Report No. FHWA-RD-74-2

DESIGN OF OPEN-GRADED ASPHALT FRICTION COURSES

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January 1974
Interim Report

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FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Washington, D.C. 20590

Technical Report Documentation Page

1. Report No. FHWA-RD-74-2	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DESIGN OF OPEN-GRADED ASPHALT FRICTION COURSES		5. Report Date January 1974
		6. Performing Organization Code
7. Author(s) R. W. Smith, J. M. Rice, S. R. Spelman		8. Performing Organization Report No.
9. Performing Organization Name and Address Federal Highway Administration Offices of Research and Development Materials Division Washington, D. C. 20590		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
		13. Type of Report and Period Covered Interim July 1973 - December 1973
12. Sponsoring Agency Name and Address U. S. Department of Transportation Federal Highway Administration Offices of Research and Development Washington, D. C. 20590		14. Sponsoring Agency Code M-0094

15. Supplementary Notes

This was a staff effort of the Paving and Structural Materials Group, HRS-22.

16. Abstract Efforts to improve pavement skid resistance have shown the advantages of using open-graded asphalt paving mixtures. Extensive implementation of these mixtures has been hampered, however, due to some difficulties encountered during construction and some deficiencies observed in service performance. These problems are partially attributable to a number of uncertainties involved in existing design methods.

A new design method has been developed which purports to satisfy the immediate needs of the highway industry. The method is a constructive blend of past experience and a new approach to the problem. The concept used is that the open-graded asphalt friction course consists predominantly of a narrowly-graded coarse aggregate fraction with a sufficiently high interstitial void capacity to provide for a relatively high asphalt content, a high air void content, and a relatively small fraction of fine aggregate. The coarse aggregate fraction provides the structure of the composite mixture while the fine aggregate fraction acts as a filler and imparts a "chocking action" to stabilize the coarse aggregate. The high asphalt content provides for mixture durability and the high air void content provides for adequate subsurface water drainage.

The described method is relatively new, but has been used successfully on several FHWA, R&D Demonstration Projects. It is believed that the proposed method provides technological improvements over other existing methods, and its use is recommended for immediate experimental application.

17. Key Words Asphalt Concrete, Open-Graded, Design Method, Skid Resistance, Porous Overlay, Surface Treatment, Plant Mix Seal		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22151	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 43	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

PREFACE

The new design technique reported here was developed by the Materials Division, Office of Research, and is offered as a logical approach to the design of open-graded asphalt friction overlays. It provides a means to surmount with reasonable assurance some of the past difficulties encountered in design, construction, and field performance. The overall simplicity of the methodology and the low capital investment in required laboratory equipment contributes to its suitability for acceptance on a national level.

The authors wish to thank Mr. Howard L. Anderson, Director, Office of Development and Mr. Alan E. Trotter, Materials Engineer, Region 15, for their continued interest and support in the conduct of the work, and also Messrs. H. J. Lentz and D. E. Weatherford for their assistance in the performance of the laboratory evaluations and designs.

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INTRODUCTION

Most of the highway community is generally familiar with the type of overlay commonly referred to as an "open-graded plant mix seal coat." From most available reports, this type of surfacing evolved from the conventional chip seal surface treatment which is used primarily to seal and maintain aged, but otherwise structurally sound, pavements. It is what its name implies - a chip seal aggregate mixed hot in a plant with a relatively high percentage of asphalt cement and placed in a compacted depth of five-eighth-inch to three-fourth-inch by an asphalt paver. The history and extent of plant mix seal usage has been adequately discussed and documented in the literature (1, 2, 3, 4, 5, 6, 7, 8) and therefore there is no further need to have another dissertation here. It shall suffice to summarize that the extended use of plant mix seals has been undesirably slowed because of a number of uncertainties and problems involved in its design and construction, in spite of the following benefits which have been associated with this type of surfacing material:

(1) improved skid resistance at high speeds during wet weather
(2) minimization of hydroplaning effects during wet weather
(3) improved road smoothness (PSI)
(4) minimization of splash and spray during wet weather
(5) minimization of wheel path rutting
(6) improved visibility of painted traffic markings
(7) improved night visibility during wet weather (less glare)
(8) lower highway noise levels
(9) retardation of ice formation on surface

Therefore, a concerted effort has recently been initiated to overcome those remaining roadblocks which prevent the motoring public from receiving the above-listed benefits.

THE PROBLEM IN PERSPECTIVE

The greatest discernible difficulty was that current design practice was not well defined. In most instances, the only design criteria available were limits on the aggregate gradation and ranges of values for asphalt content which were based primarily on field experience. Existing methods of design seemed to rely on surface treatment concepts or on the application of routine design methods that are generally only suitable for dense, cohesive type mixtures. The open-graded plant mix seal, however, does not fit into either category.

The main design consideration that created problems appeared to be the determination of the percentage of asphalt cement to be used. The amount was usually selected by conducting a series of asphalt "drainage" tests on trial mixtures at various percentages of asphalt. The basis for this design approach was simply the requirement that a sufficient quantity of asphalt cement be made available for the formation of a seal on the existing road surface, but not so much as to cause excess drainage, segregation, or handling problems during construction. The undesirable aspect of selecting asphalt content in this manner is that the *drainage test temperature* is made the controlling factor rather than, more properly, the inherent properties of the material constituents or of the resulting mixture.

When asphalt content was selected by the use of more advanced equipment, such as the Marshall or Hveem apparatus, it was found that stability and flow were quite insensitive to variations in asphalt percentage for these mixtures. The usual criteria of selecting the asphalt content on the basis of optimizing stability and flow did not provide definitive results.

The selection of asphalt content by either drainage tests or mechanical tests requires considerable engineering judgment. Afterwards, it is still quite possible to have too little asphalt which would create a raveling condition, or too much asphalt which would create a flushing condition.

The aggregate gradation has also been shown to be an important design factor. It influences the amount of internal and surface voids of the mixture, surface rugosity, asphalt content, and the resistance to densification and subsequent flushing of the asphalt under high traffic volume applications. The quantity of material smaller (or larger) than a No. 8 sieve seems to be a most important criterion in defining an acceptable aggregate gradation. Yet quantities ranging from 0 to 38 percent have been used for what is typically labeled an open-graded plant mix seal.

A DIFFERENT APPROACH

In the course of our analysis of the problem, it became evident that highway engineers have been using open-graded plant mix seals for two distinct purposes: (1) maintenance of aged and weathered pavement surfaces, and (2) specifically for the improvement of pavement friction. Since the latter purpose is the primary concern of the Federal Highway Administration, we thought it desirable to "advance" the open-graded plant mix seal still further, into the OPEN-GRADED ASPHALT FRICTION COURSE. In view of what has already been discussed, an open-graded asphalt friction course might best be considered as a plant mix seal without the excess asphalt cement which forms the aforementioned seal.

Although this distinction may seem relatively minor, it does reduce greatly the difficulty that is encountered in mixture design and pavement construction. Using this concept, a more definite design procedure can be established without the sacrifice of any of the previously listed benefits. It is still important, however, to provide a watertight seal at the interface with the existing pavement surface as is depicted in Figure 1. The recommendation is that the existing surface be treated separately from the new surfacing material. If the existing surface is dry, apply a prime coat. If it is flushed, remove the excess asphalt.

The design procedure then is based on the concept that the open-graded asphalt friction course consists predominantly of a narrowly-graded coarse aggregate fraction (which is defined here as the material that is retained on a No. 8 sieve) with a sufficiently high interstitial void capacity to provide for a relatively high asphalt content, a high air void content, and a small fraction of fine aggregate (which is defined as that material passing a No. 8 sieve). The coarse aggregate fraction provides the structure of the composite mixture while the fine aggregate fraction acts primarily as a filler within the interstitial voids.

Material Requirements

The highway community is now cognizant that pavement skid resistance is not only a function of the larger scale texture or macrotexture depicted in Figure 1, but also of the small scale texture or microtexture which can barely be felt by touch. In a typically dense-graded asphalt mixture, the pavement macrotexture is provided by the coarse aggregate, while the microtexture can be provided by both the coarse and fine aggregate. In the open-graded asphalt friction course, however, the coarse aggregate fraction must provide the necessary microtexture without assistance from the fine aggregate. It is, therefore, very important that this characteristic be considered when selecting the coarse aggregate. A number of aggregates derive their excellent microtexture properties through the process of attrition, but in some cases this can be excessive in terms of abrasion loss requirements. A compromise might, therefore, be required between friction and abrasion properties.

Note - A complete procedural version of the design method is given in Appendix A. Excerpts from the procedure, in italics, are interjected in the following discussion for rapid reference purposes.

1.1 It is recommended that relatively pure carbonate aggregates or any aggregates known to polish be excluded from the coarse aggregate fraction (material retained on No. 8 sieve). In addition, the coarse aggregate fraction should have at least 75 percent by weight of

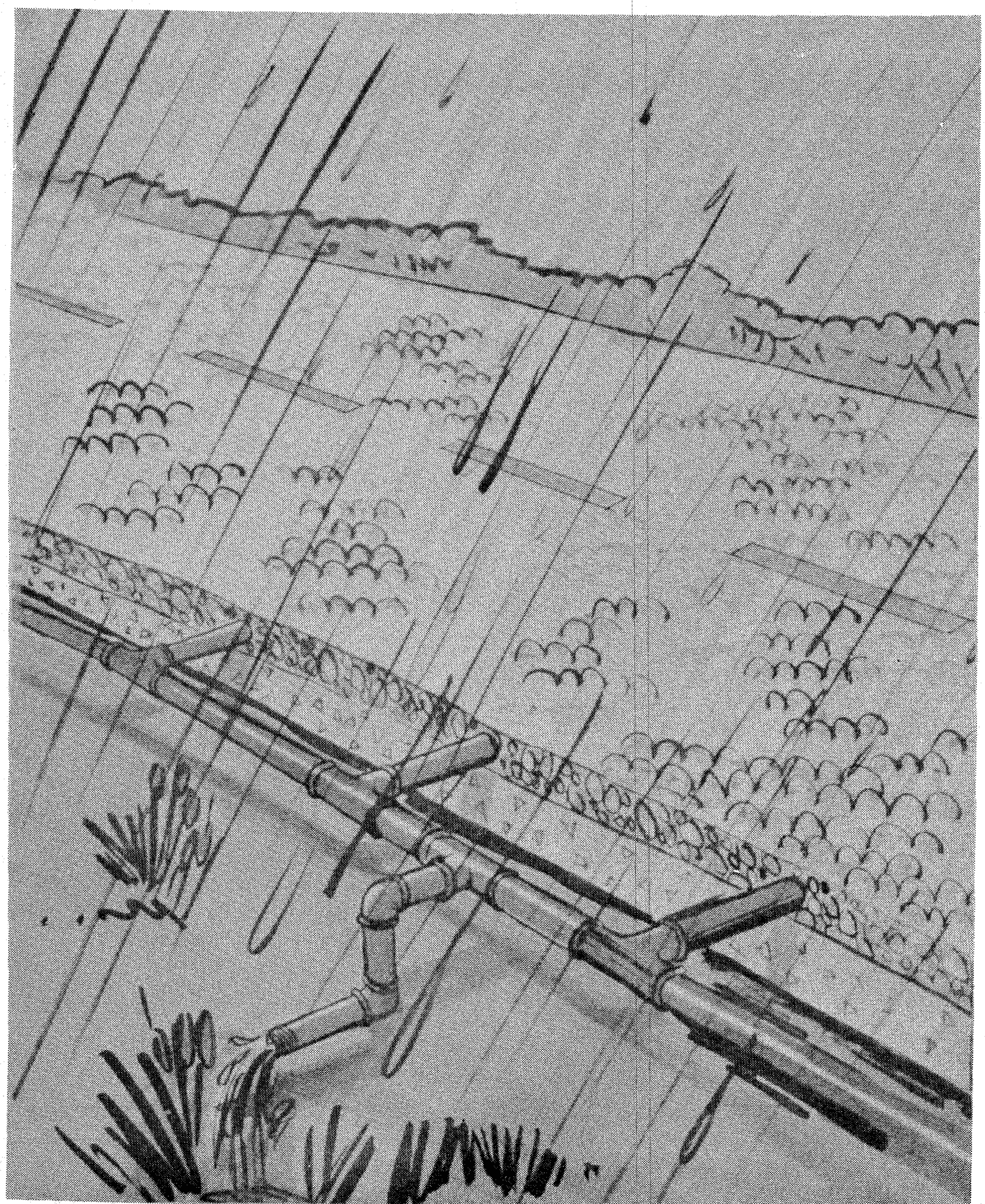

Figure 1. Open-Graded Asphalt Friction Course

particles with at least two fractured faces and 90 percent with one or more fractured faces. The abrasion loss (AASHO T 96) should not exceed 40 percent.

The attainment of the required macrotexture property is more or less implicit with the adherence to the recommended limits on the aggregate gradation which have been borrowed largely from field experience (9).

1.2 Recommended Gradation for Open-Graded Asphalt Friction Course

Sieve Size[a/]	*Percent Passing*[b/]
3/8"	*100*
# 4	*30-50*
# 8	*5-15*
#200	*2-5*

a/ U. S. Sieve Series
b/ By weight

Limits which are given for the No. 8 sieve are intended primarily as a guide. The overriding consideration which actually dictates the maximum limit is that all the material finer must fit within the interstitial voids of the composite forming material (retained on No. 8 sieve). The uniformity of the aggregate grading between the No. 8 sieve and the No. 200 sieve is an important factor affecting the quantity that can be used, as are the shape characteristics (roundness and sphericity) of the coarse aggregate fraction. The importance of having at least some fine aggregate cannot be overemphasized, as its primary purpose is to provide a "chocking action" for the stabilization of the coarse aggregate fraction. Consequently, minimum requirements have been provided.

Limits which are given for mineral dust (passing No. 200 sieve) help to assure a uniform grading of the fine aggregate to some degree, as well as to control the asphalt drainage characteristics of the mixture by effectively increasing the viscosity of the asphalt cement.

The suggested grade of asphalt cement to be used is AC-10 or AR-40 of AASHO M 226-73 I. These grades should be considered as a tentative starting point because test results obtained from the design process may indicate an advantage or a necessity to alter the asphalt grade.

1.3 The recommended grade of asphalt cement is AC-10 or AR-40, AASHO M 226-73 I. For AC-10, Table 2 requirements should apply where such asphalt is available. AR-40 requirements are given in Table 3.

Preliminary Data

It is necessary that the actual aggregates proposed for use be submitted to the mix design engineer together with any information on the proportions of each that the contractor prefers to use. The designer must be able to reconstruct the proposed job-mix in the laboratory, not only in gradation, but also in the exact proportions of the various raw materials, if these are different types.

2.1 Test coarse and fine aggregates as received for the project for gradation unless otherwise provided. If mineral filler is submitted as a separate item, it should also be tested for specification compliance. Analyze gradation results to determine if proportions of aggregates and batching operations proposed by the contractor will meet his job-mix formula and the specification limits of section 1.2.

The design process requires that separate specific gravity values be determined for the coarse aggregate fraction (material retained on No. 8 sieve) and the fine aggregate fraction (material passing No. 8 sieve) of the job-mix blend. One approach is to physically prepare a sample having the job-mix gradation as indicated in section 2.1 and then to re-separate the sample into two fractions by splitting on the No. 8 sieve. Each fraction can then be tested separately for specific gravity.

Although the above approach requires only two specific gravity determinations, it leaves the designer with little flexibility if he must eventually make an adjustment to the job-mix gradation. It is therefore desirable to determine specific gravities on the coarse and fine aggregate fractions (retained and passing No. 8 sieve) for each type of material submitted.

2.2 Determine bulk and apparent specific gravity for the coarse and fine aggregate fractions (retained and passing No. 8 sieve) for each type of material submitted. Additional specific gravity tests are not warranted where the only distinction between aggregates is size of grading. Utilizing the information verified in section 2.1, mathematically compute the bulk and apparent specific gravity for the coarse and fine aggregate fractions (retained and passing No. 8 sieve) for the proposed job-mix gradation.

The asphalt cement should be subjected to the routine tests to verify specification compliance. Information regarding the intended use of or presence of additives in the submitted sample should be provided. Typical additives are antistripping agents and silicone. When kerosene or fuel oil is used as the dilutant for the additive, the dilution proportion should also be given. Preferably, the sample of asphalt cement received at the laboratory should be a representative sample from the plant.

2.3 Test the asphalt cement to be used for specification compliance (AASHO M 226-73 I), viscosity-temperature data, and specific gravity at 77.0 F.

Asphalt Content

The method of selecting the asphalt content consists of two steps. The first is to conduct a measurement of the surface capacity (Kc) of the predominant aggregate size fraction (material retained on No. 4 sieve). Surface capacity includes absorption, superficial area, and surface roughness, all of which affect asphalt cement requirements.

3.1 Determine the surface capacity of the aggregate fraction that is retained on a No. 4 sieve in accordance with the following procedure (10):

3.1.1 Quarter out 105 g. representative of the passing three-eighth-inch and retained No. 4 sieve material.

3.1.2 Dry sample on hot plate or in 230 ± 9F oven to constant weight and allow to cool.

3.1.3 Weigh out 100.0 g. and place in a metal funnel (top diameter 3-1/2 inches, height 4-1/2 inches, orifice one-half-inch, with a piece of No. 10 sieve soldered to the bottom of the opening).

3.1.4 Completely immerse specimen in S.A.E. No. 10 lubricating oil for 5 minutes.

3.1.5 Drain for 2 minutes.

3.1.6 Place funnel containing sample in 140 F oven for 15 minutes of additional draining.

3.1.7 Pour sample from funnel into tared pan; cool and reweigh sample to nearest 0.1 g. Subtract original weight and record difference as percent oil retained (based on 100 g. of dry aggregate).

3.1.8 Use chart shown in Figure 2 for determination of "Kc."

(1) If specific gravity for the fraction is greater than 2.70 or less than 2.60, apply correction to oil retained, using formula at bottom of chart in Figure 2.

(2) Start at the bottom of chart in Figure 2 with the corrected percent of oil retained; follow straightedge vertically upward to intersection with the diagonal line; hold point, and follow the straightedge horizontally to the left. The value obtained will be the surface constant for the retained fraction and is known as "Kc."

The second step is to compute the required asphalt content from an established simple linear relationship obtained from field experience on similarly graded mixtures. Asphalt content so determined is based on weight of aggregate. A basic difference between this design procedure and its predecessors is that this value for asphalt content is to be considered final and no further adjustments are to be made based on asphalt drainage characteristics, stability, or whatever. This value was previously and appropriately termed Estimated Optimum Asphalt (EOA) in those earlier methods.

3.2 Determine the required asphalt content which is based on weight of aggregate from the following relationship (5):

$$\text{Percent Asphalt} = 2.0\ (Kc) + 4.0^{a/}$$

No correction need be applied for viscosity. The asphalt content computed from the above formula would be the same regardless of the asphalt grade.

Void Capacity of Coarse Aggregate

This portion of the procedure covers the measurement of the interstitial void capacity of the coarse aggregate fraction (material retained on No. 8 sieve) of the proposed job-mix gradation. This information is obtained by conducting a vibratory unit weight determination (11). The desirable feature of this test is the high degree of densification achieved without causing a significant amount of aggregate degradation. This test provides an indication of the minimum level of interstitial voids that will exist in the friction course after long-term densification under high traffic volumes (assuming no aggregate degradation). In essence, the compactive characteristics of the coarse aggregate fraction, as affected primarily by particle sphericity and roundness, are largely responsible for determining the suitability of the proposed job-mix gradation.

4.1 Determine the vibrated unit weight and void capacity of the coarse aggregate fraction (material retained on a No. 8 sieve) of the proposed job-mix gradation by the following procedure (11).

a/ Other equations which have been used are: EOA = 1.5 (Kc) + 3.5 and EOA = 1.5 (Kc) + 4.0 by California and Colorado, respectively.

4.1.1 - Apparatus

Rammer. - A portable electromagnetic vibrating rammer as shown in Figure 3 having a frequency of 3,600 cycles a minute, suitable for use with 115-volt alternating current. The rammer shall have a tamper foot and extension as shown in Figure 4.

Mold. - A solid-wall metal cylinder with a detachable metal base plate, and a detachable metal guide-reference bar as shown in Figure 5.

Wooden base. - A plywood disc 15 inches in diameter, 2 inches thick, with a cushion of rubber hose attached to the bottom. The disc shall be constructed so it can be firmly attached to the base plate of the compaction mold.

Timer. - A stopwatch or other timing device graduated in divisions of 1.0-second and accurate to 1.0-second, and capable of timing the unit for up to 2 minutes. An electric timing device or electrical circuits to start and stop the vibratory rammer may be used.

Dial indicator. - A dial indicator graduated in 0.001-inch with a travel range of 3.0 inches.

4.1.2 - Sample

Select a 5-lb. sample of the coarse aggregate fraction from the proposed job-mix formula as verified in section 2.1.

4.1.3 - Procedure

Pour the selected sample into the compaction mold and place the tamper foot on the sample.

Place the guide-reference bar over the shaft of the tamper foot and secure the bar to the mold with the thumb screws.

Place the vibratory rammer on the shaft of the tamper foot and vibrate for 15 seconds. During the vibration period, the operator must exert just enough pressure on the hammer to maintain contact between the sample and the tamper foot.

Remove the vibratory rammer from the shaft of the tamper foot and brush any fines from the top of the tamper foot. Measure the thickness (t) of the compacted material to the nearest 0.001-inch.

Note - *The thickness (t) of the compacted sample is determined by adding the dial reading minus the thickness of the tamper foot to the measured distance from the inside bottom of the mold and the end of the dial gage when it is seated on the guide-reference bar with stem fully extended.*

4.1.4 - Calculations

Calculate the vibrated unit weight (X) as follows:

$$X = 6912\,(w)/\,\pi\,(d)^2 t \text{ (in pounds per cubic foot)}$$

Where w = weight of coarse aggregate fraction in pounds

d = diameter of compaction mold in inches

If w = 5 lb. and d = 6 inches

$$X = 305.73/t \text{ (in pounds per cubic foot)}$$

Where t is in inches

Determine the void capacity (VMA) as follows:

$$VMA = 100(1 - X/Uc) \text{ (in percent)}$$

Where Uc = bulk solid unit weight in pcf of the coarse aggregate fraction. Uc is calculated from bulk specific gravity as determined in section 2.2 multiplied by 62.4 pcf.

Optimum Content of Fine Aggregate

The optimum content of the fine aggregate fraction is that amount which can fit within the interstitial voids of the coarse aggregate fraction, while at the same time allowing a sufficient portion of the interstitial voids for the asphalt cement and for a minimum quantity of air voids. The maximum quantity of fine aggregate is limited not by absolute volume requirements, but rather by the particle-size distribution of the fine aggregate (i.e., the fine aggregate has its own interstitial void system). An implied requirement of the design method is that the interstitial void system of the coarse aggregate fraction may not be altered (made greater) by the addition of the fine aggregate fraction. This insures an internal void system with large-sized voids for water drainage purposes. An assumption is made that the above requirement will be satisfied provided that the fine aggregate fraction is limited to a maximum of 15 percent by weight of the total aggregate (refer to section 1.2). A maximum amount of fine aggregate is desirable because of the "chocking" action it imparts to the coarse aggregate particles. This is probably most important in the prevention of mixture raveling.

A minimum air void content of 15 percent is recommended for design purposes in order to insure adequate subsurface water drainage because it is this condition which gives rise to most of the desirable features of this mixture. Information supporting the criterion of 15 percent is scarce; however, it has been shown (12), that for approximately the grading shown in section 1.2, (Marshall samples compacted at 50 blows per side yielded air void contents of 15.6 percent) the resulting water intrusion capacity of the mixture when compacted to a pavement thickness of 1 inch, proved to be sufficient.

The fine aggregate content may be expressed in general terms by the following relationship on a percentage by volume basis:

Fine Aggregate Passing No. 8 Sieve = Void Capacity (VMA) Retained No. 8 Sieve

- Design Asphalt Content

- Design Void Content

+ Asphalt Absorption by Aggregate

5.1 Determine the optimum content of fine aggregate fraction with the following relationship:

$$Y = \left[[\%\ VMA\text{-}V] - [(\%\ AC)\ (X)/Ua] \right] \div \left[[(\%\ VMA\text{-}V)/100] + [(X)/Uf] \right]$$

Where: Y = Percent Passing No. 8 Sieve by Weight

X = Actual Vibrated Unit Weight of Coarse Aggregate (Retained on No. 8 Sieve)

Uf = Theoretical Bulk Dry Solid Unit Weight of Fine Aggregate (Passing No. 8 Sieve)

Ua = Unit Weight of Asphalt Cement

% AC = Percent Asphalt by Total Weight of Aggregate

= 2.0 (Kc) + 4.0

V = Design Percent Air Voids = 15.0%

% VMA = Percent Voids Mineral Aggregate of the Coarse Aggregate (retained No. 8 sieve) = 100 - (100)(X)/Uc

Uc = Theoretical Bulk Dry Solid Unit Weight of Coarse Aggregate (retained No. 8 sieve)

Note: X, Ua, Uc, Uf are in pounds/cubic foot.

In the above relationship, asphalt absorption by aggregate has been assumed to be negligible. Since asphalt absorption requirements are considered in the test for Kc (section 3.1), the estimated air voids of 15 percent in the mixture will actually be greater by an amount equivalent to the volume of asphalt absorbed, in percent. This condition, if anything, provides an additional factor of safety.

As an alternate to the use of the mathematical relationship, one may utilize the design chart shown in Figure 6 provided that the assumptions used to compute the chart are satisfied; i.e., the specific gravity values (bulk dry) for the coarse and fine aggregate fractions do not deviate beyond the limits of 2.600 to 2.700.

If the value thus obtained for fine aggregate content is greater than 15 percent, a value of 15.0 percent shall be used.

Essentially, the designer is determining whether the use of 15 percent (by weight) of fine aggregate fraction (material passing No. 8 sieve) still insures the attainment of a minimum air void content of 15 percent in the compacted mixture. If in fact this is not the case, the value for Y will be less than 15.0 percent.

5.2 Compare the optimum fine aggregate content (Y) determined under section 5.1 to the amount passing the No. 8 sieve of the contractors proposed job-mix formula. If these values differ by more than plus or minus 1 percentage point, reconstruct a revised or adjusted job-mix formula using the value determined for optimum fine aggregate content. Recompute the proportions of coarse and fine aggregates (as received) to meet the revised job-mix formula for submission to the contractor.

Note: If the proposed and revised job-mix gradations are significantly different, it may be necessary to rerun portions of this procedure.

The requirement of section 5.2 to modify the proposed job-mix gradation because of a few percentage points difference between it and the computed job-mix gradation on the No. 8 sieve may seem somewhat inconsequential from a practical standpoint. It should be realized, though, that we are dealing with a "target value concept." Normal variability in gradation during batching operations may be as much as several percentage points on any one sieve size and this can add to any initially allowed deviation, from that value required, to produce a significantly different aggregate gradation with unacceptable characteristics.

Optimum Mixing Temperature

The optimum mixing temperature is based on the concept that the aggregate should be heated so as to be reasonably dry to facilitate coating and adhesion, yet not be so hot that the viscosity of the asphalt binder is reduced to a level which facilitates drainage and segregation of the asphalt from the aggregate during transit from the mixing plant to the jobsite. The recommended target mixing temperature is in the range that will correspond to asphalt cement viscosities of 700 to 900 centistokes.

6.1 Prepare a 1000-gram sample of aggregate in the proportions determined under section 5. Mix this sample at the asphalt content determined under section 3.2 at a temperature corresponding to an asphalt viscosity of 800 centistokes determined under section 2.3. When completely coated, transfer the mixture to a pyrex glass plate (8-9-inch diameter) and spread the mixture with a minimum of manipulation. Return to the oven at the mixing temperature. Observe the bottom of the plate after 15 and 60 minutes. A slight puddle at points of contact between aggregate and glass plate is suitable and desirable. Otherwise, repeat the test at a lower mixing temperature, or higher if necessary.

Note - If asphalt drainage occurs at a mixing temperature which is too low to provide for adequate drying of the aggregate an asphalt of a higher grade should be used (AC-20 or AR-80).

The purpose of the above test is not to determine asphalt content as has been done in the past, but rather to determine the mixing temperature at which the recommended quantity of asphalt may be used.

Rather than to discard the sample prepared under section 6.1 above, a 6-inch diameter sample may be molded in the manner described in section 4.1 except that the mold and tamper foot are heated. The specimen so formed presents a rather close resemblance to the surface texture that will be achieved on the finished pavement. These samples have been used to estimate surface macrotexture of the completed pavement using the sand patch technique.

Resistance to Effects of Water

The accessibility of the interior of the open-graded asphalt friction course to water makes it important to investigate the tendency to lose strength in the presence of moisture. The criterion of strength is not believed to be as important as the criterion of retained strength.

7.1 Conduct the Immersion-Compression Test (AASHO T 165 and T 167) on the designed mixture. Prepare samples at the optimum mixing temperature determined in section 6.1. Use a molding pressure of 2000 psi rather than the specified value of 3000 psi.

After 4-day immersion at 120 F, the index of retained strength shall not be less than 50 percent unless otherwise permitted.

Note - Additives to promote adhesion that will provide adequate retained strength may be used when necessary.

Reporting Results

An example of a report form suitable for summarizing design results is given in Appendix B.

EXTENT OF USAGE

The procedure which has been outlined is relatively new. However, in the course of conducting an initial investigation, it was possible to apply the procedure to the design of "plant mix seals" which were recently constructed under the auspice of FHWA, R&D Demonstration Project 10, in the States of New Hampshire, Minnesota, Michigan, New York, and Kentucky. These after-the-fact designs compared quite well with the designs recommended by FHWA Region 15 personnel, which were based on the Colorado procedure (8). A comparison of aggregate gradation and asphalt content results is shown in Table 1. A complete listing of pertinent information obtained by this procedure is provided in Table 2. In the case of the Kentucky and the New York designs, some one-half-inch - three-eighth-inch size material was permitted. It is believed that a relatively small quantity in the range of 5-10 percent will not significantly affect the desired mixture properties and is therefore allowable. This provision would permit the more economical use of standard sizes of aggregates.

As a result of this favorable comparison, the procedure was applied to the design of mixes for a demonstration project in the State of Mississippi. This turned out to be especially challenging as three, (and later a fourth), separate job-mix designs were requested, each containing various combinations of aggregate; crushed gravel, expanded clay

Table 1. Comparison of Open-Graded Mixture Design
Materials Division - Region 15

	New Hampshire	Minnesota	Michigan	Kentucky	New York
MATERIALS DIVISION					
Gradation, % Passing					
1/2"	100	100	100	100	100
3/8"	100	100	100	98	83
# 4	42	39	40	39	43
# 8	15	15	15	10	15
#200	2.6	3.6	3.4	3.5	3.0
Asphalt, % Agg. Basis	7.00	7.20	6.40	6.50	6.60
REGION 15					
Gradation, % Passing					
1/2"	100	100	100	100	100
3/8"	100	100	100	98	83
# 4	42	35	35	39	42
# 8	15	10	8	10	14
#200	2.6	3.2	2.4	2.0	3.0
Asphalt, % Agg. Basis	6.61	6.95	7.07	6.38	7.18

Table 2. Summary of Design - R&D Demonstration Projects and Federal Aid Projects

State	New Hampshire	Minnesota	Michigan	Kentucky	New York
Aggregate Proportions	95% Traprock 5% Natural Sand	98% Traprock 2% Filler	98% Crushed Stone 2% Filler	98% Crushed Gravel 2% Filler	98% Limestone[a/] 2% Filler
Job-Mix Gradation					
% Passing 1/2-in.	100	100	100	100	100
3/8-in.	100	100	100	98	83
No. 4	42	39	40	39	43
No. 8	15	15	15	10	15
No. 200	2.6	3.6	3.4	3.5	3.0
Asphalt Content (%)					
Mix Basis	6.5	6.7	6.0	6.1	6.2
Agg. Basis	7.0	7.2	6.4	6.5	6.6
Asphalt Grade	AC-10	85/100	85/100	AC-20	AC-10
Design Air Voids (%)	16.8	16.5	18.7	15.6	15.8
Mixing Temperature (F)	245	230	230	230	245
Retained Strength (%)	36	89	64	97[b/]	77
Compressive Strength[c/]					
Air Cured (psi)	120	133	131	143	138

a/ 46% insoluble material (+ #200 sieve).
b/ Value was 0% without antistripping agent.
c/ These results included for information purposes only.

Table 2. Summary of Design - R&D Demonstration Projects and Federal Aid Projects (continued)

State	Miss. #1	Miss. #2	Miss. #3	Miss. #4	Ohio
Aggregate Proportions	50% Crushed Gravel 49% Slag 1% Filler	59% Crushed Gravel 39% Expanded Clay 2% Filler	99% Slag 1% Filler	98% Crushed Gravel 2% Filler	99% Slag 1% Filler
Job-Mix Gradation					
% Passing 1/2-in.	100	100	100	100	100
3/8-in.	100	100	100	100	94
No. 4	41	44	39	44	45
No. 8	15	15	15.8	15	15
No. 200	2.1	2.4	2.7	2.3	2.6
Asphalt Content (%)					
Mix Basis	6.8	7.8	7.3	6.2	8.0
Agg. Basis	7.2	8.5	7.9	6.6	8.7
Asphalt Grade	AC-20	AC-20	AC-20	AC-20	AC-20
Design Air Voids (%)	17.2	17.8 d/	17.1	15.0	16.4
Mixing Temperature (F)	255	255	255	255	250
Retained Strength (%)	95	59	100	80	76
Compressive Strength c/ Air Cured (psi)	148	135	209	104	359

c/ These results included for information purposes only.
d/ Includes effect of asphalt absorption by aggregate.

(synthetic aggregate), and slag (phosphate type). A summary of results is provided in Table 2. Mixture designs 1, 2, and 3 were successfully placed in October 1973; however, it is too early to draw any conclusions regarding performance, although provisions have been made for future evaluations.

An additional design was provided to the State of Ohio and is also summarized in Table 2. The Ohio mixture is to be placed early in 1974.

CONCLUSIONS

The authors believe that the design procedure described in the preceding paragraphs is a substantial technological improvement over other existing methods used to design open-graded asphalt mixtures. This opinion is based on several considerations.

First is the simplification of the usual process required to select asphalt content. Although the value determined is still based largely on field experience, asphalt requirements are desirably dependent on the effects caused by using different types of aggregate materials (refer to the determination of Kc, section 3.1). Furthermore, the relationship used to compute asphalt content (refer to section 3.2) seems to provide for as high an asphalt content as used anywhere in practice. The use of this relatively large amount of asphalt is facilitated by requiring and providing for adjustments in mixing temperature and grade of asphalt cement, if necessary.

Second is the provision for the investigation of the compaction characteristics of the coarse aggregate. This step verifies whether adequate space is available in the composite structure for the required amount of asphalt, air voids, and a sufficient, but limited quantity of fine aggregate. Essentially, the properties and characteristics of the aggregate to be used dictate how the aggregate shall be graded (within limits) in order that the desired mixture characteristics are achieved.

Third is the knowledge that the application of this procedure would have averted the use of a mix design that was responsible for a rather extensive incidence of asphalt flushing of an open-graded plant mix seal coat placed in the Washington, D. C. area in 1969. Evaluation of the actual mix design by the proposed procedure indicates that insufficient void space was available in the coarse aggregate for the quantities of fine aggregate and asphalt cement that were used.

Further improvements in the procedure are contemplated as results of current research efforts become available. However, the procedure in its present form is recommended for immediate experimental application.

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APPENDIX A

DESIGN PROCEDURE

Material Requirements

1.1 It is recommended that relatively pure carbonate aggregates or any aggregates known to polish be excluded from the coarse aggregate fraction (material retained on No. 8 sieve). In addition, the coarse aggregate fraction should have at least 75 percent by weight of particles with at least two fractured faces and 90 percent with one or more fractured faces. The abrasion loss (AASHO T 96) should not exceed 40 percent.

1.2 Recommended Gradation for Open-Graded Asphalt Friction Course.

Sieve Size[a/]	Percent Passing[b/]
3/8"	100
#4	30-50
#8	5-15
#200	2-5

a/ U. S. Sieve Series
b/ By weight

1.3 The recommended grade of asphalt cement is AC-10 or AR-40, AASHO M 226-73 I. For AC-10, Table 2 requirements should apply where such asphalt is available. AR-40 requirements are given in Table 3.

Preliminary Data

2.1 Test coarse and fine aggregates as received for the project for gradation unless otherwise provided. If mineral filler is submitted as a separate item it should also be tested for specification compliance. Analyze gradation results to determine if proportions of aggregates and batching operations proposed by the contractor will meet his job-mix formula and the specification limits of section 1.2.

2.2 Determine bulk and apparent specific gravity for the coarse and fine aggregate fractions (retained and passing No. 8 sieve) for each type of material submitted. Additional specific gravity tests are not warranted where the only distinction between aggregates is size of grading. Utilizing the information verified in section 2.1, mathematically compute the bulk and apparent specific gravity for the coarse and fine aggregate fractions (retained and passing No. 8 sieve) for the proposed job-mix gradation.

2.3 Test the asphalt cement to be used for specification compliance (AASHO M 226-73 I), viscosity-temperature data, and specific gravity at 77.0 F.

Asphalt Content

3.1 Determine the surface capacity of the aggregate fraction that is retained on a No. 4 sieve in accordance with the following procedure (10):

Kc is determined from the percent of S. A. E. No. 10 oil retained, which represents the total effect of superficial area, the aggregate's absorptive properties and surface roughness.

3.1.1 Quarter out 105 g. representative of the passing three-eighth-inch and retained No. 4 sieve material.

3.1.2 Dry sample on hot plate or in 230 ± 9 F oven to constant weight and allow to cool.

3.1.3 Weigh out 100.0 g. and place in a metal funnel (top diameter 3-1/2 inches, height 4-1/2 inches, orifice one-half-inch with a piece of No. 10 sieve soldered to the bottom of the opening).

3.1.4 Completely immerse specimen in S. A. E. No. 10 lubricating oil for 5 minutes.

3.1.5 Drain for 2 minutes.

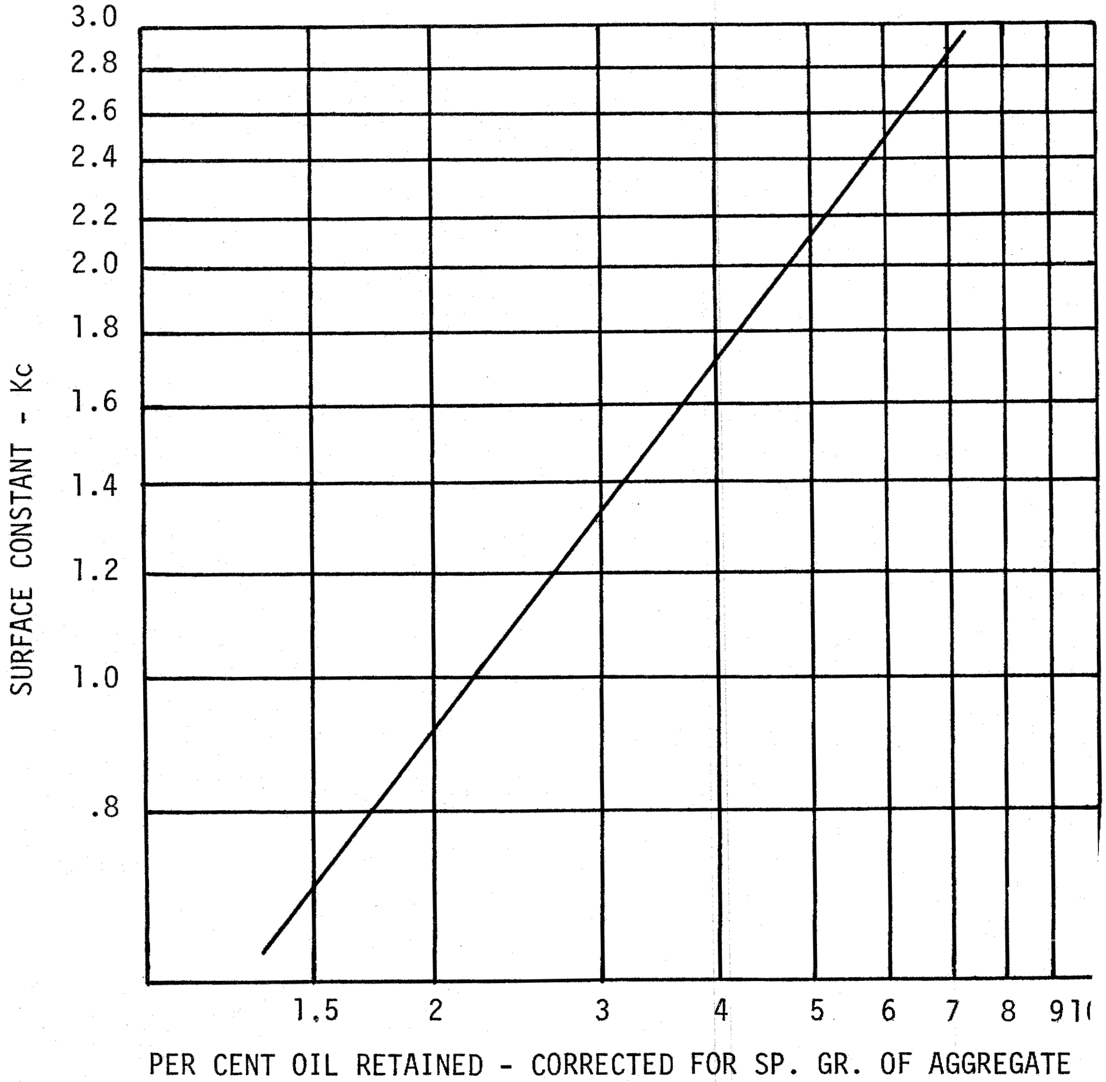
3.1.6 Place funnel containing sample in 140 F oven for 15 minutes of additional draining.

3.1.7 Pour sample from funnel into tared pan; cool, and reweigh sample to nearest 0.1 g. Subtract original weight and record difference as percent oil retained (based on 100 g. of dry aggregate).

3.1.8 Use chart shown in Figure 2 for determination of "Kc."

(1) If specific gravity for the fraction is greater than 2.70 or less than 2.60, apply correction to oil retained, using formula at bottom of chart in Figure 2.

(2) Start at the bottom of chart in Figure 2 with the corrected percent of oil retained; follow straightedge vertically upward to intersection with the diagonal line; hold point, and follow the straightedge horizontally to the left. The value obtained will be the surface constant for the retained fraction and is known as "Kc."



Material Used: Aggregate - Passing 3/8", Ret. No. 4 Sieve
Oil - SAE 10

Oil Retained Corrected (%) = Oil Retained (%) x $\frac{\text{"apparent" sp. gr. of Coarse Aggregate}}{2.65}$

igure 2. Chart for Determining Surface Capacity (Kc) of Coarse Aggregate (from Reference 10)

3.2 Determine the required asphalt content which is based on weight of aggregate from the following relationship (5):

Percent Asphalt = 2.0 (Kc) + 4.0[a/]

No correction need be applied for viscosity. The asphalt content computed from the above formula would be the same regardless of the asphalt grade.

Void Capacity of Coarse Aggregate

4.1 Determine the vibrated unit weight and void capacity of the coarse aggregate fraction (material retained on a No. 8 sieve) of the proposed job-mix gradation by the following procedure (11).

4.1.1 - Apparatus

Rammer. - A portable electromagnetic vibrating rammer as shown in Figure 3, having a frequency of 3,600 cycles a minute, suitable for use with 115-volt alternating current. The rammer shall have a tamper foot and extension as shown in Figure 4.

Mold. - A solid-wall metal cylinder with a detachable metal base plate, and a detachable metal guide-reference bar as shown in Figure 5.

Wooden Base. - A plywood disc 15 inches in diameter, 2 inches thick, with a cushion of rubber hose attached to the bottom. The disc shall be constructed so it can be firmly attached to the base plate of the compaction mold.

Timer. - A stopwatch or other timing device graduated in divisions of 1.0-second and accurate to 1.0-second, and capable of timing the unit for up to 2 minutes. An electric timing device or electrical circuits to start and stop the vibratory rammer may be used.

Dial Indicator. - A dial indicator graduated in 0.001-inch with a travel range of 3.0 inches.

4.1.2 - Sample

Select a 5-lb. sample of the coarse aggregate fraction from the proposed job-mix formula as verified in section 2.1.

4.1.3 - Procedure

Pour the selected sample into the compaction mold and place the tamper foot on the sample.

a/ Other equations which have been used are: EOA = 1.5 (Kc) + 3.5 and EOA = 1.5 (Kc) + 4.0 by California and Colorado, respectively.

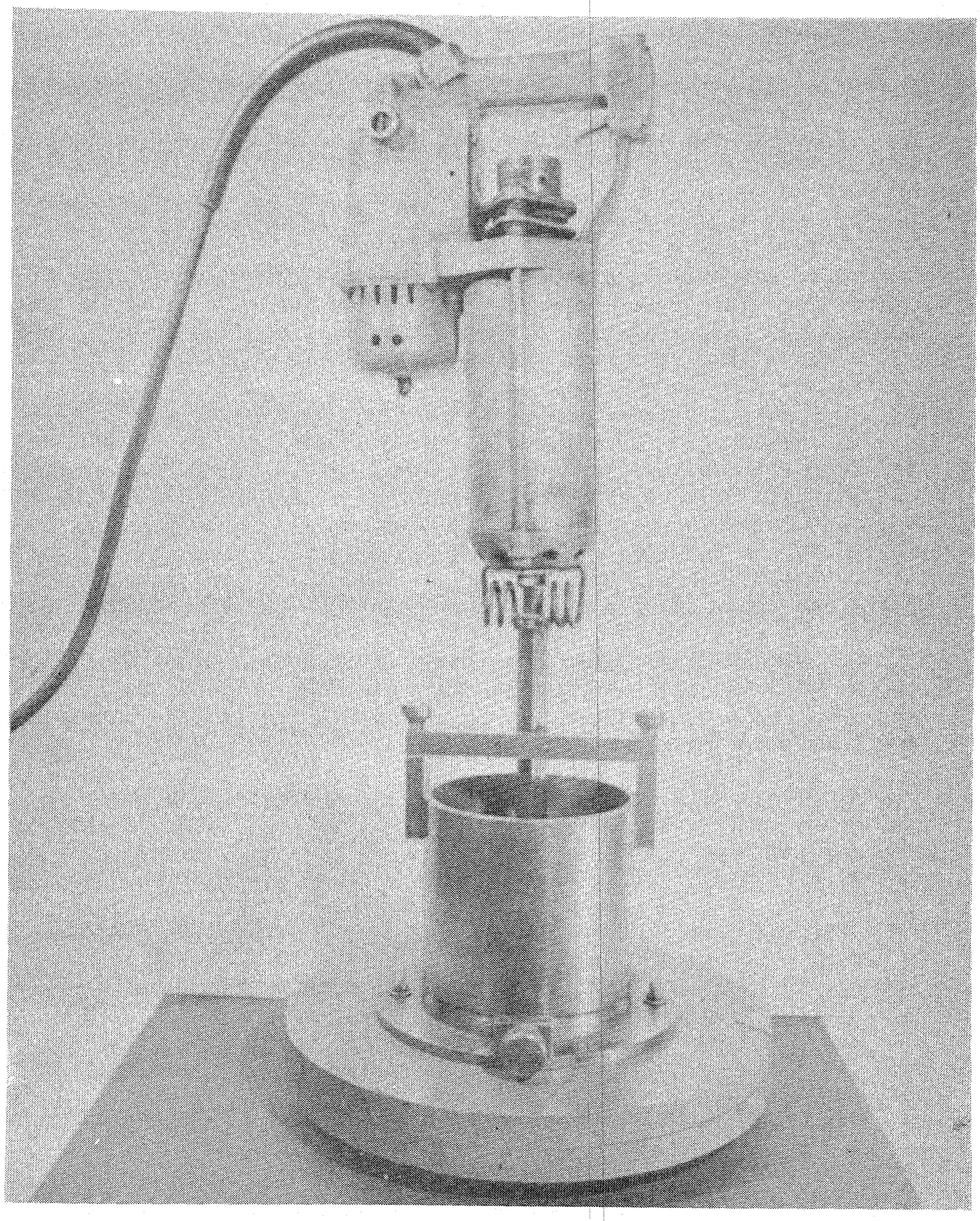


Figure 3. FHWA Vibratory Compaction Apparatus (from Reference 11)

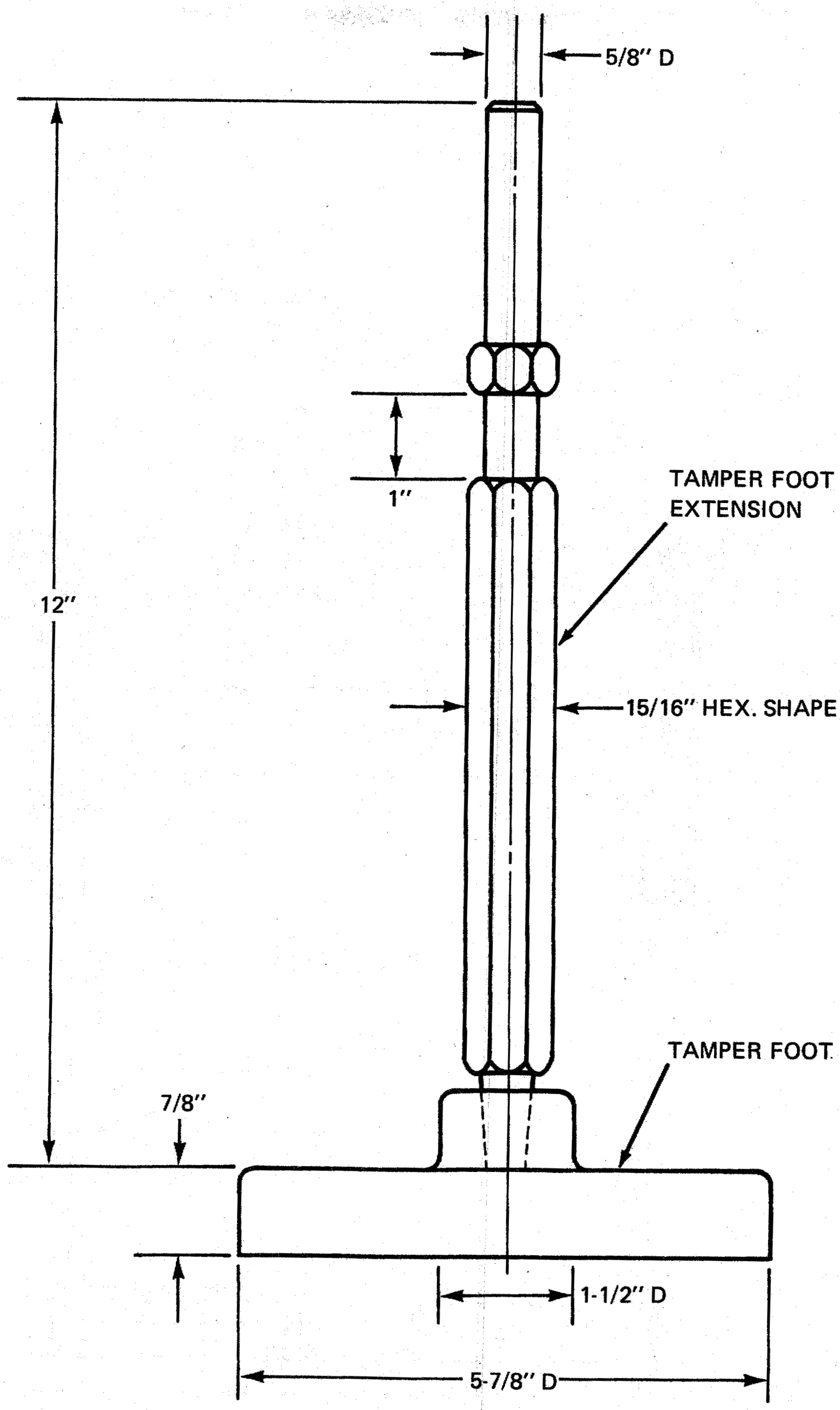


Figure 4. Tamper Foot and Extension (from Reference 11)

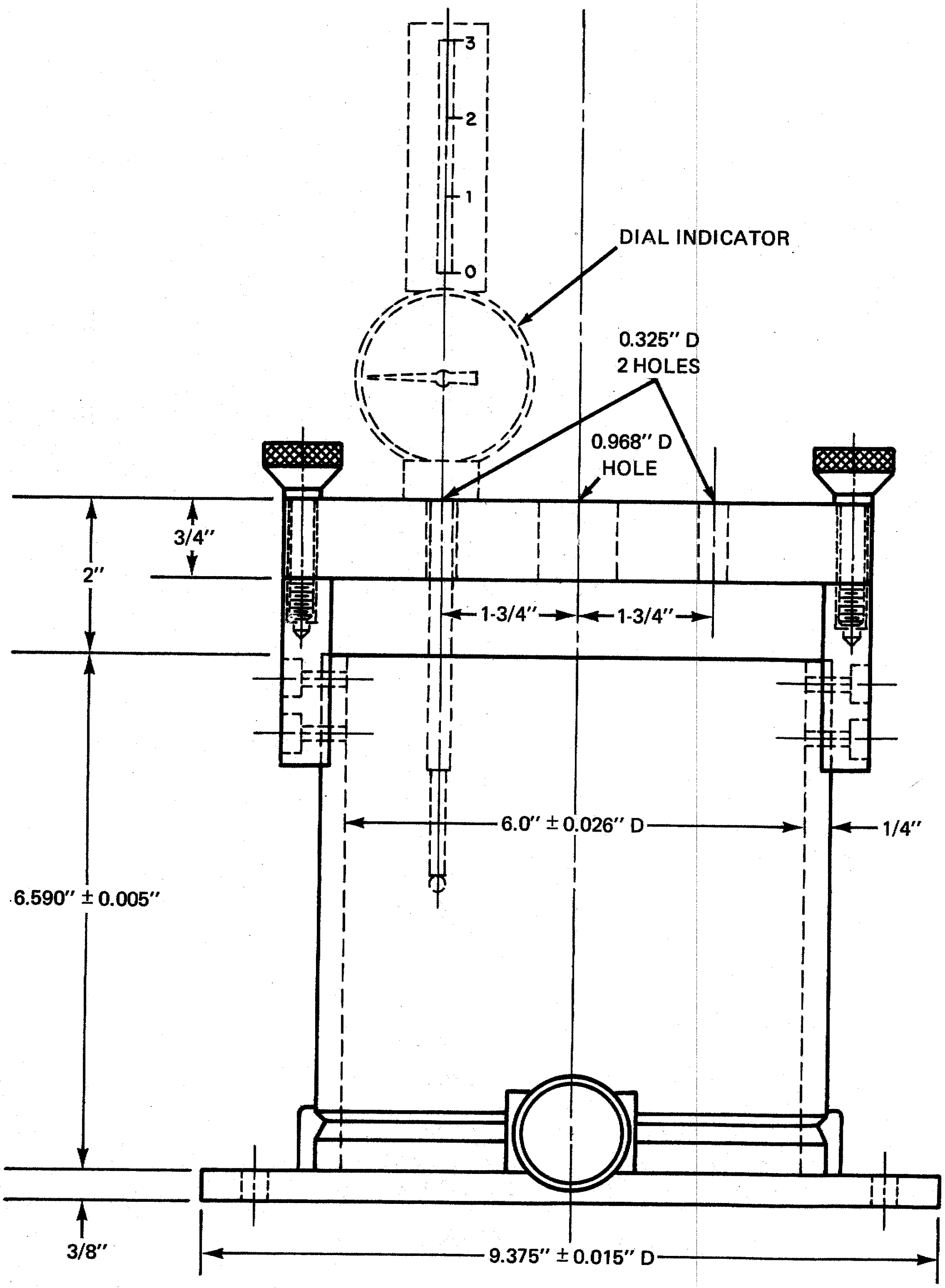


Figure 5. Cylindrical Mold for Testing Granular Materials (from Reference 11)

Place the guide-reference bar over the shaft of the tamper foot and secure the bar to the mold with the thumb screws.

Place the vibratory rammer on the shaft of the tamper foot and vibrate for 15 seconds. During the vibration period, the operator must exert just enough pressure on the hammer to maintain contact between the sample and the tamper foot.

Remove the vibratory rammer from the shaft of the tamper foot and brush any fines from the top of the tamper foot. Measure the thickness (t) of the compacted material to the nearest 0.001-inch.

Note - The thickness (t) of the compacted sample is determined by adding the dial reading minus the thickness of the tamper foot to the measured distance from the inside bottom of the mold and the end of the dial gage when it is seated on the guide-reference bar with stem fully extended.

4.1.4 - Calculations

Calculate the vibrated unit weight (X) as follows:

$X = 6912(w)/\pi(d)^2t$ (in pounds per cubic feet)

Where w = weight of coarse aggregate fraction in pounds

d = diameter of compaction mold in inches

if w = 5 lb. and d = 6 inches

$X = 305.73/t$ (in pounds per cubic foot)

where t is in inches

Determine the void capacity (VMA) as follows:

$VMA = 100(1 - X/Uc)$ (in percent)

where Uc = bulk solid unit weight in pcf of the coarse aggregate fraction. Uc is calculated from bulk specific gravity as determined in section 2.2 multiplied by 62.4 pcf.

Optimum Content of Fine Aggregate

5.1 Determine the optimum content of fine aggregate fraction with the following relationship:

$$Y = \left[[\%\ VMA - V] - [(\%\ AC)\ (X)/Ua] \right] \div \left[[(\%\ VMA - V)/100] + [(X)/Uf] \right]$$

Where; Y = Percent Passing No. 8 Sieve by Weight

X = Actual vibrated unit weight of coarse aggregate (retained No. 8 sieve)

Uf = Theoretical bulk dry solid unit weight of fine aggregate (passing No. 8 sieve)

Ua = Unit weight of asphalt cement

% AC = Percent asphalt by total weight of aggregate = 2.0 (Kc) + 4.0

V = Design percent air voids = 15.0%

% VMA = Percent voids mineral aggregate of the coarse aggregate (retained No. 8 sieve) = 100 -(100)(X)/Uc

Uc = Theoretical bulk dry solid unit weight of coarse aggregate (retained No. 8 sieve)

Note - X, Ua, Uc, Uf are in pounds/cubic foot.

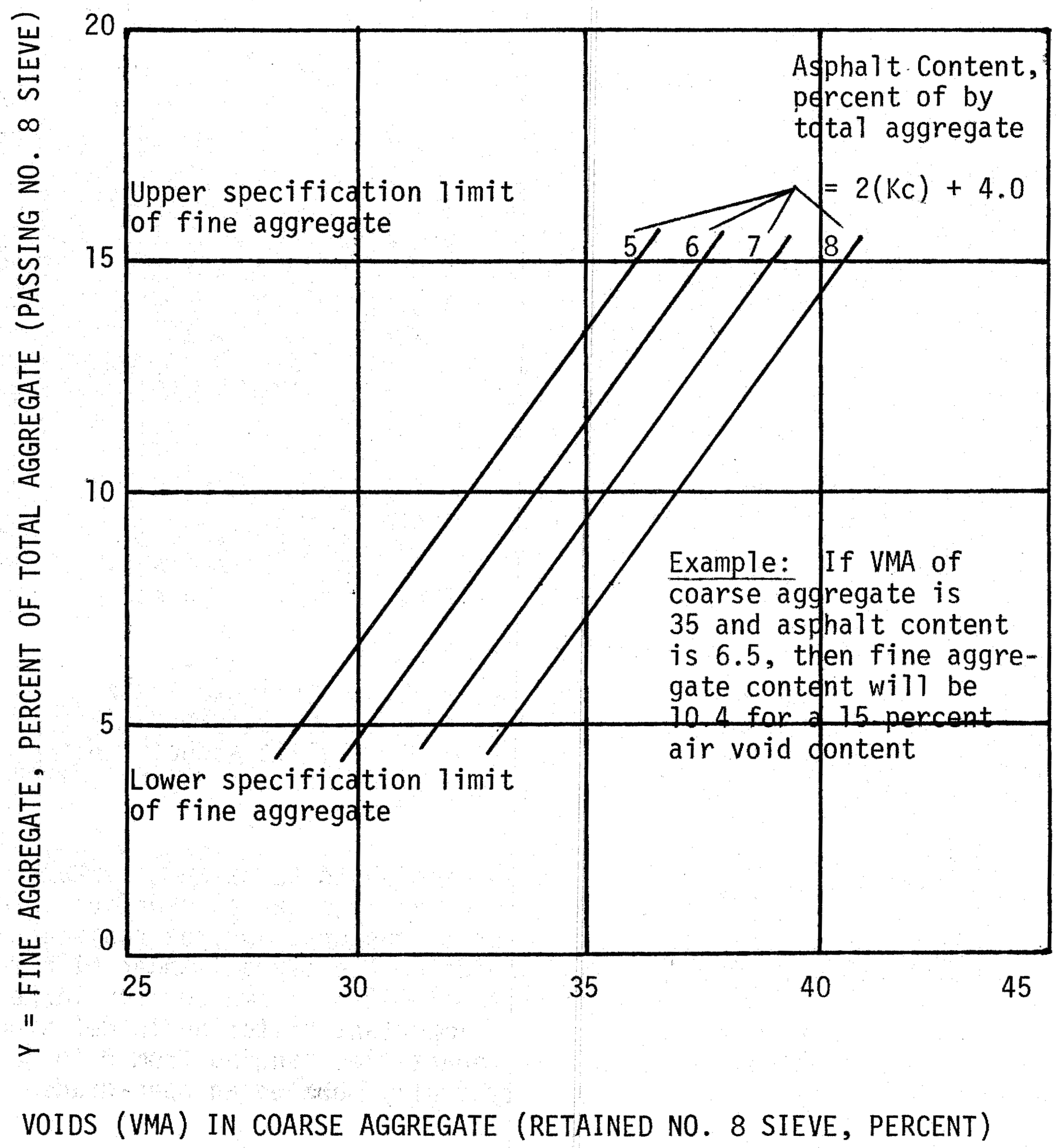
In the above relationship, asphalt absorption by aggregate has been assumed to be negligible. Since asphalt absorption requirements are considered in the test for Kc (section 3.1), the estimated air voids of 15 percent in the mixture will actually be greater by an amount equivalent to the volume of asphalt absorbed, in percent. This condition, if anything, provides an additional factor of safety.

As an alternate to the use of the mathematical relationship, one may utilize the design chart shown in Figure 6 provided that the assumptions used to compute the chart are satisfied; i.e., the specific gravity values (bulk dry) for the coarse and fine aggregate fractions do not deviate beyond the limits of 2.600 to 2.700.

If the value thus obtained for fine aggregate content is greater than 15 percent, a value of 15.0 percent shall be used.

5.2 Compare the optimum fine aggregate content (Y) determined under section 5.1 to the amount passing the No. 8 sieve of the contractor's proposed job-mix formula. If these values differ by more than plus or minus 1 percentage point, reconstruct a revised or adjusted job-mix formula using the value determined for optimum fine aggregate content. Recompute the proportions of coarse and fine aggregates (as received) to meet the revised job-mix formula for submission to the contractor.

Note - If the proposed and revised job-mix gradations are significantly different, it may be necessary to rerun portions of this procedure.



<u>Assumptions Used in Deriving Chart:</u>

Uc = 165.4 pcf (sp. gr. = 2.650)
Uf = 165.4 pcf (sp. gr. = 2.650)
Ua = 62.4 pcf (sp. gr. = 1.000)
V = 15.0 percent

Figure 6. Determination of Optimum Fine Aggregate Content

Optimum Mixing Temperature

6.1 Prepare a 1000 gram-sample of aggregate in the proportions determined under section 5. Mix this sample at the asphalt content determined under section 3.2 at a temperature corresponding to an asphalt viscosity of 800 centistokes determined under section 2.3. When completely coated, transfer the mixture to a pyrex glass plate (8-9-in. diameter) and spread the mixture with a minimum of manipulation. Return to the oven at the mixing temperature. Observe the bottom of the plate after 15 and 60 minutes. A slight puddle at points of contact between aggregate and glass plate is suitable and desirable. Otherwise, repeat the test at a lower mixing temperature, or higher if necessary.

Note - If asphalt drainage occurs at a mixing temperature which is too low to provide for adequate drying of the aggregate, an asphalt of a higher grade should be used (AC-20 or AR-80).

Resistance to Effects of Water

7.1 Conduct the Immersion-Compression Test (AASHO T 165 and T 167) on the designed mixture. Prepare samples at the optimum mixing temperature determined in section 6.1. Use a molding pressure of 2000 psi rather than the specified value of 3000 psi.

After 4-day immersion at 120 F, the index of retained strength shall not be less than 50 percent unless otherwise permitted.

Note - Additives to promote adhesion that will provide adequate retained strength may be used when necessary.

APPENDIX B

DESIGN REPORT

REPORT ON OPEN GRADED ASPHALT FRICTION COURSE DESIGN

1. AGGREGATES:

A. Proposed Proportions (by weight)

B. Proposed Job-Mix Gradation:

Sieve Size	Specification Limits	Percent Passing			Job-Mix Blend
1/2"					
3/8"	100				
# 4	30 - 50				
# 8	5 - 15				
#16					
#200	2 - 5				

C. Specific Gravity - Unit Weight

	Apparent Sp. Gr.	Bulk Sp. Gr. Dry Basis	Bulk Solid Unit Weight PCF
Coarse Aggregate (Retained No. 8 Sieve)			
Fine Aggregate (Passing No. 8 Sieve)			
3/8" - # 4 Sieve Fraction			

D. Void Capacity of Coarse Aggregate

Unit Weight (Vibrated, PCF) = ____________

Voids Mineral Aggregate (VMA, %) = ____________

E. K_c Determination

Oil Retention (g oil per 100g Aggregate) = ____________

Oil Retention (corrected, 2.65 Sp. Gr.) = ____________

K_c (from chart) = ____________

2. ASPHALT

A. Specific Gravity - Unit Weight

Specific Gravity @ 77.0° F. = ____________

Unit Weight - PCF = ____________

B. Viscosity - Temperature

Asphalt Grade = ____________

Temperature - °F.	Viscosity - CS.
290	________
275	________
260	________
245	________
230	________
215	________
Target: (-)	(700 - 900)

C. <u>Asphalt Content (AC, %)</u>

$AC = 2K_c + 4.0$

AC (Aggregate Basis) = ____________

3. <u>MIXTURE DESIGN</u>

A. <u>Optimum Fine Aggregate Content (Y)</u>

Using: Formula ____________ Chart ____________

Where: X = __________PCF VMA = ____________%

U_f = __________PCF AC = ____________%

U_c = __________PCF V = ____________%

U_a = __________PCF

Find: Y = __________ % (Specs. Limit 5 < Y < 15)

Remarks:

B. <u>Optimum Mixing Temperature</u>

Temperature - °F.	Viscosity - CS.	Drainage	Use
________	________	________	___
________	________	________	___
________	________	________	___

C. Maximum Specific Gravity of Mixture (AASHO T 209)

Specific Gravity (Vacuum Saturation) = ____________

Unit Weight (Vacuum Saturation) = __________PCF

D. Resistance to Effects of Water (AASHO T 165 & T 167, 2000 psi)

Air Dry Strength (psi) = ____________

Wet Strength (psi) = ____________ 4 Days @ 120 F.

Retained Strength (%) = ____________ 50 % Minimum

Air Voids (%) = ____________ Bulk Volume by Dimensional Measurement

Remarks:

E. Other Misc. Tests

Vibrated Asphalt Mixture - 6" Diameter, _____" Height

Air Voids (%) = __________ Bulk Volume by Dimensional Measurement

Sand Patch (in.) = ____________

4. DESIGN SUMMARY

A. Aggregate Proportions (by Weight)

B. Job-Mix Gradation

Percent Passing	
Sieve Size	Job-Mix Blend
1/2"	________
3/8"	________
# 4	________
# 8	________
# 16	________
#200	________

C. Asphalt Content

Aggregate Basis (%) = __________

Mixture Basis (%) = __________

D. Mixing Temperature

Target Value (F) = __________

Range = __________

E. Additives

F. Recommendations

Accepted _____ Rejected ________

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