Chapter 4

Flexible Pavement

CHAPTER 4

FLEXIBLE PAVEMENT

4.1 TA 5040.27, Asphalt Concrete Mix Design and Field Control, February 16, 1988.

4.2 Prevention of Premature Distress in Asphalt Concrete Pavements, Technical Paper 88-02, April 18, 1988.

4.3 Guidelines on the Use of Bag-House Fines, April 7, 1988.

4.4 Reserved.

4.5 State of the Practice on the Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier, Report Number FHWA-SA-92-022, June 9, 1992.

4.6 Reserved.

4.7 Processed Used-Oil and Heavy Fuel Oils for Use in Hot Mix Asphalt Production, June 21, 1990.

4.8 Aggregate Gradation for Highways - 0.45 Particle Size Distribution Curve, 1962.

- Aggregate Gradation: Simplification, Standardization, and Uniform Application
- A New Graphical Chart for Evaluating Aggregate Gradation

U.S. Department
of Transportation

**Federal Highway
Administration**

Memorandum

Washington, D.C. 20590

Subject: ACTION:
Asphalt Mix Design and Field Control

Date: February 16, 1988

From: Executive Director

Reply to
Attn of: HHO-12
HHO-30

To: Regional Federal Highway Administrators
Direct Federal Program Administrator

There are presently about 1,420,000 miles of intermediate or high type flexible pavements on State highways and local roads. This represents about 70 percent of the paved mileage on all public roads and streets. In 1986, about $2 billion of asphalt concrete was placed on Federal-aid projects and this amount will likely increase in the future. Information that has been gathered over a number of years by the States, FHWA, and the asphalt industry has revealed that a number of asphalt concrete pavements are experiencing premature distress and significantly reduced pavement performance periods. Types of distress identified have included bleeding, cracking, shoving, rutting, stripping, and raveling.

Two distress types, rutting and stripping, have had a high frequency of occurrence over wide areas of the United States. The reduction in pavement performance due to rutting or stripping is potentially severe from a national perspective. Due to the continuing major investment which is being made in asphalt concrete pavements and as a result of reports indicating premature rutting and stripping problems, we appointed an Ad Hoc Task Force to examine the problems of asphalt concrete pavement rutting and stripping, and to develop FHWA policy recommendations. The Task Force has completed its assignment and a copy of its report was provided to each region and division office.
In accordance with one of the Task Force's major recommendations, our Technical Advisory (TA) on this subject has been updated to reflect current knowledge. Attached for your immediate use is a copy of the TA "Asphalt Concrete Mix Design and Field Control." This TA sets forth guidance and recommendations relating to asphalt concrete paving. It covers the areas of materials selection, mixture design, mixture production, and mixture placement. The TA is intended primarily for application on high type facilities.

Each division office is to initiate an effort to compare the updated TA to present State specifications and construction practices. Differences and/or deviations are to be discussed with the State and, if appropriate, industry representatives. Some States have found it beneficial to have a formal committee composed of State, FHWA, and industry personnel to scrutinize the State's mix design, and field control procedures, and iron out differences with the TA. The TA is a consensus of current best practice, and serious consideration should be given to adopting its recommendations. Sound engineering judgment must be used in determining what is best for each particular State but deviations from the TA recommendations should be supportable.

We recognize that some States have been working in strengthening their asphalt concrete mix design and field control practices. These efforts are appropriate and continued involvement of all the field offices in encouraging conformance with the attached TA will be expected.

Other factors such as truck weights, high tire pressures, etc., also contribute to the rutting and stripping problems and we are working on these issues. We are convinced though that significant gains in solving rutting and stripping problems can be achieved by using quality materials and strengthening specifications and construction practices. We expect those States where rutting and stripping is a problem to include a priority effort to improve the design and construction of asphalt concrete pavements. The Pavement Division and the Construction and Maintenance Division are available upon request to provide technical support and guidance, which may be necessary in achieving these actions.

R. D. Morgan
Executive Director

Attachment

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

SUBJECT	FHWA TECHNICAL ADVISORY
ASPHALT CONCRETE MIX DESIGN AND FIELD CONTROL	T 5040.27 March 10, 1988

1. PURPOSE. To set forth guidance and recommendations relating to asphalt concrete paving, covering the areas of materials selection, mixture design, and mixture production and placement. The procedures and practices outlined in the Technical Advisory (TA) are directed primarily towards developing quality asphalt concrete pavements for high-type facilities. The TA can also be used as a general guide for low-volume facilities.

2. Cancellation. Federal Highway Administration (FHWA) Technical Advisory T 5040.24, Bituminous Mix Design and Field Control, dated August 22, 1985, is cancelled.

3. BACKGROUND

a. Over one-half of the Interstate System and 70 percent of all highways are paved with hot-mix asphalt concrete. Asphalt concrete is probably the largest single highway program investment today and there is no evidence that this will change in the near future. However, there is evidence that the number of premature distresses in the nation's recently constructed asphalt pavements is increasing. Heavier truck axle weights, increased tire pressures, and inadequate drainage are some of the factors leading to the increase in premature distress. The FHWA has been concerned with the deterioration in quality of asphalt concrete pavements for many years and in 1987 a special FHWA Ad Hoc Task Force studied two of the most common distresses existing today and subsequently issued a report titled "Asphalt Pavement Rutting and Stripping." The report contained both short-term and long-term recommendations for improving the quality of asphalt pavements.

b. With the variables of environment, component materials, and traffic loadings found throughout the United States, it is not surprising that there are many State-to-State or regional variations of design and construction requirements. No one set of specifications can achieve the same results in all States because of the factors mentioned above. However, there are many things that States can do to improve their current mix design and field control procedures to ensure that quality asphalt pavements will be constructed. This TA incorporates many of the FHWA Task Force recommendations and presents the current

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Level 3: SHA's(Through Divisions)
OPI: HHO-12 HHO-33

state-of-the-art in materials, mix design, plant operation, laydown and compaction, and other areas relating to quality hot-mix asphalt pavements.

4. MATERIALS

a. Aggregate is the granular material used in asphalt concrete mixtures which make up 90-95 percent of the mixture weight and provides most of the load bearing characteristics of the mix. Therefore, the quality and physical properties of the aggregates are critical to the pavement performance. The following is recommended:

(1) Aggregates should be non-plastic. The presence of clay fines in an asphalt mix can result in problems with volume swell and adhesion of asphalt to the rock contributing to stripping problems. The minus #4 sieve material should have a minimum sand equivalent value of 45 using the test method described in the American Association of State Highway and Transportation Officials (AASHTO) specification (AASHTO T176).

(2) A limit should be placed on the amounts of deleterious materials permitted in the aggregates. Specifications should limit clay lumps and friable particles to a maximum of one percent.

(3) Durability or weathering resistance should be determined by sulfate soundness testing. Specifications should require a sodium or magnesium sulfate test using the limits described in the AASHTO specification M29.

(4) Aggregate resistance to abrasion should be determined. Specifications should require a Los Angeles abrasion loss of 45 percent or less (AASHTO T96).

(5) Friction between aggregate particles is dependent on aggregate surface roughness and area of contact. As surface friction increases, so does resistance of the mix to deformation. Specifications should require at least 60 percent of the plus #4 sieve material to have at least two mechanically induced fractured faces.

(6) The quality of natural sand varies considerably from one location to another. Since most natural sands are rounded and often contain a high percentage of undesirable materials, the amount of natural sand as a general rule should be limited to 15 to 20 percent for high volume pavements and 20 to 25 percent for medium and low volume pavements. These percentages may increase or decrease depending on quality of the natural sand and the types of traffic to which the pavement will be subjected.

(7) For adequate control, aggregate gradations should be specified from the maximum particle size to the #200 sieve so each successive sieve opening is about 1/2 the previous sieve opening (for example, 1 inch, 1/2 inch, #4, #8, #16, #30, #50, #100, #200). The only accurate method to determine the amount of minus #200 sieve material is to perform a wash gradation in accordance with AASHTO T27 and AASHTO T11.

(8) The ratio of dust (minus #200 sieve material) to asphalt cement, by mass, is critical. Asphalt concrete mixes should require a maximum dust asphalt ratio of 1.2 and a minimum of 0.6.

(9) A tool which is very useful in evaluating aggregate gradations is the 0.45 power gradation chart. All mixes should be plotted on these charts as part of the mix design process (Attachment 1).

(10) An aggregate's specific gravity and absorption characteristics are extremely important in proportioning and controlling the mixture. It is recommended that AASHTO T209 be used to determine the maximum specific gravity of asphalt concrete mixes. States not using AASHTO T209 should be aware of the difficulty of determining the theoretical maximum density using individual ingredient specific gravities and their percentages in the mixture. These difficulties will result in inaccuracies in determining the specific gravity of the mixture. These inaccuracies will carry through to the calculation of the densities in the compacted mat and may result in improperly compacted pavements. It is also necessary to determine the bulk dry specific gravity of the aggregate in order to determine the voids in the mineral aggregate (VMA).

The target value for VMA should be obtained through the proper distribution of aggregate gradation to provide adequate asphalt film thickness on each particle and accommodate the design air void system. In addition, tolerance used in construction quality control should be such that the mix designed is actually produced in the field.

b. Asphalt grade and characteristics are critical to the performance of the asphalt pavement. The following is recommended:

(1) Grade(s) of asphalt cement used in hot-mix paving should be selected based on climatic conditions and past performance.

(2) It is recommended that asphalt cement be accepted on certification by the supplier (along with the testing results) and State project verification samples. Acceptance procedures should provide information on the physical properties of the asphalt in a timely manner.

(3) The physical properties of asphalt cement that are most important to hot-mix paving are shown below. Each State should obtain this information (by central laboratory or supplier tests) and should have specification requirement(s) for each property except specific gravity.

(a) Penetration 77° F

(b) Viscosity 140° F

(c) Viscosity 275° F

(d) Ductility/Temperature

(e) Specific Gravity

(f) Solubility

(g) Thin Film Oven (TFO)/Rolling TFO; Loss on Heating

(h) Residue Ductility

(i) Residue Viscosity

(j) Low temperature cracking is related to the physical properties of the asphalt and may be increased by the presence of wax in the asphalt. The low temperature ductility test at 39.2° F (4° C) can indicate where this may be a problem. The test is performed at a pull speed of 1 cm/min. Typical specification requirements are:

AASHTO M226	Table 2
AC 2.5	50 + cm
AC 5	25 + cm
AC 10	15 + cm
AC 20	5 + cm

(4) The temperature viscosity curves or absolute and kinematic viscosity information should be available at the mixing plant for each shipment of asphalt cement. This can identify a change in asphalt viscosity which necessitates a new mix design. Each State should provide temperature/viscosity information on the asphalt used in the laboratory mix design to the projects. Differences in the viscosity (as well as the penetration) of the asphalt from the asphalt used in the mix design may indicate the necessity to redesign the mix (Attachment 2).

5. MIX DESIGN

a. Asphalt concrete mixes should be designed to meet the necessary criteria based on type of roadway, traffic volumes, intended use, i.e., overlay on rigid or flexible pavements, and the season of the year the construction would be performed. Each State's mix design criteria should be as follows.

Property	Heavy Traffic Design (>1,000,000 ESAL*)	Medium Traffic Design (10,000-1,000,000 ESAL)	Light Traffic Design (<10,000 ESAL)
Marshall			
Compaction Blows	75	50	35
Stability (min.)	1,500	750	500
Flow	8-16	8-18	8-20
Hveem			
Stability (min.)	37	35	30
Swell	0.030 in.	0.030 in.	0.030 in.
Void Analysis			
Air Voids	3-5	3-5	3-5

* Equivalent Single Axle Load

MINIMUM PERCENT VOIDS IN MINERAL AGGREGATE (VMA)

Nominal Maximum Particle Size U.S.A. Standard Sieve Designation	Minimum Voids in Mineral Aggregate Percent
No. 16	23.5
No. 8	21
No. 4	18
3/8 in.	16
1/2 in.	15
3/4 in.	14
1 in.	13
1-1/2 in.	12
2 in.	11.5
2-1/2 in.	11

b. Standard mix design procedures (Marshall, Hveem) have been developed and adopted by AASHTO, however, some States have modified these procedures for their own use. Any modification from the standard procedure should be supported by correlation testing for reasonable conformity to the design values obtained using the standard mix design procedures.

c. Stripping in the asphalt pavements is not a new phenomenon, although the attention to it has intensified in recent years. Moisture susceptibility testing should be a part of every State's mix design procedure. The "Effect of Water on Compacted Bituminous Mixtures" (immersion compression test) (AASHTO T165) and "Resistance of Compacted Bituminous Mixture to Moisture Induced Damage" (AASHTO T283) are currently the only stripping test procedures which have been adopted by AASHTO. The AASHTO T283, commonly known as the Lottman Test, requires that the test specimens be compacted so as to have an air void content of 7 ± 1 percent, while AASHTO T165 does not. This air void content is what one would expect in the mat after construction compaction. There is considerable research underway on developing better tests for determining moisture damage susceptibility of the aggregate asphalt mixtures. One of the most promising test procedures is that developed by Tunnicliff and Root as reported in the National Cooperative Highway Research Program (NCHRP) Report 274. This test is similar to AASHTO T283, but it takes less time to perform. In the majority of cases hydrated lime and portland cement have proven to be the most effective anti-stripping additives.

d. The determination of air voids in the laboratory mix is a critical step in designing and controlling asphalt hot-mix. In order to determine air voids, the theoretical maximum density or the maximum specific gravity of the mix must be determined. This can be accomplished by using the "Maximum Specific Gravity of Bituminous Paving Mixtures" (Rice Vacuum Saturation) (AASHTO T209).

e. Proper mix design procedures require that each mix be designed using all of the actual ingredient materials including all additives which will be used on the project.

f. The complete information on the mix design should be sent to the plant. The following information should be included in the mix design report and sent to the plant.

(1) Ingredient materials sources

(2) Ingredient materials properties including:

(a) Specific gravities

(b) L. A. Abrasion

(c) Sand equivalent

(d) Plastic Index

(e) Absorption

(f) Asphalt temperature/viscosity curves or values

(3) Mix temperature and tolerances

(4) Mix design test property curves

(5) Target asphalt content and tolerances

(6) Target gradations for each sieve and tolerances

(7) Plot of gradation on the 0.45 power gradation chart, and

(8) Target density

g. Formal procedures should be established to require that changes to mix designs be approved by the same personnel or office that developed the original mix design.

h. After start-up, the resulting mixture should be tested to verify that it meets all of the design criteria.

6. PLANT OPERATIONS

a. In order to assure proper operation, an asphalt plant must be calibrated and inspected. Plant approval should be required and should cover each item on the asphalt plant checklist (Attachment 3).

b. To avoid or mitigate unburned fuel oil contamination of the asphalt mixture, the use of propane, butane, natural gas, coal or No. 1 or No. 2 fuel oils is recommended.

c. If the asphalt cement is overheated or otherwise aged excessively, the viscosity of the recovered asphalt will exceed that of the original asphalt by more than four times. However, if the viscosity of the recovered asphalt is less or even equal to the original viscosity, it has probably been contaminated with unburned fuel oil.

d. For drum mixer and screenless batch plants there should be three separate graded stockpiles for surface courses and four for binder and base courses. Each stockpile should contain between 15 to 50 percent by weight of the aggregate size in the mix design. The plus #4 sieve aggregate stockpile should be constructed in lifts not exceeding 3 feet to a maximum height of 12 feet. There should be enough material in the stockpiles for at least 5 days of production. The plant should be equipped with a minimum of four cold feed bins with positive separation.

e. Control testing of gradation and asphalt content should be conducted to assure a quality and consistent mixture. In many States, the contractor or supplier is required to do this testing.

f. Acceptance testing should be conducted for gradation and asphalt content of the final mixture.

g. The plotting of control and acceptance test results for gradation, asphalt content, and density on control charts at the plant provides for easy and effective analysis of test results and plant control.

h. The moisture content of the aggregate must be determined for proper control of drum mixer plants. The asphalt content is determined by the total weight of the material that passes over the weigh bridge with the correction made for moisture. Sufficient aggregate moisture contents need to be performed throughout the day to avoid deviations in the desired asphalt content.

i. Moisture contents of asphalt mixtures is also important. The extraction and nuclear asphalt content gauge procedures will count moisture as asphalt. For this reason, a moisture correction should be made. In addition, high moisture contents in asphalt mixtures can lead to compaction difficulty due to the cooling of the mix caused by evaporation of the moisture. This is particularly important with drum mixer mixes which require moisture for the mixing process. Some States specify a maximum moisture content behind the paver. A recommended maximum moisture content behind the paver is 0.5 percent.

7. LAYDOWN AND COMPACTION

a. Prior to paving start-up, equipment should be checked to assure its suitability and proper function. Project equipment approval should include the items shown on the project inspection checklist (Attachment 4).

b. Paving start-up should begin with a test strip section. This will allow for minor problems to be solved, establishment of roller patterns and number of passes, and will assure that proper placement and compaction can be attained.

c. In order to assure proper placement and compaction, it is essential that the mat be placed hot. Establishment of and compliance with the following items should be included; minimum mix, underlying pavement, and ambient temperatures. Cold weather and early or late season paving should be avoided. The practice of raising the temperature of the mixture to combat the cold conditions should not be permitted, as this will contribute to excessive aging of the asphalt cement.

d. The use of a pneumatic roller in the compaction process is strongly encouraged. When used in the intermediate rolling it will knead and seal the mat surface and aid in preventing the intrusion of surface water into the pavement layers. It will also contribute to the compaction of the mat.

e. Density requirements should be established to result in an air void system in the mat of 6-8 percent immediately after construction. This allows for the inherent additional densification under traffic to an ultimate air void content of about 3-5 percent. Density acceptance specifications should require a percentage of maximum density as determined by AASHTO T209. A percentage of test strip density or Marshall laboratory density can be used provided each is related to the maximum density. The specified density should be attained before the mat temperature drops below 175° F.

f. Density measurement should be accurate, taken frequently, and the results made available quickly for each day of production. Density should be determined by test cores, or by properly calibrated nuclear test gauges. Specifications should require several tests to be averaged to determine density results for acceptance.

g. Successive hot-mix courses should not be placed while previous layers are wet. To avoid, or minimize the penetration of water into base and binder courses, paving operations should be scheduled so that the surface layer(s) is placed within a reasonable period after these courses are constructed. To the greatest extent possible, construction should be planned to avoid the necessity of leaving layers uncovered during wet seasons of the year.

8. MISCELLANEOUS

a. Some States have established procedures to accept out-of-specification material and pavement with a reduction in price. These procedures include definition of lot size/production time, tolerances, and pay factor reductions for ingredient materials, combined mixture properties, pavement density, pavement smoothness, and lift thickness.

b. Prior to the start of production and placement operations, a preplacement conference, including all the paving participants, should be held. This conference would define duties and responsibilities for each phase of the operation as well as problem solving procedures.

c. During start-up it is very effective to have a construction and/or materials specialist at the project site to assist in identifying and solving any problem that develops.

d. Because asphalt hot-mix pavement construction is complex, it requires that each person involved understand his/her function thoroughly. It is also helpful if each person has a basic understanding of each of the many phases involved. It is recommended that States develop or use existing training to address these phases of asphalt paving.

Ronald E. Heinz
Associate Administrator for
Engineering and Program Development

4 Attachments

AGGREGATE GRADATION

It has long been established that gradation of the aggregate is one of the factors that must be carefully considered in the design of asphalt paving mixtures, especially for heavy duty highways. The purpose in establishing and controlling aggregate gradation is to provide sufficient voids in the asphalt aggregate mixture to accommodate the proper asphalt film thickness on each particle and provide the design air void system to allow for thermal expansion of the asphalt within the mix. Minimum voids in the mineral aggregate (VMA) requirements have been established and vary with the top aggregate size.

Traditionally, gradation requirements are so broad that they permit the use of paving mixtures ranging from coarse to fine and to either low or high stability. To further complicate matters, different combinations of sieve sizes are specified to control specific grading ranges. Standardization of sieve sizes and aggregate gradations, which has often been suggested, is not likely to occur because of the practice of using locally available materials to the extent possible.

In the early 1960's, the Bureau of Public Roads introduced a gradation chart (Figure #1) which is especially useful in evaluating aggregate gradations. The chart uses a horizontal scale which represents sieve size openings in microns raised to the 0.45 power and a vertical scale in percent passing. The advantage in using this chart is that, for all practical purposes, all straight lines plotted from the lower left corner of the chart, upward and toward the right to any specific nominal maximum particle size, represent maximum density gradations. The nominal maximum particle sieve size is the largest sieve size listed in the applicable specification upon which any material is permitted to be retained. An example is shown in Figure #2.

The gradations depicted in Figure #3 and #4 are exaggerated to illustrate the points being made. By using the chart, aggregate gradations can be related to maximum density gradation and used to predict if the mixture will be fine or coarse textured as shown in Figure #3.

Soon after the chart was developed, it was used to study gradations of aggregate from several mixtures that had been reported as having unsatisfactory compaction characteristics. These mixtures could not be compacted in the normal manner because they were slow in developing sufficient stability to withstand the weight of the rolling equipment. Such mixtures can be called "tender mixes." This study identified a consistent gradation pattern in these mixes as is illustrated in Figure #4.

Most notable is the hump in the curve near the #40 sieve and the flat slope between the #40 sieve and the #8 sieve. This indicates a deficiency of material in the #40 to 8# sieve range and an excess of material passing the #40 sieve. Mixtures with an aggregate exhibiting this gradation characteristic are susceptible to being tender, particularly if the fines are composed of natural sand.

As part of the bituminous mix design process, the aggregate gradation should be plotted on the 0.45 power gradation chart.

FHWA TECHNICAL ADVISORY T 5040.27
March 10, 1988
ATTACHMENT 1

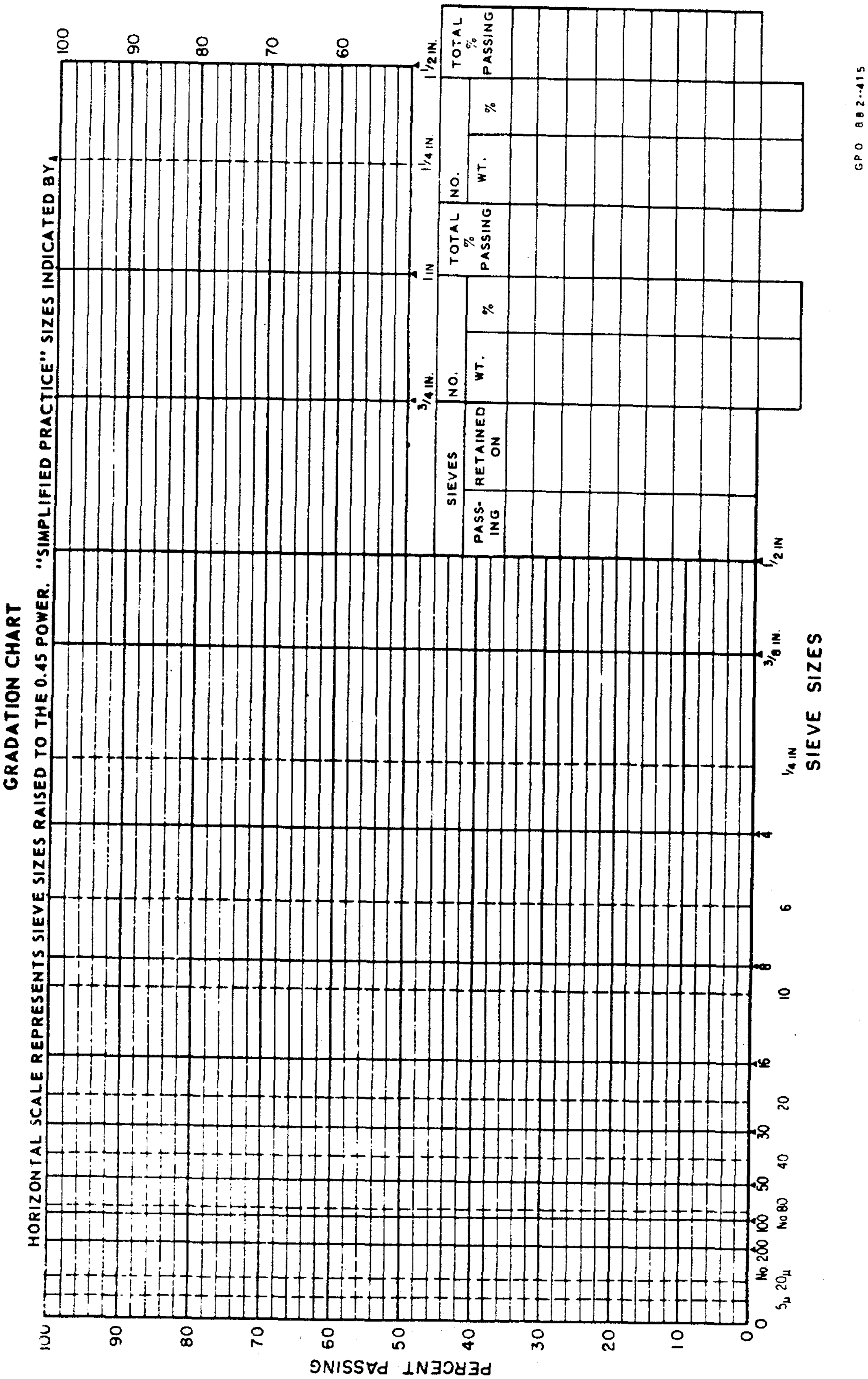


Figure #1

0.45 Power Gradation Chart

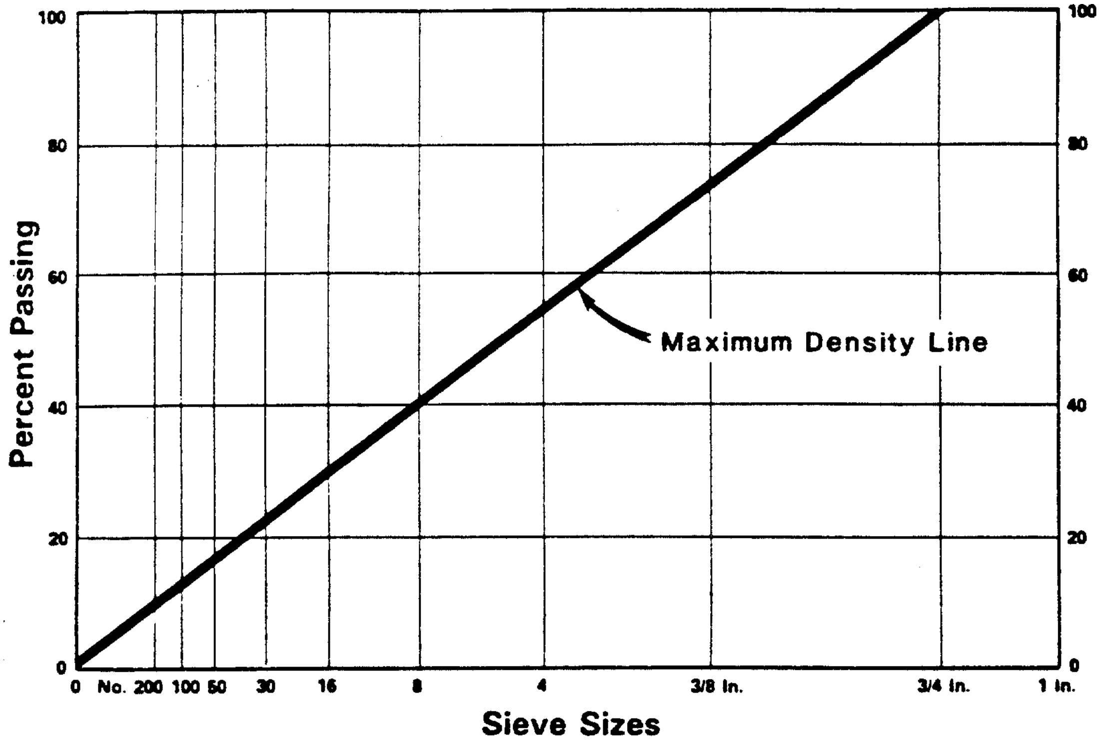


Figure #2

0.45 Power Gradation Chart

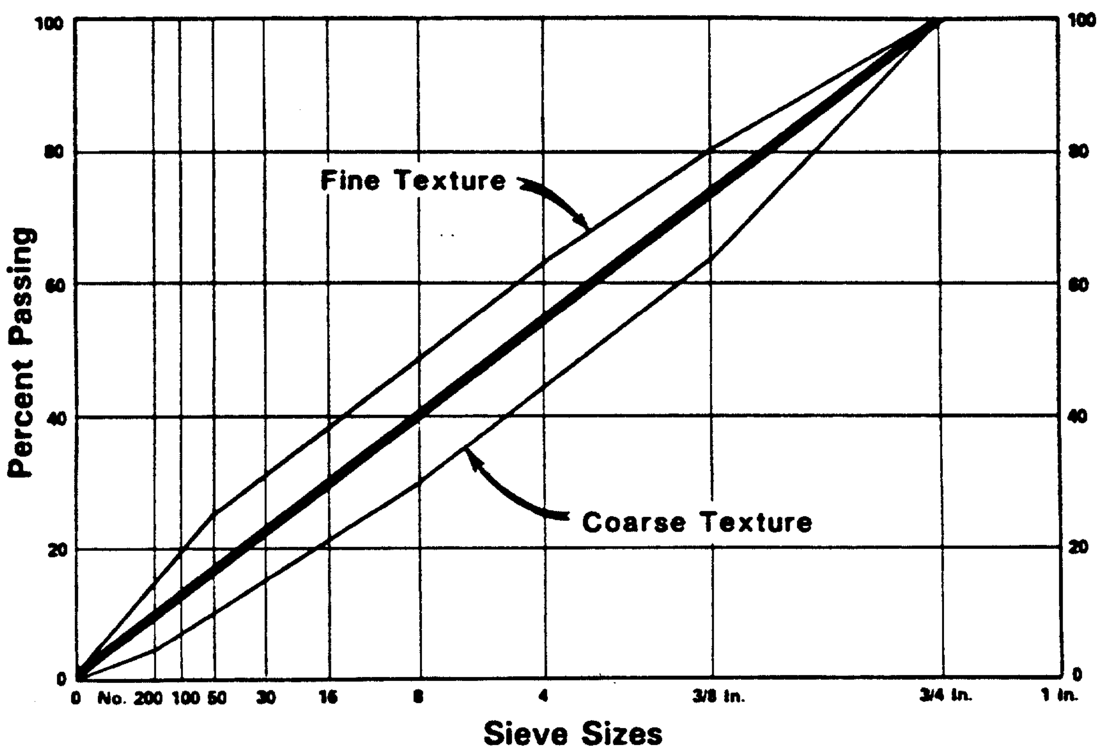


Figure #3

0.45 Power Gradation Chart

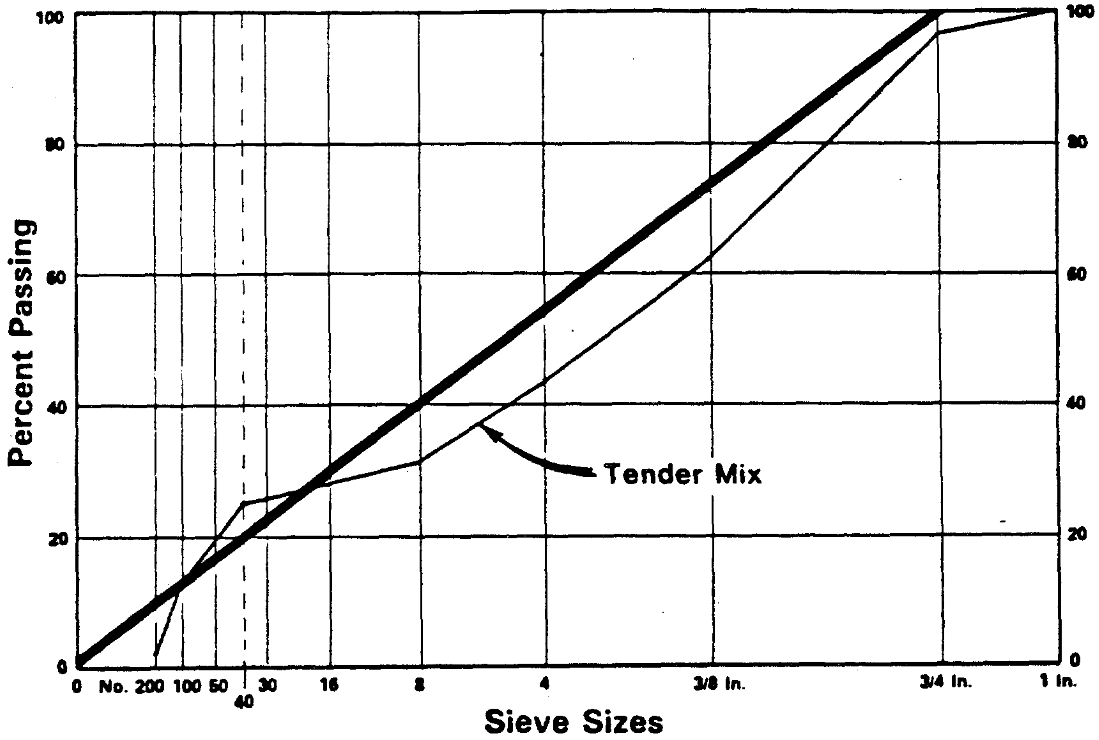


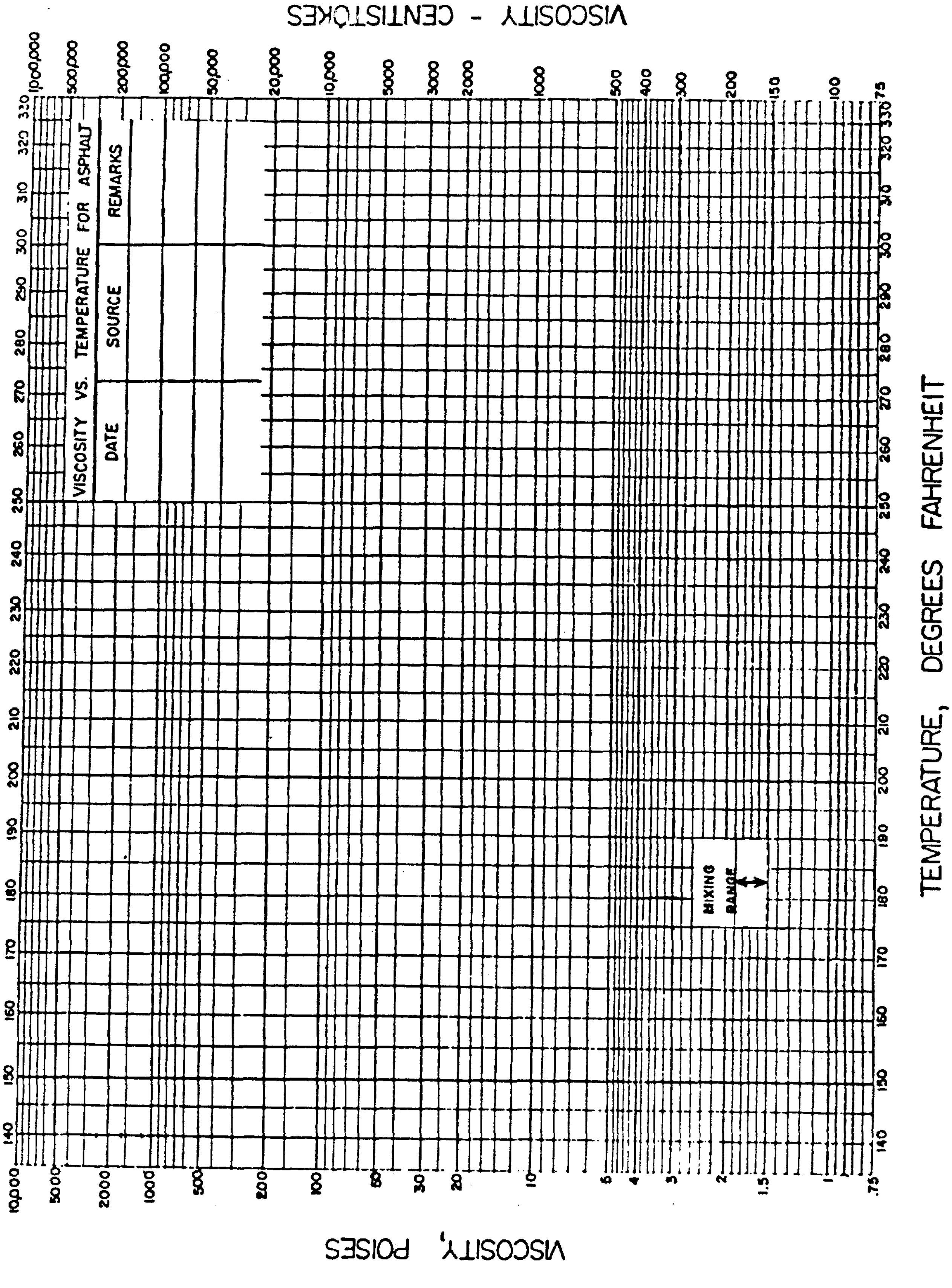
Figure #4

ASPHALT VISCOSITY

Each particular asphalt has a unique temperature-viscosity relationship. This relationship is sometimes described as temperature susceptibility. This temperature-viscosity relationship can be plotted on a modified semi-log chart as shown on the attached chart. These charts are very useful in determining the optimum mixing and compacting temperature of a particular asphalt. Past research has identified the optimum mixing temperature as that corresponding to a viscosity of 170 ± 20 centistokes, and the optimum compaction temperature as that corresponding to a viscosity of 280 ± 30 centistokes for laboratory mix design. The optimum mixing temperature should be identified for the asphalt used in the mix design and included in the mix design report which is sent to the production plant.

Prior to the oil embargo, there was a relatively fixed distribution system for crude oil. This allowed for a relatively uniform asphalt cement from each refinery. Highway agencies became familiar with the handling and performance characteristics of those asphalt cements. As a result of the embargo, a new variable distribution system is in place which allows shifting and blending of crude oils resulting in production of asphalt cements with very different temperature viscosity characteristics.

The attached chart will allow plotting the temperature-viscosity curve for the asphalts used in a State or a particular asphalt from a project. If the kinematic viscosity (275° F) of the asphalt being used changes from the kinematic viscosity of the asphalt used in the mix design by a factor of more than about two, a new mix design should be required.


VISCOSITY - CENTISTOKES
VISCOSITY VS. TEMPERATURE FOR ASPHALT
DATE
SOURCE
REMARKS
MIXING RANGE
TEMPERATURE, DEGREES FAHRENHEIT
VISCOSITY, POISES

7. Is conveyer system covered and insulated (if necessary) so as to prevent excessive loss of heat during transfer of material from mixing plant to storage bin?
8. Does storage bin have acceptable heating system?
9. Has surge or storage bin received prior evaluation and approval before using?

IX. Safety and Inspection Provisions

1. Are gears, pulleys, chains, sprockets, and other dangerous moving parts thoroughly protected?
2. Is an unobstructed and adequately guarded passage provided and maintained in and around the truck loading space for visual inspection purposes?
3. Does plant have adequate and safe stairways or guarded ladders to plant units such as mixer platforms, control platforms, hot storage bins, asphalt storage tanks, etc. where inspections are required?
4. Is an inspection platform provided with a safe stairway for sampling the asphalt mixture from loaded trucks?

X. Truck Scales

1. Are scales capable of weighing the entire vehicle at one time?
2. Do scales have digital printing recorder or automatic weight printer?
3. Have scales been checked and certified by a reputable scale company in the presence of an authorized representative of the highway department?
4. Date checked ________________ Agency Name ________________________
5. Is copy of certification available?
6. Remarks ____
____
____
____
____

XI. Transportation Equipment

1. Are truck bodies clean, tight, and in good condition?
2. Do trucks have covers to protect material from unfavorable weather conditions?
3. Is soapy water or other approved products available for coating truck bodies to prevent material from sticking? Diesel fuel should not be used.
4. Type of material used. ________________

XII. Provisions for Testing

1. Does size and location of laboratory comply with specifications?
2. Is laboratory properly equipped?
3. Is laboratory acceptable?

SPECIAL REQUIREMENTS FOR BATCH PLANTS

XIII. Weigh Box or Hopper

1. Is weigh box large enough to hold full batch?
2. Does gate close tightly so that material cannot leak into the mixer while a batch is being weighed?

XIV. Aggregate Scales

1. Are scales equipped with adjustable pointers or markers for marking the weight of each material to be weighed into the batch?
2. Are ten 50-lb. (22.7 kg) weights available for checking scales?
3. Has accuracy of weights been checked?
4. Have scales been checked and certified by a reputable scales company in the presence of an authorized representative of the highway department?
   Date checked ______________ Agency Name ____________________
   Is copy of certification available?
   Remarks ____
   ____
   ____
   ____
   ____
5. If the plant is equipped with beam type scales, are the scales equipped with a device to indicate at least the last 200 lb. (97 kg) of the required load?

XV. Asphalt Cement Bucket

1. Is bucket large enough to handle a batch in a single weighing so that the asphalt material will not overflow, splash or spill?
2. Is the bucket steamed, or oil-jacketed or equipped with properly insulated electric heating units?
3. Is the bucket equipped to deliver the asphalt material over the full length of the mixer?

XVI. Asphalt Cement Scales

1. Have scales been checked and certified by a reputable scale company in the presence of an authorized representative of the highway department?
   Date checked ________________ Agency Name ______________________
   Is copy of certification available?
   Remarks ____

   ____

2. Are scales equipped with a device to indicate at least the last 20 lb. (9.1 kg) of the approaching total load?

XVII. Screens

1. Condition of screens. Satisfactory _______ Unsatisfactory _______
2. Do the plant screens have adequate capacity and size range to properly separate all the aggregate into sizes required for proportioning so that they may be recombined consistently?

XVIII. Hot Bins

1. Number of bins? ________________
2. Are bins properly partitioned?
3. Are bins equipped with overflow pipes?
4. Will gates cut off quickly and completely?
5. Can samples be obtained from bins?
6. Are bins equipped with device to indicate the position of aggregate at the lower quarter point?

XIX. Asphalt Control

1. Are means provided for checking the quantity or rate of flow of asphalt material?
2. Time required to add asphalt material into pugmill.

XX. Mixer Unit for Batch Method

1. Is the plant equipped with an approved twin pugmill batch mixer that will produce a uniform mixture?
2. Can the mixer blades be adjusted to ensure proper and efficient mixing?
3. Are the mixer blades in satisfactory condition?
4. What is the clearance of the mixer blades? ______________ in.
5. Does the mixer gate close tight enough to prevent leakage?
6. Does the mixer discharge the mixture without appreciable segregation?
7. Is the mixer equipped with time lock?
8. Does timer lock the weigh box gate until the mixing cycle is completed?

9. Will timer control dry and wet mixing time?
10. Can timer be set in 5 second intervals throughout the designated mixing cycles?
11. Can timer be locked to prevent tampering?
12. Is a mechanical batch counter installed as part of the timing device?

XXI. Automation of Batching

1. If the plant is fully automated, is an automatic weighing, cycling and monitoring system installed as part of the batching equipment?
2. Is the automatic proportioning system capable of weighing the materials within $\pm$ 2 percent of the total sum of the batch sizes?

SPECIAL REQUIREMENT FOR DRUM MIXERS

XXII. Aggregate Delivery System

1. Number of cold feed bins? ________________
2. Are cold feed bins equipped with devices to indicate when the level of the aggregate in each bin is below the quarter point?
3. Does the cold feed have an automatic shut-off system that activates when any individual feeder is interrupted?
4. Are provisions available for conveniently sampling the full flow of material from each cold feed and the total cold feed?
5. Is the total feed weighed continuously?
6. Are there provisions for automatically correcting the wet aggregate weight to dry aggregate weight?
7. Is the flow of aggregate dry weight displayed digitally in appropriate units of weight and time and totaled?
8. Are means provided for diverting aggregate delivery into trucks, front-end loaders, or other containers for checking accuracy of aggregate delivery system?
9. Is plant equipped with a scalping screen for aggregate prior to entering the conveyor weigh belt?

XXIII. Asphalt Cement Delivery System

1. Are satisfactory means provided to introduce the proper amount of asphalt material into the mix?
2. Does the delivery system for metering the asphalt material prove accurate within $\pm$ 1 percent?
3. Does the asphalt material delivery interlock with aggregate weight control?
4. Is the asphalt material flow displayed in appropriate units of volume or weight and time and totaled?
5. Can the asphalt material be diverted into distributor trucks or other containers for checking accuracy of delivery systems?

XXIV. Drum Mixer

1. Is the drum mixer capable of drying and heating the aggregate to the moisture and temperature requirements set forth in the specifications, and capable of producing a uniform mix?
2. Does plant have provisions for diverting mixes at start-up and shutdowns or where mixing is not complete or uniform?

XXV. Is plant approved for use?
If not, explain what needs to be corrected. (Show Item Number)

____
____
____
____
____
____

PROJECT INSPECTION CHECKLIST

Compaction of Foundation

1. Have all courses of the foundation been compacted to required density?

Old Asphalt Pavement

1. Have all potholes been patched?
2. Have all necessary patches been made?
3. Have all loose material and "fat" patches been removed?
4. Have all depressions been filled and compacted?
5. Has fog seal been used on surface that has deteriorated from oxidation?
6. Has an emulsified asphalt slurry seal been applied on old surfaces with extensive cracking?

Rigid Type Pavement

1. Has pavement been under sealed where necessary?
2. Has premolded joint material and crack filler been cleaned out?
3. Have all "fat" patches been removed?
4. Has badly broken pavement been removed and patched?
5. Have all depressions been filled and compacted?

Incidental Tools

1. Do incidental tools comply with specifications? ________
2. Are all necessary tools on job before work begins?

The Engineer and the Contractor

1. Have the engineer and inspectors held a preliminary conference with the appropriate contractor personnel?
2. Has continuity of operations been planned?
3. Has the number of pavers to be used been determined?
4. Have the number and type of rollers to be used been determined?
5. Has the number of trucks to be used been determined?
6. Has the width of spread in successive layers been planned?
7. Is it understood who is to issue and who is to receive instructions?
8. Have weighing procedures and the number of load tickets to be prepared been determined?
9. Have procedures for investigation of mix been agreed upon?
10. Has method of handling traffic been established?

Preparation of Surface

1. Have all surfaces that will come into contact with the asphalt mix been cleaned and coated with asphalt?
2. Has a uniform tack coat of correct quantity been applied?

Asphalt Distributor

1. Does the asphalt distributor comply with specifications?
2. Are the heaters and pump in good working condition?
3. Have all gauges and measuring devices such as the bitumeter, tachometer, and measuring stick been calibrated?
4. Are spray bars and nozzles unclogged and set for proper application of asphalt?

Hauling Equipment

1. Are truck beds smooth and free from holds and depressions?
2. Do trucks comply with specifications?
3. Are trucks equipped with properly attached tarpaulins?
4. For cold weather or long hauls, are truck beds insulated?
5. When unloading, do trucks and paver operate together without interference?
6. Is the method of coating of contact surfaces of truck beds agreed upon?

Paver

1. Does the paver comply with specifications?
2. Is the governor on the engineer operating properly?
3. Are the slat feeders, the hopper gates, and spreader screws in good condition and adjustment?
4. Are the crawlers adjusted properly?
5. Do the pneumatic tires contain correct and uniform air pressure?
6. Is the screed heater working properly?
7. Are the tamper bars free of excessive wear?
8. Are the tamper bars correctly adjusted for stroke?
9. Are the tamper bars correctly adjusted for clearance between the back of the bar and the nose of the screed plate?
10. Are the surfaces of the screed plates true and in good condition?
11. Are mat thickness and crown controls in good condition and adjustment?
12. Are screed vibrators in good condition and adjustment?
13. Is the oscillating screed in proper position with respect to the vibrating compactor?
14. Is the automatic screed control in adjustment and is the correct sensor attached.

Spreading

1. Are the required number of pavers on job?
2. Is the mix of uniform texture?
3. Is the general appearance of the mix satisfactory?
4. Is the temperature of the mix uniform and satisfactory?
5. Does the mix satisfy the spreading requirements?
6. Has proper paver speed been determined?
7. Is the surface smoothness tolerance being checked and adhered to?
8. Is the depth of spread checked frequently?
9. Has the daily spread been checked?

Rolling

1. Are the required number of rollers on the job?
2. Is proper rolling procedure being followed?
3. Is the proper rolling pattern being followed?
4. Are joints and edges being rolled properly?

Miscellaneous

1. Are all surface irregularities being properly corrected?
2. Is efficient control of traffic being maintained?
3. Are sufficient samples being taken?
4. Are samples representative?
5. Have assistant inspectors been properly instructed?
6. Are inspection duties properly apportioned among assistants?
7. Are records complete and up-to-date?
8. Are safety measures being observed?
9. Has final clean-up and inspection been made?

U.S. Department
of Transportation
Federal Highway Administration

Memorandum

Washington, D.C. 20590

Subject: Prevention of Premature Distress In Asphalt Concrete Pavements

Date APR 18 1988

From: Chief, Pavement Division

Reply to Attn. of: HHO-12

To: Regional Federal Highway Administrators
Director Federal Program Administrator

Attached for your use are two copies of a technical paper on the prevention of premature distress in asphalt concrete pavements. The paper is an implementing action to one of the recommendations of the Ad Hoc Task Force report on "Asphalt Pavement Rutting and Stripping." The paper is intended as a companion document to Technical Advisory 5040.27. Please furnish copies to the engineers in the divisions who are responsible for implementing the recommendations of the TA. The paper may also be of use to area engineers as it provides additional background information on some points in the TA and responds to some of the questions that have been asked.

We plan to issue a paper this summer on investigating and rehabilitating rutted and stripped pavements. If you are aware of a good practice in your region on this subject, we would appreciate receiving a short writeup on it.

We appreciate the efforts of the regions and division that have offered comments on this paper. If you have any question concerning this paper or suggestions for the second one, please contact Mr. Peter Kleskovic at FTS 366-2216.

Norman J. Van Ness

TECHNICAL PAPER 88-02 - Prevention of Premature Distress in Asphalt Concrete Pavements

Asphalt concrete rutting, a channelized depression in the wheel paths, is the result of deformations either in the pavement or the subgrade. It occurs because of consolidation in the subgrade or in the pavement structure, or because of shear failure in the mix. Rutting can cause vehicle handling problems and it increases the potential for hydroplaning.

Stripping is a form of moisture damage that can severely weaken an asphalt pavement. It can take a number of forms. Water can get between the asphalt and the aggregate and break the bond between them. Water can also get between and separate the coated particles in the mix. Still another form occurs when the asphalt cement emulsifies in water. High voids or segregation can accelerate stripping by letting water into the mat. Stripping can rob a pavement of a significant portion of its life. It also contributes to early rutting because of strength loss in the stripped layer.

Rutting and stripping are being experienced throughout much of the United States. In 1987, an FHWA Ad Hoc Task Force issued a report entitled, "Asphalt Pavement Rutting and Stripping." It discussed the national and regional nature of the problems, identified causes, and made short- and long-term recommendations to correct them. One of these called for updating Technical Advisory 5040.24 to reflect current knowledge. In response to this recommendation, a new Technical Advisory 5040.27, Asphalt Mix Design and Field Control was issued on March 10, 1988.

Increased traffic loads and tire pressures have been identified as accelerating factors in the occurrence of these distresses. However, upgrading mix design procedures and construction practices to the state-of-the-art can help to mitigate the problem. Even though some States and regions may not have rutting or stripping problems now, there is probably room for improvement in every State's procedures which could add extra years of life to their pavements.

Materials Considerations

The use of locally available aggregates is an important economic factor in highway construction. Asphalt concrete is typically made using local aggregates. However, in the case of marginal materials, the economic benefit may be at the expense of durability. The use of good quality aggregates plays a major role in preventing rutting and stripping. The recommendations in Technical Advisory (TA) 5040.27 should all be considered when evaluating an aggregate.

One way to make a mix more resistant to rutting is to increase the interparticle friction between the aggregates by increasing their angularity and roughness. This is accomplished by using crushed aggregates and by limiting the amount of natural sands. The TA recommends that specifications require at least 60 percent of the plus #4 sieve aggregates to have at least two mechanically induced fractured faces. Mechanically induced fractured faces are usually rougher than flat faces made by natural processes. This rougher texture helps to keep aggregate particles from slipping by each other and also provides more bonding area for the asphalt.

The TA recommends limiting natural sands to 15 to 20 percent of the <u>total weight of the aggregates</u> for high volume roads and 20 to 25 percent for medium and low volume roads. Since natural sands tend to be round and smooth, they generally do not have good frictional properties. In addition, natural sand deposits may contain clay or organic particles. Asphalt does not adhere well to clay coated particles. Clay can also have an emulsifying effect on the asphalt in the presence of water. Both of these effects can accelerate the occurrence of stripping.

Some natural sands also consist of largely one sized particles. This can produce a gap graded mix, which is more likely to segregate. The gap grading may result in a flat slope on the 0.45 power gradation curve between the #4 and #30 sieves. If this flat slope results in more than a 3 percent hump above the maximum density line, the mix might be tender, i.e., too unstable to compact at proper temperatures.

The gradation of the aggregates is an important factor in the construction and the performance of the mat. Aggregate gradation can affect the strength and the durability of the mat, as well as its resistance to stripping or deformation. Certain gradations are more prone to segregation. For example, the larger the aggregate top size, the more care is required to prevent segregation. Gap graded aggregates are also likely to segregate due to the absence of intermediate sizes which help to stop the larger aggregate from rolling.

Asphalts can be graded by penetration, by the viscosity of the original asphalt (AC Grading) and by the viscosity of the aged residue (AR Grading). The AR-graded asphalts may have problems when used in drum mixer plants, since the asphalt may not harden as much as in a batch type plant. This could lead to rutting, since the asphalt in the mat would be softer than was assumed in the design, making the mix less stable.

AASHTO Specification M-226 sets requirements for AC and AR-graded asphalts. Tables 1 and 2 of this specification set absolute viscosity ranges at 140° F and a minimum kinematic viscosity at 275° F for AC-graded asphalts. It does not however set a maximum value for kinematic viscosity. Therefore, it is possible for two asphalts to meet the requirements of M-226 and yet have substantially different kinematic viscosities at mixing temperatures. To control this variable, attachment 2 of the TA recommends that a new mix design be performed if the kinematic viscosity of the asphalt being used at the plant changes by more than a factor of 2 from the asphalt used in the mix design.

The amount of asphalt aging occurring in the mixing process must be controlled, since highly aged asphalts will be more brittle and likely to crack. The aging process is simulated by the Thin Film Oven Test (TFOT). The viscosity of an AC-graded asphalt subjected to the TFOT should not exceed four times the nominal viscosity of the grade. For example, an AC 20 has a viscosity range of 1600 to 2400 poises. After the TFOT, its viscosity should not exceed 8000 poises.

A new feature of the TA is the low temperature ductility test. The test gives an indication of the mix's potential for low temperature cracking. The test is based on AASHTO T51, but is performed at a lower temperature of 39.2^{o} F and a slower pull speed of 1 cm per minute.

Mix Design Considerations

The purpose of a mix design procedure is to determine for a given gradation and quality of aggregates the optimum asphalt content and grade which will meet specification requirements for stability, voids, VMA, flow (Marshall), swell (Hveem), and will be close to a maximum unit weight. The selection of the optimum asphalt content is a balancing operation among these factors.

It is essential that mixes be designed using the actual project materials since certain interactions occur between aggregates, asphalts, and additives. Changing one of the ingredients may set up a completely different interaction.

Relating the density of a laboratory compacted specimen to the pavement's ultimate density under traffic is a major element in designing mixes. Asphalt mixes should be designed for 3 to 5 percent air voids, which is the desired voids level of the mat after several years of traffic. The goal is to build a pavement that is dense enough to minimize air and water intrusion but has enough voids for the asphalt to expand.

To try to simulate the effects of traffic, various levels of compactive effort are used to make laboratory design specimens. In the Marshall

Method, specimens are subjected to different numbers of hammer blows depending on the design ESALs. Specimens should be compacted with 35 blows per side for pavements that will have less than 10,000 ESALs, 50 blows for ESALs between 10,000 and 1,000,000, and 75 blows for ESALs above 1,000,000. It is important to note that specimens compacted with mechanical hammers generally have lower densities than those compacted with manual hammers. However, AASHTO allows the use of the mechanical hammer provided it has been calibrated to give results comparable to the manual hammer.

Problems may result if lab specimens have been over-compacted or under-compacted in relation to expected traffic. For a light traffic highway, a 75 blow design could cause problems because the mat will probably not reach design density under traffic and will have excessive voids, making the mix susceptible to rapid asphalt oxidation and water damage. Similarly, a heavy traffic pavement designed with only 50 blows, might be densified by traffic to the point that the mat would be deficient in voids. The mat may not have enough void spaces to permit for thermal expansion of the asphalt and the pavement would be prone to bleeding, stability loss, and rutting.

The TA provides stability values for the three ESAL ranges. Although stability is desirable, excessively high stability values may be achieved at the expense of durability. For example, to an extent stability can be increased by reducing the asphalt content. However, reducing the asphalt content too much results in thin asphalt films on the aggregate which makes the mix more prone to stripping and to age hardening.

In designing mixes, the air voids content should be based on the maximum theoretical density of the mix as determined by AASHTO T209, the Rice Test. The Rice Test is the best available procedure for determining the maximum theoretical density because of the short-test time and because it accounts for the asphalt absorbed by the aggregate. It also eliminates the error that can occur by trying to calculate a maximum specific gravity based on the percentages and specific gravities of the component aggregates.

In the past, base and binder mixes have been constructed with higher air void levels and somewhat lower asphalt contents. Typical values have been as high as 8 to 11 percent. These high void mixes are more likely to strip, because the mat is open to moisture penetration. Additionally, the aggregates typically have thinner asphalt films, which lowers mix strength and makes the mix more likely to strip. To prevent problems, bases and binder mixes should also be designed for 3 to 5 percent air voids.

The Voids in Mineral Aggregate (VMA) is a measure of the space between the aggregate particles which can accommodate the asphalt cement and the air voids. If the VMA is low, the mix will have either a low voids or asphalt content, because there is not enough empty space in the mix to accommodate both. If the VMA is too large, then too much asphalt cement will be required to achieve density and stability will be lowered. Minimum VMA values are included in the TA. These values are based on the nominal maximum aggregate size, i.e., the largest sieve on which some material can be retained.

It is recommended that the ratio of dust or minus #200 material to asphalt be kept between 0.6 and 1.2 based upon weight. For a mix containing 5 percent asphalt, the dust content should be held between 3 and 6 percent, using washed gradations. The effect of dust on the mix is complex and depends on the size, shape, gradation, and quantity of the dust. A certain amount of dust is needed to produce a dense cohesive mix. However, in some cases too much dust can result in low air voids and can stiffen the binder, resulting in a harsh mix. Fine dust can act as an asphalt extender and cause the mix to be tender. Single sized particles may increase the asphalt demand of the mix.

Evaluation of Stripping Potential

A mix design is not complete until an evaluation has been made of the mix's resistance to moisture damage. Moisture damage susceptibility can be estimated by strength loss after moisture conditioning by a number of test procedures. Probably, the most promising procedure is the Root-Tunnicliff test. It is faster than the Lottman test (AASHTO T283) and is adaptable to field control. Also, the samples are more severely conditioned than in the Immersion Compression test (AASHTO T165).

Asphalt concrete mix design is complex, therefore, it is also important to identify the reason for the loss of strength in the stripping test. The worst scenario is to use an anti-stripping additive when the problem may be due to a low asphalt content caused by a low VMA. In this case, it would be better to change the gradation to increase the VMA so that more asphalt could be put into the mix.

Once a set of materials is found to be susceptible to water damage, an additive should be selected. The type, dosage rate and method of application should be determined through laboratory testing, preferably using the Lottman or the Root-Tunnicliff Tests. Hydrated lime and portland cement have been found to be very effective in protecting mixtures from water damage. Some liquid anti-stripping additives have also been effective.

Agencies should guard against the use of any additive without adequate testing and evaluation. Some States have developed approved lists of anti-stripping additives. This is an acceptable practice provided the proposed additives are then tested with the actual project asphalt and aggregates. Reliance solely on the approved list may result in the use of additives which have no effect or which may even be detrimental to the mix.

Plant Operations

The TA covers a number of specific points necessary to ensure proper plant operations. Attachment 3 of the TA is a model checklist for inspecting asphalt plants. A few points should be stressed. Agencies using AR-graded asphalt should verify that the asphalt hardens sufficiently during mixing. This is accomplished by recovering the extracted asphalt and testing it for viscosity. This testing can also give a hint if unburned fuel oil is contaminating the asphalt.

The dust/asphalt ratio should be monitored during production. The dust/asphalt ratio has become increasingly important since the advent of baghouse dust collectors. Typically, the contractor wants to recirculate all of the captured dust into the mix. However, it is difficult to properly compensate for the extra dust during mix design, since it is difficult to meter a constant flow of dust into the actual production mix. High dust contents make the mix more sensitive to asphalt content. Depending on the size of the dust particles, the mix may have either a lower or higher asphalt demand. If the flow of dust varies during production, the mix will alternate between having too much or too little asphalt.

The asphalt plant testing program should include verification testing of the mix design. This should occur after plant start-up and periodically during production. The purpose is to verify that the production mix has the same properties as the mix that was designed. As well as being tested for asphalt content and gradation, the plant produced mix should also be run through the standard design tests such as stability, voids, density, etc. Plant produced mix may not have the same properties as specimens compacted in the lab even though they were made from the same ingredients since some aggregates produce additional mineral dust when processed through the plant. Failure to do verification testing can result in a mix being produced which has different gradations, voids, stabilities, and densities from the laboratory mix. If this happens, the benefits of doing a mix design are lost.

Laydown Operations and Compaction

Paving operations should start with the construction of a test strip. A nuclear gauge should be used to determine the number of passes needed to obtain optimum density. Cores should then be taken from the test strip to determine the bulk density, which is the true density of the mat. A correction for the nuclear gauge due to aggregate type is obtained by comparing the nuclear density values to the bulk density values. To determine if the rolling is providing the proper level of compaction and voids, the bulk density of the cores is compared to the maximum theoretical density of the mix, which should be obtained from the Rice Test.

Density specifications can be based on meeting percentages of maximum theoretical density, of lab density or of test strip density. Whichever specification is used, acceptance levels should be set so that after rolling, the mat will have air voids of 6 to 8 percent, or a density of 92 to 94 percent of maximum theoretical density.

Not enough can be said with regard to the detrimental effects of paving in cold or wet weather. Adverse ambient conditions can result in inadequate compaction, poor bonding between layers, or moisture being trapped in the pavement. Raising the temperature of the mix to compensate for cold weather conditions may age the asphalt cement excessively. Also, hot asphalt cement flows more readily and is more easily absorbed by the aggregates. The hot asphalt cement will tend to drain to the bottom of the storage bins or the truck beds resulting in fat spots in the mat corresponding to each truck load. Also, if absorption becomes significant, the mix will have a low effective asphalt content.

Paving on a cold surface can cause the temperature of the mix to drop below minimum before rolling is completed. AASHTO has recently adopted into its Guide Specifications the following suggested minimum surface temperature values for different lift thicknesses.

Compaction Thickness	Surface Course	Sub-surface Course
< 1 1/2 in.	60° F suggested	55° F suggested
1 1/2 to 2 1/2 in.	50° F suggested	45° F suggested
2 1/2 in. +	40° F suggested	35° F suggested

All rolling, including the finish rolling, should be completed before the mat temperature drops below 175° F. The 175° F should be considered an absolute minimum value, since continued rolling with a steel wheel roller can cause the mat to decompact. Compaction of the mat should begin as soon as possible after laydown.

The TA strongly encourages the use of pneumatic rollers because of their ability to knead and seal the surface of the mat. There is also some indication that they provide a more uniform level of compaction across the mat and provide better compaction at joints.

Again attention is needed during paving to make sure that a uniform mat has been produced and that no segregation is occurring in the paving operation. A number of paving practices can result in segregation such as uneven paver demand, emptying the hopper between loads, or in the loading of the paver hopper.

Conclusion

There will always be a need for additional research and new products. One area needing study, is how to relate mixture properties to pavement design procedures. Work is ongoing through SHRP to evaluate tests methods for asphalt cement and asphalt/aggregate mixtures and to monitor the long term performance of pavements. In NCHRP project 9-6(1), the Development of Asphalt-Aggregate Mixtures Analysis System, work is ongoing to develop better mix design procedures.

However, much of the current rutting and stripping problem could be corrected by using state-of-the-art knowledge in mix design and construction. This effort requires the commitment of the highway community to designing and producing high quality pavements.

U.S. Department of Transportation
Federal Highway Administration

Memorandum

Washington, D.C. 20590

Subject: Guidelines on the Use of Bag-House Fines

Date: APR - 7 1988

From: Chief, Pavement Division

Reply to Attn. of: HHO-12

To: Regional Federal Highway Administrators
Direct Federal Program Administrator

Attached is one copy of a recent National Asphalt Pavement Association (NAPA) publication on the above subject. It is the most comprehensive and informative study on this subject to date. The NAPA has made a distribution of this report to its member companies.

You will note on page 21, Summary and Conclusions, that the author recommends a maximum dust asphalt ratio of 1.2 to 1.5 by weight in Item 1. This is not completely in concert with Item 4.a (8) of the March 10, 1988, Technical Advisory T 5040.27, which recommends a maximum dust asphalt ratio of 1.2. We have no quarrel with the authors recommendations provided that his other recommendations and particularly number 3 can be, and is, strictly adhered to at the mixing plants.

We suggest that this report be given to your pavement or materials specialist.

Norman J. Van Ness

U.S. Department
of Transportation
Federal Highway
Administration

Memorandum

Subject: Transmittal of Report FHWA-SA-92-022

Date: JUN 9 1992

From: Director, Office of Engineering
Director, Office of Technology Applications

Reply to Attn of: HNG-42

To: Regional Federal Highway Administrators
Federal Lands Highway Program Administrator

Attached are copies of the *State of the Practice on the Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier* (Publication No. FHWA-SA-92-022). Sufficient copies are provided for distribution of two copies for the region office, one copy to each division office, and four copies to each State department of transportation, or as you see as appropriate.

The passage of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) has generated interest in the highway community on the subject of using scrap tire rubber in asphalt paving. The State DOT's are all aware of the provisions of Section 1038(d) which will require them to satisfy the minimum utilization of crumb rubber modifier (CRM) beginning in 1994.

The Pavement Division, with the cooperation of the Office of Technology Applications, has completed this report on the design and construction of asphalt paving materials with CRM. We believe this document will assist the State DOT's to develop an understanding of the technologies associated with CRM. This understanding is essential to form educated decisions on the implementation of ISTEA Section 1038(d).

The FHWA distribution of this document will be limited to public agencies and highway industry associations. Direct distribution is being made to the Technology Transfer Centers. Further distribution to individuals and private companies will be provided through the National Technical Information Service at (703) 487-4650.

Ray B. Griffith for Douglas A. Bernard

Thomas O. Willett

Attachments

Memorandum

U.S. Department
of Transportation

Federal Highway Administration

Subject: Asphalt Concrete Mix Design and Field Control TA 5040.27

Date: JUN 2 1 1990

From: Chief, Pavement Division
Washington, D.C. 20590-0001

Reply to Attn of: HHO-10
HHO-30

To: Regional Federal Highway Administrators
Federal Lands Highway Program Administrator

Attention: Regional Pavement and Materials Engineers

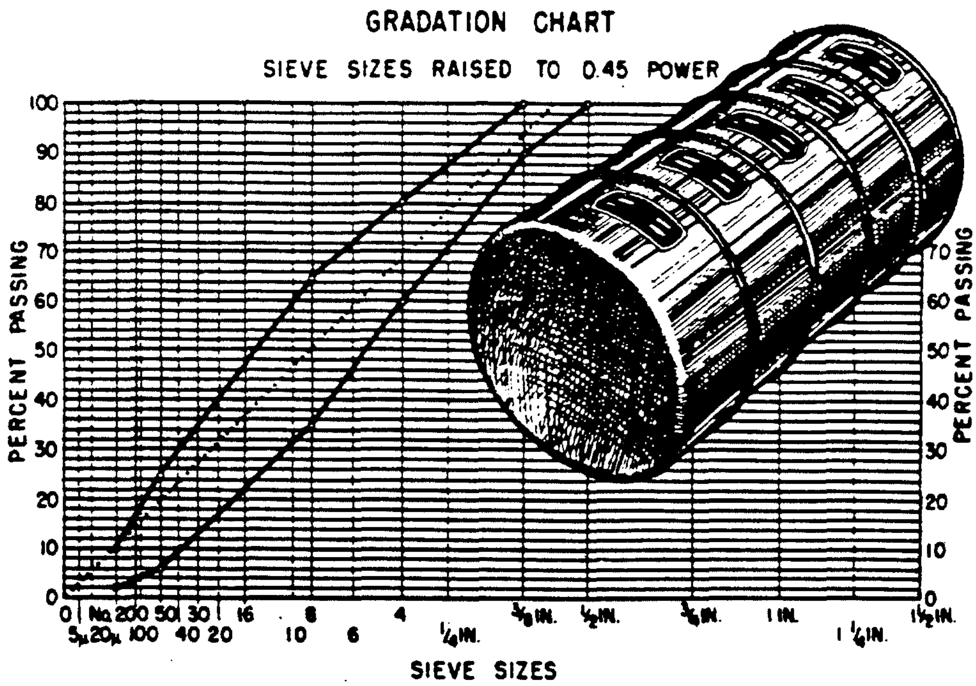
The subject Technical Advisory (TA) was issued in February 1988. The Section 6, Plant Operation, on page 8 offers suggestions and recommendations on items of importance at the mixture production plants. Item 6.b. states, "To avoid or mitigate unburned fuel oil contamination of the asphalt mixture, the use of propane, butane, natural gas, coal, or No. 1 or No. 2 fuel oils is recommended." The processed used-oil and heavy fuels oils were not included. The reason we did not include processed used-oil was that in the early to mid 1980's, there were some very shoddy practices by some used-oil processors which resulted in both combustion and environmental problems. In 1989, the Environmental Protection Agency (EPA) codified regulations on the maximum levels of metallic contents of processed used-oil. To comply, the used-oil must be treated and those processors who can do so successfully are licensed by EPA. These processed used-oils should be satisfactory for use in hot mix asphalt production.

With regard to heavy fuels, they were omitted from those recommended in the TA since they require preheating to lower their viscosities to the point where atomization and full combustion can be attained. Equipment is available to achieve full combustion and if properly used in the asphalt mixture production process, the heavy fuel oils can give satisfactory results.

In summary, it is not our intent to preclude the use of fuels that do not contaminate the mix. Regardless of the type of fuel used, our concern is that the hot mixed asphalt concrete is not damaged in the production process. The only way, that we are aware of, to assure ourselves of this is to follow the suggestion contained in 6.c. of the TA which states, "If the asphalt cement is overheated or otherwise aged excessively, the viscosity of the recovered asphalt will exceed that of the original asphalt by more than four times. However, if the viscosity of the recovered asphalt is less or even equal to the original viscosity, it has probably been contaminated with unburned fuel oil."

Louis M. Papet

AGGREGATE GRADATION FOR HIGHWAYS



Simplification, Standardization, and Uniform Application

and

A New Graphical Evaluation Chart

U.S. DEPARTMENT OF COMMERCE
BUREAU OF PUBLIC ROADS
WASHINGTON : 1962

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AGGREGATE GRADATION FOR HIGHWAYS

Aggregate Gradation: Simplification, Standardization, and Uniform Application

and

A New Graphical Chart for Evaluating Aggregate Gradation

By the Bureau of Public Roads

U.S. DEPARTMENT OF COMMERCE

Luther H. Hodges, *Secretary*

BUREAU OF PUBLIC ROADS

Rex M. Whitton, *Administrator*

United States Government Printing Office, Washington, D.C. : May 1962

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington 25, D.C. . . . . Price 25 cents

AGGREGATE GRADATION: SIMPLIFICATION, STANDARDIZATION, AND UNIFORM APPLICATION

BY THE BUREAU OF PUBLIC ROADS

This report was prepared by a special committee appointed by Assistant Federal Highway Administrator and Chief Engineer Francis C. Turner and representing the Bureau of Public Roads Offices of Engineering, Operations, and Research. The committee included Ardery R. Rankin, chairman, Office of the Assistant Administrator; Carl A. Carpenter and Russell H. Brink, Physical Research Division; Morley B. Christensen, Construction and Maintenance Division; and William B. Huffine and Norman J. Cohen, Equipment and Methods Division

The Need for Simplification

Because of the magnitude of the nationwide highway construction program and the enormous amount of public funds required to finance it, every effort must be made to develop and apply ways and means of reducing construction costs while at the same time assuring the production of only high quality work. In its continuing mission of contributing toward the accomplishment of that objective, the Bureau of Public Roads has made a study of the possibility of effecting economies through simplification, standardization, and uniform application of aggregate gradations.

In performing this study, analyses were made of the current standard specifications of the highway departments of the 50 States, the Commonwealth of Puerto Rico, and the District of Columbia. The analyses disclosed a wide diversity in the requirements pertaining to aggregate gradations. Some 215 dissimilar gradations are specified for coarse aggregates for portland cement concrete. Of these gradations 88 are for both structures and pavement, 91 are for structures only, and 36 are solely for pavements. In contrast, Part I of the *Standard Specifications for Highway Materials* of the American Association of State Highway Officials includes only 19 gradations of coarse aggregates for all highway construction (see AASHO Designation M 43–49), with only 7 designed for use in concrete pavements or bases, bridges, and incidental structures (see AASHO Designation M 80–51). Similarly, the 52 highway departments specify a total of 58 fine aggregate gradations for both pavement and structural concrete whereas AASHO specifies only 1 (see AASHO Designation M 6–51).

In addition, there is considerable lack of consistency among the States in the number and sizes of sieves used to determine the gradations; furthermore, there is no uniform method in actual use by the States for designating aggregate gradation sizes. Only two States refer to the size designations used in AASHO Designation M 80–51. Some States have their own systems of size designations and other States use no designations at all.

Obviously, a greater degree of simplicity, standardization, and uniformity of usage for aggregate gradations would be highly desirable. For example, a commercial supplier who presently furnishes aggregates under numerous varying specification requirements for several Federal, State, county, and municipal highway organizations for identical construction purposes, would certainly find it much simpler and less costly if the same few gradations with identical specification requirements were used by all these agencies. Similarly, construction contractors bidding in more than one jurisdiction could prepare their bids much more intelligently and probably at lower prices if the specification requirements and the materials designations were the same for all jurisdictions.

For reasons of economy and because of the growing scarcity of high-quality aggregates in some areas, it is essential to make as much use as possible of aggregates that are locally available. This frequently necessitates tailoring the specification requirements to fit the characteristics of such local aggregates to whatever extent may be compatible with producing high-quality construction at economical prices. Nevertheless, a much greater degree of standardization and uniform use of aggregate gradations can undoubtedly be achieved. The problem has long been recognized and has here been approached with three specific objectives:

1. To develop a minimum number of standard aggregate gradations that can be uniformly adopted nationwide for general usage, while at the same time recognizing the need for some variations by special provisions to fit locally available materials.

2. To achieve uniformity in the number and sizes of sieves to be used in specifying the aggregate gradations.

3. To develop and adopt a simple and uniform system for identification of the standard aggregate gradations.

The Simplified Practice Recommendation

A major step toward accomplishing these objectives was taken on June 30, 1948, when the Department of Commerce approved and issued Simplified Practice Recommendations R 163–48[1] for coarse aggregates, including crushed stone, gravel, and slag. A predecessor recommendation had originally been approved for promulgation in June 1936 and issued as R 163–36. It was proposed by the Joint Technical Committee of the Mineral Aggregates Association, composed of representatives of the National Sand and Gravel Association, the National Crushed Stone Association, and the National Slag Association. Producers, distributors, and users of mineral aggregate all cooperated in developing the simplified practice recommendation. An intermediate revision was approved and published in 1939 and some additional revisions subsequent to 1939 resulted in the publication of the current issue of 1948. Table 1 shows the SPR gradings that are currently in effect.

As will shortly be described, the SPR system has been essentially adopted by both the American Association of State Highway Officials and the American Society for Testing and Materials.

Value of the SPR system

The simplified practice recommendation R 163–48 embodies a number of highly logical and useful features:

1. *Standard sieves.*—The SPR gradings employ a simple and convenient, square-opening, sieve-size series based primarily on the logarithmic principle.

[1] *Coarse Aggregates (Crushed Stone, Gravel, and Slag), Simplified Practice Recommendation R 163–48*, approved June 30, 1948, National Bureau of Standards, U.S. Department of Commerce, 1948.

The basic logarithmic sieve series employed begins with a sieve having clear openings of 3 inches and each smaller sieve has clear openings the diameter of which is one-half that of the next larger one. Thus the basic series is 3-inch, 1½-inch, ¾-inch, ⅜-inch, No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, and No. 200. Because some consumer interests consider that the logarithmic series does not provide enough control in the larger sizes while others desire greater freedom in selecting maximum sizes, the gaps have been reduced in the SPR series by superimposing upon the logarithmic series, the arbitrary sizes 4-inch, 3½-inch, 2½-inch, 2-inch, 1-inch, and ½-inch. Also, two of the logarithmic sizes were left out of the SPR series—the No. 30 because it was felt that it serves no useful purpose in grading control of coarse commercial aggregates, and the No. 200 because material of this size (soil fines and commercial mineral filler for bituminous paving mixtures) is not and should not be considered an ingredient of commercial coarse aggregates. Both the No. 30 and the No. 200 sieves are required in specifying sands and fillers, as in the ASTM and AASHO standards, and both fit in the logarithmic series.

2. *Simple system.*—The SPR gradings embody a simple and readily understandable system of individual size and grading designations consisting basically of single-digit numbers.

The single-digit numbering series starts with No. 1 for the standard commercial aggregate having the largest top-size particles and progresses from No. 1 through No. 9 as the individual standard coarse aggregates decrease in size, as shown in table 2.

Because of consistent demands for certain longer gradings than the relatively short ones represented by the basic series, shown in the first column of table 2, a secondary

Table 1.—Sizes of coarse aggregate (crushed stone, gravel, and slag) from Simplified Practice Recommendation, R 163–48[1]

SPR size number	Nominal size,[2] square openings	Amounts finer than each laboratory sieve (square openings), percentage by weight														
		4-in.	3½-in.	3-in.	2½-in.	2-in.	1½-in.	1-in.	¾-in.	½-in.	⅜-in.	No. 4	No. 8	No. 16	No. 50	No. 100
1	3½–1½	100	90–100	....	25–60	....	0–15	....	0–5	....	....	....	....	....	....	....
1F[3]	3½–2	100	90–100	....	....	0–10	0–2	....	....	....	....	....	....	....	....	....
2F[3]	3–1½	....	100	90–100	....	....	0–10	0–2	....	....	....	....	....	....	....	....
2	2½–1½	....	....	100	90–100	35–70	0–15	....	0–5	....	....	....	....	....	....	....
24	2½–¾	....	....	100	90–100	....	25–60	....	0–10	0–5	....	....	....	....	....	....
3	2–1	....	....	....	100	90–100	35–70	0–15	....	0–5	....	....	....	....	....	....
357	2–No. 4	....	....	....	100	95–100	....	35–70	....	10–30	....	0–5	....	....	....	....
4	1½–¾	....	....	....	....	100	90–100	20–55	0–15	....	0–5	....	....	....	....	....
467	1½–No. 4	....	....	....	....	100	95–100	....	35–70	....	10–30	0–5	....	....	....	....
5	1–½	....	....	....	....	....	100	90–100	20–55	0–10	0–5	....	....	....	....	....
56	1–⅜	....	....	....	....	....	100	90–100	40–75	15–35	0–15	0–5	....	....	....	....
57	1–No. 4	....	....	....	....	....	100	95–100	....	25–60	....	0–10	0–5	....	....	....
6	¾–⅜	....	....	....	....	....	....	100	90–100	20–55	0–15	0–5	....	....	....	....
67	¾–No. 4	....	....	....	....	....	....	100	90–100	....	20–55	0–10	0–5	....	....	....
68	¾–No. 8	....	....	....	....	....	....	100	90–100	....	30–65	5–25	0–10	0–5	....	....
7	½–No. 4	....	....	....	....	....	....	....	100	90–100	40–70	0–15	0–5	....	....	....
78	½–No. 8	....	....	....	....	....	....	....	100	90–100	40–75	5–25	0–10	0–5	....	....
8	⅜–No. 8	....	....	....	....	....	....	....	....	100	85–100	10–30	0–10	0–5	....	....
89	⅜–No. 16	....	....	....	....	....	....	....	....	100	90–100	20–55	5–30	0–10	0–5	....
9	No. 4–No. 16	....	....	....	....	....	....	....	....	....	100	85–100	10–40	0–10	0–5	....
10	No. 4–0[4]	....	....	....	....	....	....	....	....	....	100	85–100	....	....	....	10–30
G1[5]	1½–No. 50	....	....	....	....	....	100	90–100	....	50–85	....	20–40	15–35	5–25	0–10	0–2
G2[5]	1½–No. 8	....	....	....	....	....	100	85–100	....	35–75	....	10–25	0–10	0–5	....	....
G3[5]	1½–No. 4	....	....	....	....	....	100	60–85	....	20–40	....	0–15	0–5	....	....	....

[1] *Coarse Aggregates (Crushed Stone, Gravel and Slag), Simplified Practice Recommendation R 163–48*, Approved June 30, 1948, National Bureau of Standards, U.S. Department of Commerce, p. 2.

[2] In inches, except where otherwise indicated. Numbered sieves are those of the United States Standard Sieve series.

[3] Special sizes for sewage trickling filter media.

[4] Screenings.

[5] The requirements for grading depend upon percentage of crushed particles in gravel. Size G1 is for gravel containing 20 percent or less of crushed particles; G2 is for gravel containing more than 20 percent and not more than 40 percent of crushed particles; G3 is for gravel containing crushed particles in excess of 40 percent. (Designated as railroad ballast, gravel.)

Table 2.—Basic Simplified Practice Recommendations numbering system

Basic SPR designations	Combinations of basic designations	Nominal size: Maximum	Nominal size: Minimum	Size limits: Maximum	Size limits: Minimum
1		3½-in.	1½-in.	4-in.	¾-in.
2		2½-in.	1½-in.	3-in.	¾-in.
3		2-in.	1-in.	2½-in.	½-in.
	357				
4		1½-in.	¾-in.	2-in.	⅜-in.
	467				
5		1-in.	½-in.	1½-in.	⅜-in.
	56				
	57				
6		¾-in.	⅜-in.	1-in.	No. 4.
	67				
	68				
7		½-in.	No. 4.	⅝-in.	No. 8.
	78				
8		⅜-in.	No. 8.	½-in.	No. 16.
9		No. 4.	No. 16.	⅜-in.	No. 50.

grading series was developed by combining the basic gradings. These combinations of the basic gradings are identified by corresponding combinations of the single digit numbers. Thus, standard aggregate No. 357, shown in the second column of table 2, which immediately follows No. 3 in the SPR table of gradings (table 1), is a combination of standard sizes Nos. 3, 5, and 7 in such proportions as to conform to the grading-band limits that were assigned to it. Similarly, standard aggregate No. 56, following No. 5, is a combination of standard sizes Nos. 5 and 6 in such proportions as to conform to the grading-band limits assigned to it.

Gradings Nos. 1F, 2F, G1, G2, and G3, listed in table 1, do not apply to highway work and are not included in the abridged version of table 1 that has been published in the AASHO and ASTM Standards. Item 10 (table 1) represents screenings and may be considered more or less a residual material from aggregate crushing and processing. It is not generally subject to close control, as indicated by the wide limits on the amount passing the No. 100 sieve, and is not considered pertinent to this discussion.

3. *Flexibility.*—The SPR gradings permit a high degree of flexibility.

The standard, stock aggregates can be combined to produce any reasonable total grading for roadbuilding purposes when further combined with suitable sands or mineral filler.

Adoption by AASHO and ASTM

The original SPR issuance, R 163–36, was adopted, essentially as promulgated, by the American Society for Testing and Materials in 1937 as Tentative Specification D 448–37T. It was carried as a Tentative Standard, with revisions in 1941 and 1942, until 1947, when it was advanced to Standard. The Standard was revised in 1949 and in 1954 and now appears in ASTM publications as Standard Specification D 448–54.

The simplified practice recommendation, including its numbering system, was adopted to cover standard sizes of coarse aggregate for highway construction by the American Association of State Highway Officials in 1942 and was designated AASHO Specification M 43–42. With some exceptions the SPR gradings were also adopted that year for crushed stone and crushed slag, for various specific purposes as in AASHO Designation M 75–42, base course; M 76–42, bituminous concrete base course and others; and also M 80–42, coarse aggregate for portland cement concrete; but in these individual applications the SPR numbering system was not used by AASHO until 1949. Since that year, all features of the SPR scheme have, with minor deviations,[2] been generally included in AASHO specifications for specific items as well as in the general group specification for coarse aggregates for highway construction. Some slight revisions of M 43–42 were made in 1949 and the designation was changed to M 43–49 which is still carried.

The present SPR system does not provide complete gradings for portland cement concrete or bituminous paving mixtures because it does not cover sands or mineral fillers. For both of these, however, there are AASHO and ASTM standards.

Aggregates for Portland Cement Concrete

The adoption by AASHO and ASTM of the SPR system for coarse aggregates for portland cement concrete has just been described. With regard to sand for portland cement concrete, the need for standardization is now met by AASHO Specification M 6–51 and ASTM Specification C 33–59, which are very similar to each other, as shown in table 3, and both of which have proved satisfactory in use. Both gradings utilize the logarithmic sieve sizes and are therefore compatible with the SPR system.

Aggregates for Bituminous Paving Mixtures

Coarse aggregates

AASHO has two specifications for coarse aggregates for bituminous paving mixtures: one for bituminous concrete base course, M 76–51, and one for bituminous concrete surface course, M 79–51. However, each of these is somewhat lacking in desirable flexibility in that only two SPR aggregate sizes are provided in each case.

[2] These deviations are as follows:
Size designation No. 3 (2 in. to 1 in.): Percentage passing the 2-in. sieve: 90–100 (SPR 163–48); 95–100 (AASHO M 43–49); 90–100 (ASTM D 448–54).
Size designation No. 67 (¾-in. to No. 4): Percentage passing the ¾-in. sieve: 90–100 (SPR 163–48); 90–100 (ASTM D 448–54); 95–100 (AASHO M 80–51); 90–100 (AASHO M 43–49).

Table 3.—AASHO and ASTM sand gradings for portland cement concrete

Sieve size	Percentage passing sieve: AASHO M 6–51	Percentage passing sieve: ASTM C 33–59
⅜-in.	100	100
No. 4	95–100	95–100
No. 8		80–100
No. 16	45–80	[1] 50–85
No. 30		25–60
No. 50	[2] 10–30	[2] 10–30
No. 100	[3] 2–10	[3] 2–10

[1] Prior to 1962 these requirements were 45–80.
[2] These requirements may be changed to 5–30; see referenced specifications.
[3] These requirements may be changed to 0–10; see referenced specifications.

B.2.4 Instrumentation Calibration Verification

Provision should be made to allow for verification of the signal conditioning instrumentation calibration (to account for the effects of zero and gain drifts).

General Requirements for Calibration Signal

The minimum acceptable facility for verification of conditioning instrumentation is a calibration signal subsystem. The calibration signal should be provided from such a source and in such a manner that there is little likelihood of variation in the calibration signal itself. This assurance then permits the operator to make adjustments in the measurement subsystem gain to offset the frequent small deviations which occur due to changes in ambient temperature and other operating parameters.

Force Measurement Calibration Signal

The most straightforward technique for providing a force measurement calibration signal is to make provisions for switching a high quality shunting resistor of known value in parallel with one arm of the force transducer strain gauge bridge. This induces an imbalance in the bridge equivalent to the application of a known force to the transducer. The resultant signal is sufficient to verify, or provide means of adjustment for, all elements of the force measurement system forward of the transducer itself.

Frequency of Use

Instrumentation calibration verification through use of calibration signals should be accomplished at the beginning of each day's operation after equipment warm up, at intervals of no more than 2 hours when the system is in continuous use, and upon the renewal of operation throughout the day after any period during which the signal conditioning equipment has been turned off or the unit has been allowed to stand without use for 30 minutes or more.

B.2.5 Check List

A check list should be available to the crew and should be used prior to the beginning of daily operations and on any occasion during the day when testing is is not, by any means, the only design factor for the grading bands for bituminous paving mixtures, it has had a predominating influence.

The second design step for bituminous paving mixtures consists of either determining or estimating the appropriate amount of bituminous binder to use. Here again practice has been established on the basis of experience and judgment in some cases while well established laboratory procedures, based on laboratory and field research, are used in others. In the latter case, the predominating factor determining suitable bitumen content is related to density or specifically to the void spaces available for binder in the compacted aggregate and the effect of overfilling or underfilling these voids on the stability and weather resistance of the plastic paving mixture.

Portland cement concrete

The situation with regard to portland cement concrete design is quite different. The design controls for concrete in present-day practice are fineness modulus, cement factor, and water-cement ratio with the cement factor and water-cement ratio being the primary variables used in designing for a specific strength range. The cement factor and water-cement ratio may also be varied to some extent to affect workability as measured by the slump test, with plasticizers being used occasionally to improve workability and strength. From the practical standpoint of field control, no one factor so adversely affects the strength and uniformity of the concrete as lack of control of water content. The proportions are set up on the basis of laboratory trial mixtures, utilizing the aggregates for the specific job and taking into consideration such factors as particle shape and surface texture, absorption, and others. Little or no use is made of total grading bands that might be set up on the basis of density or other possible design factors related to overall grading.

The practice of setting up the mixture for each job on the basis of laboratory tests is followed for reasons of practicality even though, for many years, research was conducted to develop the relations between the density of the aggregate, as influenced by the grading, and the quality of concrete.[3]

[3] Reference is made to this research and to the relations so established in *A Treatise on Concrete, Plain and Reinforced*, by F. W. Taylor and S. E. Thompson, 3d edition, 1916.

Table 7.— Composition of asphalt paving mixtures (from table III, ASTM specification for hot-mixed, hot-laid asphalt paving, Designation D 1663–59T)

Sieve size	Nominal maximum size of aggregates							
	2-in.	1½-in.	1-in.	¾-in.	½-in.	⅜-in.	No. 4	No. 8
	Asphalt concrete						Sand asphalt	Sheet asphalt
GRADING OF TOTAL AGGREGATE (COARSE PLUS FINE, PLUS FILLER IF REQUIRED): AMOUNTS FINER THAN EACH LABORATORY SIEVE (SQUARE OPENING), PERCENTAGE BY WEIGHT								
2½-in.	100							
2-in.	90-100	100						
1½-in.		90-100	100					
1-in.	60-80		90-100	100				
¾-in.		40-80		90-100	100			
½-in.	35-65		60-80		90-100	100		
⅜-in.				60-80		90-100	100	
No. 4	15-50	20-55	25-60	35-65	45-70	60-80	90-100	100
No. 8 [1]	10-40	10-40	15-45	20-50	25-55	35-65	65-100	95-100
No. 16							40-80	85-100
No. 30							20-65	70-95
No. 50	2-16	2-16	3-18	3-20	5-20	6-25	7-40	45-75
No. 100							3-20	20-40
No. 200 [2]	0-4	0-5	1-7	2-8	2-9	2-10	2-10	9-20
ASPHALT CEMENT, PERCENTAGE BY WEIGHT OF TOTAL MIXTURE [3]								
	3½-7½	3½-8	4-8½	4-9	4½-9½	5-10	7-12	8½-12
SUGGESTED COARSE AGGREGATES, SPR SIZES								
	3 and 57	4 and 67	5 and 7 or 57.	67 or 68 or 6 and 8.	7 or 78	8		

[1] In considering the total grading characteristics of an asphalt paving mixture the amount passing the No. 8 sieve is a significant and convenient field control point between fine and coarse aggregate. Gradings approaching the maximum amount permitted to pass the No. 8 sieve will result in pavement surfaces having comparatively fine texture, while coarse gradings approaching the minimum amount passing the No. 8 sieve will result in surfaces with comparatively coarse texture.

[2] The material passing the No. 200 sieve may consist of fine particles of the aggregates or mineral filler, or both. It shall be free from organic matter and clay particles and shall be nonplastic when tested by the method of test for liquid limit of soils (ASTM Designation D 423), and the method of test for plastic limit and plasticity index of soils (ASTM Designation D 424).

[3] The quantity of asphalt cement is given in terms of percentage by weight of the total mixture. The wide difference in the specific gravity of various aggregates, as well as a considerable difference in absorption, results in a comparatively wide range in the limiting amount of asphalt cement specified. The amount of asphalt required for a given mixture should be determined by appropriate laboratory testing or on the basis of past experience with similar mixtures, or by a combination of both.

ASTM Grading Bands for Hot-Mix Asphaltic Paving Mixtures

As already indicated, density has been generally discarded as a direct design factor for portland cement concrete but not for bituminous paving mixtures. Concurrently with the work done recently in developing a set of three sand gradings for bituminous work, ASTM has also developed a system of grading bands for combined course, fine, and filler aggregates for sand asphalt, sheet asphalt, and asphaltic concrete. These gradings are presented as table III in ASTM Standard Specification D 1663-59T. They are reproduced here in table 7.

The same industry and consumer representatives that

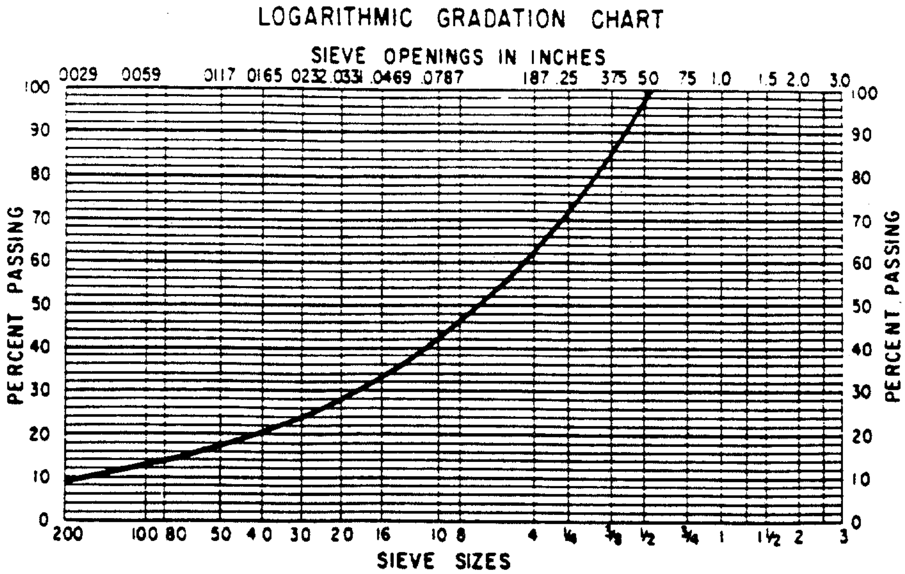


Figure 1.—A dense, stable grading plotted on the logarithmic gradation chart.

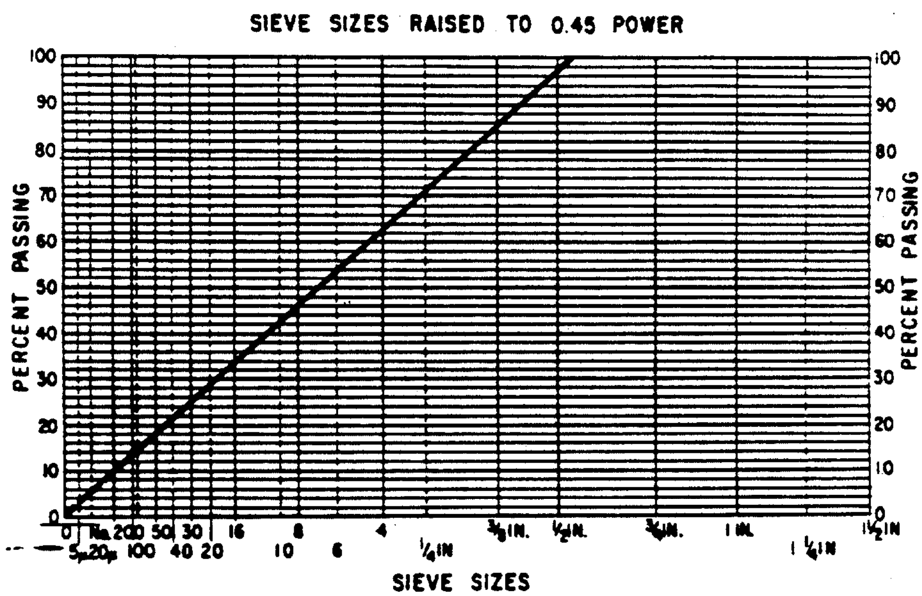


Figure 2.—Grading shown in figure 1 replotted on the 0.45-power gradation chart.

were previously named, also participated in this development. The ASTM composite gradings of table 7 are made up from SPR coarse aggregates and the ASTM sands and filler previously described. They are thus fully compatible with the SPR system. They have existed as ASTM Tentative Standards for only 2 years and were set up with the full realization that they might require some revision in the light of experience.

New gradation chart developed

In presenting the graphical material that is to follow, use is made of a new gradation chart devised by the Bureau of Public Roads, based on relations established by L. W. Nijboer of the Netherlands. Development of the chart is described in detail in the companion article in this bulletin.

In the plotting method now generally used, gradings that have proved to be highly compactible, and hence desirable as conducive to stability and resistance to moisture and weathering in bituminous paving mixtures, have a downward curving shape which is generally agreed to approximate the curve shown in figure 1. Here, the vertical scale is arithmetic and shows total percentage passing the various sieves, while the horizontal scale represents the logarithms of the sieve openings.

The simple expedient of using, for the horizontal scale, the sieve openings (inches or millimeters) raised to the 0.45 power, converts this particular curve to a straight line passing at its lower left extremity through zero percent for an imaginary sieve having zero-size openings, as shown in figure 2. Of course, grading curves having either greater or less curvature could be similarly straightened by using different exponents. It is believed, however, that the curve of figure 1 and its corresponding straight-line equivalent, figure 2, represents very nearly an ideal grading from the standpoint of density. Both research and experience indicate that the maximum particle size of the graded aggregate does not affect the shape of the maximum-density curve so that the straight-line principle using the exponent 0.45, or other basic curves and corresponding exponents, applies regardless of maximum size. The convenience of this device is readily apparent since it relieves those concerned with asphalt technology of the need to remember the exact shape of a specific curved line.

Problem mixtures

In recent years several State highway departments have reported one or more instances of difficulty with bituminous concretes produced under their own current specifications: the mixtures were hard to compact and remained "tender" for some time after rolling—that is, they were slow in developing stability. Others have reported instances of splotchy pavement surfaces where moisture was present in the aggregate. Some of these States have supplied information to the Bureau of Public Roads as to the aggregate gradings that produced these unsatisfactory mixtures.

It has been noted that, in nearly all cases, these gradings were characterized by a rise or hump in the grading curve, when plotted by the new method, because of disproportionately large quantities of finer sand fractions. It was further noted that the unsatisfactory mixtures did not contain what would be considered excessive amounts of filler, the fraction passing the No. 200 sieve.

In 1961, the Bureau of Public Roads conducted a

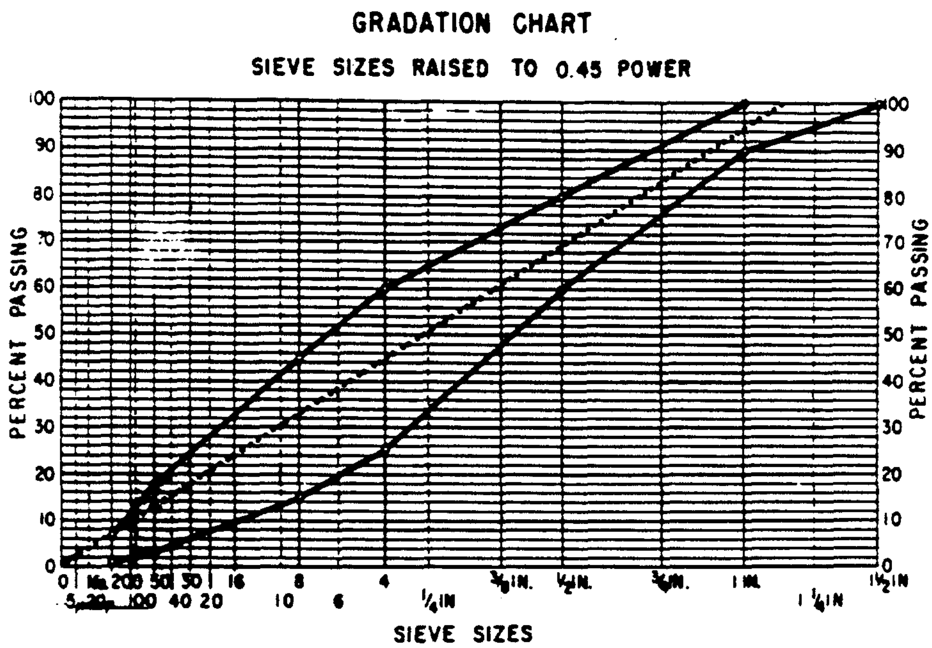


Figure 2.—ASTM limits, 1-inch nominal maximum size, compared with straight-line, maximum density grading.

laboratory study of this specific problem and utilized, for the first time, the new method of plotting gradings to facilitate interpretation of the results. Some of the results of that study are shown graphically here because they bear directly on the problem of grading control as treated in this report. They are fully reported and discussed in the companion article in this bulletin.

Among other things, the study showed that the laboratory test results were consistent with the unsatisfactory experience reported by the States on the problem mixtures described.

ASTM gradings need further study

The ASTM grading band for 1-inch maximum size asphaltic concrete is shown in figure 3 as illustrative of the eight sizes covered by ASTM Specification D 1663-59T and presented in table 7. Also shown in figure 3 is the straight (dotted) line that would represent the maximum-density grading if it can be assumed for this purpose that the maximum size for each grading may be arbitrarily established by passing the straight line midway between the upper and lower band limits for the largest sieve having both values shown.

Figures 4–6 show the aggregate gradings for the problem mixtures previously mentioned and the relation of their gradings to corresponding ASTM grading bands. These mixtures, which proved tender in the field or were splotchy when laid, were found to be low in stability when duplicated and tested in the laboratory. The two mixtures shown in figures 4 and 5 are representative of several cases in which the States reported the mixtures to be tender during construction and for considerable periods after rolling. The mixture shown in figure 6 represents several cases where splotchy pavements have been noted.

Since two of these typically humped gradings fall within the upper band limits of the corresponding ASTM gradings, even in the critical, fine sand zone, there is a strong indication that the upper band limits of the ASTM grading specifications for asphaltic concrete need some downward adjustment, at least at the No. 30 and No. 50 sieves, to further restrict the fine sand. However, a definite recommendation in this specific matter must await further study.

Basic Purpose of SPR System

The line of argument most frequently used by those opposing changes in grading control is that they are familiar and satisfied with what they are using and that they do not need or want new gradings. This points up the need for a clearer understanding of the basic purpose of the SPR scheme and of the ease with which any desired grading curve or band can be converted from one sieve-size system to another. The well established and fully validated graphical conversion method is illustrated in figure 7, which has a logarithmic horizontal scale. The equivalent straight line chart, exponent 0.45, is shown in figure 8.

In these two illustrations, an aggregate gradation band regularly specified by one of the State highway depart-

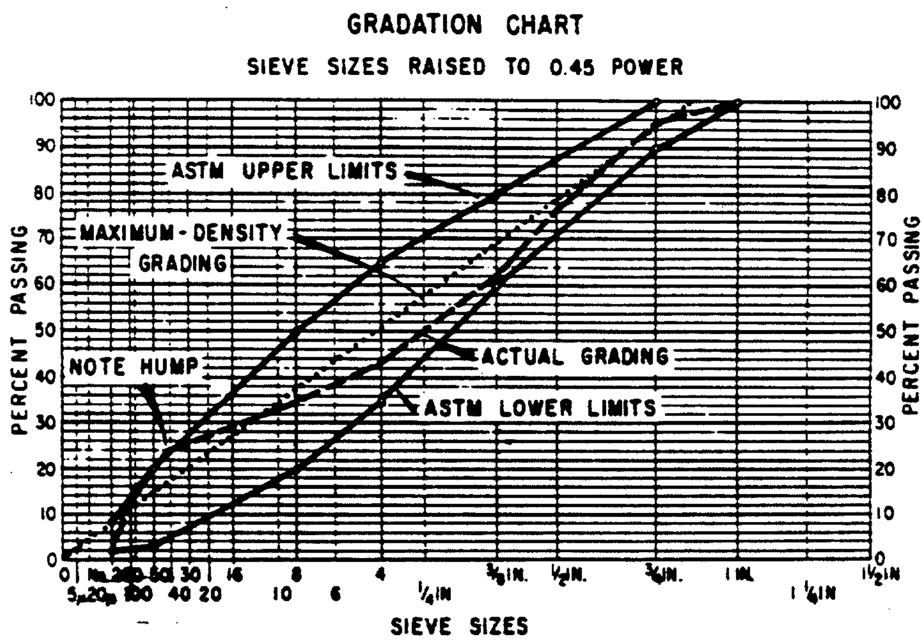


Figure 4.—Aggregate grading for a 3/4-inch nominal maximum size mixture identified as a "tender" mix.

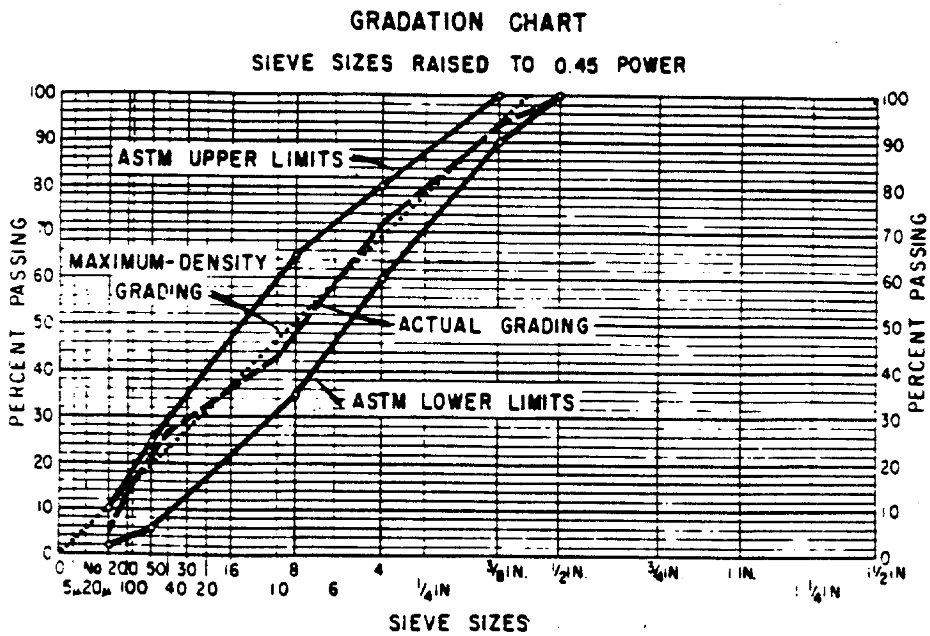


Figure 5.—Aggregate grading for a 3/8-inch nominal maximum size mixture identified as a "tender" mix.

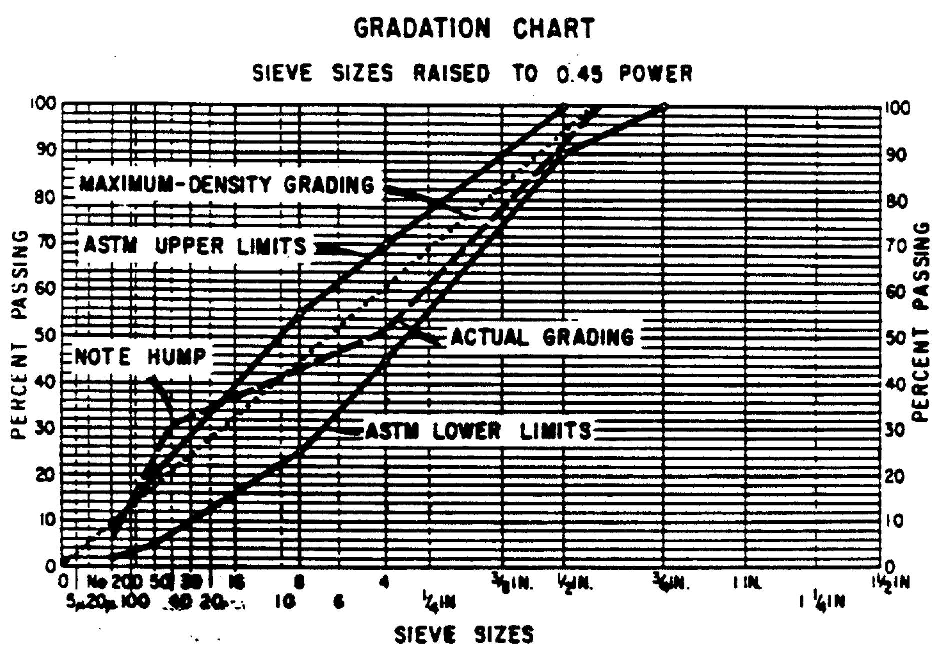


Figure 6.—Typical grading for a 1/2-inch maximum size mixture where a small amount of moisture in the aggregate has resulted in a splotchy pavement surface.

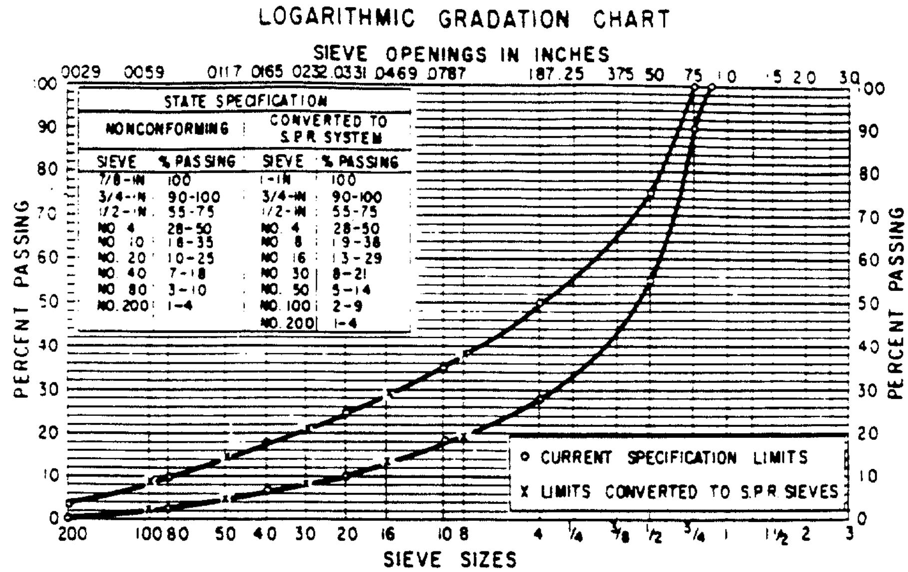


Figure 7.—Conversion of a current State specification to SPR sieve sizes, using the logarithmic gradation chart.

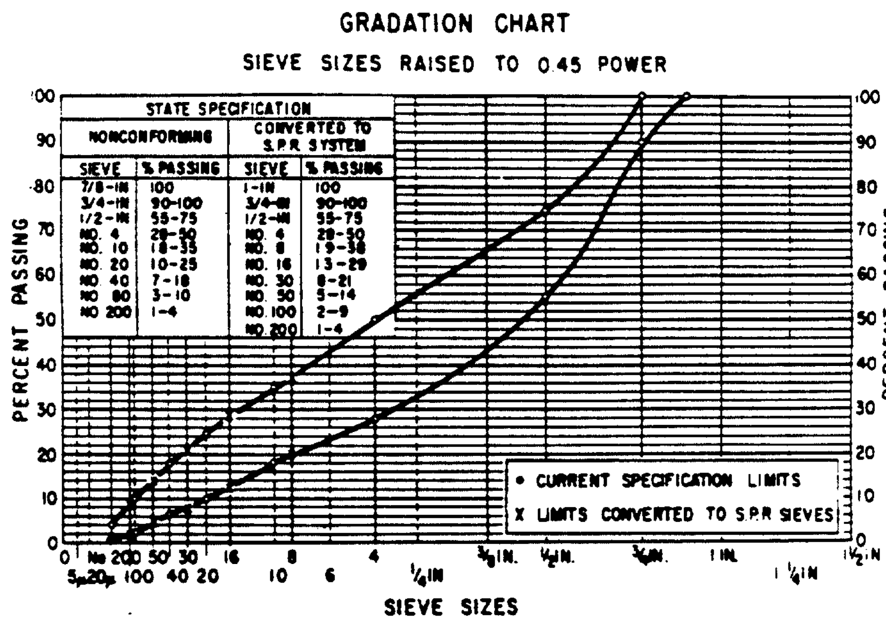


Figure 8.—Conversion of a current State specification to SPR sieve sizes, using the Public Roads gradation chart.

ments is converted from the sieve-size system traditionally used by the State to the SPR sieve-size system. The corresponding tabular gradings are shown on the charts. In making the conversion, no change is introduced in the shape or placement of the band limits and it can be stated with confidence that an aggregate produced to conform with either, will conform to the other.

Not only do these illustrations demonstrate the ease and convenience of converting other grading systems to the SPR system, or common language, but additionally, they demonstrate that the conversion does not involve changing the particle distribution of a specific, designed, or desired aggregate.

It should be pointed out in this connection that the use of the SPR sieve series to express total gradations, as for example, 1½-inch maximum size to No. 200, does not assure that specific desired gradings can always be made up from combinations of standard SPR numbered aggregate fractions with ASTM sand and filler, although in normal practice such situations should be comparatively rare.

Generally, the same freedom to modify grading band control limits to exploit field experience or the findings of research is inherent in the standardized scheme presented here as exists in the multiplicity of State specifications now in use. The need for some degree of freedom in this respect is fully recognized.

However, this philosophy cannot legitimately be used to justify the kind of trivial differences that account for a large proportion of the hundreds of aggregate gradations appearing in State specifications.

Recommended Course of Action

The study which is the subject of this report was undertaken for the purpose of furthering the three objectives mentioned—drastic reduction of "standard" gradations, agreement on sieve sizes, and agreement on a uniform system of identification of standard gradations. Because of the inherent flexibility of the SPR scheme, coupled with compatible sand and filler specifications now available as AASHO and ASTM standards, it is believed that a large proportion of the many special gradings now appearing in State specifications could be eliminated, thereby achieving important economies in highway construction. In many cases, it would only be necessary to convert to the SPR standard sieve sizes, as illustrated in figures 7 and 8, and to use SPR grading designations.

A desirable course of action and one that is strongly recommended for implementation by the American Association of State Highway Officials is essentially as follows:

1. Elimination from individual State specifications of all sieve sizes that are at variance with those officially adopted by AASHO and substitution therefor of conforming sieve sizes. This could be done easily by utilizing the method illustrated in figures 7 and 8. The new grading tables would provide the same gradations as those previously specified.

2. Elimination from individual State specifications of other gradation requirements not conforming to AASHO or related ASTM standards to the maximum practicable extent.

3. Retention for use, as special provisions or supplemental specifications, of such nonconforming gradation requirements as may be justified.

Standards Now Recommended

The following AASHO and ASTM standards are recommended for general use by all highway departments:

1. AASHO M 43–49, standard sizes of coarse aggregate for highway construction.

2. AASHO M 80–51, coarse aggregate for portland cement concrete.

3. AASHO M 6–51, fine aggregate for portland cement concrete.

4. ASTM D 692–59T, coarse aggregate for bituminous paving mixtures.[4]

5. ASTM D 1073–59T, fine aggregate for bituminous paving mixtures.

6. ASTM D 242–57T, mineral filler for sheet asphalt and bituminous concrete pavements.

In addition to the above six standards, the following tentative standard is recommended for study, possible revision, and general use:

7. ASTM D 1663–59T, hot mixed, hot laid asphalt paving mixtures.

[4] Requires one revision for adoption by AASHO to conform to AASHO M 43–49, namely for aggregate No. 3 the percentages passing the 2-in. sieve would have to be changed from 90–100 (ASTM) to 95–100, as now required in AASHO M 43–49.

The third approach is a compromise in which the pipe is wrapped in a filter fabric and the trench is backfilled with a filter aggregate or coarse sand as shown in the bottom sketch of Figure 6. In this approach, the aggregate acts as a filter keeping the fines from clogging the filter fabric. The coefficient of permeability of the filter aggregate material varies, but it is generally much lower than an open-graded aggregate backfill.

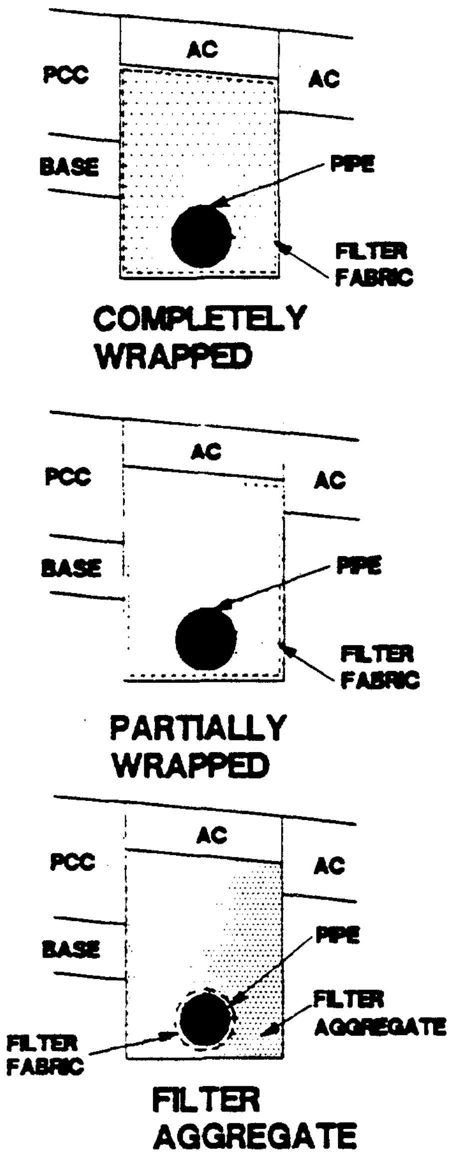


Figure 6. COMPARISON OF EDGEDRAIN DESIGN

It is pointed out that in all of the approaches any erodible fines in the base course will be washed out. The difference in the approaches is the manner in which the fines are handled.

It should be noted that there is no way to prevent a filter adjacent to a material with a high percentage of fines from eventually clogging. If of sieve sizes (see fig. 7 in the preceding article, p. 10). This chart, which will be referred to hereafter as the logarithmic gradation chart, has had wide use for some 30 years and has proven valuable in illustrating individual gradations and determining their position relative to specification limits. This type of chart, however, has one significant disadvantage in that it shows a maximum density gradation as a deeply sagging curve, the shape of which is hard to define.

To provide a better means of relating actual aggregate gradation to maximum density gradation, a new chart has been devised by the Bureau of Public Roads. The horizontal scale for the several sieve sizes of this chart is a power function rather than the logarithm of the sieve opening in microns. The vertical scale is arithmetical, the same as for the logarithmic chart. An important feature of the new chart is that it provides for a zero theoretical sieve size. Thus, for practical purposes, all straight lines plotted from the lower left corner of the chart, at zero percent passing zero theoretical sieve size, upward and toward the right to any specific maximum size, represent maximum density gradations. The exponent of the power function is 0.45, i.e., the horizontal scale represents the various sieve openings in microns raised to the 0.45 power.

Background of development

The selection of the 0.45 exponent was based on research performed by L. W. Nijboer of the Netherlands and first published in 1948.[3] Nijboer used a double logarithmic gradation chart in a study of the influence of aggregate gradation on mineral voids. All gradations used in his study were represented by straight lines, with various slopes, when plotted on his chart; the variation in slope resulting from his use of several different gradations of the same maximum (3/4-inch) size. Nijboer made two series of tests on compacted bituminous mixtures, using rounded gravel for the coarse aggregate in one series of tests and an angular crushed stone in the other. Mineral voids were determined for all of the mixtures and were plotted

[3] *Plasticity as a Factor in the Design of Dense Bituminous Road Carpets*, by L. W. Nijboer, Elsevier Publishing Co., 1948.

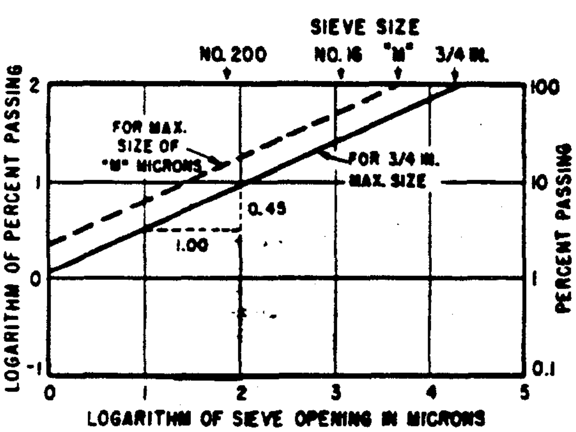


Figure 1.—Maximum density gradation plotted on a double log chart.

against the slopes of the straight line gradation curves. For both types of coarse aggregate, the minimum mineral voids, or maximum aggregate density, occurred for a gradation having a slope of 0.45 on the double log chart.

Figure 1 shows this maximum density gradation for a 3/4-inch maximum size aggregate plotted on a double log chart. The figure also illustrates a maximum density curve for a gradation with a maximum size designated as M microns. for the following discussion in which it is assumed that all maximum density curves have a slope of 0.45 on the double log chart regardless of maximum size.

In developing the equation for a maximum density curve let:

M = maximum size of aggregate in microns.

S = size of opening for a particular sieve.

P = percentage passing the particular sieve.

$\log B$ = intercept on vertical axis of the chart

The general equation of the curve is:

$$\log P = \log B - 0.45 \log S \quad \ldots\ldots\ldots\ldots (1)$$

Other equations are:

$$\log 100 - \log B = 0.45 (\log M - \log 1); \text{ or}$$

$$2 - \log B = 0.45 (\log M); \text{ or}$$

$$\log B = 2 - 0.45 \log M \quad \ldots\ldots\ldots\ldots (2)$$

Substituting equation (2) in equation (1) we have:

$$\log P = 2 - 0.45 \log M - 0.45 \log S; \text{ or}$$

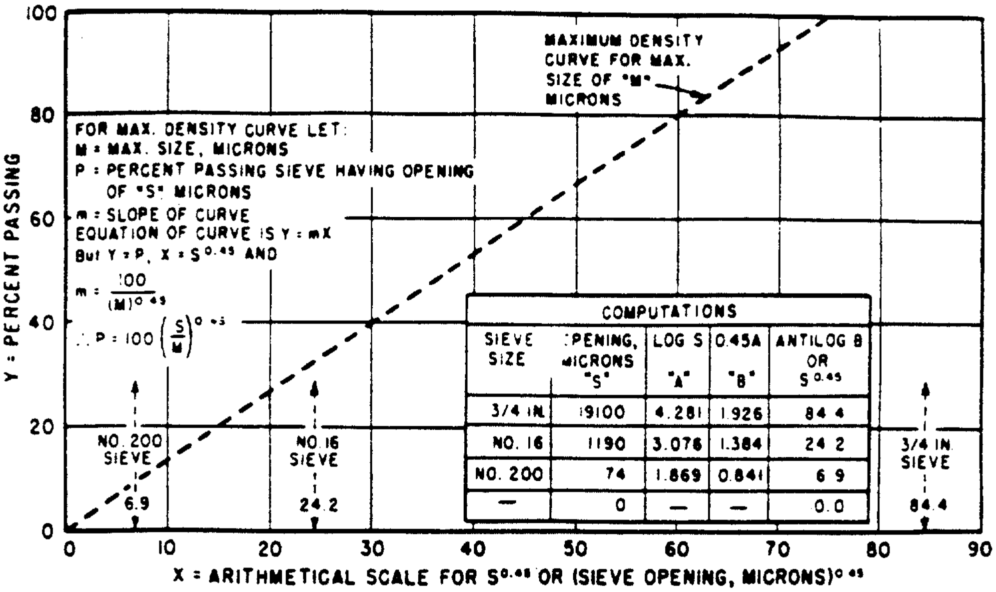
$$\log P = 2 - 0.45 (\log S - \log M); \text{ or}$$

$$P = 100 \left(\frac{S}{M}\right)^{0.45} \quad \ldots\ldots\ldots\ldots (3)$$

The exponent in equation (3) is the one used in designing the new gradation chart. By the use of logarithms, the sizes of sieve openings in microns were raised to the 0.45 power. These values were then employed with a suitable arithmetical scale for establishing the horizontal position of each sieve. The procedure is illustrated for a few of the sieve sizes on figure 2.

Figure 2 also illustrates how maximum density gradation is indicated for a gradation having a maximum size of M microns: simply by plotting a straight line from the origin, at the lower left corner of the chart, to the selected maximum size at the top of the chart. As can be seen from the information on the left side of the chart, the equation for such a line is that shown above as equation (3). Thus, any gradation that will plot as a straight line through the origin of the new chart will also plot as a straight line on the double log chart of Nijboer and will have a slope of 0.45.

The new gradation chart described in this article, and hereafter referred to as the Public Roads gradation chart, is not, strictly speaking, an entirely new type. The National Crushed Stone Association, in its *Crushed Stone Journal*, has been using a square-root gradation chart for several years to illustrate gradations. The only difference between the Association's chart and the new one presented here is that the former is based on an exponent of 0.50 for the power function instead of 0.45. The research of Nijboer and data to be presented later in this article show that 0.45 is a more realistic value for indicating maximum density.



SIEVE SIZE	OPENING, MICRONS "S"	LOG S "A"	0.45A "B"	ANTILOG B OR $S^{0.45}$
3/4 IN.	19100	4.281	1.926	84.4
NO. 16	1190	3.076	1.384	24.2
NO. 200	74	1.869	0.841	6.9
—	0	—	—	0.0

Figure 2.—Illustration of computations and method of positioning sieve sizes in setting up the Public Roads gradation chart.

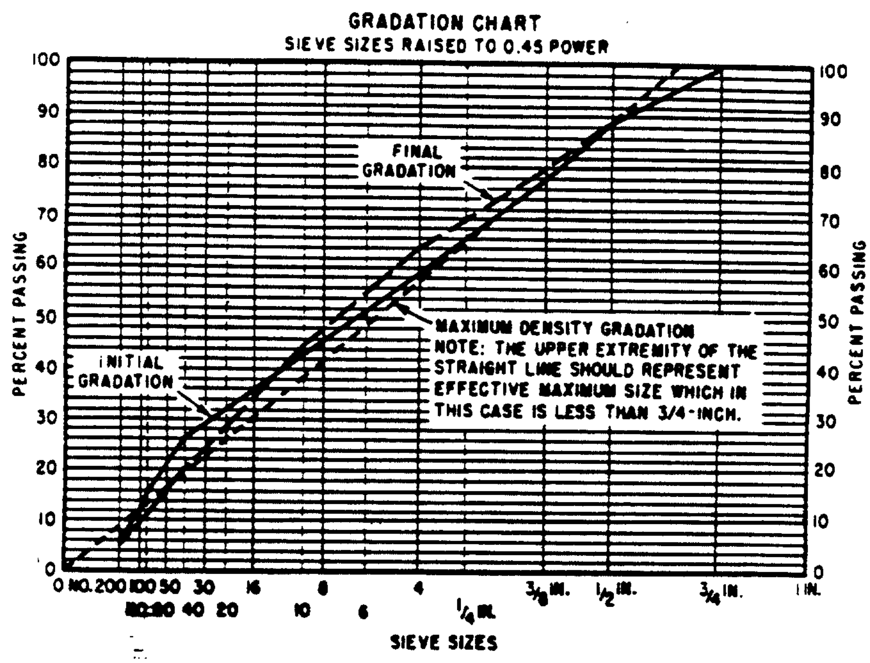


Figure 3.—Gradations of problem mixture (project A) compared with maximum density gradation.

Using Chart in Study of Tender Mixes

Soon after the Public Roads gradation chart was developed it was used to study gradations of aggregate from several bituminous mixtures that had been reported as having unsatisfactory compaction characteristics. During the past 4 or 5 years, engineers have reported several instances of hot asphaltic concrete mixtures that conformed to their specifications but could not be compacted in the normal manner because they were slow in developing sufficient stability to withstand the weight of rolling equipment. Such mixtures are usually called "tender" mixes.

Those having experience with such mixtures have tended to place most of the blame on the particular asphalt used. Occasionally it was recognized that such factors as high temperatures of the mixture, the air, and the underlying structure, excessively heavy rolling equipment, or the presence of moisture in the mixture might contribute to the unsatisfactory condition. The possibility was very seldom considered that aggregate gradation could be an equally important factor and that the grading requirements used could be contributing to this problem.

To illustrate the type of aggregate gradation that seems to be rather consistently associated with tender mixtures, some specific examples from three different parts of the country are discussed in the paragraphs that follow.

On a 1958 construction project, identified as project A, the engineers were careful to select cold feed materials and proportions for the wearing course mixture that would provide a median gradation within the specification limits. Despite these precautions, the resulting mixture had the characteristics of a tender mix. It was described as a critical mixture which did not compact satisfactorily at any asphalt content within the specification limits. At asphalt contents only slightly below the one that was most nearly satisfactory, the mixture was friable and developed cracks behind the finishing machine. At only slightly higher asphalt contents the mixture was too unstable to compact.

Although the engineers suspected the asphalt was at fault they decided to try a modified gradation, which resulted in a less critical mixture with greatly improved compaction characteristics. The initial and final gradations and the corresponding maximum density gradation are shown plotted on the Public Roads gradation chart in figure 3. Attention is called to the hump in the curve above the maximum density line at the Nos. 50, 40, and 30 sieve sizes for the initial gradation used in the unsatisfactory mixture and to the absence of a hump at these sieve sizes for the final gradation which produced the more satisfactory mixture.

Figure 4 shows gradations used on three other projects, each having a hump above the maximum density line at about the No. 30 sieve when plotted on the Public Roads chart. Two of these, for projects B and D, built in 1958 in a different State than project A, are gradations of mixtures containing gravel and sand that were described

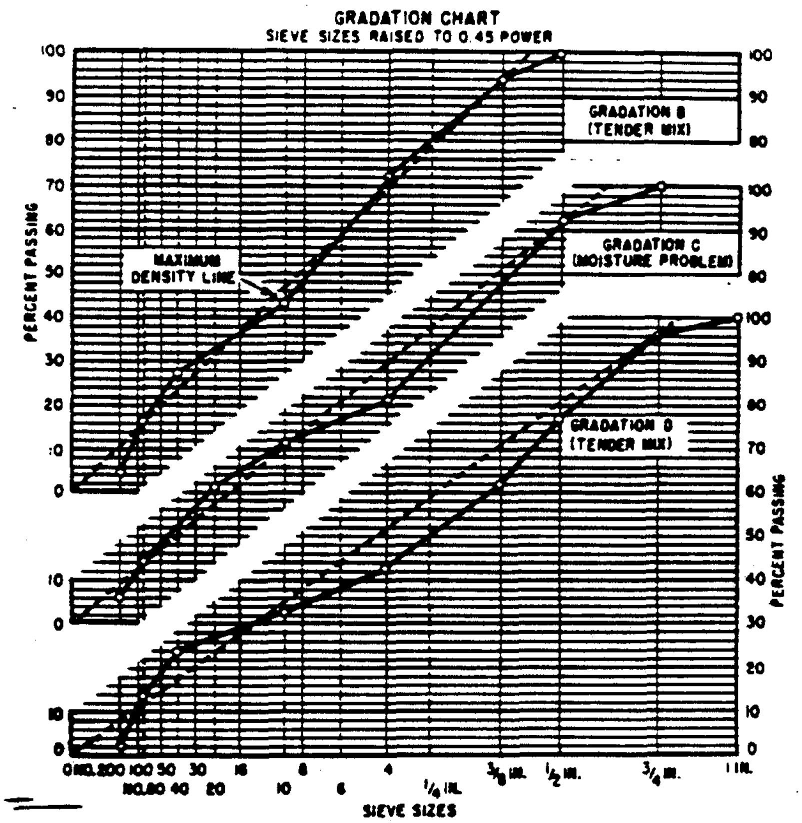


Figure 4.—Gradations of problem mixtures (projects B, C, and D) compared with maximum density gradations.

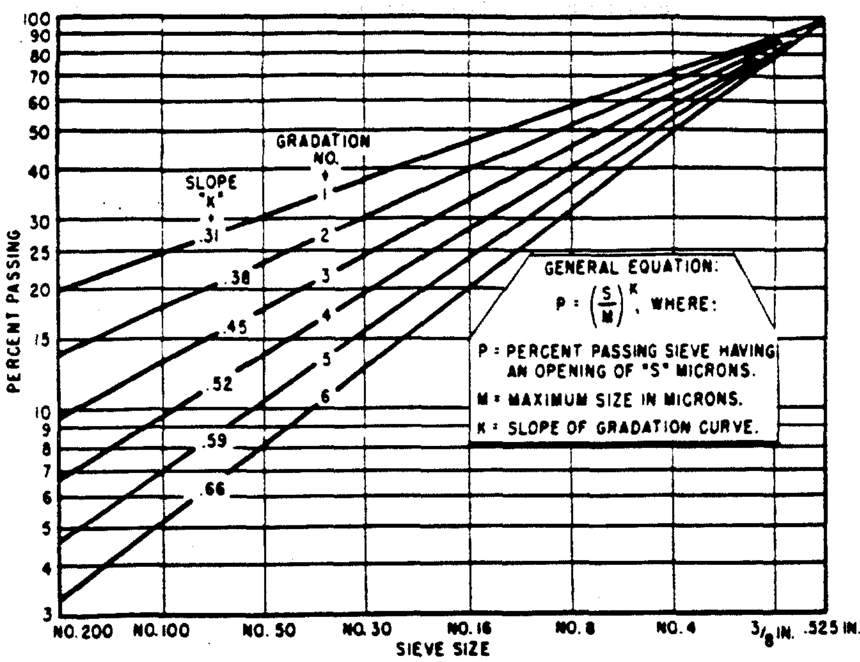
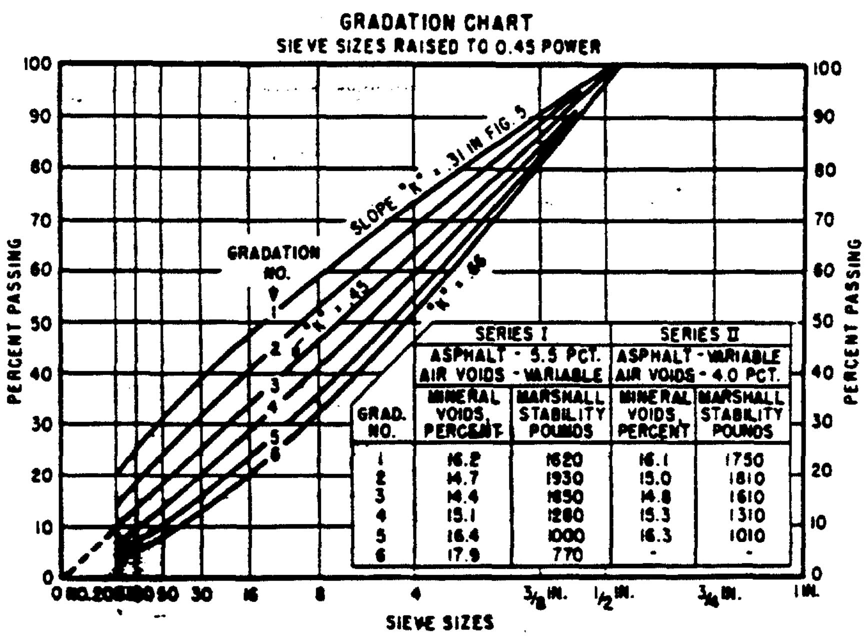


Figure 5.—Gradations Nos. 1-6 plotted on double log chart.



GRAD. NO.	SERIES I: ASPHALT - 5.5 PCT. AIR VOIDS - VARIABLE: MINERAL VOIDS, PERCENT	SERIES I: MARSHALL STABILITY POUNDS	SERIES II: ASPHALT - VARIABLE AIR VOIDS - 4.0 PCT.: MINERAL VOIDS, PERCENT	SERIES II: MARSHALL STABILITY POUNDS
1	16.2	1620	16.1	1750
2	14.7	1930	15.0	1810
3	14.4	1650	14.8	1610
4	15.1	1280	15.3	1310
5	16.4	1000	16.3	1010
6	17.9	770	-	-

Figure 6.—Gradations Nos. 1-6 (straight-line gradations in fig. 5) plotted on the Public Roads gradation chart.

as tender mixes. The third gradation, for project C, is typical of those used in a State which has had considerable difficulty with moisture problems in laying bituminous pavements containing certain coarse aggregates. A very small amount of moisture in such mixtures often results in a splotchy pavement surface.

There have been exceptions, but nearly all gradation curves of problem mixtures studied by the research laboratories of the Bureau of Public Roads have been characterized by a hump above the maximum density line at or near the No. 30 sieve. Such mixtures have an excess of fine sand in relation to total sand. This excess not only results in lower compacted densities but tends to float the larger particles and destroy stability that might otherwise result from coarse aggregate interlock. In addition, fine sand is inherently less stable than coarse sand.

Thus, improper aggregate gradation is identified as an important contributing factor to the unsatisfactory behavior of some bituminous mixtures. Other factors, such as asphalt characteristics, high temperatures, and moisture vapor cannot be ruled out; but unsatisfactory grading, particularly oversanding in the fine sizes, must not be overlooked as a possible source of trouble.

Laboratory Evaluation of Gradation Chart

To evaluate further the usefulness of the new Public Roads gradation chart, a laboratory study was undertaken with two main objectives: To substantiate Nijboer's findings, and to determine more precisely the effect of "hump" gradations on mineral voids and stability of compacted asphaltic concrete. The study employed the gyratory method of molding and the Marshall stability test.

The investigation was limited to 24 different gradations of gravel, sand, and limestone dust aggregate having a maximum size of 0.525 inch. These gradations are shown in table 1 of the appendix (p. 24), together with values for effective specific gravity values which were used in computing voids.

Verification of 0.45 exponent

In order to verify Nijboer's findings, the first six gradations were made up so that they would plot as straight lines with varying slopes *K* on the double log chart, as shown in figure 5. When plotted on the New Public Roads

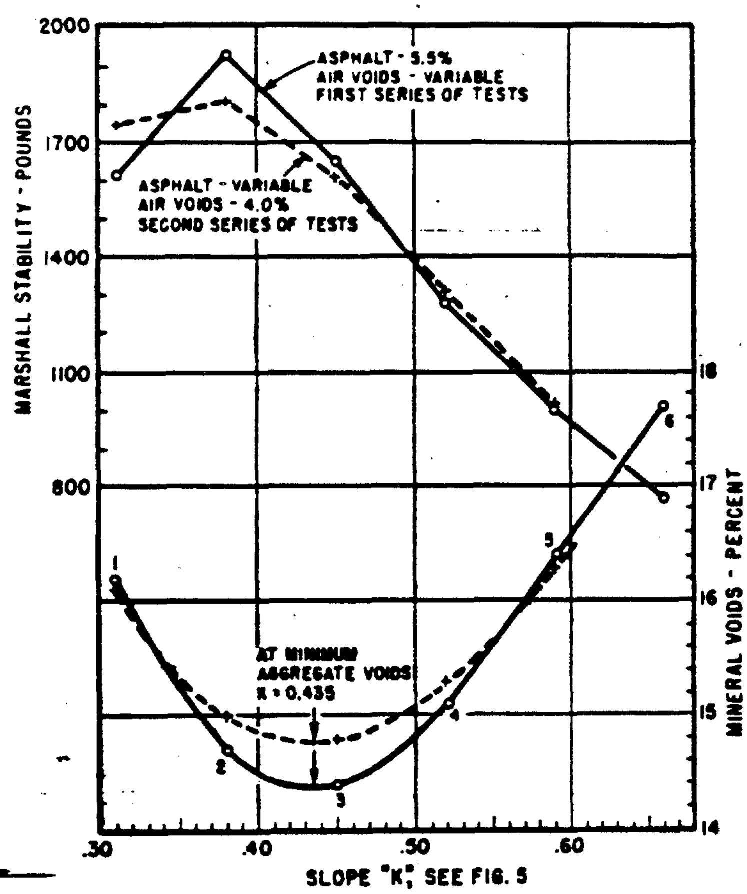


Figure 7.—Mineral voids and Marshall stabilities of gradations Nos. 1–6.

4.8.20

gradation chart, figure 6, five of these gradings plotted as curves because of the variations in the exponent K. Only gradation No. 3, which had a slope (or exponent K) of 0.45 in figure 5, plotted as a straight line in figure 6. Figure 6 also contains, for ready reference, data on mineral voids and Marshall stability extracted from table 4 of the appendix. It will be noted that the aggregates were combined with asphalt in two series of mixtures, one with constant asphalt content of 5.5 percent and the other with variable asphalt content to produce constant air voids of 4.0 percent.

Figure 7 shows the Marshall stability and mineral void values in graphical form. In the upper part of this figure, Marshall stability (see tabulation, fig. 6) is plotted against K or slope from the double log chart (see fig. 5). The solid-line curve represents test results for a constant percentage of asphalt, the first series of tests; the dashed line represents results for a constant percentage of air voids, the second series of tests. Corresponding curves for mineral voids are shown in the lower part of the figure.

It will be noted in figure 7 that minimum aggregate voids, or maximum aggregate densities, occur at the point where K equals 0.435. This is slightly lower than Nijboer's value of 0.45 on which the new Public Roads gradation chart is based, but the slight difference is not considered significant. Figure 7 also shows that the value of K had a pronounced effect on Marshall stability for both series of tests. For the coarsest grained aggregate (grading No. 6, for which $K=0.66$), stability was less than 800 pounds. For the finest grained aggregate of the study (grading No. 1, for which $K=0.31$), stability was between 1,600 and 1,750 pounds for the two series. The maximum values for the two series were between 1,800 and 1,950 pounds.

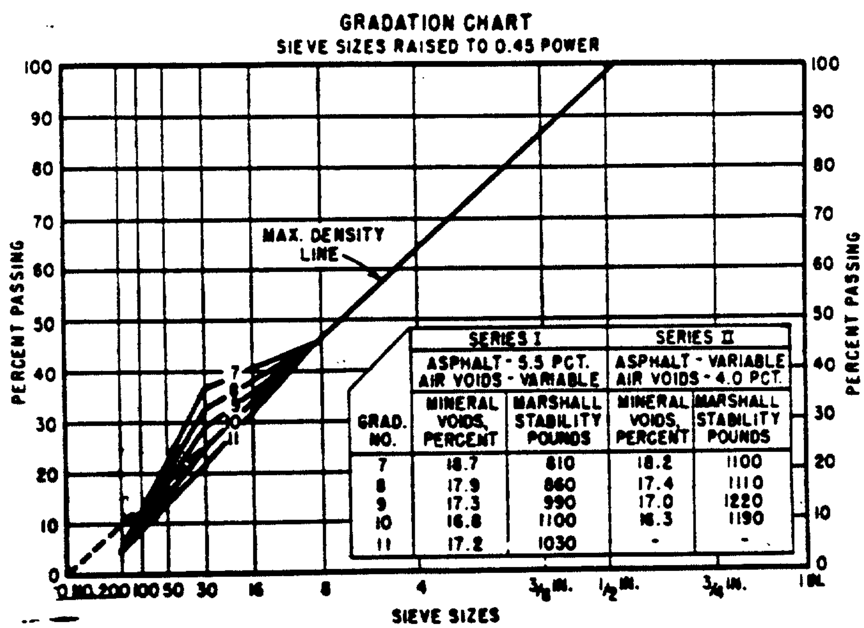
Study of "hump" gradations

Figures 8–10 use the Public Roads gradation chart to illustrate gradations that plotted with a hump at the No. 30 sieve size and to compare them with a maximum density curve (gradations Nos. 7–11 and 13–21, shown in table 1 of the appendix). Each of these figures also includes a tabulation (extracted from table 4 of the appendix) showing mineral voids and stability for mixtures with constant asphalt content and with a constant volume of air voids.

Figure 8 shows the gradation curves and test results for gradations Nos. 7–11, each of which had 46.0 percent passing the No. 8 sieve, the same as that for the maximum density curve. These gradations are considered optimum in the amount of total sand.

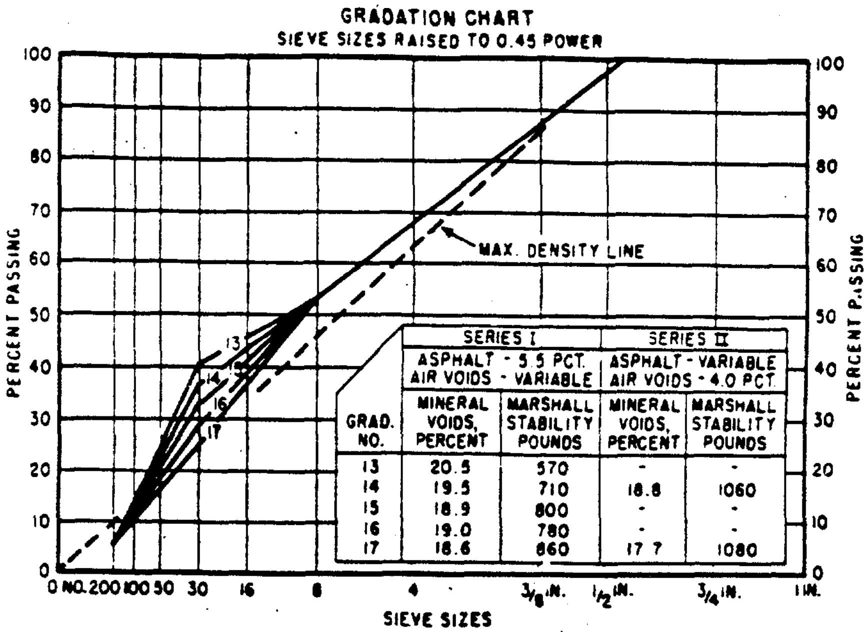
As will be seen in figure 8, the curve for gradation No. 11 plotted as a straight line from the No. 8 sieve to the No. 200 sieve and this portion of the curve is below the maximum density line. The curve for gradation No. 10 is on the maximum density line from maximum size to the No. 30 sieve but then drops below the maximum density line to the No. 200 sieve; it therefore has a slight hump at the No. 30 sieve but the fact that this hump is not above the maximum density line is considered significant since gradation No. 10 had the lowest mineral voids of this group of gradations for both series of tests, and also had the highest stability for the series in which asphalt content was maintained constant. Its stability was only 30 pounds lower than the highest value in the second test series, where air voids were maintained constant.

The humps at the No. 30 sieve size for gradations Nos. 9, 8, and 7 are progressively larger than that for gradation No. 10 and are all above the maximum density line. As the humps become more pronounced the gradations show increasing void contents and decreasing stabilities.



GRAD. NO.	SERIES I: ASPHALT - 5.5 PCT. AIR VOIDS - VARIABLE		SERIES II: ASPHALT - VARIABLE AIR VOIDS - 4.0 PCT.	
	MINERAL VOIDS, PERCENT	MARSHALL STABILITY POUNDS	MINERAL VOIDS, PERCENT	MARSHALL STABILITY POUNDS
7	18.7	810	18.2	1100
8	17.9	860	17.4	1110
9	17.3	990	17.0	1220
10	16.8	1100	16.3	1190
11	17.2	1030	-	-

Figure 8.—Hump gradations of gravel mixtures, medium in total sand.



GRAD. NO.	SERIES I: ASPHALT - 5.5 PCT. AIR VOIDS - VARIABLE		SERIES II: ASPHALT - VARIABLE AIR VOIDS - 4.0 PCT.	
	MINERAL VOIDS, PERCENT	MARSHALL STABILITY POUNDS	MINERAL VOIDS, PERCENT	MARSHALL STABILITY POUNDS
13	20.5	570	-	-
14	19.5	710	18.8	1060
15	18.9	800	-	-
16	19.0	780	-	-
17	18.6	860	17.7	1080

Figure 9.—Hump gradations of gravel mixtures, high in total sand.

Figure 9 shows the gradation curves and test results for gradations Nos. 13–17, all of which had 53.3 percent passing the No. 8 sieve and are considered high in total sand when compared to the gradations shown in figure 8.

The curve for gradation No. 17 does not have a hump at the No. 30 sieve size; it is a straight line from the No. 8 to the No. 200 sieve and intersects the maximum density curve at the No. 30 sieve. This gradation showed the lowest value of mineral voids for the group. The curve for gradation No. 16 has a slight hump above the maximum density curve at the No. 30 sieve size, and gradation curves Nos. 15, 14, and 13 have increasingly larger humps. Allowing for experimental error, it will be noted that, in general, increasing magnitude of the hump corresponded with increasing mineral voids and decreasing stability for the series of tests where the asphalt was maintained constant. Where the air voids were maintained constant, in the two instances shown, there was a slight increase in mineral voids but no significant change in stability.

Figure 10 shows the curves for gradations Nos. 18–21, which had 38.9 percent passing the No. 8 sieve and are considered low in total sand when compared to the gradations shown in figure 8.

The entire curve for gradation No. 21 plotted below the maximum density line and has a very slight hump at the No. 30 sieve size. The curve for gradation No. 20 has a slight hump and touches the maximum density line at the No. 30 sieve size; otherwise it is completely below the maximum density line. This is considered significant since gradation No. 20 had the lowest mineral voids and the highest stability of this group of gradations in both series of tests.

Gradation No. 19 had a considerable hump at the No. 30 sieve size, above the maximum density curve. This gradation had greater mineral voids and less stability than those of gradation No. 20. Gradation No. 18 had the largest hump of the group and it also had the highest percentage of mineral voids and the lowest stabilities.

Conclusions on hump gradations

The above discussions, based on figures 9–10, of humps in gradation curves at the No. 30 sieve size, may be summarized as follows:

1. A hump above the maximum density line in all cases was associated with a lower aggregate density (higher mineral voids) than a hump that just touches the maximum density line.

2. In nearly all cases the hump also was associated with a lower Marshall stability value. The reduction in stability was more pronounced for the series of tests in which the asphalt content was maintained constant than for the series in which the asphalt content was varied to provide a constant volume of air voids.

3. The greater the magnitude of the hump above the maximum density line, the lower was the aggregate density (in all cases) and the stability (in nearly all cases).

Thus, based on results of laboratory tests of gravel mixtures, the presence of a hump in the aggregate gradation curve at about the No. 30 sieve and above the maximum density line is indicative of an undesirable gradation. The extent to which differences in laboratory density and stability can be related to field compaction and performance characteristics is not now known. However, the results of these laboratory tests and studies of known field examples discussed earlier do show that "hump" gradations may be a contributing factor toward the unsatisfactory behavior of mixtures. Further verification of their effect should be determined by controlled field studies.

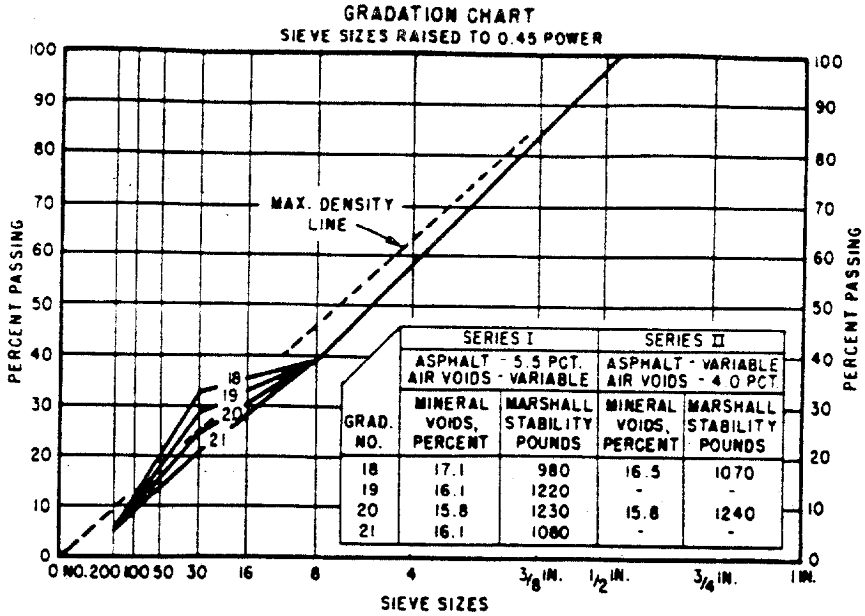


Figure 10.—Hump gradations of gravel mixtures, low in total sand.

Use of chart in improving gradations

One of the advantageous uses of the Public Roads gradation chart is in revising gradations to obtain greater or lesser mineral voids. Often it is desirable to decrease the mineral voids to provide a more stable mixture. At other times it is desirable to increase the mineral voids to allow room for more asphalt in the mixture and thereby improve its durability: for example, McLeod [3] prefers to maintain a minimum of 15-percent mineral voids in the compacted mixture.

Based on this 15-percent voids criterion the maximum density gradation used in these tests, No. 3, would not be satisfactory since it had mineral voids of 14.4 and 14.8 percent, respectively, for the first and second series of tests. Gradation No. 10, which is similar to gradation No. 3 except for a lower dust content, would be satisfactory because its respective mineral voids were 16.8 and 16.3 percent, appreciably greater than the 15-percent criterion. Thus, one effective way of modifying a gradation to provide greater or lesser mineral voids is to change its dust content. However, this may not be practical or it may be more economical to modify the gradation at other sieve sizes.

If the modification is to be made by varying the gradation of the sand portion, figures 8–10 suggest that it might be done by increasing or decreasing the percentage passing the No. 30 sieve for the entire aggregate while maintaining constant the percentages passing the No. 8 and No. 200 sieves. In figure 10, for example, if gradation No. 19 should prove too dense it could be modified to a less dense gradation by increasing the percentage of aggregate passing the No. 30 sieve and thereby moving the gradation curve away from the maximum density line: or it could be made denser by reducing the percentage passing the No. 30 sieve to bring the curve closer to the maximum density line.

If, however, the modification is to be made by adjusting the percentage of sand or by varying the gradation of the coarse aggregate, another factor must be taken into account. An allowance must be made for the fact that skip gradations can promote higher density.

Skip gradations

Figure 11 shows curves and data for three skip gradations, Nos. 22–24. The slope of these curves between the No. 4 and No. 8 sieve sizes is appreciably less than the slopes of the remaining portions. They might be referred to as gradations that plot with a hump at the No. 8 sieve size. Figure 11 also shows curves and data for the maximum density gradation, No. 3, and for gradation No. 12 which plots as a straight line from the maximum size to the same percentage passing the No. 200 sieve as that of the other curves.

Comparing the curves in figure 11 with respect to their positions relative to the maximum density line is complicated by the fact that some of them cross it. For example, gradation No. 12 plotted closer to the maximum density line than gradation No. 22 at the No. 4 and larger sieve sizes, but further from the line at the No. 16 and smaller sieve sizes. On the average, however, gradation No. 12 plotted closer to the maximum density line than gradation No. 22, and it showed the higher density (lower mineral voids).

Similarly, skip gradation No. 22 plotted closer to the maximum density line than skip gradation No. 23 at the

[3] *Relationships between Density, Bitumen Content, and Voids Properties of Compacted Bituminous Paving Mixtures*, by N. W. McLeod, Proceedings of the 35th annual meeting of the Highway Research Board, vol. 35, 1956, pp. 327–404.

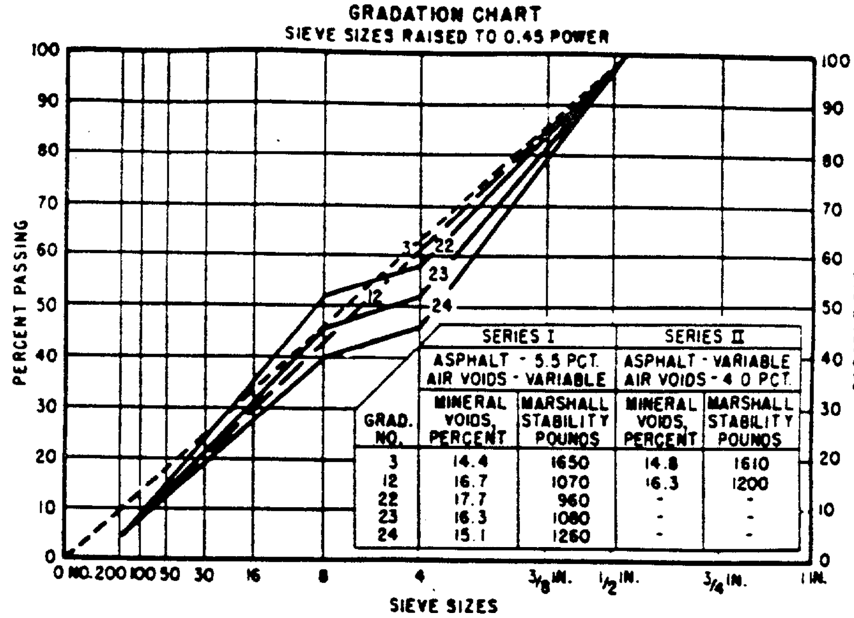


Figure 11.—Skip gradations compared with gradations Nos. 3 and 12.

No. 4 and larger sieve sizes, further from the line at the No. 8 sieve size, and again closer to the line at the No. 30 and smaller sieves. Which gradation plotted closer to the maximum density line on the average is questionable, but gradation No. 23 had the higher density.

There is no doubt that gradation No. 24 plotted the furthest from the maximum density line and it showed the highest density of the three skip gradations. Its density, however, was not as great as that of gradation No. 3, the one that is used to represent maximum density on

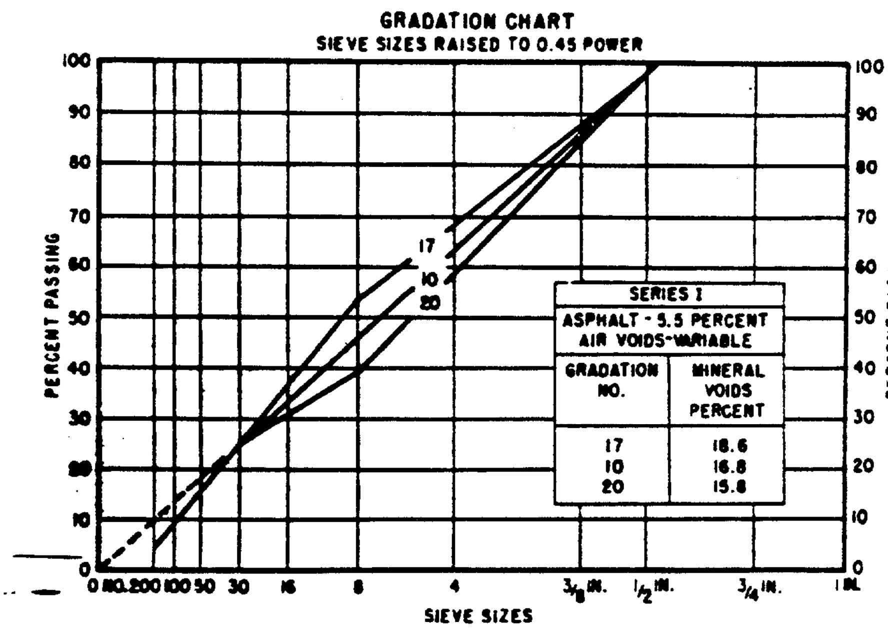


Figure 12.—Gradations varying in percentage passing No. 8 sieve, with medium percentage passing No. 30 sieve.

the gradation chart. But this does not preclude the possibility that there may be other skip gradations of the same maximum size that will exceed the density of gradation No. 3.

Figures 12 and 13 compare data for gradations that vary in the percentage passing the No. 8 sieve. These were selected from previous figures used to illustrate "hump" gradations. They provide the same indications as figure 11. For example, in figure 12, gradation No. 20 plotted further from the maximum density line than gradation No. 10 but had the higher density. The same relationship held for gradations Nos. 18 and 8 in figure 13. Incidentally, gradation No. 20 in figure 12 and gradations Nos. 8 and 18 in figure 13 can be classified as skip gradations as well as "hump" gradations because they plot with slopes flatter between the No. 8 and the No. 30 sieve size than elsewhere.

In reference to the higher density skip gradations in figures 11–13, it is considered important to note that in all cases the right-hand portion of the gradation curve was below the maximum density line. This fact must be taken into account when using the maximum density line as a reference for adjusting skip gradations to provide a lower or a higher density.

Conclusions

The laboratory study covered by this article was limited to data representing 24 different gradations of aggregate of a single maximum size. Only one asphalt and one type of aggregate were used in the mixtures. Based on these limited conditions, the following conclusions are warranted:

1. The new Public Roads gradation chart provides a much more convenient means of studying aggregate gradations than the logarithmic chart now commonly used. The greater convenience results from the fact that maximum density gradations can be represented on the chart by a straight line from a theoretical zero percent passing zero sieve size to 100 percent passing the effective maximum size.

2. This maximum density line constitutes a new design tool, in that it serves as an easily remembered line in comparing different gradations or in adjusting gradations to provide desired voids and stability characteristics.

3. For gradations of the same type of aggregate which plot as smooth curves entirely above or below the maximum density line, those closest to the line will usually represent gradations yielding the lowest voids in the compacted mixture.

4. For gradations of the same type of aggregate which plot as identical curves except for the portion between the No. 8 and the No. 200 sieves, those that show appreciable humps above the maximum density line at about the No. 30 sieve will have higher mineral voids and lower Marshall stabilities than those plotting with lesser humps. Analysis of several problem mixtures from field projects has clearly confirmed this finding and points up the detrimental effect of gradation humps in the finer aggregate sizes.

5. For skip gradations, low mineral voids are associated with curves that stay appreciably below the maximum density line in the right-hand or coarse aggregate zone of the chart.

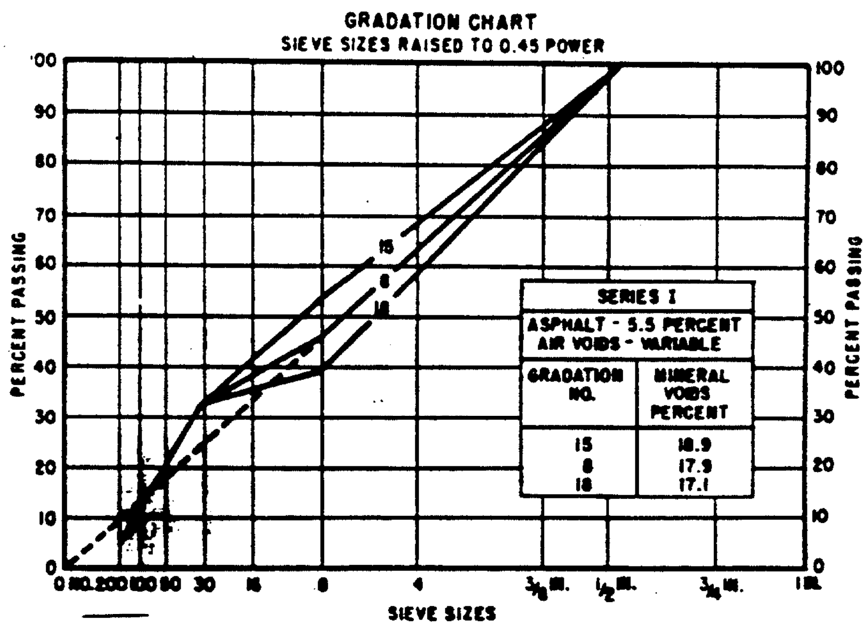


Figure 13.—Gradations varying in percentage passing No. 8 sieve, with high percentage passing No. 30 sieve.

APPENDIX: PROCEDURE AND DETAILS OF PROJECT

Processing aggregate

Table 1 shows the aggregate gradations used in the study and includes values of effective specific gravity which were used in computing voids. The effective specific gravities are rational values determined directly on several of the mixtures by the Rice vacuum saturation procedure.[4]

The aggregate larger than the No. 4 sieve and a portion of that passing the No. 4 sieve and retained on the No. 8 sieve was an uncrushed river gravel. The remainder of the aggregate consisted of sand from the same source and a commercial limestone mineral filler. The amount of mineral filler used varied with the gradation. In all cases 60 percent of the total aggregate passing the No. 200 sieve consisted of limestone dust.

Table 2 gives the apparent and bulk specific gravities of the three stock aggregates. Rational values of apparent and bulk specific gravity of the combined aggregate representing different gradations were not determined.

In preparing the aggregate to be combined to meet the several gradations, the gravel and the sand larger than the No. 8 sieve were accurately separated into 0.525-inch to ½-inch, ½-inch to No. 4, and No. 4 to No. 8 sieve size fractions. Since it is very difficult to obtain clean separations for fine size aggregate in large quantities, no attempt was made to separate the sand into exact sieve size fractions. Instead, it was separated into approximate sizes by a relatively rapid sieving process, and the gradations of the several fractions were then accurately determined and used in computing the correct proportions to provide the desired combined gradations.

Preparing mixtures and test specimens

An 85–100 penetration grade asphalt was used in all mixtures. Table 3 gives its test properties.

The mixtures were prepared in a laboratory mixer from aggregate heated to 325° F. and asphalt heated to 300° F. Each batch was just sufficient for one test specimen, which, immediately after being mixed, was compacted in a gyratory mold heated to 200° F. Figure 14 (p. 26) shows the gyratory compactor used in molding the specimens.

The test specimens, 4 inches in diameter and 2½ inches in height, were molded by applying 30 gyrations at a 1-degree angle and under a foot pressure of 100 p.s.i. Previous work by McRae and McDaniel[5] indicated that this procedure produced densities corresponding to those of the 50-blow, hand-compacted Marshall specimen.

Tests performed

The specimens were tested for bulk specific gravity, Marshall stability, and Marshall flow value. Bulk specific gravity was determined by the procedure described in Section 4(a) of AASHO Method T-165. Air and mineral voids, based on effective specific gravity of the aggregate, were computed from the bulk specific gravities.

[4] *Maximum Specific Gravity of Bituminous Mixtures by Vacuum Saturation Procedure*, by J. M. Rice, in *Symposium on Specific Gravity of Bituminous Coated Aggregates*, Special Technical Publication No. 191, American Society for Testing Materials, June 1956, pp. 43–61.

[5] *Progress Report on the Corps of Engineers' Kneading Compactor for Bituminous Mixtures*, by J. L. McRae and A. R. McDaniel, Proceedings of the Association of Asphalt Paving Technologists, vol. 27, 1958, pp. 357–382.

Table 1.—Gradation and effective specific gravity of aggregate blends

Gradation No.	Percentage passing indicated sieve: 0.525 in.	½-in.	⅜-in.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Effective specific gravity[1]
1	100	[illegible]	[illegible]	73	58.6	47.3	38.0	30.8	24.9	20.0	2.651
2	100	[illegible]	[illegible]	[illegible]	52.0	39.9	30.6	23.6	18.1	13.9	2.650
3	100	[illegible]	[illegible]	[illegible]	46.0	32.7	24.6	18.0	13.2	9.7	2.649
4	100	[illegible]	94	59	40.8	28.5	19.8	13.8	9.7	6.7	2.648
5	100	97	82	56	38.2	24.0	15.9	10.6	7.1	4.7	2.646
6	100	97	80	51	32.1	20.3	12.8	8.1	5.2	3.2	2.643
7	[illegible]	[illegible]	[illegible]	[illegible]	48.0	40.6	30.6	22.6	12.3	4.7	2.665
8	[illegible]	[illegible]	[illegible]	[illegible]	44.0	38.3	32.6	20.4	11.4	4.7	2.661
9	[illegible]	[illegible]	[illegible]	[illegible]	48.0	36.0	28.6	18.1	10.4	4.7	2.658
10	[illegible]	[illegible]	[illegible]	[illegible]	46.0	33.7	24.6	15.9	9.4	4.7	2.655
11	[illegible]	[illegible]	[illegible]	[illegible]	46.0	32.0	21.6	14.2	8.7	4.7	2.653
12	[illegible]	[illegible]	85	61	43.1	30.1	20.4	13.5	5.4	4.7	2.651
13	[illegible]	[illegible]	[illegible]	[illegible]	53.3	46.0	40.6	24.9	12.3	4.7	2.670
14	100	[illegible]	[illegible]	[illegible]	53.3	42.7	36.6	22.6	12.3	4.7	2.667
15	[illegible]	[illegible]	[illegible]	[illegible]	53.3	41.4	32.6	20.4	11.4	4.7	2.663
16	[illegible]	[illegible]	[illegible]	[illegible]	53.3	38.1	28.6	18.1	10.4	4.7	2.660
17	[illegible]	[illegible]	[illegible]	[illegible]	53.3	36.8	24.6	15.9	9.4	4.7	2.657
18	100	[illegible]	84	58	38.9	36.3	32.6	20.4	11.4	4.7	2.659
19	100	[illegible]	84	58	38.9	32.0	28.6	18.1	10.4	4.7	2.656
20	100	[illegible]	84	58	38.9	30.7	24.6	15.9	9.5	4.7	2.653
21	100	[illegible]	84	[illegible]	38.6	28.4	20.6	13.6	8.5	4.7	2.650
22	100	[illegible]	84	58	52.0	38.0	24.1	15.6	9.3	4.7	2.657
23	100	97	82	[illegible]	46.0	32.0	21.6	14.2	8.7	4.7	2.653
24	100	97	80	46	40.0	28.1	19.2	12.8	8.1	4.7	2.649

[1] Rational values allowing for gradation and based on the results of several tests by the Rice vacuum saturation procedure.

Table 2.—Physical properties of aggregates [1]

	Gravel		Sand	Limestone mineral filler
	¾-in. to ⅜-in.	⅜-in. to No. 4		
Apparent specific gravity	2.66	2.66	2.67	2.71
Bulk specific gravity	2.59	2.62	2.58	....
Water absorption, percent	1.0	.6	1.4	....

[1] AASHO methods T 84 and T 85.

Two series of tests were conducted, the results of which are summarized in table 4. The first series was performed on all 24 gradations shown in table 1. All 24 mixtures contained 5.5 percent of asphalt by weight of the aggregate. A total of 72 test specimens, 3 for each of the 24 gradations, was made. The work was done in three rounds, one round of 24 specimens being prepared on each of three different days. The test results for each group of three corresponding specimens from the three rounds were averaged.

The second series of tests was performed on 14 of the 24 gradations. Asphalt contents were computed from the results of the first series of tests to produce air voids in pairs of compacted specimens slightly greater and slightly less than 4 percent so that test results for this second test series could be interpolated for exactly 4-percent air voids. A total of 84 specimens, 3 pairs for each of the 14 gradations, was made. The work was done in 3 rounds, 1 round of 28 specimens for the 14 gradations being prepared on each of 3 different days. The test results for each group of corresponding specimens were averaged.

Table 3.—Physical properties of asphalt

Property	Value
Original asphalt:	
Specific gravity, 77°/77° F	1.018
Flash point, C.O.C ......°F	540
Softening point ......°F	117
Penetration, 77° F, 100 g., 5 sec	93
Ductility, 77° F ......cm	220
Bitumen ......percent	99.8
After oven loss test (AASHO T 47)	
Loss ......percent	0.06
Penetration	90
Retained penetration ......percent	98
After thin-film oven test (AASHO T 179)	
Loss ......percent	0.20
Softening point ......°F	132
Penetration	54
Retained penetration ......percent	58
Ductility ......cm	196

Table 4.—Physical properties of gyratory compacted gravel mixtures

Gradation No.	1st series of tests: [1] Asphalt, 5.5 percent; [2] air voids, variable					2d series of tests: [1, 4] Asphalt, variable; air voids, 4.0 percent [3]				
	Bulk specific gravity	Mineral voids [3]	Air voids [3]	Marshall stability	Marshall flow	Asphalt content [2]	Bulk specific gravity	Mineral voids [3]	Marshall stability	Marshall flow
		Percent	Percent	Pounds		Percent		Percent	Pounds	
1	2.344	16.2	4.2	1,620	9	5.32	2.347	16.1	1,750	8
2	2.384	14.7	2.5	1,[illegible]	10	4.85	2.384	15.0	1,310	8
3	2.382	14.4	2.1	1,640	10	4.8[illegible]	2.387	14.8	1,610	8
4	2.373	15.1	2.9	1,280	9	5.12	2.357	15.3	1,310	9
5	2.334	16.4	4.4	1,000	9	5.6[illegible]	2.340	16.3	1,010	8
6	2.280	17.9	6.2	770	9	....	....	....	....	....
7	2.2[illegible]	18.7	7.0	890	7	6.64	2.294	18.2	1,100	7
8	2.304	17.9	6.5	[illegible]	8	6.22	2.3[illegible]	17.4	1,110	7
9	2.320	17.8	6.4	[illegible]	8	5.97	2.3[illegible]	17.0	1,220	8
10	2.321	16.8	4.8	1,160	9	5.64	2.347	16.3	1,190	7
11	2.318	17.2	5.5	1,0[illegible]	8	....	....	....	....	....
12	2.3[illegible]	16.7	4.7	1,070	9	5.66	2.344	16.8	1,200	9
13	2.240	20.6	9.6	670	7	....	....	....	....	....
14	2.265	19.6	7.9	710	7	6.[illegible]	2.317	18.8	1,080	8
15	2.277	18.9	7.2	[illegible]	7	....	....	....	....	....
16	2.276	19.0	7.3	7[illegible]	8	....	....	....	....	....
17	2.2[illegible]	18.6	6.9	[illegible]	8	6.38	2.326	17.7	1,080	8
18	2.2[illegible]	17.1	5.2	[illegible]	7	5.70	2.348	16.5	1,070	7
19	2.3[illegible]	16.1	4.1	1,2[illegible]	8	....	....	....	....	....
20	2.365	15.8	2.8	1,2[illegible]	9	5.34	2.366	15.8	1,240	8
21	2.340	16.1	4.1	1,0[illegible]	8	....	....	....	....	....
22	2.3[illegible]	17.7	5.9	[illegible]	8	....	....	....	....	....
23	2.340	16.8	4.3	1,0[illegible]	8	....	....	....	....	....
24	2.376	15.1	2.9	1,280	8	....	....	....	....	....

[1] Averages of 3 values, 1 per round for 3 rounds of tests.
[2] By weight of aggregate.
[3] Based on effective specific gravity of the aggregate.
[4] Interpolated values from results at 2 asphalt contents.