ASPHALT STABILIZATION OF SELECTED SAND AND GRAVEL BASE COURSES

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THESIS

This is to certify that the

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ABSTRACT

ASPHALT STABILIZATION OF SELECTED
SAND AND GRAVEL BASE COURSES

by John Charles Riley

Throughout the United States there are many areas which are totally void of high quality aggregates suitable for use in standard highway base courses. One method of remedying this situation is to render the lower quality aggregates suitable for use by stabilization with asphalt cement.

This thesis is concerned with an analysis of the effectiveness of the stabilization of certain sand asphalt and sand-gravel asphalt mixtures. Samples of the materials were prepared and tested for Marshall Stability and unconfined compressive strength. Results were then compared primarily to one set of specifications for asphalt treated base courses.

From the results obtained, it is theorized that, in the stabilization of sand with asphalt, the asphalt serves to increase intergranular friction as well as to

produce cohesive resistance.

The only mixtures that had maximum strengths, or stabilities, which were found to occur at or slightly below optimum density, high enough to qualify for a base course by the standards used, were the sand-gravel mixtures using 85/100 penetration asphalt.

By a comparison of test results and specification limits, the lower specification limit for a suitable base course material, based on its unconfined compressive strength, is proposed to be between 80 and 90 pounds per square inch at a test temperature of 77°F.

ASPHALT STABILIZATION OF SELECTED SAND AND GRAVEL BASE COURSES

By

John Charles Riley

A THESIS

Submitted to
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In particular, I would like to thank my advisor, Dr. Gail C. Blomquist for his able guidance and encouragement in the writing of this thesis.

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CHAPTER I

INTRODUCTION

The increase in the volume of heavy wheel loads applied to highways and airport runways in our time coupled with the diminishing supply of high quality aggregates has necessitated the stabilization of lower quality aggregates for use in the construction of numerous highways and airports. Asphaltic materials have been employed for some of this necessary stabilization, but design engineers are hampered by the lack of a proven method for designing a base course of materials thus stabilized. In fact, there has been developed no criteria for evaluating the suitability of some of these sub-standard materials after they have been stabilized.

It is the purpose of this thesis to attempt development of some criteria for utilization of certain sub-standard base course materials through a program of physical research and testing with limited field correlation.

CHAPTER II

BACKGROUND

Bituminous soil stabilization, as far as highway and airport construction are concerned, is the process of strengthening a soil or aiding it in retaining its natural strength by adding certain asphaltic materials to make it more resistant to deformation and displacement under the loads applied to it.

In general, asphalt treated base courses are not a product of modern day technology for they have been in use since the early 1900's. In the early years they were used mainly for city street construction where heavy loads riding on steel-rimmed wheels or solid rubber tires had to be supported. However, the advent of the low-pressure tire, which spread the load over a larger area, decreased the necessity for asphalt treated bases.[1] Thus, for a

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[1] Reference 8, p. 5, (references are listed in the Bibliography).

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number of years the use of such bases was limited. In more recent times, however, the higher pressure tires, heavier wheel loads, larger volumes of traffic, and decreased sources of high quality aggregates have encouraged a revival of the use of asphalt bases.

There are numerous advantages of asphalt stabilized bases which warrant their use in present day highway construction. Some of these advantages, which stem from their combination of flexibility and slab-like effect, may be listed as follows:[2]

1. good pressure distribution on the subgrade.
2. dampening of shocks.
3. uniform structure without expansion joints.
4. same coefficient of expansion for the base and the asphalt surface.
5. adjustment to ground movement (settlement and frost heave.)
6. protection against frost damage from above as surface water is kept from entering the subgrade.

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[2] Ref. 17, p. 127

Other a

7. traffic requirements can be met by varying the number of layers.

Other advantages include the following:[3]

1. Bases can be rolled to meet close evenness tolerances when spreading machines are used.
2. Bases can carry traffic as temporary roadways.
3. Local aggregates can generally be used.
4. Various surface types can be used.
5. They lower stresses on the subgrade, thus reducing total thickness requirements.
6. Construction delays due to bad weather can be held to a minimum because these bases can be laid rapidly and promptly compacted, thus making them watertight.
7. They prevent capillary moisture and water vapor from reaching pavement courses.
8. Because they are frost resistant, less granular material is required for shoulders.
9. They provide ease and uniformity of compaction.

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[3] Ref. 8, p. 14.

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10. Machine laid bases help improve surface riding qualities.

At the present state of technology, asphalt treated bases are not without limitations. Other than the normally accepted material and equipment limitations, the primary disadvantage is the lack of knowledge of design, specification, and control on the part of the engineer. For this reason many engineers are unwilling to recommend this type of construction.

In spite of this wariness on the part of some engineers, a large number of projects have been constructed using asphalt bases. One such project was the Alger Road Project in Gratiot County, Michigan. This project, constructed for Gratiot County during the summer of 1963, was in four sections, one of which was a control section constructed with normally accepted procedures. The base course on the other sections was a hot-mixed, hot-laid sand asphalt base mixed with 85/100 penetration grade asphalt cement. Other details concerning the subgrade, subbase, asphalt base courses and the asphalt surface course[4] may

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[4] See also reference 31.

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be seen in the plan of the project contained in Appendix H.

The results from the AASHO Road Test were used as the basis for the design of the pavement structure for this project.[5]

Having been associated with this Gratiot County job, the author was able to secure field samples of the asphalt treated base materials to test in the laboratory along with mixes prepared in the laboratory using aggregates obtained from the stockpiles from which the field mixes were made. These aggregates were sub-standard local aggregates which could not have been satisfactorily used without a stabilizing agent. This project was not entirely unique, but it is serving as another step in the advancement of asphalt treated base course technology.

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[5] Ref. 31

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CHAPTER III

REVIEW OF LITERATURE

Although soils were stabilized with bituminous materials as far back as the early 1900's, formal research in this field did not begin until the late 1930's. At this time the Florida State Road Department began studies in sand asphalt stabilization under the direction of Mr. H. C. Weathers, a materials engineer. By 1940 the study had been taken up by Mr. A. W. Mohr and Mr. C. L. McKesson, engineers with American Bitumuls Company.[1]

In the major portion of this early research emulsified asphalts and cut-back asphalts were employed as the asphalt stabilizing agent. Today other bituminous materials are also employed, but the earlier work served to define the factors involved in stabilization with all

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[1] Ref. 18, p. 118.

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Probably the most basic principle concerning asphalt stabilization that was realized from early investigations, concerned the function of the asphalt material in the mixture. In a mixture of a cohesive soil and asphalt, the asphalt serves to waterproof the soil, thus aiding it in retaining its natural strength. In a mixture of a non-cohesive sandy soil with asphalt, the asphalt serves as a binder or cementing agent.[2] The theory behind the stabilization of sand with asphalt is to provide the optimum thickness of asphalt film around each grain to produce cohesive resistance with as little loss of grain to grain frictional resistance as possible.[3] A slight variation of this, according to McKesson,[4] is that the thin films of asphalt accomplish stability by increasing the grain to grain frictional resistance. True, some cohesion is obtained, but it is believed that the treatment depends primarily on the increased friction. Thus, the following types of bituminous soil stabilization

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[2] Ref. 26, p. 275. [3] Ref. 44, p. 278.

[4] Ref. 28, p. 863.

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may be defined:[5] (1) soil-asphalt; a waterproofed cohesive soil system, and (2) sand-asphalt; a system in which loose beach, dune, pit, or river sand is cemented together by asphalt material.

Water-proofing types of bituminous soil stabilization can be further subdivided as outlined by Benson:[6]

1. Intimate mixes of soil and asphalt, in which, essentially, each soil particle is surrounded by a protective film of asphalt.

2. Waterproofed mechanical stabilization in which capillaries in mixtures of aggregate and soil are effectively "plugged" by asphalt particles.

3. Phase-mixed stabilization in which nodules or aggregations of plastic soil are encased in a thick protective film of asphalt.

4. Membrane enveloping, in which large soil masses, as an entire fill section or a placed base, is wrapped up in a protective membrane to prevent loss or gain of moisture.

Another subdivision that might be added to this list is that of oiled earth, which is an earth road surface which has been waterproofed and rendered abrasion resistant by the application of slow or medium-curing road oils.[7]

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[5] Ref. 21, p. 5. [6] Ref. 12, p. 166.

[7] Ref. 21, p. 5.

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A great deal of the material written on the subject of asphalt soil stabilization to date has dealt with the factors which affect the stability of soil asphalt and sand-asphalt mixtures.[8] These factors have been grouped into primary factors and contributory factors[9] in Figure 1. The degree of importance of some of these factors may depend somewhat on the type of aggregate used.[10] For example, the stabilities and strengths of non-cohesive granular materials when mixed with asphalt tend to be proportional to the amount of mixing only up to the point where an intimate mix is obtained. Further mixing results in little or no increase in strength.[11] On the other hand, the stabilities and strengths of cohesive materials, when mixed with asphalt, continue to vary with mixing time.[12]

Most of the early asphalt treated base courses that were laid used an asphalt emulsion or cut-back asphalt

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[8] References 11, 13, 16, 20, 22, 23, 24, 27, 28, 29, 30, 32, 33, 35, 36, 38, 43.

[9] Ref. 13, p. 121, and Ref. 24, p. 17.

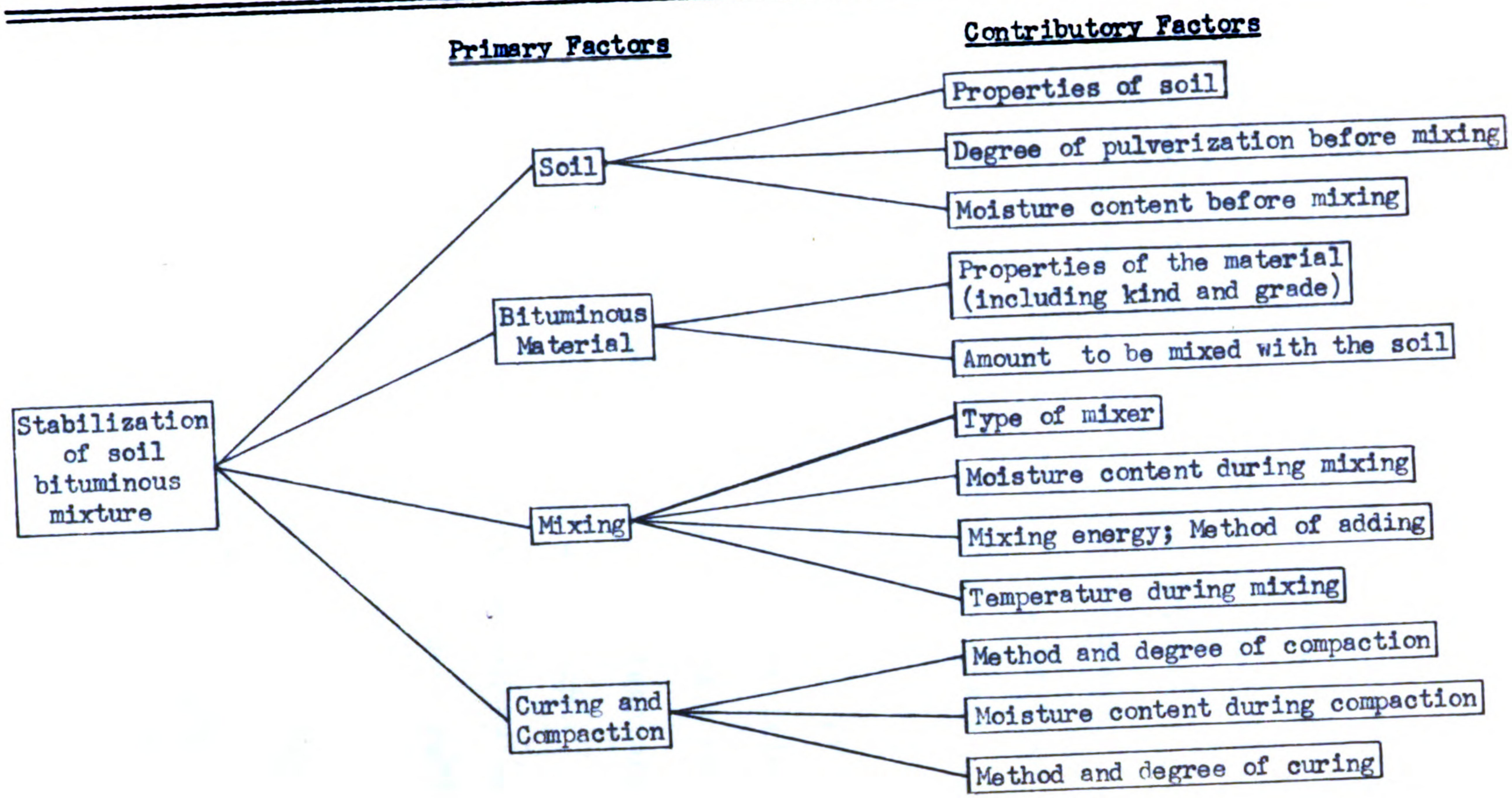
[10] Ref. 14, p. 489. [11] Ref. 13, p. 131.

[12] Ref. 13, pp. 132, 134.

FIGURE 1.

FIGURE 1.

VARIABLES AFFECTING STABILITY OF SAND AND SAND ASPHALT MIXTURES



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mixed in a traveling plant or road mixed. More recently, however, there has been a trend toward hot-mixed, hot-laid bases. In this country only eleven out of forty-eight states (Alaska and Hawaii not included) had not used this type of asphalt treated base as of the beginning of 1963.[13] Germany, however, has probably been the most extensive user of this type of base. Since 1955 Germany has laid over 40 million square meters of road surface over hot-mix asphalt bases.[14] As a result of the experience they had gained, the Germans were able to publish, in the spring of 1960, a set of tentative specifications for hot-mix bases. The three different types of mixes, which are based on the amount of material retained on the number 10 sieve, are shown in Table 4. Another portion of these specifications, which gives thickness and mix design criteria for hot-mix bases under various traffic conditions, may be seen in Table 5.[15]

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[13] Ref. 39, pp. 9,10. [14] Ref. 37, p. 173.

[15] Ref. 37, pp. 173-174.

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Some laboratory research on hot-mix bases has been carried on in this country too. Warden and Hudson conducted laboratory studies on Natural Aggregate Bituminous Concrete (NABC) in conjunction with field experience in sand-gravel asphalt treated base technology gained in connection with the Garden State Parkway in New Jersey.[16] As a result of these studies the following conclusions were reached:[17]

1. A wide range of sand gravel may be used insofar as gradation is concerned. Practical limits for per cent passing and Job-Mix Formula tolerances are:

Sieve Size	Per cent Passing	Job-Mix Formula Tolerance*
No. 4	45 - 75	6%
No. 20	20 - 50	4%
No. 200	2 - 8	1%

*Consistent with ±0.3% A. C. tolerance

2. As the lower courses of the pavement do not reach as high temperatures as the surface, Marshall stability at 140F is not critical. However, a stability of 500 lbs. appears to be a practical minimum value for this type of construction. Flow should be less than 0.14 inches.

[16] Ref. 42, pp. 291-312. [17] Ref. 42, pp. 311-312.

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3. There has been some indication of a plastic condition developing in the lower course of the asphalt bound base, both during construction and under traffic, when high asphalt contents are used. To provide adequate protection against surface rutting it is advisable to maintain total voids at 5 to 7 per cent for both sand and sand-gravel mixtures. The acceptable range of voids filled with asphalt appears to be 60 - 70 per cent for sand-gravel and 65 - 75 per cent for sand mixtures.

4. The natural fillers occurring as minus No. 200 material in aggregate deposits should be tested in advance. Natural fillers which have a pronounced effect on penetration and ductility of the filler-bitumen mortar should be avoided.

5. Field experience indicates that, due to the softening effect of solvents and solvent vapors on asphalt bound bases, emulsion rather than cut-back should be used for tack coats.

6. Economical and satisfactory black base mixtures can be produced using a wide range of local materials. Further economies may result if it can be demonstrated that under actual highway conditions black base can be substituted for thicker courses of other types of base construction.

In regard to conclusion 4 above, another possible solution to this problem is a construction method employed in Germany. In that country Portland cement concrete side strips, 20 to 30 inches wide, encase the surface, binder, and base course layers of roads designed for heavy

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Also, conclusion 6 deserves a comment regarding substitution of asphalt treated base for thicker courses of other types of base construction. It has been found, or at least theorized, that one inch of asphalt treated base is equivalent to from 1½ to 5 inches of untreated material.[19]

The construction of asphalt treated base courses is, in most respects, quite similar to surface course construction. The methods employed in construction, which are of primary interest, are mixing, spreading, and compacting of the mixture. These have been listed in Table 1.[20] In general, one or more types of binders--asphalt emulsions, cut-back asphalts, asphalt cements, and tar--can be used for stabilization when some combination of these mixing, spreading and compaction methods is employed.

For the previously mentioned asphalt base project

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[18] Ref. 37, p. 175. [19] Ref. 8, p. 11.

[20] Ref. 1, and Ref. 21.

TABLE 1.

ASPHALT BASE CONSTRUCTION METHODS

Mixing	Spreading	Compacting Rollers
Central plant	Paving machine	Steel wheel
Traveling plant	Blade grader	3 wheeled
Mixed in place		2-axle tandem
blade mixed		3-axle tandem
rototiller		Pneumatic tired
multipleblade drags		Sheepsfoot
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in Gratiot County, Michigan, the base mixture was prepared in a central mixing plant, spread by an asphalt paving machine, and compacted with a two-axle tandem steel wheeled roller. It was found that the mix temperature, which was originally 260°F, had to be lowered to 210°F to expedite compaction.[21] This situation was also found in Germany where rolling temperatures, depending on the type of mix, range from 140°F to 280°F.[22]

Samples of the aggregate and asphalt cement proposed for use on the Gratiot County, Michigan, project, as well as field samples of two of the job mixes, were sent to Chicago Testing Laboratory, Inc. by Mr. Berl Fleury of Leonard Refineries, Alma, Michigan. Copies of the technical reports returned, as contained in Appendix C,[23] may be used for a comparison with other results presented herein.

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[21] Ref. 31. [22] Ref. 37, p. 174. [23] Ref. 19.

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CHAPTER IV

PROCEDURE

The general procedure followed in conducting the research described herein was one of testing a series of laboratory mixed samples in addition to various field mixed samples for comparison and control. The field mixes employed were the three variations of asphalt treated base on the Alger Road project in Gratiot County, Michigan, and a surface course mix, utilizing State of Michigan specification 31A aggregate,[1] mixed for some paving operations at Michigan State University in October, 1963.

The laboratory mixes were prepared from representative samples of aggregates obtained from the stockpiles of aggregate which were employed in the plant mixes for the Alger Road project. These aggregates consisted of two types: (1) a gap-graded sand with an effective size of 0.0078 inch, a uniformity coefficient of 2.3, and an

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[1] Ref. 40

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AASHO classification of A-3(0); and (2) a uniformily graded gravel with an effective size of 0.0095 inch, a uniformity coefficient of 10.4, and an AASHO classification of A-1-b(0). Both aggregates were pit run with only that material retained on a 3/4 inch sieve removed before mixing. The grain size distribution curves for these aggregates are contained in Appendix D. The asphalt cements used in the laboratory mixes were 85/100 penetration and 120/150 penetration.

The mixtures prepared for testing can be grouped into the following four categories: (1) a mixture of 85/100 penetration asphalt and sand, (2) a mixture of 85/100 penetration asphalt and an aggregate mixture consisting of 50 per cent sand and 50 per cent gravel, (3) a mixture of 120/150 penetration asphalt and sand, and (4) a mixture of 120/150 penetration asphalt and the sand-gravel mixture. Within each of these categories the asphalt content of the mixtures were varied over a range generally in increments of one-half per cent.

At almost every asphalt content in the above categories, twelve samples were prepared from the mixtures. Six of these samples were tested for Marshall

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Stability, three at 77°F and three at 100°F, and six were tested in unconfined compression, again, three at 77°F and three at 100°F.

The field samples that were used for comparison and control, were of four types: (1) 3 per cent asphalt with sand, (2) 3½ per cent asphalt with sand, (3) 4 per cent asphalt with sand-gravel, and (4) surface course material which employed Michigan 31A aggregate. The asphalt employed in these mixes was 85/100 penetration grade asphalt cement. The asphalt contents listed for these field mixes are nominal percentages according to the job-mix formula for the Gratiot County, Michigan, project. The same number and types of samples were molded and tested for these mixtures as for the laboratory mixtures.

The samples molded for testing in the Marshall apparatus were prepared and tested in accordance with ASTM Designation: D 1559-58T[2] with the following variations: First, mixtures were prepared and molded at 210°F since this was the temperature found best suited for compaction

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[2]Ref. 5, pp. 1006-1013.

on the Alger Road project. Second, samples were brought to testing temperature in air baths rather than in water baths. Finally, samples were tested at 77°F and 100°F rather than at 140°F because many of the samples would have shown little, if any, strength at the higher temperature, and because the lower temperatures are more indicative of temperatures actually reached in highway base courses. Before testing, the samples were cured at room temperature for at least two weeks. In Figure 2 is shown the testing apparatus set up ready for a test.

The samples made for testing in unconfined compression were prepared and tested in accordance with ASTM Designation: D 1074-58 T[3] with the following variations: First, rather than preparing just enough mix for one sample, sufficient amounts were prepared at each mixing to mold six samples, each four inches high and four inches in diameter. Second, mixtures were mixed and molded at 210°F. Finally, samples were tested at 100°F as well as at 77°F. The time interval between the end of curing at 140°F and the testing of the sample was generally about 24 hours.

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[3] Ref. 4, pp. 922-926.

FIGURE 2.

APPARATUS FOR TESTING
MARSHALL SAMPLES

Samples tested at 100°F were oven heated and maintained at this temperature for approximately 4 hours.

In preparing test specimens from field samples, the mixtures were heated to 210°F after which samples were molded and cured as outlined above. The surface course material which employed Michigan 31A aggregate, was heated to 325°F, the temperature at which it was compacted on the job, before molding samples. Two of the eight Marshall samples prepared from this mix were tested at 140°F to provide comparisons to be made with values generally obtained for Marshall Stability.

In order to determine the actual asphalt contents of the various field mixes, extractions were carried out on samples of each of the different mixes. The procedure followed for conducting these extraction tests was in accordance with ASTM Designation:[4] D 1097-58 with the following variations: First, the solvent used was Chlorothene-Nu rather than benzene. Second, the filter ring weight increase was not determined and used in the calculations. Finally, the extract was not saved and analyzed

[4] Ref. 3, pp. 904-906.

for ash content.

The specific gravities of the compressed asphalt mixtures were determined in accordance with ASTM Designation[5] D 1188-56.

The specific gravities of the asphalt materials were determined in accordance with ASTM Designation[6] D 70-52 procedure for asphalt cements and pitches.

The values of specific gravity used for the sand and gravel aggregates were as reported by Chicago Testing Laboratory (see Appendix C.) The specific gravity of the aggregate employed in the surface course mix which employed Michigan 31A aggregate, was determined in the laboratory by the method suggested by Lambe.[7]

To determine the grain size distribution of the sand and of the gravel, a sieve analysis of each was performed. The procedure followed for this was as prescribed by ASTM Designation[8]: C 136-46. The sieve size sequence is given in Table 2 of Appendix E along with the size of the openings in each sieve.

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[5] Ref. 7, pp. 1049-1050. [6] Ref. 6, pp. 1044-1046.

[7] Ref. 25, pp. 15-21. [8] Ref. 2, pp. 536-538.

In the course of the investigation of these aggregates a total of 447 samples were made and tested. For each sample, after molding, the weight in air and the weight in water were determined. After curing and being brought to the proper temperature, the sample was tested and its strength, and flow in the case of the Marshall Stability determinations, were recorded.

With these three elements of data for each sample, and knowing the specific gravities and percentages of the constituents of the sample, the following quantities were determined: the volume of the sample; the Marshall Stability in pounds, or the compressive strength in pounds per square inch; the bulk specific gravity; the bulk density; the theoretical maximum specific gravity; the per cent air voids, or voids in the total mix; the per cent voids in the mineral aggregate; the per cent voids filled with bitumen; the per cent difference between strength, or stability, at 77°F and at 100°F; and a density factor which is the strength or stability of the specimen divided by its density. For the Marshall Stability determinations, the flow values were recorded as was, for all tests, the temperature of the sample at the time of the test.

Generally, three samples were tested identically to obtain average results. That is, three samples having the same composition were tested at the same temperature by the same method of test. The previously listed quantities for the three samples were then averaged. If, however, it was felt that any one or more of the samples gave, for some reason, erroneous results, the results obtained for that sample were not considered. In this way average results were obtained for each mixture.

Because of the volume of work involved in calculating the necessary quantities for so many samples, a computer program was written to instruct the computer how to do the calculations. The basic data for each sample, its weight in water and in air, its strength or stability, and the specific gravities and percentages of its constituents, were fed into the computer along with the program. The result was a print-out of all the previously listed quantities, including desired average quantities, except the per cent difference in strength or stability at 77°F and at 100°F which the computer was not instructed to calculate. A complete explanation and copy of the computer program used can be found in Appendix G. A listing of the formulas used in calculating the previously listed quantities is contained in Appendix F.

CHAPTER V

RESULTS

Laboratory Test Results

Some of the basic data employed in obtaining the results discussed herein are actually results themselves--results of specific gravity tests. The various values of specific gravity used in calculating the other results were determined in the laboratory except for the values of specific gravity of the sand and gravel aggregates. These latter values were obtained from Chicago Testing Laboratory, Inc., Technical Report No. 13125-6 (see Appendix C.) All values of specific gravity used are listed in Table 1 of Appendix E.

Since the average quantities determined for each set of samples were the only ones employed, they are the only ones presented herein. These results have been tabulated in Appendix A. Table 1A of this Appendix lists the following quantities: (1) the sample number; (2) the sample series--series A are field mixed samples of 85/100 penetration asphalt cement, series B are laboratory mixed samples of 85/100 penetration asphalt cement, and series C are laboratory mixed samples of 120/150 penetration asphalt cement; (3) the aggregate type--S is sand, S-G is the sand-gravel mixture, and 31A is the State of Michigan specification 31A aggregate; (4) the asphalt content; (5) the Marshall Stabilities of samples tested at 77°F and at 100°F; and (6) the Marshall Flow values at these temperatures. Table 1B contains: (1) the per cent difference in Marshall Stabilities at 77°F and 100°F, (2) the densities of specimens tested at 77°F and at 100°F, (3) the density factors of specimens tested at 77°F and at 100°F, (4) the per cent voids filled with bitumen, and (5) the per cent air voids. Tables 2A and 2B contain the respective values, where applicable, for specimens tested in unconfined compression. The results tabulated in these tables have been plotted graphically for clarity and ease of interpretation. These graphs are contained in Appendix B.

Graphs 1 through 4 show stability or strength variations with asphalt content. From Graphs 1 and 2, it can be observed that the optimum asphalt content for sand mixed with 85/100 penetration asphalt cement (AC 85/100) is between 3½ and 5 per cent and for the sand-gravel asphalt mixture is between 3 and 4½ per cent. From Graphs 3 and 4, it can be noted that the optimum asphalt (AC 120/150) content is between 2½ and 3½ per cent for the sand asphalt mixture and between 2½ and 4½ per cent for the sand-gravel asphalt mixture.

Although some higher strengths are reached at higher asphalt contents on some of these graphs, it must be kept in mind that the materials being considered are intended for use as a base course. As such the asphalt content should be limited to not more than approximately 7 per cent. Higher asphalt contents would be indicative of a surface course rather than base course material.

Further investigation of Graphs 1 through 4 reveals an expected fact. This is, the samples prepared with 85/100 penetration asphalt were consistently stronger, especially at the lower test temperature, than those prepared with 120/150 penetration asphalt. It can also be noted from Graphs 1 through 4 that there is a proportionately greater change in strength over the testing temperature interval at high asphalt contents than at low asphalt contents. Thus, it is evident that at lower asphalt contents the mixture relies more on grain to grain frictional resistance for strength than at higher asphalt contents. From this it might be reasoned that the mechanism of stabilization is actually a compromise between the theory as stated by Wooltorton[1] and the theory advanced by McKesson.[2] In stabilizing a sand with asphalt, the thin films of asphalt surrounding the particles serve to produce cohesive resistance as well as increase grain to grain frictional resistance. The percentage of the total strength supplied by each of the two actions depends upon the temperature and asphalt content of the mixture. The proportion of the total strength supplied by the cohesive resistance varies directly with asphalt content and inversely with temperature.

Graphs 5 through 8 indicate the variation of the Marshall Flow value with asphalt content. These graphs appear to be rather erratic, a little more so for tests conducted at 77°F than for those at 100°F. One reason for at least some small variations is the difficulty in reading the flow dial at precisely the right instant when

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[1] Ref. 44, p. 278. [2] Ref. 28, p. 863.

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conducting the test. Because of the speed of the test, a reading taken just a little early or late can result in some degree of variation. Even small variations, when plotted on a graph with as large a scale as has been used here, can be magnified and made to appear as large variations. A possible cause for even larger variations than attributable to reading difficulties stems from the nature of the sample itself. At lower temperatures, such as 77°F, as the sample is compressed, a combination of frictional resistance and cohesion tend to hold the sample together. As further strain occurs, numerous frictional resistance and cohesion points break eventually resulting in failure. It can be concluded that some samples may reach this failure point more rapidly than others but at no less stability. At the higher temperature the asphalt is softer and acts slightly more as a lubricant. The higher temperature would result in decreased cohesion. The particles being slightly better lubricated than at the lower temperature, and with cohesive bonds weakened, will slide past each other more readily. Thus, at the higher temperature the mechanism of failure would occur more regularly and more consistently.

Even though the Marshall Flow versus asphalt content graphs, Graphs 5 through 8, are rather erratic, some general results can be ascertained from them. From Graphs 5 and 7 it can be observed that the sand and sand-gravel samples made with 85/100 penetration asphalt yielded maximum flows between 4 and 5 per cent. Graphs 6 and 8 indicate samples made with 120/150 penetration asphalt yielded maximum flows between 5 and 7 per cent. Compared to the maximum stabilities, these maximum flows occur at the high end of the maximum stability range for the AC 85/100 samples and from ½ to 4½ per cent asphalt above the range for the AC 120/150 samples.

Graphs 9 through 12 demonstrate the variation of density with asphalt content. Upon examination of these graphs several facts are discernable. First, the sand-gravel samples compacted to higher densities than the sand samples. This reflects the better gradation of the sand-gravel mixture than of the sand alone. Second, as the asphalt content increases, the density of the sample increases also, at least up to a point. This point that is reached is the optimum density, beyond which further addition of asphalt would start over-filling the voids, thus reducing the density. Graphs 9 and 10 demonstrate the optimum densities having been reached. Examination of Graphs 1 and 2, which show the stabilities of these respective samples, reveals that the maximum stability or strength is reached at or slightly below optimum density. Examination of the other density graphs point out that no optimum densities have been reached. When these graphs are compared with their respective strength or stability graphs, it can be seen that some of the samples had not reached a peak strength, so the above mentioned stability density relationship may hold for them also. A third fact discernable from these graphs is that optimum strengths or stabilities occur at or slightly below optimum densities. A fourth fact that can be observed is that the Marshall Test specimens, Graphs 9 and 11, compacted to higher densities under fifty blows on each face than the unconfined compression specimens, Graphs 10 and 12, did under a static load of 3000 pounds per square inch.

Graphs 13 through 16 indicate the variation of the density factor with asphalt content. This density factor, a fabrication of the author, is merely the strength or the stability divided by the density. It's purpose was i

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to provide a single parameter, involving both the sample's strength and density, which are interdependent to start with. This parameter, when plotted against asphalt content, would show the optimum asphalt content as affected by both density and stability or strength. It can be seen by comparing Graphs 13 through 16 with the stability and strength graphs, Graphs 1 through 4, that corresponding plots are very nearly the same shape. This might have been expected since stability and density are considered closely related.

The next four graphs, Graphs 17 through 20, indicate how variations in asphalt content affect the per cent of voids filled with bitumen. As might be expected, the per cent of voids filled varies directly with asphalt content in a straight-line proportion. Two other facts may be noted from these graphs. First, at any particular asphalt content, the sand-gravel mixtures have a higher percentage of voids filled than the sand mixtures. This, again, is a reflection of the better gradation of the sand-gravel mixture than of the sand alone. Also, the slopes of the lines representing the sand-gravel mixtures are consistently greater than those lines representing the sand mixtures. This indicates that there are fewer voids in the sand-gravel mixture than in the sand mixture. Again, this is relatable to the differences in gradation of the two aggregates.

The second fact that can be realized from Graphs 17 through 20 and their respective slopes, is that the rate of increase in per cent voids filled is independent of asphalt penetration grade. Also, it is dependent upon the method of compaction since samples compacted for testing in the Marshall apparatus showed only slightly greater rates of increase of per cent voids filled than those compacted for testing in unconfined compression. The magnitude of the per cent voids filled appears to be independent of the asphalt penetration grade used. The method of compaction does, however, influence the per cent voids filled. The dynamic compaction employed in the molding of Marshall Test specimens yielded higher percentages of voids filled than did the static compaction employed in the molding of samples to be tested in unconfined compression, at a given asphalt content. This would be a logical deduction, though, in light of the differences in densities previously noted.

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On the next four graphs, Graphs 21 through 24, are plotted the per cent difference in stabilities or strengths at 77°F and 100°F against asphalt content.

It can be seen from these curves that the per cent difference in Marshall Stabilities for the sand samples, Graph 21, reaches a higher level than the curve for the more dense sand-gravel samples, Graph 23. On the other hand, the curves of the per cent difference in unconfined compressive strengths for both the sand and the sand-gravel mixtures, Graphs 22 and 24 respectively, are nearly the same. These differences could possibly be explained in the following manner. The sand-gravel samples made for Marshall Stability determinations were the most dense of all the samples. Because of their high density, their stability resulted primarily from the grain to grain frictional resistance. The sand samples made for testing in the Marshall apparatus were less dense than the sand-gravel ones, so they gained a larger portion of their strength from cohesive resistance. The samples made for testing in unconfined compression were also less dense than what appears to be a critical density value lying between that of the sand-gravel mixtures made for testing in the Marshall apparatus and that of the sand-gravel mixtures made for testing in unconfined compression. Because of their lower densities, these samples also relied in large measure on the cohesive resistance supplied by the asphalt for their strength. Thus, a possible addition to the previously stated theory of the mechanism of stabilization (see page 33) might be that the percentage of the total strength supplied by the two actions, friction and cohesion, depends also on the density of the mixture. Mixtures having densities below some critical value, in this case the critical value is apparently between 125 and 130 pounds per cubic foot, rely primarily on the cohesive resistance supplied by the asphalt. Further proof that the asphalt content of the mixture affects the degree to which the strength or stability results from each of the two actions can be seen on Graphs 21 through 24 by the shape of the curves. For the less dense mixtures, the reliance on the effects of the asphalt increases rapidly with increasing asphalt content up to an asphalt content of about 4 or 5 per cent. Past 4 or 5 per cent addition of asphalt has less effect on the strength or stability of the mixture. Thus, above 4 or 5 per cent asphalt the grain to grain friction comes into play to a larger extent than below this asphalt content.

Graph 25 represents an attempt to establish some correlation between the Marshall Stability and unconfined compressive strength. Due to the comparatively small number of tests conducted, a definite correlation could not be established. The graph does, however, show a possible correlation by the dashed line through the points. The points which appear most erroneous in relation to the dashed line, are those representing some samples molded with AC 85/100 and tested at 77°F. A possible explanation of this error is that the sand samples made for testing in the Marshall apparatus cured for a considerably longer time than most of the other samples. This might have resulted in slightly higher than normal Marshall Stabilities which when plotted against normal unconfined compressive strengths, would locate the points above the correlation line.

The three graphs contained in Appendix D represent the grain size distribution of the sand, the gravel, and the sand-gravel mixture, respectively. The dashed curves which also appear on these graphs, represent ideal gradings based on Weymouth's theory of particle interference. This theory states, essentially, that an aggregate conforming to this gradation could be compacted to the greatest density of any aggregate having 100 per cent of its material passing the 3/4 inch sieve.[3] The greater densities obtained with the sand-gravel mixtures as compared to the sand mixtures would seem to substantiate this theory. Also, in light of this theory, it appears from the three graphs that a mixture of only gravel and asphalt would have provided an even more stable and more dense mix than the sand-gravel combination. Proof of this can be seen in Chicago Testing Laboratory Technical Report No. 13125-6 (See Appendix C.)

It can be noted by comparing other results presented in this report to respective results in Tables 1A and 1B, that the Marshall Stability values obtained by Chicago Testing Laboratory were considerably lower than those obtained by the author. This difference might have been caused by the lengthy curing times and air bath heating methods used by the author.

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[3] Ref. 34.

Field Correlation

The results obtained for the samples mixed in the field, which have been listed in Tables 1, A and B, and in Tables 2, A and B, have been plotted, whenever possible, on the appropriate previously discussed graphs. Since these samples were taken from the field, they had to be re-heated before samples could be molded. Because asphalt oxidizes when hot films of it are exposed to air[4], thus causing it to increase in strength, it would be expected that the results for these samples will be affected accordingly. Field samples were cured for a considerable length of time before being molded, thus these additional affects might also be expected to show up in the results.

The field samples from the Gratiot County, Michigan, project gave results that were generally as expected. These results were comparable to results obtained from tests on some of the same mixtures by Chicago Testing Laboratory (see Technical Reports No. 13947 and No. 14759-60 in Appendix C.) Some of the results were lower

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[4] Ref. 15, p. 54.

than the values obtained from laboratory mixes, but the majority of the results fell slightly above the laboratory mix results. Thus, the laboratory results gave a good indication of what might be expected of field mixes.

The results of tests run on the surface course material made with 31A aggregate were considerably higher than all other results, as they should have been, thus they could not be plotted on the appropriate graphs. These results have been grouped in tabular form, Tables 2 and 3, with the results obtained for the other field mixtures and the highest stabilities or strengths obtained for the laboratory mixtures. If we compare these results with standard specifications, we find that the surface course material is well within the specification limits for pavements designed to carry medium traffic as set forth by the Asphalt Institute.[5] Since the stabilities of the sand-gravel mixes made with 85/100 penetration asphalt compare rather favorably with the stability of the surface course materials tested, it would be a safe assumption that these sand-gravel mixtures would also meet

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[5] Ref. 9, p. 72A.

TABLE 2.

SELECTED MARSHALL TEST RESULTS

	FIELD MIXES				LAB. MIXES			
Asphalt Penetration	85/100	85/100			85/100		120/150	
Aggregate type	31A	S	S	S-G	S	S-G	S	S-G
Asphalt content, %	6.14	2.97	3.59	4.05	5.0	3.0	3.5	4.0 & 4.5[a]
Stability, lbs.								
at 77°F	6335	2372	2392	4502	3421	4513	1526	2756
at 100°F	2683	---	889	2056	1042	1680	532	949
at 140°F	934	---	---	---	---	---	---	---
Flow, 0.01 in.								
at 77°F	16.6	8.2	9.7	9.3	10.1	7.3	8.7	6.4
at 100°F	10.9	---	7.1	7.9	9.5	5.9	9.8	8.4
at 140°F	11.8	---	---	---	---	---	---	---

TABLE 2 - Continued

Difference in stability, %	57.7	---	62.8	54.3	73.9	62.8	65.1	72.4[b]
Density, lbs./ft.^{3}	146.5	119.8	120.2	130.3	125.3	128.3	120.6	130.9[b]
Voids filled, %	76.52	18.96	22.93	33.29	35.40	23.89	22.46	32.99[b]
Air voids, %	4.31	23.77	22.74	16.65	17.85	19.20	22.77	16.59[b]
Density factor, ft.^{3}								
at 77°F	43.33	19.80	20.21	35.21	27.36	35.10	11.63	21.05
at 100°F	18.31	---	7.27	15.51	7.11	13.12	2.35	7.27
at 140°F	6.36	---	---	---	---	---	---	---

[a] 4.5% at 77°F and 4.0% at 100°F

[b] samples tested at 77°F

TABLE 3.

SELECTED UNCONFINED COMPRESSION TEST RESULTS

		FIELD MIXES			LAB. MIXES			
Asphalt Penetration	85/100	85/100			85/100		120/150	
Aggregate type	31A	S	S	S-G	S	S-G	S	S-G
Asphalt content, %	6.14	2.97	3.45	3.83	5.0	4.0 & 3.0[a]	2.5	4.5 & 2.5[b]
Strength, lbs./in.^{2}	654.99							
at 77°F	654.99	86.91	146.18	181.79	72.98	143.74	59.32	82.48
at 100°F	235.27	29.46	58.15	52.92	22.24	43.39	27.65	35.43
Density, lbs./ft.^{3}, samples tested at								
77°F	140.9	116.5	118.5	124.9	116.5	127.2	112.6	125.5
100°F	140.8	117.6	119.4	125.5	117.2	123.1	112.0	121.7

TABLE 3 - Continued

Density factor, ft.^{3}/in.^{2}								
at 77°F	4.648	0.746	1.233	1.456	0.626	1.130	0.527	0.657
at 100°F	1.671	0.251	0.487	0.422	0.190	0.352	0.247	0.291
Difference in strength, %	64.1	66.1	60.2	70.9	69.5	---	53.4	---
Voids filled, %	63.08	17.79	21.25	27.15	28.06	29.89[c]	13.14	31.55[c]
Air voids, %	7.91	25.22	23.76	20.12	23.39	18.66[c]	29.04	19.18[c]

[a] 4.0% at 77°F and 3.0% at 100°F

[b] 4.5% at 77°F and 2.5% at 100°F

[c] samples tested at 77°F

the stability requirements for a surface course material. On this basis these mixes would be entirely suitable for their intended use in a base course.

When these results are compared to the proposed German specifications[6] (see Tables 4 and 5) we find, by projecting the values given to a base value that could be obtained in a test run at 140°F, the results are generally favorable. By comparing the amount of material retained on the No. 10 sieve, as shown on the grain size distribution curves of Appendix D, with Table 4 requirements, it can be noted that the sand asphalt mixture forms a type A (fine-grained) base and the sand-gravel asphalt mixture forms a type B (medium-grained) base. Examination of Table 5 reveals, assuming medium traffic, that, for the sand asphalt and sand-gravel asphalt field mixtures, the asphalt contents of both mixes are low and their total voids slightly high, but their stabilities and flow values show that they might conceivably be strong enough to act as a base material. The laboratory mixed sand asphalt (AC 85/100) mixture, however, meets the asphalt content and total voids requirements and, judging from its stability and flow values at 77°F and 100°F, it would

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[6] Ref. 37, pp. 173-174.

TABLE 4.

TYPES OF GRADED HOT-MIX ASPHALT BASES

Type of asphalt base	A	B	C
Designation	Fine-grained bases	Medium-grained bases	Coarse-grained bases
Coarse aggregate retained on No. 10 sieve, % by wt.	0 - 20	20 - 60	60 - 80
Maximum size of stone, mm	---	45	45
Main components of aggregate mix	Natural sand or blends with crushed sand	Sandy gravel, crushed aggr. or blends	Gravel or crushed aggr. or blends
Additional components for aggregate mix	Stone dust, crushed sand	Stone dust, natural sand, crushed sand, crushed stone	Stone dust, natural sand, crushed sand, crushed stone
Asphalt pen. grade	50/70 70/100	50/70 70/100 (160/210)	(50/70) 70/100 160/210
Minimum asphalt content, % by wt.	4.0	3.5	3.0

TABLE 5.

TENTATIVE DESIGN CRITERIA FOR HOT-MIX ASPHALT BASES

<table>
<tr><td>Type of traffic</td><td colspan="2">Light</td><td colspan="2">Medium</td><td colspan="2">Heavy</td><td colspan="2">Very Heavy</td></tr>
<tr><td>Thickness of surface and binder courses, (in.)</td><td colspan="2">1.2-</td><td colspan="2">1.2-2.0[a]</td><td colspan="2">2.0-3.1[a]</td><td colspan="2">3.1+</td></tr>
<tr><td>Thickness of base courses,[b] (in.)</td><td colspan="2">2.0-4.0</td><td colspan="2">4.0-6.0</td><td colspan="2">4.7-7.0</td><td colspan="2">6.3-7.8</td></tr>
<tr><td>Marshall:
Stability, 140 F (lbs.)
Flow value (1/100 in.)</td><td colspan="2">440
3.9-15.7</td><td colspan="2">440
3.9-15.7</td><td colspan="2">660
3.9-15.7</td><td colspan="2">660
3.9-15.7</td></tr>
<tr><td>Voids total mix:
Type of base
Maximum % by vol.
Minimum % by vol.</td><td>
A
20
2</td><td colspan="2">
B
16
2</td><td>
C
12
2</td><td>
A
16
2</td><td colspan="2">
B
12
2</td><td>
C
10
2</td></tr>
<tr><td>% Density of Marshall specimen[c]</td><td colspan="2">95</td><td colspan="2">95</td><td colspan="2">95</td><td colspan="2">95</td></tr>
</table>

[a]If the thickness of the surface and binder courses is less than indicated above, the minimum requirement for stability should be raised by 110 lbs.

[b]For type A mixes the upper limits should be chosen.

[c]If laid in several layers, the density of the compacted first layer should be at least 90%.

also meet the required stability and flow value . Further inspection reveals (see Chicago Testing Laboratory Technical Report No. 14759-60 in Appendix C) that the stability of these sand asphalt mixtures at 140°F is not sufficient to allow their use as a base. Since the stability at 100°F listed in Technical Report 14759-60 is comparable to stabilities at similar asphalt contents listed in Table 1A, it is expected that similar results would also have been obtained at 140°F by the author had the samples been tested at that temperature. The sand asphalt (AC 120/150) mix appears to be not only too low in asphalt content but also not of high enough stability to serve as a base course.

As previously mentioned, the sand-gravel asphalt (AC 85/100) mixtures, both field and laboratory mixes, would probably meet stability requirements for a base course. Further indication of this is given in Chicago Testing Laboratory Technical Report No. 13947 (see Appendix C) in which a field mixed sand-gravel sample was tested at 120°F as well as at 80°F and 100°F. When compared with the specifications being dealt with here, the further indication of the suitability of the sand-gravel asphalt

(AC 85/100) mixtures becomes apparent. In addition to the stability requirements, these mixes also meet the asphalt content and flow value requirements. Their total voids are, however, borderline or slightly above, but they would probably still prove to be quite adequate as base course materials. These same comments all seem to hold true for the sand-gravel asphalt (AC 120/150) mixture except for its stability. The stability of this mixture is more near the magnitude obtained for the sand asphalt (AC 85/100) mixtures. The affect of temperature on the stability of this mixture varies from the affect of temperature on the sand asphalt (AC 85/100) mixtures. This difference can be noted by comparing Chicago Testing Laboratory Technical Reports No. 13947 and No. 14759-60 of Appendix C, which contain results of tests conducted at various temperatures on a sand-gravel mixture and the sand mixture, respectively.

There are no specifications for base courses that utilize the unconfined compressive strength as a basis of determination, hence it is difficult to assess these materials on its basis. However, the results indicate that the minimum compressive strength which should be permitted for these mixtures, would be between 80 and 90 pounds per square inch at a test temperature of 77°F.

Due to the nature of the aggregates employed, especially the lack of material passing the No. 200 sieve which would account for the high percentage of air voids experienced, most specifications preclude its use. It is felt that these sub-standard materials can be effectively stabilized for use in a highway or airport runway base course.

CHAPTER VI

CONCLUSIONS

From the results obtained during the course of the research described here, the following conclusions may be drawn:

1. In the stabilization of sand with asphalt, the thin films of asphalt surrounding the particles serve to increase intergranular frictional resistance as well as to produce cohesive resistance. The percentage of the total strength or stability of the mixture supplied by the cohesive resistance varies directly with asphalt content, inversely with temperature, and directly with density, up to a critical density value beyond which density affects are much less.

2. When the German specifications of Tables 4 and 5 are used, a suitable mixture for highway base courses is sand-gravel mixed with 3 to 4 per cent of 85/100 penetration asphalt. A mixture which might be classed as borderline between

acceptance and rejection, is sand-gravel mixed with 4 to 4½ per cent of 120/150 penetration asphalt. Mixtures not suitable for base courses, according to these specifications, are: sand mixed with 3 to 5 per cent of 85/100 penetration asphalt and sand mixed with 3½ per cent of 120/150 penetration asphalt.

3. Maximum strengths or stabilities occur at or slightly below optimum densities.

4. The minimum specification limit for a suitable base course material based on unconfined compressive strength is a strength of from 80 to 90 pounds per square inch at a test temperature of 77°F.

In the course of conducting this research and writing this thesis, the author has come to strongly realize the need for further research in this field. Of course, there are always variations of aggregates which need investigation. It is felt, however, that the prime need at this time is to study the following factors in relation to materials similar to those used here to determine their effects on the testing methods. These factors

are: (1) mixing time, (2) curing time, (3) mixing temperature, (4) testing temperature, and (5) moisture content at the time of the test or time immersed in a water bath.

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APPENDIX A

TABULATED RESULTS

TABLE 1A.

MARSHALL TEST RESULTS

Sample number	Sample series	Agg. type	Asphalt content (%)	Stability (lbs.) 77°F	Stability (lbs.) 100°F	Flow value (0.01 in.) 77°F	Flow value (0.01 in.) 100°F
1	A	S	2.97	2372	---	8.2	---
2	A	S	3.59	2392	889	9.7	7.1
3[a]	A	S-G	4.05	4502	2056	9.3	7.9
4	A	31A	6.14	6335	2683	16.6	10.9
5[a,c]	A	31A	6.14	934	---	11.8	---
6	B	S	2.0	1544	---	7.3	---
7	B	S	2.5	1491	603	4.8	6.2
8	B	S	3.0	2255	787	9.1	7.0
9	B	S	3.5	2645	841	8.6	8.3
10	B	S	4.0	2887	844	10.9	9.9
11[d]	B	S	4.5	3521	1042	10.1	9.8
12	B	S	4.5	3171	734	8.8	11.1
13[d]	B	S	4.5	2582	601	10.7	9.9
14	B	S	5.0	3421	893	12.7	10.0
15	B	S	6.0	3224	731	12.5	10.0
16	B	S	7.0	2650	525	12.1	10.3

TABLE 1B.

MARSHALL SAMPLE PARAMETERS

Diff. in stability (%)	Bulk Den. (lbs./ft.^{3}) 77°F	Bulk Den. (lbs./ft.^{3}) 100°F	Den. factor (ft.^{3}) 77°F	Den. factor (ft.^{3}) 100°F	Voids filled (%)	Air voids (%)
---	119.8	---	19.80	---	18.96	23.77
62.8	118.4	122.2	20.21	7.27	22.93	22.74
54.3	127.9	132.6	35.21	15.51	33.29	16.65
57.7	146.2	146.5	43.33	18.31	76.52	4.31
---	146.8	---	6.36	---	77.84	4.01
---	115.2	---	13.41	---	11.75	27.25
59.6	114.8	114.6	12.98	5.27	13.98	27.54
65.1	118.9	118.1	18.97	6.66	18.44	24.57
68.2	120.1	119.6	22.01	7.03	22.09	23.12
70.8	120.3	120.5	23.99	7.00	25.32	22.20
70.4	123.1	122.8	28.59	8.49	30.20	19.97
76.9	123.8	123.4	25.62	5.95	30.74	19.56
76.7	120.8	120.7	21.37	4.98	28.41	21.39
73.9	125.0	125.5	27.36	7.11	35.40	17.85
77.3	125.8	126.2	25.63	5.80	42.14	16.20
81.0	125.2	125.0	21.16	4.20	46.76	15.57

TABLE 1A (continued)

Sample number	Sample series	Agg. type	Asphalt content (%)	Stability (lbs.) 77°F	Stability (lbs.) 100°F	Flow value (0.01 in.) 77°F	Flow value (0.01 in.) 100°F
17	B	S-G	2.5	3876	1616	5.7	5.1
18	B	S-G	3.0	4513	1680	7.3	5.9
19[d]	B	S-G	3.0	2880	860	8.6	6.5
20[d]	B	S-G	3.0	3230	1105	7.1	7.0
21	B	S-G	3.5	4085	1429	8.1	6.9
22[d]	B	S-G	3.5	2795	816	9.4	7.3
23[d]	B	S-G	3.5	3793	1227	7.6	7.1
24	B	S-G	4.0	4509	1356	8.6	7.3
25	B	S-G	4.5	4264	1394	10.3	7.3
26	B	S-G	5.0	3713	1328	10.0	7.2
27	C	S	3.0	1338	393	8.5	8.2
28	C	S	3.5	1526[f]	532	8.7	9.8
29	C	S	4.0	1408	285	10.8	9.1
30	C	S	4.5	1469	185[e]	11.7	9.0
31	C	S	5.0	1557	241[f]	11.0	9.7
32	C	S	6.0	1824	397	12.4	9.9
33	C	S	6.5	1856	393	12.0	11.7
34[a]	C	S	7.0	1822	409	12.8	11.7
35[a]	C	S	7.5	1972	463	12.3	11.5

TABLE 1B (continued)

Diff. in stability (%)	Bulk den. (lbs./ft.^{3}) 77°F	Bulk den. (lbs./ft.^{3}) 100°F	Den. factor (ft.^{3}) 77°F	Den. factor (ft.^{3}) 100°F	Voids filled (%)	Air voids (%)
58.3	127.4	127.0	30.43	12.70	19.56	20.49
62.8	128.5	128.0	35.10	13.12	23.89	19.20
70.1	128.3	128.1	22.45	6.71	23.83	19.23
65.8	126.3	126.7	25.56	8.71	22.66	20.28
65.0	128.7	128.3	31.71	11.13	27.62	18.44
70.8	127.8	128.0	21.87	6.38	27.12	18.81
67.7	129.2	129.2	29.35	9.50	28.23	17.97
69.9	129.7	127.6	34.75	10.62	31.30	17.69
67.3	131.1	130.8	32.50	10.65	37.14	15.61
64.2	129.9	131.2	28.52	10.12	40.13	15.25
70.6	119.5	119.3	11.19	3.29	18.96	23.96
65.1	120.3	120.9	12.68	4.40	22.46	22.77
79.8	121.1	121.1	11.63	2.35	25.83	21.76
87.4	122.2	122.8	12.03	1.51	29.83	20.28
84.5	123.0	123.1	12.66	1.96	33.17	19.38
78.2	125.8	125.5	14.49	3.16	41.83	16.41
78.8	126.5	125.9	14.67	3.12	45.44	15.41
77.6	127.6	127.7	14.27	3.20	50.25	13.84
76.5	127.9	128.1	15.41	3.61	53.68	12.96

TABLE 1A (continued)

Sample number	Sample series	Agg. type	Asphalt content (%)	Stability (lbs.) 77°F	Stability (lbs.) 100°F	Flow value (0.01 in.) 77°F	Flow value (0.01 in.) 100°F
78[a]	C	S	8.0	2233	514	11.2	11.0
79[b]	C	S	9.0	2399	585	11.3	10.4
36	C	S-G	2.0	1548	472	5.1	5.0
37	C	S-G	2.5	2407	749	5.6	6.5
38	C	S-G	3.0	2323	964	6.3	6.5
39	C	S-G	3.5	2505	835[f]	7.5	6.0
40	C	S-G	4.0	2579	949	8.4	6.4
41	C	S-G	4.5	2756	762	8.4	7.3
42	C	S-G	5.0	2561	817	11.5	9.7
43[a]	C	S-G	6.0	2522	702	12.5	8.9
44[a]	C	S-G	6.5	2977	831	10.2	8.1
80[a]	C	S-G	7.0	2982	917	10.3	8.1
81[b]	C	S-G	8.0	3118	941	14.0	11.0

[a]These results were obtained from tests performed on only two samples at each temperature.

[b]These results were obtained from tests performed on only one sample at each temperature.

[c]These samples were tested at 140°F.

[d]These results were not considered because they appeared to be erroneous.

TABLE 1B (continued)

Diff. in stability (%)	Bulk Den. (lbs./ft.^{3}) 77°F	Bulk Den. (lbs./ft.^{3}) 100°F	Den. factor (ft.^{3}) 77°F	Den. factor (ft.^{3}) 100°F	Voids filled (%)	Air voids (%)
77.0	129.7	129.3	17.21	3.97	58.82	11.35
75.6	130.6	130.0	18.37	4.50	65.75	9.56
69.5	126.6	126.7	12.23	3.72	15.66	21.41
68.9	128.2	127.5	18.77	5.87	20.00	20.04
58.5	128.1	127.9	18.14	7.53	23.73	19.34
66.7	129.2	129.7	19.39	5.10	28.52	17.79
63.2	130.3	130.4	19.79	7.27	32.99	16.59
72.4	130.9	130.7	21.05	5.83	37.02	15.69
68.1	131.4	131.4	19.49	6.22	41.21	14.68
72.2	131.4	131.4	19.20	5.34	48.63	13.04
72.1	133.9	134.3	22.24	6.18	56.34	10.58
69.2	135.3	135.9	22.04	6.75	61.43	9.33
69.8	137.9	138.3	22.61	6.80	73.21	6.33

[e]These results were obtained from tests performed on only two samples at this temperature.

[f]These results were obtained from tests performed on only one sample at this temperature.

TABLE 2A.

UNCONFINED COMPRESSION TEST RESULTS

Sample number	Sample series	Agg. type	Asphalt content (%)	Strength (psi) 77°F	Strength (psi) 100°F	Diff. in strength (%)
45[a]	A	S	2.97	86.91	29.46	66.1
46	A	S	3.45	146.18	58.15	60.2
47	A	S-G	3.83	181.79	52.92	70.9
48	A	31A	6.14	654.99	235.27	64.1
49	C	S	2.0	30.10	12.32	59.1
50	C	S	2.5	59.32	27.65	53.4
51	C	S	3.0	45.73	18.31	60.0
52	C	S	3.5	46.79	17.73	62.1
53	C	S	4.0	45.44	15.02	67.0
54	C	S	4.5	49.71	15.50	68.8
55	C	S	5.0	42.20	14.41	65.9
56[a]	C	S	6.0	40.21	10.83	73.1
57	C	S-G	2.0	65.29	30.52	53.3
58	C	S-G	2.5	70.36	35.43	49.6
59	C	S-G	3.0	72.58	26.83	63.0
60	C	S-G	3.5	74.34	24.87	66.6
61	C	S-G	4.0	67.99	22.66	66.7

TABLE 2B.

UNCONFINED COMPRESSION SAMPLE PARAMETERS

Bulk density ($lbs./ft.^3$) 77°F	Bulk density ($lbs./ft.^3$) 100°F	Density factor ($ft.^3/in.^2$) 77°F	Density factor ($ft.^3/in.^2$) 100°F	Voids filled (%)	Air voids (%)
116.5	117.6	0.746	0.251	17.79	25.22
118.5	119.4	1.233	0.487	21.25	23.76
124.9	125.5	1.456	0.422	27.15	20.12
140.9	140.8	4.648	1.671	63.08	7.91
111.5	111.1	0.270	0.111	10.34	30.21
112.6	112.0	0.527	0.247	13.14	29.04
112.9	113.3	0.405	0.162	15.94	27.99
113.5	114.0	0.412	0.156	18.73	27.03
113.5	113.3	0.400	0.133	20.99	26.72
114.5	114.7	0.434	0.135	24.11	25.39
116.2	116.1	0.363	0.124	27.59	23.84
117.1	116.9	0.343	0.093	33.19	22.12
121.5	122.3	0.537	0.250	13.58	24.35
121.2	121.7	0.580	0.291	16.52	24.06
122.2	122.6	0.594	0.219	20.11	22.87
123.2	123.5	0.603	0.202	23.79	21.68
122.8	123.2	0.553	0.184	26.55	21.33

TABLE 2A (continued)

Sample number	Sample series	Agg. type	Asphalt content (%)	Strength (psi) 77°F	Strength (psi) 100°F	Diff. in strength (%)
62	C	S-G	4.5	82.48	25.37	69.2
63	C	S-G	5.0	76.04	24.58	67.7
64[a]	C	S-G	6.0	78.78	26.24	66.7
65[a]	B	S	3.0	53.51	17.84	66.7
66	B	S	3.5	62.00	22.80	63.2
67	B	S	4.0	59.52	18.84	68.4
68	B	S	4.5	63.85	21.39	66.5
69	B	S	5.0	72.98	22.24	69.5
70	B	S	5.5	72.26	20.83	71.2
71	B	S	6.0	65.66	19.61	70.1
72	B	S-G	2.5	103.64	41.77	59.7
73	B	S-G	3.0	108.49	43.39	60.0
74	B	S-G	3.5	114.99	38.46	66.6
75	B	S-G	4.0	143.74	36.52	74.6
76	B	S-G	4.5	129.22	42.48	67.1
77	B	S-G	5.0	109.95	32.81	70.2

[a]These results were obtained from tests performed on only two samples at each temperature.

TABLE 2B (continued)

Bulk density (lbs./ft.^{3}) 77°F	Bulk density (lbs./ft.^{3}) 100°F	Density factor (ft.^{3}/in.^{2}) 77°F	Density factor (ft.^{3}/in.^{2}) 100°F	Voids filled (%)	Air voids (%)
125.5	125.3	0.657	0.203	31.55	19.18
124.7	124.7	0.610	0.197	33.95	19.01
126.8	128.0	0.621	0.205	42.74	16.04
114.3	114.8	0.468	0.155	16.54	27.08
113.4	113.8	0.547	0.200	18.61	27.15
113.7	113.6	0.524	0.166	21.08	26.57
114.8	114.8	0.556	0.186	24.21	25.25
116.5	117.2	0.626	0.190	28.06	23.39
118.0	118.1	0.612	0.176	31.53	22.02
118.3	118.5	0.555	0.166	34.31	21.24
122.6	121.9	0.846	0.434	16.85	23.59
124.2	123.1	0.874	0.352	20.81	22.09
124.3	124.9	0.925	0.308	24.62	20.89
127.2	127.1	1.130	0.287	29.89	18.66
126.8	127.0	1.019	0.334	32.90	18.21
126.1	125.7	0.872	0.261	35.01	18.26

APPENDIX B

GRAPHS OF RESULTS

.GRAPHS

The results tabulated in Appendix A have been plotted on graphs for ease of interpretation. These graphs appear in the following pages, and a discussion of them is presented in Chapter V.

A legend for the graphs appearing in this Appendix appears on the following page. This legend applies to all the graphs presented unless otherwise noted. The temperatures listed in this legend refer to the temperatures at which the samples were tested.

LEGEND

Lab Mixes

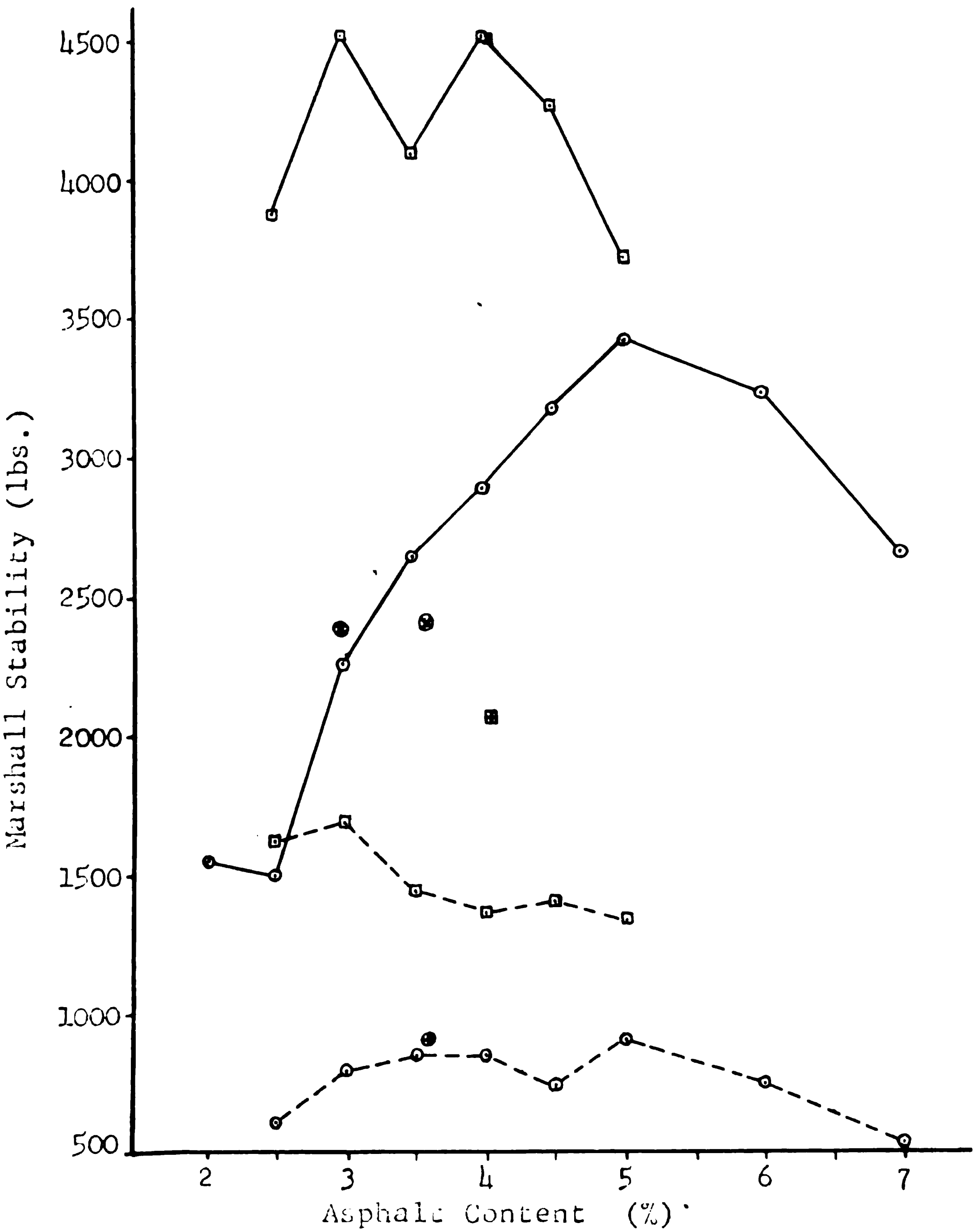
□——□	Sand-gravel, 77°F
□- - - -□	Sand-gravel, 100°F
⊙——⊙	Sand, 77°F
⊙- - - -⊙	Sand, 100°F

Field Mixes

■	Sand-gravel, 77°F
⊞	Sand-gravel, 100°F
●	Sand, 77°F
⊕	Sand, 100°F

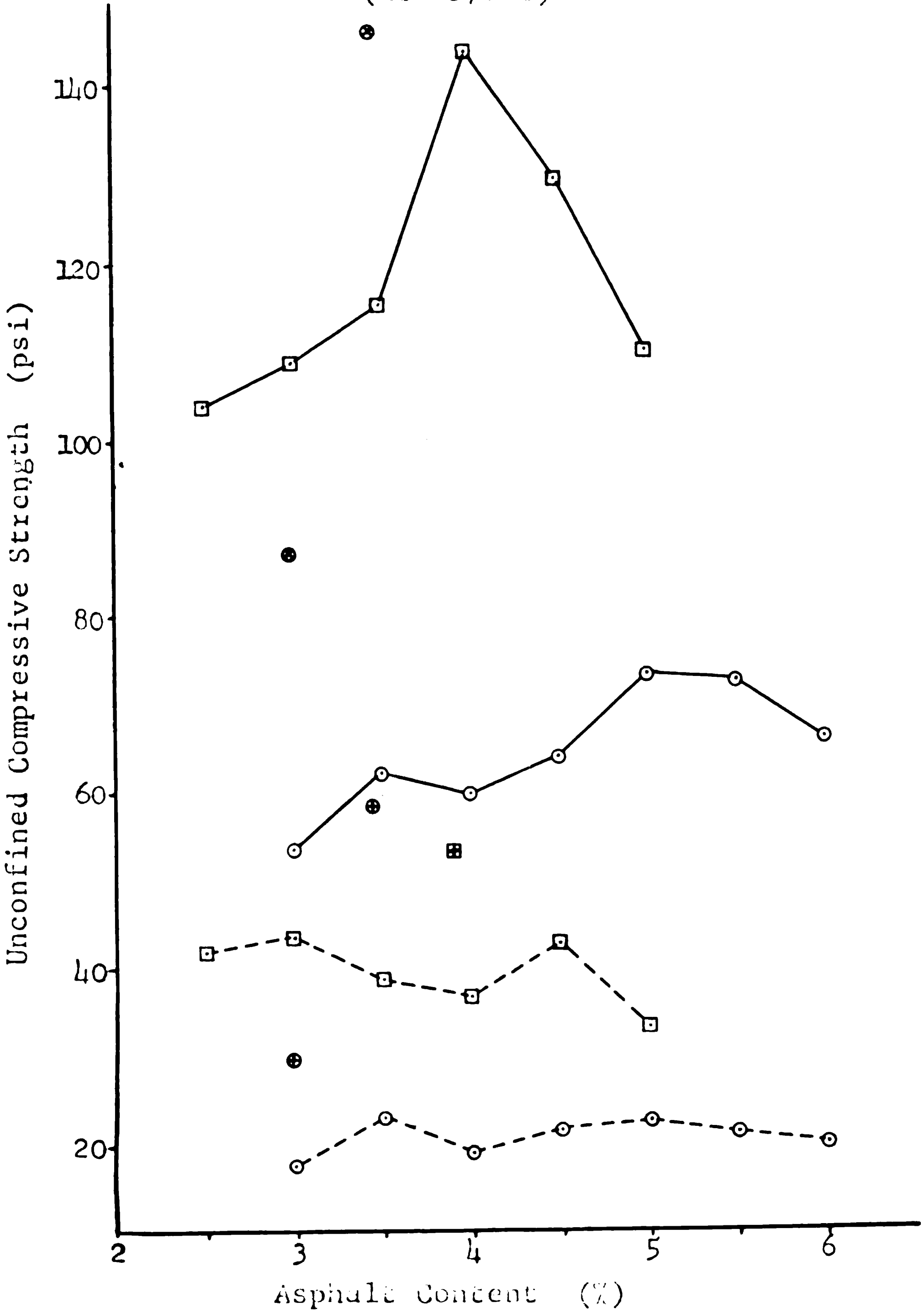
GRAPH 1.

MARSHALL STABILITY VARIATION
WITH ASPHALT CONTENT
(AC 85/100)



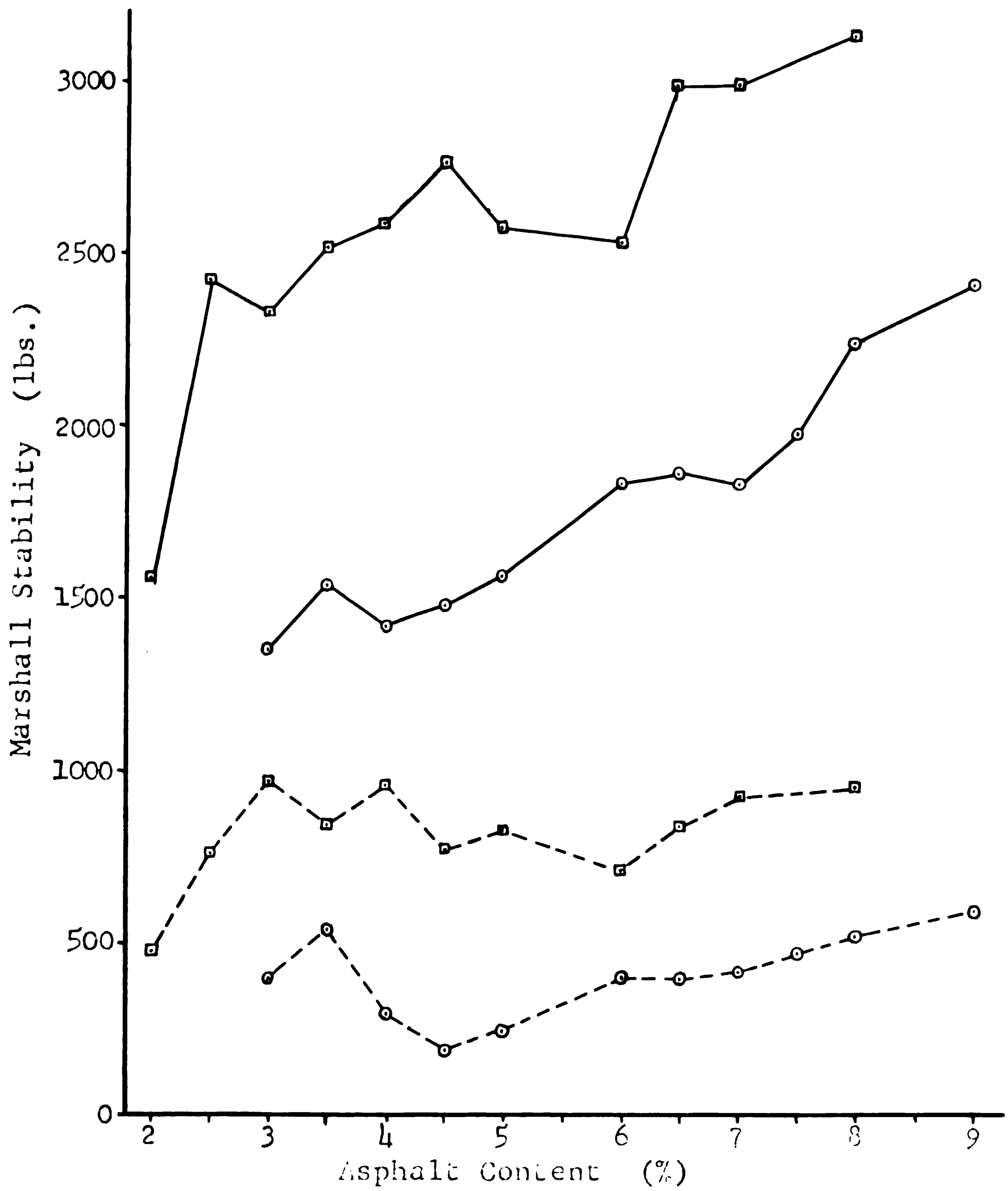
GRAPH 2.

UNCONFINED COMPRESSIVE STRENGTH VARIATION WITH ASPHALT CONTENT (AC 85/100)



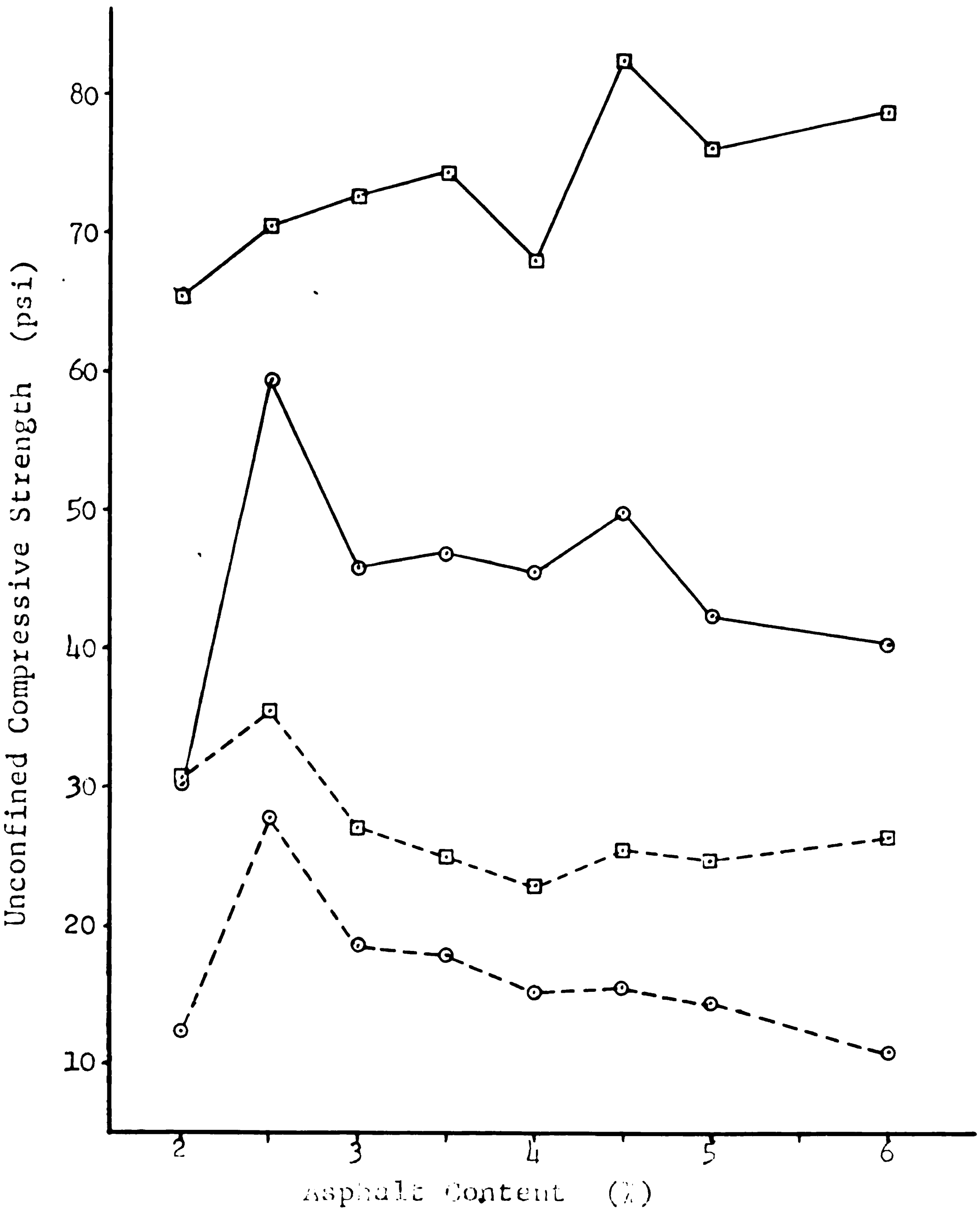
GRAPH 3

MARSHALL STABILITY VARIATION
WITH ASPHALT CONTENT
(AC120/150)



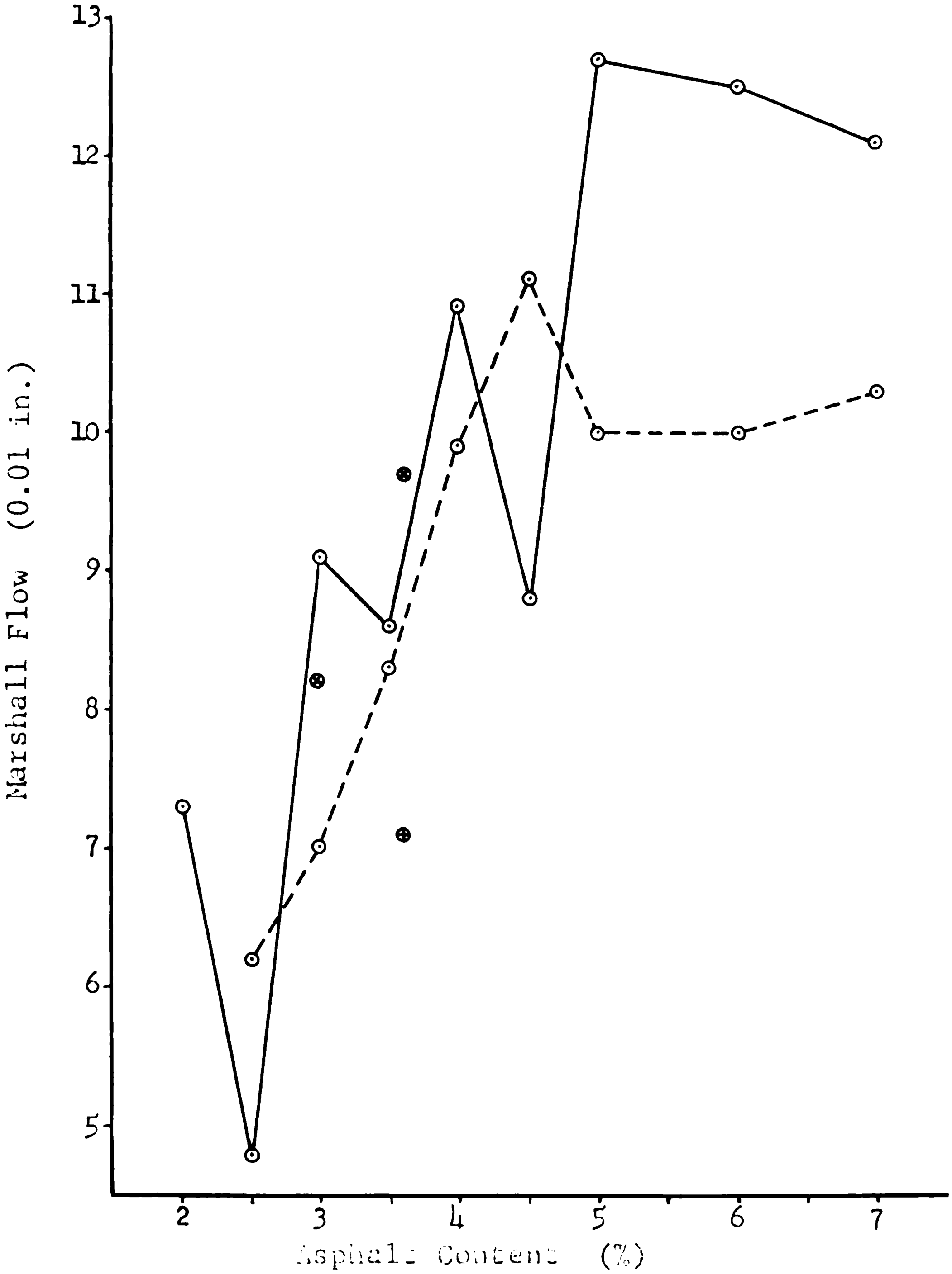
GRAPH 4.

UNCONFINED COMPRESSIVE STRENGTH
VARIATION WITH ASPHALT CONTENT
(AC 120/150)



GRAPH 5.

MARSHALL FLOW VARIATION
WITH ASPHALT CONTENT
(AC 85/100)



MARSHALL FLOW VARIATION
WITH ASPHALT CONTENT
(AC 120/150)

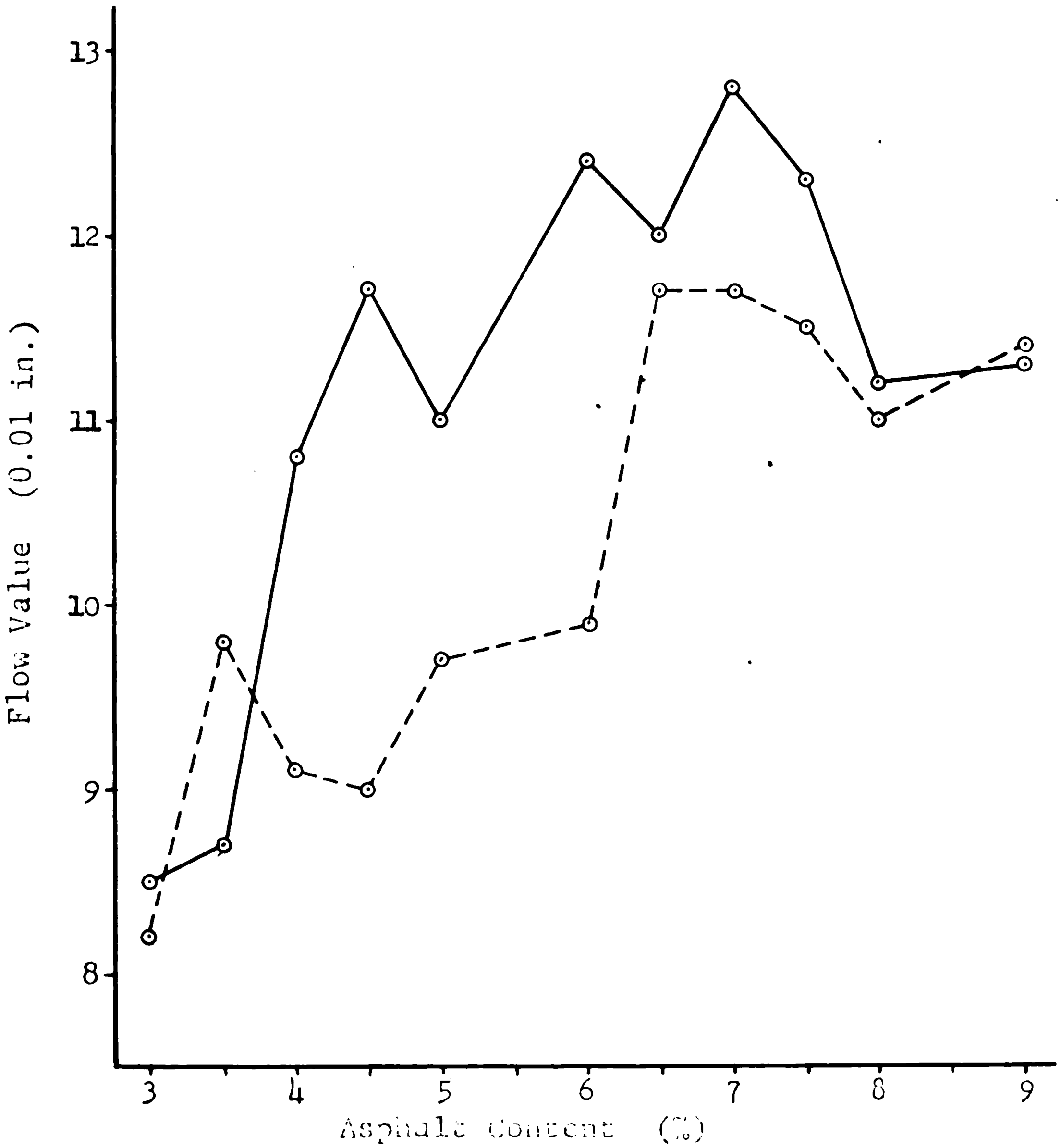
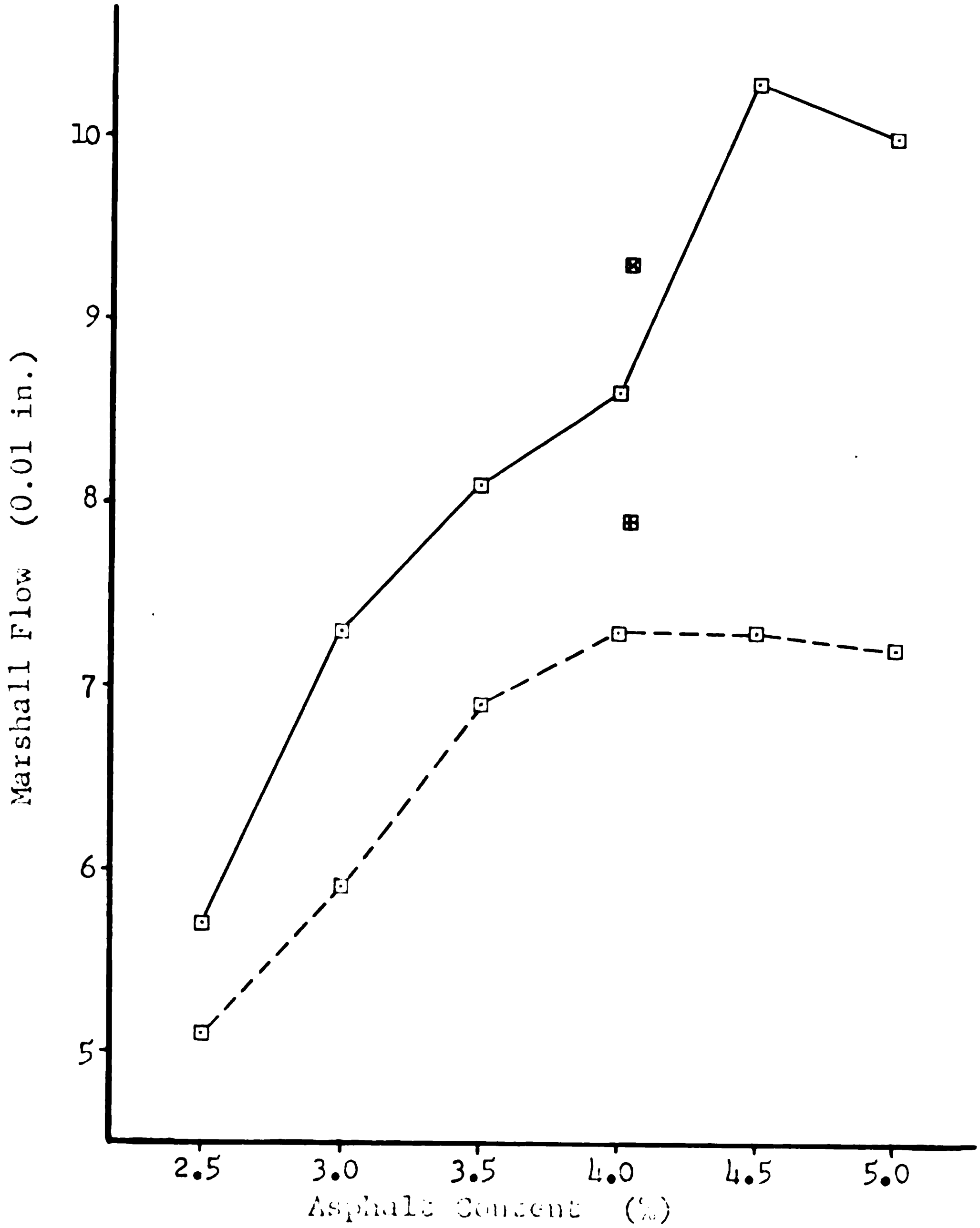


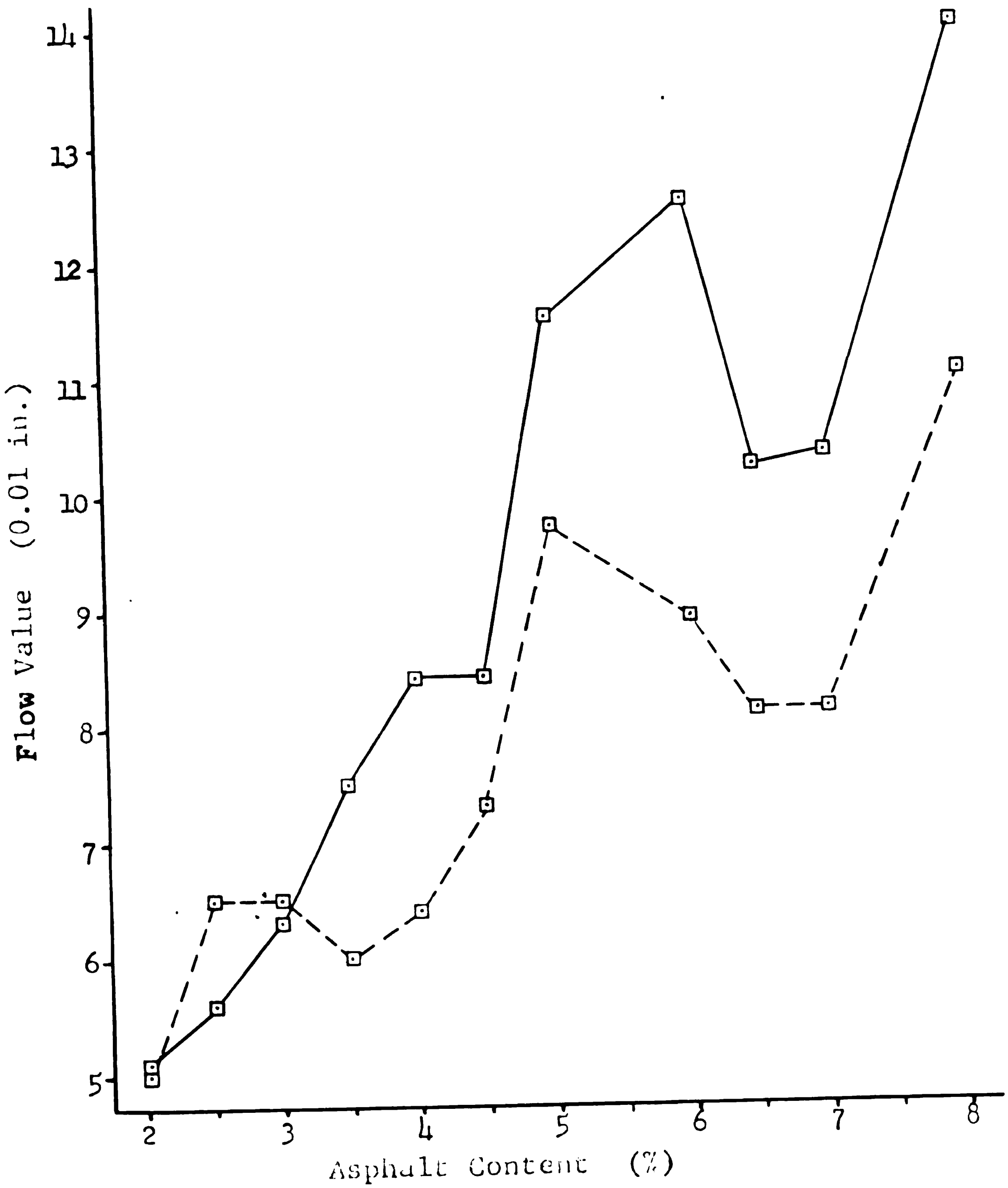
FIGURE [illegible].

MARSHALL FLOW VARIATION
WITH ASPHALT CONTENT
([illegible])



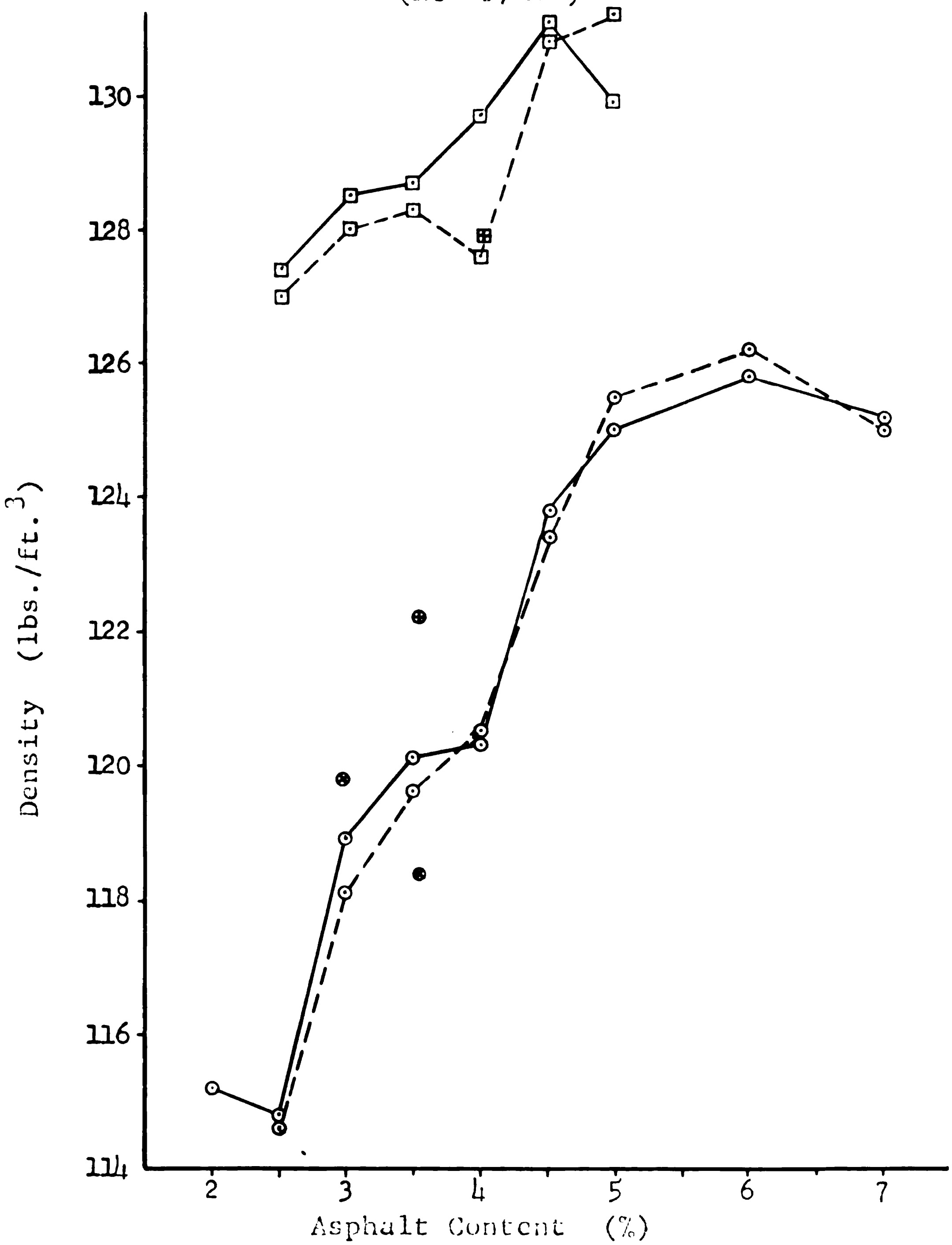
GRAPH 5.

MARSHALL FLOW VARIATION
WITH ASPHALT CONTENT
(AC 120/150)



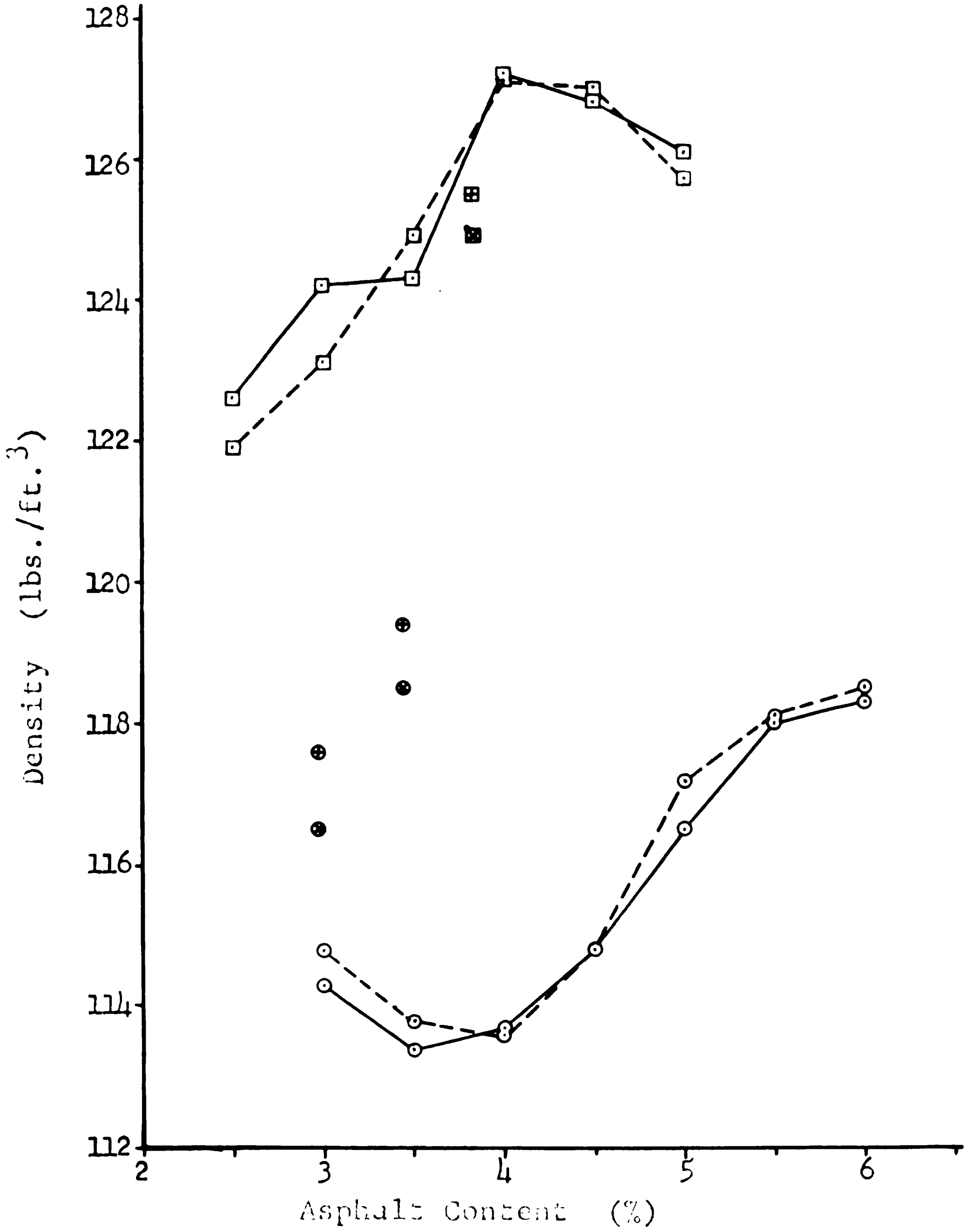
GRAPH 9.

DENSITY VARIATION WITH
ASPHALT CONTENT
(AC 85/100)



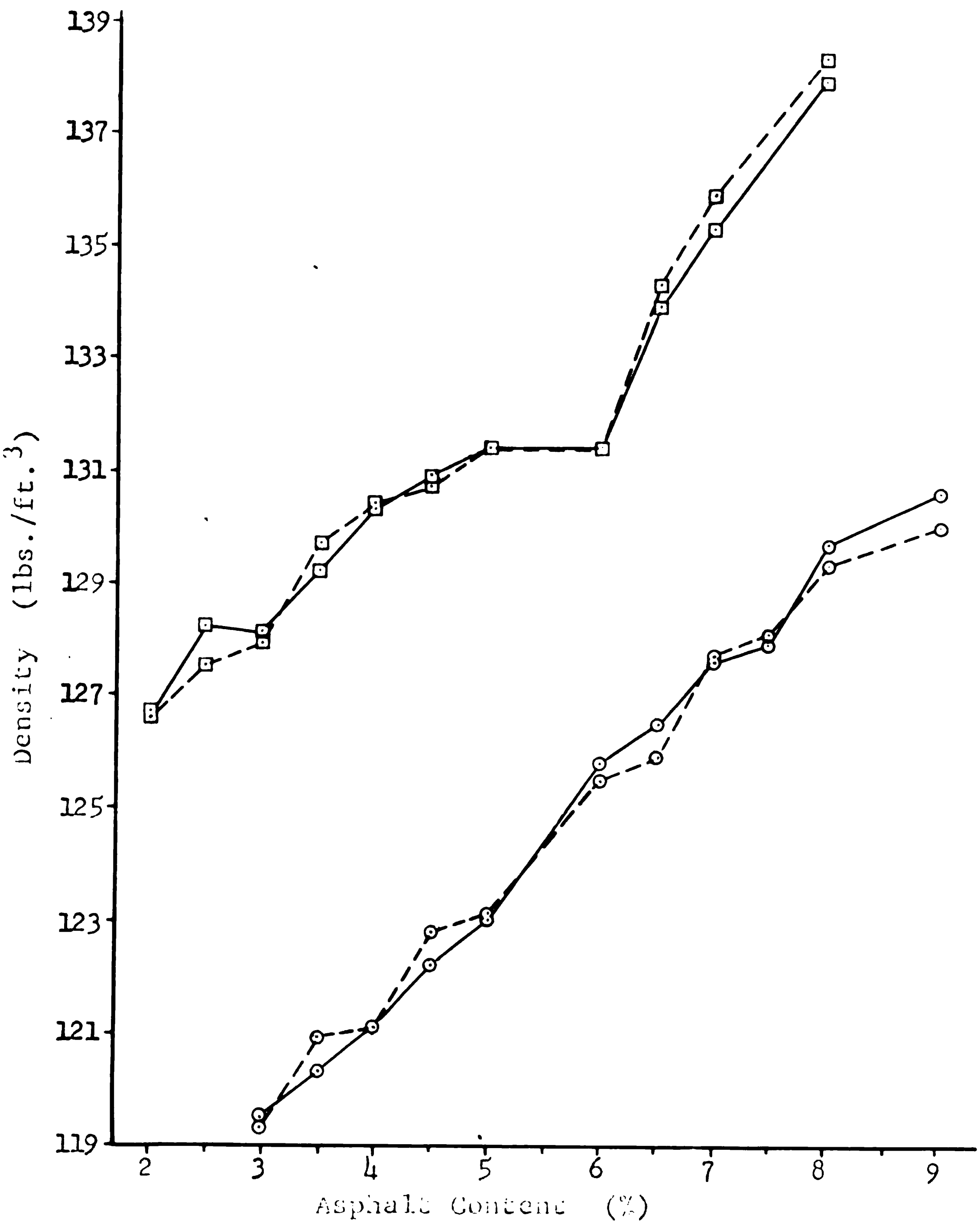
GRAPH 10.

DENSITY VARIATION WITH
ASPHALT CONTENT
(AC 85/100)



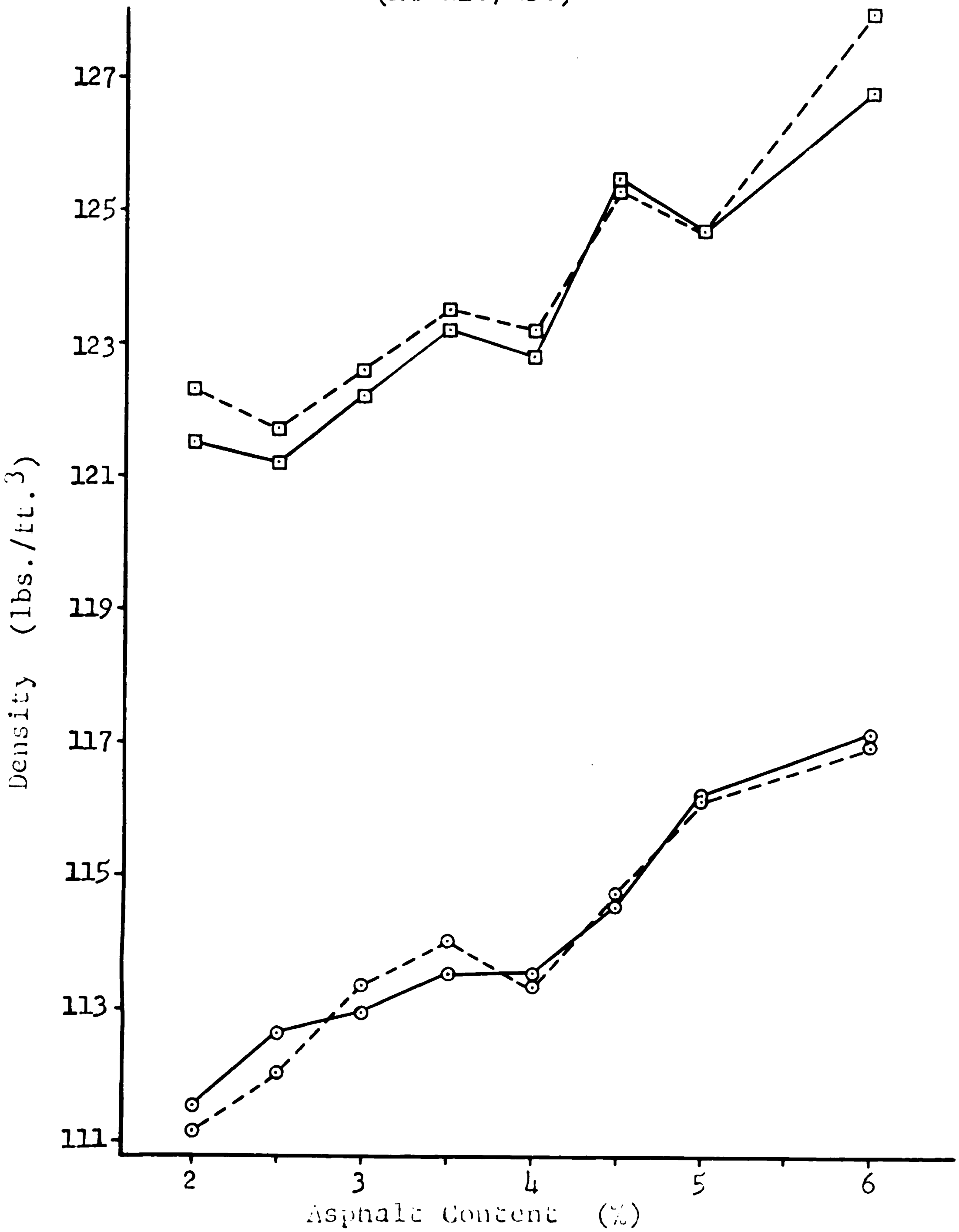
GRAPH 11.

DENSITY VARIATION WITH
ASPHALT CONTENT
(AC 120/150)



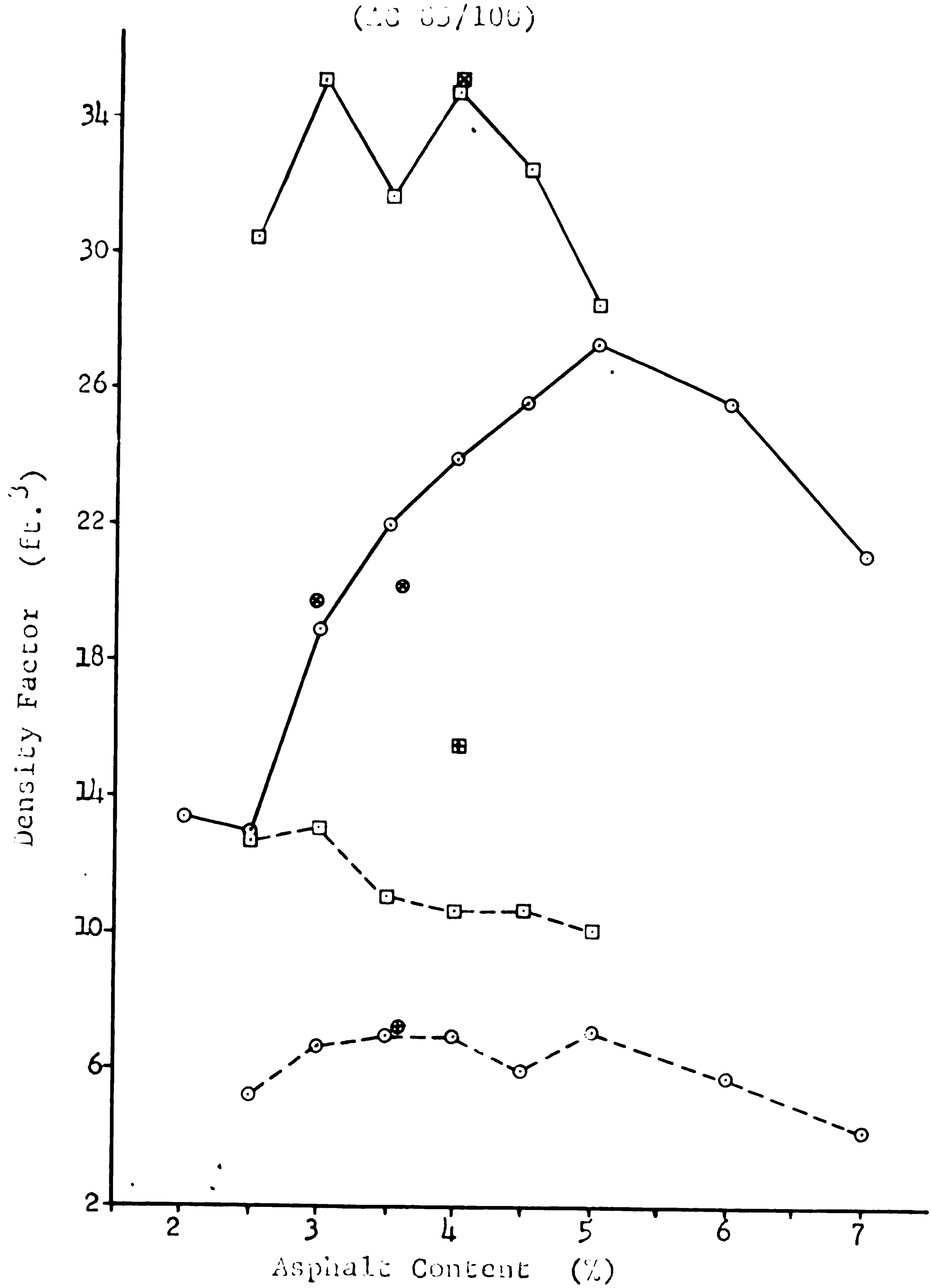
GRAPH 12.

DENSITY VARIATION WITH
ASPHALT CONTENT
(AC 120/150)



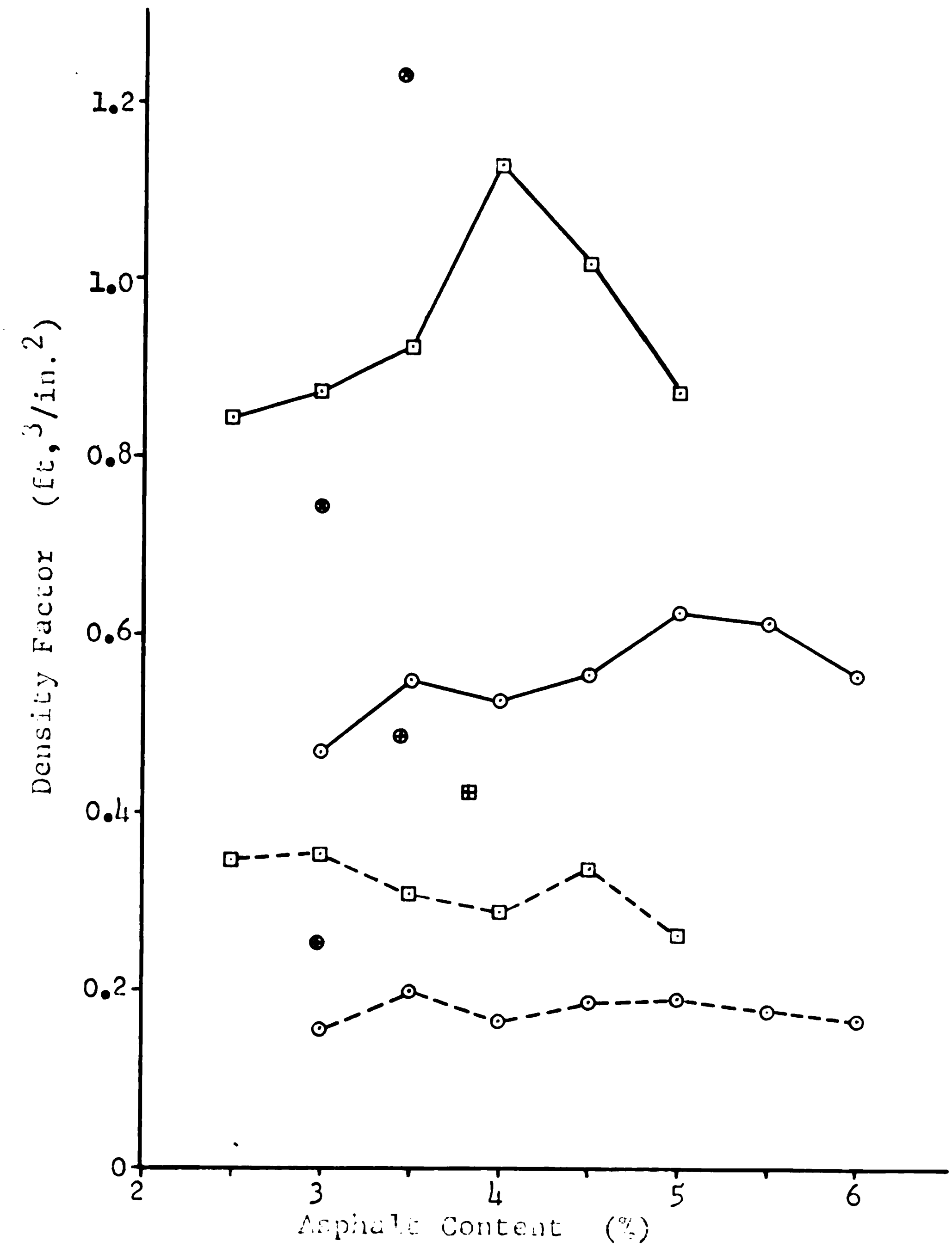
GRAPH 13.

DENSITY FACTOR VARIATION
WITH ASPHALT CONTENT
(AC 85/100)



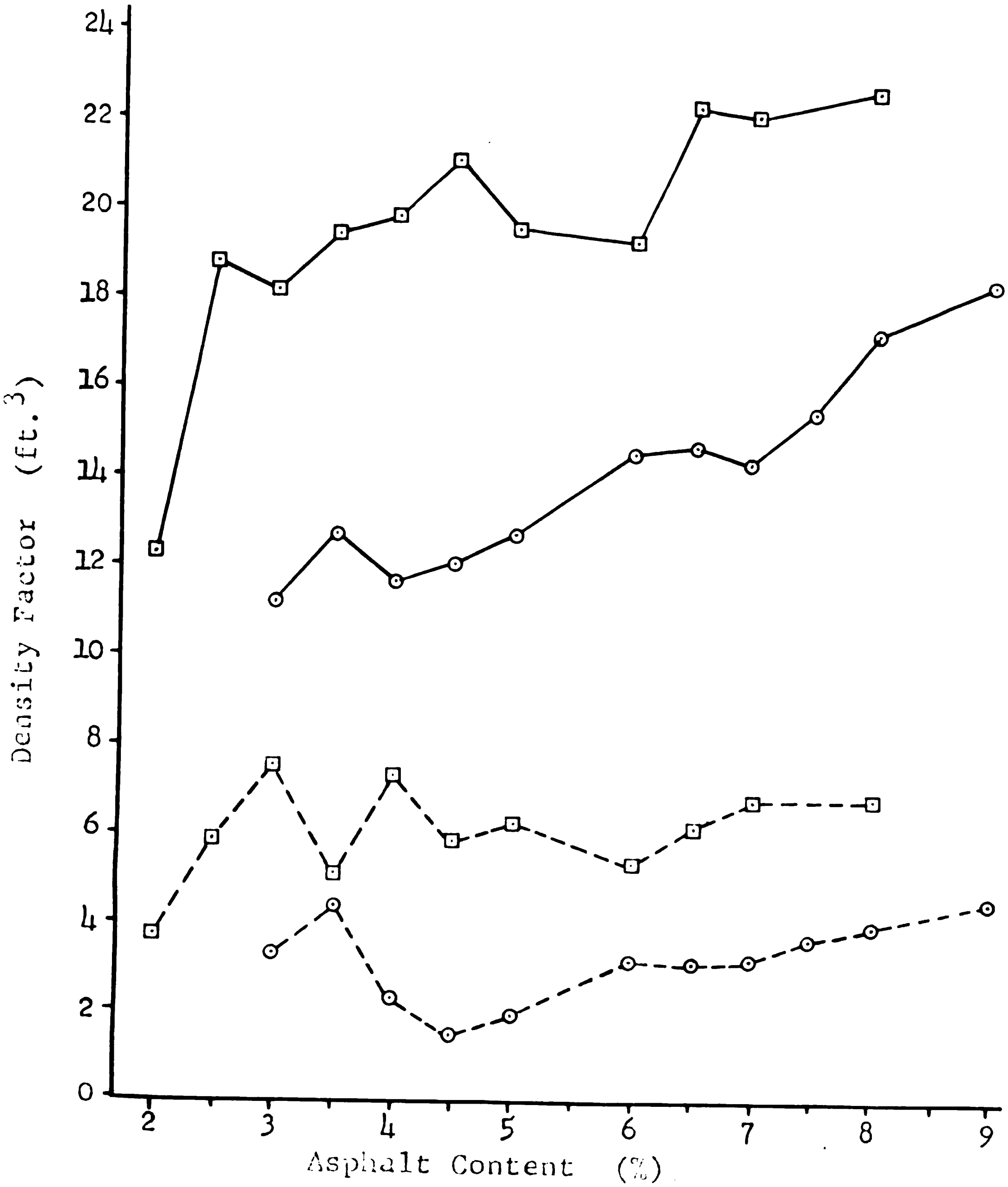
GRAPH 11.

DENSITY FACTOR VARIATION
WITH ASPHALT CONTENT
(AC 85/100)



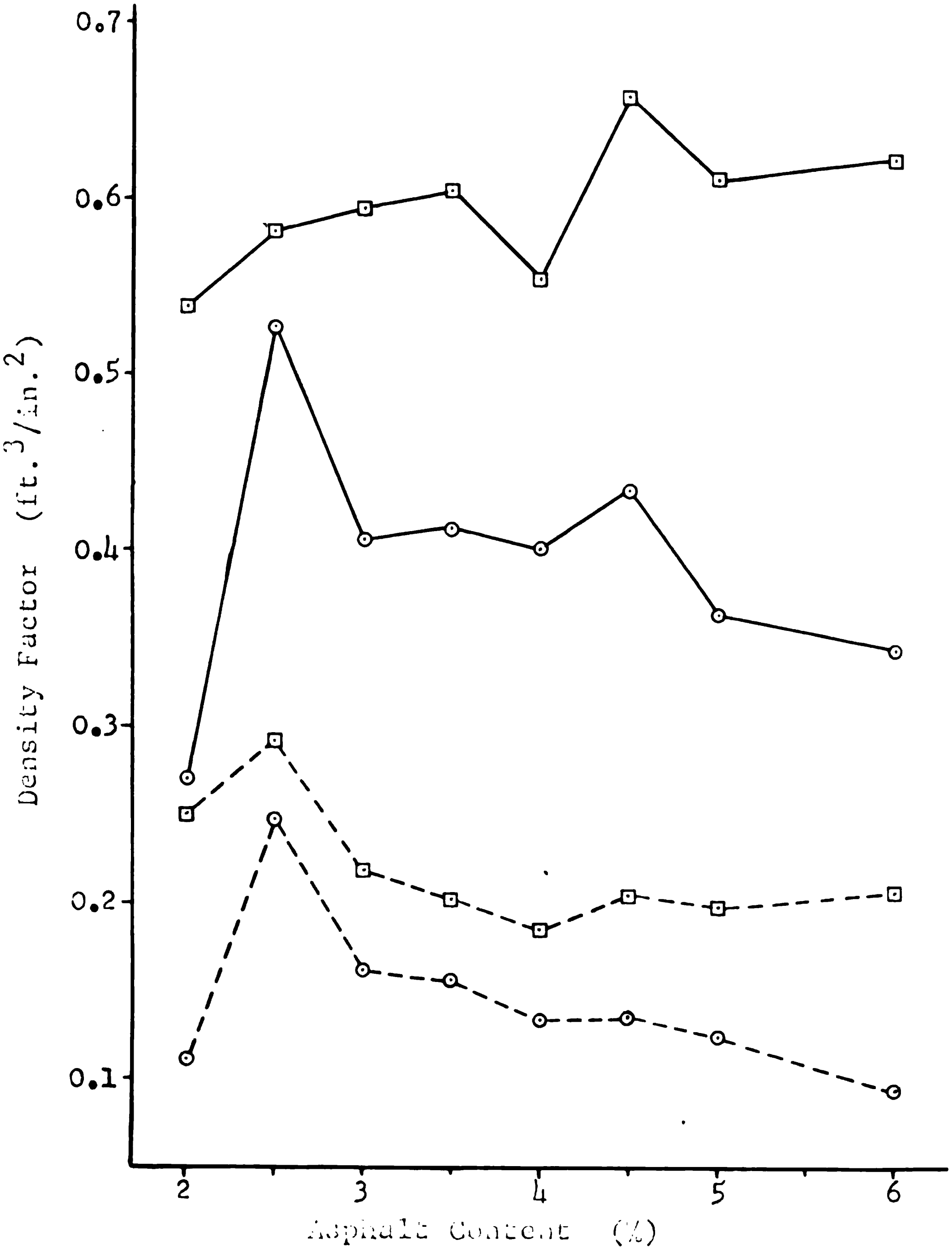
GRAPH 15.

DENSITY FACTOR VARIATION
WITH ASPHALT CONTENT
(AC 120/150)



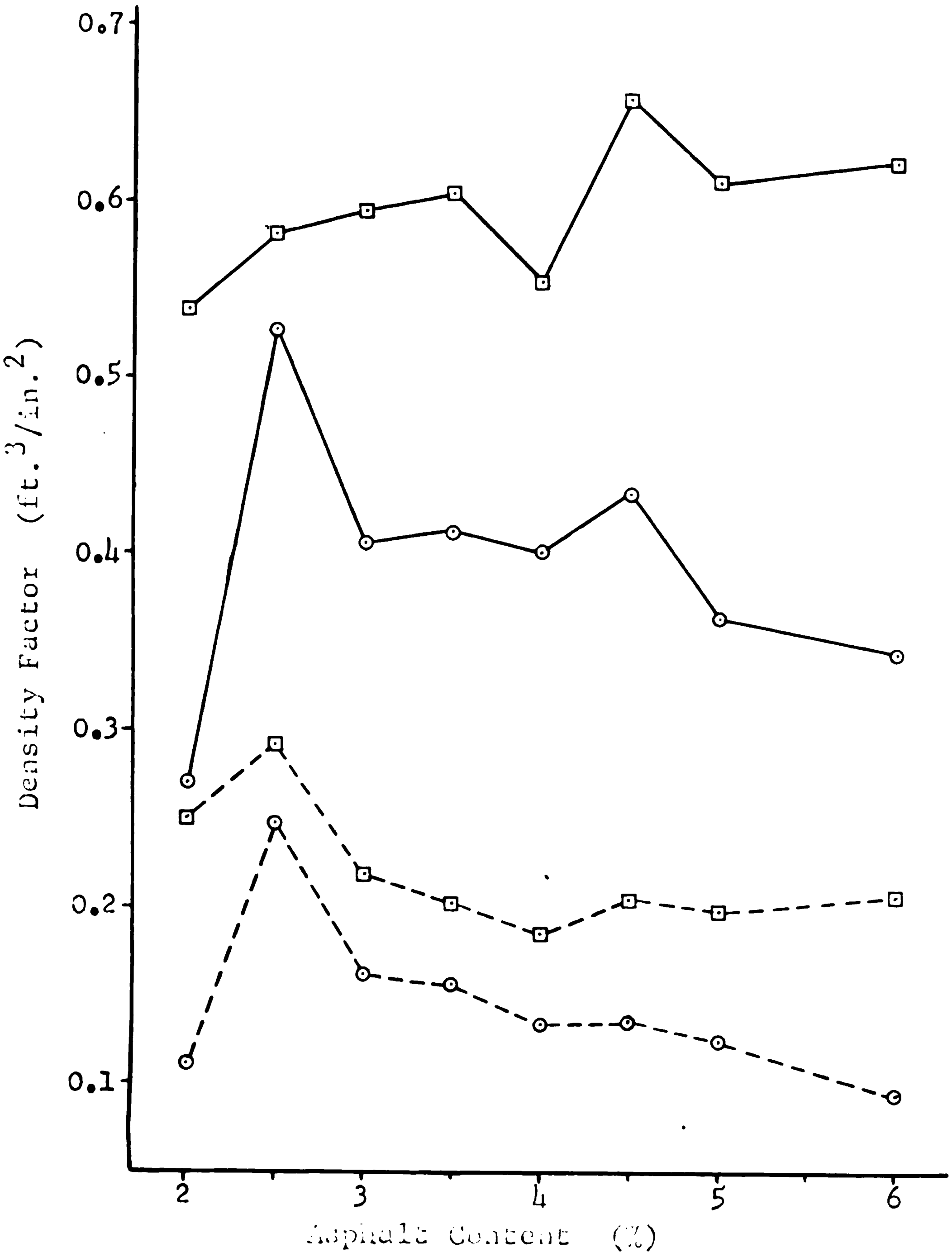
GRAPH 16.

DENSITY FACTOR VARIATION
WITH ASPHALT CONTENT
(AC 120/150)



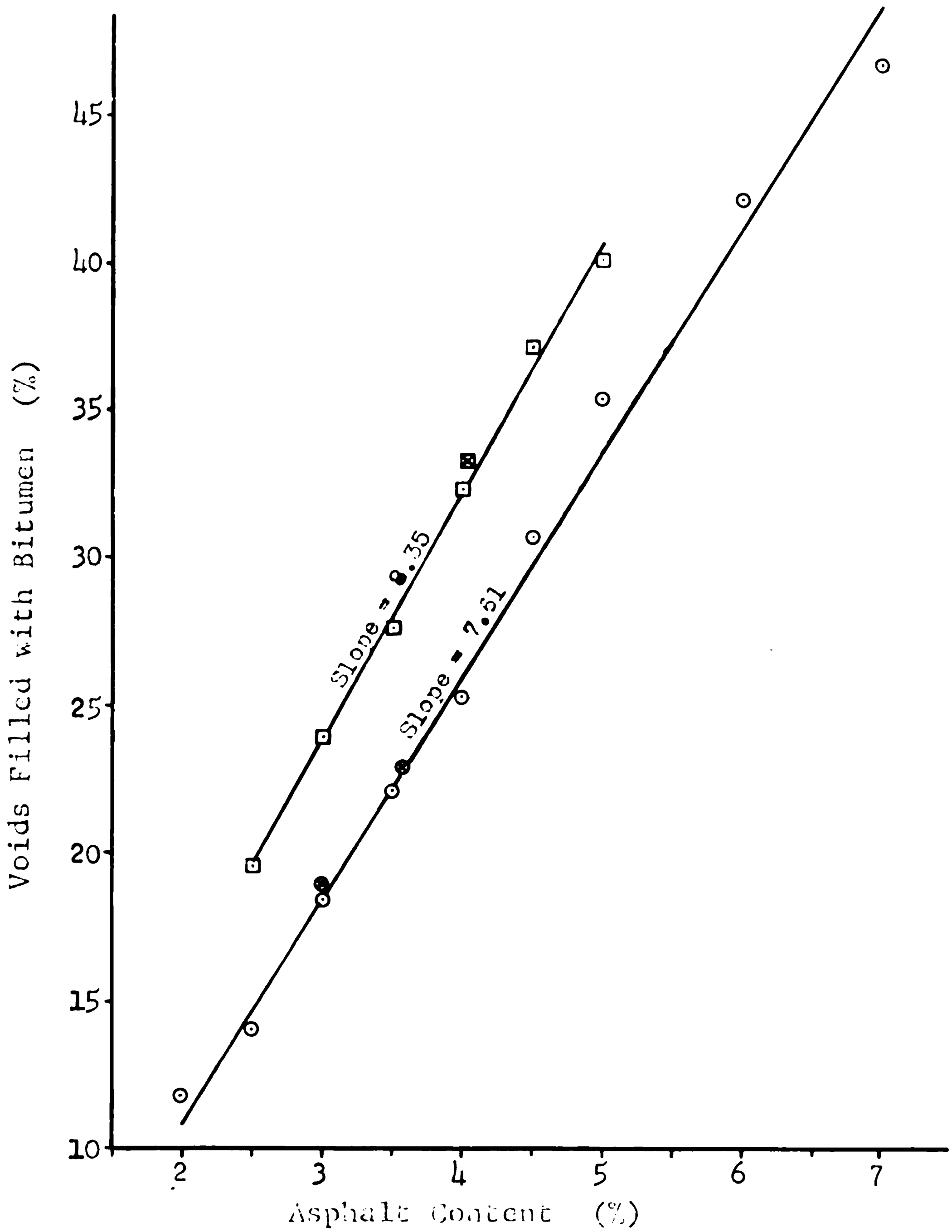
GRAPH 16.

DENSITY FACTOR VARIATION
WITH ASPHALT CONTENT
(AC 120/150)



GRAPH 17.

EFFECT OF VARYING ASPHALT CONTENT
ON VOIDS FILLED WITH BITUMEN
(AC 85/100)



GRAPH 13.

EFFECT OF VARYING ASPHALT CONTENT
ON VOIDS FILLED WITH BITUMEN
(AC 85/100)

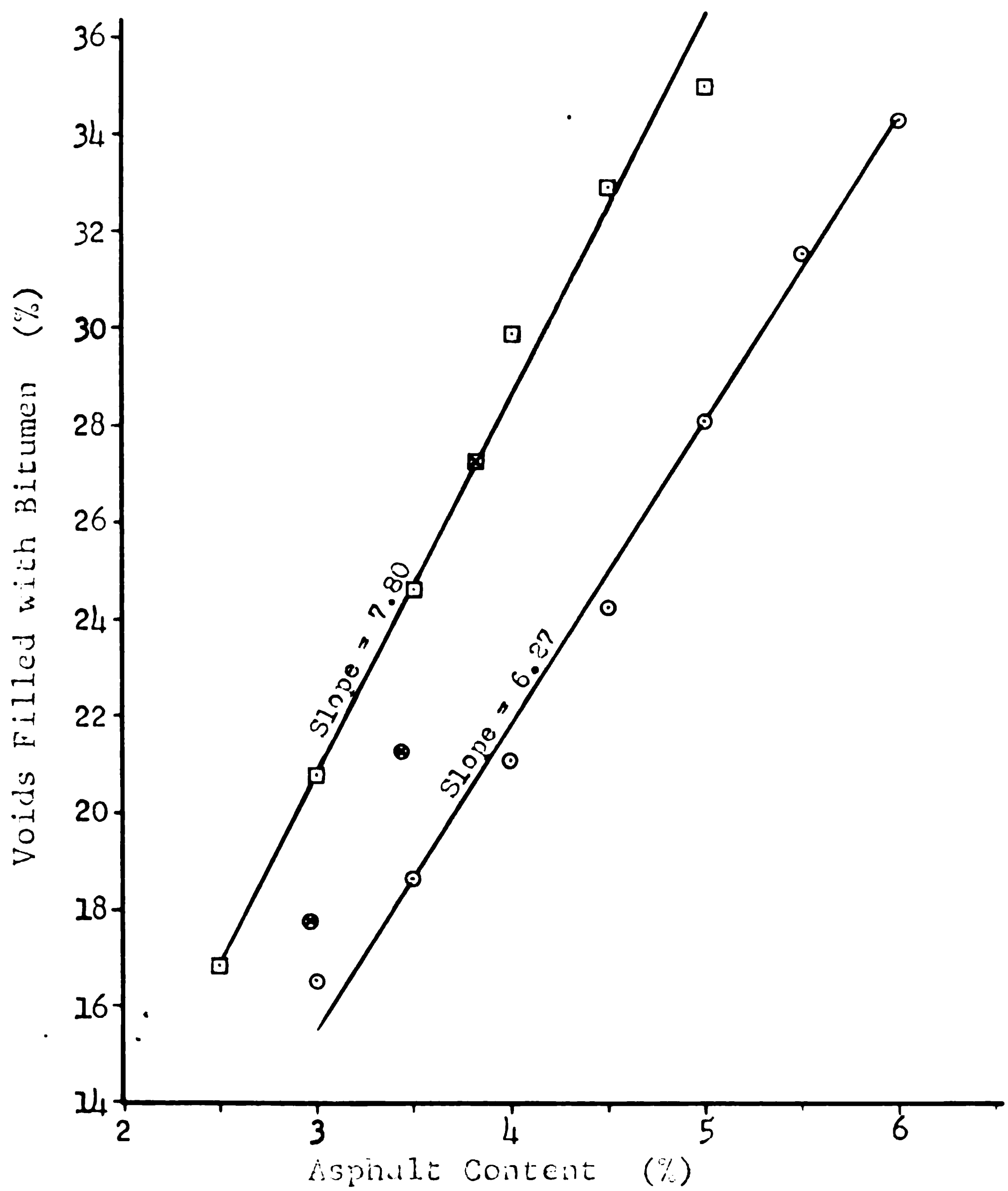


CHART 1.

EFFECT OF VARYING ASPHALT CONTENT
ON VOIDS FILLED WITH BITUMEN
(AC 120/150)

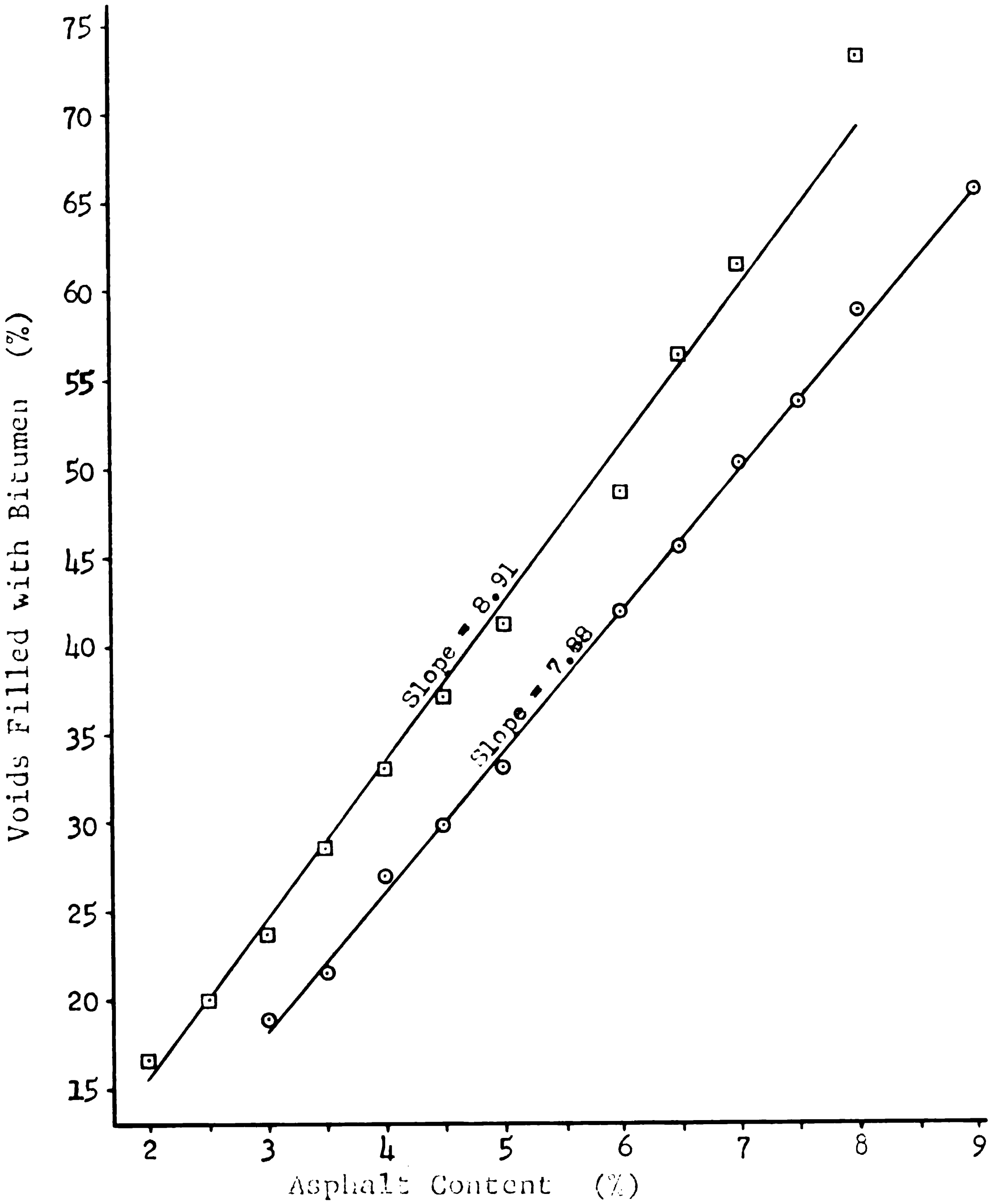
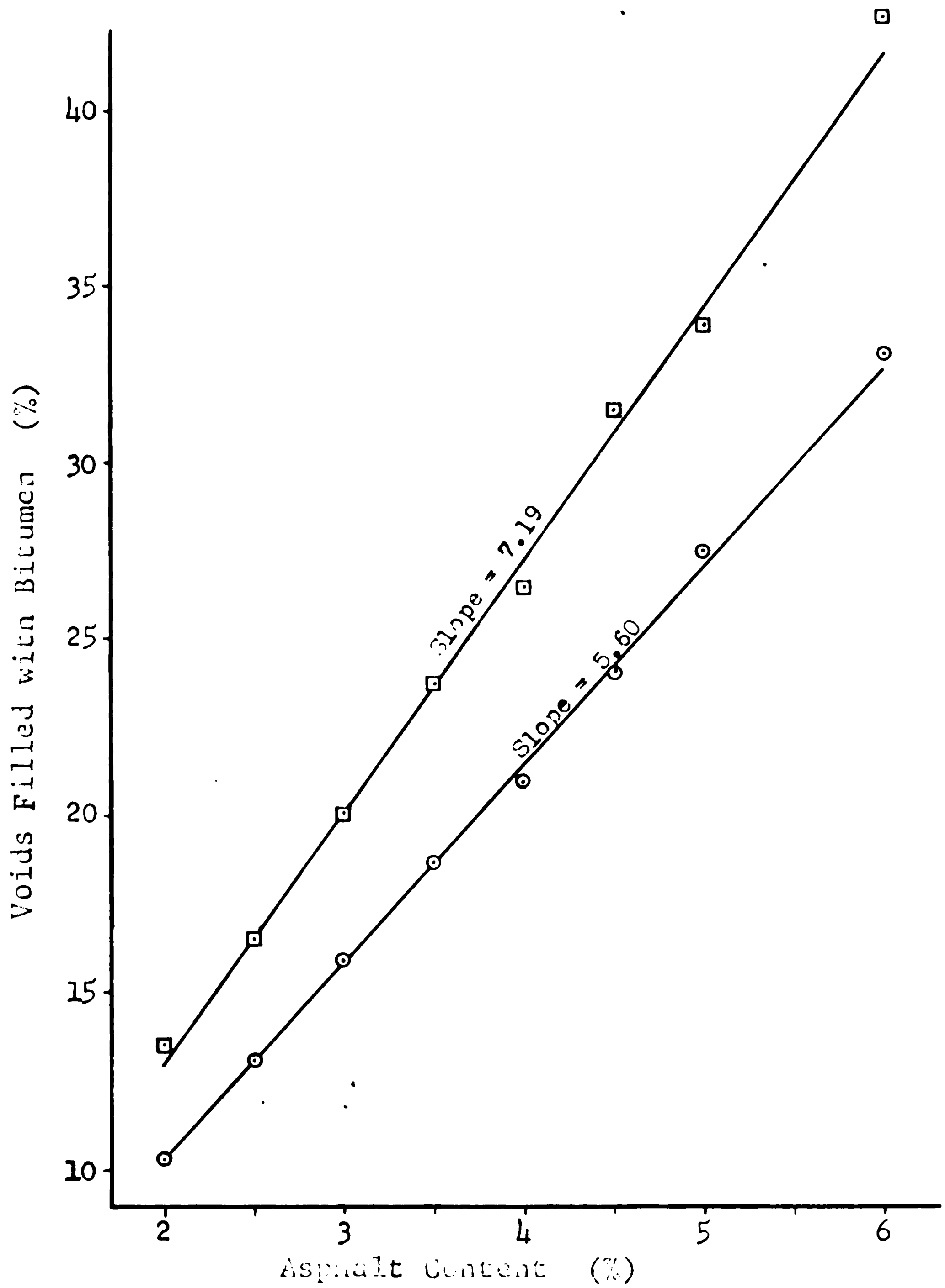


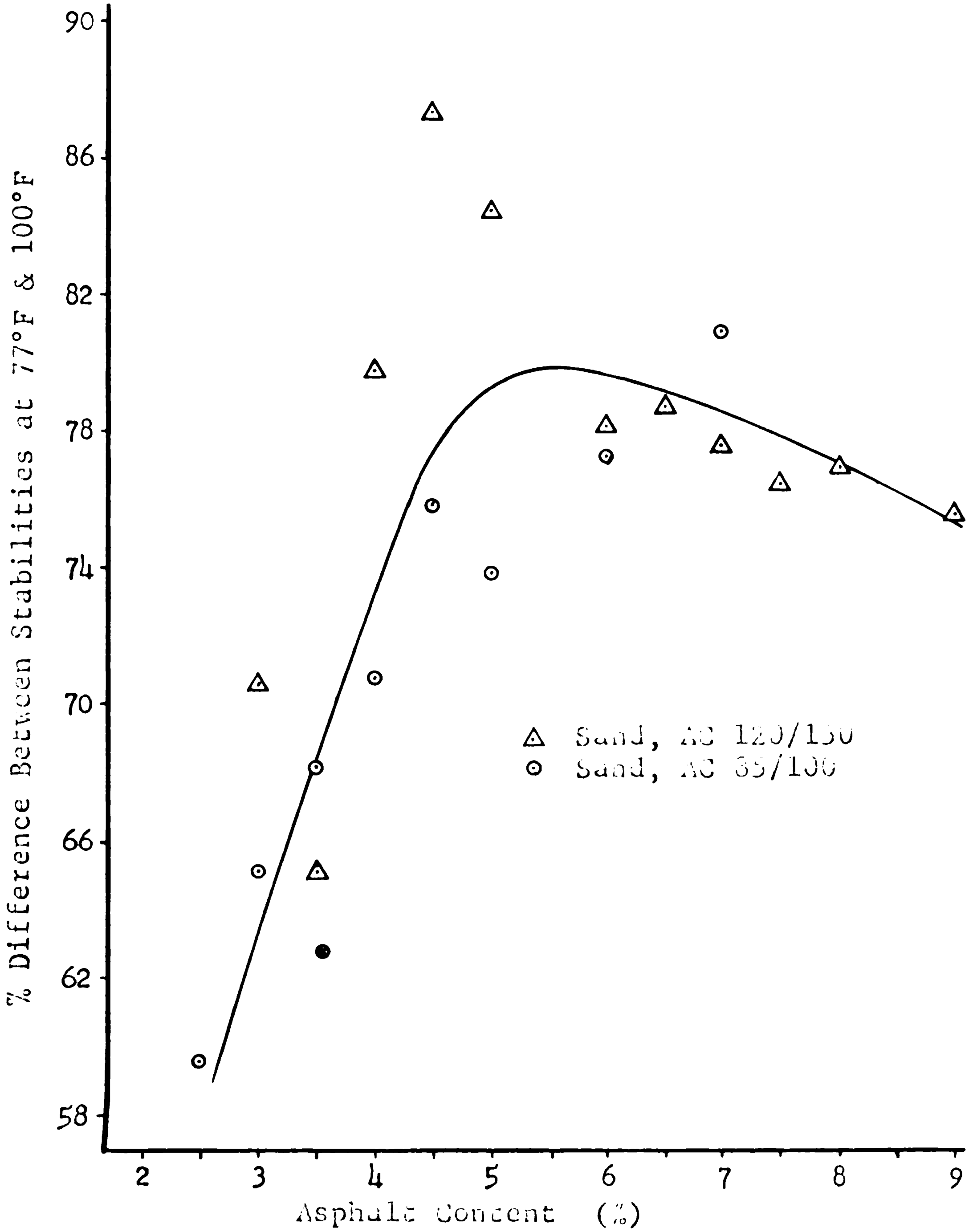
FIGURE 20.

EFFECT OF VARYING ASPHALT CONTENT
ON VOIDS FILLED WITH BITUMEN
(AC 120/150)



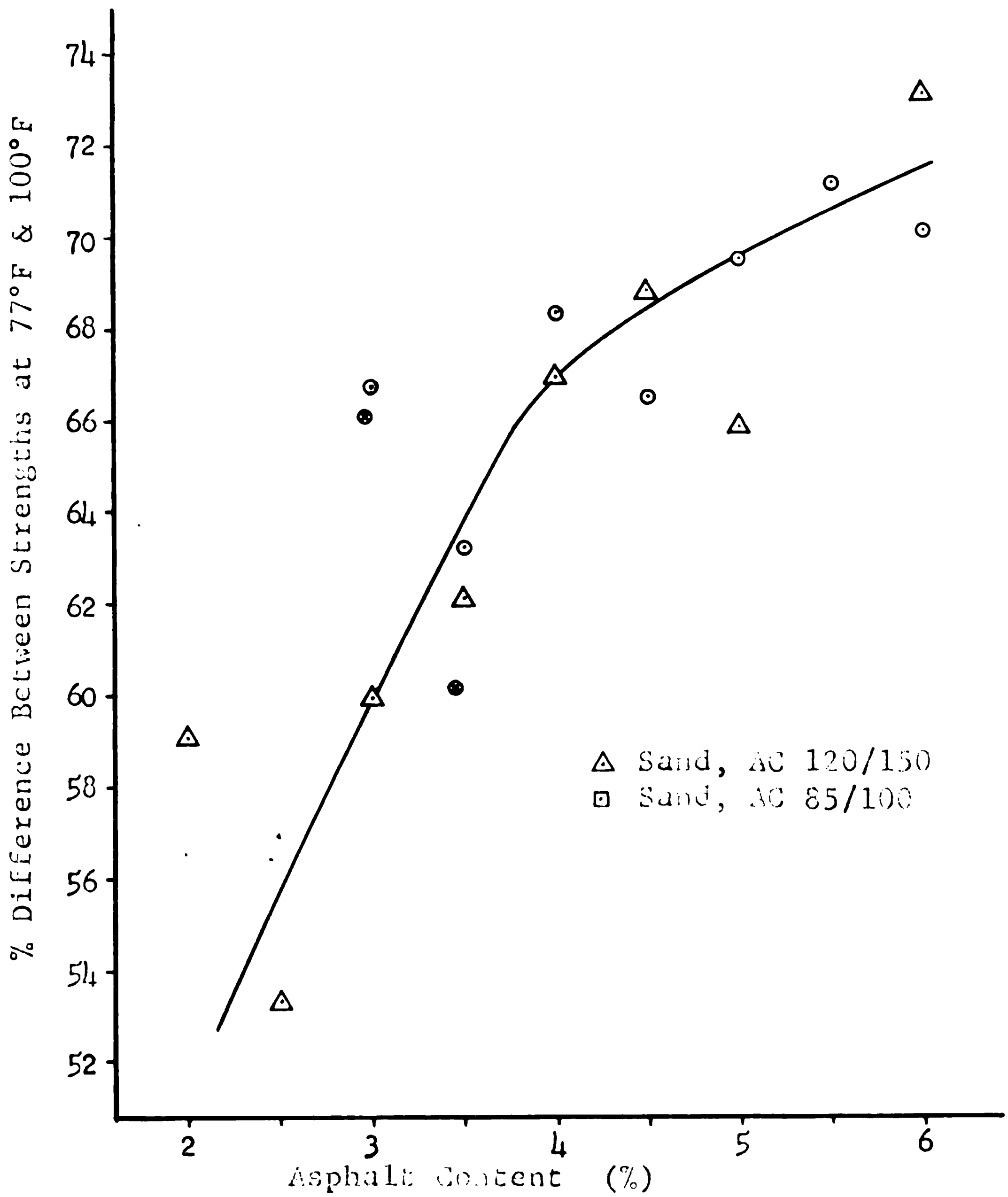
GRAPH 21.

EFFECT OF VARYING ASPHALT CONTENT
ON PER CENT DIFFERENCE BETWEEN
STABILITIES AT 77°F AND 100°F



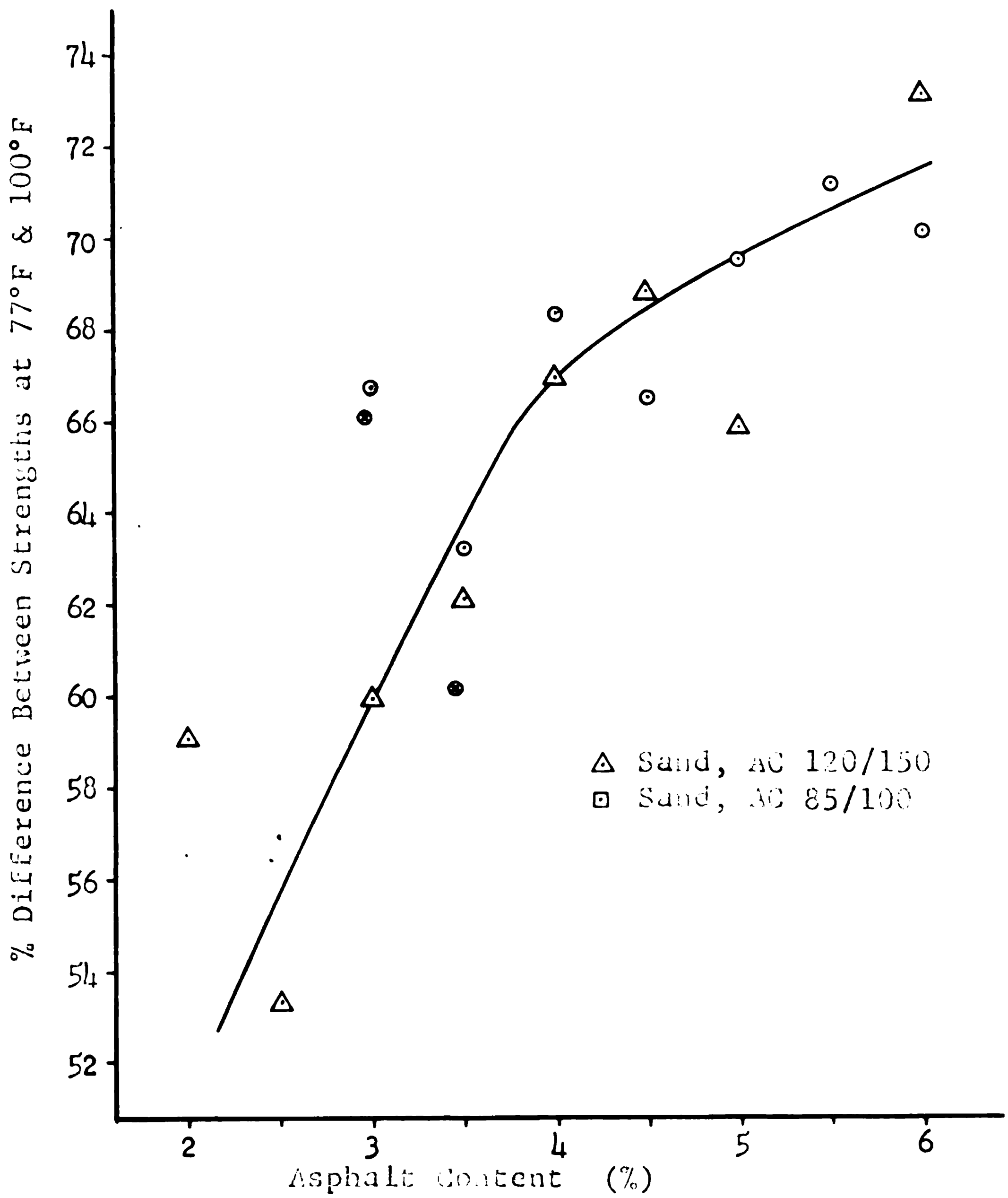
GRAPH 22.

EFFECT OF VARYING ASPHALT CONTENT
ON PER CENT DIFFERENCE BETWEEN
STRENGTHS AT 77°F AND 100°F



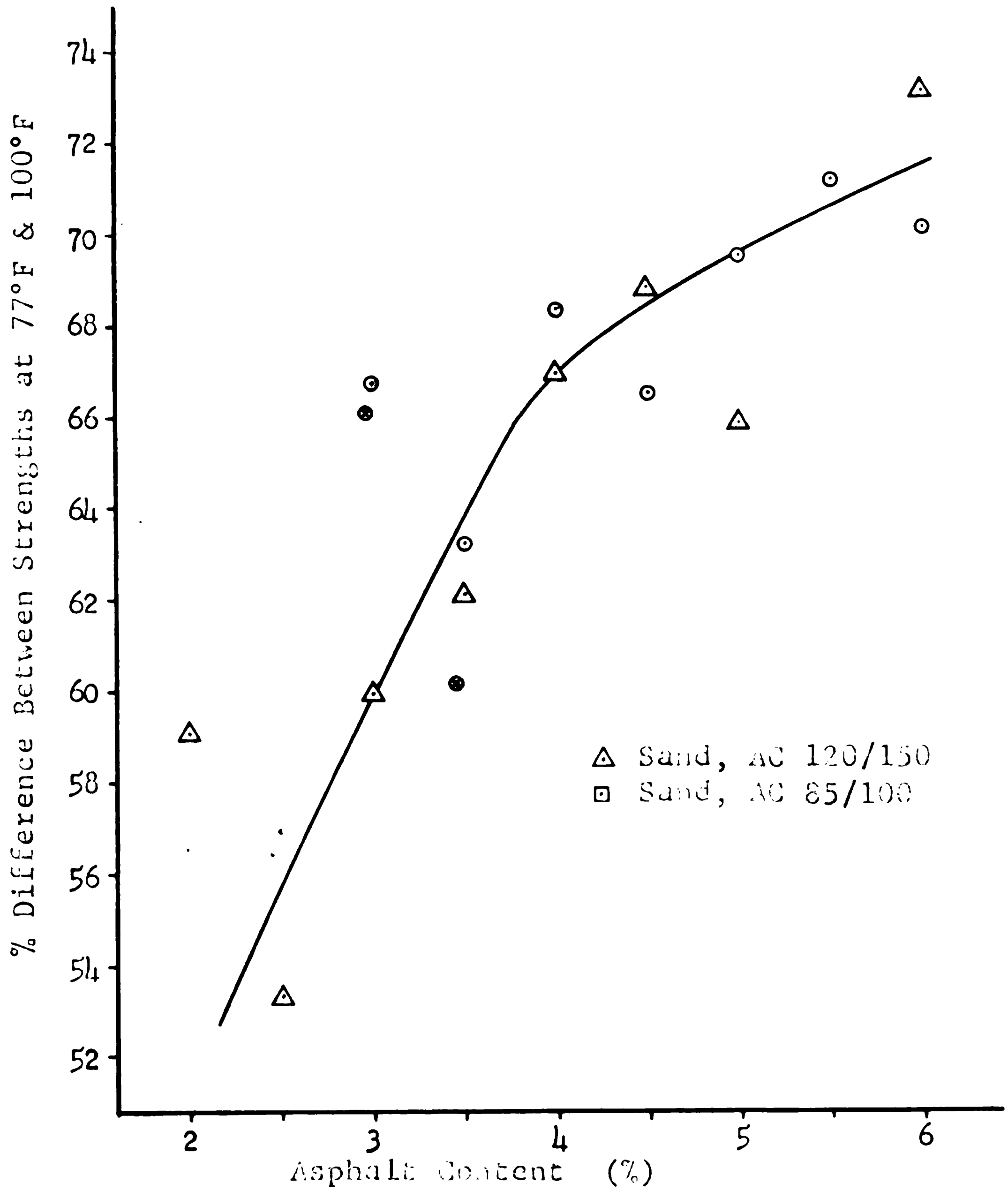
GRAPH 22.

EFFECT OF VARYING ASPHALT CONTENT
ON PER CENT DIFFERENCE BETWEEN
STRENGTHS AT 77°F AND 100°F



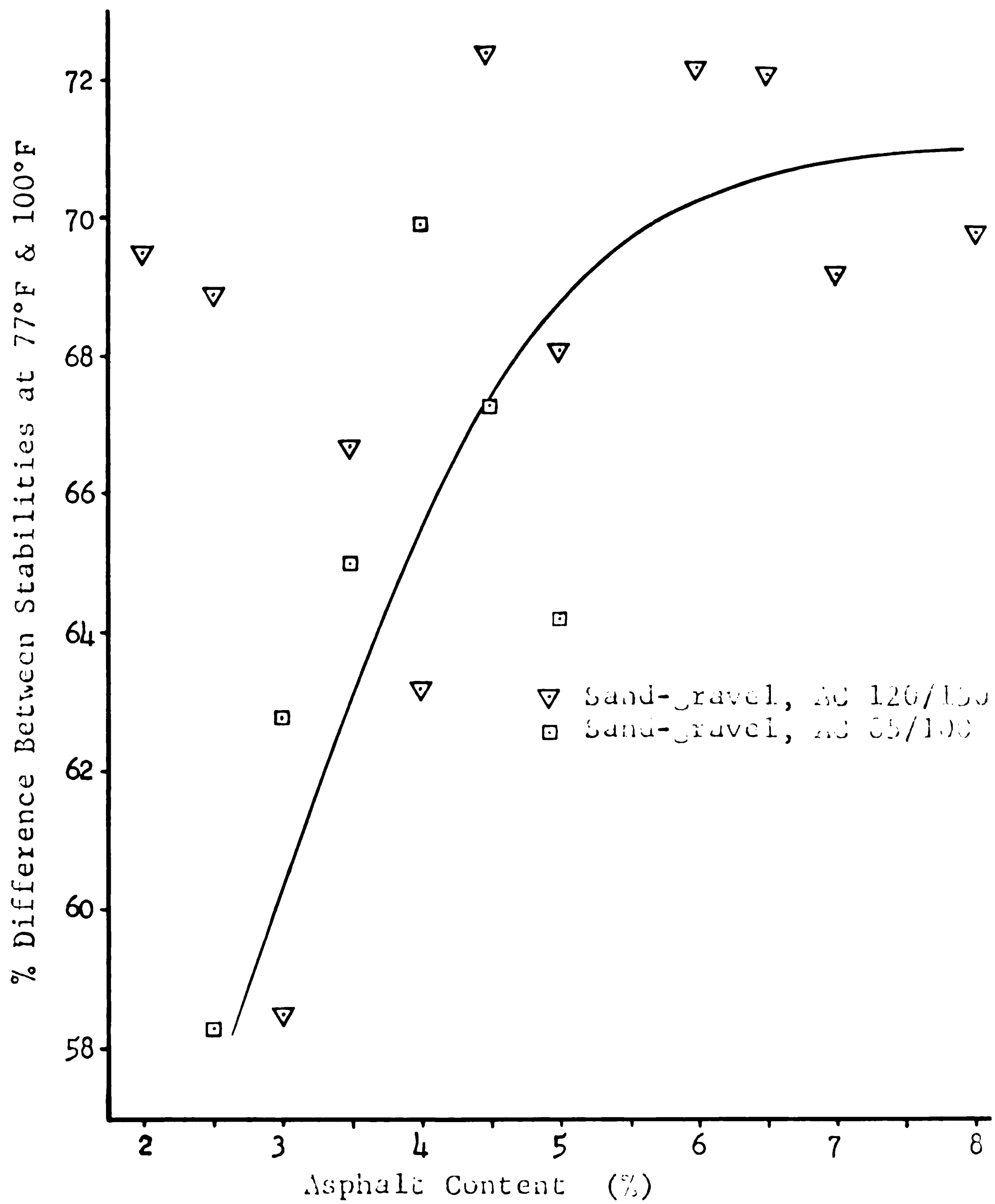
GRAPH 22.

EFFECT OF VARYING ASPHALT CONTENT
ON PER CENT DIFFERENCE BETWEEN
STRENGTHS AT 77°F AND 100°F



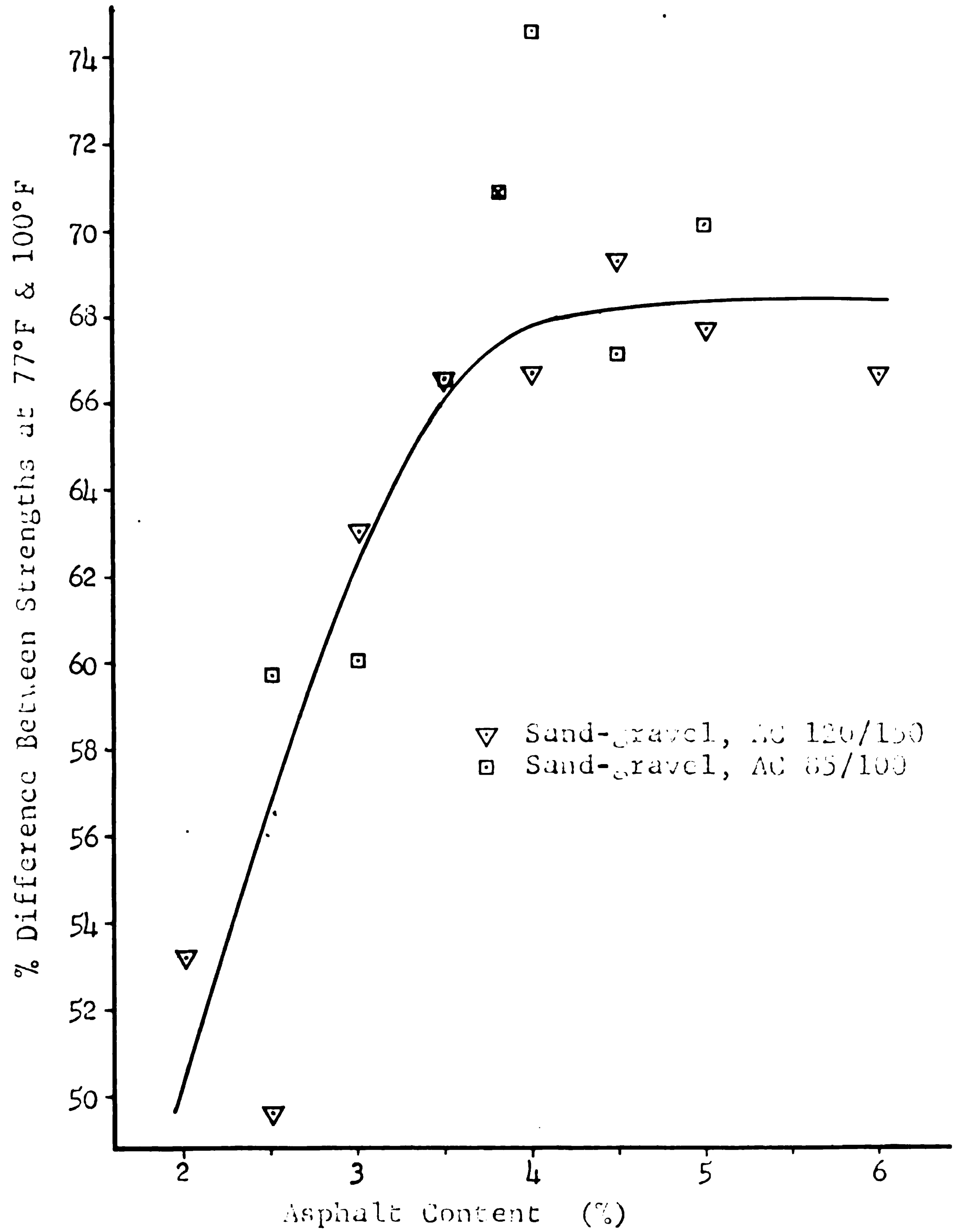
GRAPH 23.

EFFECT OF VARYING ASPHALT CONTENT
ON PER CENT DIFFERENCE BETWEEN
STABILITIES AT 77°F AND 100°F



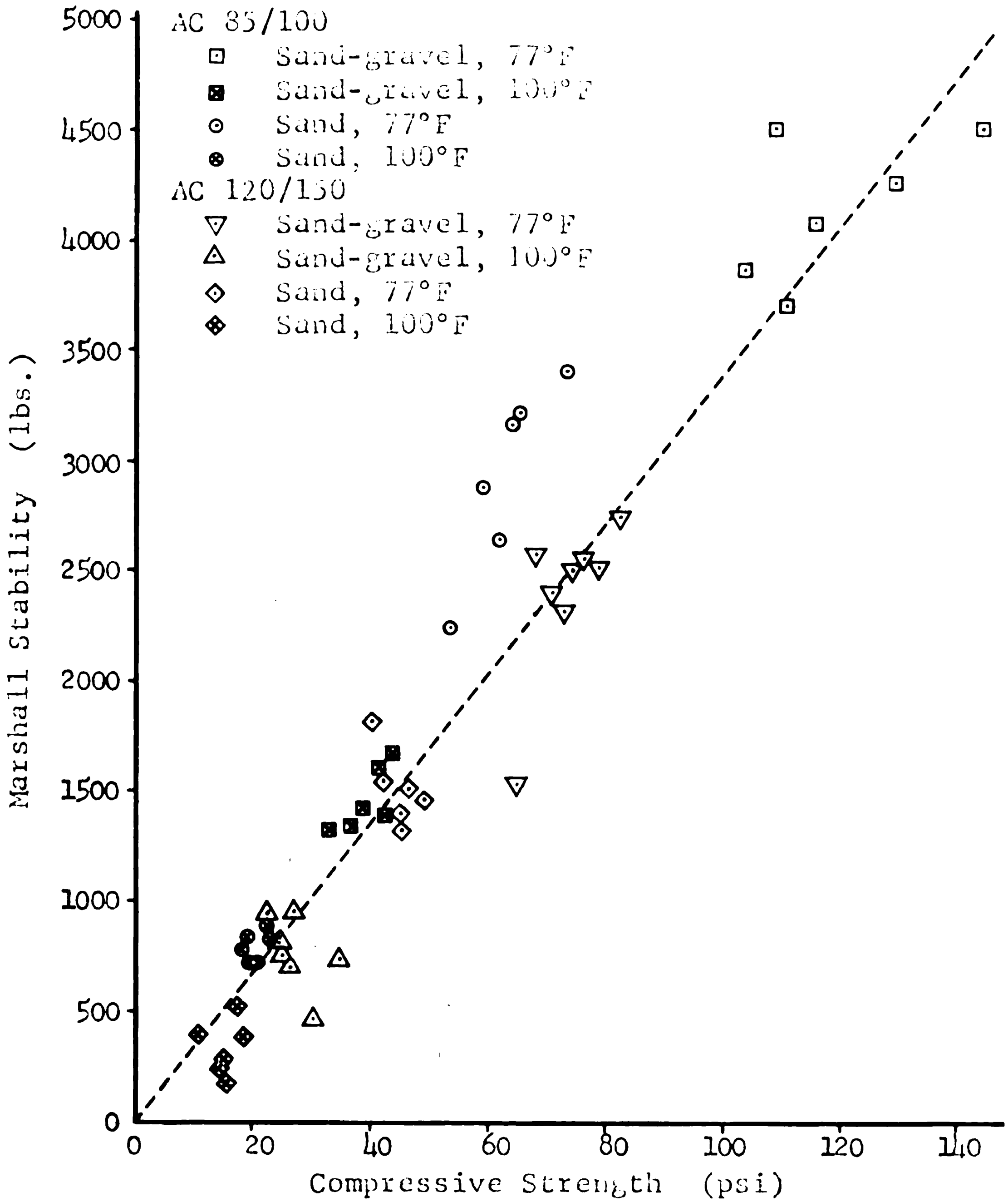
GRAPH 24.

EFFECT OF VARYING ASPHALT CONTENT
ON PER CENT DIFFERENCE BETWEEN
STRENGTHS AT 77°F AND 100°F



GRAPH 2[illegible].

CORRELATION BETWEEN MARSHALL
STABILITY AND UNCONFINED
COMPRESSIVE STRENGTH



APPENDIX C

CHICAGO TESTING LABORATORY, INC.

TECHNICAL REPORT

CHICAGO TESTING LABORATORY, INC.

TECHNICAL REPORT

No. 08960

To: Leonard Refineries, Inc.; Alma, Michigan

Attention: Mr. Berl Fleury Date: May 28, 1962

Subject: Marshall Stability Tests on Sand-Asphalt Mixture for Base

Leonard Refineries was desirous of obtaining Marshall Stability Test data on sand-asphalt mix for base construction using samples of sand and AC 100/120 supplied by them. The sieve analysis and specific gravity of the sand is shown in Table 1 and the asphalt had a penetration at 77°F of 107 with a specific gravity at 77°F of 1.025.

Laboratory mixtures were prepared using the sand as received with varying asphalt contents. Marshall Test specimens were made and tested in accordance with ASTM D 1559-60T at a compaction temperature of 250°F and 50 blows of the hammer on each face. After it was observed that the Marshall Test data at 140°F were low, additional test specimens were prepared and Marshall values at 100°F were determined.

The Marshall Test data are shown in Table 2.

CONTENTS:

Marshall Test values at 140°F are low, but much higher when tested at 100°F. The voids are quite high with correspondingly low Voids Filled which is to be expected with sand of this grading. Higher asphalt content to reduce the void content would have produced an unstable mixture. The use of mineral filler would reduce the air void content and probably improve the other properties of the mixture.

The Stability and Flow values at 100°F are quite good. Since it is doubtful that a base course would reach this temperature, it appears that this sand mixed with about 5% AC 100/120 would probably be satisfactory for base course construction providing it can be properly laid and compacted without undue disturbance of the sub base by the trucks and paving machine.

Respectfully submitted,

CHICAGO TESTING LABORATORY, INC.

TABLE 1

SIEVE ANALYSIS OF SAND

Sieve Size	Percent Passing Cumulative
5/8"	100.0
1/2"	98.9
3/8"	97.6
No. 4	92.5
No. 10	85.5
No. 40	52.9
No. 80	12.4
No. 200	3.4
Specific Gravity	2.63

TABLE 2.

TEST RESULTS OF MIXTURES

Mixture No.	1	2	3	1	2	3
Asphalt Content, %	4.5	5.0	5.5	4.5	5.0	5.5
Marshall Tests at	140°F			100°F		
Specific Gravity at 77°F	2.05	2.05	2.06	2.08	2.07	2.07
Theo. Max. Sp. Gr.	2.46	2.44	2.42	2.46	2.44	2.42
Air Voids, %	16.7	16.8	14.9	15.4	15.1	14.5
VMA, %	25.6	26.8	25.9	24.5	25.2	25.6
Voids Filled, %	34.8	37.3	42.5	37.1	40.0	43.4
Stability, lbs.	245	255	158	1731	1527	1165
Flow, lbs. [0.01 in.]	8.7	9.3	12.0	9.3	11.0	11.8

CHICAGO TESTING LABORATORY, INC.

TECHNICAL REPORT

No. 13125-6

To: Leonard Refineries, Inc.; Alma, Michigan

Attention: Mr. Berl Fleury Date: April 25, 1963

Subject: Bituminous Mixtures Containing Fine Sand and Gravel For Subbase and Base Construction

Leonard Refineries submitted samples of fine sand and gravel to evaluate for use in bituminous subbase and base pavement construction. It was decided during discussions with Mr. Fleury that Marshall Tests should be made on a series of mixtures composed of fine sand, another series made with gravel and a third series composed of equal parts of sand and gravel. It was also decided that the Marshall Tests would be made at 77°F for the fine sand mixtures and at 100°F for the gravel and sand-gravel mixtures. Leonard also submitted a sample of AC 85/100 asphalt (penetration at 77°F was 90, and specific gravity at 77°F was 1.028) for use in these mixtures.

LABORATORY TESTS:

There were a few pieces of oversize aggregate in the gravel and fine sand, and therefore, the gravel was scalped over a 3/4" screen and the fine sand over a No. 4 screen prior to testing. The sieve analyses and specific gravities of the scalped fine sand and gravel are shown in Table 1.

In order to obtain some idea of the characteristics of bituminous mixtures made with these aggregates, small batches of mixtures were prepared by hand, using 3.0% and 3.5% of asphalt for the sand and gravel mixtures, respectively. These were subjected to CTL Shear Tests.

The specimens for the Shear Tests were prepared at 325°F in 2" diameter molds. Sufficient mixture was used to produce specimens 1.5" high, and the compaction was accomplished by a double plunger method at 5000 psi. The specimens were weighed in and out of water for determining specific gravity. The Shear strength along the circumference at 77°F was then determined by a split ring method in the Shear Test apparatus.

The mixtures for Marshall Tests were prepared in a mechanical mixer in accordance with ASTM D 1559-60T with compaction at 250°F with 50 blows of the hammer on each face. The specimens were then tested in the usual Marshall manner with the exception that the stability and flow for the sand mixtures were made at 77°F, and the gravel and gravel-sand mixtures were determined at 100°F.

The test results for these mixtures are shown in Table 2.

COMMENTS:

There is not much information available in the literature concerning this type of construction for subbase and base courses. There is also apparently no Marshall Test criteria for designing mixtures for this service. However, the results of the Marshall Tests show rather good stability and flow values at the test temperatures used.

Based upon the Marshall Test results, it appears that the fine sand mixed with 3.0% to 3.5% asphalt or a 50/50 blend of sand and gravel mixed with about 3.5% to 4% should be satisfactory for a subbase course and would certainly be more stable and carry a heavier load than either the sand or gravel without bitumen. The results of the Marshall Tests also indicate that a mixture of the gravel with about 4% asphalt should be worth while for an experimental base course.

Based upon the appearance, handling qualities and test results of these mixtures in the laboratory, it would be our estimate that the bituminous mixture should be comparable in a ration of a minimum of 1.5 or 2.0 per thickness of plain sand or gravel.

It was interesting to note that the CTL Shear Test results on the two mixtures tested were in good agreement with those of the Marshall Test.

Respectfully submitted,

CHICAGO TESTING LABORATORY, INC.

TABLE 1

TEST RESULTS ON AGGREGATE SAMPLES

Sieve Analysis	Percent Passing Cumulative	
	Gravel	Fine Sand
3/4"	100.0	
5/8"	98.6	
1/2"	97.2	
3/8"	95.0	
No. 4	87.0	
No. 10	73.1	100.0
No. 40	44.1	88.4
No. 80	4.2	10.8
No. 200	1.1	4.6
Specific Gravity	2.70	2.64

TABLE 1.

MARSHALL TEST RESULTS ON BITUMINOUS MIXTURES

Mix No.	1	2	3	4	5	6	7	8	9
Composition, %:									
Fine Sand	97.0	96.5	96.0	---	---	---	48.25	48.00	47.75
Gravel	---	---	---	96.5	96.0	95.5	48.25	48.00	47.75
AC 85/100	3.0	3.5	4.0	3.5	4.0	4.5	3.50	4.00	4.50
Marshall Tests:									
Sp. Gr. at 77 F	1.78	1.82	1.84	2.06	2.09	2.06	1.95	1.96	1.95
Theo. Max. Sp. Gr.	2.52	2.50	2.48	2.55	2.53	2.51	2.53	2.51	2.49
Air Voids, %	29.4	27.2	25.8	19.2	17.4	17.9	22.9	21.9	21.7
VMA, %	34.6	33.4	33.0	26.2	25.6	26.9	29.6	29.5	30.2
Voids Filled, %	15.0	18.5	21.8	26.8	32.0	33.4	22.6	25.8	28.2
Stability, lbs.:									
at 77 F	875	535	480	---	---	---	---	---	---
at 100 F	---	---	---	1285	1245	1190	575	595	680
Flow, 0.01"									
at 77 F	6.0	8.0	8.3	---	---	---	---	---	---
at 100 F	---	---	---	7.0	8.7	10.0	8.0	9.0	9.3
CTL Shear Test:									
Sp. Gr. at 77 F	1.79	---	---	2.03	---	---	---	---	---
Air Voids	29.0	---	---	20.4	---	---	---	---	---
Shear at 77 F, psi.	24.8	---	---	42.7	---	---	---	---	---

TABLE [illegible].

MARSHALL TEST RESULTS ON BITUMINOUS MIXTURES

Mix No.	1	2	3	4	5	6	7	8	9
Composition, %:									
Fine Sand	97.0	96.5	96.0	---	---	---	48.25	48.00	47.75
Gravel	---	---	---	96.5	96.0	95.5	48.25	48.00	47.75
AC 85/100	3.0	3.5	4.0	3.5	4.0	4.5	3.50	4.00	4.50
Marshall Tests:									
Sp. Gr. at 77 F	1.78	1.82	1.84	2.06	2.09	2.06	1.95	1.96	1.95
Theo. Max. Sp. Gr.	2.52	2.50	2.48	2.55	2.53	2.51	2.53	2.51	2.49
Air Voids, %	29.4	27.2	25.8	19.2	17.4	17.9	22.9	21.9	21.7
VMA, %	34.6	33.4	33.0	26.2	25.6	26.9	29.6	29.5	30.2
Voids Filled, %	15.0	18.5	21.8	26.8	32.0	33.4	22.6	25.8	28.2
Stability, lbs.:									
at 77 F	875	535	480	---	---	---	---	---	---
at 100 F	---	---	---	1285	1245	1190	575	595	680
Flow, 0.01"									
at 77 F	6.0	8.0	8.3	---	---	---	---	---	---
at 100 F	---	---	---	7.0	8.7	10.0	8.0	9.0	9.3
CTL Shear Test:									
Sp. Gr. at 77 F	1.79	---	---	2.03	---	---	---	---	---
Air Voids	29.0	---	---	20.4	---	---	---	---	---
Shear at 77 F, psi.	24.8	---	---	42.7	---	---	---	---	---

CHICAGO TESTING LABORATORY, INC.

TECHNICAL REPORT

No. 13947

To: Leonard Refineries, Inc.; Alma, Michigan

Attention: Mr. Berl Fleury   Date: June 24, 1963

Subject: Tests on Bituminous Base Mixture from the Gratiot County Experimental Project

Leonard Refineries submitted a sample of bituminous stabilized gravel used for a base course on the experimental project at Gratiot County.

Mr. Fleury requested that an analysis be made of the mixture as well as Marshall and Shear Tests at various temperatures. Test methods used were the same as those described in an earlier report on this project (CTL Report No. 13125-6 of April 25, 1963.)

There was not sufficient amount of sample to make more than five Marshall test specimens and five Shear test specimens. Therefore, the extraction and recovery test were made on Marshall specimens which had been tested. In considering the recovery test data, it should be noted that the mixtures were reheated, and therefore, the asphalt was subjected to additional hardening.

The test results are shown on the accompanying table.

Respectfully submitted,

CHICAGO TESTING LABORATORY, INC.

TEST RESULTS OF BITUMINOUS MIXTURE
EXPERIMENTAL BITUMINOUS BASE PROJECT

Extraction Test:	
% Passing	
3/4"	100.0
5/8"	98.4
1/2"	94.7
3/8"	91.2
No. 4	82.1
No. 10	72.4
No. 40	44.8
No. 80	6.0
No. 200	2.7
Bitumen, %	4.2
Moisture, %	Trace
Recovered Bitumen:	
Penetration at 77°F 100/5	45
Ductility at 77°F, 5/60, cm	115
Ash, %	0.7
Marshall Tests - Compacted at 250°F	
50 Blows on each face	
Specific Gravity at 77°F	2.10
Theo. Maximum Specific Gravity	2.55
Air Voids, %	17.6
VMA, %	26.2
Voids filled with Bit., %	32.8
Tests at 80°F:	
Stability, lbs.	3890
Flow, 0.01"	10
Tests at 100°F:	
Stability, lbs.	2710
Flow, 0.01"	9.7
Tests at 120°F:	
Stability, lbs.	1430
Flow, 0.01"	11

Shear Tests at 100°F:

Specific Gravity at 77°F	2.04
Theo. Maximum Specific Gravity	2.55
Air Voids, %	20.4
Shear Strength, psi	34.7

CHICAGO TESTING LABORATORY, INC.

TECHNICAL REPORT

No. 14759-60

To: Leonard Refineries, Inc.; Alma, Michigan

Attention: Mr. Berl Fleury Date: August 6, 1963

Subject: Test Results on Bituminous Sand Base Course from Gratiot County Experimental Project

Leonard Refineries submitted a sample of bituminous stabilized sand which was used for a base course on the experimental project in Gratiot County. Previous tests were made on the stabilized gravel base course from this project and the results are shown in CTL Report No. 13947.

Mr. Fleury requested that the same tests be made on this mixture as were carried out on the stabilized gravel. The tests were all made in the same manner. The extraction and recovery tests shown were made on the Marshall specimens after testing.

The test results are shown in the accompanying table.

Respectfully submitted,

CHICAGO TESTING LABORATORY, INC.

TEST RESULTS OF BITUMINOUS SAND BASE COURSE

GRATIOT COUNTY, MICHIGAN

Extraction Test:	
% Passing	
5/8"	100.0
1/2"	99.7
3/8"	98.4
No. 4	95.2
No. 10	90.5
No. 40	58.1
No. 80	5.7
No. 200	1.7
Bitumen, %	3.1
Moisture	Trace
Recovered Bitumen:	
Penetration at 77°F, 100/5	68
Ductility at 77°F, 5/60, cm	150
Ash, %	1.8
Marshall Tests - Compacted at 250°F, 50 Blows	
Specific Gravity at 77°F	2.00
Theo. Max. Sp. Gr.	2.53
Air Voids, %	20.9
VMA, %	27.0
Voids filled with Bitumen, %	22.6
Tests at 80°F:	
Stability, lbs	2645
Flow, 0.01"	10
Tests at 100°F:	
Stability, lbs.	1040
Flow, 0.01"	10
Tests at 120°F:	
Stability, lbs.	290
Flow, 0.01"	7

Tests at 140°F:	
Stability, lbs.	120
Flow, 0.01"	7
CTL Shear Tests at 100°F:	
Specific Gravity at 77°F	1.89
Theo. Max. Sp. Gr.	2.53
Air Voids, %	25.3
Shear Strength, psi	11.8

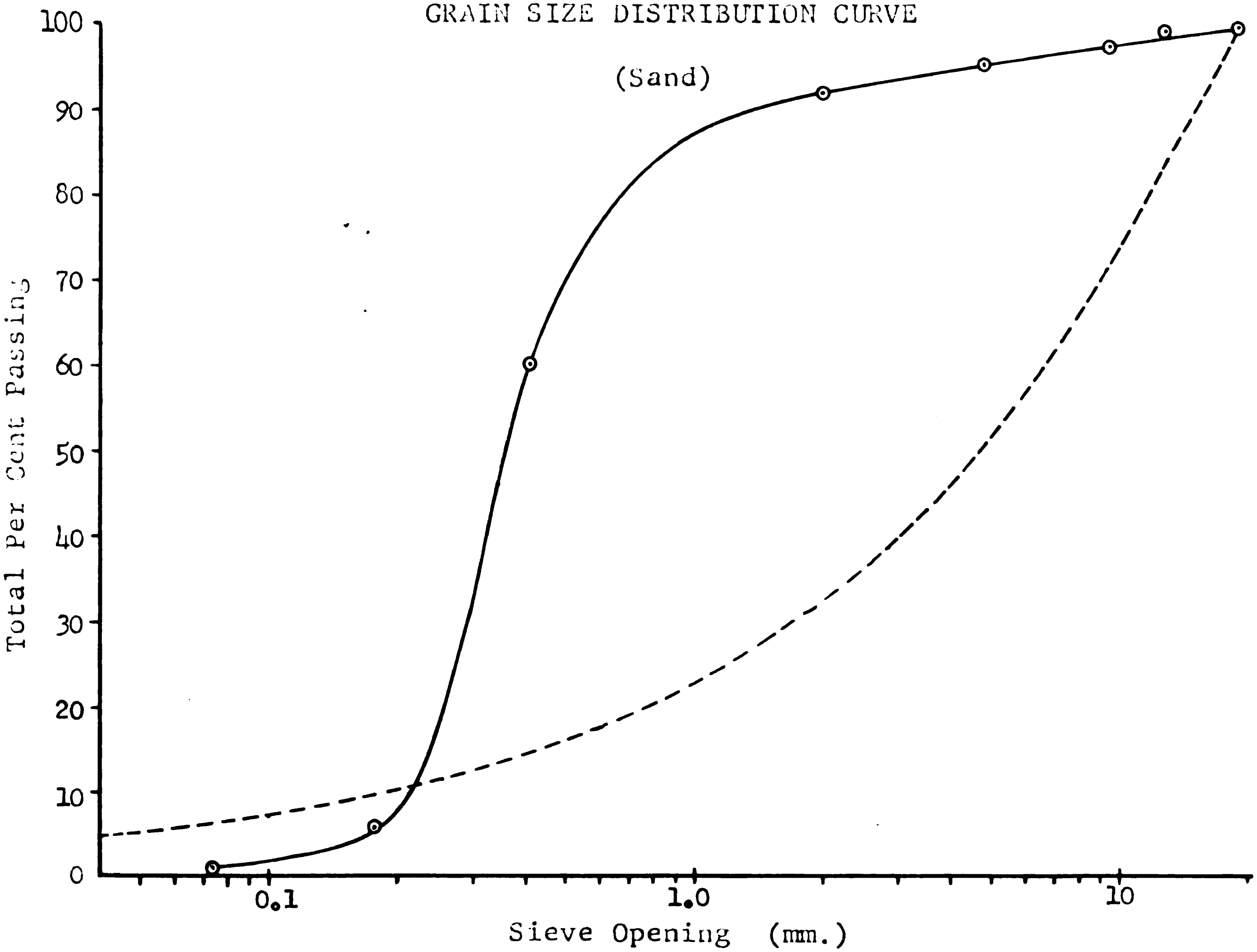
APPENDIX D

GRAIN SIZE DISTRIBUTION CURVES

GRAPH 1.

GRAIN SIZE DISTRIBUTION CURVE

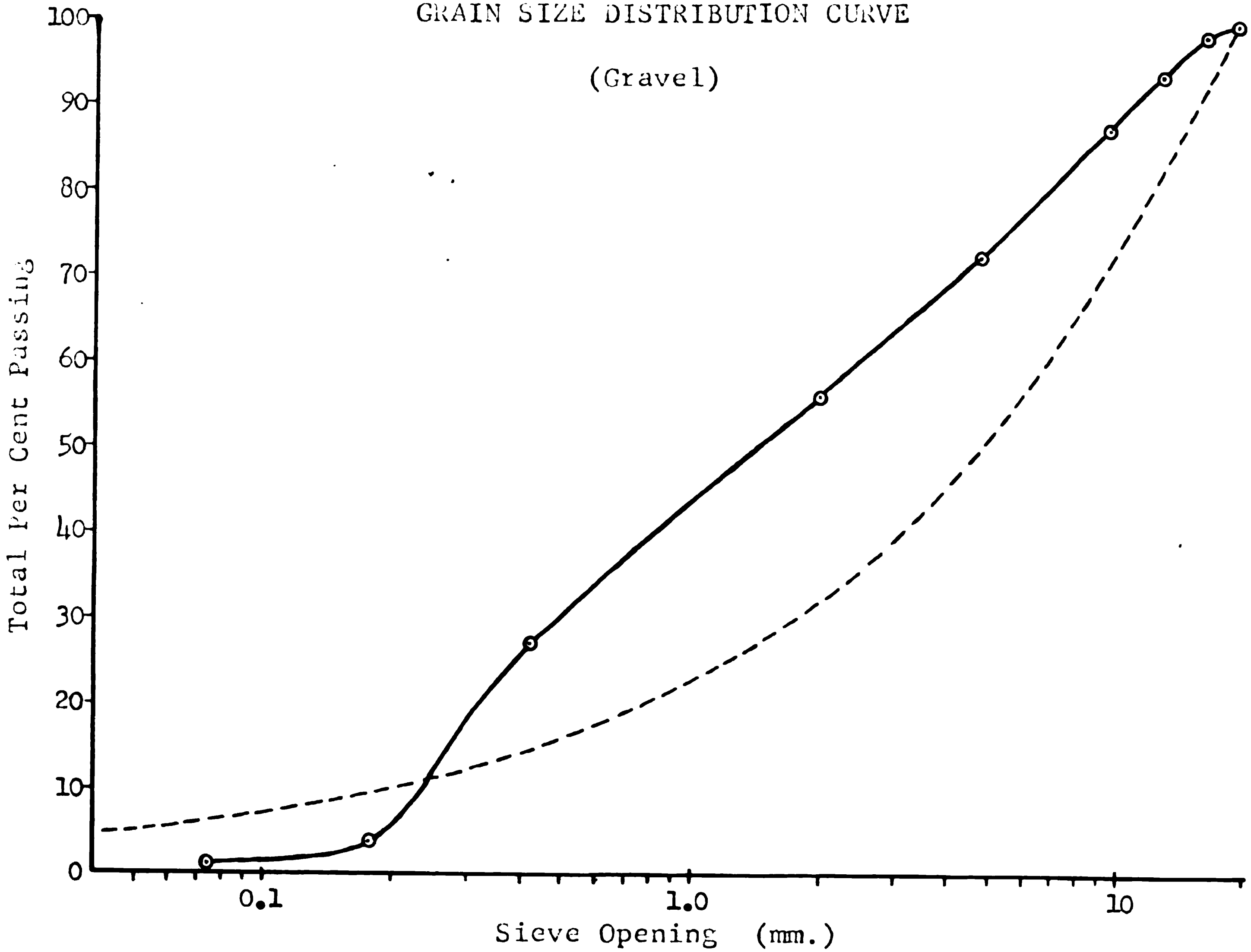
(Sand)



GRAPH 2.

GRAIN SIZE DISTRIBUTION CURVE

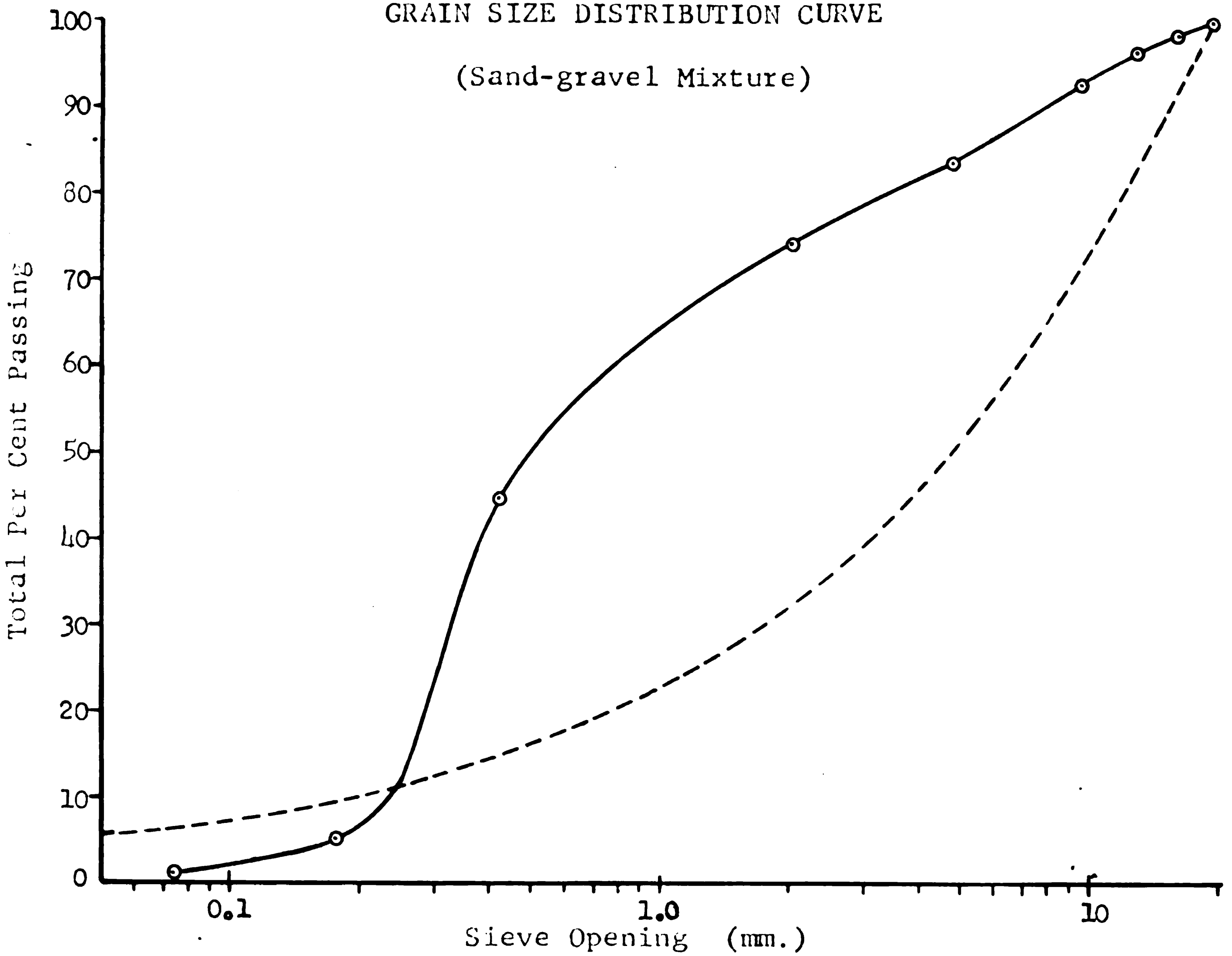
(Gravel)



GRAPH 3.

GRAIN SIZE DISTRIBUTION CURVE

(Sand-gravel Mixture)



APPENDIX E

TABLES OF SPECIFIC GRAVITIES

AND SIEVE SIZES

TABLE 1.

SPECIFIC GRAVITIES OF MIX CONSTITUENTS

Sand	2.64
Gravel	2.70
AC 85/100	1.028
AC 120/150	1.026
31A top aggregate	2.70

TABLE 2.

SIEVE SIZE SEQUENCE FOR GRAIN SIZE ANALYSIS OF AGGREGATE

Sieve	Opening size (in.)	Opening size (mm)
5/8 "	.625	15.9
1/2"	.500	12.7
3/8"	.375	9.52
No. 4	.187	4.76
No. 10	.0787	2.00
No. 40	.0165	0.42
No. 80	.0070	0.177
No. 200	.0029	0.074

APPENDIX F

MATHEMATICAL RELATIONSHIPS USED IN CALCULATIONS

MATHEMATICAL RELATIONSHIPS USED IN CALCULATIONS

Starting with a few basic data, several parameters were calculated for each sample. The following is a list of the mathematical relationships used for these calculations preceeded by an explanation of the symbols used therein.

SYMBOLS

P_1, P_2, P_3 - per cent of the asphalt, sand, and gravel, respectively, in the mix

G_1, G_2, G_3 - specific gravity of the asphalt, sand, and gravel, respectively, in the mix

W_a - sample weight in air in grams

W_w - sample weight in water in grams

V_b - total volume of the sample in cubic centimeters

V_{ag} - volume of the total aggregate in cubic centimeters

P_{ag} - per cent aggregate in the mix

G_{ag} - specific gravity of the aggregate in the mix

St(77) - stability or strength at 77°F in pounds or pounds per square inch

St(100) - stability or strength at 100°F in pounds or pounds per square inch

D_{10} - maximum diameter of the smallest 10 per cent of the aggregate

D_{60} - maximum diameter of the smallest 60 per cent of the aggregate

Mathematical Relationships

1. Bulk Specific Gravity[1] - D_b

$$D_b = \frac{W_a}{W_a - W_w}$$

$$D_b = \frac{W_a}{V_b}$$

2. Theoretical maximum specific gravity[2] - D_m

$$D_m = \frac{100}{\frac{P_1}{G_1} \quad \frac{P_2}{G_2} \quad \frac{P_3}{G_3}}$$

3. Air voids in the compacted mix or total voids[3] - V_v, in %

$$V_v = 100 \times \frac{D_m - D_b}{D_m}$$

4. Specific gravity of the aggregate[4] - G_{ag}

$$G_{ag} = \frac{100}{\frac{P_2}{G_2} \quad \frac{P_3}{G_3}}$$

5. Volume of aggregate as per cent of the total volume. of the sample[5] - % V_{ag}, in %

$$\% V_{ag} = \frac{P_{ag} \times W_a}{G_{ag} \times V_b}$$

$$\% V_{ag} = \frac{P_{ag}}{G_{ag}} \times D_b$$

---

[1]Ref. 10, p. 161. [2]Ref. 10, p. 163. [3]Ref. 10, p. 165

[4]Ref. 10, p. 158. [5]Ref. 10, p. 165. Ref. 10, p.

6. Voids in the mineral aggregate[6] - VMA, in %

$$VMA = 100 - \% V_{ag}$$

7. Voids filled with bitumen[7] - VFB, in %

$$VFB = \frac{VMA - V_v}{VMA}$$

8. Density factor - DF, in cubic feet or cubic feet per square inch

$$DF = \frac{\text{stability or strength}}{\text{density}}$$

9. Difference in stabilities or strengths at 77°F and 100°F - % difference, in %

$$\%\ diff = \frac{St(77) - St(100)}{St(77)}$$

10. Uniformity Coefficient of the aggregate[8] - VC

$$VC = \frac{D_{60}}{D_{10}}$$

11. Effective size of the aggregate[9] - ES, in millimeters

$$ES = D_{10}$$

---

[6]Ref. 10, p. 167. [7]Ref. 10, p. 167

[8]Ref. 41, p. 21. [9]Ref. 41, p. 21

APPENDIX G

COMPUTER PROGRAM

COMPUTER PROGRAM

The computer program, a copy of which appears herein starting on page 139, was written in FORTRAN computer language for use in the Control Data Corporation 3600 computer at Michigan State University. This program was written to expedite the computation of several parameters for each of the many samples tested. All except the last three formulas listed in Appendix F were utilized in this program. In addition, average values of certain quantities calculated for similarly tested samples were calculated.

The program used was identical to that shown starting on page 139 except for the numbers which appear at the left margin opposite each statement of the program. These numbers have been added for clarity and ease of reference. An explanation of the most important symbols used in the program appears on pages 137 and 138.

Statements 1 through 27 of the program serve to get information into the computer, tell it in what manner to print the results, tell it to print certain column headings and the manner in which to print them, and reserve space in the computer's memory for a number of quantities. Statement 28 tells the computer how to calculate the theoretical maximum specific gravity for each group of six samples molded from one batch of material. Statement 29 then tells the computer to execute statements 30 through 55 using the information entered for the six samples in order beginning with the first sample. Statements 30 and 31 merely correct the weights in water of a particular set of six samples whose weights had to be entered into the computer 100 grams too low. This was necessary because of the way the data cards were to be read by the computer. Statements 32 through 35 instruct the computer to calculate, respectively, the total volume of the sample, its bulk specific gravity, its density and the air voids it contains. Statements 36 through 41 tell the computer what value of specific gravity to use for the aggregate. Statements 42 through 45 instruct the computer to calculate, respectively, the volume of aggregate as a percentage of the total volume, the voids in the mineral aggregate, the voids filled with bitumen and the density factor of the sample. Statements 46 through 52 instruct the computer to check the sample volume against a particular volume interval, and tells the computer what to print if the volume of the sample is small, within the interval, or large. Statements 53 and 54 then tell the computer to print whether the sample is small, of correct volume or large, the volume of the sample, its strength or stability, its density factor, its bulk specific gravity, its density, its theoretical maximum specific gravity, its air void, voids in the mineral aggregate and the voids filled with bitumen.

After the above calculations have been made and the results printed for each of the six samples, the computer proceeds to calculate average values of density, voids filled with bitumen, density factor and strength. Separate averages are calculated for samples tested at 77°F and for those tested at 100°F. These operations are performed by the computer as specified by statements 56 through 73. Statements 76 and 77 then tell the computer to print the temperature of the test and average values of the sample strength or stability, density factor, density, and voids filled. Statement 76 also tells the computer to print the per cent asphalt, per cent sand and the specific gravity of the asphalt for each group of six samples.

After the computer has printed these average values, it returns to statement 25 which instructs it to start performing all the calculations mentioned above for the next group of six samples.

This routine of calculations and printing of results was executed for each of the 81 groups of six samples. When a group contained less than six samples, the proper data was entered into the computer for each of the existing samples, and for those samples which did not exist in the group of six, the data was entered as zero. For example, if only four samples were molded and tested from a particular batch, the proper data was entered for the four samples. For the other two non-existing samples necessary to make a total of six samples, the data was entered as zero.

When the computer reaches statement 78 after performing the calculations for the eighty-first group of six samples, it continues on to statements 79 through 81 which cause it to stop.

In order to get the basic data into the computer, it was necessary to use two groups of data cards. In the first group each card contained the following data for one sample: an identification number, the sample weight in air in grams, the sample weight in water in grams, and the strength or stability in pounds per square inch or pounds, respectively. A typical data card of this group might appear as follows: 374164168185011783. The first three digits are the identification number. In this case the sample is the third one in the seventy-fourth group of six samples. The next five digits represent the weight of the sample in air--1641.6 grams. The following four digits represent the weight of the sample in water--818.5 grams. The last six digits represent the stability or, in this case, the strength of the sample--0117.83 pounds per square inch.

In the second group of data cards, each card contained the following data for a group of six samples: an identification number, the asphalt content of the group in per cent, the per cent sand, the per cent gravel and the specific gravities of the asphalt, sand and gravel, respectively. A typical data card of this group might appear as follows: 7435048254825102826427O. The first two digits represent the identification number. In this case the data contained on the card is for the seventy-fourth group of six samples. The next three digits represent the asphalt content--3.50 per cent. The next eight digits represent the per cent sand and per cent gravel, respectively--48.25 and 48.25 per cent. Had the samples consisted of sand and no gravel, the per cent gravel would have been entered as 0000. The last ten digits represent the specific gravities of the asphalt, sand and gravel, respectively--1.028, 2.64 and 2.70. Again, if there had been no gravel in the mixture, the specific gravity of the gravel could have been omitted since the computer would read those three empty spaces as zero.

Because of the way the computer is instructed to read the data cards, it is necessary that the data be put on the card, starting in the first column, exactly as shown in the above examples when this computer program is going to be used. The decimal points are omitted because the statements which tell the computer how to read the data cards also tell it where the decimal points are to be located.

Once a computer program, such as the one presented here, has been written, a great many man hours of work can be saved by its use. This fact becomes evident when one realizes that the work performed by the computer for the author would have required approximately 5 man hours of work. The computer performed the work in 34 seconds.

EXPLANATION OF SYMBOLS USED

WA - sample weight in air, grams

WW - sample weight in water, grams

STR - sample strength or stability, pounds per square inch or pounds, respectively

DM - theoretical maximum specific gravity

PA - asphalt content, per cent

PS - sand content, per cent

PG - gravel content, per cent

SGA - specific gravity of the asphalt

SGS - specific gravity of the sand

SGG - specific gravity of the gravel

VA - volume of the sample, cubic centimeters

DB - bulk specific gravity

DEN - density, pounds per cubic foot

VV - air voids, per cent

GAV - specific gravity of the aggregate

VAG - volume of the aggregate as a per cent of the total volume, per cent

VMA - voids in the mineral aggregate, per cent

VFILL - voids filled with bitumen, per cent

DENFAC - density factor, cubic feet or cubic feet, per square inch

AVDS - average density of samples tested at 77°F, pounds per cubic foot

AVDH - average density of samples tested at 100°F, pounds per cubic foot

AVVS - average voids filled with bitumen of samples, tested at 77°F, per cent

AVVH - average voids filled with bitumen of samples, tested at 100°F, per cent

AVDFS - average density factor of samples tested at 77°F, cubic feet or cubic feet per square inch

AVDFH - average density factor of samples tested at 100°F, cubic feet or cubic feet per square inch

STRENS - average strength or stability at 77°F, pounds per square inch or pounds, respectively

STRENH - average strength or stability at 100°F, pounds per square inch or pounds, respectively

COMPUTER PROGRAM

```
1.   * 051330 Riley, J C          2MIN,1,C.O.P.
2.          PROGRAM ASPHALT
3.        2 FORMAT (1HO, 37HC C RILEY   ASPHALT BASE
            COMPUTATIONS)
4.        3 FORMAT (3A1)
5.        4 FORMAT (3X, F5.1, F4.1, F6.2)
6.        5 FORMAT (1HO, 5X, 89HTEMP        AVSTREN
7.       2 2AVDENFAC       AVDEN      AVVFILL        PA
          2PS        SGA)
8.        6 FORMAT (2X, 109HTEST       VOLUM       STREN
9.          3DENFAC       SPGR       DENSITY     TMSG
          3AIRV       VMA       VFILL)
10.       7 FORMAT (//3X, 12)
11.       8 FORMAT (2X, F3.2, F4.2, F4.2, F4.3, F3.2, F3.2)
12.       9 FORMAT (11X, A1, F6.1, 6X, F8.2, 7X, F8.4, 4X,
13.         4F6.3, 7X, F6.1, 5X, F6.3, 4X, F6.2, 4X, F6.2,
          44X, F6.2)
14.      10 FORMAT (6X, F4.0, 7X, F8.2, 6X, F8.4, 7X, F6.1,
15.         75X, F6.2, 7X, F5.2, 5X, F6.2, 4X, F6.3)
16.         PRINT 2
17.         PRINT 5
```

```
      PRINT 6
      DIMENSION WA(6,81), WW(6,81), STR(6,81), DM
     5(81), VA(6,81), DB(6,81), DEN(6,81), VV(6,81),
     5VFILL(6,81), DENFAC(6,81)
      READ 3, A, B, C
      DO 11  J = 1,81
      DO 11  1 = 1,6
   11 READ 4, WA(I,J), WW(I,J), STR(I,J)
      DO 26  K = 1,81
      PRINT 7, K
      READ 8, PA, PS, PG, SGA, SGS, SGG
      DM(K) = 100. / (PA/SGA + PS/SGS + PG/SGG)
      DO 17  L = 1,6
      IF (K - 48)  28, 27, 28
   27 WW(L,48) = 100. + WW(L,48)
   28 VA(L,K) = WA(L,K) - WW(L,K)
      DB(L,K) = WA(L,K) / VA(L,K)
      DEN(L,K) = DB(L,K) * 62.3
      VV(L,K) = 100. * ((DM(K) - DB(L,K)) / DM(K))
      IF (PS - PG)  29, 30, 31
   29 GAV = 2.70
```

```
      GO TO 32
   30 GAV = 2.67
      GO TO 32
   31 GAV = 2.64
   32 VAG = ((PS + PG) / GAV) * DB(L,K)
      VMA = 100. - VAG
      VFILL(L,K) = 100. * ((VMA -VV(L,K)) / VMA)
      DENFAC(L,K) = STR(L,K) / DEN(L,K)
      IF (VA(L,K) - 843.87) 12, 15, 13
   12 IF (VA(L,K) - 802.70) 14, 15, 15
   13 Z = A
      GO TO 16
   14 Z = B
      GO TO 16
   15 Z = C
   16 PRINT 9, Z, VA(L,K), STR(L,K), DENFAC(L,K),
     6DB(L,K), DEN(L,K), DM(K), VV(L,K), VMA,
     6FVILL(L,K)
   17 CONTINUE
      X = 1.
      Y = 1.
      IF (WA(6,K)) 18, 18, 21
```

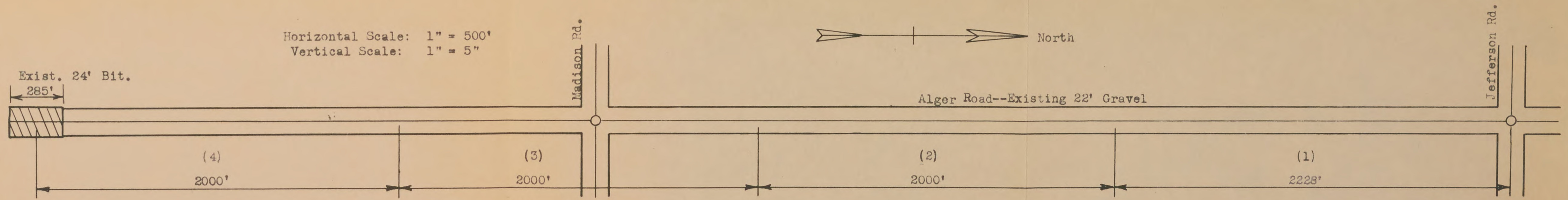
```
18 IF (WA(5,K)) 19, 19, 22
19 IF (WA(4,K)) 20, 20, 23
20 IF (WA(3,K)) 25, 25, 24
21 X = X + 1.
22 Y = Y + 1.
23 X = X + 1.
24 Y = Y + 1.
25 AVDS = (DEN(1,K) + DEN(3,K) + DEN(5,K)) / Y
   AVDH = (DEN(2,K) + DEN(4,K) + DEN(6,K)) / X
   AVVS = (VFILL(1,K) + VFILL(3,K) + VFILL(5,K))
   / Y
   AVVH = (VFILL(2,K) + VFILL(4,K) + VFILL(6,K))
   / X
   AVDFS = (DENFAC(1,K) + DENFAC(3,K) + DENFAC(5,
   K)) / Y
   AVDFH = (DENFAC(2,K) + DENFAC(4,K) + DENFAC(6,
   K)) / X
   STRENS = (STR(1,K) + STR(3,K) + STR(5,K)) / Y
   STRENH = (STR(2,K) + STR(4,K) + STR(6,K)) / X
   D = 77.
   E = 100.
```

```
76.         PRINT 10, D, STRENS, AVDFS, AVDS, AVVS, PA,
            PS, SGA
77.         PRINT 10, E, STRENH, AVDFH, AVDH, AVVH
78.         CONTINUE
79.         STOP
80.         END
81.         END
```

APPENDIX H

SAND-GRAVEL ASPHALT BASE EXPERIMENTAL PROJECT, ALGER ROAD, GRATIOT COUNTY, MICHIGAN

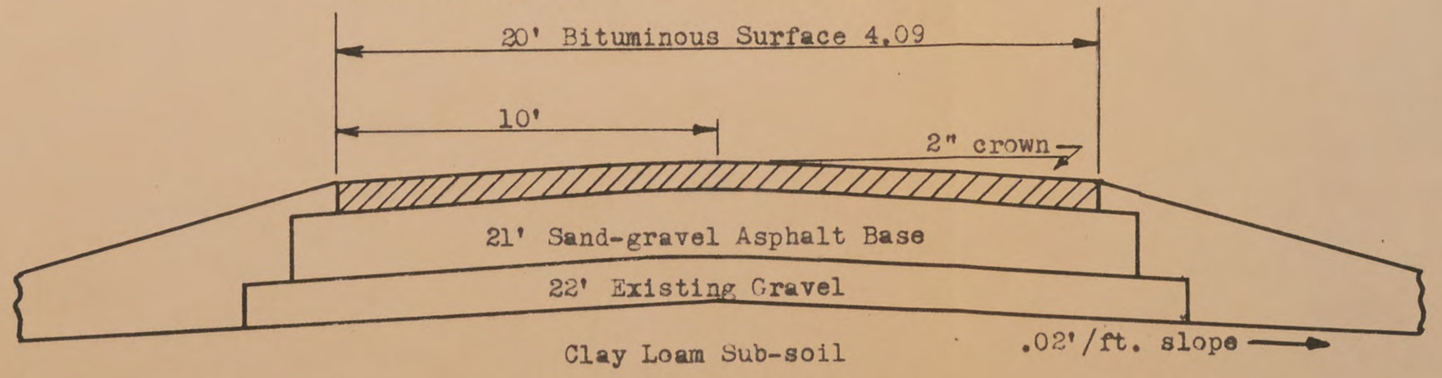
SAND-GRAVEL ASPHALT BASE
EXPERIMENTAL PROJECT
ALGER ROAD
GRATIOT COUNTY, MICHIGAN



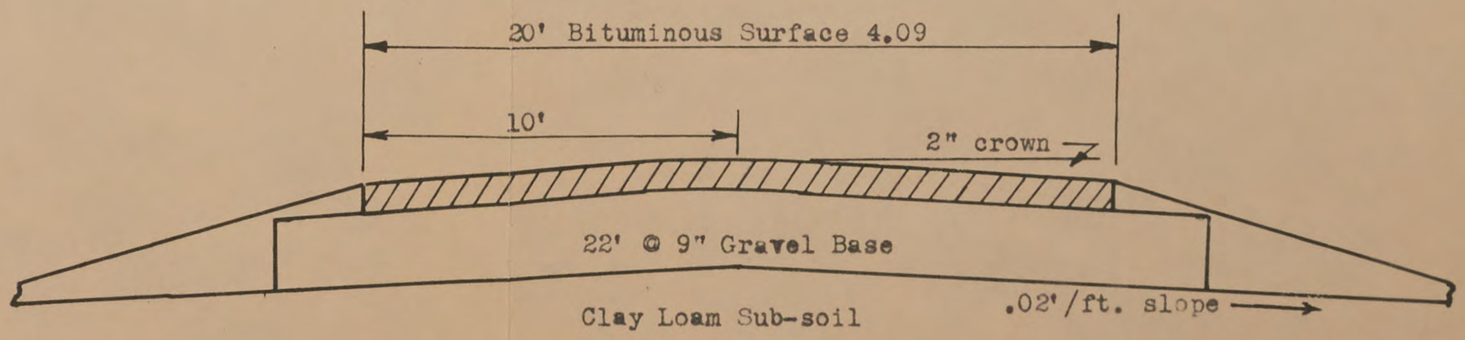
(4)	(3)	(2)	(1)
6.0± Asp. 'E' 1.5" Bituminous Surface 4.09	6.0± Asp. 'E' Bit. Surface Course 4.09	6.0± 'E' 2" Bit. Surface Course 4.09	6.0± Asp. 'A' 2" Bit. Surface Course 4.09
4.0% Asp. 5" Sand-gravel Asphalt Mix 'D' 2 courses	4.0% Asp. 3" Sand-gravel Asphalt Mix 'D' 1 course 3.0% Asp. 3" Sand Asphalt Mix 'C'	3.5% Asp. 5.5" Sand Asphalt Mix 'B' 2 courses	6" Gravel Base 4.01
3" Existing Gravel	3" Existing Gravel	3" Existing Gravel	3" Existing Gravel

Order of Construction - 'A' through 'E'

Natural Sandy Loam Sub-soil



Typical Cross Section
(not to scale)
For Sections (2), (3), and (4)



Typical Cross Section
(not to scale)
For Section (1)