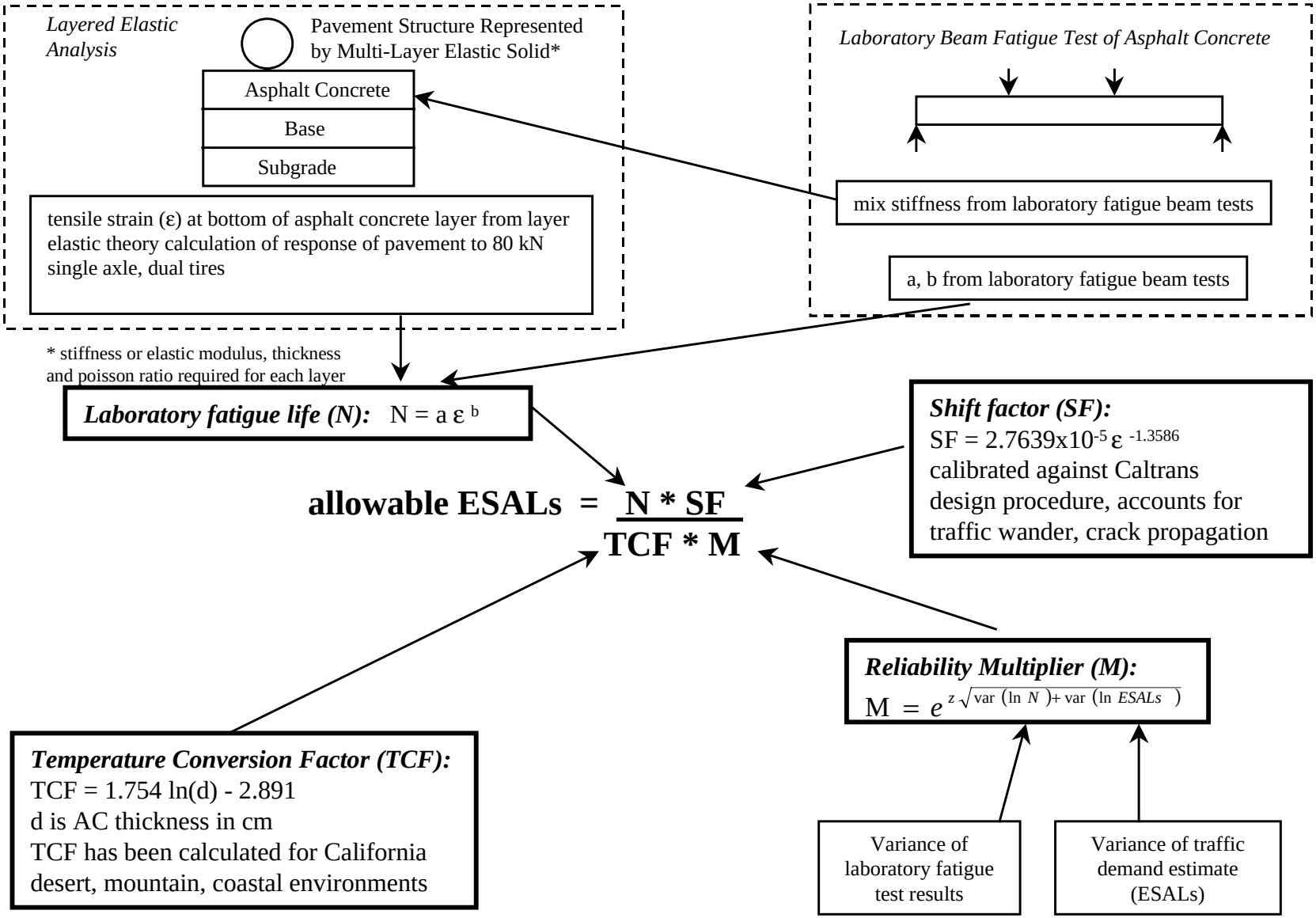

Figure 24. Fatigue Analysis Procedure.

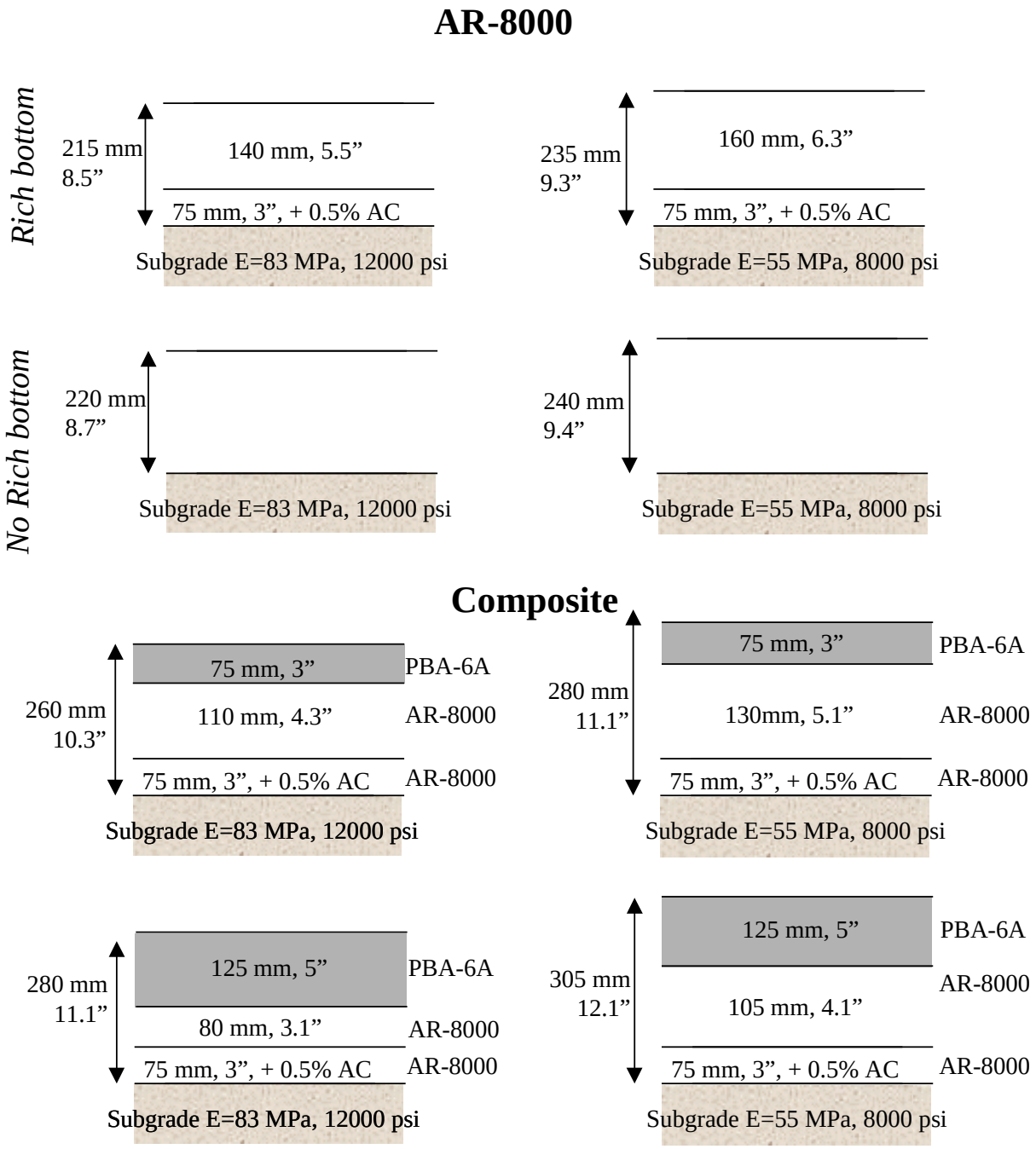

Figure 25. Structural Sections for AR-8000 and Composite Pavements (6 Percent Voids in AC Layer and 3 Percent in Rich Bottom Layer).

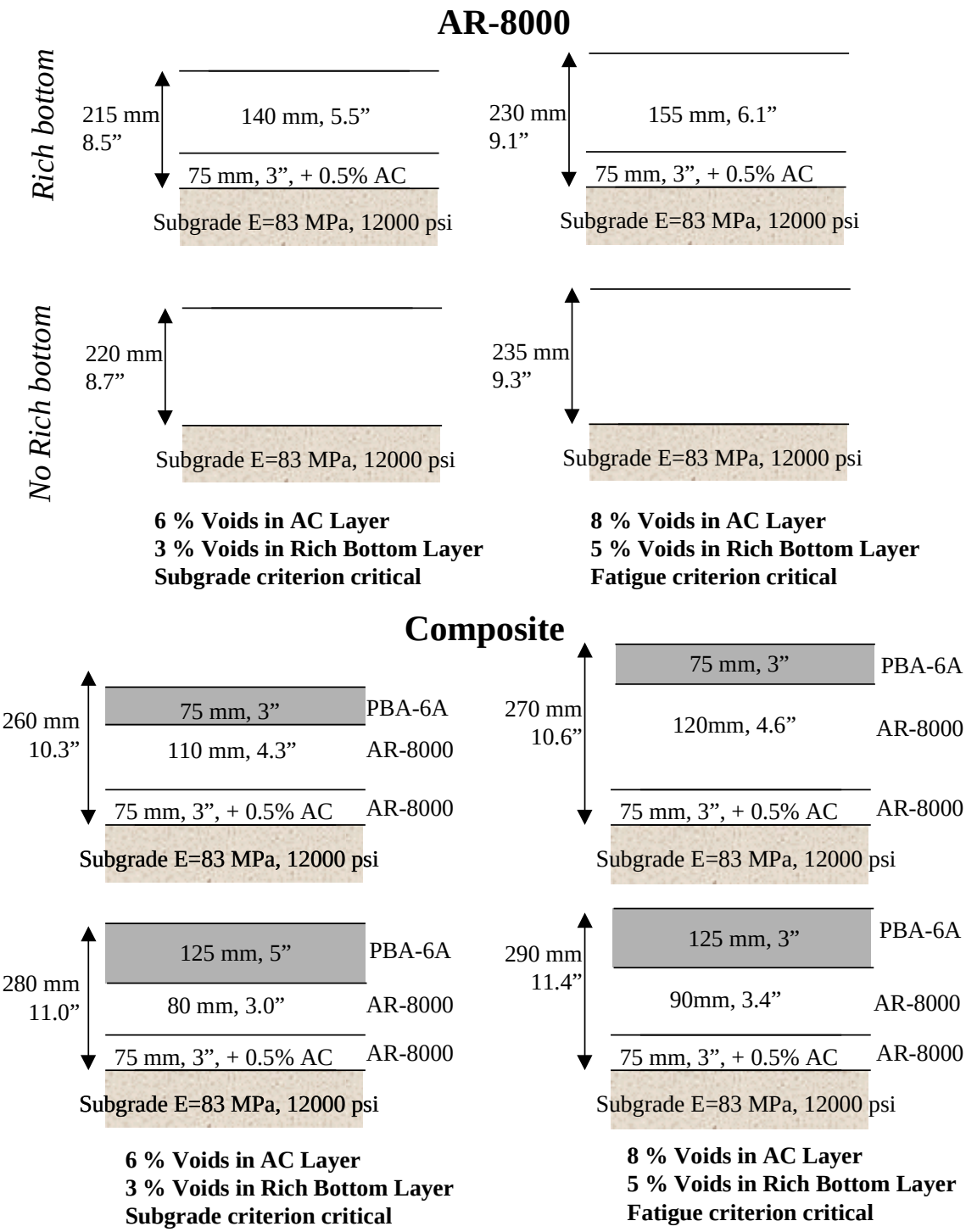

Figure 26. Structural Sections for AR-8000 and Composite Pavements with Increase in Air-Void Contents.

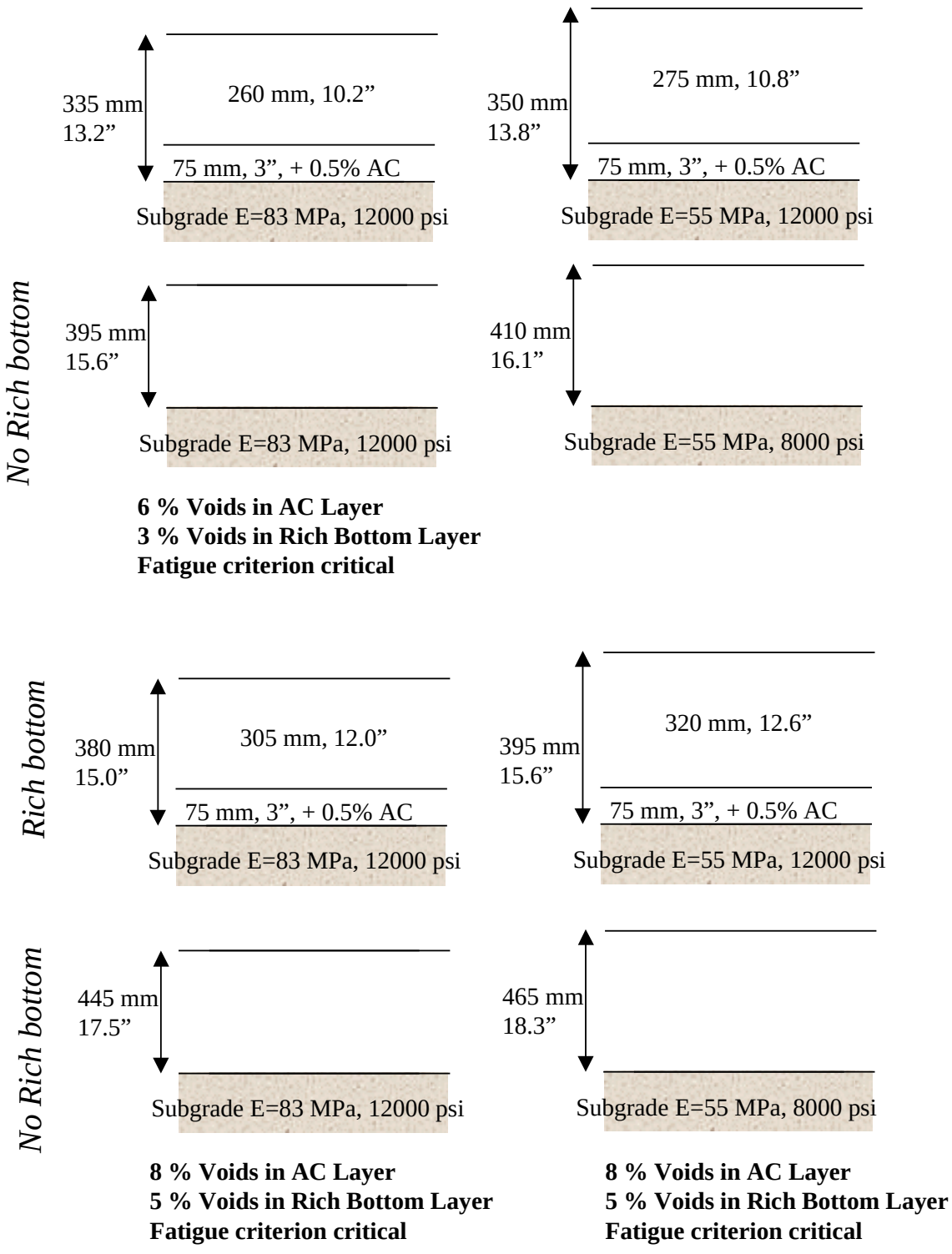

Figure 27a. Structural Sections for Valley Asphalt with Increasing Air-Void Contents.

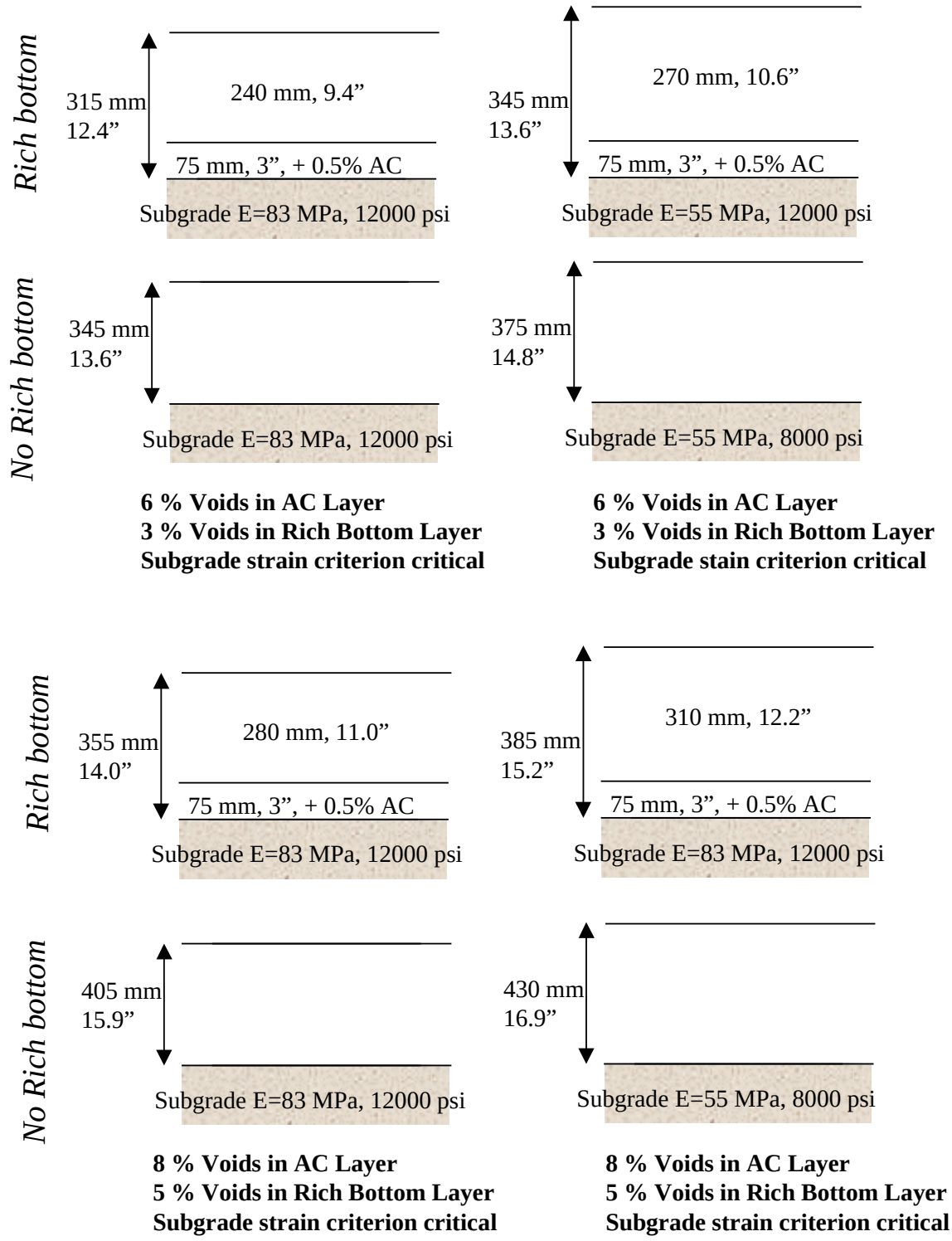

Figure 27b. Structural Sections for Coastal Asphalt with Increasing Air-Void Contents.

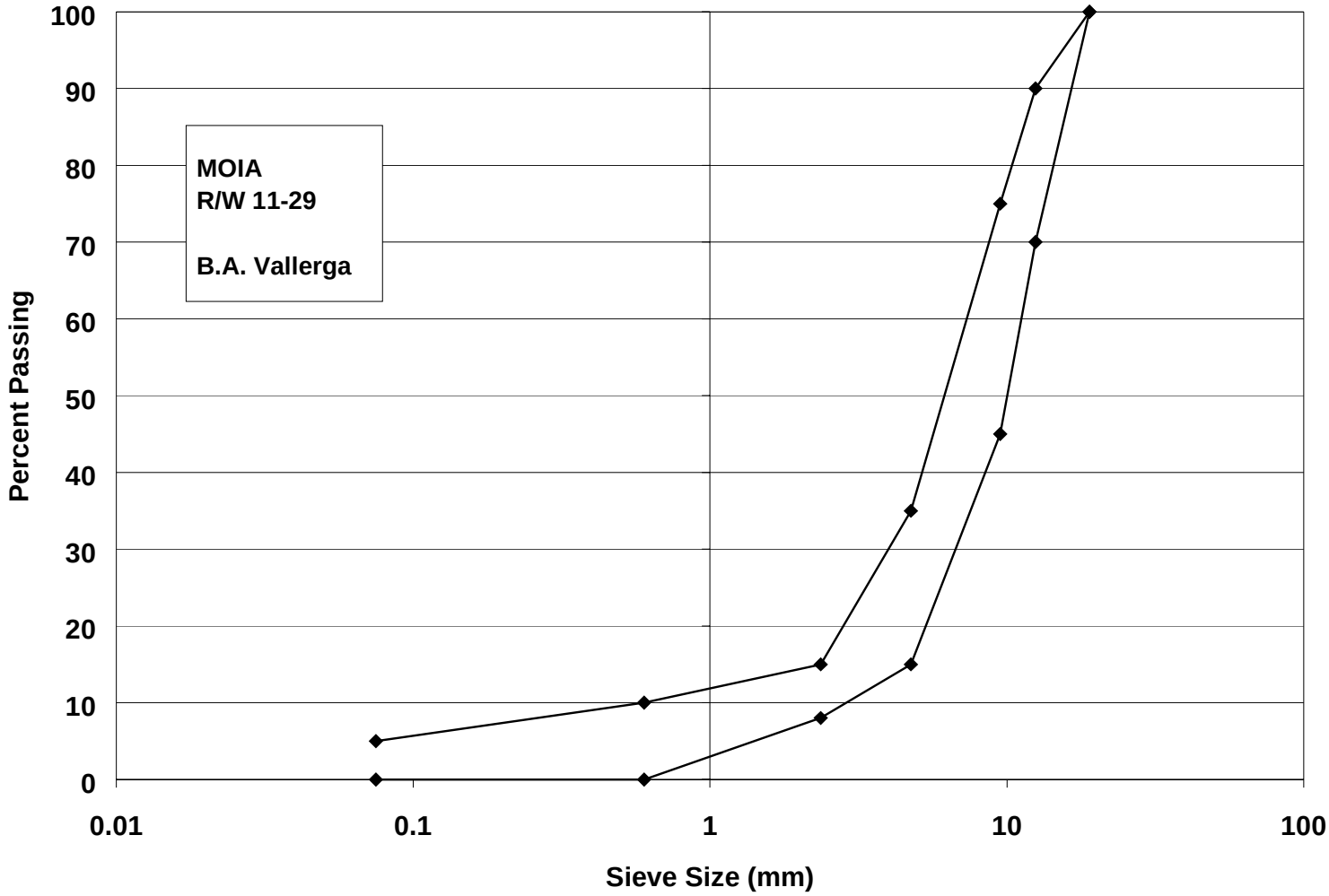

Figure 28. Open-Graded Aggregate Gradation (Porous Friction Course).