SUPERPAVE MIX DESIGN
TESTS METHODS AND REQUIREMENTS

by

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Abstract

Superpave is an acronym for Superior Performing Asphalt Pavements. It is the product of the Strategic Highway Research Program. Superpave includes a new mixture design and analysis system based on performance characteristics of the pavement. It is a multi-faceted system with a tiered approach to designing asphalt mixtures based on desired performance.

There is a great deal of work underway to refine and validate the existing Superpave requirements. The National Cooperative Research Program, Federal Highway Administration, and the State Departments of Transportation are all working on filling the gaps and improving the way we specify, design and build our asphalt pavements. Superpave is only the beginning not the end of our road to true performance based design and construction specifications. Superpave has put us well ahead on that road, but there will always be things to improve on.

1. Introduction

Superpave is an acronym for Superior Performing Asphalt Pavements. It is the product of the Strategic Highway Research Program. Superpave includes a new mixture design and analysis system based on performance characteristics of the pavement. It is a multi-faceted system with a tiered approach to designing asphalt mixtures based on desired performance. Superpave includes some old rules of thumb and some new and mechanistic based features. The Superpave mix design system is quickly becoming the standard system used in the United States (US). The US was looking for a new system to overcome pavement problems such as rutting and low temperature cracking that had become common with the use of design systems such as Marshall and Hveem. The Superpave system offers solutions to these problems through a rational approach.

The Superpave system builds from the simple to the complex. The extent to which the designer utilizes the system is based on the traffic and climate for the pavement to be built. The system includes an asphalt binder specification that uses new binder physical property tests; a series of aggregate tests and specifications; a hot mix asphalt (HMA) design and analysis system; and computer software to integrate the system components. For low volume roads in moderate climates a simple system using materials selection and volumetric mix design is used. As the traffic level for the road to be designed increases the design requirements increase to improve reliability. At the higher traffic levels extensive performance testing is recommended to assure the highest reliability. A unique feature of the Superpave system is that its tests are performed at temperatures and aging conditions that more realistically represent those encountered by in-service pavements.

2. Materials Selection Binder

The design process starts with material selection. The key aspect to the performance of any asphalt mixture is the selection of the optimum materials that will be used in the mixture. One of the key components of Superpave is materials selection. The binders are selected using the performance based Binder Specification and aggregates are selected using performance related aggregate criteria.

The asphalt binder will effect the various performance aspects of the asphalt mixture such as permanent deformation, fatigue cracking, and low temperature cracking. The Superpave binder specification is intended to select the binder to optimize its effect on the performance of the pavement. The binder is selected based on the climate of the pavement where it will be used, the expected traffic, and the location in the pavement structure. The binders are evaluated at the expected highest pavement temperature and lowest pavement temperatures. The average 7 day high temperature is used to determine the critical maximum pavement temperature at a depth of 20 mm in the pavement. The average lowest yearly temperature is used to determine the critical minimum pavement temperature at the surface (Kennedy et al, 1994). An intermediate pavement temperature is determined from a relationship of the high and low temperatures ([7 day average high - average lowest]/2 + 4). For mixes that will be place lower down in the pavement structure temperatures are adjusted to reflect those layers. Using pavement temperatures to select the binder allows for the selection of a binder that will meet both high and low temperature needs for the pavement being placed.

The algorithm used to convert high air temperature to pavement temperature was developed by at the University of Illinois under contract to the Federal Highway Administration (FHWA). The algorithm used to convert low air temperature to pavement temperature was developed by the FHWA Long Term Pavement Performance program from data collected from 30 weather stations and pavement monitoring sites throughout North America (Mohsani and Symos, 1998). These systems allow the designer to accurately determine the pavement temperatures which have a tremendous effect on performance. The asphalt binder is tested using new equipment and test procedures as described in the American Association State Highway and Transportation Officials AASHTO (1997) Provisional Standards.

3. Materials Selection Aggregates

The next step in the Superpave design process is the selection of the aggregate to be used in the mix. Aggregates are the major components of hot mix asphalt. The quality of the aggregates is critical to the performance of the asphalt mixes. Aggregates make up 80 to 85% of the mixture by volume. Aggregate characteristics are a major factor in the performance of an asphalt mixture. In the Superpave mixture design system many aggregate criteria were included to assure the performance of the asphalt mix. These criteria included coarse aggregate angularity, uncompacted voids in fine aggregate or fine aggregate angularity (FAA), flat and elongated particles, clay content, and gradation parameters. The recommended limits set by SHRP on these aggregate criteria were established by consensus of a group of experts based on years of previous research and experience by the Modified Delphi group (Cominsky, 1994).

Numerous studies have indicated mixture stability increased with an increase of crushed particles to replace rounded gravels and sands. Brown and Cross (1992) reported on an extensive study of material properties and their relationship to pavement performance. The study included 42 pavements in 14 different states. Rut depth measurements were taken, mix design information, construction records, traffic counts, and pavement samples collected, for each of the pavements.

The study included a detailed laboratory testing program on samples of the asphalt mixture from rutted and good performing pavements. The data were analyzed to determine material and mixture properties and identify those properties that are necessary for the construction of rut resistant pavements. Of all the materials and mixture properties studied coarse and fine aggregate angularity correlated best to pavement rutting.

Rounded aggregate provides minimal interlock and will easily role over one another allowing movement within the hot mix pavement. Increasing fractured faces of the coarse aggregate will improve stability of a mix. The Superpave design criteria recommends increasing the amount of fractured faces for coarse aggregate with increasing traffic. The actual numbers recommended have not been verified, but are in line with past experience. Increasing the fractured faces in many cases will also, increase the Voids in Mineral Aggregate (VMA) of the mix, typically improving durability.

To determine the angularity of the aggregate the coarse aggregate angularity test is performed. Coarse aggregate angularity is defined as the percent by weight of aggregates larger than 4.75 millimeters with one or more fractured faces. Many State Highway Agencies have protocols to measure coarse aggregate angularity. These usually involve manually counting particles to determine fractured faces. Fractured faces are normally defined by a fractured surface that is larger than 25 percent of the maximum aspect ratio of the aggregate.

Table 1: Coarse Aggregate Angularity Criteria

Traffic, million ESAL's	Depth form the Surface	
	< 100 mm	> 100 mm
<0.3	55/-	-/-
< 1	65/-	-/-
< 3	75/-	50/-
< 10	85/80	60/-
< 30	95/90	80/70
< 100	100/100	95/90
> 100	100/100	100/100

Note: "85/80" denotes the 85% of the coarse aggregate has one or more fractured faces and 80% has two or more fractured faces.

Fine aggregate angularity is defined as the percent air voids present in loosely compacted aggregates smaller than 2.36 millimeter. Higher void contents correspond to higher fractured faces. In the test, a sample of fine aggregate is poured into a small calibrated cylinder by flowing through a standard funnel. By determining the weight of fine aggregate in the filled cylinder of known volume, void content can be calculated as the difference between the cylinder volume and fine aggregate volume collected in the cylinder. The fine aggregate bulk specific gravity is used to compute fine aggregate volume:

Kandhal, Khatri, and Motter (1992) reported on 27 different manufactured and natural sand which were evaluated using several different test methods. In the study all manufactured fine aggregates except one were found to exhibit uncompacted void contents of 44.5 or greater and all the natural fine aggregates had uncompacted void contents lower than 44.5. The fine aggregate angularity test helps define the nature of the fine aggregate. For high volume roads Superpave recommends FAA's of 45. Brown and Cross indicated FAA's in the 42 to 45 range performed best in rut resistance. The SHRP researchers took a conservative approach and set 45 as a minimum value for the FAA test for high volume roads. Based on data indicating most manufactured fines are above 44 and natural fines are below 44, setting the specification at 45 basically requires manufactured sands for high volume roads.

Table 2: Fine Aggregate Angularity Criteria

Traffic, million ESAL's	Depth form the Surface	
	< 100 mm	> 100 mm
<0.3	-	-
< 1	40	-
< 3	40	40
< 10	45	40
< 30	45	40
< 100	45	45
> 100	45	45

Note: Criteria are percent air voids in loosely compacted fine aggregate.

Fine aggregates with FAA's less than 40 have been shown to reduce VMA in a mix. FAA's of 45 will typically increase the VMA in a mix, improving durability and stability. Care must be taken when using aggregate with high FAA's 47 or 48. These aggregates can excessively open up a mix causing high VMA's and create a potential for over asphalting the mix creating possible instability.

The requirements for coarse and fine aggregate angularity were not set based on extensive new research. Past studies and experience were the major sources for establishing the limits set for the Superpave requirements. Not all highway agencies agree with these requirements. Areas with limited crushed stone often feel the coarse aggregate angularity requirements are too restrictive. Questions about the ability of the FAA test to identify manufactured fine aggregate has been questioned. Some manufactured cubical fine aggregates do not always produce FAA results of 45 or greater. These concerns have created controversy and slowed the implementation of the Superpave system.

Several research projects are underway to address these questions and improve the Superpave system. Indiana DOT currently has a project underway with Purdue University to evaluate the FAA test and determine a new or supplemental test to better evaluate the fine aggregate to identify angularity. There is also a pooled fund project 176 at Purdue University to evaluate the Superpave coarse and fine aggregate angularity requirements and determine their relationship to performance for refinement of the specifications.

Flat and elongated aggregate can also effect performance. This characteristic is the percentage by weight of coarse aggregates that have a specified maximum to minimum dimension ratio. The procedure uses a proportional caliper device (figure II) to measure the dimensional ratio of a representative sample of aggregate particles. In the figure, the aggregate particle is first placed with its largest dimension between the swinging arm and fixed post at position A. The swinging arm then remains stationary while the aggregate is placed between the swinging arm and fixed post at position B. If the aggregate fits within this gap, then it is counted as a flat or elongated particle.

Flat and elongated particles will breakdown during the construction process changing the gradation of the mix and the overall mix properties. Flat slivered aggregate also has a tendency to lay flat in the pavement causing slip planes and reducing aggregate interlock. The current Superpave recommendations are thin and elongated (max to min dimension) aggregates with a 5 to 1 ratio should not exceed 10% of the plus 4.75 mm sieve material. These recommendations are not consistent with the current ASTM test procedures. The test procedure, ASTM D 4791, "Flat or Elongated Particles in Coarse Aggregate" is performed on coarse aggregate larger than 9.5 millimeters. The ASTM procedure also evaluates flat (thickness to width) and elongated (width to length).

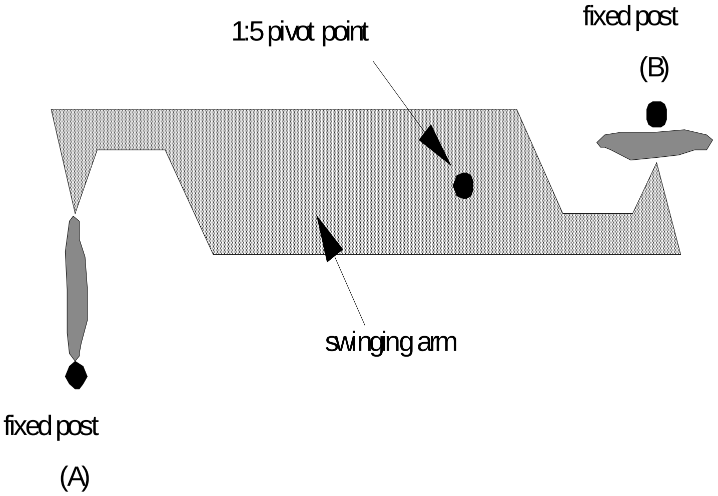

Fig. 1: ASTM D 4791 Proportional Caliper.

Several highway agencies have existing specifications for flat and elongated aggregate. These specifications typically where instituted for Stone Mastic Asphalt (SMA). These SMA specifications are generally more restrictive than the Superpave Specification. The "Guidelines for Materials, Production, and Placement of Stone Matrix Asphalt (SMA)," National Asphalt Pavement Association, IS118, 1994; set a flat and elongated ratio of 3 to 1 not to exceed 20% of the + 4.75 mm material. There has been consideration of changing the recommendation for the Superpave Specifications to a 3 to 1 ratio. This would be more restrictive, but the actual percentages that should be established based on performance, which has yet to be determined. If possible past experience should be used in establishing a criteria. NCHRP project 4-19 evaluated flat and elongated requirements against performance tests, but, only limited test was performed and no definitive recommendations could be made.

Table 3: Flat or Elongated Particles in Coarse Aggregates, ASTM D 4791

Flat, Elongated Particles Criteria	
Estimated Traffic million 80 kN ESALs	**Percent maximum**
< 0.3	-
< 1	-
< 3	10
< 10	10
< 30	10
< 100	10
> 100	10

Note: Criteria are presented as maximum percent by weight of flat and elongated particles.

The volume of fines or mineral aggregate smaller the .075mm will also have an effect on the performance of a mix. Fines can have several different effects on a mix. Anderson and Tarris (1982) demonstrated too much fine material can make a mix brittle and or drive up the asphalt demand. Too little fines can make a mix tender and increase its sensitivity to changes in asphalt content. The exact quantity of fines which will cause these effects can not be determined by percentage of fines in the mix or the gradation of the fines. The only way to determine the actual effect is to perform mix testing. However, staying in ranges typically used in the industry such as the ratio of fines to effective asphalt content (F/A) of 1 to 1.2, will generally be safe. Ratios in this range have historically not been detrimental to the mix. The Superpave specification allows F/A ratios from 0.6 to 1.2. Experience with stone mastic asphalt indicates that for coarse mixes, one plotting below the maximum density line, fines to asphalt ratios may be allowed to go as high as 1.6. If the VMA of the mix is maintained above the minimum value for the nominal aggregate size the extra fines will help stiffen the binder and reduce drain-down and potential for rutting. Additional work quantifying the specifics of the fines to asphalt ratio is still to be done.

Table 4: Aggregate Tests

Consensus Properties	Source Properties (Set by SHA)
• Coarse Aggregate Angularity *(based on PennDOT 621)* • Uncompacted Void Content of Fine Aggregate (AASHTO TP 33) • Elongated Particles (D 4791) • Sand Equivalent (T 176)	• Resistance to Abrasion (T 96) • Soundness (T 104) • Clay Lumps & Friable Particles (T 112)

There are several other aggregate tests specified to be run on the aggregate used in a Superpave Asphalt mixture. All the tests are listed in Table 4. Superpave requires the consensus and source properties be determined for the design aggregate blend. The aggregate criteria are based on combined aggregates rather than individual aggregate components. However, it is recommended that the tests be performed on the individual aggregates; until historical results are accumulated and also to allow for the blending of the aggregates in the mix design. Following all the rules will not guaranty performance. However, following the rules will improve the probability for success.

4. Gradation Requirements

After the specific characteristics of the aggregate are determined, they then have to be combined to produce a mix gradation. Gradation controls are also an important part of the Superpave specifications. The Superpave gradation control centers around the use of the Federal Highway Administrations (FHWA) 0.45 power chart. The 0.45 power chart maximum density line is used to evaluate the potential performance of a gradation. The concept of an aggregate maximum density line was first validated by Nijboer (1948). Goode and Lufsey (1962) refined the concepts of the maximum density line. Huber and Schuler (1992) established the gradation requirements and control points for the Superpave systems use of the FHWA .45 power chart.

Superpave establishes specific definitions for classifying gradations and a standard set of sieves to classify the gradation with. The Superpave system also defines how the Maximum Density Line will be drawn. The maximum density line is plotted from the origin to the maximum aggregate size of the FHWA 0.45 power chart. Superpave classifies gradations based on their nominal aggregate size defined as the, “one size larger than the first size to retain more than 10% by weight of agg.” The maximum aggregate size is defined as, “one sieve size larger than the nominal aggregate size. The Superpave system allows for the comparison of gradations from one agency to another.

The Superpave system also establishes a restricted zone through which a gradation plotted on the FHWA 0.45 chart should not pass through. The Restricted Zone is an area drawn on the maximum density line, typically from the 0.03 mm sieve to the 2.36 mm size. The restricted zone was intended to limit the amount of natural sands that can be used in a mix and discourage producing gradations which plot right on the maximum density line. These requirements have generated the most controversy. Many highway agencies have used gradations which passed through the restricted zone. These gradations allow the use of larger volumes of fine aggregate which are typically more plentiful and less expensive to produce.

The National Cooperative Highway Research Program 9-14 “Investigation of the Restricted Zone in the Superpave Gradation Specification, ” was established to evaluate the need for a restricted zone in the specifications. The project is intended to evaluate if the aggregate requirements make the restricted zone unnecessary or redundant. Under the project various gradations which pass through and around the restricted zone with varied aggregate properties such as CAA, FAA, Flat and Elongated; will be evaluated. The Superpave performance tests such as the Superpave Shear Tester and loaded wheel testers will be used to evaluate performance.

5. Volumetric Mix design

When the binder and aggregates have been selected for the asphalt mixture they have to be combined to produce the optimum mixture properties. Several trial blends are evaluated to determine the optimum mixture. The Superpave Gyratory Compactor (SGC) is used to do this. The SGC is a mechanical compaction device comprised of a reaction frame, rotating base, and motor; loading system, loading ram, and pressure gauge; height measuring and recordation system, mold and base plate. The SGC produces 150 mm diameter by 115 mm high cylindrical specimens. The intent of the SGC is to produce specimens that have the same aggregate orientation and engineering properties as cores cut from the pavement. Several studies where undertaken to evaluate the gyratories ability to produce specimens with properties similar to an actual pavement.

A study conducted at Texas A & M University evaluated the gyratory compactor, Marshall hammer, ELF linear kneading compactor and the gyratory compactor (Button and Little, 1992). Loose mixture from paving projects was compacted to air void contents similar to core removed from roadway. The specimens from the various compactors were tested for mechanical properties such as indirect tensile resilient modulus, indirect tensile strength, strain at failure, and compressive creep. The study indicated that there was not a great deal of difference between the various compactors, but overall the gyratory compactor produced specimens that were most similar to the roadway cores. Also, the gyratory compactor was the easiest to use.

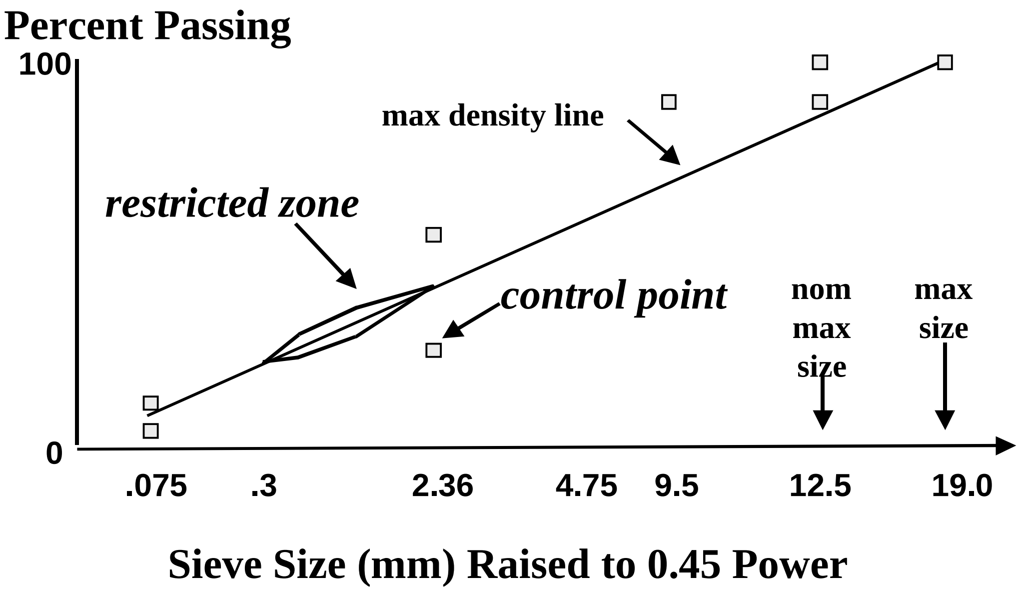

Fig. 2: Superpave Gradation Control Chart

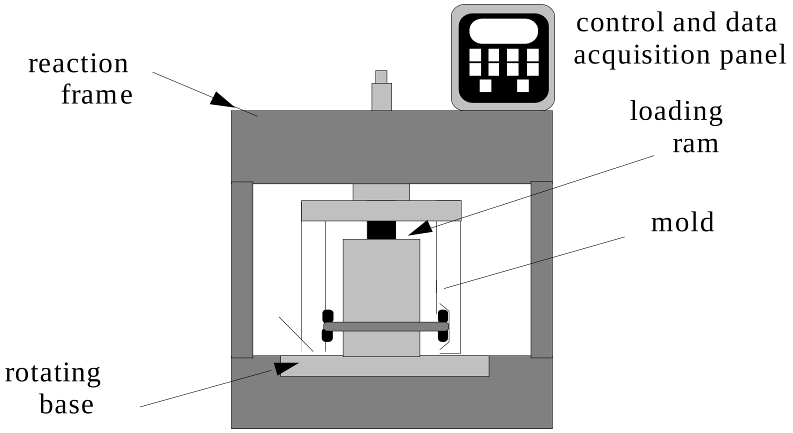

Figure 3: Superpave Gyratory Compactor

The mix is compacted to a predetermined number of gyrations in the SGC based on the expected traffic and pavement temperature. The SUPERPAVE™ compaction criteria are based on three points during the compactive effort: N initial (N_i), design (N_d), and maximum (N_m) number of gyrations. These various levels of gyrations were established from in service pavements with different traffic levels and design temperatures. Limiting criteria based on the percent of G_{mm} or air voids in the compacted mix has also been established for the initial, design, and maximum number of gyrations:

Table 5: Gyratory compaction Criteria.

Number of Gyrations	Compaction Criteria
Initial, N_i	> 89 % G_{mm}
Design, N_d	= 96 % G_{mm}
Maximum, N_m	> 98 % G_{mm}

The number of gyrations used for compaction is defined as a function of the average design high air temperature at the paving location and the expected traffic. The following table indicates the required design number of gyrations (N_d).

Table 6: Gyratory Design Compaction levels.

Estimated Traffic million 80 kN ESALs	7 Day Average Design High Air Temperature											
	< 39EC			39EC - 40EC			41EC - 42EC			43EC - 44EC		
	N_I	N_d	N_m	N_I	N_d	N_m	N_I	N_d	N_m	N_I	N_d	N_m
< 0.3	7	68	104	7	74	114	7	78	121	7	82	127
< 1	7	76	117	7	83	129	7	88	138	8	93	146
< 3	7	86	134	8	95	150	8	100	158	8	105	167
< 10	8	96	152	8	106	169	8	113	181	9	119	192
< 30	8	109	174	9	121	195	9	128	208	9	135	220
< 100	9	126	204	9	139	228	9	146	240	10	153	253
> 100	9	142	233	10	158	262	10	165	275	10	172	288

The volumetric properties of the compacted mixture are used to select the optimum job mix formula (JMF) in the Superpave design system. Properties such as Voids in Mineral Aggregates (VMA), Air Voids in the compacted mix (Va), and Voids Filled with Asphalt (VFA), are determined for the compacted mix and evaluated against the established Superpave criteria. To select the optimum JMF, trial gradations are compacted to the specified level of gyration with an estimated binder content. Typically two specimens are compacted for each gradation and binder content. The compacted specimens are evaluated to determine if they will have the minimum VMA at the design number of gyrations. If the mixture will meet the minimum VMA requirements the most economical blend is selected and an optimum binder content is determine, one which will produce 4% air voids in the compacted mix at the design number of gyrations and be above the minimum VMA. The minimum VMA requirements are set based on the nominal maximum aggregate size. The VFA of the compacted mix is also determine to assure the mix will not be over asphalted.

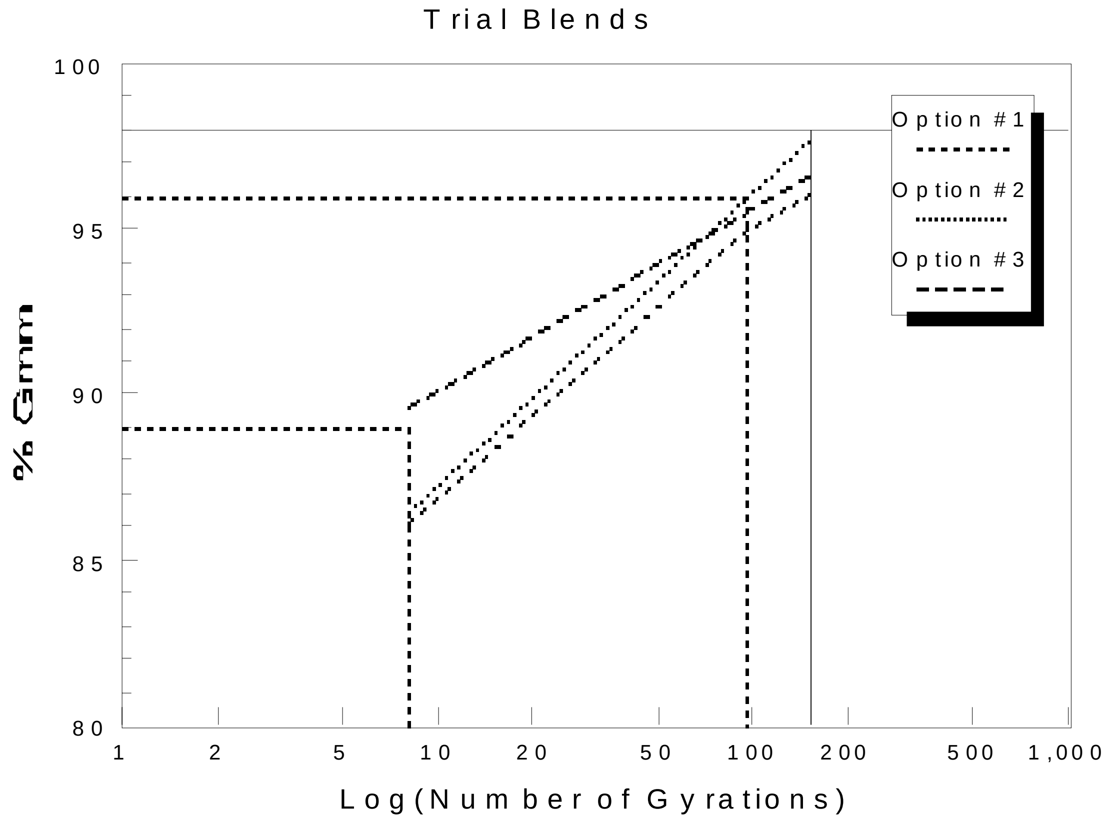

Figure 4: Gyratory Compaction Curves.

Table 7: Superpave VMA criteria.

Voids in Mineral Aggregate Criteria					
Estimated Traffic million 80 kN ESALs	**Nominal Maximum Sieve Size**				
	9.5mm	12.5mm	19.0mm	25.0mm	37.5mm
< 0.3	15.0 %	14.0 %	13.0 %	12.0 %	11.0 %
< 1					
< 3					
< 10					
< 30					
< 100					
> 100					

Note: Based on the Asphalt Institutes Recommendations at 4.0 % V_a, (VMA = volume of air plus volume of effective asphalt).

Table 8: Superpave VFA Criteria

Voids Filled with Asphalt Criteria		
Estimated Traffic Million 80 kN ESALs	**Range**	
	Minimum	**Maximum**
< 0.3	70	80
< 1	65	78
< 3	65	78
< 10	65	75
< 30	65	75
< 100	65	75
> 100	65	75

The final step in the Superpave volumetric design process is to determine the moisture sensitivity of the mix. American Association of State Highway and Transportation Officials (AASHTO) Test Procedure T 283 " Moisture Sensitivity of Compacted Paving Mixtures" is used to determine if the design trial mix formula will be susceptible to damage by moisture in the pavement. If the test indicates a problem an anti-stripping additive is added to the mix. This additive may be hydrated lime or some type of liquid anti-strip

Table 9: F/A Ratio Criteria based on effective asphalt binder content

Fines to Asphalt Ratio Criteria		
Estimated Traffic Million 80 kN ESALs	**Range**	
	Minimum	**Maximum**
< 0.3	0.6	1.2
< 1		
< 3		
< 10		
< 30		
< 100		
> 100		

This completes the volumetric design process. For many pavements placed in the U.S. this is the end of the mix design process, however, for agencies that wish, mixture performance tests are also available to evaluate the mixtures ability to perform on the roadway.

6. Performance Testing

Superpave volumetric mix design is the key step in developing a well-performing asphalt mixture. Under SHRP, additional laboratory analysis tests and performance prediction models were developed to further determine the capabilities of Superpave mixtures to perform well for the specific project design traffic and climatic condition.

The framework of the Superpave asphalt mix analysis system that was developed under SHRP includes a system of analytical pavement performance models that take results from laboratory tests and determine if the design mixture would perform under the design conditions. Several test procedures were developed to impose various stress and temperature conditions to asphalt mixture specimens to characterize the many properties necessary to model pavement behavior. SHRP developed two performance test devices: the Superpave Shear Tester (SST) and the Indirect Tensile Tester (IDT) (FHWA, 1997).

Recently, the University of Maryland, under contract to FHWA, critically evaluated the original SHRP analytical models. Some concerns and suggestions for improvement were documented in a Models Evaluation Report. As a result of the models evaluation, changes will be made in the system that was developed under SHRP. What the extent of these changes will be and what the final Superpave Mix Analysis System will look like will quite different from that originally delivered by SHRP. However, the basic performance analysis framework and the test equipment that were developed under SHRP are still useful tools. The IDT and associated low temperature cracking models will remain as part of any future pavement performance analysis system. The SST does produce test results that can be used to evaluate the potential performance of an asphalt mix.

7. Conclusions

Since the completion of the SHRP 5 year effort in 1993, over 300 pavement sections and several million tons of mix have been placed using the Superpave Mix Design System. Typically these pavements have been providing excellent performance. There have been a few failures of these early pavements and we have learned a great deal from these failures. Certain aggregates and gradations can produce mixes that will meet the all Superpave requirements but still fail. We can put too much asphalt in a mix. Recommendations have been made to establish a maximum VMA requirement to avoid this problem. Some Superpave mixes are very difficult to compact on the roadway, which is key to performance. This problem will have to be solved and we will do that.

There is a great deal of work underway to refine and validate the existing Superpave requirements. The National Cooperative Research Program, Federal Highway Administration, and the State Departments of Transportation are all working on filling the gaps and improving the way we specify, design and build our asphalt pavements. Superpave is only the beginning not the end of our road to true performance based design and construction specifications. Superpave has put us well ahead on that road, but there will always be things to improve on.

8. References

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