LABORATORY STUDY OF ASPHALT PAVING MIXTURES

by W. K. BOYD*

INTRODUCTION

This paper summarizes the results of a portion of an extensive laboratory test program performed to study the basic factors that affect the quality of asphalt paving mixtures. Since only a very limited amount of work had been done previously with the Marshall equipment with respect to its selection for use, the new study also permitted an opportunity to develop and improve techniques and procedures for testing and for making a design analysis. In this laboratory program the factors that were studied to determine their effect on the quality of an asphalt paving mixture were: (a) amount of asphalt cement, (b) aggregate gradation, (c) aggregate type, (d) filler, and (e) penetration grade of asphalt cement. Since the technique for sample preparation was the same for all tests, the factor of density produced by different compactive efforts was not a consideration. It is recognized that the density of a mix has an important bearing on its properties, as will be discussed in considerable detail in a later paper.

In order to evaluate and compare the quality of two or more asphalt mixtures it was necessary first to develop tools or yardsticks for measuring certain properties of each prepared test specimen. The selected Marshall test provided a means of measuring the strength and plasticity of a test specimen which could be expressed as numerical values. In addition, the specific gravity of each specimen could be determined and used in the computation of such properties as total weight, unit weight of aggregate only, from which such properties as aggregate and total weight, the percent voids in both the aggregate and total mix, and the percent of the total voids filled with asphalt. In all cases the properties named were determined for each specimen prepared and tested and they were used to compare and evaluate one specimen with respect to another. The effects of the different variables studied are presented in the following paragraphs.

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EFFECT OF ASPHALT CONTENT

In the entire laboratory study the variations produced by changes in asphalt content were the first variables to be compared. That is, for a given type and gradation of aggregate, a number of test specimens were prepared under exactly comparable conditions at each of several asphalt contents. The results of changes in asphalt content on the seven test properties chosen for study are presented for a typical example on Figure 1.

Stability - It can be seen on Figure 1 that the stability of a mixture increases with additional increments of asphalt to a maximum value and then decreases with further addition of asphalt. It is therefore possible to express, as numerical values, the comparative strength of any given mix for various asphalt contents. In the laboratory study the amount of asphalt required to produce maximum stability was the sole criterion for determining the asphalt content at which the other properties of asphalt mixtures would be compared. Later in this symposium it will be shown that other criteria for selecting optimum asphalt should also be considered. However, for the purpose of this laboratory investigation the properties at maximum stability provided a definite basis by which all mixtures could be evaluated and compared.

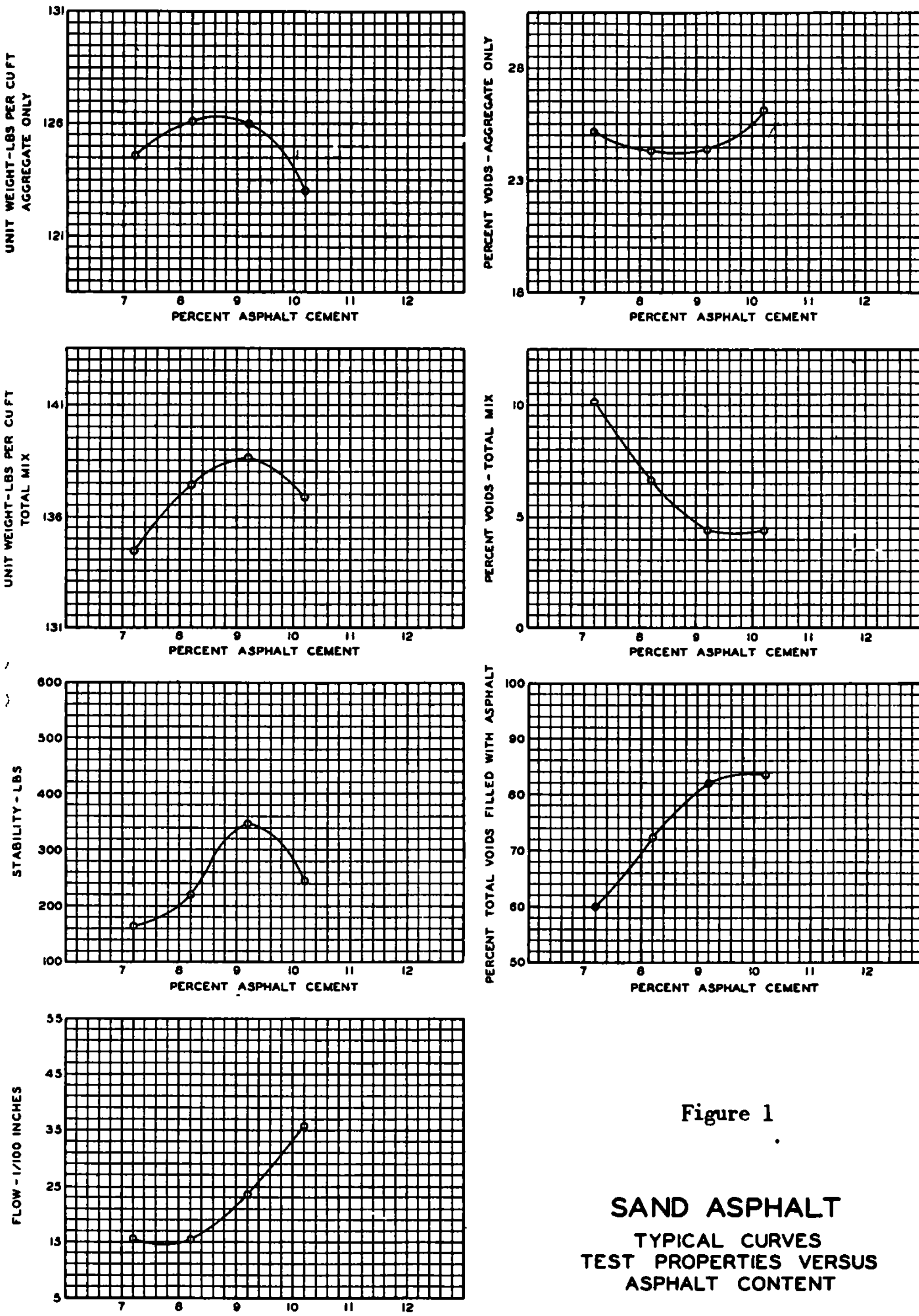


Figure 1

SAND ASPHALT

TYPICAL CURVES
TEST PROPERTIES VERSUS
ASPHALT CONTENT

Flow - The amount of plasticity inherent in a paving mixture for various percentages of asphalt may be measured with the Marshall equipment by the flow test. This test measures, in units of 1/100 of an inch, the amount of deformation required to produce failure of the test specimens. Referring to Figure 1, the flow value increases with the addition of asphalt. Referring to both the stability and flow curves, it can be seen by inspecting the stability curve that values of equal stability can be selected both below and above the optimum asphalt content. The flow curve shows that such values do not represent equally stable mixtures, since a mix with a lower flow value may be entirely stable, while the mix with the higher flow may be plastic and displace badly under traffic. For this reason stability must be associated with flow when comparison between two mixes is made. At optimum asphalt, however, the flow value of the mixes studied in the investigation varied only within a very narrow range. Since comparison of the other variables, aggregate gradation and aggregate type, will be at optimum, the flow value will not be a factor. It will be shown later in another paper that flow is considered an important measure of the quality of an asphalt mixture under traffic.

Density

Total weight - The total weight curve shown on Figure 1 indicates that the total weight of an asphalt mixture increases with additional increments of asphalt to a maximum value beyond which it decreases. The increase in total weight is accounted for by the fact that more asphalt provides greater lubrication which permits the aggregate to be seated together more compactly and each added increment (up to a certain limit) occupies a greater percent of the voids between aggregate particles, thus adding weight to the mass. For a given compactive effort a point is reached where the asphalt replaces aggregate in the mass and, being a lighter material, causes a reduction in the total weight of the specimen. For extremely coarse and open gradation, particularly asphaltic concretes, it was not possible to develop a typical asphalt versus total weight curve, because the voids between aggregate particles are excessively large.

Aggregate weight - With the total weight of the specimen determined by test and knowing the percent of asphalt that has been added, the unit weight of the aggregate portion may be found by computation. A typical curve in which the aggregate weight is compared with variation in asphalt is shown on Figure 1. In all cases the amount of asphalt required to produce maximum aggregate density was less than that required for maximum total density. By examining the aggregate weight curve it can be seen that there is a small range of asphalt contents over which the aggregate structure remains approximately constant. Any increase in the amount of asphalt in this range is utilized in filling additional voids and adds weight to the total mix. Further additions of asphalt above this range separate the particles and cause a loss in aggregate weight, but because this loss may be offset by an increment of asphalt which fills a greater amount of the remaining voids, the total weight may increase. Therefore, in all cases the curves based on aggregate weight reached a maximum value at a lesser amount of asphalt than did the curves based on total weight.

Percent voids total mix - The portion of the total volume of a specimen occupied by aggregate and asphalt comprises the solid fraction and may be termed the percent by volume of solids in the paving mixture. The complement of percent solids is percent voids total mix. On Figure 1 a curve for this test property is plotted with a scale showing the percent voids total mix on one side and the percent solids on the other side. Referring to these curves, it is apparent that as asphalt is added the voids in the aggregate fraction become less until a point is reached where the mass contains a minimum of voids, and any further increase in asphalt spreads the aggregate particles apart leaving the percent voids virtually unchanged. Therefore the point on the curve where the rate of curvature changes indicates the percent asphalt required to secure the maximum practical density.

Percent voids aggregate only - Aggregate weight of a test specimen may be converted to volume by calculation and expressed as a percent of the total volume of the mixture. The ratio of the volume occupied by aggregate to the total volume of the mass is termed percent solids aggregate only. The complement of this value is termed percent voids aggregate only. The amount of asphalt that produces the greatest aggregate weight is the same as will produce the least percent voids in the aggregate.

Percent voids filled with asphalt - The ratio of the volume of asphalt in a mix to the aggregate voids may be expressed as the asphalt-void ratio. For example, if the aggregate occupies 80 percent of the volume of a test specimen, the voids available for asphalt are 20 percent. If asphalt fills 15 percent of the aggregate voids, then 15/20 or 75 percent of the available voids are filled.

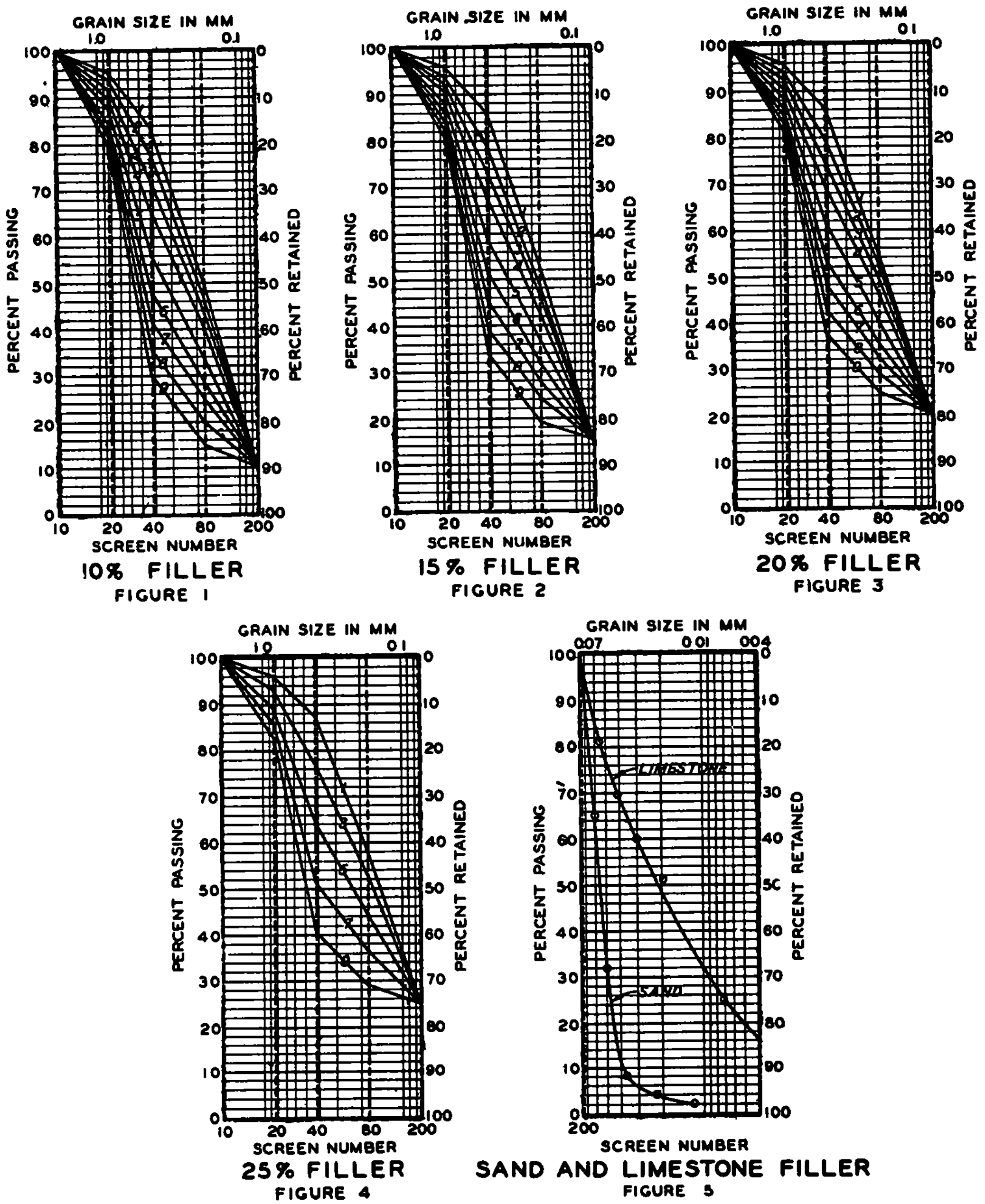
From Figure 1 it can be seen that a higher percentage of voids is filled with each additional increment of asphalt. Since it has no peak value as is the case with some of the other properties, and bacause the values at optimum asphalt for satisfactory graded mixes vary only within a narrow range of values, the property is of little importance in this paper. However, the property will be shown to have considerable importance in the papers to be given later.

Importance of asphalt content - It is evident from the discussion just presented that the test properties are affected a great deal by the amount of asphalt that is included in an aggregate mixture. If a very small amount is used, the resulting mix is brittle, has low strength or stability, the weight is comparatively low, and the voids excessively large. If too much asphalt is used, the resulting mix is too plastic, has little strength and also may be considered unsatisfactory. It is considered that asphalt content is the most critical variable in a paving mixture. In the following paragraphs asphalt mixtures will be compared in which other factors are variables. In all cases the values shown will reflect the test properties of an asphalt mixture at its optimum asphalt content as determined by the stability test. The data presented are summaries only. In all cases a series of test specimens was prepared in which asphalt content was the variable and from which optimum asphalt was selected.

EFFECT OF AGGREGATE GRADATION

Sand Asphalt - In order to investigate the effect of aggregate gradation on sand asphalt, nine blends of fine aggregate covering a wide range of gradation were prepared. The blends are designated gradations 1 through 9, with gradation 1 the finest and gradation 9 the coarsest mix. These blends provided fine aggregates, all of which passed the No. 10 sieve, varying from a coarse to a very fine gradation. In general, the principal difference between the nine gradations occurred in the amount of material passing the No. 40 sieve with minor differences in the amount of material passing the No. 80 sieve. Sufficient limestone dust was added to each of these nine basic blended materials to give mixtures having a total of 10, 15, and 20 percent of filler. In addition, limestone dust was added to gradations 1, 3, 5, 7, and 9 to give mixtures having a total of 25 percent filler. The gradations of these blends are shown on Figure 2.

On Figure 3 the results of variation in fine aggregate gradations are shown by curves for all test properties. In all cases the curves drawn through the plotted points represent the changes that result when the gradation of the fine aggregate is varied with the quantity of filler held constant. The curves representing flow (Figure 3) indicate no significant trend and for the purpose of this analysis it is assumed that they are all satisfactory. All curves representing stability show a progressive increase in numerical value from gradations 1 through 7 with a tendency for lower values on gradations 8 and 9. Unit weights (both total and aggregate) show a progressive increase in numerical value from gradations 1 through 8 with a tendency for lower values for gradation 9. The percent voids (total mix and aggregate) generally decreased progressively from gradations 1 through 7

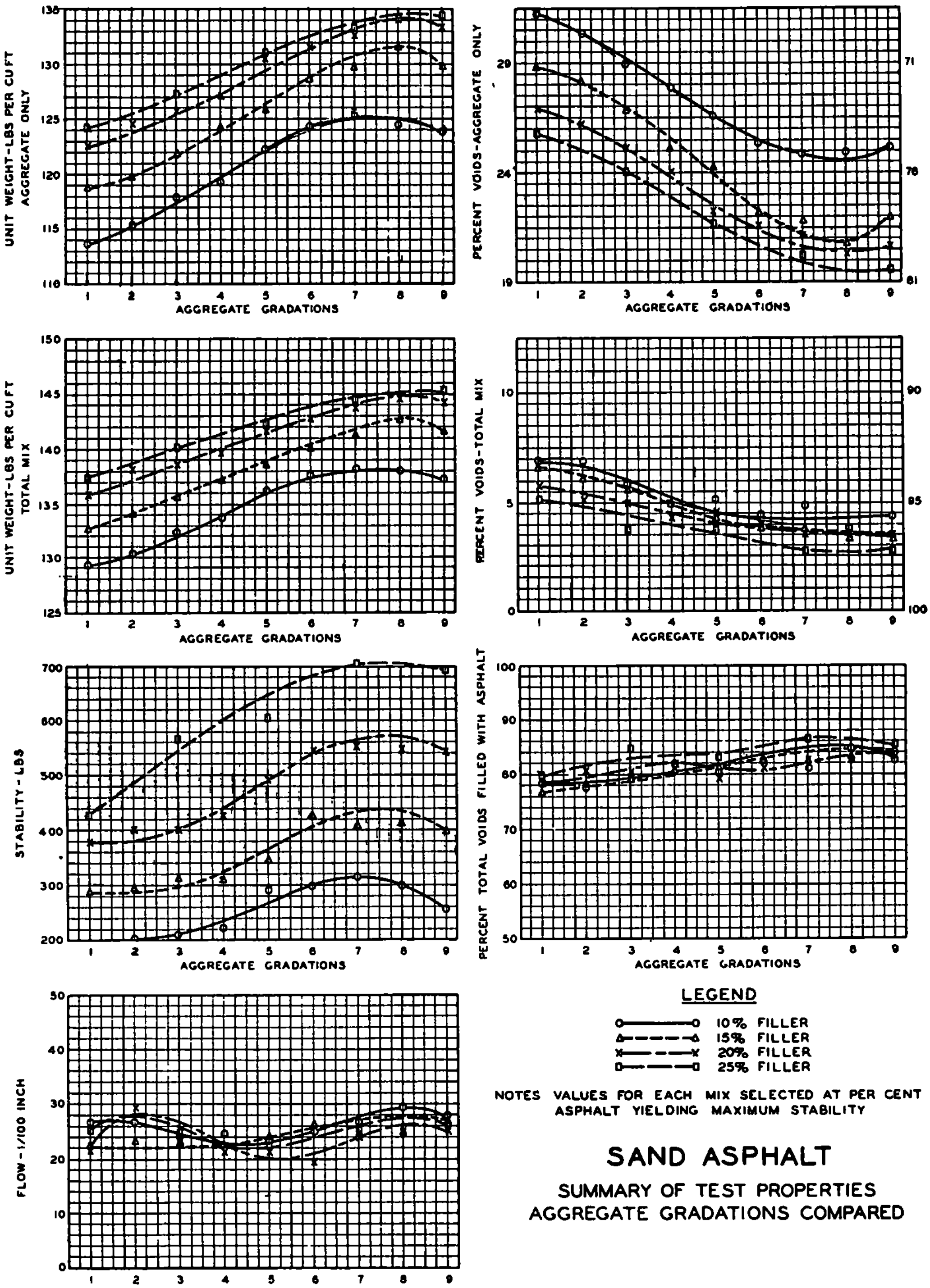


AGGREGATE GRADING CHARTS

SAND ASPHALT

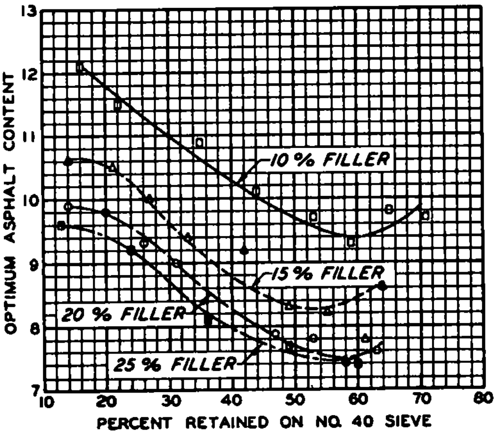
Figure 2

with a tendency to remain constant or increase for gradations 8 and 9. The curves representing asphalt-void ratios indicate a slight trend to fill more of the voids with asphalt progressively from gradations 1 through 9. The data indicate that increasing the amount of fine aggregate retained on a No. 40 screen to as much as



UNIT WEIGHT-LBS PER CU FT AGGREGATE ONLY
AGGREGATE GRADATIONS
PERCENT VOIDS-AGGREGATE ONLY
PERCENT SOLIDS-AGGREGATE ONLY
UNIT WEIGHT-LBS PER CU FT TOTAL MIX
PERCENT VOIDS-TOTAL MIX
PERCENT SOLIDS-TOTAL MIX
STABILITY - LBS
PERCENT TOTAL VOIDS FILLED WITH ASPHALT
FLOW - 1/100 INCH
LEGEND
10% FILLER
15% FILLER
20% FILLER
25% FILLER
NOTES VALUES FOR EACH MIX SELECTED AT PER CENT ASPHALT YIELDING MAXIMUM STABILITY
SAND ASPHALT
SUMMARY OF TEST PROPERTIES
AGGREGATE GRADATIONS COMPARED

Figure 3.



SAND ASPHALT

SUMMARY OF OPTIMUM ASPHALT CONTENTS

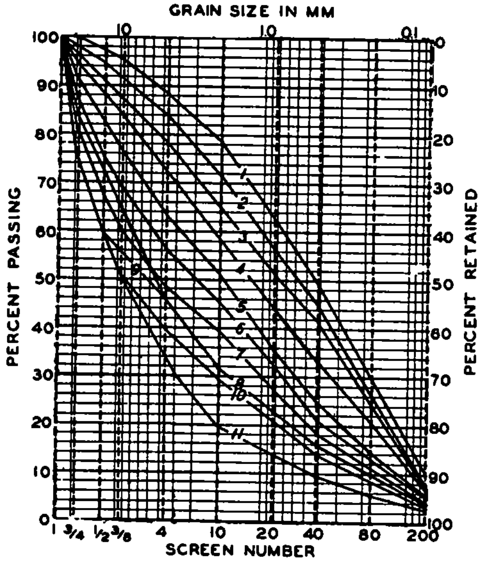
Figure 4.

about 55 to 65 percent of the total aggregate improved a sand asphalt mixture, the exact amount being contingent on the amount of filler present in the mixture. It is not inferred that sand asphalt mixtures containing finer gradations are unsatisfactory, as no limits for the test properties have been established.

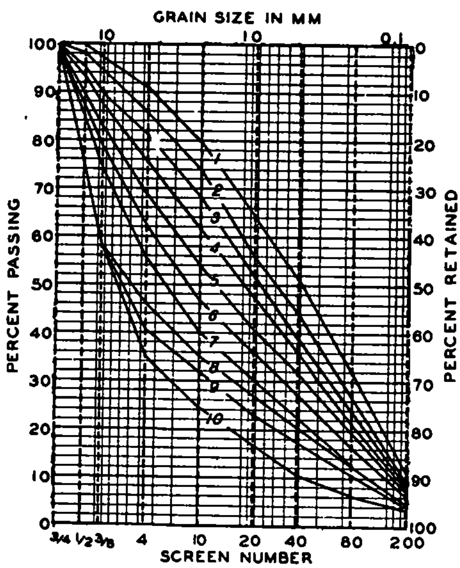
Effect on optimum asphalt - On Figure 4 the amount of asphalt determined as optimum is shown by a curve for each variation in aggregate gradation and for each of four filler contents. It can be seen that the amount of asphalt required for optimum was reduced with incremental increases in the amounts of coarse sand until about 50 to 60 percent of the total aggregate is retained on the No. 40 screen. A further increase in coarse sand again increased the optimum asphalt content. This trend was duplicated by the curves for percent voids aggregates only shown on Figure 3, and suggests that the amount of asphalt required is dependent on the available voids. If the four curves on Figure 4 are compared, it is seen that they are in the order of filler content. That is, a given aggregate gradation with 15 percent filler required less asphalt for optimum than the same gradation with 10 percent filler, still less for 20, and least with 25 percent filler. It is apparent that both asphalt and filler are void filling materials and will supplement each other (within limits) in a paving mixture.

Asphaltic concrete - In order to investigate the effect of aggregate gradations on asphalt concrete mixtures, ten blends each were prepared for the 3/4 and ½-in. maximum aggregate size and eleven blends for the 1-in. size. Blends have been designated gradation 1 through 10 (or 11), blend 1 being the finest. Gradation curves for the blends are shown on Figure 5. Test series conforming to the gradation curves shown were prepared using uncrushed gravel and slag as the coarse aggregate. Also, test series were made conforming to the gradation curves for 3/4 in. maximum size using crushed limestone and crushed gravel, in addition to the series for uncrushed gravel and slag. In all cases the fine aggregate fraction consisted of a blend of two local sands. Limestone dust was used as the filler. In general, the principal variation in the gradation curves occurred in the coarse aggregate fraction. If the gradations of the fine aggregates were replotted on the basis of 100 percent passing a No. 10 sieve, they would be reasonably comparable.

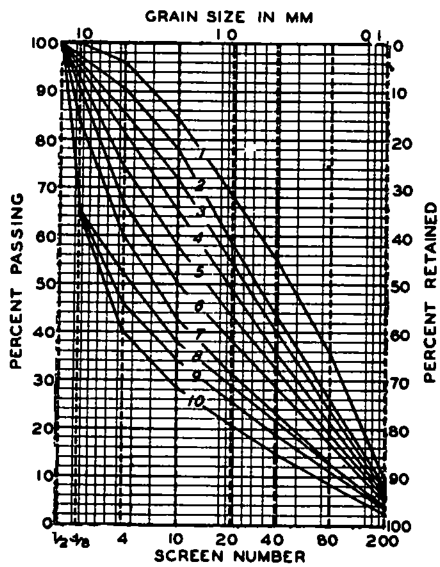
Uncrushed gravel - Summary test results on specimens prepared with uncrushed gravel in which the percent of coarse aggregate varied from about 15 to 80 percent of the total aggregate and for three (½-, 3/4-, and 1-in.) maximum size materials are shown on Figure 6. With each added increment of coarse aggregate the stability and all density properties were improved until the mixture was composed of approximately 60 to 70 percent coarse aggregate. There was a rather indefinite trend in the percent voids filled with asphalt to increase until more than 70 percent coarse aggregate was included in the mixture; beyond 70 percent the value dropped markedly. It is clear that in these tests stability was dependent on density, which means that (for any given aggregate type) the gradation which permits the least aggregate voids, or the highest density, will usually possess the highest structural strength. From visual inspection of the test specimens, it was observed that those containing more than 70 percent coarse aggregate would not



I INCH MAXIMUM
FIGURE 1



3/4 INCH MAXIMUM
FIGURE 2



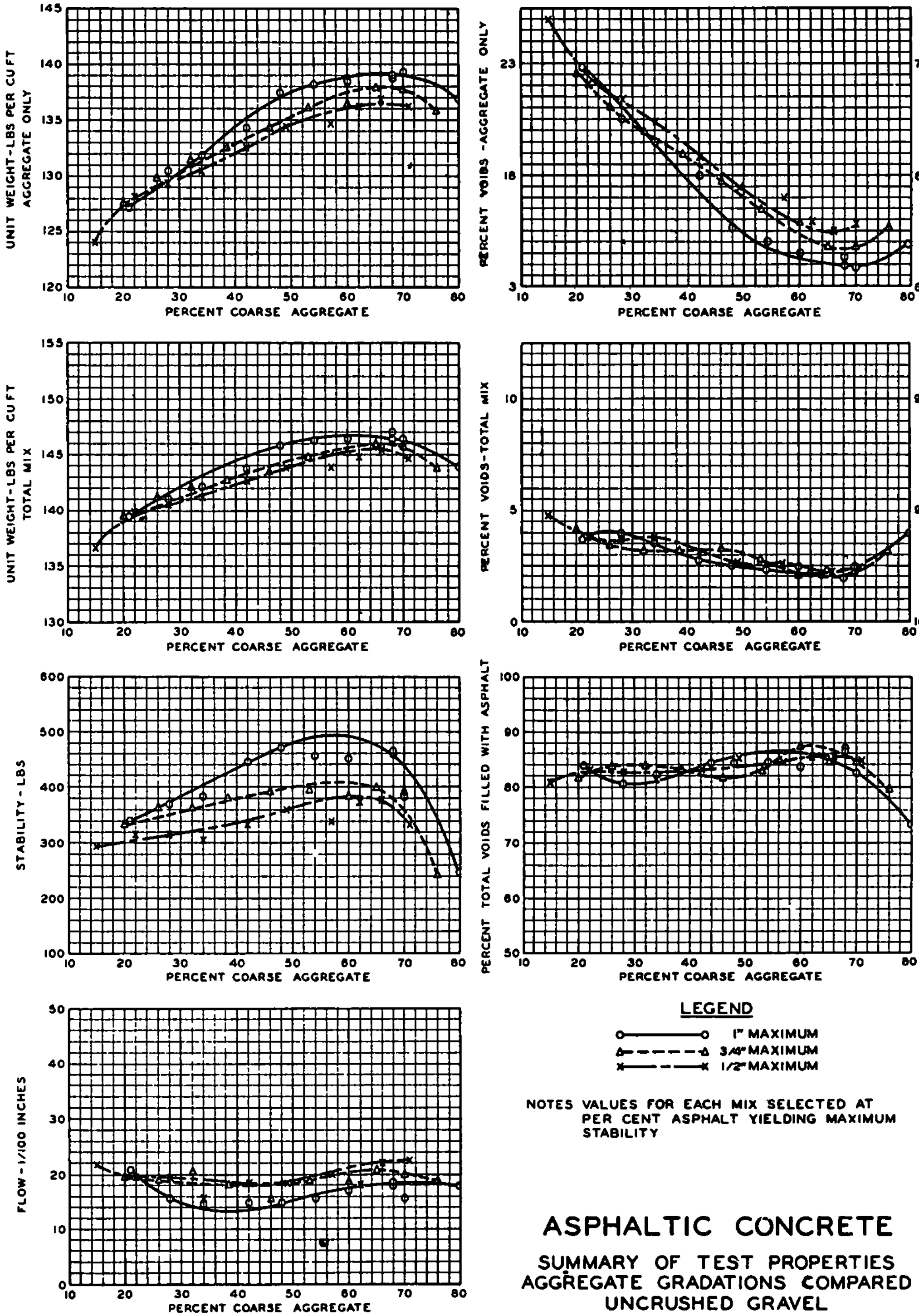
1/2 INCH MAXIMUM
FIGURE 3

NOTE SCREEN NUMBERS REFER TO U S STANDARD SIEVE

AGGREGATE GRADING CHARTS
ASPHALTIC CONCRETE

Figure 5

produce a desirable wearing course paving mixture because of their open texture. The curves for ½, 3/4, and 1 in. maximum size aggregate also show that there was an improvement in both stability and density (slight) as the maximum size increased. Therefore, in general, both for economy (less crushing, screening, etc.) and greater strength, the largest maximum size aggregate consistent with pavement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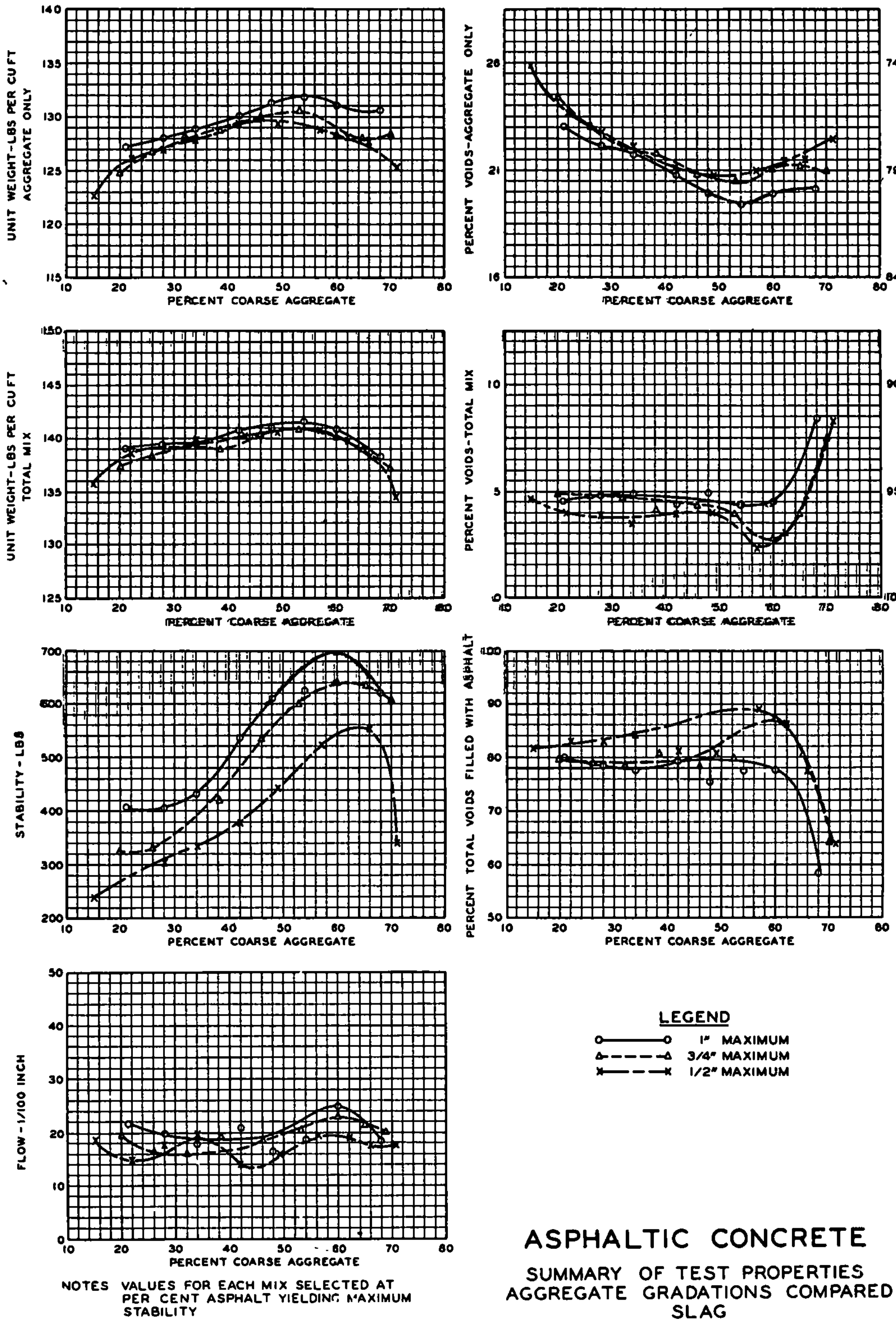
PERCENT COARSE AGGREGATE
PERCENT VOIDS-AGGREGATE ONLY
PERCENT SOLIDS-AGGREGATE ONLY
UNIT WEIGHT-LBS PER CU FT TOTAL MIX
PERCENT VOIDS-TOTAL MIX
PERCENT SOLIDS-TOTAL MIX
STABILITY-LBS
PERCENT TOTAL VOIDS FILLED WITH ASPHALT
FLOW-1/100 INCHES
LEGEND
1" MAXIMUM
3/4" MAXIMUM
1/2" MAXIMUM
NOTES VALUES FOR EACH MIX SELECTED AT PER CENT ASPHALT YIELDING MAXIMUM STABILITY
ASPHALTIC CONCRETE
SUMMARY OF TEST PROPERTIES
AGGREGATE GRADATIONS COMPARED
UNCRUSHED GRAVEL

Figure 6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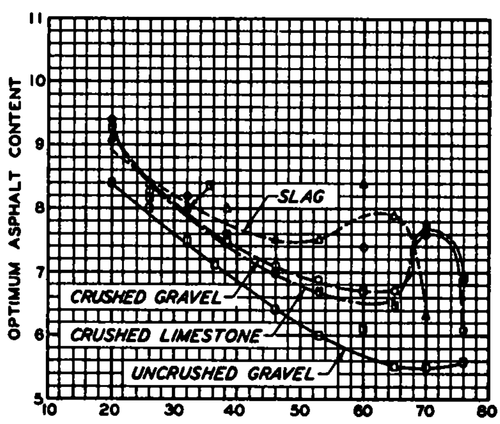
PERCENT VOIDS-AGGREGATE ONLY
PERCENT SOLIDS-AGGREGATE ONLY
UNIT WEIGHT-LBS PER CU FT TOTAL MIX
PERCENT VOIDS-TOTAL MIX
PERCENT SOLIDS-TOTAL MIX
STABILITY-LBS
PERCENT TOTAL VOIDS FILLED WITH ASPHALT
FLOW-1/100 INCH
PERCENT COARSE AGGREGATE
LEGEND
1" MAXIMUM
3/4" MAXIMUM
1/2" MAXIMUM
NOTES VALUES FOR EACH MIX SELECTED AT PER CENT ASPHALT YIELDING MAXIMUM STABILITY
ASPHALTIC CONCRETE
SUMMARY OF TEST PROPERTIES
AGGREGATE GRADATIONS COMPARED
SLAG

Figure 7

thickness and construction should be used.

Slag - In general, the statements concerning uncrushed gravel, are true for mixtures containing slag as the coarse aggregate fraction, as shown on Figure 7. However, maximum values for stability and density were secured at about 60 percent coarse aggregate for the slag rather than the slightly higher range indicated for uncrushed gravel. This was due to the facts that slag was a much lighter material and that all percentages were based on weight, the volume of slag being greater for equal weights of the two materials. The specific gravity of a material should therefore be considered when any statement concerning maximum amounts of coarse aggregate is made.



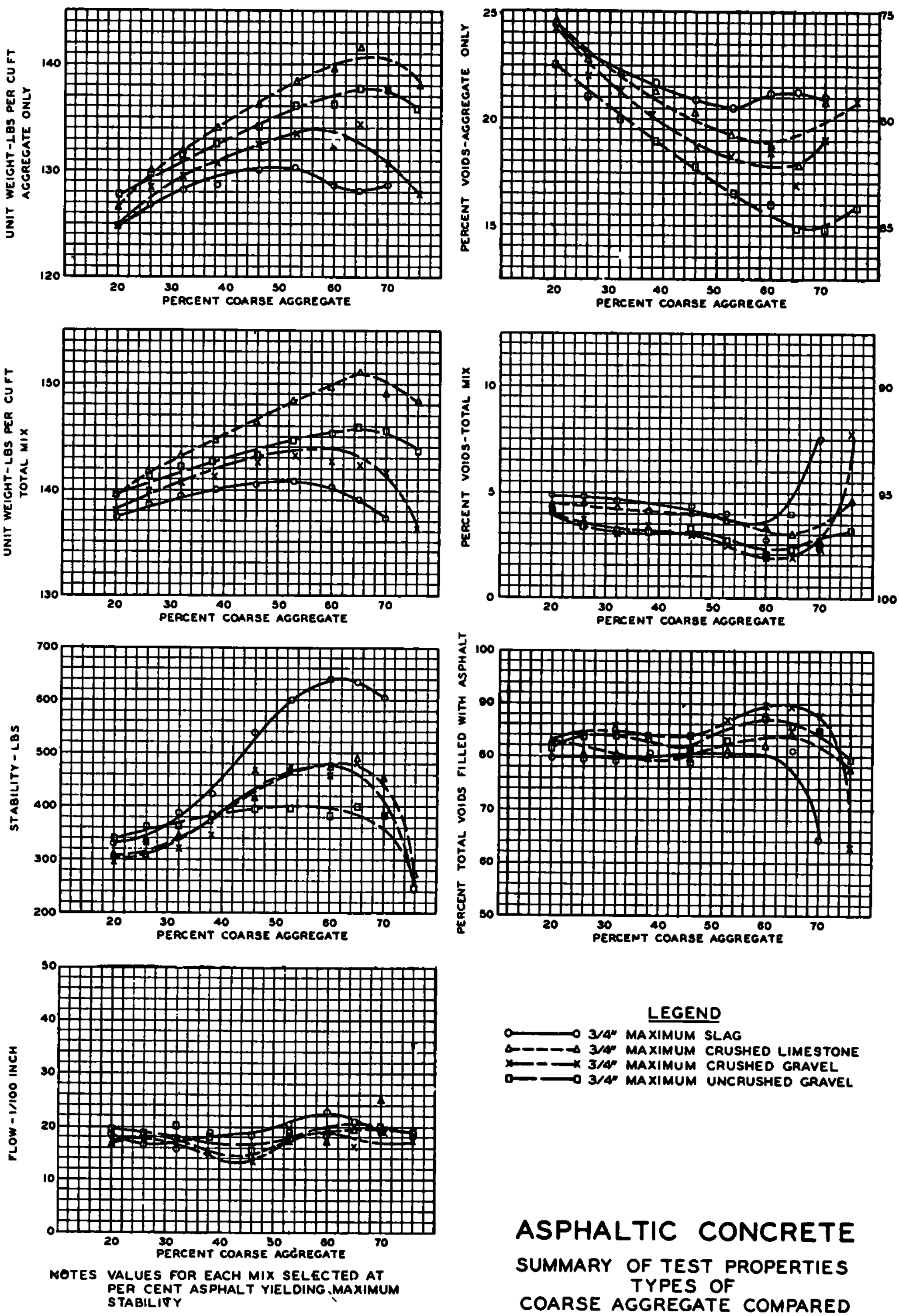
ASPHALTIC CONCRETE
SUMMARY OF OPTIMUM ASPHALT CONTENTS
3/4 INCH MAXIMUM SIZE

Figure 8

Effect on optimum asphalt - On Figure 8 is shown the amount of asphalt indicated as optimum for different aggregate gradations and aggregate types. All of the curves have the same general characteristics and show that less asphalt was required with each additional increment of coarse aggregate added to the paving mixture until the total amount of coarse aggregate exceeded about 55 percent for slag and about 65 percent for crushed limestone and gravel. Below these limits the trend for less asphalt corresponds directly with the reduction in the aggregate voids (Figure 9). Since at optimum about the same percent of the aggregate voids was always filled with asphalt, the amount of asphalt at optimum must be reduced with each incremental increase in coarse aggregate. It may be noted that there was a point (65 percent for slag and 70 percent for crushed limestone and gravel) where the ratio between aggregate voids and percent asphalt in the mix was not constant. Apparently the voids became excessively large so that they were not filled to the same extent as were smaller voids, and the amount required for optimum asphalt was sharply reduced. As previously discussed, all test specimens in the laboratory study were compacted at one compaction effort. It will be shown in later papers that this compaction effort was low. A greater compaction effort will produce higher densities, reduce aggregate voids, and any given mixture will consequently require less asphalt for the optimum value than is shown by these data. Therefore, the data should be compared only from a qualitative standpoint.

EFFECT OF AGGREGATE TYPE

A summary of test properties for four types of coarse aggregate 3/4 in. maximum size, is presented on Figure 9. It should be noted that the various density curves show the same trends with change in amount of coarse aggregate and, with respect to each other, reflect the difference in their specific gravities. Slag had the lowest apparent specific gravity and the greatest amount of voids in the aggregate of the four types compared. It also had the highest stability. Crushed limestone was the heaviest material; yet the aggregate voids were high, being exceeded only by the slag. It is apparent that comparisons of types of aggregate on a weight basis for specification purposes are not necessarily valid while limiting values for stability, flow, percent voids aggregate only, percent voids total mix, and percent voids filled with asphalt may be established which apply to all aggregates. However, as has been discussed in previous paragraphs, a weight basis is of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PERCENT COARSE AGGREGATE
PERCENT VOIDS-AGGREGATE ONLY
PERCENT SOLIDS-AGGREGATE ONLY
UNIT WEIGHT-LBS PER CU FT TOTAL MIX
PERCENT VOIDS-TOTAL MIX
PERCENT SOLIDS-TOTAL MIX
STABILITY - LBS
PERCENT TOTAL VOIDS FILLED WITH ASPHALT
FLOW - 1/100 INCH
LEGEND
3/4" MAXIMUM SLAG
3/4" MAXIMUM CRUSHED LIMESTONE
3/4" MAXIMUM CRUSHED GRAVEL
3/4" MAXIMUM UNCRUSHED GRAVEL
ASPHALTIC CONCRETE
SUMMARY OF TEST PROPERTIES
TYPES OF
COARSE AGGREGATE COMPARED
NOTES VALUES FOR EACH MIX SELECTED AT PER CENT ASPHALT YIELDING MAXIMUM STABILITY

Figure 9

considerable importance in the design analysis and construction control of a specific asphalt paving mixture. With regard to stability (see Figure 9), the stability curves were grouped closely together when the coarse aggregate was less than about 40 percent of the total mix (this assumes that about 34 percent slag by weight was equivalent in volume to 40 percent of the other materials). For mixtures containing more than 40 percent coarse aggregate, the curves begin to spread with the stability for crushed materials higher than for uncrushed material, slag being the highest of all materials tested. Apparently when the coarse aggregate was less than 40 percent of the total, it was effective principally in reducing the voids and increasing the density with each particle floating in the matrix independently of the others. When present in excess of about 40 percent, the quality of the material became effective by particle to particle contact, as reflected by higher stability values for crushed materials and slag when compared to uncrushed gravel.

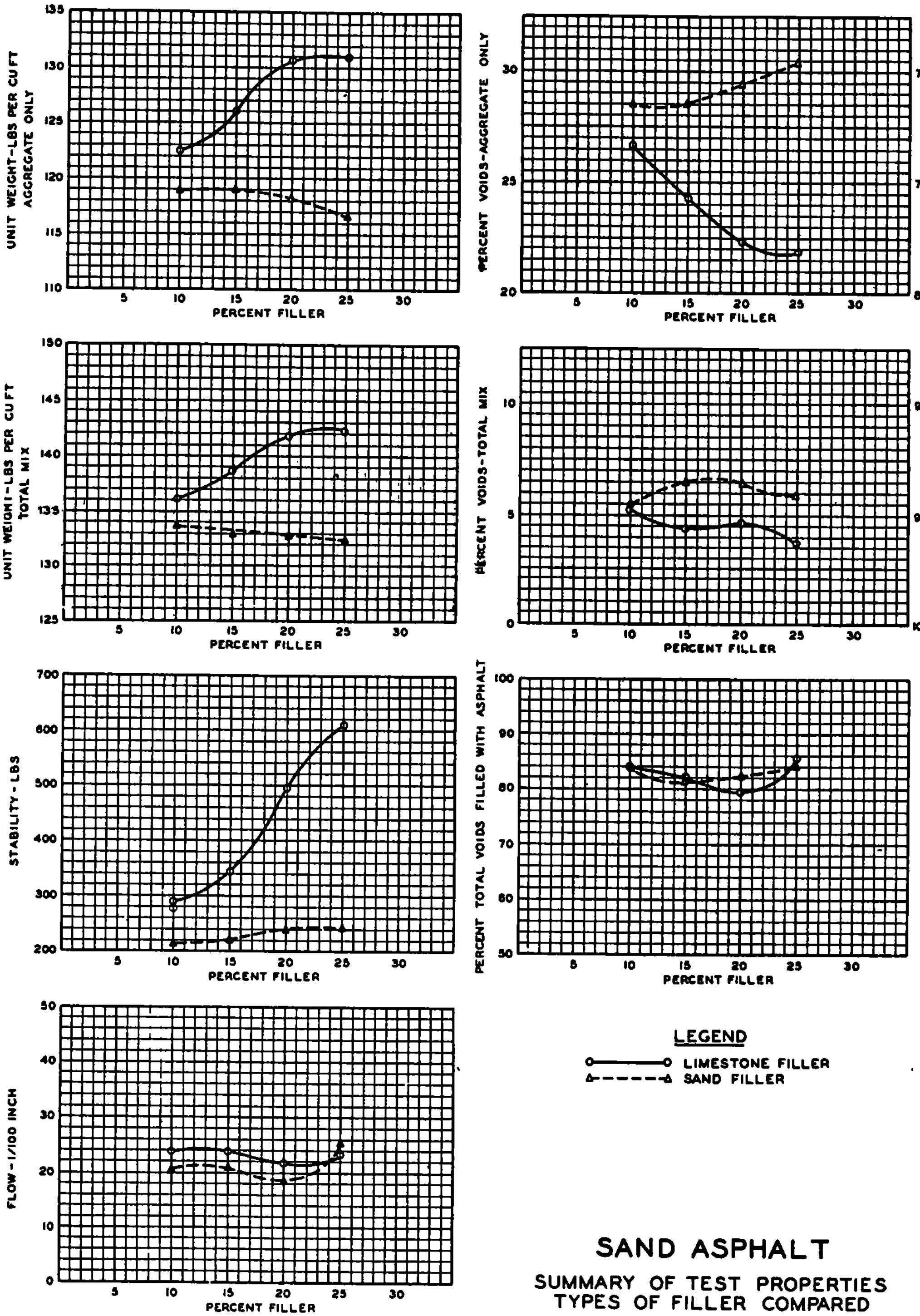
FILLER

Effect of amount of filler - From Figure 3 it can be seen that 15, 20, and 25 percent filler in the nine basic gradations show progressive improvements in the properties over those secured for respective gradations with 10 percent filler. The data on Figure 4 show that as the amount of filler is increased, optimum asphalt content is reduced. The function of filler in a mix is readily apparent from a review of these two figures. Incremental increases in filler up to about a maximum of 20 percent increased the stability, increased the total and aggregate weight, reduced both the aggregate and total voids, and required less asphalt. It is believed that the amount of filler selected for a particular design should include the following considerations: (a) the amount required to produce satisfactory stability, (b) the amount required to produce satisfactory void values, (c) the gradation of the aggregate, and (d) relative cost of asphalt cement, aggregate, and filler. There are other considerations which may modify the maximum amount of filler that is desirable in a mix, such as the flexibility of a mix or the tendency to check and crack during construction rolling; however, these factors were not determined by the laboratory study. In Appendix B of Waterways Experiment Station Technical Memorandum No. 3-254*(1)* a method of analysis is presented which indicated that, based on laboratory tests only, the maximum amount of filler for any of the mixes shown was about 2C percent.

Effect of type of filler - The test results obtained by substituting 10, 15, 20, and 25 percent sand passing a No. 200 mesh sieve for equal quantities of limestone filler are shown for a typical case on Figure 10. It is apparent that equal amounts of sand filler do not improve the desirable properties of a mixture (increased stability and density, decreased voids) to the same extent as limestone filler. Increasing the quantity of limestone filler (up to a certain point) increased stability and density and decreased the voids; however, this was not necessarily true for sand filler, and it can be seen in some cases that additional increments of sand filler were actually detrimental. A gradation curve for each type of filler is shown on Figure 2. The sand filler was composed largely of material between 0.07 and 0.03 mm in size, whereas the limestone filler was well graded with approximately 17 percent finer than 0.004 mm. If the properties of an asphalt mixture are to be improved by adding filler, it is essential that the filler be well graded and that it include material finer than 0.01 mm in size. Otherwise, filler may become a void-producing rather than a void-filling material.

EFFECT OF PENETRATION GRADE OF ASPHALT

Tests were conducted to determine the effect of penetration grade of asphalt cement on the test properties. Four grades of asphalt cement having penetrations of 53, 80, 117, and 135 were used. Results of these tests are summarized on Figure 11. All tests were conducted at optimum asphalt content. It can be seen that the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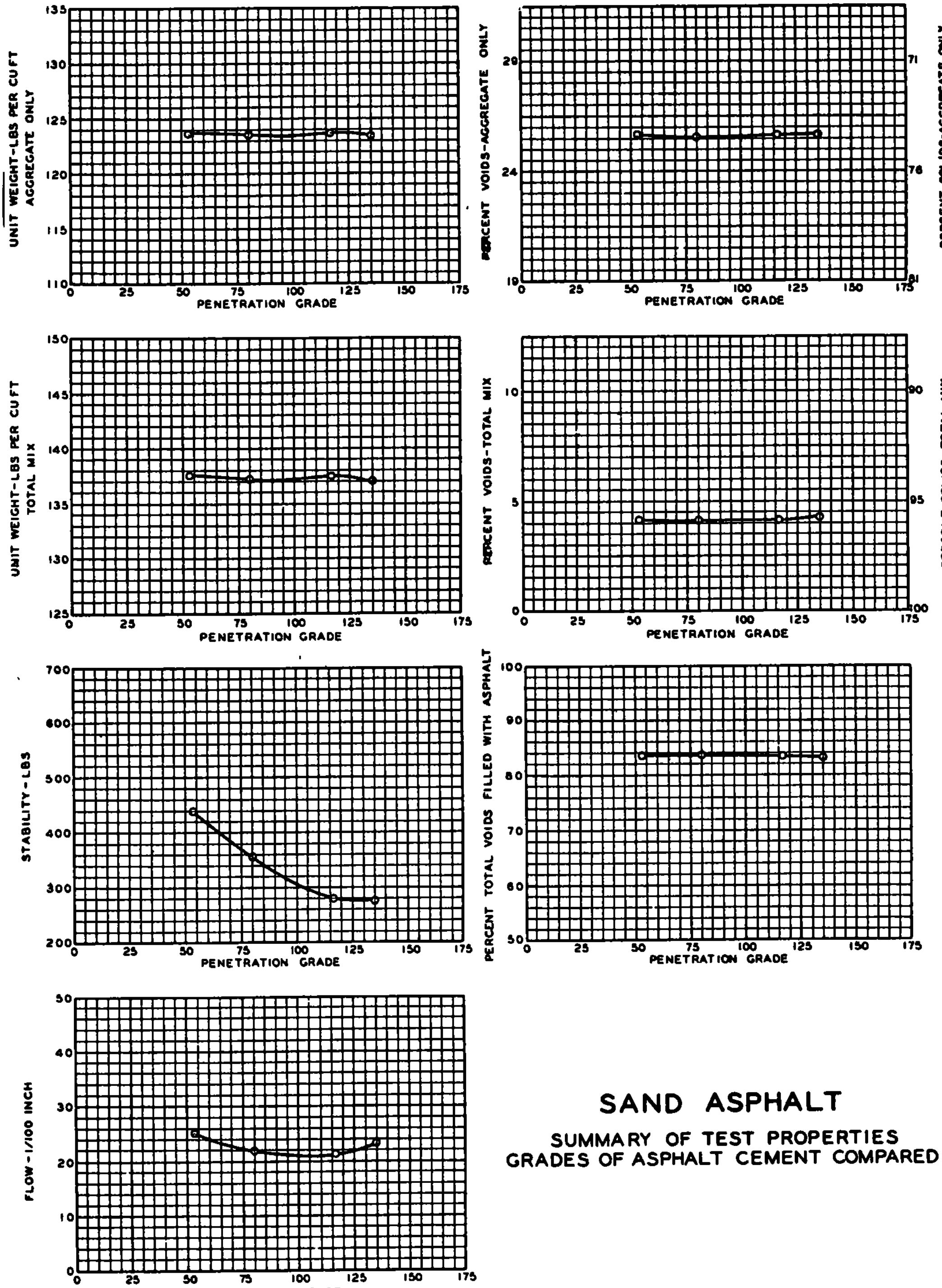
PERCENT FILLER
PERCENT VOIDS-AGGREGATE ONLY
PERCENT SOLIDS-AGGREGATE ONLY
UNIT WEIGHT-LBS PER CU FT TOTAL MIX
PERCENT VOIDS-TOTAL MIX
PERCENT SOLIDS-TOTAL MIX
STABILITY-LBS
PERCENT TOTAL VOIDS FILLED WITH ASPHALT
FLOW-1/100 INCH
LEGEND
LIMESTONE FILLER
SAND FILLER
SAND ASPHALT
SUMMARY OF TEST PROPERTIES
TYPES OF FILLER COMPARED

Figure 10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PERCENT VOIDS-AGGREGATE ONLY
PERCENT SOLIDS-AGGREGATE ONLY
UNIT WEIGHT-LBS PER CU FT TOTAL MIX
PERCENT VOIDS-TOTAL MIX
PERCENT SOLIDS-TOTAL MIX
STABILITY-LBS
PERCENT TOTAL VOIDS FILLED WITH ASPHALT
FLOW-1/100 INCH
PENETRATION GRADE
SAND ASPHALT
SUMMARY OF TEST PROPERTIES
GRADES OF ASPHALT CEMENT COMPARED

Figure 11

use of different grades of asphalt cement had little or no effect on any property except stability. Increased Marshall stability can be secured by using a lower penetration asphalt.

CONCLUSIONS

The conclusions given in the following paragraphs are believed warranted on the basis of the information and data presented in this paper. A more complete discussion and analyses of the laboratory study, together with additional conclusions, may be found in Appendix B of Waterways Experiment Station TM 3-254*(1)*.

The Marshall stability test is an empirical test whereby the relative strength of basically different asphaltic mixtures can be compared.

The flow test, an integral part of the stability test, measures the relative plasticity of asphaltic mixtures.

Incremental increases of asphalt cement to asphalt mixtures will increase the amount of flow; therefore, mixtures of equal stability which contain unequal amounts of asphalt cement may be compared on the basis of flow.

Incremental increases of asphalt to a given aggregate mixture will produce an increase in the total weight to some maximum value, after which further increases of asphalt will cause the total weight of the mixture to decrease.

In general, an increase in the density produces an increase in the stability of a mixture.

Density, expressed as unit weight, cannot be used in a relative comparison of different types of aggregate mixtures; however, it is considered to be of practical value in the design analysis and control of a specific asphalt mixture.

The amount of asphalt required to produce maximum density of the aggregate only is less than that required to produce maximum total weight.

The percent voids total mix is dependent on (a) asphalt content, (b) aggregate gradation, (c) filler content, (d) compactive effort, and (e) aggregate type.

Where the asphalt content is the only variable, the selection of a percent asphalt required to produce maximum aggregate density may be made on the basis of the amount of aggregate voids.

The quantity of asphalt cement required for optimum asphalt content decreases as the aggregate voids decrease.

Well graded fine and coarse aggregate mixtures prepared at optimum asphalt and with a prescribed compactive effort will have an asphalt-void ratio that varies within very narrow limits.

Very open or harsh-graded aggregates, when used in asphaltic mixtures, give an asphalt-void ratio at optimum asphalt content considerably less than that of well-graded aggregates.

The addition of coarse sand (No. 10-40) up to about 60 percent of the total aggregate improved the test properties of sand asphalt mixtures for the materials tested.

While the addition of coarse sand up to about 60 percent improved the test properties, the definite limit of coarse sand depends on the gradation of the fine fractions of the aggregate (No. 40-200) and the amount and type of filler.

The measured properties of an asphaltic concrete mixture were improved by the addition of coarse aggregate to a maximum of between 60 and 70 percent of the total aggregate.

An increase in the maximum size of aggregate (from ½ to 1 in.) improved the test properties of the mixture.

The test properties of a mixture were not changed by the type of aggregate (slag, crushed gravel, uncrushed gravel, or crushed limestone) when present in the mixture in amounts less than 40 percent.

When the amount of coarse aggregate exceeded 40 percent, the type of aggregate became effective; slag produced the highest stability, crushed gravel and crushed limestone were about equal and produced the next highest stability, and uncrushed gravel produced the lowest stability.

The addition of filler to an aggregate mixture increased the stability, total and aggregate weight, and reduced the aggregate and total voids and the amount of asphalt required for optimum.

The maximum amount of filler to be

added to an asphalt mixture was not determined and is dependent on several factors: (a) amount necessary to produce a satisfactory stability, (b) amount necessary to meet specified void requirements, (c) aggregate gradation requirements, (d) relative cost of asphalt cement, sand, and filler, and (e) other possible factors not considered in this study, such as durability and flexibility.

The addition of a well-graded filler to a sand asphalt mixture improved the measured test properties.

The addition of a poorly-graded sand filler did not improve the measured test properties of a sand asphalt mixture.

The use of different penetration grades (between 50 and 135) of asphalt cement had no effect on any measured property except stability which was increased with each decrease in the penetration grade of asphalt.