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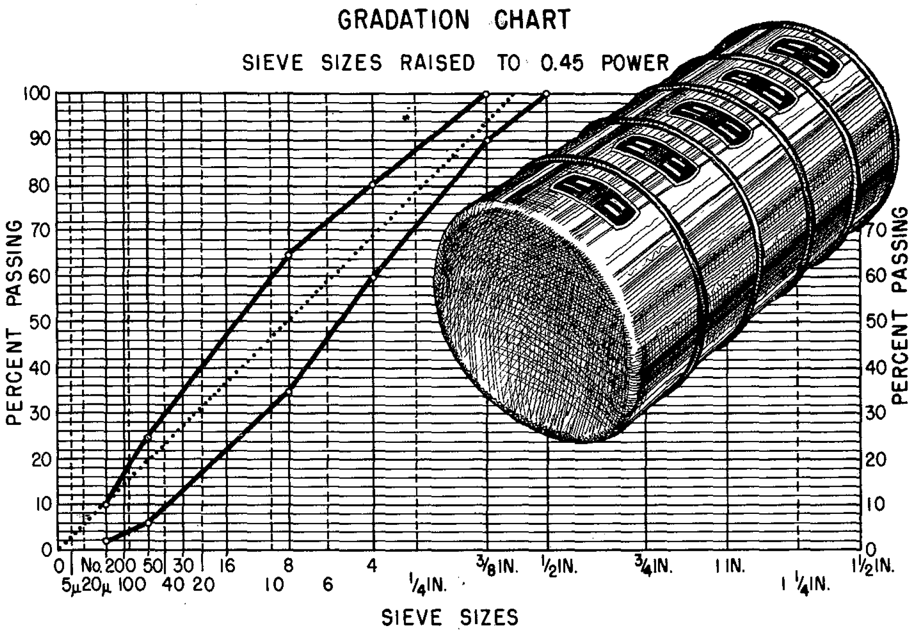
AGGREGATE GRADATION FOR HIGHWAYS



Simplification, Standardization, and Uniform Application

and

A New Graphical Evaluation Chart

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

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
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Foreword

The tremendous highway improvement program now underway in the United States has sparked the development of many new methods and techniques for engineering and construction. Their range has been diverse, but all have had common objectives: The most effective use of manpower, materials, machinery, and money. Some of the developments have been novel, even spectacular—new applications of photogrammetry, automatic guidance of roadbuilding machines, nuclear testing, and use of the electronic computer, for example.

But there are other, less dramatic approaches toward the stated objectives that can be equally significant and equally productive of efficiency and economy. Among these lies an especially fertile field—simplification, standardization, and uniformity, within reason, of design practices and construction specifications.

Within this broad area, aggregate gradation specifications seem particularly susceptible to improvement. It was with this objective that the Bureau of Public Roads undertook the analytical study reported in the first article in this pamphlet. It merits the careful consideration of all roadbuilding agencies and, it is hoped, prompt attention along the lines of the recommended course of action.

Because it is closely related to the objective of improving aggregate gradations, there is included in this pamphlet an article on the development and use of the new Public Roads graphical chart for evaluating aggregate gradations.

Contents

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	95–100	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	80–100		50–85		20–40	15–35	5–25	0–10	0–2
G2 [5]	1½–No. 8						100	65–100		35–75		10–35	0–10	0–5		
G3 [5]	1½–No. 4						100	60–95		25–50		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		Size limits	
		Maximum	Minimum	Maximum	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	¾-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: 95–100 (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	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 1952 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.

Table 4.—Grading requirements for coarse aggregate for bituminous paving mixtures, from ASTM Designation D 692–59T

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

[1] 4,760-micron. [2] 2,380-micron. [3] 1,190-micron.

ASTM has had for some years a specification for coarse aggregates for bituminous paving mixtures, D 692, covering 9 standard SPR sizes. In 1959 the then current version, D 692–54, was amended by adding SPR aggregates Nos. 5, 6, and 68, and the specification now carries the designation D 692–59T. It has much greater flexibility, therefore, than the current AASHO specifications. The current ASTM requirements are shown in table 4.

Sands

In the case of sands for bituminous paving mixtures, ASTM has recently completed a committee study of current practices with the participation of representatives of the AASHO Materials Committee, the Highway Research Board, the Asphalt Institute, the National Slag Association, the National Sand and Gravel Association, the National Ready Mixed Concrete Association, and the National Crushed Stone Association. The Bureau of Public Roads was actively represented in all of this ASTM committee work. Following this study and with the participation of the same representatives, ASTM has revised its previous specifications for fine aggregates for sheet asphalt and bituminous concrete pavements, and now provides for three sand types under Specification D 1073–59T, fine aggregates for bituminous paving mixtures, as shown in table 5. These gradings also utilize the logarithmic sieve series and are therefore compatible with the SPR system.

Table 5.—Grading requirements [1] for fine aggregate for bituminous pavements, from ASTM Designation D 1073–59T

Sieve size	Amounts finer than each laboratory sieve (square openings), percentage by weight		
	Grading No. 1	Grading No. 2	Grading No. 3
⅜-in.	100		100
No. 4	95–100	100	80–100
No. 8	70–100	95–100	65–100
No. 16	40–80	85–100	40–80
No. 30	20–65	65–90	20–65
No. 50	7–40	30–60	7–40
No. 100	2–20	5–25	2–20
No. 200	0–10	0–5	0–10

[1] It is recognized that for certain purposes satisfactory results may be obtained with materials not conforming to these specifications. In such cases the use of fine aggregate not conforming to the grading requirements of these specifications may be authorized only under special provisions based on field experience or laboratory studies of the possibility of designing a mixture of materials to be used on the job that will yield bituminous paving mixtures equivalent to the job-mix requirements.

Mineral filler

The current ASTM specification for mineral filler, Designation D 242–57T, was last revised in 1957 and is generally representative of present thinking. It fails to restrict the types of mineral that could be approved for use as fillers but, in controlling the grading, it utilizes the logarithmic sieve series and is therefore compatible with the SPR system. The grading requirements are shown in table 6. Control below the No. 200 sieve is under study.

Table 6.—ASTM mineral filler grading, from ASTM Designation D 242–57T [1]

Sieve size	Percentage passing
No. 30	100
No. 50	95–100
No. 100	90–100
No. 200	70–100

[1] "The mineral filler shall consist of limestone dust, portland cement, or other suitable mineral matter . . ."

Combined Gradings

Bituminous paving mixtures

In general, current design practice for bituminous paving mixtures differs from that for portland cement concrete. As step one in bituminous mix design, it is almost a universal practice to set up definite grading patterns for bituminous paving mixtures wherein the coarse aggregate, the fine aggregate or sand, and the mineral filler are combined to produce gradings that will fall within specified bands delineated by minimum and maximum limits for each sieve. In some cases the gradings have been established mainly through experience, but more frequently they have been established through laboratory and field research which has shown, among other things, that high density within certain limits promotes stability, and that high density without limits promotes resistance to weathering of the bituminous binder. While the factor of density 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		60-80		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	80-100	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	2-15	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 coarse, 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

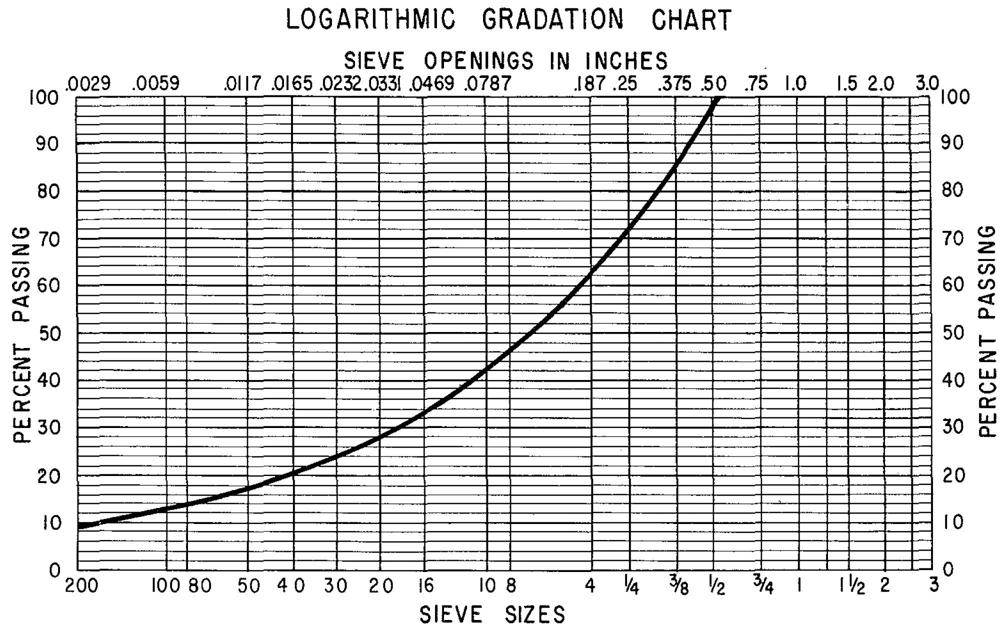


Figure 1.—A dense, stable grading plotted on the logarithmic gradation chart.

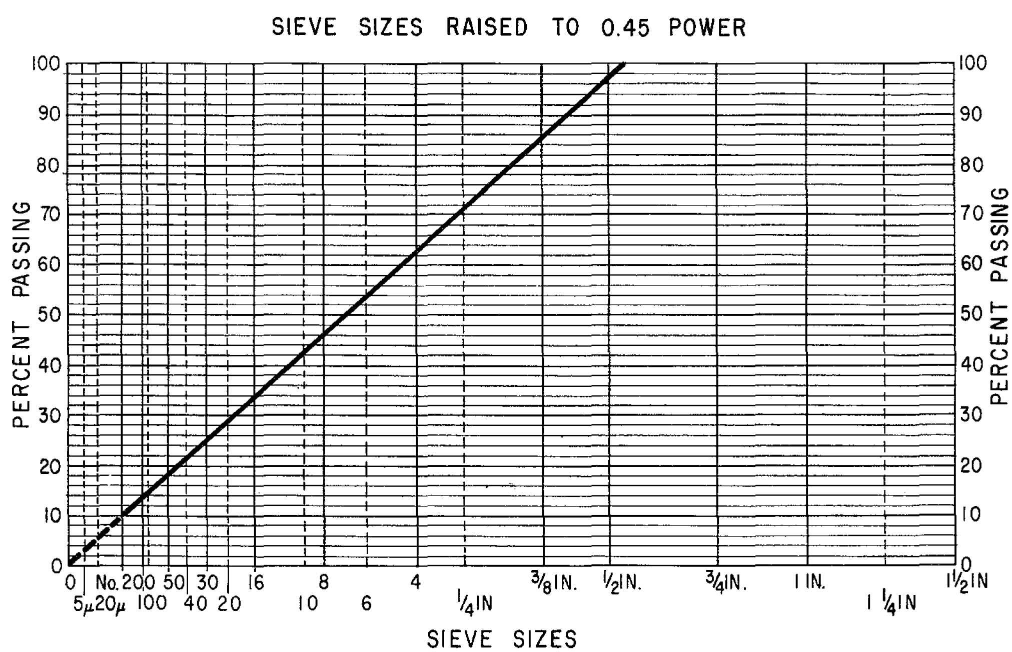


Figure 2.—Grading shown in figure 1 replotted on the 0.45-power gradation chart.

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

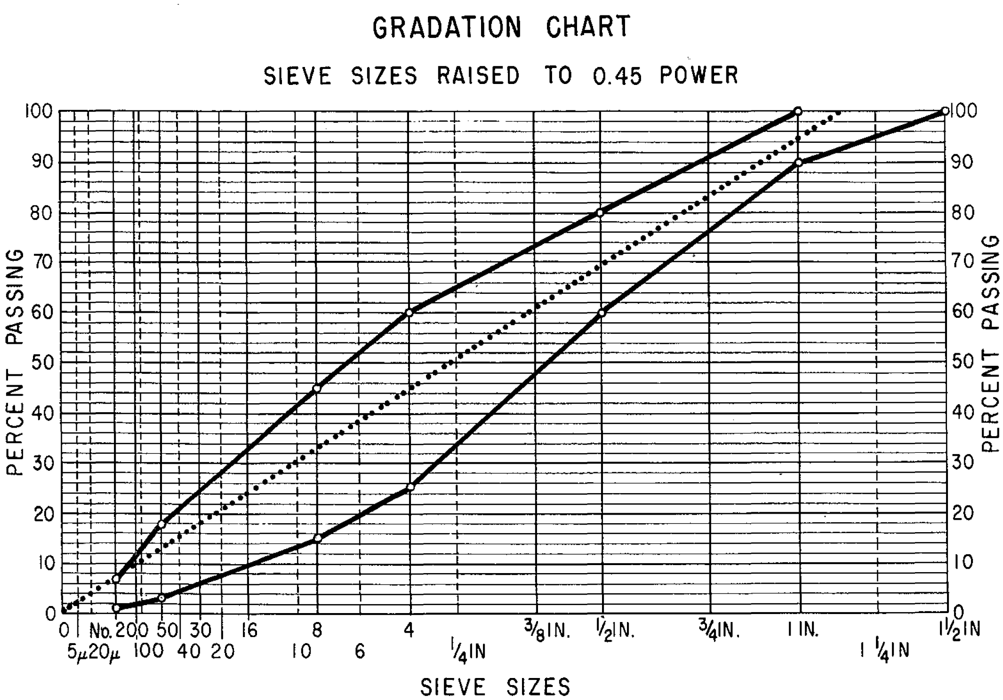


Figure 3.—ASTM limits, 1-inch nominal maximum size, compared with straight-line, maximum density grading.

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-

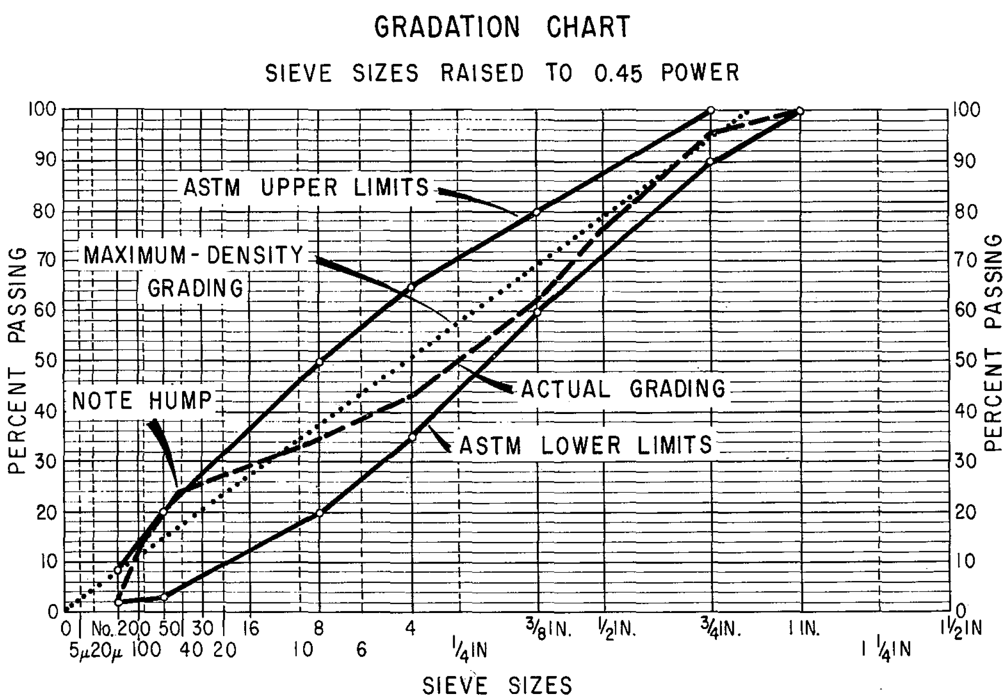


Figure 4.—Aggregate grading for a 3/4-inch nominal maximum size mixture identified as a "tender" mix.

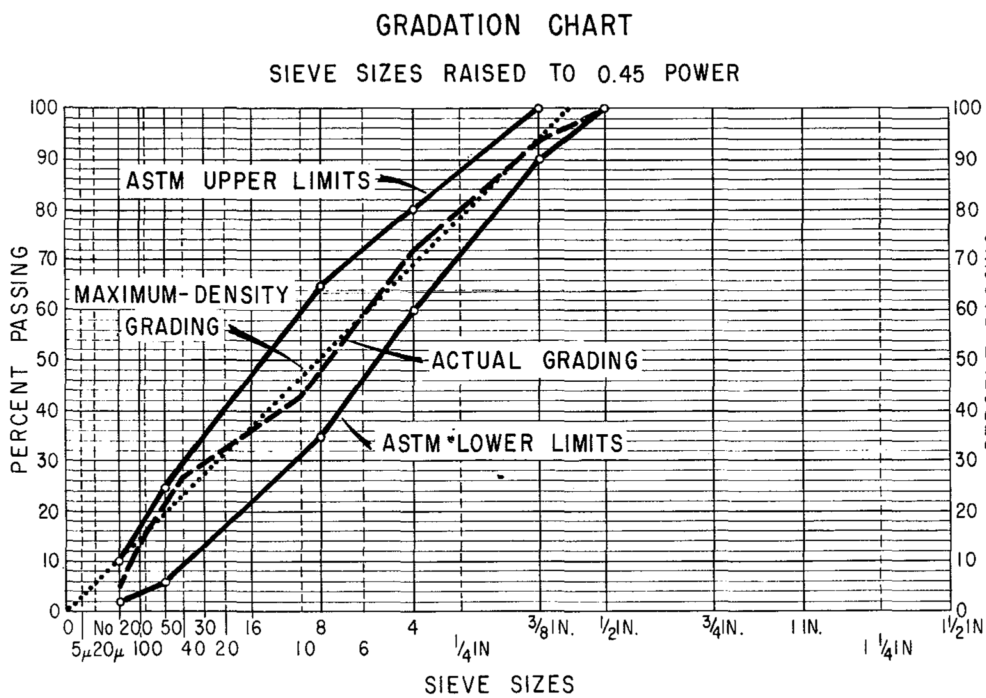


Figure 5.—Aggregate grading for a 3/8-inch nominal maximum size mixture identified as a "tender" mix.

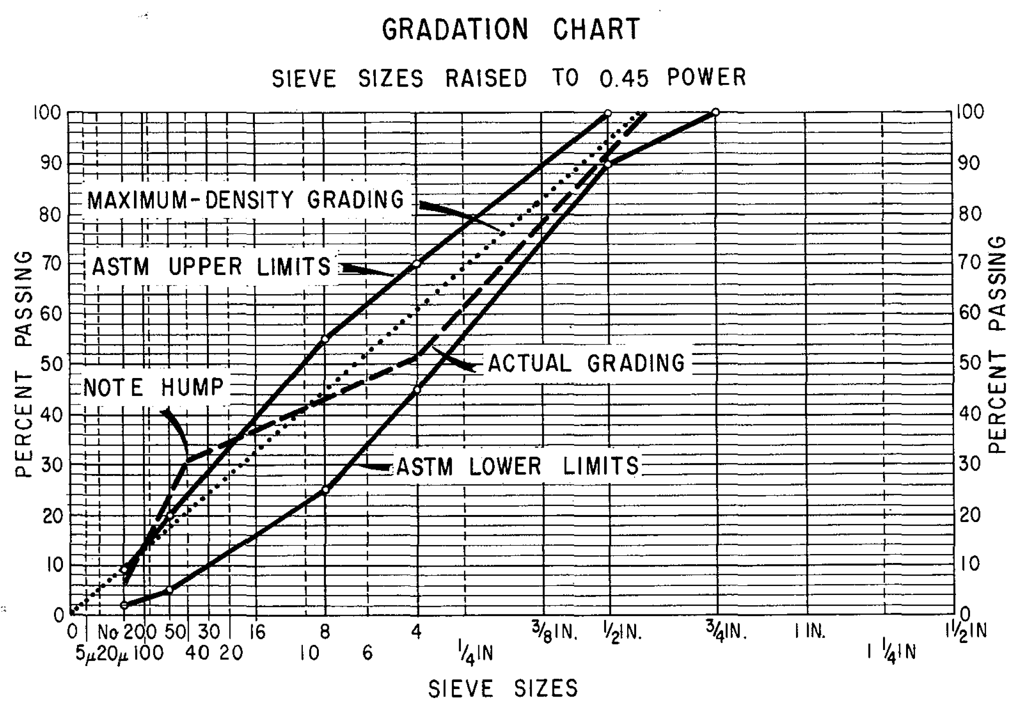


Figure 6.—Typical grading for a 1/2-inch maximum size mixture where a small amount of moisture in the aggregate has resulted in a splotchy pavement surface.

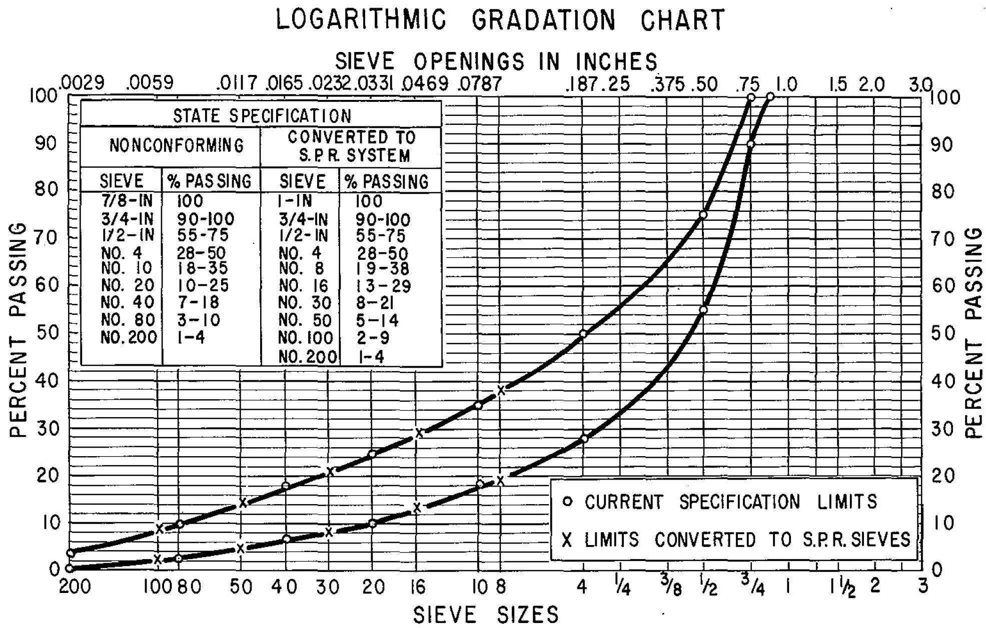


Figure 7.—Conversion of a current State specification to SPR sieve sizes, using the logarithmic gradation chart.

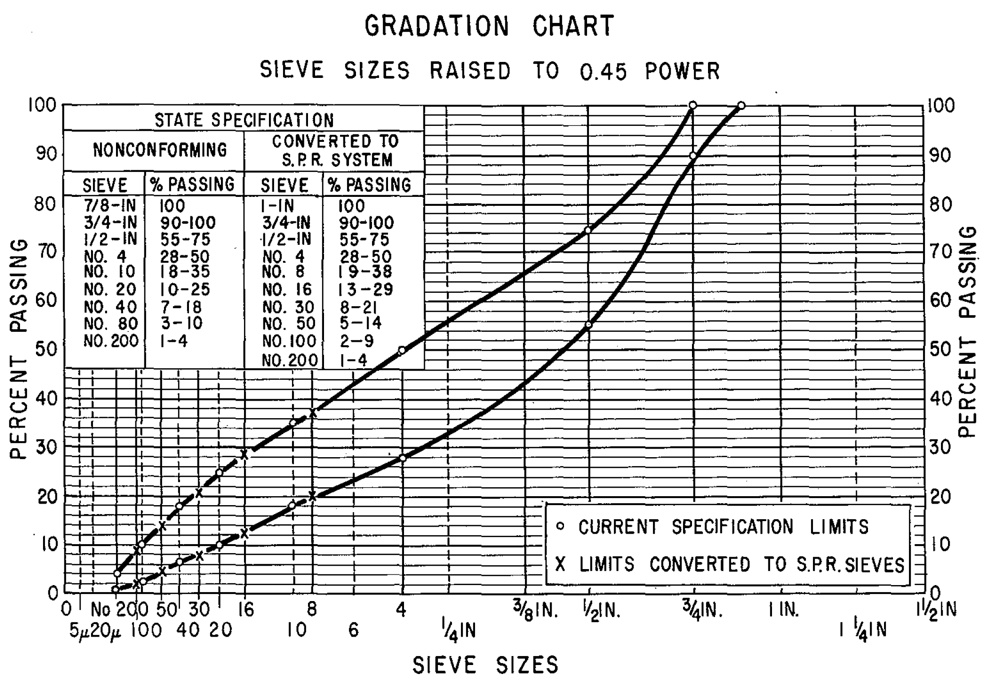


Figure 8.—Conversion of a current State specification to SPR sieve sizes, using the Public Roads gradation chart.

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.

A NEW GRAPHICAL CHART FOR EVALUATING AGGREGATE GRADATION

By the Physical Research Division
Bureau of Public Roads

Reported [1] by Joseph F. Goode, Highway Research Engineer
and Lawrence A. Lufsey, Highway Engineering Technician

The Problem of Diverse Gradations

As forcefully brought home in the companion article in this bulletin, there is a wide diversity in the requirements pertaining to aggregate gradations in the current standard specifications of the State highway departments, and the multiplicity would be increased many fold if the specifications of county, city, and other government jurisdictions responsible for highway construction were taken into account. It is obviously questionable that so many variants are necessary, or that they all are as good as they might be.

Engineers are becoming increasingly aware of the importance of the proper design of bituminous paving mixtures to provide pavements that will meet the demands of modern traffic. They generally agree that gradation of the aggregate is one of the factors that must be carefully considered, especially for heavy duty highways. But they disagree as to what gradations are the more satisfactory. This can be verified by examining the gradation requirements of specifications used by the various State highway departments and other agencies. They differ widely.

Some specifications are so broad that they permit the use of paving mixtures ranging from those that result in open and coarse surface textured pavements to those that are tight and fine grained. They also permit the use of paving mixtures of either low or high stability. Within these gradation limits the engineer often has considerable leeway in selecting pavement type to his liking, and whether the most satisfactory gradation is selected will depend on his judgment or experience.

Other specifications are narrow enough to permit little variation in pavement type and characteristics. But these tighter specifications differ enough among themselves to result in a wide range in types and characteristics of pavement.

A review of the many different gradation requirements will also show that engineers do not agree as to method for specifying gradations. They employ at least four different methods:

1. Percentages by weight of total aggregate passing each of several specified sieves (total percent passing basis).
2. Percentages by weight of total aggregate retained on each of several specified sieves (total percent retained basis).
3. Percentages by weight of total aggregate between consecutive sizes of specified sieves (passing and retained, total aggregate basis).
4. Percentages of aggregate, by weight of bituminous mixture, between consecutive sizes of specified sieves (passing and retained, mix basis).

To complicate matters further, different combinations of sieve sizes are specified to control specific grading ranges and a few agencies even specify round opening screens for coarse aggregate grading control.

Such nonuniformity in methods of expressing gradations adds to the difficulty of studying and evaluating aggregate gradations in terms of construction characteristics and pavement performance. In some instances it also tends to add unnecessarily to the construction costs. Standardization of sieve sizes and aggregate gradations and the conscientious use of such standards would almost certainly result in fewer, more uniform, and probably better specifications, and in more economical construction.

Development of a New Gradation Chart

The primary purpose of this article is to present and illustrate the use of a new aggregate gradation chart that will be especially valuable in developing more realistic specifications and in evaluating individual gradations.

Those accustomed to expressing gradations as percentages passing the various sieves are thoroughly familiar with the common gradation chart in which percentages passing are shown arithmetically on the vertical scale and the logarithmic scale is used for the horizontal spacing

[1] Presented at the annual meeting of the Association of Asphalt Paving Technologists, New Orleans, La., Jan. 30, 1962.

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.[2] 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 (¾-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 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.

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

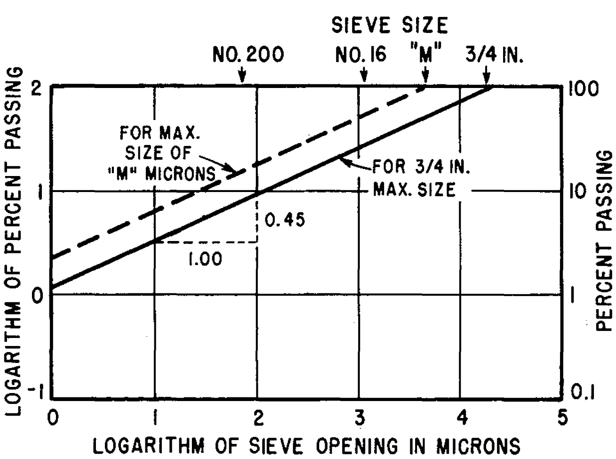


Figure 1.—Maximum density gradation plotted on a double log chart.

Figure 1 shows this maximum density gradation for a ¾-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:

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

Other equations are:

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

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

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

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

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

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

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

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.

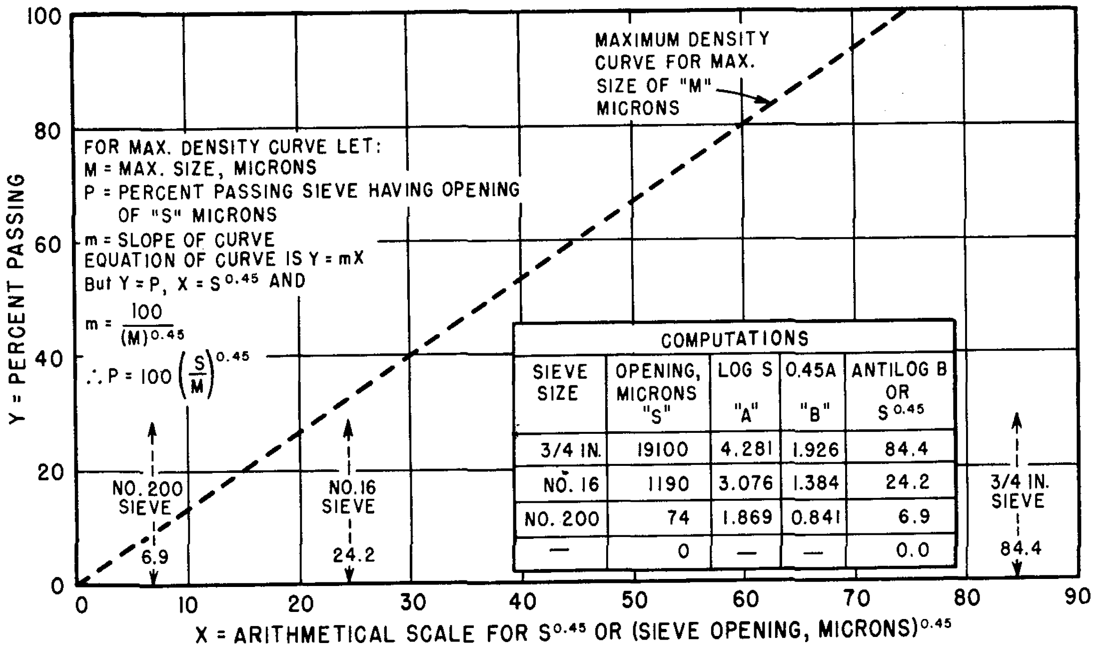


Figure 2.—Illustration of computations and method of positioning sieve sizes in setting up the Public Roads gradation chart.

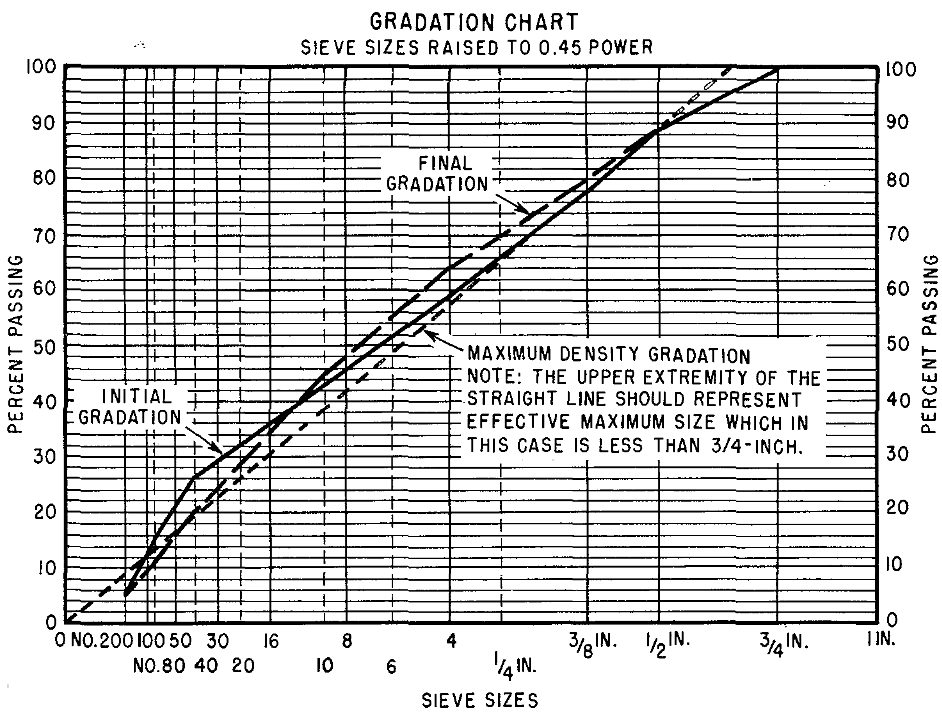


Figure 3.—Gradations of problem mixture (project A) compared with maximum density gradation.

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 struction 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

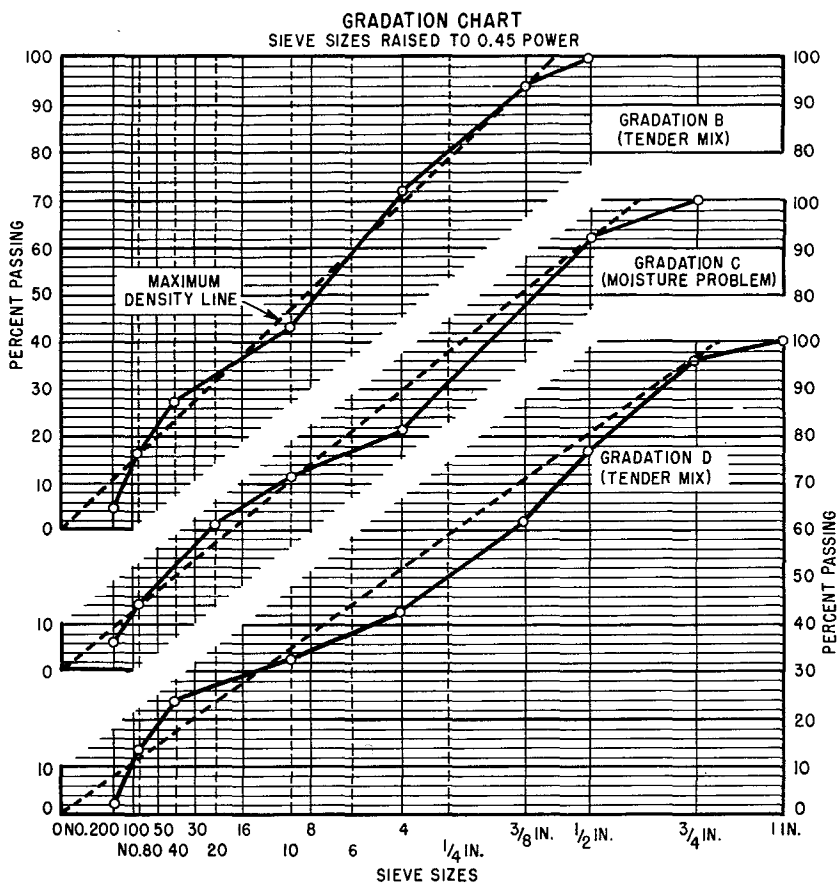


Figure 4.—Gradations of problem mixtures (projects B, C, and D) compared with maximum density gradations.

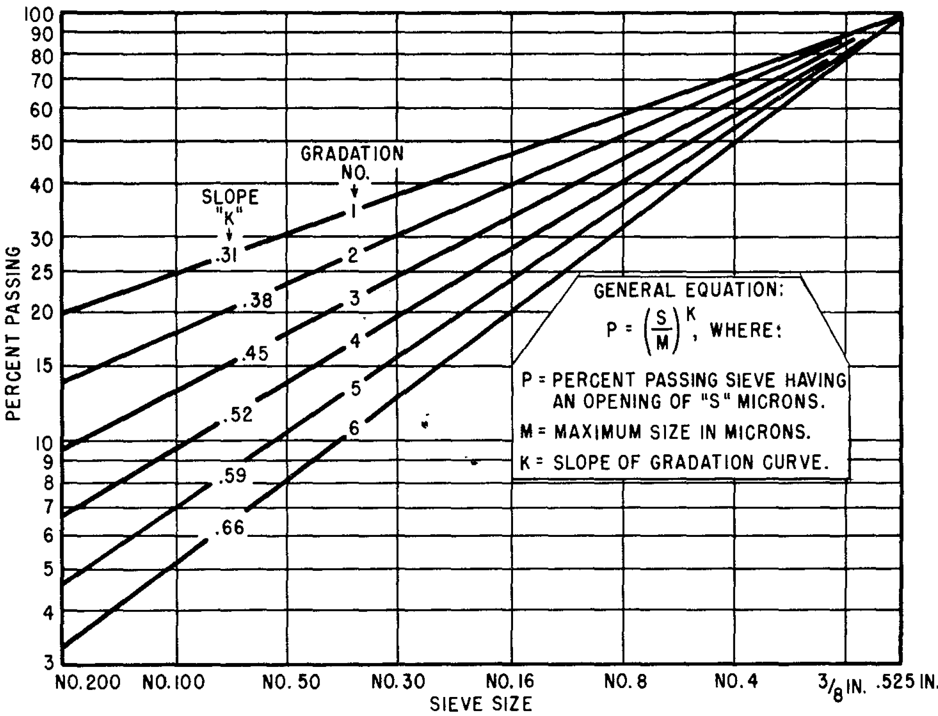
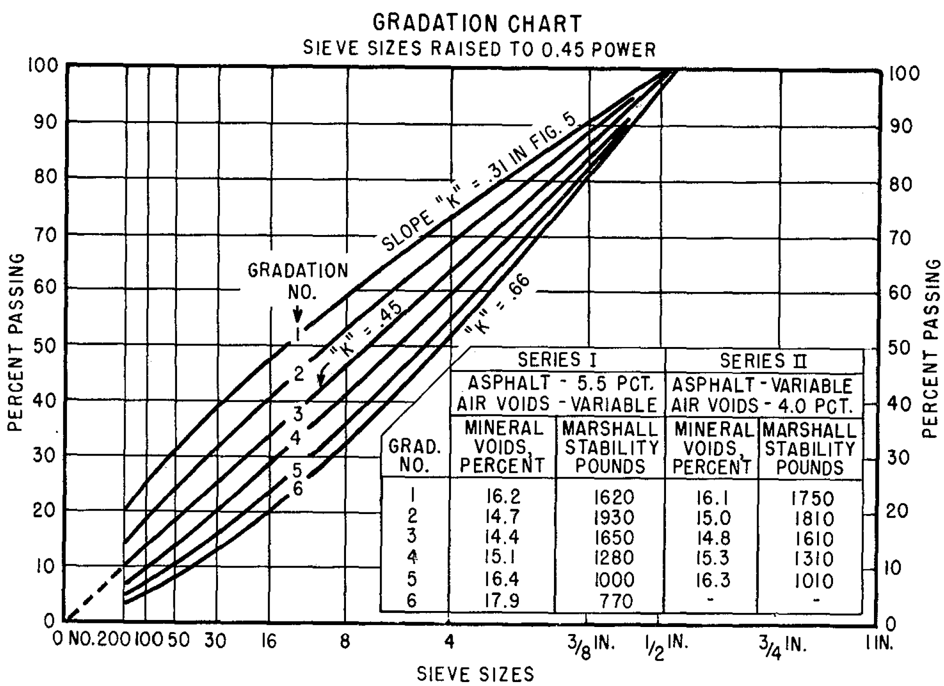


Figure 5.—Gradations Nos. 1–6 plotted on double log chart.



GRAD. NO.	SERIES I: ASPHALT - 5.5 PCT. AIR VOIDS - VARIABLE — MINERAL VOIDS, PERCENT	MARSHALL STABILITY POUNDS	SERIES II: ASPHALT - VARIABLE AIR VOIDS - 4.0 PCT. — MINERAL VOIDS, PERCENT	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

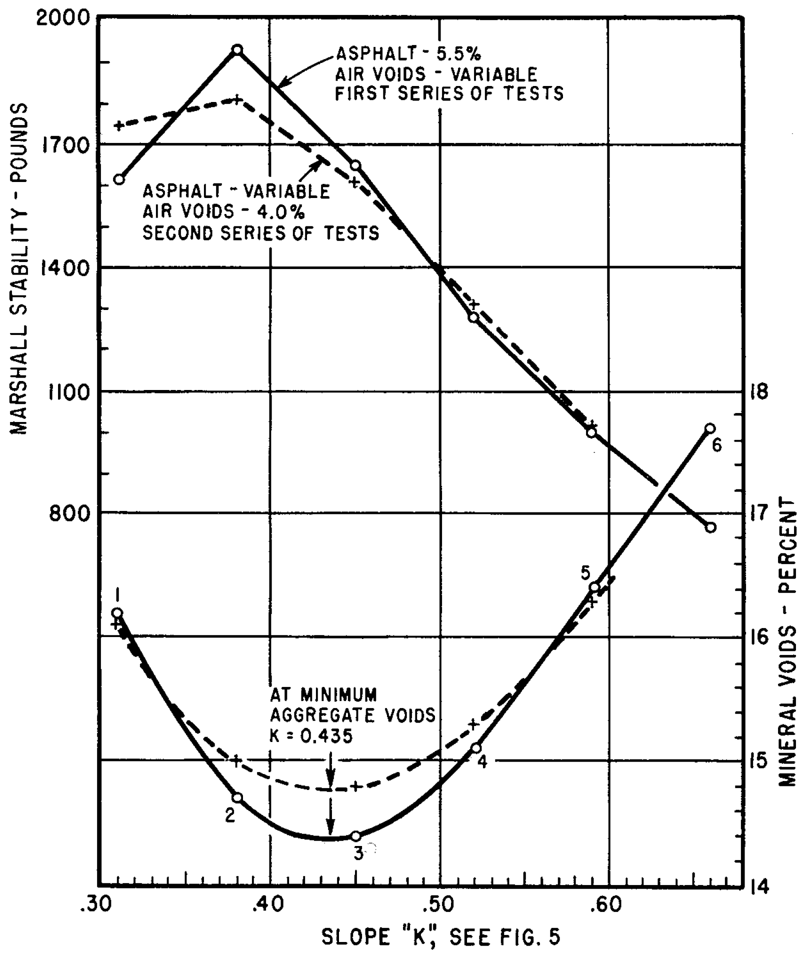


Figure 7.—Mineral voids and Marshall stabilities of gradations Nos. 1–6.

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.

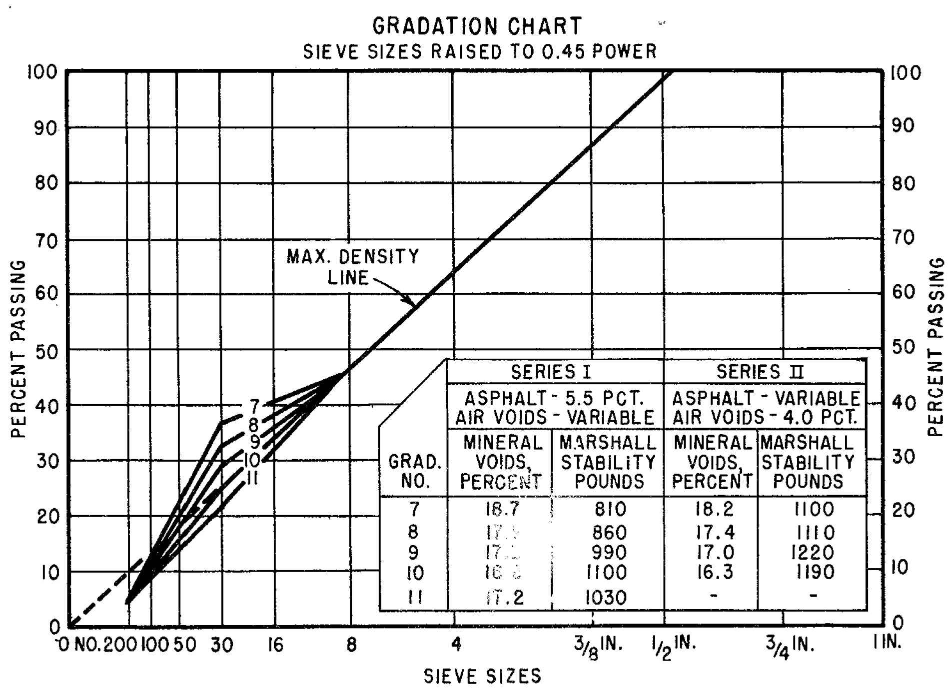
Study of "hump" gradations

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.

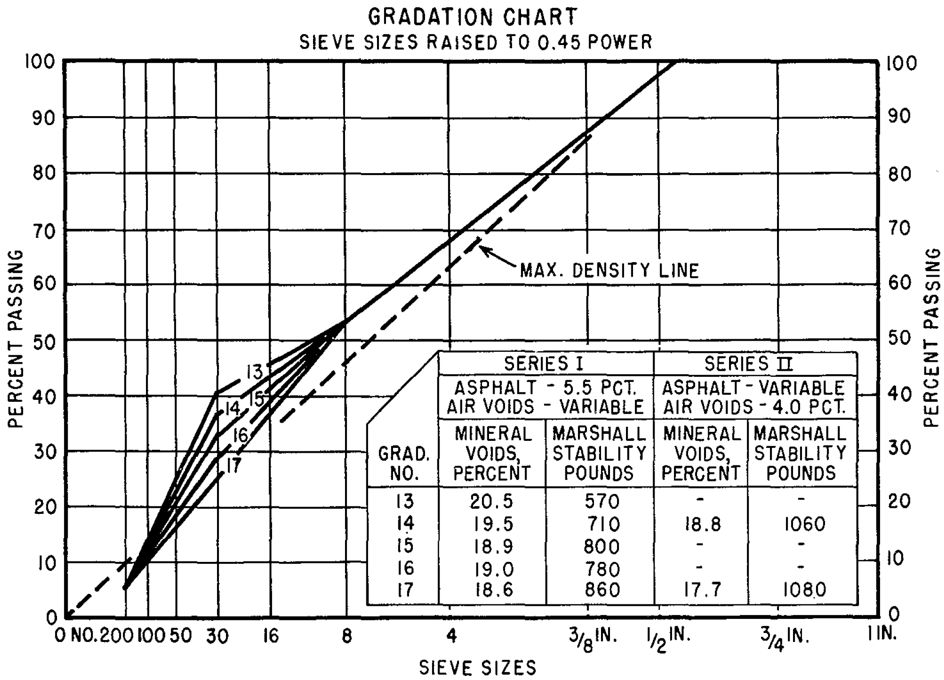
As will be seen in figure 8, the curve for gradation No. 11 plotted as a straight line from the No. 8 sieve to the No. 200 sieve and this portion of the curve is below the maximum density line. The curve for gradation No. 10 is on the maximum density line from maximum size to the No. 30 sieve but then 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 — 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
7	18.7	810	18.2	1100
8	[illegible]	860	17.4	1110
9	[illegible]	990	17.0	1220
10	[illegible]	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 — 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
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

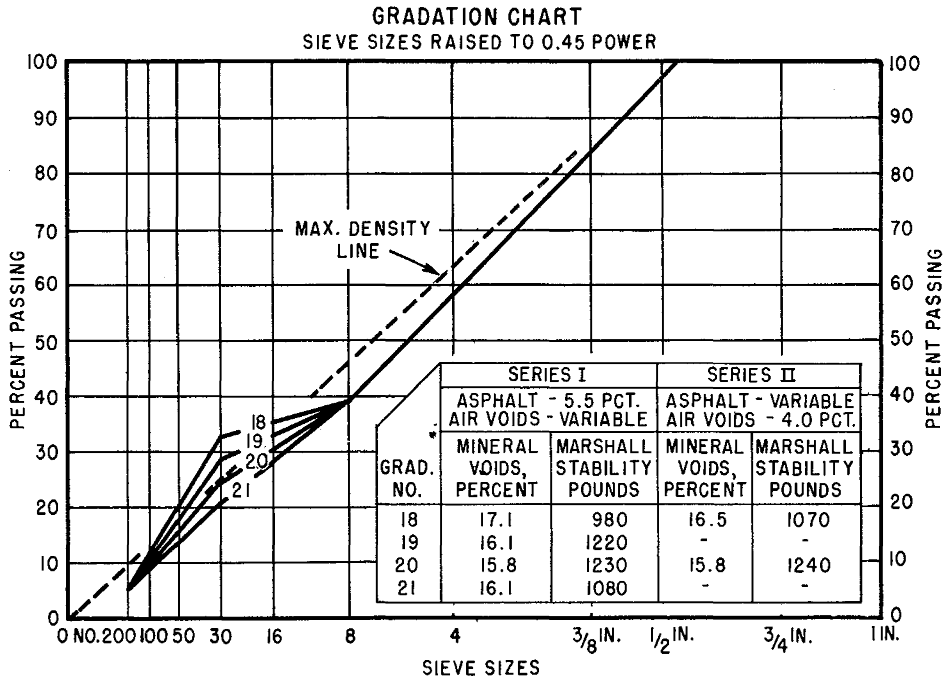
The above discussions, based on figures 8–10, of humps in gradation curves at the No. 30 sieve size, may be summarized as follows:

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.



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
18	17.1	980	16.5	1070
19	16.1	1220	-	-
20	15.8	1230	15.8	1240
21	16.1	1080	-	-

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.

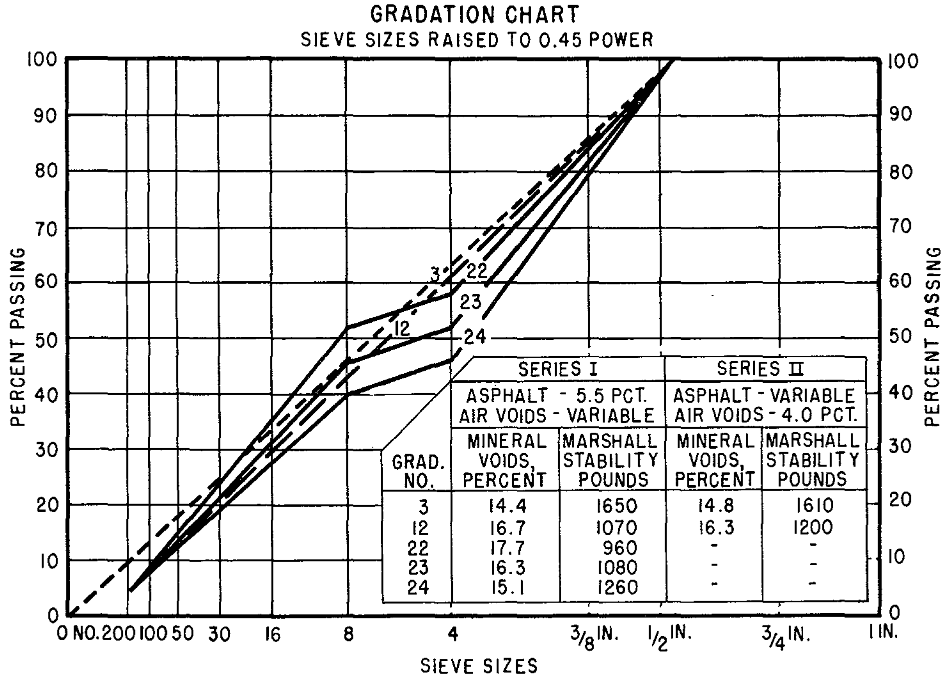
Skip gradations

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.

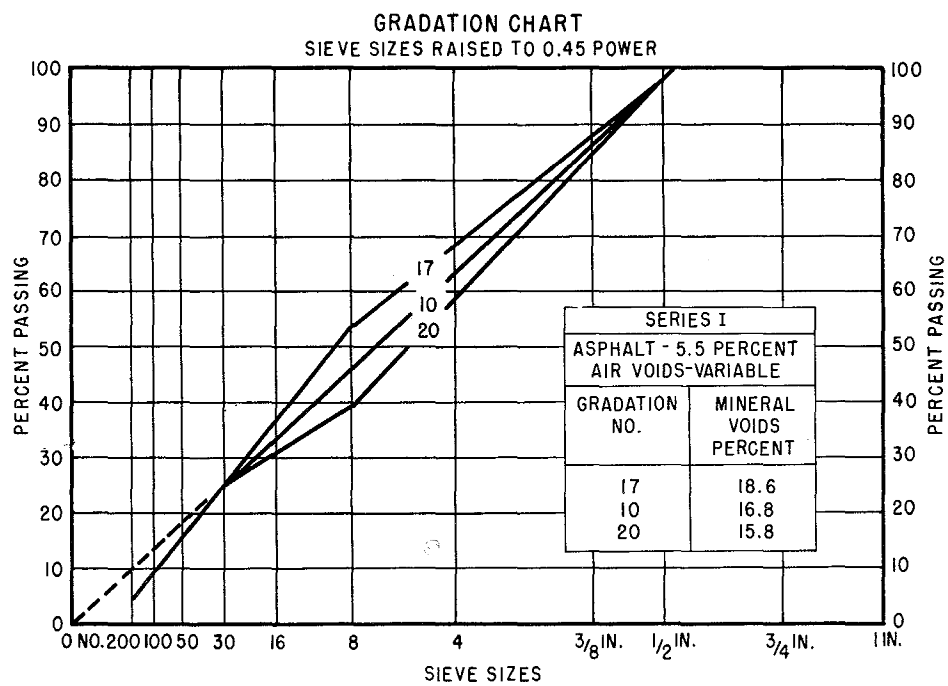


GRAD. NO.	SERIES I — ASPHALT - 5.5 PCT. AIR VOIDS - VARIABLE: MINERAL VOIDS, PERCENT	SERIES I — MARSHALL STABILITY POUNDS	SERIES II — ASPHALT - VARIABLE AIR VOIDS - 4.0 PCT.: MINERAL VOIDS, PERCENT	SERIES II — MARSHALL STABILITY POUNDS
3	14.4	1650	14.8	1610
12	16.7	1070	16.3	1200
22	17.7	960	-	-
23	16.3	1080	-	-
24	15.1	1260	-	-

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



SERIES I — ASPHALT - 5.5 PERCENT AIR VOIDS-VARIABLE: GRADATION NO.	MINERAL VOIDS PERCENT
17	18.6
10	16.8
20	15.8

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.

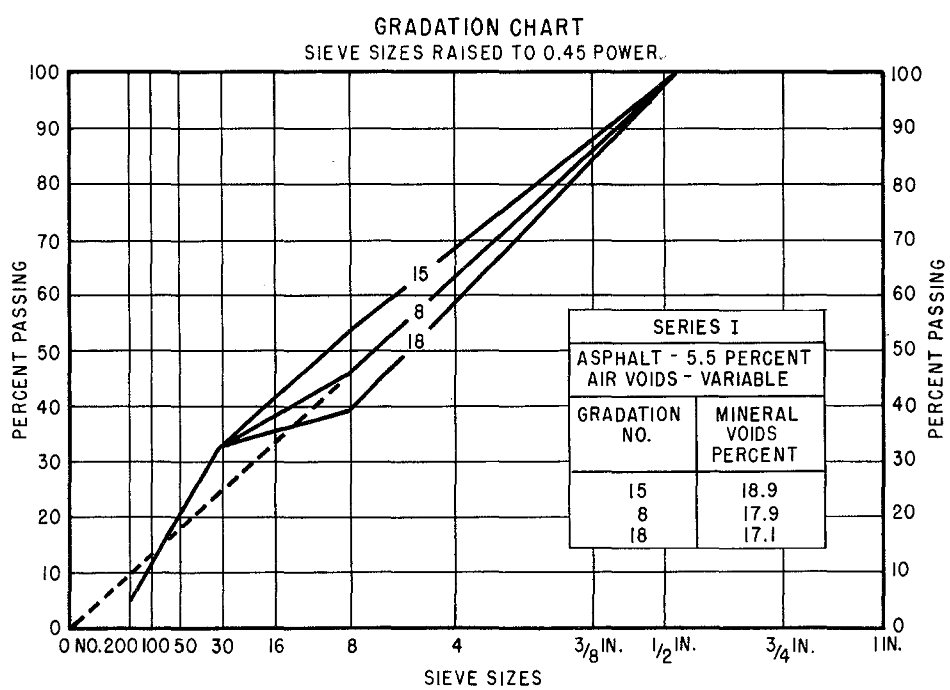


Figure 13.—Gradations varying in percentage passing No. 8 sieve, with high percentage passing No. 30 sieve.

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 ⅜-inch, ⅜-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										Effective specific gravity[1]
	0.525 in.	½-in.	⅜-in.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	
1	100	99	90	73	58.6	47.3	38.0	30.8	24.8	20.0	2.651
2	100	98	88	68	52.0	39.9	30.6	23.6	18.1	13.9	2.650
3	100	98	86	63	46.0	33.7	24.6	18.0	13.2	9.7	2.649
4	100	98	84	59	40.8	28.5	19.8	13.8	9.7	6.7	2.648
5	100	97	82	55	36.2	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	100	98	86	63	46.0	40.6	36.6	22.6	12.3	4.7	2.665
8	100	98	86	63	46.0	38.3	32.6	20.4	11.4	4.7	2.661
9	100	98	86	63	46.0	36.0	28.6	18.1	10.4	4.7	2.658
10	100	98	86	63	46.0	33.7	24.6	15.9	9.4	4.7	2.655
11	100	98	86	63	46.0	32.0	21.6	14.2	8.7	4.7	2.653
12	100	98	85	61	43.1	30.1	20.4	13.5	8.4	4.7	2.651
13	100	98	88	68	53.3	46.0	40.6	24.9	13.3	4.7	2.670
14	100	98	88	68	53.3	43.7	36.6	22.6	12.3	4.7	2.667
15	100	98	88	68	53.3	41.4	32.6	20.4	11.4	4.7	2.663
16	100	98	88	68	53.3	39.1	28.6	18.1	10.4	4.7	2.660
17	100	98	88	68	53.3	36.8	24.6	15.9	9.4	4.7	2.657
18	100	98	84	58	38.9	35.3	32.6	20.4	11.4	4.7	2.659
19	100	98	84	58	38.9	33.0	28.6	18.1	10.4	4.7	2.656
20	100	98	84	58	38.9	30.7	24.6	15.9	9.5	4.7	2.653
21	100	98	84	58	38.9	28.4	20.6	13.6	8.5	4.7	2.650
22	100	98	84	58	52.0	36.0	24.1	15.6	9.3	4.7	2.657
23	100	97	82	52	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
	½-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	1.016
Flash point, C.O.C. °F	540
Softening point °F	117
Penetration, 77° F, 100 g., 5 sec	93
Ductility, 77° F cm	230
Bitumen percent	99.8
After oven loss test (AASHO T 47):	
Loss percent	0.06
Penetration	80
Retained penetration percent	86
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	5.52	2.347	16.1	1,750	8
2	2.384	14.7	2.5	1,930	10	4.95	2.364	15.0	1,810	8
3	2.392	14.4	2.1	1,650	10	4.83	2.367	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	5.62	2.340	16.3	1,010	8
6	2.290	17.9	6.2	770	9					
7	2.286	18.7	7.0	810	7	6.64	2.324	18.2	1,100	7
8	2.304	17.9	6.1	860	8	6.22	2.333	17.4	1,110	7
9	2.320	17.3	5.4	990	8	5.97	2.339	17.0	1,220	8
10	2.331	16.8	4.8	1,100	9	5.64	2.347	16.3	1,190	7
11	2.318	17.2	5.3	1,030	8					
12	2.330	16.7	4.7	1,070	9	5.65	2.344	16.3	1,200	9
13	2.240	20.5	9.0	570	7					
14	2.265	19.5	7.9	710	7	6.93	2.317	18.8	1,060	8
15	2.277	18.9	7.2	800	7					
16	2.274	19.0	7.3	780	8					
17	2.282	18.6	6.9	860	8	6.38	2.325	17.7	1,080	8
18	2.326	17.1	5.2	980	7	5.70	2.348	16.5	1,070	7
19	2.350	16.1	4.1	1,220	8					
20	2.355	15.8	3.8	1,230	9	5.34	2.355	15.8	1,240	8
21	2.346	16.1	4.1	1,080	8					
22	2.306	17.7	5.9	960	8					
23	2.343	16.3	4.3	1,080	8					
24	2.374	15.1	2.9	1,260	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.

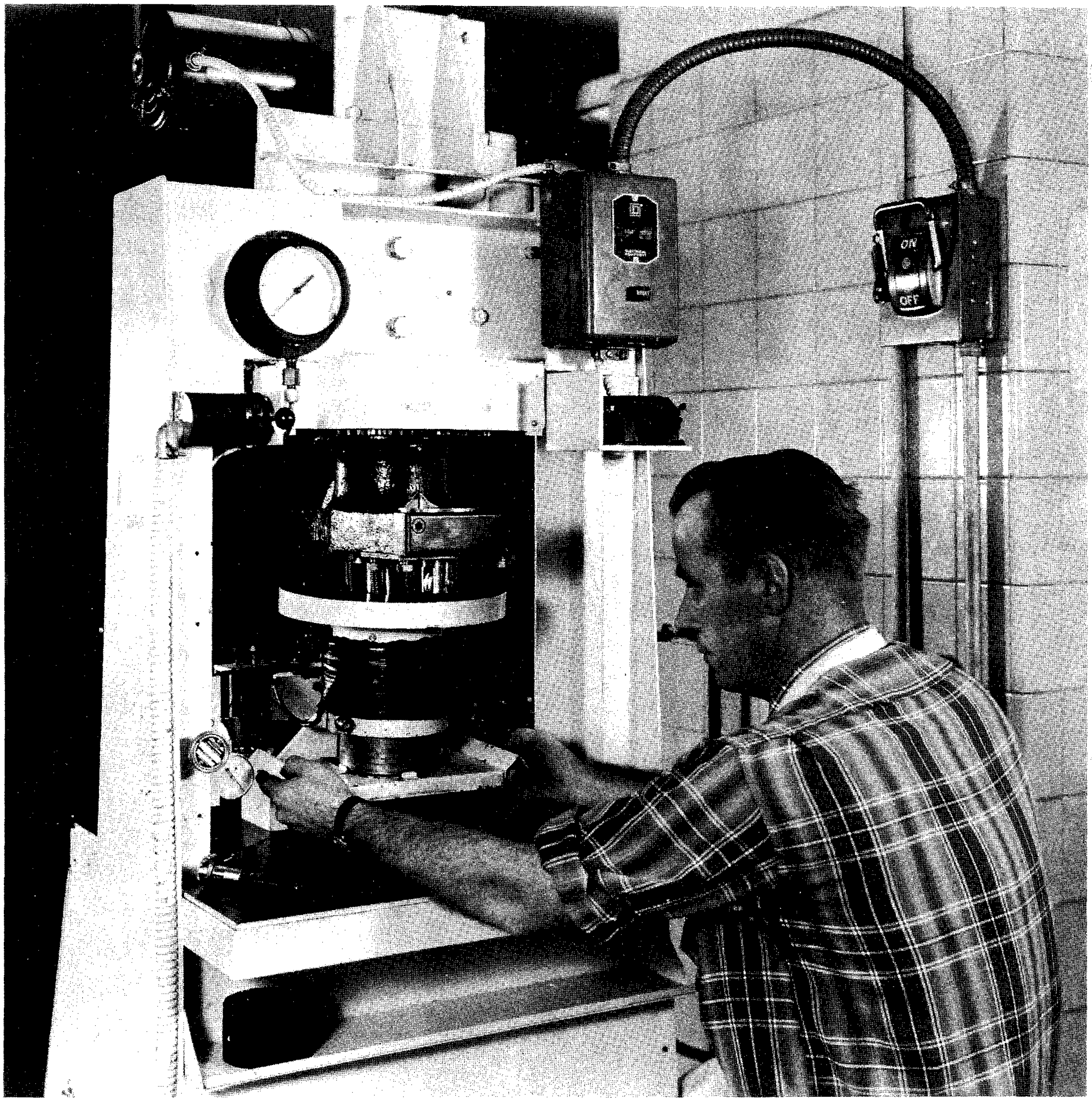


Figure 14.—Mechanical gyratory compactor used in molding test specimens.

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