Standardization of Asphalt Viscosity and Mix Design Procedures

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ABSTRACT

STANDARDIZATION OF ASPHALT VISCOSITY AND MIX DESIGN PROCEDURES

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The main purpose of this work was: (a) to develop practical procedures for grading asphalt cements by viscosity, and (b) to devise a computerized procedure for bituminous concrete mix design. Both goals were achieved.

Part A of the report describes a method of grading asphalts used in Michigan by viscosity at 25 C. All together four viscosity grades are proposed: 150-250, 400-650, 900-1400 and 1800-2500 kilopoises, replacing the present 200-250, 120-150, 85-100 and 60-70 penetration grades, respectively.

Detailed graphical viscosity charts have been prepared for six sources (producers) of asphalts which permit producers to select their asphalts for sale (to the consumer) on the basis of viscosity at 60 C and 135 C. These charts are ready to be used for practical application.

At the end of Part A a brief description of a test using a constant penetration rate is given. More work is needed to see whether such a test could be used as a simplified method to measure viscosity at 25 C. The present predicted

number of 18 viscosity tests per day using the cone-plate viscometer is fair and can be used until a faster test procedure is developed.

Part B of the report describes the development of a computerized procedure for designing bituminous concrete mixes. The Marshall method, modified to suit Michigan conditions, is used as the basis for the design program. The method includes both numerical and graphical analyses. This method has immediate practical application and is already being used by the Michigan Department of State Highways and Transportation. The code for the design is MICHMIX. A similar design package using the Marshall method as described by The Asphalt Institute is also included in the report (AIMIX).

The second section of Part B presented in this report involves further measurements and calculations towards improvements over the Marshall design, which requires 15 or more laboratory made specimens for testing to obtain the answers. Again, more work is needed in this area to make further improvements. In the meanwhile, the computerized Marshall method should be useful for practical design purposes.

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DISCLAIMER

STANDARDIZATION OF ASPHALT VISCOSITY AND MIX DESIGN PROCEDURES

PART A - VISCOSITY

1. Grading of Asphalts Used in Michigan by Viscosity at 25 C.

The penetration test has served as a useful tool for grading of asphalts at 25 C for a long time. At present, the trend is toward use of the fundamental property of viscosity as a yardstick for classifying the various types of asphalts. In this change from penetration grading to viscosity grading of asphalt cements, much discussion has been generated as to what standard temperature would be best. The temperature at 60 C is presently being used by a number of agencies. This has shifted the basic control point of asphalt consistency measurement from 25 C to 60 C, which is well above the average field temperatures in Northern climates. Therefore, a research program was undertaken to attempt to develop procedures for measuring viscosity at temperatures of 25 C and lower (1,2). This work has indicated that a cone-plate viscometer and shear rate of 2×10^{-2} sec^{-1} at 25 C can be used for asphalts supplied to Michigan.

It is recognized that measuring viscosity at 25 C is more difficult and may be less accurate than at 60 C. Also, it takes longer to run a viscosity test at 25 C than at 60 C.

This part of the present report describes the further work in an effort to develop methods to grade asphalt cements on the basis of viscosity measured at 25 C. A test procedure for the routine testing of asphalt cements at 25 C is presented. Further, viscosity measurements at 25 C are correlated with viscosities measured at 60 C and 135 C. From these correlations, proposed viscosity grading limits for six asphalt sources in Michigan have been determined. Using these limits, a series of twenty-four graphs were constructed for the six sources and four asphalt grades. The viscosity limits were set for both original and aged asphalts.

1.1 Cone-plate viscosity measurement and time.

The method of testing for viscosity of asphalt cements by the cone-plate viscometer can be found in Appendix G of Reference 1. This method of testing was followed except for two "improvements":

(a) Three weights were used during the test. The first weight was applied only to find the proper range of weights to use. In order to calculate viscosity at a shear rate of $2x10^{-2}$ sec^{-1}, one shear rate had to be below and another above a certain time (101 to 103.5 seconds, depending upon the shear rate constant K_D). The second and third weights were chosen to accommodate this constraint. From the viscosity and shear values associated with the two weights, the viscosity at $2x10^{-2}$ sec^{-1} was interpolated. See Table 1 for a typical run.

(b) It was also found that asphalts with small samples to draw from were prone to higher viscosities than their penetration would indicate. Apparently, the asphalt "dries out" if there is only a little of it in the bottom of a sample can. To prevent this from happening, the sample should be no less than a full 6 oz. sample can. This is quite important.

As mentioned before, the shear rate of 2×10^{-2} $\sec^{-1}$ appears to be "optimum" for Michigan asphalts. If the test is performed at a higher shear rate, there is a risk (with some asphalts) of running into so-called non-Newtonian region where shear stress is no longer proportional to shear rate. On the other hand, if the shear rate is too slow, it takes a long time to obtain a viscosity measurement for a given asphalt.

At present, about 50 penetration tests can be made per day (8 hours) by two operators. A brief study on the number of viscosity tests possible per 8-hour day (two operators) indicates that 18 readings are possible. To achieve this, four cone-plate assemblies and two constant temperature baths are needed. The scheduling for such an operation is given in Figure 1. Although slightly less than half as many samples can be tested by using the cone-plate viscometer as compared to regular penetration, this viscosity test procedure appears to have definite practical promise. Also, the training time for a technician to run the test is minimal.

1.2 Asphalts used in this investigation.

The asphalts used in this investigation were all obtained from the MDSHT Bituminous Testing Laboratory. These asphalt samples were collected in 1973, 1974 and 1975 for research and testing purposes. Data from 73 different asphalts ranging from high to low penetrations were available for use in this study and are shown in Table 2. The 1973 and 1974 data have been reported previously in References 1 and 2. The viscosities at 135 C have been corrected for the change in specific gravity of the asphalt with change in temperature. The specific gravity was used in the conversion from stokes to poises. This minimal correction was neglected previously. Also shown are additional viscosity measurements at 107 C (225 F) and 121 C (250 F). The 1975 data has not been previously reported.

The asphalts presented in Table 2 are labeled as "original" asphalts to distinguish them from the "aged" asphalts in Table 3. For the 1975 samples, twenty-eight asphalts were aged by subjecting them to the thin-film oven test (ASTM D1754). The standard penetration and viscosity at various temperatures were then determined for these samples.

After consultation with MDSHT personnel, six sources were selected for detailed study in this investigation. These sources, A-'75, E-'74, G-'74, I-'74, J-'75 and N-'75, furnish the bulk of the asphalt used in Michigan. Also, they are the ones for which the most complete data is available. The test results for these asphalts have been abstracted from Tables 2 and 3 are are presented in Table 4 for ready reference.

1.3 Viscosity - temperature curves for the six sources.

The viscosity data for the six sources is first presented in a series of viscosity vs. temperature curves, Figures 2 through 7. These curves are drawn on the ASTM Standard Viscosity-Temperature Chart for Asphalts (D 2493). The solid curves show the relationship for the original asphalts and the dashed curves for the aged asphalts. Each curve represents a different asphalt grade.

The aged data shown for asphalts A-'75, J-'75 and N-'75 are the results from the laboratory tests. There were no aged data for E-'74, G-'74 and I-'74. The aged curves for these three asphalts were constructed by a method to be discussed later in this section.

Examination of these six figures show that for a given asphalt grade, viscosity decreases as the temperature increases. Also, for a given temperature, the viscosity decreases as the standard penetration increases. Further, for a given asphalt, the curves for the different grades are nearly parallel. These relationships are valid for both the original and aged data. In addition, the aged asphalt curves, for the three sources where results were available, are close to being parallel to the original asphalt curves. Apparently, the effect of aging is to translate the original curves upwards, or in other words, aging increases the viscosity for a given asphalt.

The apparent parallelism of the viscosity vs. temperature curves was used to construct aged curves for the three 1974 sources by the following method. The respective differences between the log log of aged viscosity data (expressed in centipoises) and the log log of the original viscosity data (centipoises) was determined for all samples in which aged data was available. The results are shown in Table 5. For a given temperature, this difference is fairly consistent and an average value was computed. At 25 C, the differences ranged from 0.017 to 0.038 with 20 of the 25 samples falling between 0.027 and 0.038. Comparable figures at 60 C are 0.018 to 0.039 with 17 of 22 ranging from 0.028 to 0.039; and at 135 C, 0.016 to 0.031 with 18 of 20 falling between 0.020 and 0.031. The aged curves for the three 1974 sources were drawn by adding the average difference at each temperature to the original viscosities at that temperature for each penetration grade.

1.4 Development of viscosity grading charts.

There were two main objectives in this viscosity grading investigation. One was to develop viscosity grading charts for the various types of asphalts that could be used by manufacturers to determine if their asphalts could meet the viscosity grading requirements at 25 C. The second was to establish the viscosity grading limits.

The first objective is dealt with at this point in the report. As mentioned in the introductory remarks, it takes longer to run viscosity tests at 25 C than at higher temperatures. In addition, there is no generally accepted test procedure at 25 C at this time while there are standard test procedures for determining viscosity at 60 C and 140 C (ASTM D 2170 and D 2171). Suppliers are accustomed to using these standard procedures. For these reasons it was felt that the viscosity grading charts should be developed so viscosity measurements at any of the three temperatures could be employed.

Twenty-four viscosity grading charts, Figures 16 through 39, were developed, one for each of four viscosity grades for the six sources. The viscosity, temperature and penetration data were used to establish the necessary relationships for the construction of the charts. The relationships were determined by regression analysis techniques using the method of least squares. The best fit curve was a power function of the form $y = cx^a$.

Using the original data for each source and grade, the viscosity at 60 C, the viscosity at 25 C and the standard penetration at 25 C were respectively regressed on the viscosity at 135 C. For the three 1975 sources, for which aged data was available, relationships were obtained between the viscosity at 60 C, the viscosity at 25 C, and the viscosity at 135 C separately. As for the three 1974 sources where aged data was unavailable, the estimated viscosity vs. temperature results were employed to obtain the viscosity relationships.

The results of these regression analyses are given in Tables 6 through 11. Presented are the measured or estimated values of the viscosities and penetrations, the calculated values and the percent differences between the measured or estimated values and the calculated values. Below each table are shown the regression equations relating the viscosities at 25 C and 60 C to the viscosity at 135 C, and, for the original asphalts, the standard penetration to the viscosity at 135 C.

The error ranged from 0 percent to a maximum of 21.0 percent. Of the 110 calculated values, 69.1 percent fall between 0 to 4.9 percent; 22.7 percent between 5.0 to 9.9 percent; 5.5 percent between 10.0 to 14.9 percent; 1.8 percent between 15.0 to 19.9 percent; and 0.9 percent between 20.0 to 24.9 percent.

Typical plots of the results are presented in Figures 8 through 13. The first three are for the A-'75 asphalt where the fit was good. The second three are for I-'74 asphalt where the fit was not as good. The best fit for the six sources was the N-'75 asphalt.

A different procedure was used to determine the relationships between viscosity and penetration for the aged asphalts. In Figure 14, the logarithm of the viscosity in poises at 25 C for all the aged data is plotted against the logarithm of the penetration at 25 C. It is apparent from the graph that one curve will not give a good fit to all the points. Therefore, two curves are used: one for penetration values above 70, and another for the penetration values below 70. A regression analysis was made on the data below 70 penetration since this relationship was needed in constructing the scales. The resulting curve is shown as a solid line. Pendleton, in his equation relating viscosity to penetration, found also that two equations were necessary (Reference 1, page 4). It is felt that this discontinuity is associated with the shape of the penetration needle which changes from a truncated right circular cone to a right circular cylinder.

With the above relationships available, the viscosity grading charts were then developed. Each chart is divided into two parts. The lower part presents the relationships between the viscosities at the three temperatures for the original asphalts; the upper part is for the aged asphalts. The horizontal spacing of the three vertical lines is in proportion to the temperatures. The vertical scales were constructed as follows: on the right hand vertical line, an arithmetic scale was established covering the desired range of viscosities at 135 C. The scales for the middle line, viscosity at 60 C, and the left line, viscosity at 25 C, were then determined from the approximate regression equation relating viscosity at 60 C or 25 C to the viscosity at 135 C. Penetration scales at 25 C were also obtained using the relationships discussed above.

1.5 Establishing the tentative viscosity grading limits.

As stated earlier, the second objective of the viscosity grading investigation was to establish tentative grading limits using viscosity at 25 C for the four asphalt grades in common use in Michigan. There were two main considerations that entered into the setting of these limits. First, the viscosity values selected had to be such that they could be easily remembered. The second consideration was that differences between the limits for the four grades and differences in the limits between grades should vary in a logical manner.

To aid in determining the limits, Figure 15, in which the logarithm of the viscosity at 25 C in poises for all the original data vs. the logarithm of the penetration at 25 C, was plotted. Examination of the graph indicates that the points fall into four groups which correspond to the old penetration grading system. The tentative viscosity grading limits were established by bounding each group of points with horizontal lines. The limits proposed are 1800-2500 kilopoises, 900-1400 kilopoises, 400-650 kilopoises and 150-250 kilopoises for the four grades of asphalt used in Michigan. They meet the first consideration.

Table 12 presents two comparisons between the penetration system of grading and the proposed viscosity at 25 C system. In the top part of the table, the difference between the upper and lower limits for the four penetration grades and the four viscosity grades have been computed. A ratio was found by dividing each difference by the difference for the 85-100 penetration grade or the 900-1400 viscosity grade. The inverse of the viscosity ratio was computed since the viscosity varies as the inverse of the penetration. In the bottom part of the table, the same procedure was followed by finding differences between the adjacent limits for the four grades. Examination of the ratios for the penetration system and the inverse ratios for the viscosity system show that viscosity ratios vary in much the same manner as the conventional penetration system.

With establishment of viscosity grading limits, the remaining problem was to determine viscosity limits for the price adjustment called for in the 1973 MDSHT Standard Specification for Highway Construction 4.12.28. This specification calls for a decreased payment where the penetration of recovered asphalt from pavement cores falls within the range indicated in Table 4.12-2. For reference, this table is reproduced as Table 13 in this report. The lower penetration value of the grade was used for determining the aging limits. The percent penetration of the recovered asphalt has been added to the table and follows the recovered penetrations in parentheses.

The procedure used to determine the viscosity limits for reduced payment is best explained by means of an example. Reference is made to Figure 16, the viscosity grading chart for the 1800-2500 kilopoises grade of the A-'75 asphalt. The penetration range for this grade was 59 to 70 as found from the lower part of the chart. The lower limit, 59, was multiplied by the percentages given in Table 13 to obtain the recovered penetration requirements. These penetration values were then converted to viscosity values by means of the regression equation for aged data that relates the viscosity at 25 C to the penetration at 25 C.

The results of these computations for the four grades and six sources are presented in Tables 14 through 17. Examination of the tables show that at a given reduced payment limit, the viscosities are about the same. For example, for

1800-2500 kilopoises asphalt, the viscosities for the six sources range from 1.55×10^7 to 2.13×10^7 poises for the limit at which 10 percent decrease in payment starts. These six values were averaged together to arrive at the limit, 1.8×10^7 poises, shown on the charts. The same method was used to obtain the other limits.

1.6 Use of the charts.

As stated earlier, suppliers may run the viscosity tests at 60 C and 135 C using the standard ASTM procedures. To show how the viscosity grading charts (Figures 16 through 39) would be used, the viscosities from Table 5 for the six sources and four grades have been plotted on the appropriate grading charts. A straight line has been drawn through the 135 C and 60 C viscosity points and extended to the 25 C viscosity line. In most cases, this line is reasonably horizontal and intersects the 25 C viscosity line at or near the measured viscosity at 25 C.

There are three cases where the intersection value is significantly different from the measured viscosity at 25 C. These cases are shown in Figures 21, 27 and 32. In each case the straight line has a definite slope.

In practice, the supplier would determine the viscosity at 60 C and 135 C of the asphalt he intends to furnish to meet, say, the 900-1400 kilopoises grade asphalt. He would plot these points on his chart for that grade. If the points fall within the horizontal lines, and the straight line through the points intersects the 25 C viscosity line within the limits, and is reasonably horizontal, the supplier would be fairly sure that his asphalt would be accepted. The MDSHT would determine the viscosity at 25 C to see if it meets the viscosity grading specification. If the slope of the line departed significantly from the horizontal, the supplier would be alerted to the possibility that the asphalt might not meet specifications.

The same procedure could be used to see if an asphalt meets the aging requirements. Viscosities at 60 C and 135 C conducted on samples subjected to the thin-film oven test would be plotted on the chart. The straight line would be drawn and the intersections determined. If the line falls below the reduced payment limit, the supplier could be reasonably sure that his asphalt would meet the laboratory acceptance tests conducted at 25 C.

1.7 Continued improvement.

As mentioned before, Figures 16 through 39 can be used by the asphalt supplier and the user (MDSHT) to control the acceptance of asphalt on the basis of viscosity at 25 C. These charts should be tried under actual practical conditions as soon as possible. It can be expected that changes and adjustments will be necessary with passage of time and new sources of asphalt. However, a method has been established which permits a systematic approach for such adjustments. Since the described approach is based on viscosity grading using three different temperatures, a definite improvement in asphalt consistency control has been achieved.

2. Further Trials to Simplify the Measurement of Viscosity at 25 C.

During the studies in 1973-74 (1) viscosities for 43 asphalts of various hardness were measured at 25 C, 60 C and 135 C. Parallel to this three types of penetrations were run at 25 C. The results indicated that the best correlation between penetration and viscosity at 25 C was obtained when the standard penetration needle was first submerged 70 dmm so that the truncated cone end of the needle was covered by asphalt. The test was then run just like in the standard penetration procedure (ASTM D 5). Using a log viscosity versus log penetration (submerged), a straight line regression curve was obtained with correlation coefficient of 0.991595 and 95.6% of the tested values within 0-20% from the mean. It was felt that further improvements in the correlation between viscosity and some simplified penetration test could be realized if certain parameters in the "penetration" test could be better controlled. One of these parameters is the shear rate. It is a well-known fact that a 200 penetration asphalt permits the needle, on the average, to go down twice as fast as a 100 penetration asphalt (5 sec, 100 g, 25 C). Thus, the relative shear rates developed in each asphalt will be different and may affect the results. This led to the idea of trying a penetration test where the rate of penetration is constant and the load is allowed to vary. This work will be described below.

2.1 Test apparatus and test procedure.

The basic test apparatus for the constant rate penetration test consists of:

(a) Instron testing machine capable of constant rate downward movement, a 2000-gram load cell, and a strip chart recorder accurate to 1-gram reading.

(b) Specially made holding device for the needle weighing approximately 200 grams.

(c) Large constant temperature bath capable of keeping the temperature at 25 ± 0.1 C.

(d) Insulated transfer dish for holding the asphalt specimens during the test.

The specimens are prepared similar to the procedure in a regular penetration test (ASTM D 5). They are then placed in an insulated transfer dish and set in the Instron testing machine. The downward movement of the penetration needle is activated simultaneously with a strip chart recorder. There is no need for the operator to set the needle on top of the asphalt sample as in a regular test. As soon as the needle touches the asphalt in the container (at 25 C) the strip chart recorder pen starts to move indicating a contact and subsequent penetration. The needle moves down into the asphalt at 1 inch per minute for 30 seconds. So, the total depth of penetration and penetration rate for all asphalts is kept identical.

The weight of the holding device and the needle keeps the load cell in tension. The recorded value on the strip chart is in actuality a reduction of the tension on the load cell. The area under the strip chart curve for a fixed penetration value is measured and compared with viscosity. Just as in the standard penetration test, the final value is taken as an average of three readings.

2.2 Asphalts used and results.

All together 28 different asphalts, with a range of viscosity values between 1.42×10^5 to 3.97×10^6 (at 25 C), were used in the constant penetration rate study. These asphalts with their viscosities and constant penetration data are tabulated in Table 18. Three penetration values were obtained for each asphalt. The constant penetration values are in ergs (work units) and they were obtained by measuring the area under the curve from the strip chart as shown in Figure 40 (grams x cm of penetration) and multiplying this product by 980.1 (gravitational constant). These units were adopted primarily for convenience and any other system can be used.

Table 18 also gives standard deviation (ergs) and the coefficient of deviation D (in percent). All but two asphalts have a coefficient of deviation less than 10%. It is thought that with improved techniques and equipment the reproducibility of the results could be further improved and made at least similar to that of a regular penetration test.

Data on regression analysis is shown in Table 19 and Figure 41. The correlation coefficient is 0.993, and 96.4% of the tested values are within 0-20% from the mean. Thus numerically the correlation between viscosity and this constant rate penetration test is better than for previously mentioned submerged penetration. However, there are some points in Figure 41 which appear to be distant from the regression line. One of them is in the upper right hand corner (starred). The repeatability of the starred penetration measurement was good with D = 2.58%. This is not an isolated case, when Tables 18 and 19 are compared. What this may indicate is that the shear rate, shear stress or some other factors are still influencing the correlation between viscosity and this new constant rate penetration test. The test itself is as fast as the regular penetration test. More work is needed in this area.

PART B - MIX DESIGN

1. Computerized Marshall Mix Design.

1.1 Basis for design.

The Marshall method of mix design is one of the most widely used methods of designing asphalt concrete paving mixtures. Generally speaking, there are three parts to the Marshall method:

(a) Preparation of test specimens.

(b) Testing.

(c) Analysis - interpretation of test data.

Computerization of the Marshall method described here deals mainly with the analysis of the test data. Two program packages have been developed:

(a) AIMIX - that which handles the Marshall method as found in the third edition of The Asphalt Institute's Manual Mix Design Method of Asphalt Concrete (MS-2), October, 1969 (3).

(b) MICHMIX - a modified Marshall method used by the Michigan Department of State Highways and Transportation.

AIMIX is a program written in FORTRAN IV and all calculated data is presented in tabular form. MICHMIX is also written in FORTRAN IV with *PLOTSYS (a University of Michigan graphical package) and calculated data is presented in tabular form with accompanying graphs.

Due to the length, a listing of the FORTRAN IV commands for AIMIX and the FORTRAN IV and *PLOTSYS commands for MICHMIX has been omitted.**

The basic mix design procedure for AIMIX can be found in publication MS-2 of The Asphalt Institute (3). MICHMIX differs from The Asphalt Institute's procedure in the calculations of air voids and V.M.A. An additional factor V.F.A. (voids filled with asphalt) is also included. For the procedure used see Reference 4 and Table 23.

In both programs certain data must be entered and there are some constraints on how it must be done. In AIMIX the following data must be entered:

(a) [ITC] = traffic category (light=1, medium=2, heavy=3)
(b) [LEV] = level of mix (surface and leveling=0, base=1)
(c) [PS] = nominal maximum particle size in millimeters
(d) [SGAS] = specific gravity of asphalt

[**] The programs are available by writing to Professor Egons Tons, The University of Michigan, Department of Civil Engineering, 1227 East Engineering Building, Ann Arbor, Michigan 48104, or Mr. Paul J. Serafin, Supervising Engineer, Bituminous Technical Services Unit, Michigan Department of State Highways and Transportation, P. O. Box 619, Ann Arbor, Michigan 48107.

(e) [SGAGG(1)]= specific gravity of aggregate (coarse, fine, and mineral filler)

(f) [A(1)] = asphalt absorption (for three fractions of aggregate), in percent

(g) [P(1)] = percentage of total aggregate (three fractions)

(h) [X(1)] = list of asphalt content used, in percent

(i) [WAIR(1)] = weight of each specimen in air

(j) [WWAT(1)] = weight of each specimen in water

(k) [STAB(1)] = stability for each specimen

(l) [FLOW(1)] = flow for each specimen

(m) [N] = number of specimens (total)

(n) [NT] = number of specimens for each asphalt content.

In MICHMIX the following data must be entered:

(a) [ITC] = traffic category (light=1, medium=2, heavy=3)

(b) [LEV] = level of mix (surface and leveling=0, base=1)

(c) [PS] = nominal maximum particle size in millimeters

(d) [SGAS] = specific gravity of asphalt

(e) [N] = number of specimens (total)

(f) [NT] = number of specimens for each asphalt content

(g) [SGS(1)] = specific gravity of liquid(s) used in G_{mm} (maximum theoretical specific gravity) determination

(h) [X(1)] = list of asphalt contents used, in percent

(i) [WAIR(1)] = weight of each specimen in air

(j) [WWAT(1)] = weight of each specimen in water

(k) [STAB(1)] = stability (dial reading) for each specimen

(l) [FLOW(1)] = flow for each specimen

(m) [WF(1)] = weight of flask (for G_{mm} determination)

(n) [WS(1)] = weight of liquid used in G_{mm} determination

(o) [WFM(1)] = weight of flask and mix

(p) [WFMS(1)] = weight of flask, mix, and liquid.

The constraints for both programs are as follows:

(a) A minimum of five, and a maximum of seven, different asphalt contents must be used.

(b) Asphalt content increments must be at equal intervals.

(c) An equal number of specimens must be used for each asphalt content. The minimum number of specimens is 1, and maximum is 6, for AIMIX; and 2 and 7, respectively, for MICHMIX.

(d) For MICHMIX there must always be two weights for each asphalt content for weight of flask [WF(1)];

weight of liquid [WS(1)]; weight of flask and mix [WFM(1)]; and weight of flask, mix, and liquid [WFMS(1)]. (See Table 24.)

(e) For MICHMIX there must be two specific gravities of liquid entered [SGS(1)]. If the same liquid is used for both flasks, the specific gravity of the one liquid used must be entered twice.

1.2 Data analysis.

Data for both programs is entered using a NAMELIST declaration, which is a format-free input (5). The data does, however, have to be in order. See Table 21 for AIMIX input, and Table 25 for MICHMIX input.

Once the data is prepared it can be entered either by cards or terminal. However, there are some special aspects in both programs that need explanation in order to interpret the output correctly.

Incorporated into both programs is a statistical test for determining outlying points using a method developed by Grubbs based on Student's T-test (6). This test looks at the stability, specific gravity, and flow data to see if there is statistical agreement between the values (within 95% confidence limits) at each specific asphalt content. If one point is determined as an outlier, it will be omitted from the average. The Grubbs' test works when three or more values at a specific asphalt content are given. The main weakness of the Grubbs' test is that when all values except one are equal, the one not equal will be eliminated as an outlier. Take the flow values of 9, 9, 9 and 11. The 11 value will be determined as an outlier and will be omitted--which may be undesirable. However, in both programs the Grubbs' test has been modified for the flow test values. The reason for this modification is that the flow readings are rounded-off values (to the nearest interger) and this affects the distribution unfairly. If a flow value has been determined outlier, the other values are checked to see if they are equal to each other. If not, the extreme point is omitted; if they are equal, then the extreme point is checked to see if it is within 20% of the average. If it is within 20% of the average, it is kept. Otherwise, it is omitted.

Also, in both programs, stability dial readings can be read in directly if the calibration constant is written into the program. In MICHMIX this has already been done to accommodate the present MDSHT equipment. In AIMIX it has not. The instruction

```
XSTAB(I,J) = CF* YSTAB(I,J)
```

can be changed to

```
XSTAB(I,J) = CF* YSTAB(I,J)* 15.
```

where 15 is the calibrative constant, for example, to accommodate directly entering of dial readings. The program also adjusts the stability according to the volume of the specimen. The correction factor for adjusting the stability was derived by running a regression analysis of the values presented in MS-2 Table III-1 (3). The factor was found to be expressed best by the third degree polynomial,

$$CF = -1.027\times10^{-7}(VOL)^3 + 1.657\times10^{-4}(VOL)^2 - .09143(VOL) + 18.19,$$

where

CF = correction factor,

VOL = volume of specimen in cubic centimeters.

This correction factor will introduce some variance from the tabular values in MS-2 Table III-1, but not over 3%.

When analysis of Marshall data is done conventionally, graphs are drawn using the calculated and observed data. Both AIMIX and MICHMIX use the least-square method of regression to fit curves to the data. In AIMIX, second and third degree polynomials are fitted to the five plots: specific gravity, stability, air voids, V.M.A., and flow vs. asphalt content by weight of mix. The correlation coefficient of the second and third degree polynomials are compared, and the equation with the highest coefficient is selected. In MICHMIX all regressions, except for flow vs. asphalt contents, are the comparisons between second and third degree polynomials. Maximum theoretical specific gravity vs. asphalt content is theoretically a straight line, and a first degree polynomial is fitted. The curve fitting routine is also equipped with 95% upper and lower confidence limits to determine if any of the average points lie outside this range. If they do, then the point is omitted and another regression is run.

Both programs also give the optimum asphalt content which is the average of:

(a) Asphalt content at maximum stability.

(b) Asphalt content at maximum specific gravity.

(c) Asphalt content providing proper air voids (4% air voids for surface and leveling, 5.5% for base).

If it is impossible to design the mix for the proper air voids, a message on the output will be printed:

```
***CANNOT DESIGN FOR PROPER AIR VOIDS WITHIN GIVEN ASPHALT
   CONTENT RANGE***
```

The optimal asphalt content given in this case will be the average of the asphalt content at maximum stability and the asphalt content at maximum specific gravity.

Error messages will also be printed for a deficiency in V.M.A. or a flow outside the acceptable range (reference to MS-2 (3)).

An output example for AIMIX is shown in Table 22. The input data is taken from the example in MS-2 as shown in Table 20. Figure 42 shows graphs drawn using the regression values from AIMIX.

It can be seen from the examples presented that the program does a generally good job of analysis. The comparison between AIMIX and the example from MS-2 (Table 20) is good.

	AIMIX	MS-2
Asphalt content at maximum stability	4.56	4.8
Asphalt content at maximum specific gravity	5.15	5.1
Asphalt content providing proper air voids	4.36	4.3
Optimum asphalt content	4.69	4.7

An output for MICHMIX is shown in Table 26. The graphical output shown in Figures 43 to 49 can be obtained on a plotter or a cathode ray tube terminal.

The asphalt content of 4.88% at maximum stability for this example may be low (Table 26, page 3). Otherwise, MICHMIX's curve fitting routines seemed to do well.

The Grubbs' test did throw out some values in both design examples which probably should not have been. This was due to all but one point being nearly equal. However, if the values are all approximately equal and one is omitted, the average will change little (example from Table 26, page 3 - 1488*, 1465, 1461, 1466).

1.3 Advantages of the program.

The advantages of AIMIX and MICHMIX are several. First there is a savings in time. It takes approximately one-half hour to prepare, input, receive, and interpret the data for each mix design. Conventional data analysis takes much longer. It takes MDSHT approximately 8 man-hours for each mix design to analyze Marshall data by conventional methods. The second advantage is that there are no computational errors. Third, least-square regression provides an excellent curve fit if the data is reasonable. Fourth, with no computational errors and a better curve fit, generally a better optimum asphalt content value can be obtained. Fifth, a very neat and professional looking report is achieved. The MDSHT has already adopted MICHMIX for operational use.

1.4 Special precautions

If one is to use either MICHMIX or AIMIX, two recommendations are pertinent:

(a) Use at least 4 specimens for each asphalt content (this helps to establish more realistic limits for the Grubbs' test and should give truer averages at each asphalt content).

(b) Graphs should always accompany each design and they should be analyzed. The output from the two programs is always subject to human review.

2. Further Work on Mix Design Factors

2.1 Previous work.

Many attempts have been made to define the geometric characteristics of aggregates to facilitate a unified bituminous mixture design procedure. The packing volume concept of Tons and Goetz (7) served as the basis of previous work. Tons and Ishai (8) refined this concept to develop a simple pouring test which would evaluate the particle characteristics of shape, angularity or roundness, and roughness or surface texture. Using the common aggregate parameters of apparent specific gravity, bulk specific gravity, and water absorption along with the derived pouring test parameters, an accurate prediction of overall particle irregularity can be made. Tons et al. (7) defined the packing volume of a particle as the volume enclosed under a thin membrane stretched along the particle surface, as shown in Figure 50. The term rugosity has been used to describe the ratio of the volume of asphalt lost under this imaginary membrane to the surface area of the membrane.

Using the rugosity values obtained for specific fractions of the overall aggregate mixture and considering interaction of particles of various sizes, a mixture design program was developed. A revised version of this program is shown in Appendix B. Aggregate factors vital to this program may also be calculated by computer, and this aggregate parameter program is shown in Appendix A.

2.2 Calibration of pouring test apparatus for rugosity determination.

Considerable time was spent on standardization and calibration of apparatus used in the pouring test. A variety of pouring tests were performed using aggregates, glass beads, and precision steel ball bearings of various sizes with different types and sizes of orifices and different sizes of catch containers. Table 27 shows a compilation of the various container sizes and bead types and sizes used in the tests.

Glass beads and steel ball bearings were also hand-packed into various containers in the hope of establishing a practical limit of packing for each sphere-container combination. Appendix C illustrates the pouring test apparatus and indicates the two previously used fraction-container size combinations. A new container size spectrum is also proposed based on present knowledge of pouring test parameters.

Significance of the following factors was evaluated:

(a) Pouring time.
(b) Pouring height.
(c) Orifice size.
(d) Orifice type.
(e) Container-particle volume ratio for standard beads.
(f) Container-particle volume ratio for aggregates.
(g) Variability of standard beads.
(h) Catch container volume-area ratio.
(i) Ratio of volume poured to volume caught.
(j) Catch container shape.

It may be assumed that as particles are poured more slowly, mutual interference between them will decrease, resulting in higher packing density. This assumption was verified by Tons and Ishai (8) and present tests agreed with previous findings.

Pouring height was also found to be significant. Tests performed with P#8-R#10 crushed gravel using a one-inch cone orifice and 234 ml. catch container gave an approximately linear relationship between pouring height and caught weight of aggregate as shown in Figure 51. A similar series of tests were performed with 1, 3, 4, 5 and 6 mm. glass beads and here the caught weight increase was not quite linear at heights greater than 3-4 inches. The relationship example for 3 mm. beads is shown in Figure 52.

The previously used pouring height of 21 cm. (approx. 8 in.), while in the non-linear range for the glass beads, has worked well. Previous research with fourteen experimental aggregates used this pouring height as a standard, and mix designs based on the rugosity values obtained were in close agreement with Marshall mix designs. For future designs, however, small adjustments are proposed from this study.

The factor of pouring orifice size is significant in that it directly affects pouring time. Orifice size must be chosen to allow particles to pour slowly, but must be kept large enough to preclude bridging of particles. Although particle bridging and the resultant intermittent pouring did not significantly affect caught weight, such slow pouring is time consuming and not necessary to insure packing optimization.

Orifice type also had a pouring time related effect. For purposes of tests, orifices were defined as being either plate type or cone type as illustrated by Figure 53. Opening type is significant only for large opening/particle size ratios (8-10). This is due to the fact that the cone type orifice significantly reduces pouring time, as the rock particles can slide down the smooth cone sides more easily. The opening type was insignificant at small opening/particle size ratios. This behavior is predicted by the caught weight-pouring time relationship mentioned previously, which indicated no further significant increase in caught weight beyond a sufficiently long pouring time. Beyond such a point it is immaterial whether pouring time is increased by a reduction in opening size or a change of opening type.

The ratio of catch container volume to the volume of an individual particle was found to have a very significant effect on packing of standard beads. Extensive work was done to define this effect. Figure 54 shows the relationship for a wide range of standard beads (smooth, spherical particles) and containers where hand packing of beads was employed. When such behavior was observed in hand packing tests, it was logical to predict a similar phenomenon in pouring tests. A test was designed to define the relationship statistically. Appendix D describes the conduct of this test and presents a method to adjust packing specific gravity to counteract volume ratio effects.

Unlike the smooth particles, aggregates packed uniformly well for most ratios of container volume to individual particle volume. Figure 55 shows the results of a series of tests performed with P1"-R3/4" and P3/4"-R1/2" slag fractions. In these tests, although the container volume-particle volume ratio varied widely, the statistical analysis of variance shows no significant difference in packing efficiency for the range considered for the two aggregate sizes. In light of these tests, we may conclude that the rough aggregate particles are not much affected by container boundary effects.

Consider the simultaneous analysis of the rough aggregate and the smooth spheres used as a basis for packing specific gravity. As explained in detail in Appendix D, the boundary effects for the beads may be corrected statistically. The rough aggregate particles need no correction for boundary effects. Now, both the smooth beads and the rough aggregate particles may be viewed as randomly packed particles occupying some small portion of an infinitely large collection of particles. As such, the difference in volumes occupied by the respective smooth and rough particles in this small portion of the mass will differ by only the rugosity volume.

Two other parameters associated with the test apparatus were found to be insignificant. The ratio of catch container volume to catch container inside surface area was found to be insignificant, as demonstrated in Appendix D. The ratio of volume poured to volume caught was also found to be insignificant for ratios between 1.1 and 1.7. Table 29 shows the results of the statistical analysis.

Present research was directed at standardizing catch container shape rather than evaluating container shape as such. All catch containers were constructed by modifying commercially available stainless steel griffin beakers. To alleviate as many variables as possible, it is recommended that all catch containers be right circular cylinders, the bottom-side intersection having a circular radius at least as large as that of the standard beads to be poured into it. The dimensions of the 250 ml. and 600 ml. containers are shown in Figure 56.

Having determined the relative significance of each pouring test variable, the following recommendations may be made for calibrating pouring test apparatus:

(a) For a given size aggregate fraction, select a catch container from Table C-1, Appendix C.

(b) Determine catch container volume by any convenient and reliable method, i.e., mensuration formula, water calibration, etc.

(c) Standard smooth particles (glass beads) should be used to represent particles with zero rugosity for comparison purposes in the pouring test. A bead size is specified in Table C-1, Appendix C, for any fraction size, and in general standard bead diameter should be approximately the same as the diameter of the aggregate particle it is intended to represent. Properties of the standard beads which must be determined are apparent specific gravity and coefficient of deviation of bead weight. The latter can be determined with sufficient accuracy by weighing 20 to 50 beads individually. For beads smaller than 1 mm.

diameter, this is not practical, and no correction for bead size variability is considered in this range.

(d) Select an orifice diameter which will allow aggregate or beads to flow as slowly as possible without bridging within the cone. The same size orifice need not be used for both the aggregate fraction and the associated standard bead, but an orifice size should be chosen based on flow characteristics of the material being poured. As a guide, the first trial orifice size should be chosen with diameter approximately 6-8 times the diameter of the particle being poured.

2.3 Comparison of calculated asphalt content with Marshall optimum asphalt content.

Based on the aggregate factors determined for each fraction of an aggregate blend, a prediction of optimum asphalt content may be made as recommended in Appendix E. The work of Tons and Ishai (8) dealt with a six-fraction mix. In an effort to illustrate the applicability of the packing factor concept on a broader scale, it was decided to compare the calculated optimum asphalt content for seven gravel mixes recently used by the Michigan Department of State Highways and Transportation. The optimum asphalt content for these mixes was determined by the Marshall mix design method. A typical MDSHT design data sheet is shown in Tables 30 and 31.

Table 32 shows the composition of the various aggregate blends by size of aggregate. Since the actual aggregates used in the mix design specimens were not available, packing specific gravity values were based on a weighted mean of natural and crushed gravel parameters determined by Tons and Ishai for Michigan sources (8). Because maximum specific gravity and asphalt content tests were not run on each fraction, it was considered the same for all fractions. Water absorption was taken as the weighted mean of the absorptions of the aggregates making up the individual fractions. Flyash, used as a mineral filler, was considered to have an absorption of zero. Although this is not completely correct, the amount used in each mix was very small, and the simplification was not considered to be a serious departure.

As detailed in Appendix E, selection of an optimum asphalt content was based on a minimum calculated packing V.M.A. in conjunction with an air void content of 4%. It must be noted that compaction of a number of Marshall specimens is necessary for optimum asphalt prediction, since for any particular asphalt content, we must know mix specific gravity at that content as a result of a standardized compaction effort. Knowing the mix specific gravity for any asphalt content, we can easily enter the design tables and determine packing V.M.A. As in the Marshall method of mix design, it is best to bracket the optimum value with trial specimens. As shown in Table 33 optimum asphalt contents predicted by this method agree closely with MDSHT design values.

From the work done so far, it is apparent that for the time being the Marshall approach is a useful practical method for designing mixes. The future outlook for a more "fundamental" mix design is good, but more work is needed to eliminate the necessity for a trial-and-error specimen making and testing.

CONCLUSIONS

The conclusions are concerned with the two parts of this report, namely: (a) grading of asphalts by viscosity at 25 C, and (b) computerized bituminous concrete design. On the basis of work done so far, the following is pertinent:

(a) A workable method for measuring asphalt viscosity at 25 C has been developed using the cone-plate viscometer. At the shear rate of 2×10^{-2} $\sec^{-1}$, 18 samples per 8-hour day can be tested.

(b) USING THE VISCOSITY AT 25 C AS A STANDARD, PRACTICAL VISCOSITY CHARTS FOR ASPHALT CEMENTS FOR SIX SOURCES (SUPPLIERS) IN MICHIGAN HAVE BEEN DEVELOPED. A DESIRED VISCOSITY (HARDNESS) ASPHALT (AT 25 C) CAN BE SPECIFIED ON THE BASIS OF VISCOSITY AT 135 C AND 60 C SO THAT THE SUPPLIER DOES NOT HAVE TO MEASURE VISCOSITY AT 25 C.

(c) Specification limits for viscosity due to aging of different asphalt cements have also been produced in a graphical form.

(d) The constant rate penetration test at 25 C showed a better correlation with viscosity (at 25 C) than the regular and submerged penetration tests. More work in this area is needed.

(e) A PRACTICAL COMPUTERIZED PROCEDURE HAS BEEN PRESENTED FOR CALCULATIONS IN THE DESIGN OF BITUMINOUS CONCRETE MIXES USING A MODIFIED MARSHALL TEST PROCEDURE AS THE BASIS.

(f) The mix design method gives both numerical and graphical display of the results to be used for engineering decisions.

(g) Additional work on mix design using fundamental properties of materials has indicated promise for further design improvements in the future.

RECOMMENDATIONS

(a) The viscosity grading approach should be tried as soon as possible to make minor adjustments where necessary.

(b) The cone-plate viscometer with 18 tests per day is still not a very fast method to determine asphalt viscosity at 25 C. Further work on simplified viscosity measuring methods is desirable, if time and funds permit.

(c) The Marshall method is a good practical way for designing mixes, even though it involves certain amount of trial-and-error testing. Future pursuits towards a more "fundamental" design method should be of interest.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. Egons Tons, Tsuneyoshi Funazaki and Richard Moore, "Low Temperature Measurement of Asphalts for Viscosity and Ductility," Research Report, The University of Michigan, Department of Civil Engineering, December, 1974.

2. Egons Tons and Alfred P. Chritz, "Grading of Asphalt Cements by Viscosity," Technical paper presented at the Annual Meeting of The Association of Asphalt Paving Technologists, February, 1975.

3. The Asphalt Institute, "Mix Design Methods for Asphalt Concrete," MS-2, October, 1969.

4. P. J. Serafin, "Measurement of Maximum Theoretical Specific Gravity of a Bituminous Mixture," Michigan Department of State Highways, June, 1956.

5. B. Carnahan and J. O. Wilkes, "Digital Computing, Fortran IV, WATFIU, and MTS," The University of Michigan, Chemical Engineering Department, 1973.

6. F. E. Grubbs, "Sample Criteria for Testing Outlying Observations," Ann. Math. Stat., 21:27-58 (1950).

7. Egons Tons and W. H. Goetz, "Packing Volume Concept for Aggregates," Research Report No. 24, Joint Highway Research Project, Purdue University, September, 1967.

8. Egons Tons and Ilan Ishai, "Design Factors for Bituminous Concrete," Research Report, The University of Michigan, Department of Civil Engineering, May, 1973.

9. D. J. Fox and K. E. Guire, "Documentation for Michigan Interactive Data Analysis System," 2nd Ed., The Statistical Research Laboratory of The University of Michigan, September, 1973.

TABLES

TABLE 1

TYPICAL VISCOSITY RUN DATA

SAMPLE - 75B-30(120-150)#5

TEMP - 25 C

LARGE CONE - THIN STRING

Weight (g)	Degrees	Time (sec)	t/θ (sec/deg)	Viscosity (poises)		Shear Rate (sec^{-1})
500	1	57.7	57.7	$4.42\text{x}10^{5}$		
200	1	145.7	145.7	$4.47\text{x}10^{5}$	$4.46\text{x}10^{5}$	$1.39\text{x}10^{-2}$
500	1	57.9	57.9	$4.44\text{x}10^{5}$		$3.50\text{x}10^{-2}$

TABLE 2

AVERAGE PENETRATION AND VISCOSITIES - ORIGINAL ASPHALTS

Sample Identification				Standard Penetration	Viscosity (Poises)				
No.	MDSHT Code No.	Pen. Grade	Sample Source	@ 25 C	@ 25 C	@ 60 C	@ 107 C	@ 121 C	@ 135 C
1	73B-1	60-70	I - '72	63	$2.44x10^{6}$	2840	23.35	9.62	5.24
2	73B-2	85-100	I - '72	86	$9.32x10^{5}$	1270	14.70	6.26	3.46
3	73B-3	120-150	I - '72	128	$4.65x10^{5}$	790	9.10	4.65	2.74
4	73B-4	200-250	I - '72	245	$1.44x10^{5}$	387	7.08	3.33	1.99
5	73B-5	60-70	A - '72	59	$2.45x10^{6}$	2140	17.58	6.64	3.63
6	73B-6	85-100	A - '72	91	$9.16x10^{5}$	1200	13.06	5.21	2.86
7	73B-7	120-150	A - '72	137	$4.56x10^{5}$	629	8.98	3.65	2.11
8	73B-11	120-150	C - '72	133	$4.84x10^{5}$	870	10.95	4.97	2.90
9	73B-12	200-250	C - '72	236	$1.56x10^{5}$	430	7.82	3.52	2.20
10	73B-13	85-100	D - '72	79	$1.23x10^{6}$	1690	15.58	6.06	3.42
11	73B-17	200-250	E - '72	220	$1.88x10^{5}$	372	6.78	3.12	1.93
12	73B-18	85-100	G - '72	87	$1.04x10^{6}$	1590	15.68	6.41	3.42
13	73B-19	120-150	G - '72	134	$4.72x10^{5}$	885	12.00	4.68	2.70
14	73B-21	60-70	N - '72	63	$3.25x10^{6}$	2340	20.60	7.74	3.92
15	73B-22	85-100	N - '72	83	$1.12x10^{6}$	1460	13.46	5.63	3.19
16	73B-23	120-150	N - '72	145	$3.57x10^{5}$	784	10.63	4.43	2.41
17	74B-1	60-70	G - '74	71	$1.91x10^{6}$	2660	18.93	8.24	4.56
18	74B-2	85-100	G - '74	101	$8.72x10^{5}$	1510	14.99	6.18	3.50
19	74B-3	120-150	G - '74	133	$4.88x10^{5}$	943	10.67	5.30	3.03
20	74B-4	200-250	G - '74	210	$1.95x10^{5}$	569	8.36	3.87	2.15
21	74B-5	60-70	N - '74	64	$1.94x10^{6}$	2460	18.47	7.79	4.13
22	74B-6	85-100	N - '74	99	$8.12x10^{5}$	1300	14.02	5.07	2.97

TABLE 2 (Continued)
Page 2

Sample Identification				Standard Penetration	Viscosity (Poises)				
No.	MDSHT Code No.	Pen. Grade	Sample Source	@ 25 C	@ 25 C	@ 60 C	@ 107 C	@ 121 C	@ 135 C
23	74B-7	120-150	N - '74	132	$4.63\text{x}10^{5}$	771	9.31	4.25	2.51
24	74B-8	200-250	N - '74	237	$1.74\text{x}10^{5}$	402	6.59	3.06	1.83
25	74B-9	85-100	J - '74	90	$1.07\text{x}10^{6}$	1710	14.38	6.33	3.71
26	74B-10	120-150	J - '74	128	$4.88\text{x}10^{5}$	1010	10.85	4.39	2.86
27	74B-11	200-250	J - '74	249	$1.61\text{x}10^{5}$	480	6.88	3.20	1.98
28	74B-12	60-70	I - '74	63	$2.60\text{x}10^{6}$	3130	21.62	9.33	5.36
29	74B-13	85-100	I - '74	89	$9.83\text{x}10^{5}$	1230	13.85	6.19	3.68
30	74B-14	120-150	I - '74	134	$4.74\text{x}10^{5}$	861	10.59	5.00	3.07
31	74B-15	200-250	I - '74	244	$1.63\text{x}10^{5}$	392	6.63	3.26	2.03
32	74B-18	120-150	P - '74	159	$5.50\text{x}10^{5}$	387	5.40	2.57	1.59
33	74B-19	200-250	P - '74	289	$2.08\text{x}10^{5}$	161	3.22	1.62	1.04
34	74B-21	85-100	Q - '74	96	$8.04\text{x}10^{5}$	817	9.23	4.05	2.35
35	74B-22	60-70	A - '74	69	$2.33\text{x}10^{6}$	1840	16.55	5.46	3.42
36	74B-23	85-100	A - '74	95	$1.03\text{x}10^{6}$	1110	9.85	4.48	2.72
37	74B-24	120-150	A - '74	124	$5.60\text{x}10^{5}$	721	7.71	3.54	2.25
38	74B-25	200-250	A - '74	235	$1.69\text{x}10^{5}$	354	5.08	2.43	1.50
39	74B-26	60-70	E - '74	68	$2.42\text{x}10^{6}$	1930	14.28	6.41	3.71
40	74B-27	85-100	E - '74	82	$1.33\text{x}10^{6}$	1230	11.15	5.20	3.11
41	74B-28	120-150	E - '74	125	$5.54\text{x}10^{5}$	683	8.10	3.88	2.36
42	74B-29	200-250	E - '74	226	$1.94\text{x}10^{5}$	388	6.02	2.88	1.81
43	74B-30	85-100	O - '74	87	$1.30\text{x}10^{6}$	1410	12.75	5.58	3.36
44	73B-9	60-70	C - '72	64		2680	21.38	9.41	4.54
45	73B-16	120-150	E - '72	119		720	9.54	4.50	2.72

TABLE 2 (Continued)
Page 3

Sample Identification				Standard Penetration	Viscosity (Poises)				
No.	MDSHT Code No.	Pen. Grade	Sample Source	@ 25 C	@ 25 C	@ 60 C	@ 107 C	@ 121 C	@ 135 C
46	73B-3384*	120-150	N - '72	139					
47	73B-3830*	60-70	N - '72	68					
48	73B-8205*	85-100	N - '72	94					
49	75B- 1	85-100	N - '75	98	8.19x10^{5}	1220	14.10	6.09	2.93
50	75B- 2	120-150	N - '75	128	4.85x10^{5}	850	11.54	5.07	2.49
51	75B- 3	200-250	N - '75	234	1.44x10^{5}	370	7.73	3.33	1.71
52	75B- 4	85-100	J - '75	92	1.04x10^{6}	1120	13.68	5.39	2.76
53	75B- 5	120-150	J - '75	133	4.67x10^{5}	827	11.63	5.26	2.57
54	75B- 6	250-300	J - '75	310	1.42x10^{5}	469	4.52	2.19	1.23
55	75B- 7	85-100	J - '75	94	1.12x10^{6}	1290	15.09	6.33	3.59
56	75B- 8	120-150	J - '75	129	5.28x10^{5}	810	11.24	4.98	2.69
57	75B- 9	200-250	J - '75	218	2.40x10^{5}	435	7.81	3.41	1.89
58	75B-10	85-100	A - '75	93	-----	1060	13.18	6.18	2.58
59	75B-11	120-150	A - '75	160	-----	565	8.80	4.38	1.97
60	75B-12	85-100	D - '75	87	-----	1430	13.60	6.74	3.30
61	75B-13	85-100	T - '75	96	9.65x10^{5}	1290	12.82	6.25	3.06
62	75B-14	60-70	U - '75	61	3.97x10^{6}	3370	33.89	13.39	6.42
63	75B-15	85-100	G - '75	95	9.43x10^{5}	1480	17.32	7.07	3.46
64	75B-16	120-150	G - '75	133	5.46x10^{5}	830	12.46	5.36	2.64
65	75B-17	60-70	A - '75	63	2.31x10^{6}	1650	16.85	6.88	3.26
66	75B-18	85-100	A - '75	87	1.12x10^{6}	1030	12.14	5.01	2.61

TABLE 2 (Continued)
Page 4

Sample Identification				Standard Penetration	Viscosity (Poises)				
No.	MDSHT Code No.	Pen. Grade	Sample Source	@ 25 C	@ 25 C	@ 60 C	@ 107 C	@ 121 C	@ 135 C
67	75B-19	120-150	A - '75	129	$5.75x10^5$	627	8.65	4.17	2.13
68	75B-20	200-250	A - '75	237	$1.97x10^5$	311	6.74	3.06	1.61
69	75B-24	60-70	E - '75	63	$2.41x10^6$	2870	18.12	7.87	3.46
70	75B-25	85-100	E - '75	88	$1.36x10^6$	1370	14.97	6.38	3.09
71	75B-26	120-150	E - '75	122	$6.41x10^5$	831	12.08	5.12	2.71
72	75B-30	120-150	U - '75	135	$4.50x10^5$	920	13.74	6.16	3.05
73	75B-31	85-100	I - '75	98	$8.62x10^5$	1260	15.49	6.66	3.26
74	75B-32	120-150	I - '75	139	$4.74x10^5$	653	10.78	5.07	2.53
75	75B-33	200-250	I - '75	241	$2.02x10^5$	423	8.57	3.95	2.10
76	75B-34	60-70	D - '75	69	$2.05x10^6$	2090	22.86	8.28	4.15

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*Data not used. Included to keep sample numbers consecutive.

TABLE 3

AVERAGE PENETRATION AND VISCOSITIES - AGED ASPHALTS

Sample Identification				Standard Penetration	Viscosity (Poises)		
No.	MDSHT Code No.	Pen. Grade	Sample Source	@ 25 C	@ 25 C	@ 60 C	@ 135 C
1	75B- 1	85-100	N - '75	64	$3.29x10^{6}$	2660	4.20
2	75B- 2	120-150	N - '75	79	$1.83x10^{6}$	1890	3.51
3	75B- 3	200-250	N - '75	145	$6.12x10^{5}$	855	2.23
4	75B- 4	85-100	J - '75	53	$5.55x10^{6}$	2790	4.16
5	75B- 5	120-150	J - '75	73	$2.24x10^{6}$	2090	3.69
6	75B- 6	120-150	J - '75	159	$5.31x10^{5}$	408	1.61
7	75B- 7	85-100	J - '75	54	$4.73x10^{6}$	3540	4.54
8	75B- 8	120-150	J - '75	69	$2.27x10^{6}$	2310	3.90
9	75B- 9	200-250	J - '75	104	$1.01x10^{6}$	1100	2.63
10	75B-10	85-100	A - '75	58	$5.05x10^{6}$	2910	3.81
11	75B-11	120-150	A - '75	85	$1.93x10^{6}$	1290	2.81
12	75B-12	85-100	D - '75	53	$5.83x10^{6}$	3550	4.93
13	75B-13	85-100	T - '75	61	$3.48x10^{6}$	3040	4.26
14	75B-14	60-70	U - '75	43	$9.43x10^{6}$	9010	8.65
15	75B-15	85-100	G - '75	60	$3.45x10^{6}$	2480	4.90
16	75B-16	120-150	G - '75	78	$1.88x10^{6}$	2190	3.91
17	75B-17	60-70	A - '75	40	$8.70x10^{6}$	4150	4.71
18	75B-18	85-100	A - '75	53	$4.43x10^{6}$	2470	3.67
19	75B-19	120-150	A - '75	72	$2.03x10^{6}$	1400	2.88

TABLE 3 (Continued)
Page 2

Sample Identification				Standard Penetration	Viscosity (Poises)		
No.	MDSHT Code No.	Pen. Grade	Sample Source	@ 25 C	@ 25 C	@ 60 C	@ 125 C
20	75B-20	200-250	A - '75	117	$8.69\text{x}10^5$	687	2.22
21	75B-24	60-70	E - '75	44	$8.69\text{x}10^6$	3650	4.79
22	75B-25	85-100	E - '75	49	$5.28\text{x}10^6$	3890	4.73
23	75B-26	120-150	E - '75	75	$1.99\text{x}10^6$	1650	3.31
24	75B-30	120-150	V - '75	89	$1.11\text{x}10^6$	1510	3.79
25	75B-31	85-100	I - '75	72	$1.78\text{x}10^6$	1740	4.03
26	75B-32	120-150	I - '75	86	$1.01\text{x}10^6$	1060	3.08
27	75B-33	200-250	I - '75	142	$5.03\text{x}10^5$	726	2.58
28	75B-34	60-70	D - '75	48	$6.91\text{x}10^6$	4670	5.61

TABLE 4

AVERAGE PENETRATION AND VISCOSITIES FOR SIX SOURCES - ORIGINAL AND AGED ASPHALTS

Sample Identification				Standard Penetration	Viscosity (Poises)				
No.	MDSHT Code No.	Pen. Grade	Sample Source	@ 25 C	@ 25 C	@ 60 C	@ 107 C	@ 121 C	@ 135 C
ORIGINAL									
17	74B- 1	60-70	G - '74	71	1.91×10^6	2660	18.93	8.24	4.56
18	74B- 2	85-100	G - '74	101	8.72×10^5	1510	14.99	6.18	3.50
19	74B- 3	120-150	G - '74	133	4.88×10^5	943	10.67	5.30	3.03
20	74B- 4	200-250	G - '74	210	1.95×10^5	569	8.36	3.87	2.15
28	74B-12	60-70	I - '74	63	2.60×10^6	3130	21.62	9.33	5.36
29	74B-13	85-100	I - '74	89	$9.83.10^5$	1230	13.85	6.19	3.68
30	74B-14	120-120	I - '74	134	4.74×10^5	861	10.59	5.00	3.07
31	74B-15	200-250	I - '74	244	1.63×10^5	392	6.63	3.26	2.03
39	74B-26	60-70	E - '74	68	2.42×10^6	1930	14.28	6.41	3.71
40	74B-27	85-100	E - '74	82	1.33×10^6	1230	11.15	5.20	3.11
41	74B-28	120-150	E - '74	125	5.54×10^5	683	8.10	3.88	2.36
42	74B-29	200-250	E - '74	226	1.94×10^5	388	6.02	2.88	1.81
49	75B- 1	85-100	N - '75	98	8.19×10^5	1220	14.10	6.09	2.93
50	75B- 2	120-150	N - '75	128	4.85×10^5	850	11.54	5.07	2.49
51	75B- 3	200-250	N - '75	234	1.44×10^5	370	7.73	3.33	1.71
55	75B- 7	85-100	J - '75	94	1.12×10^6	1290	15.09	6.33	3.59
56	75B- 8	120-150	J - '75	129	5.28×10^5	810	11.24	4.98	2.69
57	75B- 9	200-250	J - '75	218	2.40×10^5	435	7.81	3.41	1.89
65	75B-17	60-70	A - '75	63	2.31×10^6	1650	16.85	6.88	3.26

TABLE 4 (Continued)

Page 2

Sample Identification				Standard Penetration	Viscosity (Poises)				
No.	MDSHT Code No.	Pen. Grade	Sample Source	@ 25 C	@ 25 C	@ 60 C	@ 107 C	@ 121 C	@ 135 C
66	75B-18	85-100	A - '75	87	$1.12x10^6$	1030	12.14	5.01	2.61
67	75B-19	120-150	A - '75	129	$5.75x10^5$	627	8.65	4.17	2.13
68	75B-20	200-250	A - '75	237	$1.97x10^5$	311	6.74	3.06	1.61
AGED					@ 25 C		@ 60 C		@ 135 C
1	75B- 1	85-100	N - '75	64	$3.29x10^6$		2660		4.20
2	75B- 2	120-150	N - '75	79	$1.83x10^6$		1890		3.51
3	75B- 3	200-250	N - '75	145	$6.12x10^5$		855		2.23
7	75B- 7	85-100	J - '75	54	$4.73x10^6$		3540		4.54
8	75B- 8	120-150	J - '75	69	$2.27x10^6$		2310		3.90
9	75B- 9	200-250	J - '75	104	$1.01x10^6$		1100		2.63
17	75B-17	60-70	A - '75	40	$8.70x10^6$		4150		4.71
18	75B-18	85-100	A - '75	53	$4.43x10^6$		2470		3.67
19	75B-19	120-150	A - '75	72	$2.03x10^6$		1400		2.88
20	75B-20	200-250	A - '75	117	$8.69x10^5$		687		2.22

TABLE 5

DIFFERENCES BETWEEN AGED VISCOSITY AND ORIGINAL VISCOSITY

Sample No.	Log Log Aged Viscosity - Log Log Original Viscosity @ 25 C	@ 60 C	@ 135 C
75B - 1	.032	.028	.027
75B - 2	.031	.030	.026
75B - 3	.037	.033	.027
75B - 4	.038	.033	.031
75B - 5	.037	.034	.028
75B - 6	.034	--	.024
75B - 7	.033	.036	.017
75B - 8	.034	.039	.028
75B - 9	.035	.036	.027
75B - 13	.030	.030	.025
75B - 14	.019	.032	.020
75B - 15	.030	.018	.025
75B - 16	.029	.036	.030
75B - 17	.029	.032	.027
75B - 18	.031	.032	.026
75B - 19	.030	.031	.023
75B - 20	.037	.032	.027
75B - 24	.028	--	.024
75B - 25	.030	.037	.031
75B - 26	.027	.026	.016
75B - 30	.022	.018	--
75B - 31	.017	--	--
75B - 32	.018	.019	--
75B - 33	.023	.022	--
75B - 34	.027	.028	--
	Average = .030	Avg. = .030	Avg. = .026

TABLE 6

REGRESSION ANALYSIS RESULTS FOR A - '75 ASPHALTS

USING ORIGINAL DATA

Measured $\eta135$	Measured $\eta60$	Calculated $\eta60$	% Difference	Measured $\eta25$	Calculated $\eta25$	% Difference	Measured p	Calculated p	% Difference
3.26	1650	1695	2.8	2.31×10^6	2.39×10^6	3.4	63	60	-4.8
2.61	1030	1000	-3.0	1.12×10^6	1.10×10^6	-1.6	87	91.4	5.0
2.13	627	617	-1.6	5.75×10^5	5.43×10^5	-5.6	129	134.2	4.0
1.61	311	317	2.0	1.97×10^5	2.05×10^5	4.0	237	227.9	-3.8

$\eta60 = 102.3(\eta135)^{2.376}$ $\eta25 = 3.905 \times 10^4 \times (\eta135)^{3.481}$ $p = 561.1(\eta135)^{-1.892}$

USING AGED DATA

Measured $\eta135$	Measured $\eta60$	Calculated $\eta60$	% Difference	Measured $\eta25$	Calculated $\eta25$	% Difference
4.71	4150	4322	4.1	8.7×10^6	9.07×10^6	4.2
3.67	2470	2382	-3.6	4.43×10^6	4.21×10^6	-5.1
2.88	1400	1335	-4.6	2.03×10^6	1.99×10^6	-1.8
2.22	687	717	4.4	8.69×10^5	8.95×10^5	3.0

$\eta60 = 106.8(\eta135)^{2.388}$ $\eta25 = 7.679 \times 10^4 \times (\eta135)^{3.079}$

$\eta135$ = Viscosity in poises at 135 C

$\eta60$ = Viscosity in poises at 60 C

$\eta25$ = Viscosity in poises at 25 C

p = Standard Penetration at 25 C

TABLE 7

REGRESSION ANALYSIS RESULTS FOR J - '75 ASPHALTS

USING ORIGINAL DATA

Measured $\eta 135$	Measured $\eta 60$	Calculated $\eta 60$	% Difference	Measured $\eta 25$	Calculated $\eta 25$	% Difference	Measured p	Calculated p	% Difference
3.59	1290	1301	0.9	1.12×10^6	1.1×10^6	-2.1	94	92	-2.2
2.69	810	797	-1.6	5.28×10^5	5.49×10^5	4.0	129	134	4.2
1.89	435	438	0.7	2.4×10^5	2.36×10^5	-1.7	218	214	-1.8

$\eta 60 = 148.7(\eta 135)^{1.697}$ $\eta 25 = 5.134\times10^4 x(\eta 135)^{2.395}$ $p = 495.1(\eta 135)^{-1.318}$

USING AGED DATA

Measured $\eta 135$	Measured $\eta 60$	Calculated $\eta 60$	% Difference	Measured $\eta 25$	Calculated $\eta 25$	% Difference
4.54	3540	3381	-4.5	4.73×10^6	4.12×10^6	-12.8
3.90	2310	2462	6.6	2.27×10^6	2.75×10^6	21.0
2.63	1100	1081	-1.8	1.01×10^6	9.58×10^5	-5.2

$\eta 60 = 143.3(\eta 135)^{2.089}$ $\eta 25 = 7.221\times10^4 x(\eta 135)^{2.673}$

$\eta 135$ = Viscosity in poises at 135 C
$\eta 60$ = Viscosity in poises at 60 C
$\eta 25$ = Viscosity in poises at 25 C
p = Standard Penetration at 25 C

TABLE 8

REGRESSION ANALYSIS RESULTS FOR N - '75 ASPHALTS

USING ORIGINAL DATA

Measured η135	Measured η60	Calculated η60	% Difference	Measured η25	Calculated η25	% Difference	Measured p	Calculated p	% Difference
2.93	1220	1220	0.0	8.19×10^{5}	8.195×10^{5}	0.1	98	98.2	0.2
2.49	850	851	0.1	4.85×10^{5}	4.846×10^{5}	-0.1	128	127.7	-0.3
1.71	370	370	0.0	1.44×10^{5}	1.44×10^{5}	0.0	234	234.2	0.1

$\eta 60 = 112.7(\eta 135)^{2.215}$ $\eta 25 = 2.548\times10^{4}\times(\eta 135)^{3.229}$ $p = 556.8(\eta 135)^{-1.614}$

USING AGED DATA

Measured η135	Measured η60	Calculated η60	% Difference	Measured η25	Calculated η25	% Difference
4.2	2660	2636	-0.9	3.29×10^{6}	3.13×10^{6}	-4.8
3.51	1890	1914	1.3	1.83×10^{6}	1.96×10^{6}	7.1
2.23	855	852	-0.4	6.12×10^{5}	6.00×10^{5}	-1.9

$\eta 60 = 203.7(\eta 135)^{1.784}$ $\eta 25 = 7.401\times10^{4}\times(\eta 135)^{2.61}$

η135 = Viscosity in poises at 135 C
η60 = Viscosity in poises at 60 C
η25 = Viscosity in poises at 25 C
p = Standard Penetration at 25 C

TABLE 9

REGRESSION ANALYSIS RESULTS FOR E - '74 ASPHALTS

USING ORIGINAL DATA

Measured $\eta 135$	Measured $\eta 60$	Calculated $\eta 60$	% Difference	Measured $\eta 25$	Calculated $\eta 25$	% Difference	Measured p	Calculated p	% Difference
3.71	1930	1878	-2.7	2.42×10^6	2.48×10^6	2.3	68	63.8	-6.2
3.11	1230	1270	3.3	1.33×10^6	1.34×10^6	0.7	82	85.7	4.5
2.36	683	689	0.9	5.54×10^5	5.13×10^5	-7.5	125	136	8.8
1.81	388	383	-1.3	1.94×10^5	2.03×10^5	4.8	226	212	-6.2

$\eta 60 = 102.8(\eta 135)^{2.216}$ $\eta 25 = 2.576\times10^4 x(\eta 135)^{3.483}$ $p = 572.4(\eta 135)^{-1.674}$

USING AGED DATA

Estimated $\eta 135$	Estimated $\eta 60$	Calculated $\eta 60$	% Difference	Estimated $\eta 25$	Calculated $\eta 25$	% Difference
5.40	4600	4507	-2.0	9.6×10^6	1.01×10^7	5.4
4.40	2800	2864	2.3	5.1×10^6	4.96×10^6	-2.7
3.30	1500	1515	1.0	2.0×10^6	1.82×10^6	-8.8
2.50	830	820	-1.2	6.5×10^5	6.94×10^5	6.8

$\eta 60 \cong 107.8\ (\eta 135)^{2.213}$ $\eta 25 = 2.864\times10^4 x(\eta 135)^{3.479}$

$\eta 135$ = Viscosity in poises at 135 C
$\eta 60$ = Viscosity in poises at 60 C
$\eta 25$ = Viscosity in poises at 25 C
p = Standard Penetration at 25 C

TABLE 10

REGRESSION ANALYSIS RESULTS FOR G - '74 ASPHALTS

USING ORIGINAL DATA

Measured $\eta135$	Measured $\eta60$	Calculated $\eta60$	% Difference	Measured $\eta25$	Calculated $\eta25$	% Difference	Measured p	Calculated p	% Difference
4.56	2660	2542	-4.5	$1.91x10^{6}$	$1.88x10^{6}$	-1.6	71	70.8	-0.3
3.50	1510	1466	-2.9	$8.72x10^{5}$	$8.38x10^{5}$	-4.2	101	104	3.0
3.03	943	1086	15.2	$4.88x10^{5}$	$5.37x10^{5}$	10.1	133	128	-3.4
2.15	569	532	-6.4	$1.95x10^{5}$	$1.88x10^{5}$	-3.7	210	211.8	0.9

$\eta60 = 108.4\ (\eta135)^{2.079}$ $\eta25 = 1.801x10^{4}x(\eta135)^{3.063}$ $p = 646.7(\eta135)^{-1.458}$

USING AGED DATA

Estimated $\eta135$	Estimated $\eta60$	Calculated $\eta60$	% Difference	Estimated $\eta25$	Calculated $\eta25$	% Difference
6.70	6500	6261	-3.7	$7.5x10^{6}$	$7.42x10^{6}$	-1.1
5.00	3500	3351	-4.3	$3.2x10^{6}$	$3.01x10^{6}$	-5.8
4.30	2100	2428	15.6	$1.7x10^{6}$	$1.9x10^{6}$	11.5
3.00	1200	1125	-6.2	$6.5x10^{5}$	$6.26x10^{5}$	-3.7

$\eta60 = 107.7(\eta135)^{2.136}$ $\eta25 = 2.127x10^{4}x(\eta135)^{3.078}$

$\eta135$ = Viscosity in poises at 135 C
$\eta60$ = Viscosity in poises at 60 C
$\eta25$ = Viscosity in poises at 25 C
p = Standard Penetration at 25 C

TABLE 11

REGRESSION ANALYSIS RESULTS FOR I - '74 ASPHALTS

USING ORIGINAL DATA

Measured $\eta135$	Measured $\eta60$	Calculated $\eta60$	% Difference	Measured $\eta25$	Calculated $\eta25$	% Difference	Measured p	Calculated p	% Difference
5.36	3130	2943	-6.0	$2.6x10^{6}$	$2.64x10^{6}$	1.6	63	59	-6.4
3.68	1230	1321	7.4	$9.83x10^{5}$	$8.90x10^{5}$	-9.4	89	101	13.3
3.07	861	898	4.3	$4.74x10^{5}$	$5.27x10^{5}$	11.2	134	130.7	-2.5
2.03	392	372	-5.1	$1.63x10^{5}$	$1.59x10^{5}$	-2.2	244	235.8	-3.3

$\eta60 = 82.4\ (\eta135)^{2.13}$ $\quad$ $\eta25 = 2.057x10^{4}\ x\ (\eta135)^{2.892}$ $\quad$ $p = 648\ (\eta135)^{-1.428}$

USING AGED DATA

Estimated $\eta135$	Estimated $\eta60$	Calculated $\eta60$	% Difference	Estimated $\eta25$	Calculated $\eta25$	% Difference
8.00	7700	7187	-6.7	$10.0x10^{6}$	$10.5x10^{6}$	4.5
5.40	2800	3064	9.4	$3.7x10^{6}$	$3.3x10^{6}$	-10.8
4.40	1900	1965	3.4	$1.7x10^{6}$	$1.81x10^{6}$	6.5
2.90	840	795	-5.3	$5.3x10^{5}$	$5.34x10^{5}$	0.7

$\eta60 = 78.98(\eta135)^{2.169}$ $\quad$ $\eta25 = 2.354\ x10^{4}x\ (\eta135)^{2.931}$

$\eta135$ = Viscosity in poises at 135 C
$\eta60$ = Viscosity in poises at 60 C
$\eta25$ = Viscosity in poises at 135 C
p = Standard Penetration at 25 C

TABLE 12

COMPARISON BETWEEN PENETRATION AND VISCOSITY SYSTEMS

Penetration Limits	Difference	Ratio	Viscosity Limits	Difference	Ratio	$\frac{1}{\text{Ratio}}$
60- 70	10	0.67	1800-2500	700	1.40	0.71
85-100	15	1.0	900-1400	500	1.0	1.0
120-150	30	2.0	400- 650	250	0.5	2.0
200-250	50	3.33	150- 250	100	0.2	5.0

Limits Between Penetration Grades	Difference	Ratio	Limits Between Viscosity Grades	Difference	Ratio	$\frac{1}{\text{Ratio}}$
70- 85	15	0.75	1400-1800	400	1.60	0.63
100-120	20	1.0	650- 900	250	1.0	1.0
150-200	50	2.5	250- 400	150	0.6	1.67

TABLE 13

PRICE ADJUSTMENT FOR BITUMINOUS PAVEMENT WHERE ASPHALT IN PAVEMENT IS DEFICIENT IN PENETRATION REQUIREMENTS

Grade of Asphalt Cement	10% Decrease Penetration		50% Decrease Penetration		90% Decrease Penetration
	From	To	From	To	Below
60- 70	32(53.3%)	25(41.7%)	--	--	25(41.7%)
85-100	43(50.6%)	31(36.5%)	30(35.3%)	25(29.4%)	25(29.4%)
120-150	55(45.8%)	38(31.7%)	37(30.8%)	25(20.8%)	25(20.8%)
200-250	80(40.0%)	52(26.0%)	51(25.5%)	25(12.5%)	25(12.5%)

TABLE 14

DERIVATION OF PRICE ADJUSTMENT LIMITS FOR 1800-2500 KILOPOISES(@25C)GRADE ASPHALTS

		10% Decrease				50% Decrease				90% Decrease	
		From		To		From		To		Below	
Source	Penetration	Pen.	Viscosity (Poises)	Pen.	Viscosity (Poises)	Pen.	Viscosity (Poises)	Pen.	Viscosity (Poises)	Pen.	Viscosity (Poises)
A-'75	59 to 70	31	1.96×10^{7}	25	3.37×10^{7}	--	-------	--	-------	25	3.37×10^{7}
J-'75	58 to 70	31	1.96×10^{7}	24	3.73×10^{7}	--	-------	--	-------	24	3.73×10^{7}
N-'75	56 to 67	30	2.13×10^{7}	23	4.15×10^{7}	--	-------	--	-------	23	4.15×10^{7}
E-'74	63 to 74	34	1.55×10^{7}	26	3.05×10^{7}	--	-------	--	-------	26	3.05×10^{7}
G-'74	62 to 72	33	1.67×10^{7}	26	3.05×10^{7}	--	-------	--	-------	26	3.05×10^{7}
I-'74	61 to 71	33	1.67×10^{7}	25	3.37×10^{7}	--	-------	--	-------	25	3.37×10^{7}
Average			1.82×10^{7}		3.45×10^{7}						3.45×10^{7}
Limit			1.8×10^{7}		3.5×10^{7}						3.5×10^{7}

TABLE 15

DERIVATION OF PRICE ADJUSTMENT LIMITS FOR 900-1400 KILOPOISES (@25C) GRADE ASPHALTS

		10% Decrease				50% Decrease				90% Decrease	
		From		To		From		To		Below	
Source	Penetration	Pen.	Viscosity (Poises)	Pen.	Viscosity (Poises)	Pen.	Viscosity (Poises)	Pen.	Viscosity (Poises)	Pen.	Viscosity (Poises)
A-'75	80 to 101	40	$1.03x10^7$	29	$2.32x10^7$	28	$2.53x10^7$	24	$3.73x10^7$	24	$3.73x10^7$
J-'75	80 to 102	40	$1.03x10^7$	29	$2.32x10^7$	28	$2.53x10^7$	24	$3.73x10^7$	24	$3.73x10^7$
N-'75	75 to 94	38	$1.17x10^7$	27	$2.77x10^7$	26	$3.05x10^7$	22	$4.65x10^7$	22	$4.65x10^7$
E-'74	84 to 104	42	$9.12x10^6$	31	$1.96x10^7$	30	$2.13x10^7$	25	$3.37x10^7$	25	$3.37x10^7$
G-'74	81 to 100	41	$9.69x10^6$	30	$2.13x10^7$	29	$2.32x10^7$	24	$3.73x10^7$	24	$3.73x10^7$
I-'74	81 to 100	41	$9.69x10^6$	30	$2.13x10^7$	29	$2.32x10^7$	24	$3.73x10^7$	24	$3.73x10^7$
Average			$1.01x10^7$		$2.27x10^7$		$2.48x10^7$		$3.82x10^7$		$3.82x10^7$
Limit			$1.0x10^7$		$2.4x10^7$		$2.4x10^7$		$3.8x10^7$		$3.8x10^7$

TABLE 16

DERIVATION OF PRICE ADJUSTMENT LIMITS FOR 400-650 KILOPOISES (@25C) GRADE ASPHALT

		10% Decrease				50% Decrease				90% Decrease	
Source	Penetration	From		To		From		To		Below	
		Pen.	Viscosity (Poises)	Pen.	Viscosity (Poises)	Pen.	Viscosity (Poises)	Pen.	Viscosity (Poises)	Pen.	Viscosity (Poises)
A-'75	122 to 158	56	$4.42x10^6$	39	$1.10x10^7$	38	$1.17x10^7$	25	$3.37x10^7$	25	$3.37x10^7$
J-'75	123 to 160	56	$4.42x10^6$	39	$1.10x10^7$	38	$1.17x10^7$	26	$3.05x10^7$	26	$3.05x10^7$
N-'75	110 to 140	50	$5.88x10^6$	35	$1.44x10^7$	34	$1.67x10^7$	23	$4.15x10^7$	23	$4.15x10^7$
E-'74	121 to 153	55	$4.62x10^6$	38	$1.17x10^7$	37	$1.25x10^7$	25	$3.37x10^7$	25	$3.37x10^7$
G-'74	117 to 148	54	$4.84x10^6$	37	$1.25x10^7$	36	$1.34x10^7$	24	$3.73x10^7$	24	$3.73x10^7$
I-'74	118 to 150	54	$4.84x10^6$	37	$1.25x10^7$	36	$1.34x10^7$	25	$3.37x10^7$	25	$3.37x10^7$
Average			$4.84x10^6$		$1.22x10^7$		$1.32x10^7$		$3.51x10^7$		$3.51x10^7$
Limit			$5.0x10^6$		$1.3x10^7$		$1.3x10^7$		$3.5x10^7$		$3.5x10^7$

TABLE 17

DERIVATION OF PRICE ADJUSTMENT LIMITS FOR 150-250 KILOPOISES(@25C) GRADE ASPHALTS

		10% Decrease				50% Decrease				90% Decrease	
Source	Penetration	From		To		From		To		Below	
		Pen.	Viscosity (Poises)	Pen.	Viscosity (Poises)	Pen.	Viscosity (Poises)	Pen.	Viscosity (Poises)	Pen.	Viscosity (Poises)
A-'75	205 to 270	82	$1.69x10^6$	53	$5.08x10^6$	52	$5.33x10^6$	26	$3.05x10^7$	26	$3.05x10^7$
J-'75	207 to 274	83	$1.64x10^6$	54	$4.84x10^6$	53	$5.08x10^6$	26	$3.05x10^7$	26	$3.05x10^7$
N-'75	178 to 230	71	$2.43x10^6$	46	$7.25x10^6$	45	$7.66x10^6$	22	$4.65x10^7$	22	$4.65x10^7$
E-'74	192 to 245	77	$1.98x10^6$	50	$5.88x10^6$	49	$6.19x10^6$	24	$3.73x10^7$	24	$3.73x10^7$
G-'74	185 to 236	74	$2.19x10^6$	48	$6.51x10^6$	47	$6.87x10^6$	23	$4.15x10^7$	23	$4.15x10^7$
I-'74	189 to 243	76	$2.05x10^6$	49	$6.19x10^6$	48	$6.51x10^6$	24	$3.73x10^7$	24	$3.73x10^7$
Average			$2.0x10^6$		$5.96x10^6$		$6.27x10^6$		$3.73x10^7$		$3.73x10^7$
Limit			$2.0x10^6$		$6.0x10^6$		$6.0x10^6$		$3.8x10^7$		$3.8x10^7$

TABLE 18

CONSTANT RATE OF PENETRATION DATA AND VISCOSITY AT 25 C FOR 28 MICHIGAN ASPHALTS

MDSHT Code No.	Viscosity (Poises)	Penetration Energy (Ergs)			Average	Standard Deviation	Coefficient of Deviation
		Reading 1	Reading 2	Reading 3			
75B- 1	8.19×10^{5}	42,820	41,973	42,655	42,484	449.6	1.06
75B- 2	4.85×10^{5}	25,171	24,686	25,395	25,084	362.9	1.45
75B- 3	1.44×10^{5}	8,631	8,631	8,669	8,644	21.6	0.25
75B- 4	1.04×10^{6}	48,138	48,910	50,168	49,072	1024.7	2.09
75B- 5	4.67×10^{5}	22,842	23,004	22,481	22,776	267.7	1.18
75B- 6	1.42×10^{5}	6,514	7,327	6,389	6,410	95.1	1.48
75B- 7	1.12×10^{6}	45,585	42,708	47,777	45,357	2542.3	5.61
75B- 8	5.28×10^{5}	25,097	26,379	26,666	26,047	855.4	3.21
75B- 9	2.40×10^{5}	12,206	12,455	12,480	12,380	151.2	1.22
75B-13	9.65×10^{5}	42,596	44,290	44,115	43,667	931.6	2.13
75B-14	3.97×10^{6}	123,677	118,882	124,860	122,473	3165.8	2.58
75B-15	9.43×10^{5}	42,484	43,405	43,343	43,077	515.1	1.20
75B-16	5.46×10^{5}	27,002	27,363	27,139	27,168	182.2	0.67
75B-17	2.31×10^{6}	111,907	89,862	95,716	99,162	11.419	11.52
75B-18	1.12×10^{6}	52,012	49,944	46,145	49,367	2975.4	6.03
75B-19	5.75×10^{5}	25,317	25,097	24,847	25,105	261.7	1.04
75B-20	1.97×10^{5}	8,831	8,905	8,918	8,884	47.1	0.53
75B-21	1.48×10^{6}	77,370	76,822	63,943	72,712	7598.4	10.45
75B-22	8.27×10^{5}	35,484	35,696	37,900	36,360	1338.1	3.68

TABLE 18 (Continued)

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CONSTANT RATE OF PENETRATION DATA AND VISCOSITY AT 25 C FOR 28 MICHIGAN ASPHALTS

MSDHT Code No.	Viscosity (Poises)	Penetration Energy (Ergs)			Average	Standard Deviation	Coefficient of Deviation
		Reading 1	Reading 2	Reading 3			
75B-23	3.05×10^5	14,398	14,622	14,024	14,348	302.0	2.10
75B-24	2.41×10^6	110,724	107,511	109,914	109,383	1671.3	1.53
75B-25	1.36×10^6	57,928	62,499	62,623	61,016	2675.7	4.39
75B-26	6.41×10^5	30,116	29,742	29,954	29,937	184.4	0.63
75B-30	4.50×10^5	21,771	22,817	22,406	22,332	527.1	2.36
75B-31	8.62×10^5	40,391	38,212	34,849	37,817	2798.2	7.38
75B-32	4.74×10^5	20,140	20,264	20,140	20,181	71.9	0.36
75B-33	2.02×10^5	10,960	11,745	11,023	11,243	436.2	3.88
75B-34	2.05×10^6	85,827	84,494	73,496	81,272	6767.1	8.33

TABLE 19

REGRESSION ANALYSIS FOR CONSTANT RATE OF PENETRATION VS. VISCOSITY AT 25 C

Polynomial Coef. A0, A1,...,A(ND)
0.2163E 01 0.1088E 01
Linear Log Function, Y=C*X**A1
C= 0.8696E 01

Mean= 0.6786E 06
Sample Standard Deviation of Y= 0.9208E 06
Standard Error of Estimate= 0.725743E 05
Correlation Coefficient= 0.99295

Sample	Penetration	Viscosity	Estimated Viscosity	%Error	Coef. of Dev.
75B-6	0.6410E 04	0.1420E 06	0.1206E 06	-15.0	1.48
75B-3	0.8644E 04	0.1440E 06	0.1670E 06	16.0	0.25
75B-20	0.8884E 04	0.1970E 06	0.1721E 06	-12.6	0.53
75B-33	0.1124E 05	0.2020E 06	0.2223E 06	10.1	3.88
75B-9	0.1248E 05	0.2400E 06	0.2491E 06	3.8	1.22
75B-23	0.1435E 05	0.3050E 06	0.2899E 06	-4.9	2.10
75B-32	0.2018E 05	0.4740E 06	0.4202E 06	-11.4	0.36
75B-30	0.2233E 05	0.4500E 06	0.4692E 06	4.3	2.36
75B-5	0.2278E 05	0.4670E 06	0.4793E 06	2.6	1.18
75B-2	0.2508E 05	0.4850E 06	0.5324E 06	9.8	1.45
75B-19	0.2511E 05	0.5750E 06	0.5329E 06	-7.3	1.04
75B-8	0.2605E 05	0.5280E 06	0.5547E 06	5.0	3.21

TABLE 19 (Continued)
page 2

Sample	Penetration	Viscosity	Estimated Viscosity	%Error	Coef. of Dev.
75B-16	0.2717E 05	0.5400E 06	0.5807E 06	6.4	0.67
75B-26	0.2994E 05	0.6410E 06	0.6454E 06	0.7	0.63
75B-22	0.3636E 05	0.8270E 06	0.7974E 06	-3.6	3.68
75B-31	0.3782E 05	0.8620E 06	0.8322E 06	-3.5	7.38
75B-1	0.4248E 05	0.8190E 06	0.9445E 06	15.3	1.06
75B-15	0.4308E 05	0.9430E 06	0.9589E 06	1.7	1.20
75B-13	0.4367E 05	0.9630E 06	0.9732E 06	1.1	2.13
75B-7	0.4536E 05	0.1120E 07	0.1014E 07	-9.4	5.61
75B-4	0.4907E 05	0.1040E 07	0.1105E 07	6.2	2.09
75B-18	0.4937E 05	0.1120E 07	0.1112E 07	-0.7	6.03
75B-25	0.6102E 05	0.1360E 07	0.1400E 07	3.0	4.39
75B-21	0.7271E 05	0.1480E 07	0.1695E 07	14.5	10.45
75B-34	0.8127E 05	0.2050E 07	0.1913E 07	-6.7	8.33
75B-17	0.9916E 05	0.2310E 07	0.2375E 07	2.8	11.52
75B-24	0.1094E 06	0.2410E 07	0.2643E 07	9.7	1.53
75B-14	0.1225E 06	0.3970E 07	0.2989E 07	-24.7	2.58

% of Estimated Y Within Range of Tested Value

Range	0-4.99%	5-9.99%	10-19.99%	20-29.99%	30-39.99%	40-49.99%	> 50%
	42.9	28.6	25.0	3.6	0.0	0.0	0.0

TABLE 20

MARSHALL MIX DESIGN DATA FROM ASPHALT INSTITUTE'S MS-2

HOT MIX DESIGN DATA by the MARSHALL METHOD

Trial Mix Series: 3 - B
52% C.A.; 48% F.A.
75 Blow Compaction

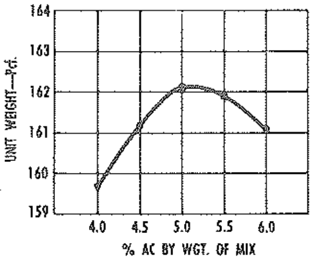
Project: F-003-4(2)
Location: Lewis - North
Date: July 17, 1961

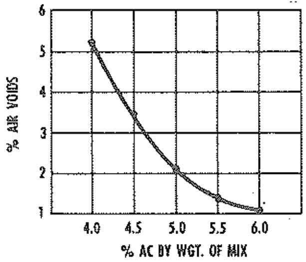
Sp. Gr. AC: 1.022
Avg. Bulk Sp. Gr. Total Agg. 2.885

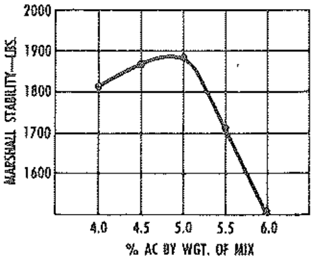
Pen. Grade AC: 85-100
Absorbed AC, lbs./100 lbs. Dry Agg. 0.16

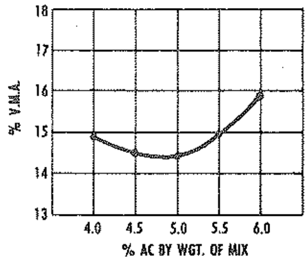
Lab. No. for AC Used: 61 - 205
Lab. Nos. for Agg. Used: 61-551; 61-552; 61-553

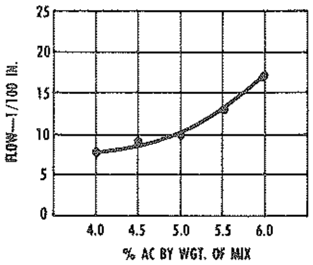
% AC-SPEC. NO.	% AC-SPEC. NO.	SPEC. HGT.-IN.	WEIGHT-GRAMS		BULK VOL.-CC.	BULK S.G. COMP.-MIX	VOLUME - % TOTAL			% V.M.A.	EFFEC. ASPHALT CONTENT	UNIT WGT. PCF.	STABILITY-LBS.		FLOW 1/100"
			IN AIR	IN WATER			EFFEC. AC	AGG.	AIR VOIDS				MEAS.	ADJUST.	
% AC by wgt. of Agg.	% AC by wgt. of Mix										% by wgt. of Mix			*	
4.17	4.0-A		1306.8	794.8	512.0	2.552							1790	1790	8
	B		1309.5	796.4	513.1	2.563							1810	1810	8
	C		1309.6	798.5	511.1	2.562							1850	1850	8
	Avg.					2.559	9.6	85.2	5.2	14.8	3.9	159.7		1817	8
4.71	4.5-A		1315.3	806.3	509.0	2.584							1900	1900	8
	B		1315.1	806.8	508.3	2.587							1735	1804	10
	C		1311.6	803.5	508.1	2.581							1810	1882	8
	Avg.					2.584	11.0	85.5	3.5	14.5	4.4	161.2		1862	9
5.26	5.0-A		1320.1	812.1	508.0	2.599							1875	1875	11
	B		1318.1	811.0	507.1	2.599							1900	1976	10
	C		1318.7	811.0	507.7	2.597							1740	1810	10
	Avg.					2.598	12.3	85.6	2.1	14.4	4.9	162.1		1887	10
5.82	5.5-A		1320.5	811.5	509.0	2.594							1785	1785	13
	B		1326.1	814.7	511.4	2.593							1685	1685	14
	C		1324.2	814.6	509.6	2.599							1685	1685	13
	Avg.					2.595	13.6	85.0	1.4	15.0	5.4	161.9		1718	13
6.38	6.0-A		1327.6	813.6	514.0	2.583							1490	1490	17
	B		1330.7	815.4	515.3	2.582							1440	1440	17
	C		1329.3	814.4	514.9	2.582							1580	1580	17
	Avg.					2.582	14.8	84.1	1.1	15.9	5.9	161.1		1503	17











	Percent
(a) Asphalt content at maximum stability	4.8
(b) Asphalt content at maximum unit weight	5.1
(c) Asphalt content providing 4 percent air voids (median of 3 to 5 percent range for surfacing mix, Heavy and Very Heavy traffic category in the design criteria table below)	4.3
Optimum asphalt content, average	4.7

TABLE 21

AIMIX INPUT

IBM FORTRAN Coding Form GX28-7327-6 U/M 050**
Printed in U.S.A.

PROGRAM
PROGRAMMER
DATE
PUNCHING INSTRUCTIONS: GRAPHIC / PUNCH
PAGE OF
CARD ELECTRO NUMBER*

COMM. | STATEMENT NUMBER | CONT. | FORTRAN STATEMENT | IDENTIFICATION SEQUENCE

```
&PHALT ITC=3,LEV=0,PS=25.4,SGAS=1.022,SGAGG(1)=2.885,2.882,2.885,A(1)=
.16,.16,.16,P(1)=60.,35.,5.,X(1)=4.,4.5,5.,5.5,6.,WAIR(1)= 1306.8,
1309.5,1309.6,1315.3,1315.1,1311.6,1320.1,1318.1,1318.7,1320.5,1326.1,
1324.2,1327.6,1330.7,1329.3,WWAT(1)=794.3,796.4,798.5,806.3,806.8,
803.5,812.1,811.,811.,811.5,814.7,814.6,813.6,815.4,814.4,STAB(1)=
1790.,1810.,1850.,1900.,1735.,1810.,1875.,1900.,1740.,1785.,1685.,
1685.,1490.,1440.,1580.,FLOW(1)=8.,8.,8.,8.,10.,8.,11.,10.,10.,13.,14.,
13.,17.,17.,17.,N=15,NT=3, &END
```

*A standard card form, IBM electro 888157, is available for punching statements from this form

**Number of forms per pad may vary slightly

TABLE 22

EXAMPLE OF OUTPUT FOR AIMIX

```
ITC= 3     LEV= 0      PS=  25.4      SGAS= 1.022
SGAGG(1)=  2.885  2.882  2.885
A(1)=       0.16   0.16   0.16
P(1)=      60.00  35.00   5.00
X(1)=       4.0      4.5      5.0      5.5      6.0
        WAIR(1)=    WWAT(1)=  STAB(1)=  FLOW(1)=
 1       1306.8       794.3     1790.       8.
 2       1309.5       796.4     1810.       8.
 3       1309.6       798.5     1850.       8.
 4       1315.3       806.3     1900.       8.
 5       1315.1       806.8     1735.      10.
 6       1311.6       803.5     1810.       8.
 7       1320.1       812.1     1875.      11.
 8       1318.1       811.0     1900.      10.
 9       1318.7       811.0     1740.      10.
10       1320.5       811.5     1785.      13.
11       1326.1       814.7     1685.      14.
12       1324.2       814.6     1685.      13.
13       1327.6       813.6     1490.      17.
14       1330.7       815.4     1440.      17.
15       1329.3       814.4     1580.      17.
N=15  NT=  3
POINT DETERMINED AS OUTLIER IN S.G. DETERMINATION     2.562
POLYNOMIAL COEF. A0,A1,...,A(ND)
     1.7540       0.3233      -0.0309
DEGREE POLYNOMIAL= 2
CORRELATION COEFFICIENT=  0.99468

POLYNOMIAL COEF. A0,A1,...,A(ND)
     0.9611       0.8103      -0.1294       0.0066
DEGREE POLYNOMIAL= 3
CORRELATION COEFFICIENT=  0.99833

FOR S.G. REGRESSION 3RD DEGREE POLYNOMIAL FITS BEST
X=       4.00 Y=       2.552
X=       4.10 Y=       2.560
X=       4.20 Y=       2.568
X=       4.30 Y=       2.574
X=       4.40 Y=       2.580
X=       4.50 Y=       2.585
X=       4.60 Y=       2.589
X=       4.70 Y=       2.592
X=       4.80 Y=       2.595
X=       4.90 Y=       2.597
X=       5.00 Y=       2.598
X=       5.10 Y=       2.599
X=       5.20 Y=       2.599
X=       5.30 Y=       2.598
X=       5.40 Y=       2.597
X=       5.50 Y=       2.595
X=       5.60 Y=       2.593
X=       5.70 Y=       2.591
X=       5.80 Y=       2.588
X=       5.90 Y=       2.586
X=       6.00 Y=       2.582
DENSEST ASPHALT CONTENT= 5.15
MAXIMUM S.G.=2.599
POINT DETERMINED AS OUTLIER IN STABILITY TESTS   1854.
POLYNOMIAL COEF. A0,A1,...,A(ND)
 -1903.7070   1677.0391   -183.9019
```

TABLE 22 (continued)
page 2

```
DEGREE POLYNOMIAL= 2
CORRELATION COEFFICIENT=  0.97585

POLYNOMIAL COEF. A0,A1,...,A(ND)
  -981.4883   1114.0403    -70.6754      -7.5056
DEGREE POLYNOMIAL= 3
CORRELATION COEFFICIENT=  0.95306

FOR STABILITY REGRESSION 2ND DEGREE POLYNOMIAL FITS BEST
X=        4.00 Y=    1862.019
X=        4.10 Y=    1880.761
X=        4.20 Y=    1895.829
X=        4.30 Y=    1907.214
X=        4.40 Y=    1914.924
X=        4.50 Y=    1918.954
X=        4.60 Y=    1919.306
X=        4.70 Y=    1915.982
X=        4.80 Y=    1908.984
X=        4.90 Y=    1898.301
X=        5.00 Y=    1883.941
X=        5.10 Y=    1865.906
X=        5.20 Y=    1844.185
X=        5.30 Y=    1818.797
X=        5.40 Y=    1789.727
X=        5.50 Y=    1756.977
X=        5.60 Y=    1720.547
X=        5.70 Y=    1680.445
X=        5.80 Y=    1636.663
X=        5.90 Y=    1589.199
X=        6.00 Y=    1538.059
OPTIMAL STABILITY ASPHALT CONTENT= 4.56
MAXIMUM STABILITY=1920.
POLYNOMIAL COEF. A0,A1,...,A(ND)
     41.7856     -13.7059        1.1540
DEGREE POLYNOMIAL= 2
CORRELATION COEFFICIENT=  0.99934

POLYNOMIAL COEF. A0,A1,...,A(ND)
    -98.7493      72.3038     -16.1869       1.1523
DEGREE POLYNOMIAL= 3
CORRELATION COEFFICIENT=  0.93533

FOR AIR VOID REGRESSION 2ND DEGREE POLYNOMIAL FITS BEST
X=        4.00 Y=         5.426
X=        4.10 Y=         4.990
X=        4.20 Y=         4.573
X=        4.30 Y=         4.183
X=        4.40 Y=         3.821
X=        4.50 Y=         3.478
X=        4.60 Y=         3.157
X=        4.70 Y=         2.860
X=        4.80 Y=         2.586
X=        4.90 Y=         2.335
X=        5.00 Y=         2.107
X=        5.10 Y=         1.901
X=        5.20 Y=         1.720
X=        5.30 Y=         1.561
X=        5.40 Y=         1.425
X=        5.50 Y=         1.312
X=        5.60 Y=         1.223
```

TABLE 22 (continued)
page 3

```
X=       5.70 Y=       1.156
X=       5.80 Y=       1.112
X=       5.90 Y=       1.092
X=       6.00 Y=       1.095
ASPHALT CONTENT PROVIDING PROPER AIR VOIDS= 4.36
POLYNOMIAL COEF. A0,A1,...,A(ND)
    37.9204      -9.8224       1.0245
DEGREE POLYNOMIAL= 2
CORRELATION COEFFICIENT=  0.99370

POLYNOMIAL COEF. A0,A1,...,A(ND)
  -106.2979      78.4415     -16.7709       1.1825
DEGREE POLYNOMIAL= 3
CORRELATION COEFFICIENT NOT APPLICABLE

FOR VMA REGRESSION 2ND DEGREE POLYNOMIAL FITS BEST
X=       4.00 Y=      15.022
X=       4.10 Y=      14.873
X=       4.20 Y=      14.738
X=       4.30 Y=      14.627
X=       4.40 Y=      14.536
X=       4.50 Y=      14.465
X=       4.60 Y=      14.415
X=       4.70 Y=      14.386
X=       4.80 Y=      14.377
X=       4.90 Y=      14.388
X=       5.00 Y=      14.420
X=       5.10 Y=      14.473
X=       5.20 Y=      14.546
X=       5.30 Y=      14.639
X=       5.40 Y=      14.753
X=       5.50 Y=      14.888
X=       5.60 Y=      15.042
X=       5.70 Y=      15.218
X=       5.80 Y=      15.414
X=       5.90 Y=      15.630
X=       6.00 Y=      15.867
POLYNOMIAL COEF. A0,A1,...,A(ND)
    40.4370     -16.5424       2.1075
DEGREE POLYNOMIAL= 2
CORRELATION COEFFICIENT=  0.99954

POLYNOMIAL COEF. A0,A1,...,A(ND)
  -126.6128      85.6846     -18.5010       1.3693
DEGREE POLYNOMIAL= 3
CORRELATION COEFFICIENT=  0.97853

FOR FLOW REGRESSION 2ND DEGREE POLYNOMIAL FITS BEST
X=       4.00 Y=       7.968
X=       4.10 Y=       8.040
X=       4.20 Y=       8.135
X=       4.30 Y=       8.273
X=       4.40 Y=       8.452
X=       4.50 Y=       8.673
X=       4.60 Y=       8.937
X=       4.70 Y=       9.243
X=       4.80 Y=       9.591
X=       4.90 Y=       9.981
X=       5.00 Y=      10.413
X=       5.10 Y=      10.887
```

TABLE 22 (continued)
page 4

```
X=        5.20 Y=       11.404
X=        5.30 Y=       11.962
X=        5.40 Y=       12.563
X=        5.50 Y=       13.206
X=        5.60 Y=       13.891
X=        5.70 Y=       14.619
X=        5.80 Y=       15.388
X=        5.90 Y=       16.200
X=        6.00 Y=       17.053
```

```
A.C.    DRY WT. WET WT.  BULK    AIR    VMA    STABILITY    FLOW
BY WT.                   S.G.    VOIDS          DIAL ADJUST
 4.00   1306.60  794.80  2.552                 1790.  1846.   8.
 4.00   1309.50  796.40  2.552                 1810.  1861.   8.
 4.00   1309.60  798.50  2.562*                1850.  1912.   8.
AVERAGE                  2.552   5.44   15.04         1873.   8.0
REGRESSION               2.552   5.43   15.02         1862.   8.0

 4.50   1315.30  806.30  2.584                 1900.  1973.   8.
 4.50   1315.10  806.80  2.587                 1735.  1805.  10.
 4.50   1311.60  803.50  2.581                 1810.  1884.   8.
AVERAGE                  2.584   3.44   14.42         1888.   8.7
REGRESSION               2.585   3.40   14.47         1919.   8.7

 5.00   1320.10  812.10  2.599                 1875.  1952.  11.
 5.00   1318.10  811.00  2.599                 1900.  1983.  10.
 5.00   1318.70  811.00  2.597                 1740.  1813.  10.
AVERAGE                  2.598   2.09   14.41         1916.  10.3
REGRESSION               2.598   2.11   14.42         1884.  10.4

 5.50   1320.50  811.50  2.594                 1785.  1854.* 13.
 5.50   1326.10  814.70  2.593                 1685.  1740.  14.
 5.50   1324.20  814.60  2.599                 1685.  1748.  13.
AVERAGE                  2.595   1.38   14.96         1744.  13.3
REGRESSION               2.595   1.31   14.89         1757.  13.2

 6.00   1327.60  813.60  2.583                 1490.  1529.  17.
 6.00   1330.70  815.40  2.582                 1440.  1473.  17.
 6.00   1329.30  814.40  2.582                 1580.  1617.  17.
AVERAGE                  2.582   1.06   15.83         1540.  17.0
REGRESSION               2.582   1.09   15.87         1538.  17.1

* DETERMINED AS OUTLYING POINT BY STUDENT'S TEST AND OMITTED
ASPHALT CONTENT AT MAXIMUM STABILITY                 4.56
ASPHALT CONTENT AT MAXIMUM SPECIFIC GRAVITY          5.15
ASPHALT CONTENT PROVIDING PROPER AIR VOIDS           4.36
***OPTIMUM ASPHALT CONTENT,AVERAGE***                4.69
OPTIMUM ASPHALT CONTENT=    4.69
@ OPTIMUM
SPECIFIC GRAVITY=           2.592
STABILITY=               1916.
AIR VOIDS=                  2.89
V.M.A.=                    14.39
FLOW=                       9.21
```

1621 C (10/74)

TABLE 23

LABORATORY TEST DATA EXAMPLE FOR MICHMIX

PROJECT NO.	DATE SAMPLED	SAMPLE NOS.
CONTRACTOR		TYPE SAMPLE

Sample Identification		1	2	3	4	Avg	
Laboratory Number							
Average Thickness of core	ins.						
(A) Wt. in air	g.	1240.6	1245.0	1250.5	1247.0		
(B) Wt. in water	g.	723.3	726.0	730.4	728.4		
(C) Volume of sample	(A – B) ml.	517.3	519.0	520.1	518.6		
(D) ACTUAL SPECIFIC GRAVITY	(A/C)	2.398	2.399	2.404	2.405	2.401	
UNIT WEIGHT (62.4D)	lbs./cu. ft.						
Flask No.							
(E) Wt. flask + mix + solvent	g.		2715.4		2176.6	2446.0	
(F) Wt. flask + mix	g.		1387.0		1400.3	1393.6	
(G) Wt. flask	g.		749.3		797.8	773.5	
(H) Wt. mix	(F – G) g.					620.1	
(J) Wt. solvent only (flask filled)	g.		1690.1		965.1	1327.6	
(K) Wt. solvent above mix	(E – F) g.		1328.4		776.3	1052.4	
(L) Wt. solv. disp. by mix	(J – K) g.		361.7		188.8	275.2	
(M) Spec. Grav. solvent	25/25° C		1.453		0.792		
(N) Volume of mix	(L/M) ml.		248.9		238.4		
(P) THEORETICAL MAXIMUM SPECIFIC GRAVITY	(H/N)		2.562		2.527	2.544	
(Q)	(P – D)					.143	
(R) AIR VOIDS IN TOTAL MIX	(Q/P) 100=%					5.62	
(S) Bitumen in mix, by wt.	%					4.5	
(T) Spec. Grav. bitumen	25/25° C					1.025	
(U) TOTAL VOIDS FILLED WITH BITUMEN	$\frac{DS}{RT + DS} = \%$					65.2	
VOIDS IN MINERAL AGGREGATE	$\frac{100\,R}{100 - U} = \%$					16.2	
Stability, Ames dial rd'g.	0.0001 in.	86	85	85	85		
Stability, uncorr. (from chart)							
Stab., thick. corr. ratio (from chart)							
MARSHALL STABILITY (Corrected)	lbs.						
FLOW	0.01 in.	10	9	10	9		

Remarks:

TABLE 24

WORK SHEET FOR EXAMPLE USED IN MICHMIX

PROJECT NO.	DATE TESTED	SAMPLE NOS.
CONTRACTOR		TYPE SAMPLE

&PHALT ITC = 3,LEV = 0,PS = 1 8.0,SGAS = 1.0 2 5,N = 2 4,NT = 4,

SGS(1) = 1.4 5 3 (Tri), 0.7 9 2 (Meth), (Fill both blocks when one liquid is used)

X(1) = 4.5,5.0,5.5,6.0,6.5,7.0,__.__,__.__,

MARSHALL NO.	WAIR(1) =	WWAT(1) =	STAB(1) =	FLOW(1) =	WF(1) =	WS(1) =	WFM(1) =	WFMS(1) =
1	1240.6,	723.3,	86..,	10..,	Flask No.	--	--	--
2	1245.0,	726.0,	85..,	9..,	749.3,	1690.1,	1387.0,	2715.4,
3	1250.5,	730.4,	85..,	10..,	Flask No.	--	--	--
4	1247.0,	728.4,	85..,	9..,	797.8,	965.1,	1400.3,	2176.6,
5	1245.2,	728.0,	86..,	10..,	Flask No.	--	--	--
6	1243.1,	724.3,	83..,	8..,	726.8,	1729.7,	1331.2,	2714.0,
7	1240.0,	722.0,	83..,	9..,	Flask No.	--	--	--
8	1239.6,	723.7,	80..,	9..,	781.1,	972.9,	1411.5,	2184.2,
9	1245.1,	731.8,	83..,	11..,	Flask No.	--	--	--
10	1243.6,	730.6,	85..,	11..,	765.0,	1663.1,	1418.3,	2704.2,
11	1239.6,	729.1,	91..,	11..,	Flask No.	--	--	--
12	1237.2,	726.7,	85..,	11..,	782.9,	974.7,	1365.3,	2154.3,
13	1238.9,	724.7,	74..,	13..,	Flask No.	--	--	--
14	1228.2,	718.7,	77..,	13..,	658.8,	1791.4,	1290.3,	2712.8,
15	1232.6,	718.5,	77..,	12..,	Flask No.	--	--	--
16	1238.5,	719.3,	60..,	11..,	628.0,	977.9,	1229.2,	2013.6,
17	1230.3,	716.2,	68..,	16..,	Flask No.	--	--	--
18	1234.6,	720.0,	67..,	15..,	740.5,	1658.6,	1338.8,	2649.3,
19	1220.8,	714.3,	63..,	14..,	Flask No.	--	--	--
20	1230.8,	720.2,	69..,	14..,	635.2,	977.9,	1261.6,	2036.7,
21	1225.6,	712.3,	59..,	18..,	Flask No.	--	--	--
22	1225.2,	713.8,	52..,	20..,	878.8,	1553.7,	1510.9,	2692.7,
23	1223.5,	712.1,	62..,	17..,	Flask No.	--	--	--
24	1221.1,	710.1,	58..,	20..,	645.0,	979.4,	1229.4,	2017.4,
	.,	.,	.,	.,	Flask No.	--	--	--
	.,	.,	.,	.,	.,	.,	.,	.,
	.,	.,	.,	.,	Flask No.	--	--	--
	.,	.,	.,	.,	.,	.,	.,	.,
	.,	.,	.,	.,	Flask No.	--	--	--
	.,	.,	.,	.,	.,	.,	.,	.,
	.,	.,	.,	.,	Flask No.	--	--	--
	.,	.,	.,	.,	.,	.,	.,	.,

TABLE 25

MICHMIX INPUT

IBM FORTRAN Coding Form

GX28-7327-6 U/M 050**
Printed in U.S.A.

PROGRAM
PROGRAMMER
DATE
PUNCHING INSTRUCTIONS
GRAPHIC
PUNCH
PAGE OF
CARD ELECTRO NUMBER*

C FOR COMMENT | STATEMENT NUMBER | CONT. | FORTRAN STATEMENT | IDENTIFICATION SEQUENCE

```
&PHALT ITC=3,LEV=0,PS=18.,SGAS=1.025,N=24,NT=4,SGS(1)=1.453,.792,
X(1)=4.5,5.,5.5,6.,6.5,7.,WAIR(1)=1240.6,1245.,1250.5,1247.,1245.2,
1243.1,1240.,1239.6,1245.1,1243.6,1239.6,1237.2,1238.9,1228.2,1232.6,
1238.5,1230.3,1234.6,1220.8,1230.8,1225.6,1225.2,1223.5,1221.1,
WWAT(1)=723.3,726.,730.4,728.4,728.,724.3,722.,723.7,731.8,730.6,729.1,
726.7,724.7,718.7,718.5,719.3,716.2,720.,714.3,720.2,712.3,713.8,712.1,
710.1,STAB(1)=86.,85.,85.,85.,86.,83.,83.,80.,83.,85.,91.,85.,74.,77.,
77.,60.,68.,67.,63.,69.,59.,52.,62.,58.,FLOW(1)=10.,9.,10.,9.,10.,8.,
9.,9.,11.,11.,11.,11.,13.,13.,12.,11.,16.,15.,14.,14.,18.,20.,17.,20.,
WF(1)=749.3,797.8,726.8,781.1,765.,782.9,658.8,628.,740.5,635.2,878.8,
645.,WS(1)=1690.1,965.1,1729.7,972.9,663.1,974.7,1791.4,977.9,1658.6,
977.9,1553.7,979.4,WFM(1)=1387.,1400.3,1331.2,1411.5,1418.3,1365.3,
1290.3,1229.3,1338.8,1261.6,1510.9,1229.4,WFMS(1)=2715.4,2176.6,2714.,
2184.2,2704.2,2154.3,2712.8,2013.6,2649.3,2036.7,2692.7,2017.4,&END
```

*A standard card form, IBM electro 888157, is available for punching statements from this form

**Number of forms per pad may vary slightly

TABLE 26

EXAMPLE OF OUTPUT FOR MICHMIX

```
ITC= 3      LFV= 0      PS=  18.0
SGAS= 1.025      N=24      NT= 4       SGS(I)= 1.453   0.792
X(I)=        4.5        5.0        5.5        6.0        6.5        7.0
      WAIR(I)=   WWAT(I)=   STAB(I)=  FLOW(I)=  WF(I)=    WS(I)=    WFM(I)=   WFMS(I)=
 1     1240.6      723.3        86.    10.
 2     1245.0      726.0        85.     9.      749.3    1690.1    1387.0    2715.4
 3     1250.5      730.4        85.    10.
 4     1247.0      728.4        85.     9.      797.8     965.1    1400.3    2176.6
 5     1245.2      728.0        86.    10.
 6     1243.1      724.3        83.     8.      726.8    1729.7    1331.2    2714.0
 7     1240.0      722.0        83.     9.
 8     1239.6      723.7        80.     9.      781.1     972.9    1411.5    2184.2
 9     1245.1      731.8        83.    11.
10     1243.6      730.6        85.    11.      765.0    1663.1    1418.3    2704.2
11     1239.6      729.1        91.    11.
12     1237.2      726.7        85.    11.      782.9     974.7    1365.3    2154.3
13     1238.9      724.7        74.    13.
14     1228.2      718.7        77.    13.      658.8    1791.4    1290.3    2712.8
15     1232.6      718.5        77.    12.
16     1233.5      719.3        60.    11.      628.0     977.9    1229.2    2013.6
17     1230.3      716.2        68.    16.
18     1234.6      720.0        67.    15.      740.5    1658.6    1338.8    2649.3
19     1220.8      714.3        63.    14.
20     1230.8      720.2        69.    14.      635.2     977.9    1261.6    2036.7
21     1225.6      712.3        59.    18.
22     1225.2      713.8        52.    20.      878.8    1553.7    1510.9    2692.7
23     1223.5      712.1        62.    17.
24     1221.1      710.1        58.    20.      645.0     979.4    1229.4    2017.4
POLYNOMIAL COEF. A0,A1,...,A(ND)
      2.0897       0.1156      -0.0104
DEGREE POLYNOMIAL= 2
CORRELATION COEFFICIENT=  0.34697

POLYNOMIAL COEF. A0,A1,...,A(ND)
      1.7146       0.3174      -0.0461        0.0021
DEGREE POLYNOMIAL= 3
CORRELATION COEFFICIENT NOT APPLICABLE

FOR S.G. REGRESSION 2ND DEGREE POLYNOMIAL FITS BEST


PDS: PLOT DESCRIPTION GENERATION BEGINS ***
DENSEST ASPHALT CONTENT= 5.57
MAXIMUM S.G.=2.412
POINT DETERMINED AS OUTLIER IN STABILITY TESTS   1488.
POINT DETERMINED AS OUTLIER IN STABILITY TESTS   1064.
POLYNOMIAL COEF. A0,A1,...,A(ND)
  -949.2395      993.3433    -101.8136
DEGREE POLYNOMIAL= 2
CORRELATION COEFFICIENT=  0.96480

POLYNOMIAL COEF. A0,A1,...,A(ND)
 -6367.1367   3895.2739   -613.0728       29.6422
DEGREE POLYNOMIAL= 3
CORRELATION COEFFICIENT=  0.95245

FOR STABILITY REGRESSION 2ND DEGREE POLYNOMIAL FITS BEST
OPTIMAL STABILITY ASPHALT CONTENT= 4.88
MAXIMUM STABILITY=1474.
POLYNOMIAL COEF. A0,A1,...,A(ND)
```

TABLE 26 (continued)
page 2

```
     2.7056      -0.0373
DEGREE POLYNOMIAL= 1
CORRELATION COEFFICIENT=  0.97757

POLYNOMIAL COEF. A0,A1,...,A(ND)
    28.9034      -7.6905       0.5568
DEGREE POLYNOMIAL= 2
CORRELATION COEFFICIENT=  0.95929

POLYNOMIAL COEF. A0,A1,...,A(ND)
   100.3823     -45.9673       7.2988      -0.3908
DEGREE POLYNOMIAL= 3
CORRELATION COEFFICIENT=  0.96264

FOR AIR VOID REGRESSION 3RD DEGREE POLYNOMIAL FITS BEST
ASPHALT CONTENT PROVIDING PROPER AIR VOIDS= 5.08
POLYNOMIAL COEF. A0,A1,...,A(ND)
   -74.8226      45.5390      -3.1949
DEGREE POLYNOMIAL= 2
CORRELATION COEFFICIENT=  0.97745

POLYNOMIAL COEF. A0,A1,...,A(ND)
  -414.4326     227.4218     -35.2355       1.8575
DEGREE POLYNOMIAL= 3
CORRELATION COEFFICIENT=  0.97759

POLYNOMIAL COEF. A0,A1,...,A(ND)
    27.1094      -4.6807       0.4967
DEGREE POLYNOMIAL= 2
CORRELATION COEFFICIENT=  0.94977

POLYNOMIAL COEF. A0,A1,...,A(ND)
   103.3255     -45.4880       7.6834      -0.4165
DEGREE POLYNOMIAL= 3
CORRELATION COEFFICIENT=  0.95972

FOR VMA REGRESSION 3RD DEGREE POLYNOMIAL FITS BEST
POLYNOMIAL COEF. A0,A1,...,A(ND)
    47.9516     -16.4610       1.7531
DEGREE POLYNOMIAL= 2
CORRELATION COEFFICIENT=  0.99212

POLYNOMIAL COEF. A0,A1,...,A(ND)
    39.6047 .   -12.0003       0.9690       0.0454
DEGREE POLYNOMIAL= 3
CORRELATION COEFFICIENT=  0.98824

FOR FLOW REGRESSION 2ND DEGREE POLYNOMIAL FITS BEST
```

TABLE 26 (continued)
page 3

```
A.C.   DRY WT  WET WT  BULK   MAX SG  AIR     VMA    VFA        STABILITY     FLOW
BY WT                  S.G.   THEOR.  VOIDS                     DIAL ADJUSTED
 4.5   1240.6  723.3   2.398  2.562                             86.  1488.* 10.
 4.5   1245.0  726.0   2.399  2.527                             85.  1465.   9.
 4.5   1250.5  730.4   2.404                                    85.  1461.  10.
 4.5   1247.0  728.4   2.405                                    85.  1466.   9.
AVERAGE                2.401  2.545   5.62    16.2   65.2            1464.   9.5
REGRESSION             2.400  2.538   5.72    16.3   64.7            1459.   9.4
 5.0   1245.2  728.0   2.408  2.532                             86.  1488.  10.
 5.0   1243.1  724.3   2.396  2.494                             83.  1431.   8.
 5.0   1240.0  722.0   2.394                                    83.  1434.   9.
 5.0   1239.6  723.7   2.403                                    80.  1389.   9.
AVERAGE                2.400  2.513   4.48    16.2   72.3            1436.   9.0
REGRESSION             2.408  2.519   4.17    15.9   74.0            1472.   9.5
 5.5   1245.1  731.8   2.426  2.517                             83.  1450.  11.
 5.5   1243.6  730.6   2.424  2.484                             85.  1486.  11.
 5.5   1239.6  729.1   2.428                                    91.  1554.  11.
 5.5   1237.2  726.7   2.424                                    85.  1495.  11.
AVERAGE                2.425  2.500   2.99    16.0   81.3            1496.  11.0
REGRESSION             2.412  2.501   3.33    16.3   79.6            1434.  10.4
 6.0   1238.9  724.7   2.409  2.487                             74.  1290.  13.
 6.0   1228.2  718.7   2.411  2.461                             77.  1350.  13.
 6.0   1232.6  718.5   2.398                                    77.  1343.  12.
 6.0   1238.5  719.3   2.385                                    60.  1064.* 11.
AVERAGE                2.401  2.474   2.96    17.0   82.6            1330.  12.3
REGRESSION             2.410  2.482   2.92    17.0   82.8            1346.  12.3
 6.5   1230.3  716.2   2.393  2.497                             68.  1186.  16.
 6.5   1234.6  720.0   2.399  2.446                             67.  1167.  15.
 6.5   1220.8  714.3   2.410                                    63.  1119.  14.
 6.5   1230.8  720.2   2.410                                    69.  1214.  14.
AVERAGE                2.403  2.472   2.77    18.0   84.6            1171.  14.8
REGRESSION             2.403  2.463   2.64    17.9   85.2            1206.  15.0
 7.0   1225.6  712.3   2.388  2.470                             59.  1061.  18.
 7.0   1225.2  713.8   2.396  2.418                             52.   940.  20.
 7.0   1223.5  712.1   2.392                                    62.  1088.  17.
 7.0   1221.1  710.1   2.390                                    58.  1049.  20.
AVERAGE                2.391  2.444   2.15    18.5   88.4            1034.  18.8
REGRESSION             2.390  2.445   2.21    18.5   88.1            1015.  18.6
* DETERMINED AS OUTLYING POINT BY STUDENT'S TEST AND OMITTED
ASPHALT CONTENT AT MAXIMUM STABILITY                4.88
ASPHALT CONTENT AT MAXIMUM SPECIFIC GRAVITY         5.57
ASPHALT CONTENT PROVIDING PROPER AIR VOIDS          5.08
***OPTIMUM ASPHALT CONTENT;AVERAGE***               5.18
OPTIMUM ASPHALT CONTENT=      5.18
@ OPTIMUM
SPECIFIC GRAVITY=             2.410
STABILITY=                 1465.
AIR VOIDS=                    3.80
V.M.A.=                      15.97
FLOW=                         9.72
VOIDS FILLED WITH ASHPHALT=  76.30
```

TABLE 27

COMPILATION OF STANDARD BEAD SIZES USED IN TESTS

Bead Diameter, mm.	Bead Type	Individual Bead Volume, cc.	Coef. of Deviation of Bead Weight (Percent)
15	glass	1.77	6.5
6	glass	0.133	4.4
5	glass	0.065	6.5
4	glass	0.034	9.9
3	glass	0.014	11.4
6.35	steel	0.134	0.02
3.70	steel	0.033	0.03

TABLE 28

COMPILATION OF STANDARD CONTAINER DIMENSIONS

Nominal Size	Height, cm.	Inside Dia., cm.	Calibrated Volume, cc.
250 ml.	7.6	6.4	234.1
600 ml.	9.5	8.4	519.9
1200 ml.	12.0	10.2	996.0
2000 ml.	15.2	12.2	1798
4000 ml.	18.0	15.4	3350
(The following cans are not proposed as standards, but were used for some tests:)			
3 oz.	3.5	5.4	77.9
6 oz.	4.8	7.0	184.8
10 oz.	5.2	7.9	249.5

TABLE 29

ANOVA TABLE FOR POURED VOLUME-CAUGHT VOLUME RATIOS 1.1-1.7

Source of Variation	DF	Sum of Squares	Mean Square	F Ratio	$F_{0.95(6,28)}$
Between Ratios	6	1.6	0.267	0.664	2.42
Within Ratios	28	11.25	0.402		

TABLE 30

DESIGN DATA FOR MIX I (MDSH&T)

Form 1801 (Rev. 5/70)
(General)

STATE OF MICHIGAN
DEPARTMENT OF STATE HIGHWAYS

TESTING AND RESEARCH DIVISION
TESTING LABORATORY SECTION

UNIVERSITY OF MICHIGAN
ANN ARBOR

REPORT OF TEST

Control Section Identification	General
Job No.	
Laboratory No.	75B-1167 thru 1190
Date	May 30, 1975

Sheet 1 of 2

Report on sample of BITUMINOUS AGGREGATE MIXTURE (Marshalls)
Date sampled May 22, 1975 Date received May 27, 1975
Source of material --
Sampled from Laboratory Mixture Quantity Represented ---
Submitted by F. Carian, Testing Laboratory Section
Intended use Surfacing (20A) Specification 4.11, 1973 Std Specs

TEST RESULTS

Marshall Test Results:

Laboratory No. 75B-	1167-1170	1171-1174	1175-1178	1179-1182	1183-1186	1187-1190
Marshall No.	177-180	181-184	185-188	189-192	193-196	197-200
Actual Sp. Gr.	2.389	2.399	2.411	2.412	2.403	2.382
Theoretical Max. Sp. Gr.	2.519	2.506	2.484	2.475	2.461	2.428
Air Voids, %	5.2	4.3	2.9	2.5	2.4	1.9
Voids Filled with Bitumen, %	67	73	81	85	87	90
Voids in Mineral Agg., %	15.6	16.0	15.9	16.7	17.6	18.2
Stability, lb.	1,090	1,160	1,310	1,200	1,120	827
Flow, 0.01 inch	9	9	11	13	14	15

Aggregate Proportions, %:

20A Dense Graded	99.0	--	--	--	--	--
3MF (Flyash)	1.0	--	--	--	--	--

REMARKS:

See sheet 2

cc:
File
D.F. Malott
A.P. Chritz
M. Etelamaki
F. Carian
R.R. Hofmeister

pmb

TABLE 31

DESIGN DATA FOR MIX I (MDSH&T)

Form 1801 (Rev. 5/70)
(General)

STATE OF MICHIGAN
DEPARTMENT OF STATE HIGHWAYS

TESTING AND RESEARCH DIVISION
TESTING LABORATORY SECTION

UNIVERSITY OF MICHIGAN
ANN ARBOR

REPORT OF TEST

Control Section Identification	General
Job No.	
Laboratory No.	75B-1167 thru 1190
Date	May 30, 1975

Sheet 2 of 2

Report on sample of BITUMINOUS AGGREGATE MIXTURE (Marshalls)
Date sampled Date received
Source of material
Sampled from Quantity Represented
Submitted by
Intended use Specification

TEST RESULTS

Aggregate Gradation: Calculated						
Cumulative Percent Passing						
3/4-inch	100	--	--	--	--	--
1/2-inch	89.6	--	--	--	--	--
3/8-inch	78.2	--	--	--	--	--
No. 4	58.2	--	--	--	--	--
No. 8	47.6	--	--	--	--	--
No. 16	41.0	--	--	--	--	--
No. 30	35.8	--	--	--	--	--
No. 50	17.0	--	--	--	--	--
No. 100	7.4	--	--	--	--	--
No. 200	5.7	--	--	--	--	--
Mixture Proportions, %						
20A-Retained #8	50.01	49.75	49.49	49.23	48.96	48.71
20A-Passing #8	44.53	44.31	44.07	43.83	43.60	43.36
3MF (Flyash)	0.96	0.94	0.94	0.94	0.94	0.93
Bitumen	4.5	5.0	5.5	6.0	6.5	7.0
Calculated Max. Theor. Sp.Gr.	2.550	2.530	2.511	2.491	2.473	2.454
Air Voids, %	6.3	5.2	4.0	3.2	2.8	2.9
Voids Filled with Bitumen, %	62	69	76	82	84	85
Voids in Mineral Agg, %	16.8	16.9	16.9	17.3	18.1	19.2

Materials	Source	App.Sp.Gr.	Bulk Sp.Gr.	Absorption,%
20A-Ret. #4	Lake Constr. Co., Pit #16-69	2.7742	2.6248	2.0518
20A-Pass #4	Lake Constr. Co., Pit #16-69	2.7132	2.63	1.25
3MF (Flyash)	Consumers, Essexville	2.450		
85/100 Asp.	Trumbull, Detroit	1.025		

REMARKS:

Designed for Project No. Mb 16081 / 07544A.

Mix Design, %
P8- 47.0
P200- 6.0
Bitumen-4.5 thru 7.0

pmb

TABLE 32

AGGREGATE BLENDS IN COMPARISON MIXES

Cumulative % Passing	Mix I	II	III	IV	V	VI	VII
3/4-inch	100	100					
1/2-inch	89.6	97.5	100	100	100	100	100
3/8-inch	78.2	82.0	99	99	99	99	99
No. 4	58.2	65.3	63	67	71	75	77
No. 8	47.6	52.0	46	51	55	60	63
No. 16	41.0	40.3	31	35	39	42	44
No. 30	35.8	27.7	21	23	24	27	28
No. 50	17.0	15.4	12.3	13.1	13	14.6	14.1
No. 100	7.4	8.0	8.6	8.8	8.9	9.1	8.2
No. 200	5.7	5.8	6.8	6.8	6.9	6.9	6.0

TABLE 33

COMPARISON OF CALCULATED OPTIMUM WITH MDSH&T MARSHALL OPTIMUM

Comparison Mix	MDSH&T Marshall Optimum	Design Table Prediction	Design Table Control
I	5.5%	5.5%	Min. packing VMA
II	5.5%	5.5%	Min. packing VMA
III	5.7%	5.6-5.8%	4% air voids (Min. packing VMA)
IV	5.6%	5.6%	Min. packing VMA
V	6.0%	5.9-6.0%	4% air voids (Min. packing VMA)
VI	6.0%	5.9-6.0%	4% air voids
VII	6.3%	6.5%	Min. packing VMA

FIGURES

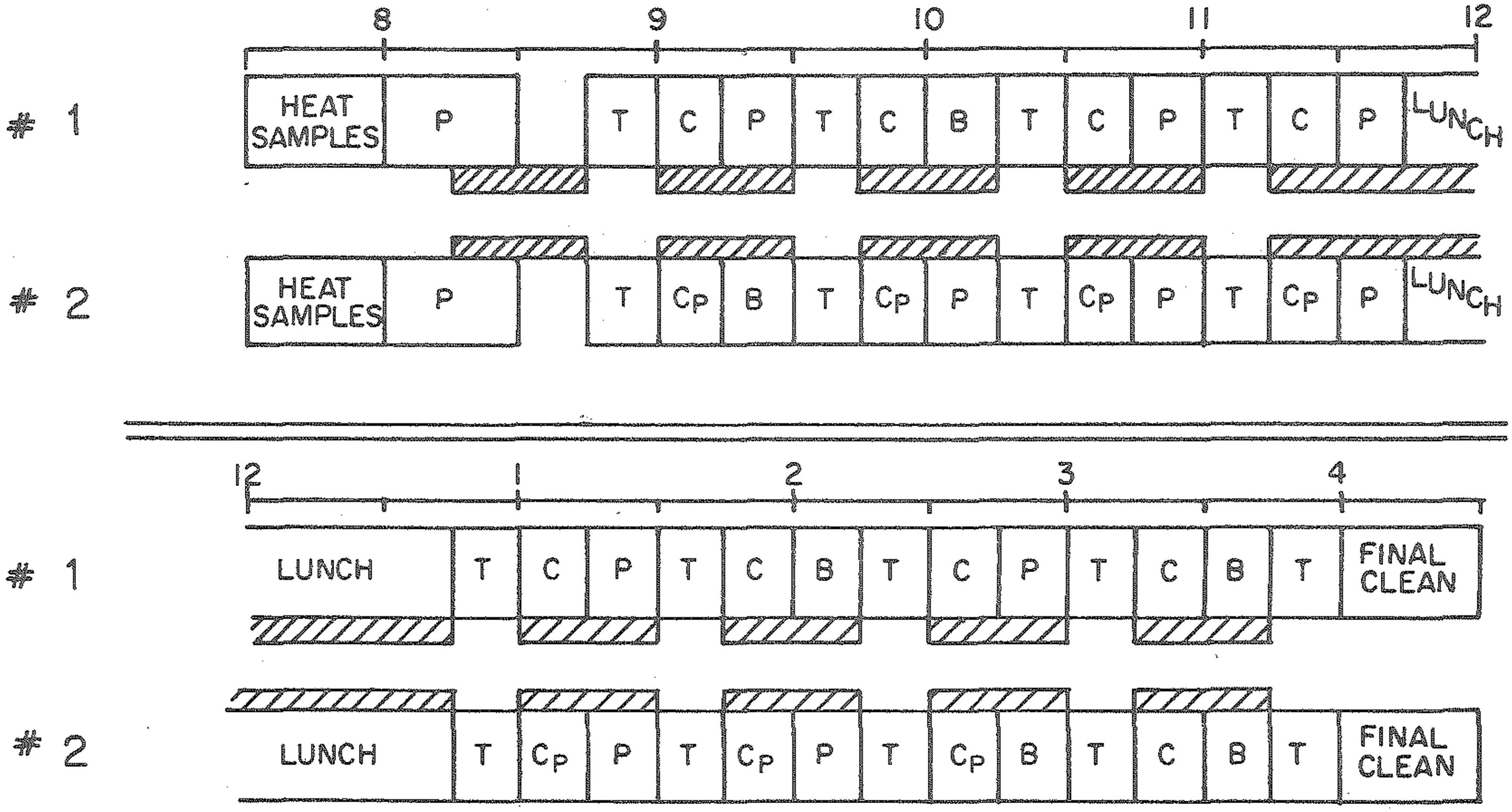


Figure 1. Work flow diagram for cone-plate viscometer tests using 2 operators, 4 viscometer heads, and 2 constant temperature bath set-ups. Maximum 18 tests per day.

KEY

▨ – BATH
P – PREPARATION
T – TEST
C – CLEAN
B – COFFEE BREAK
C_p – COMPUTATIONS

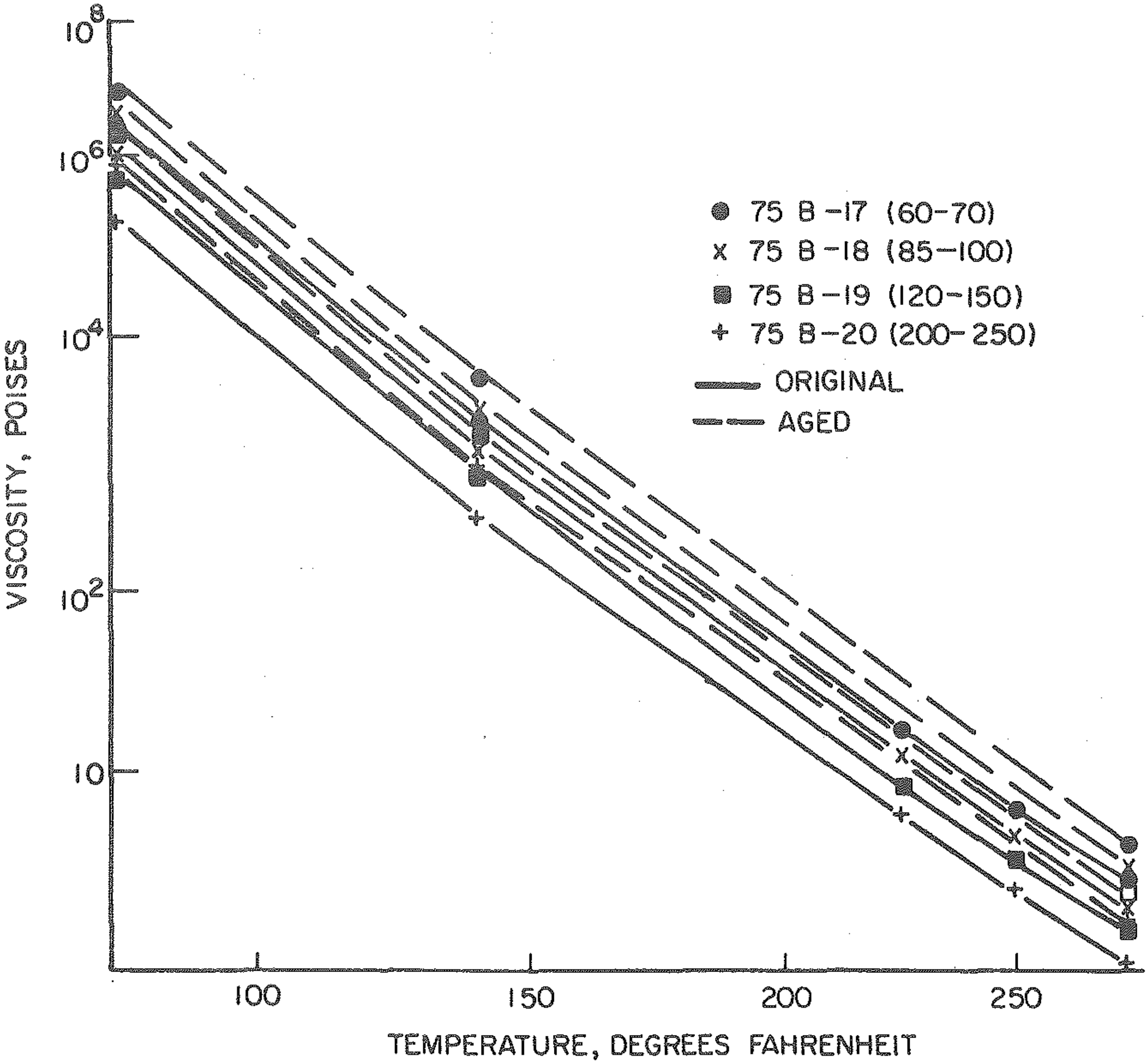


Figure 2. Viscosity-temperature curves of original and aged asphalts, 4 grades, source A-'75.

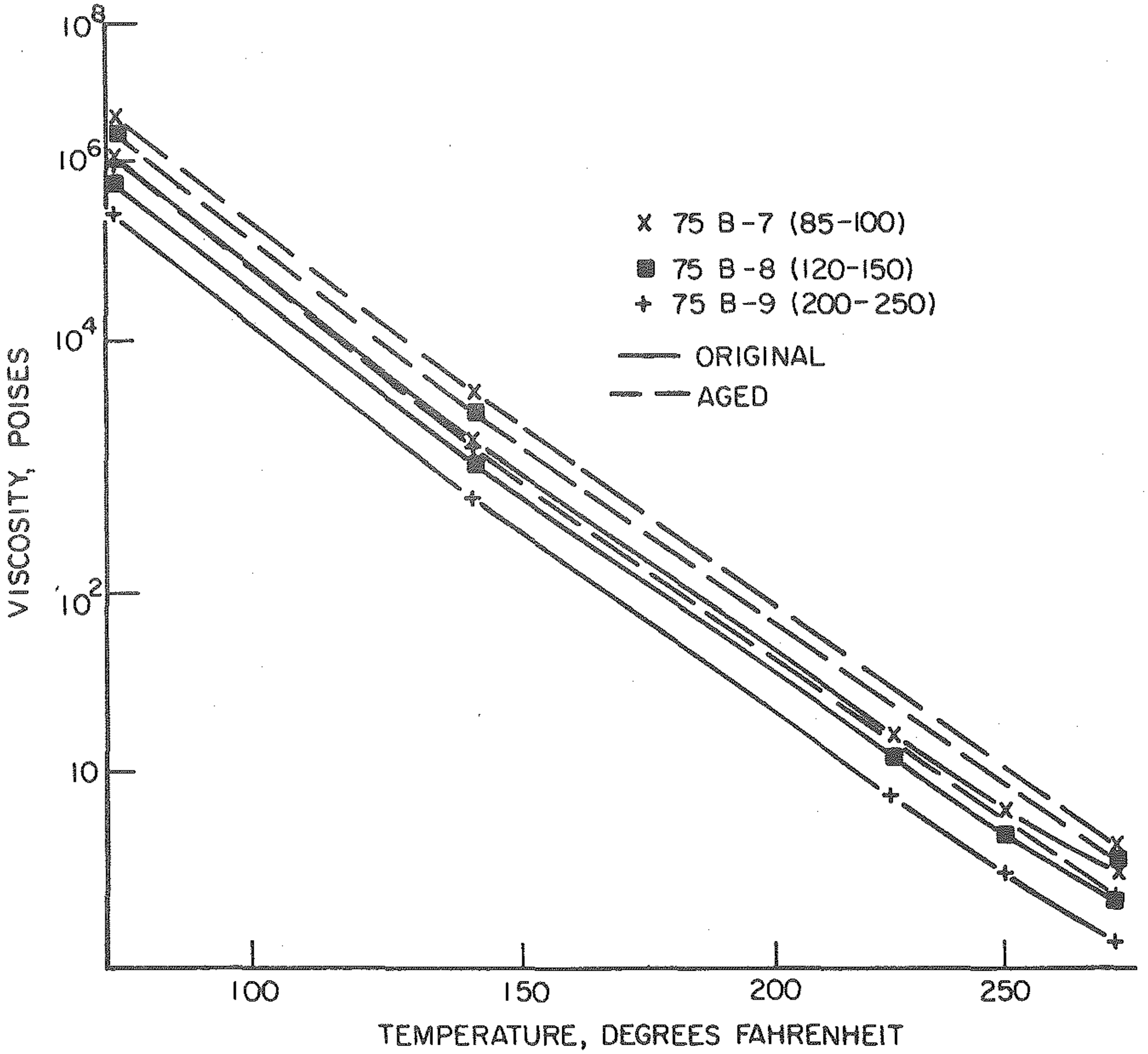


Figure 3. Viscosity-temperature curves of original and aged asphalts, 4 grades, source J-'75.

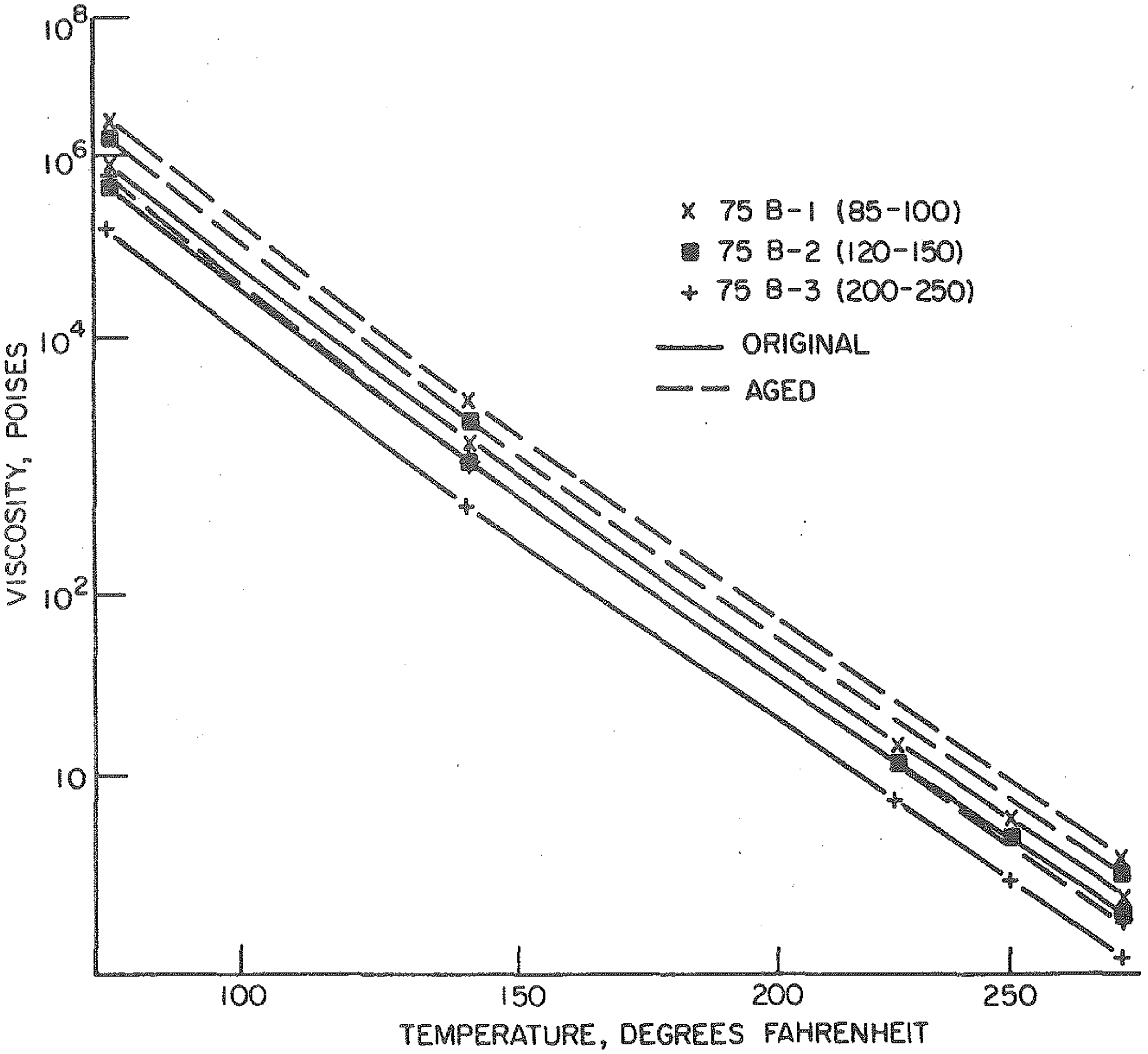


Figure 4. Viscosity-temperature curves of original and aged asphalts, 4 grades, source N-'75.

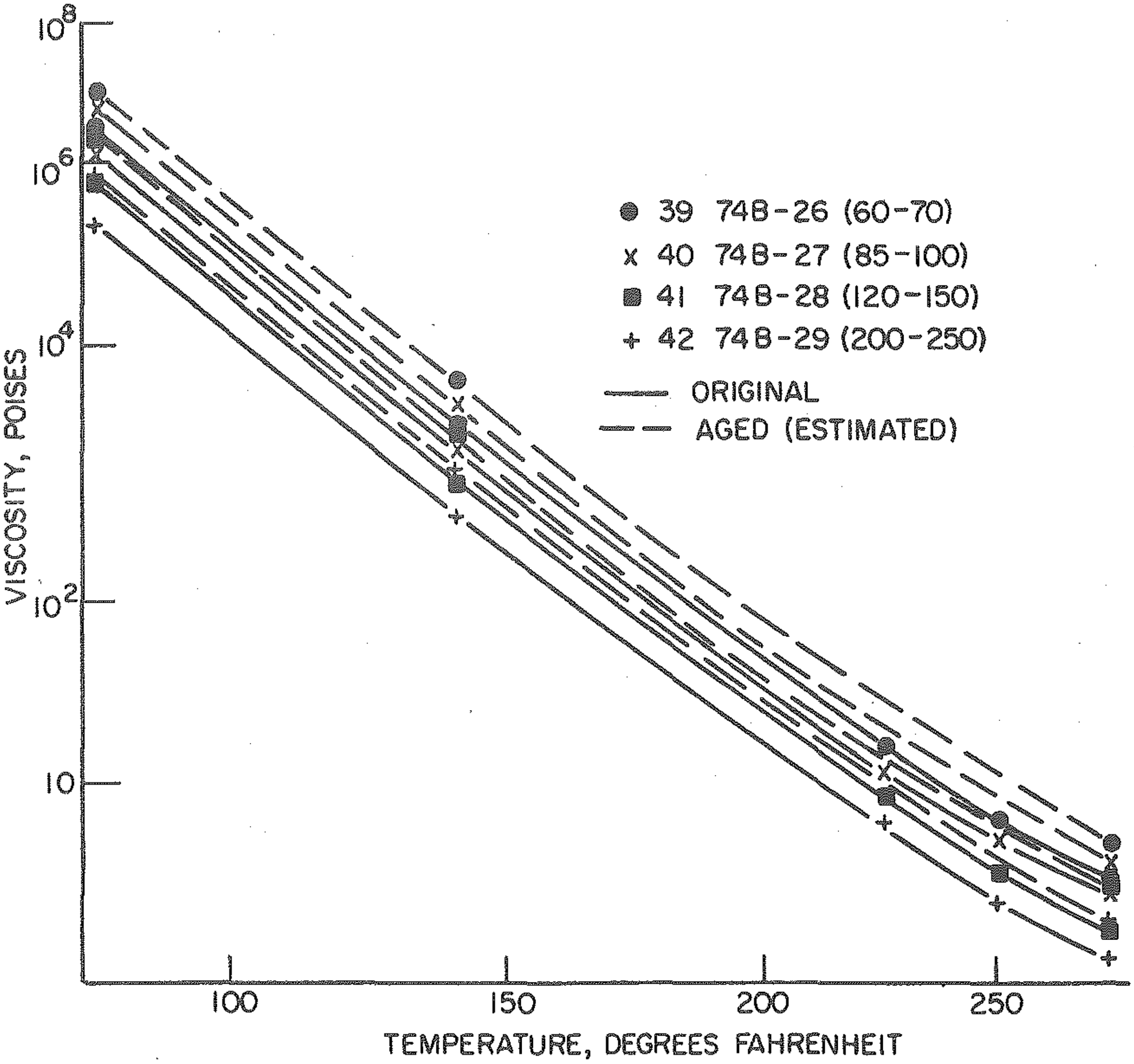


Figure 5. Viscosity-temperature curves of original and aged asphalts, 4 grades, source E-'74.

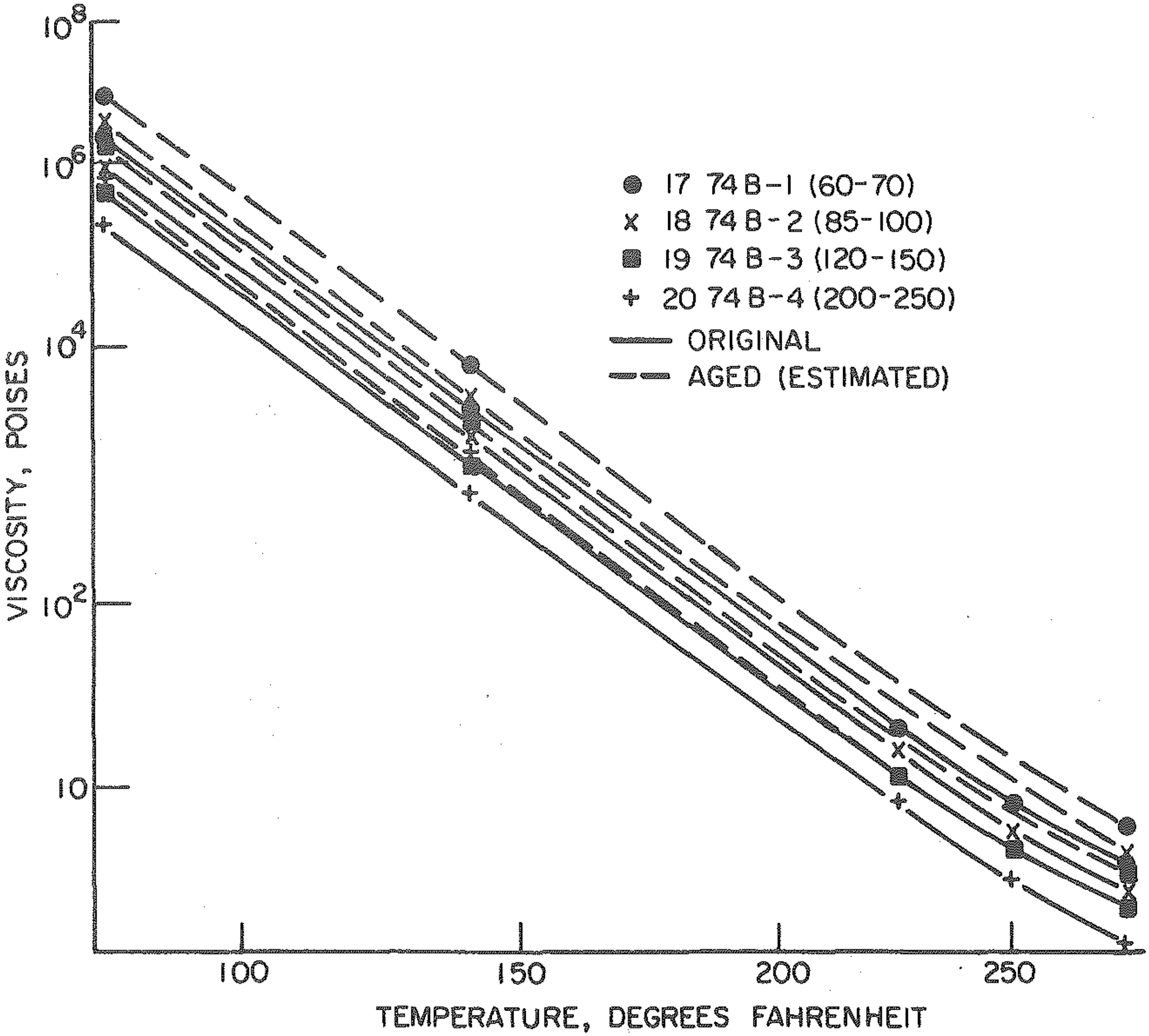


Figure 6. Viscosity-temperature curves of original and aged asphalts, 4 grades, source G-'74.

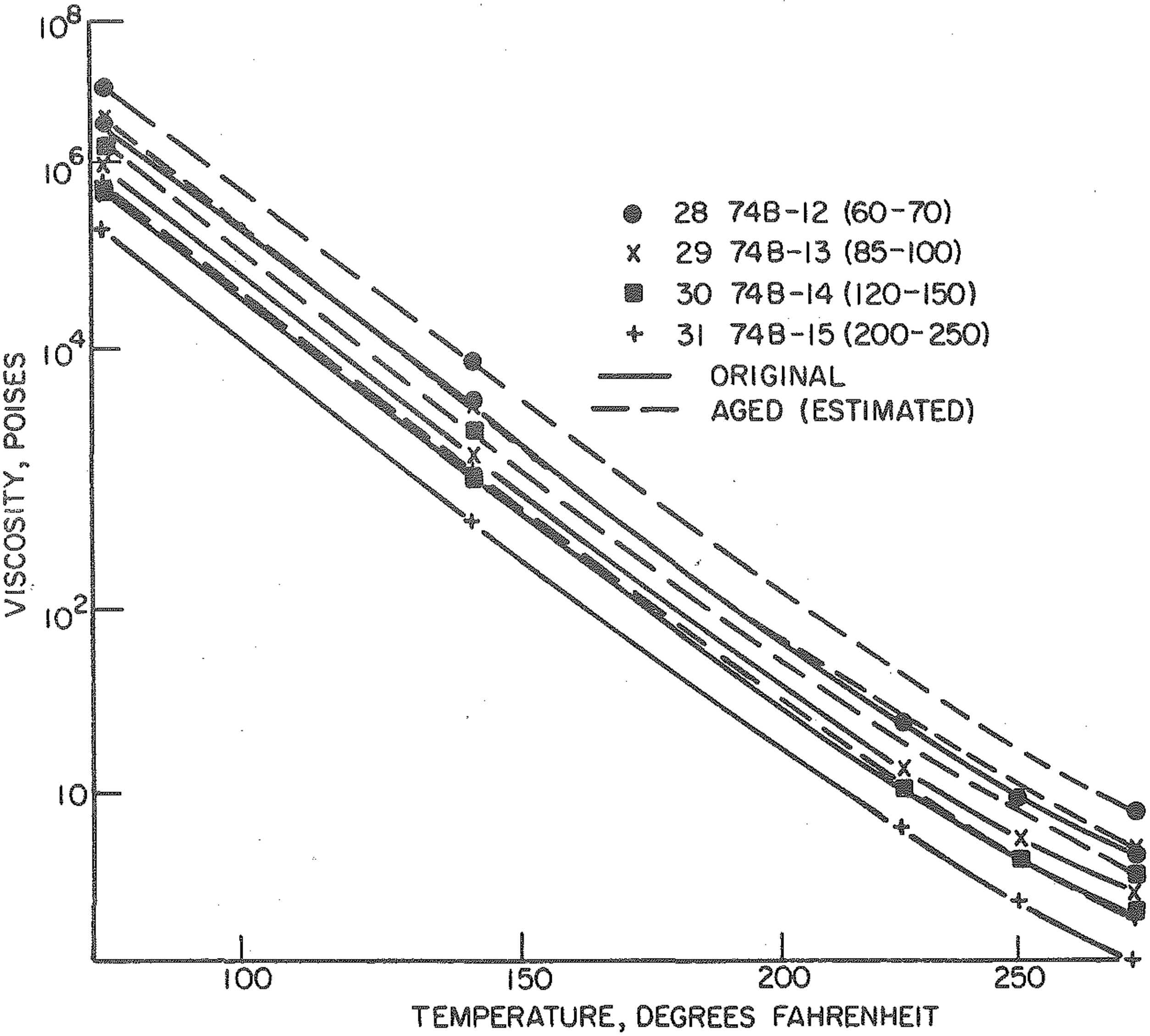


Figure 7. Viscosity-temperature curves of original and aged asphalts, 4 grades, source I-'74.

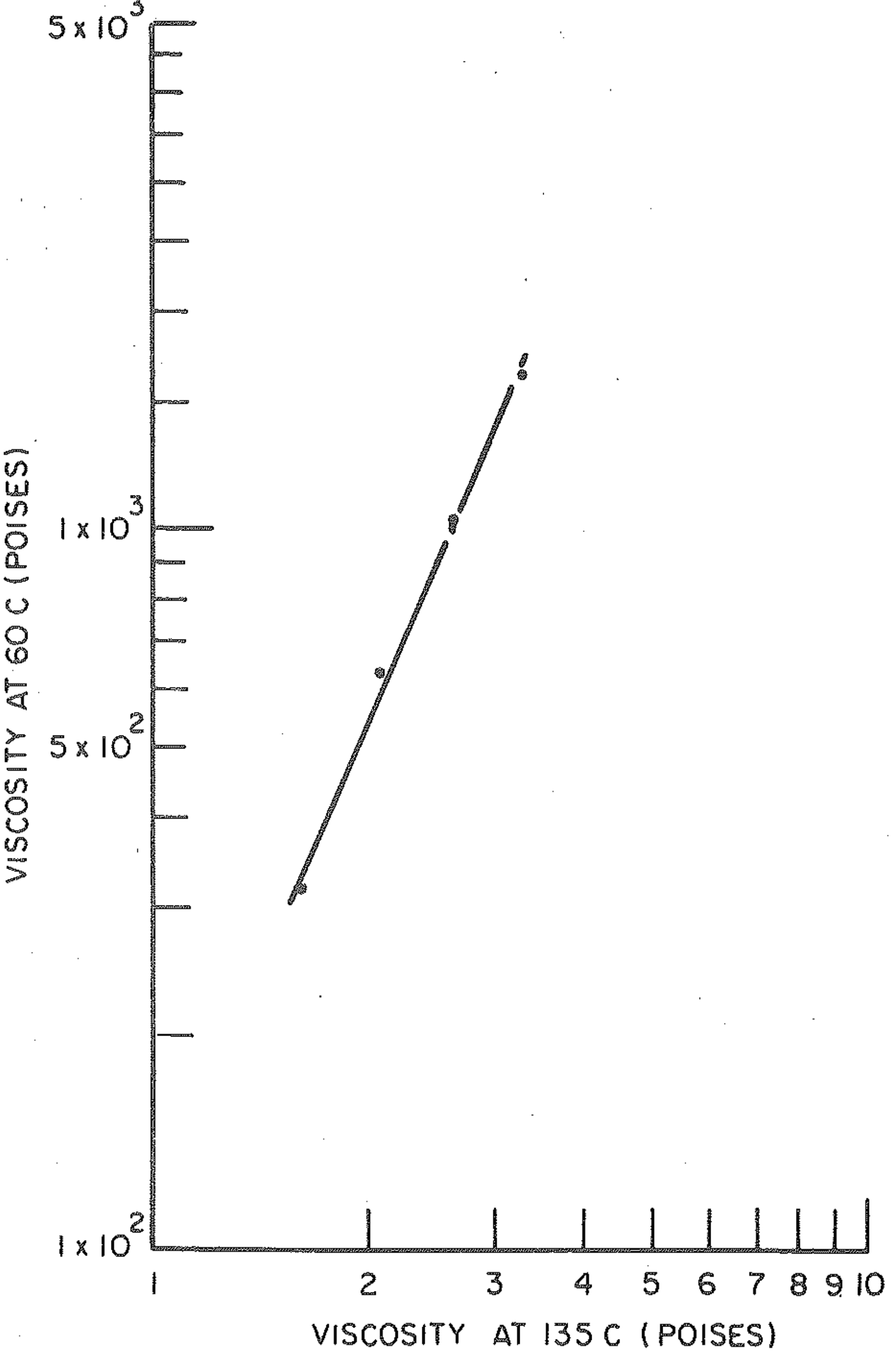


Figure 8. Viscosity at 60 C vs. viscosity at 135 C for A-'75 asphalt.

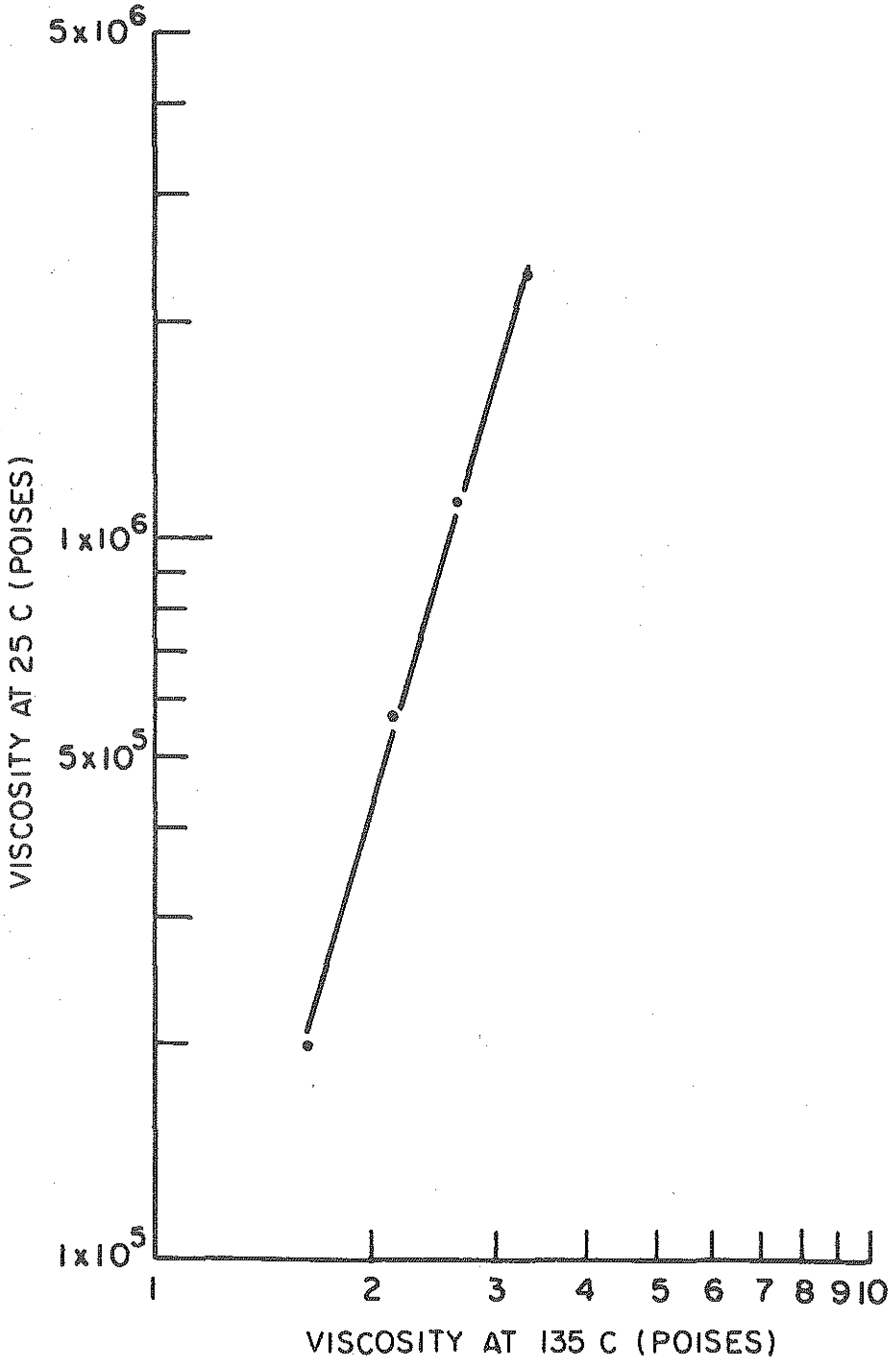


Figure 9. Viscosity at 25 C vs. viscosity at 135 C for A-'75 asphalt.

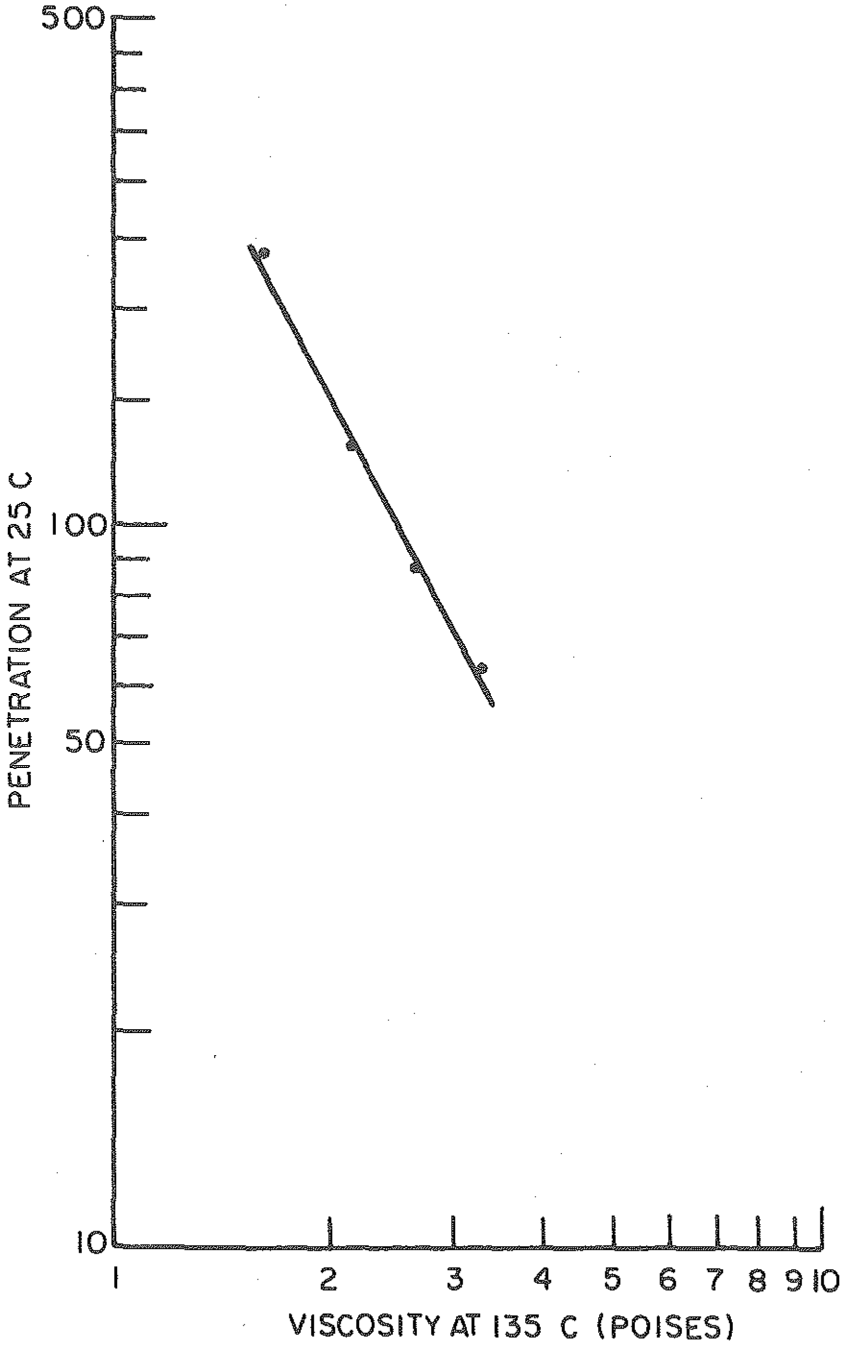


Figure 10. Penetration at 25 C vs. viscosity at 135 C for A-'75 asphalt.

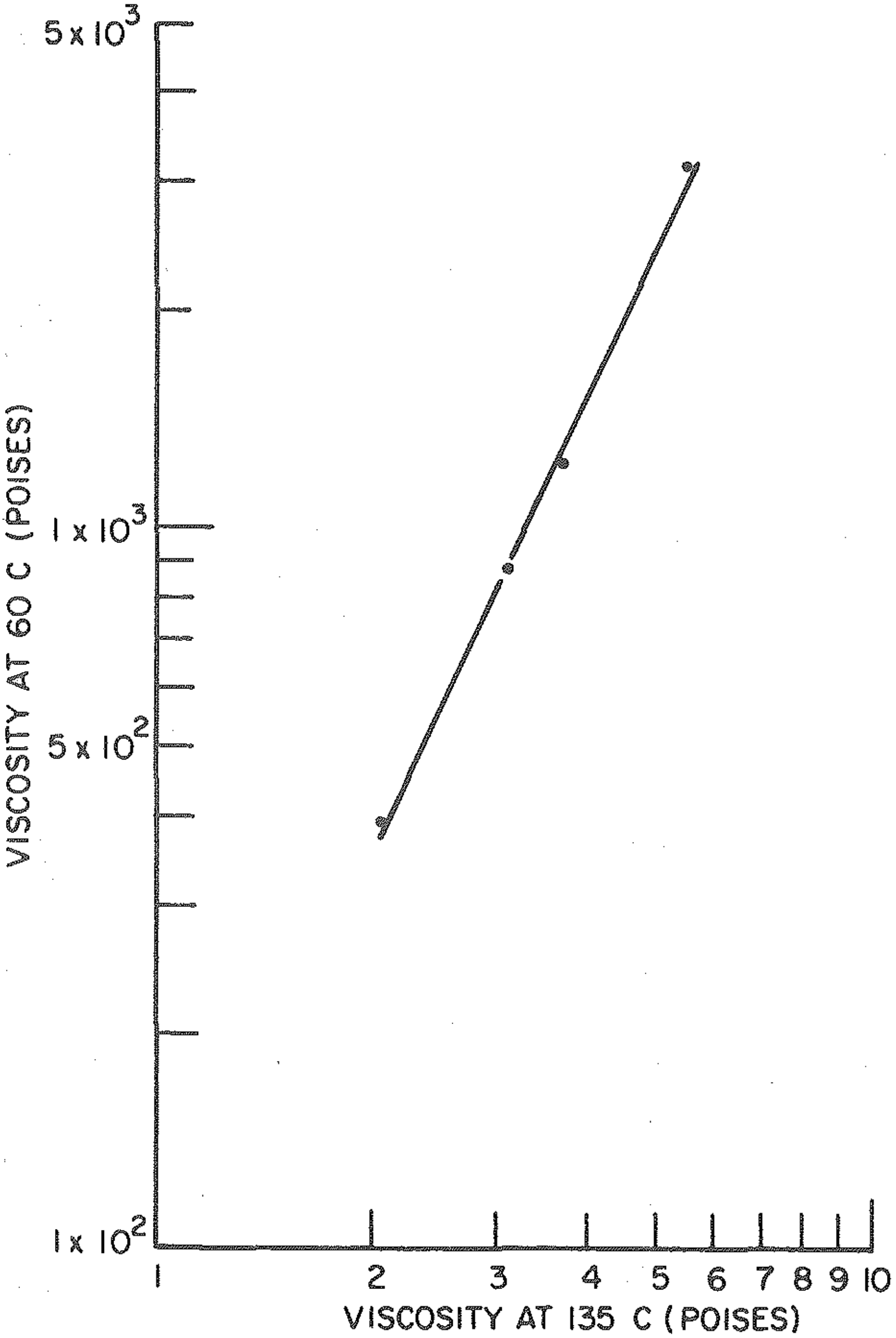


Figure 11. Viscosity at 60 C vs. viscosity at 135 C for I-'74 asphalt.

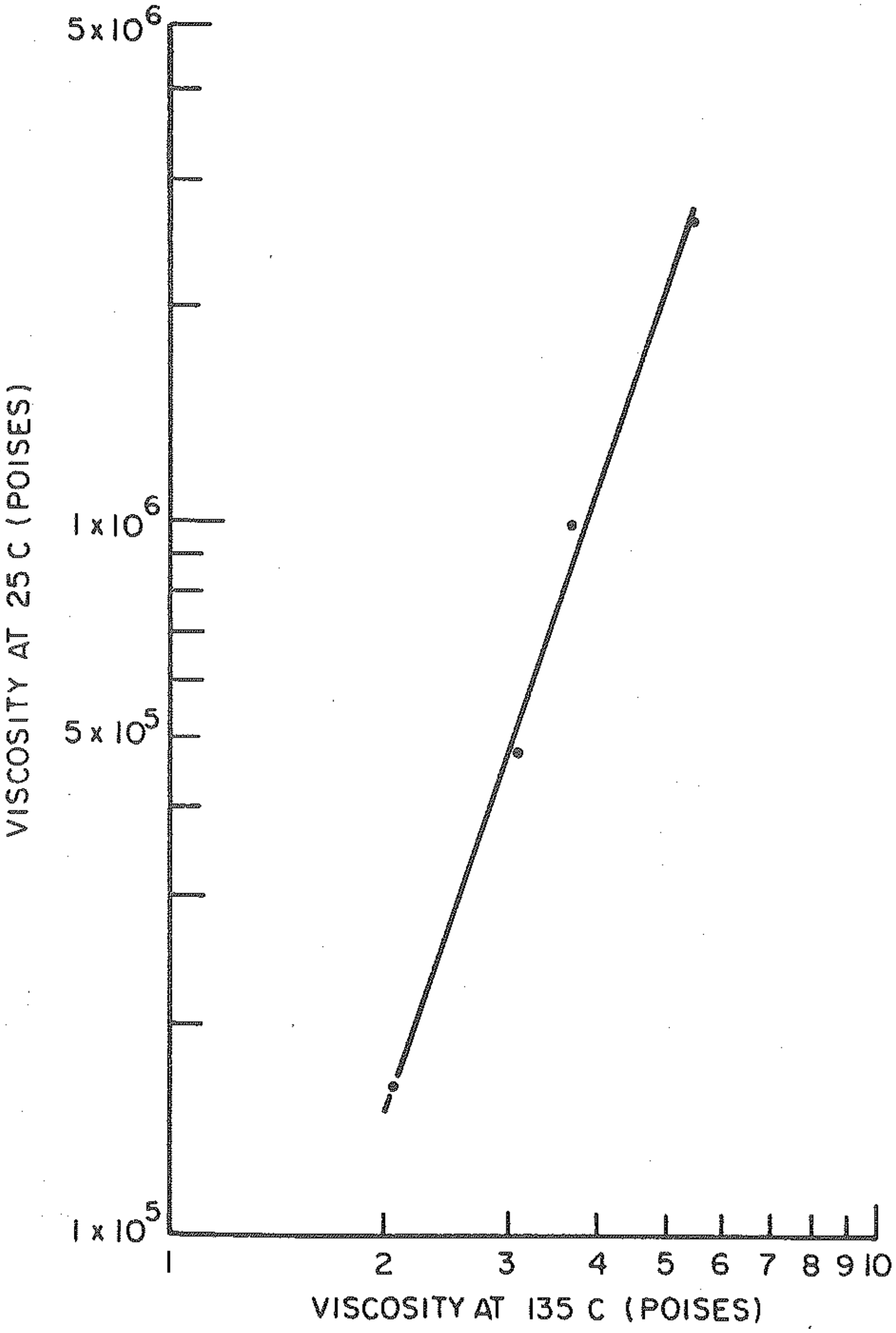


Figure 12. Viscosity at 25 C vs. viscosity at 135 C for I-'74 asphalt.

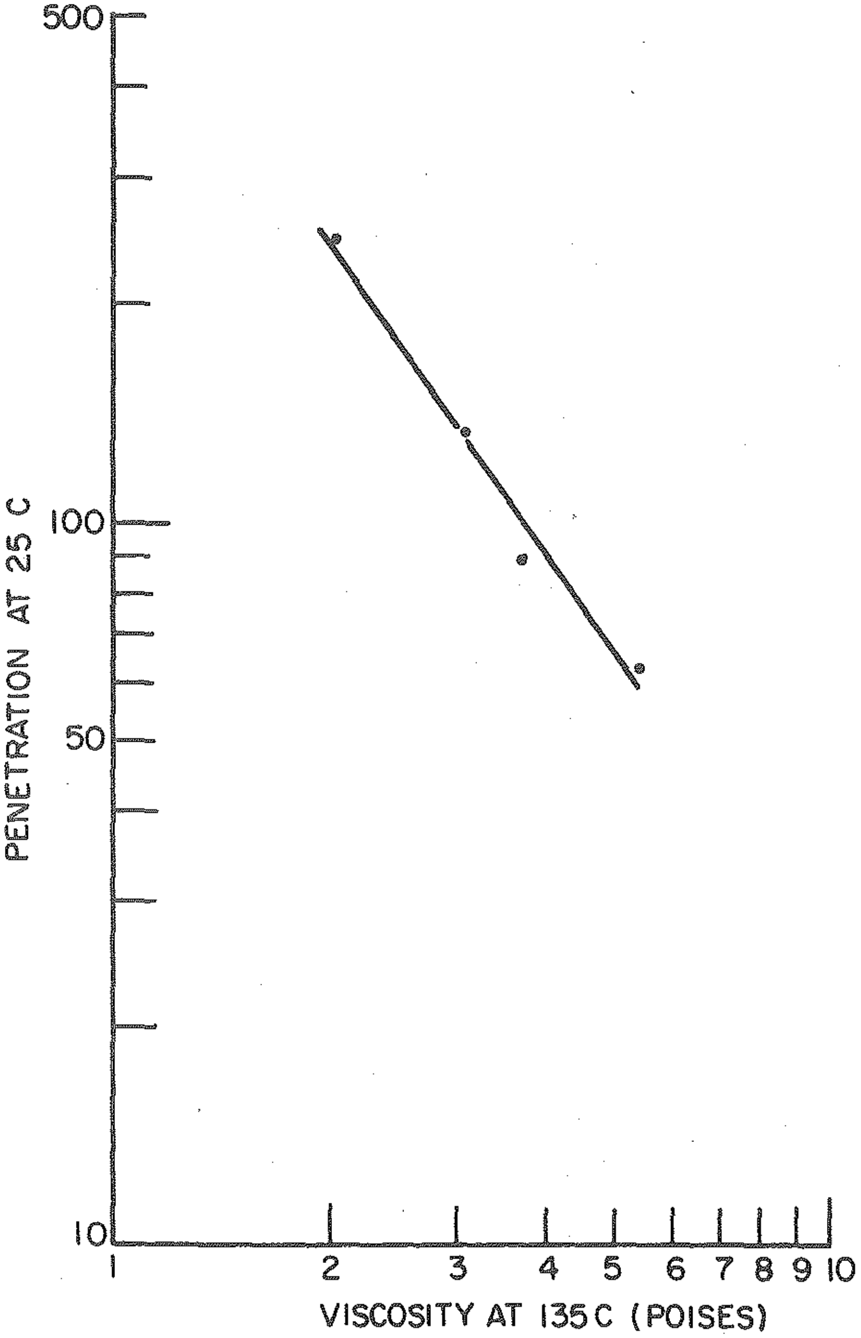


Figure 13. Penetration at 25 C vs. viscosity at 135 C for I-'74 asphalt.

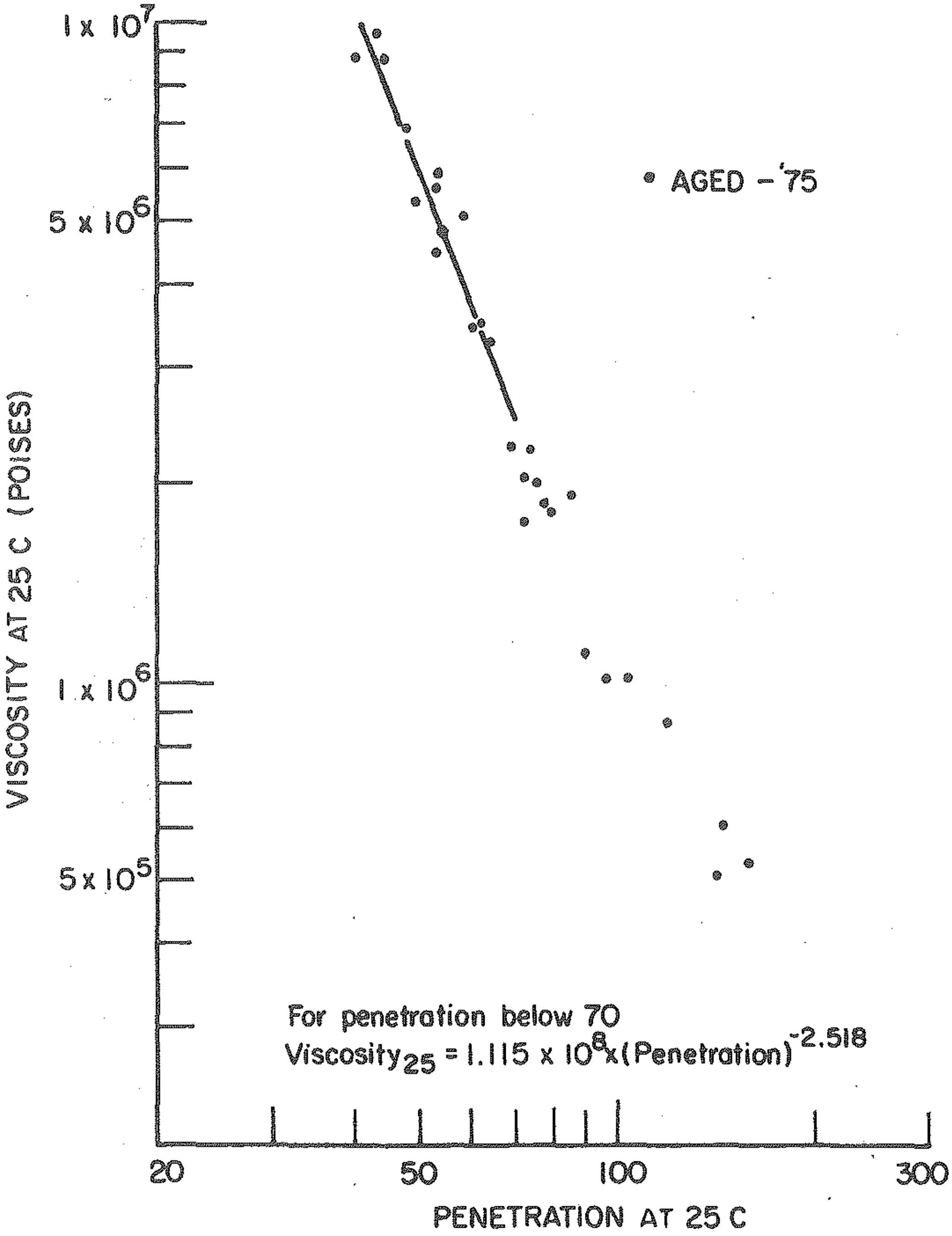


Figure 14. Viscosity vs. penetration at 25 C for aged asphalts.

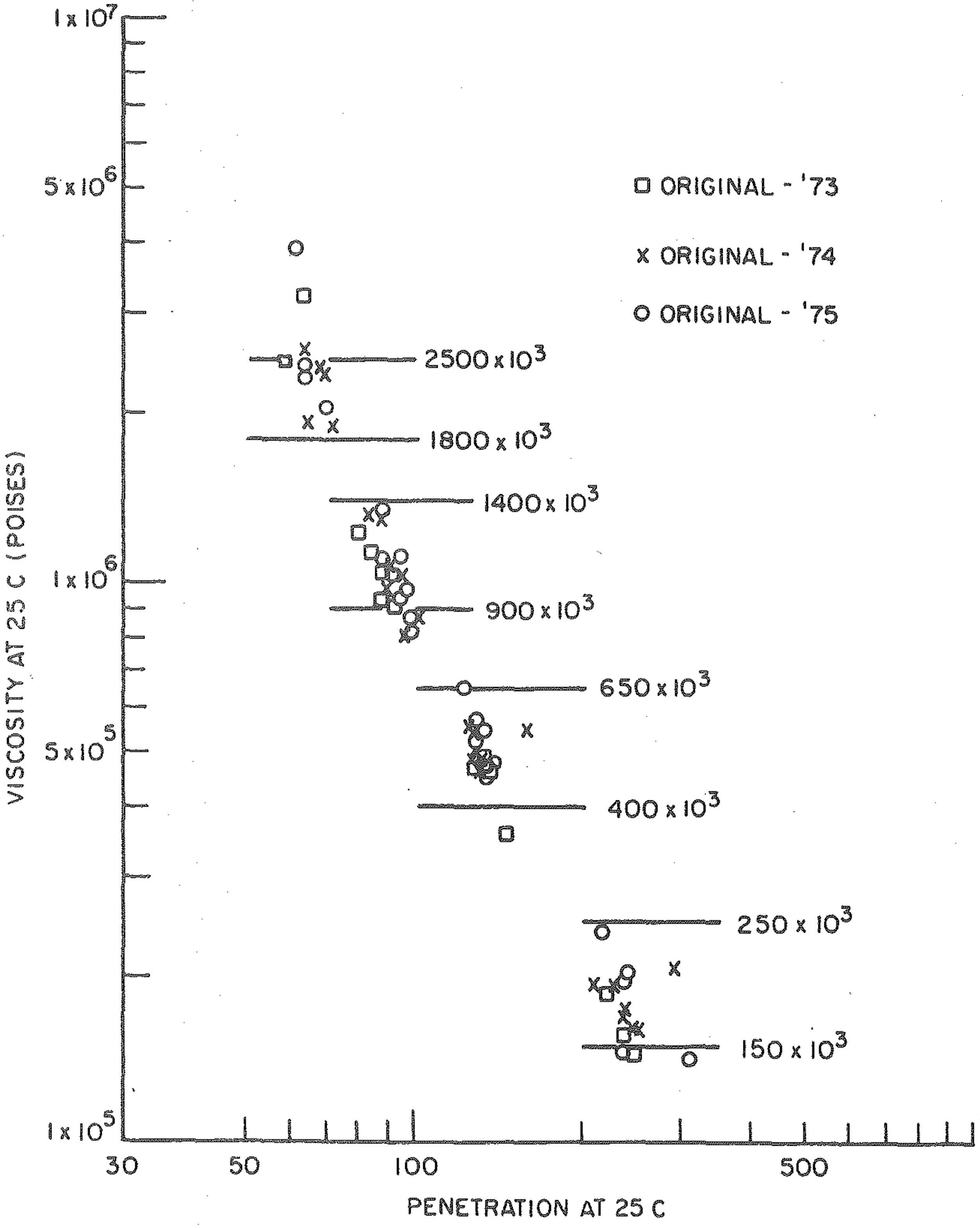


Figure 15. Viscosity vs. penetration at 25 C for original asphalts.

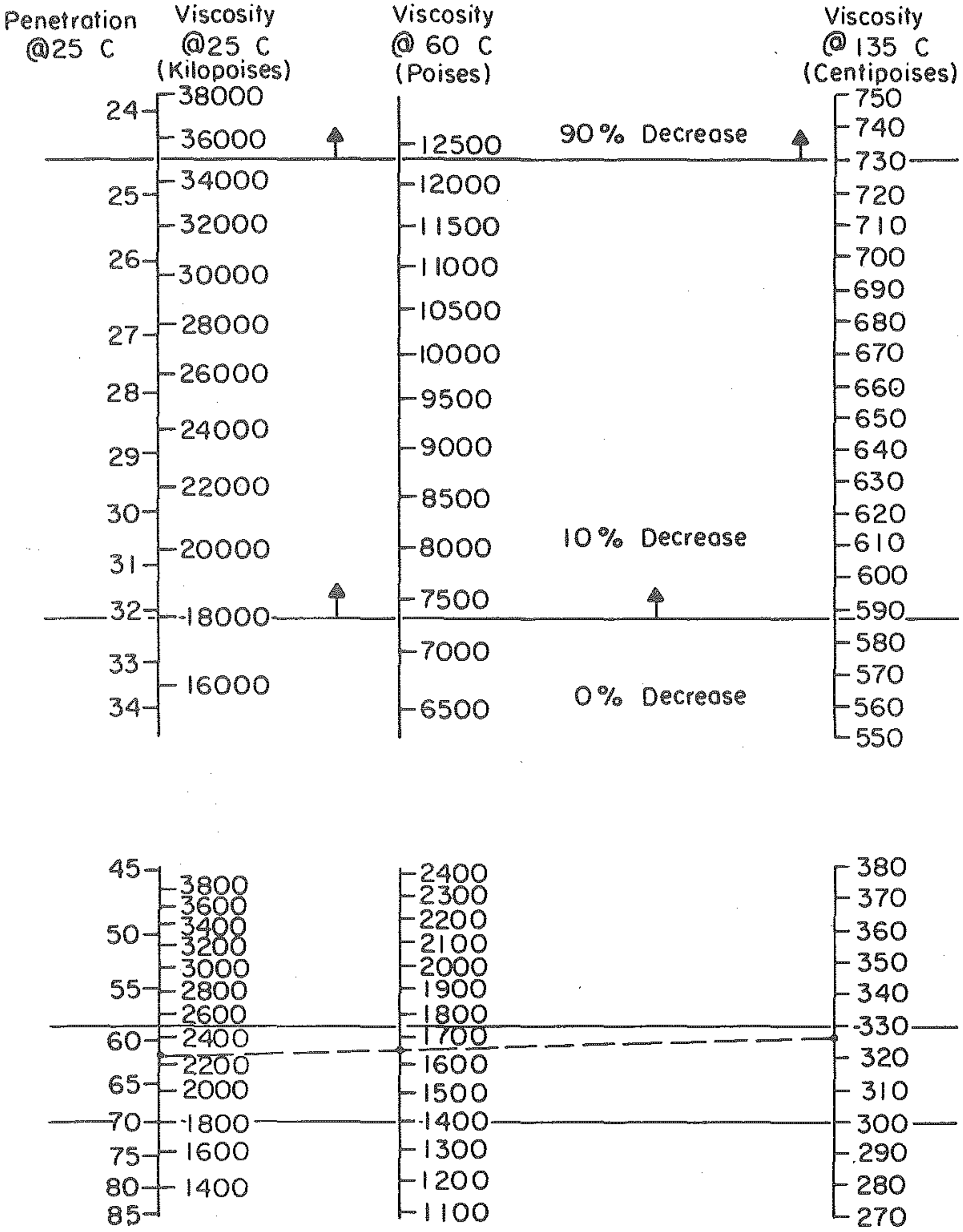


Figure 16. Viscosity grading chart for 1800-2500 kilopoises asphalt at 25 C, source A-'75.

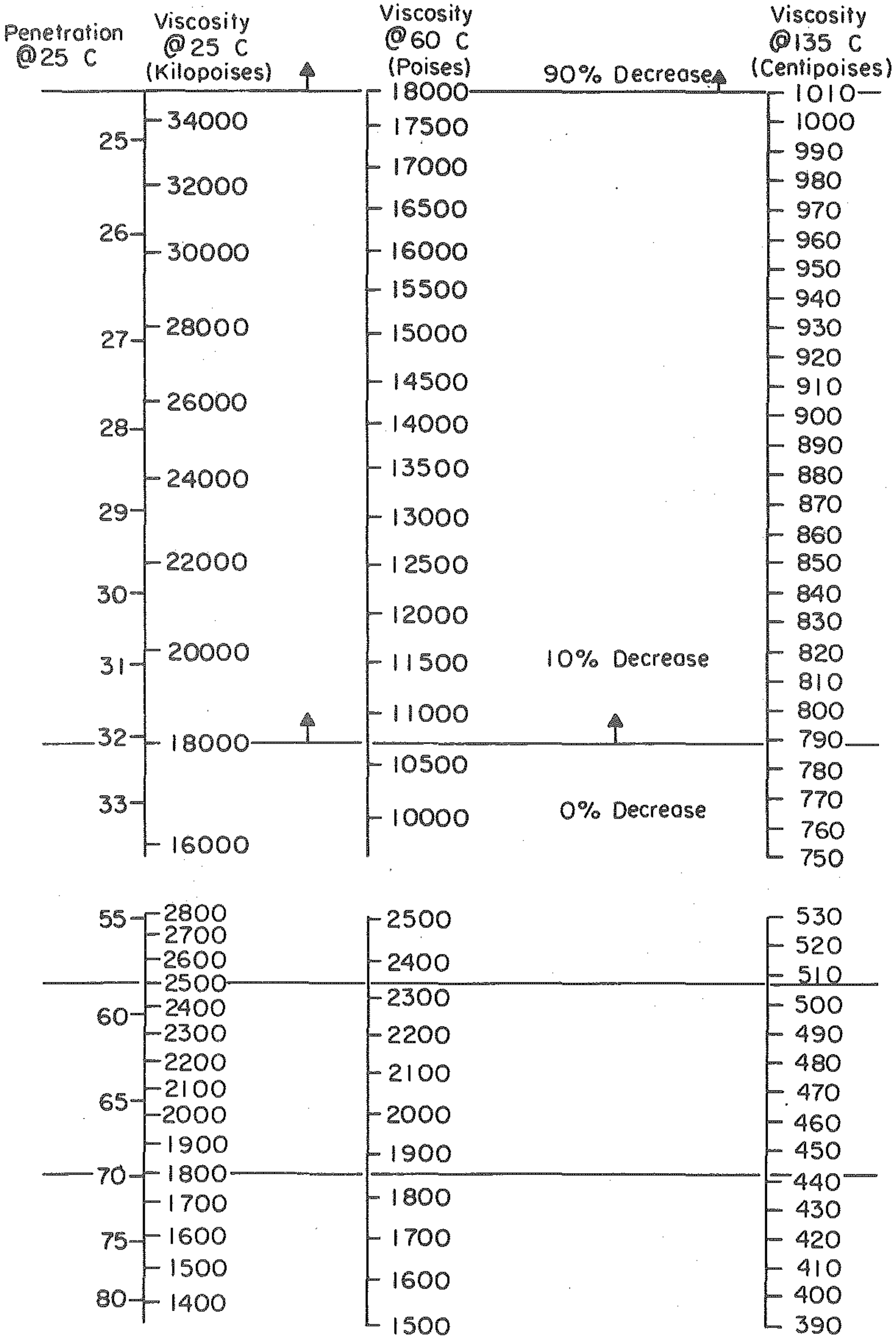


Figure 17. Viscosity grading chart for 1800-2500 kilopoises asphalt at 25 C, source J-'75.

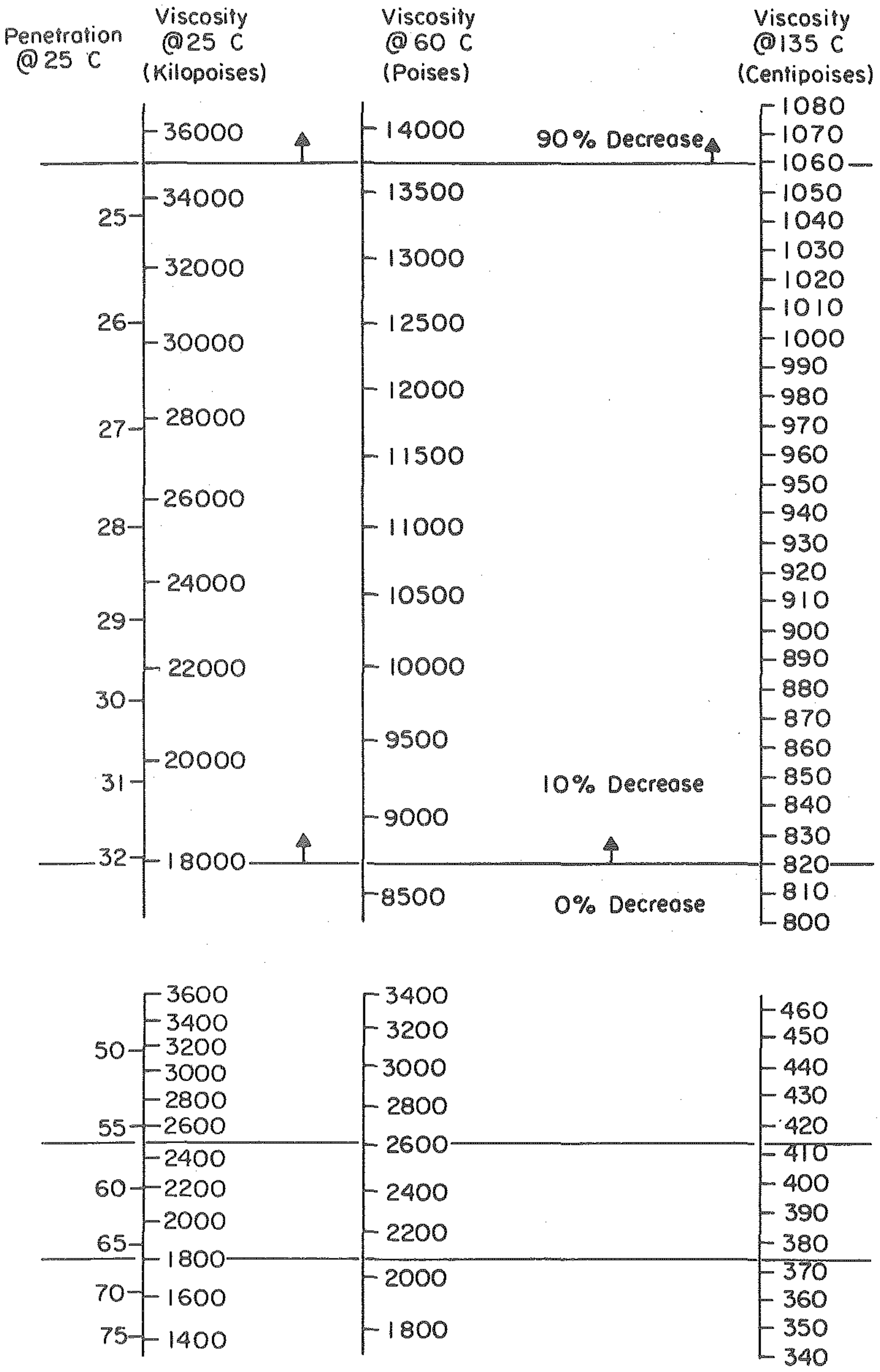


Figure 18. Viscosity grading chart for 1800-2500 kilopoises asphalt at 25 C, source N-'75.

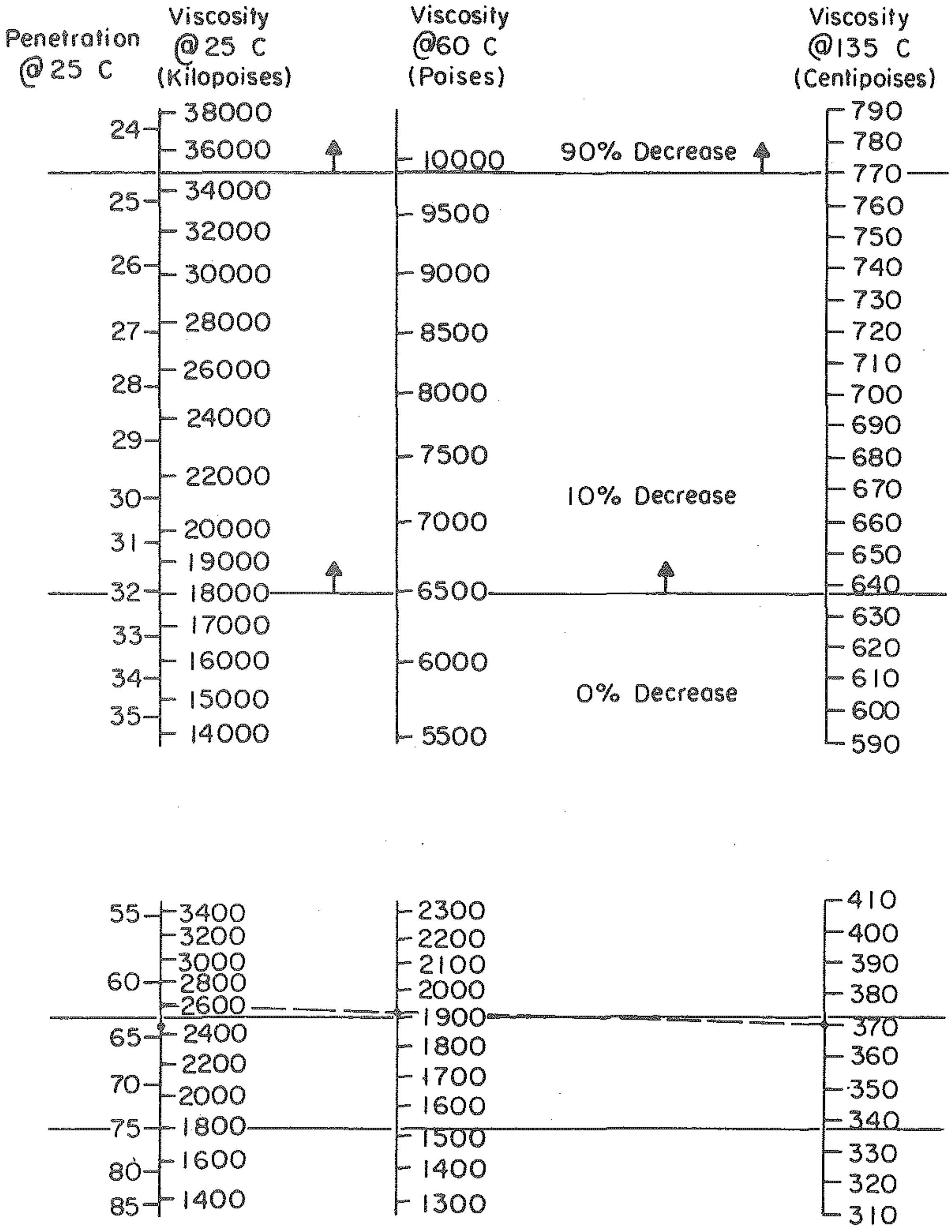


Figure 19. Viscosity grading chart for 1800-2500 kilopoises asphalt at 25 C, source E-'74.

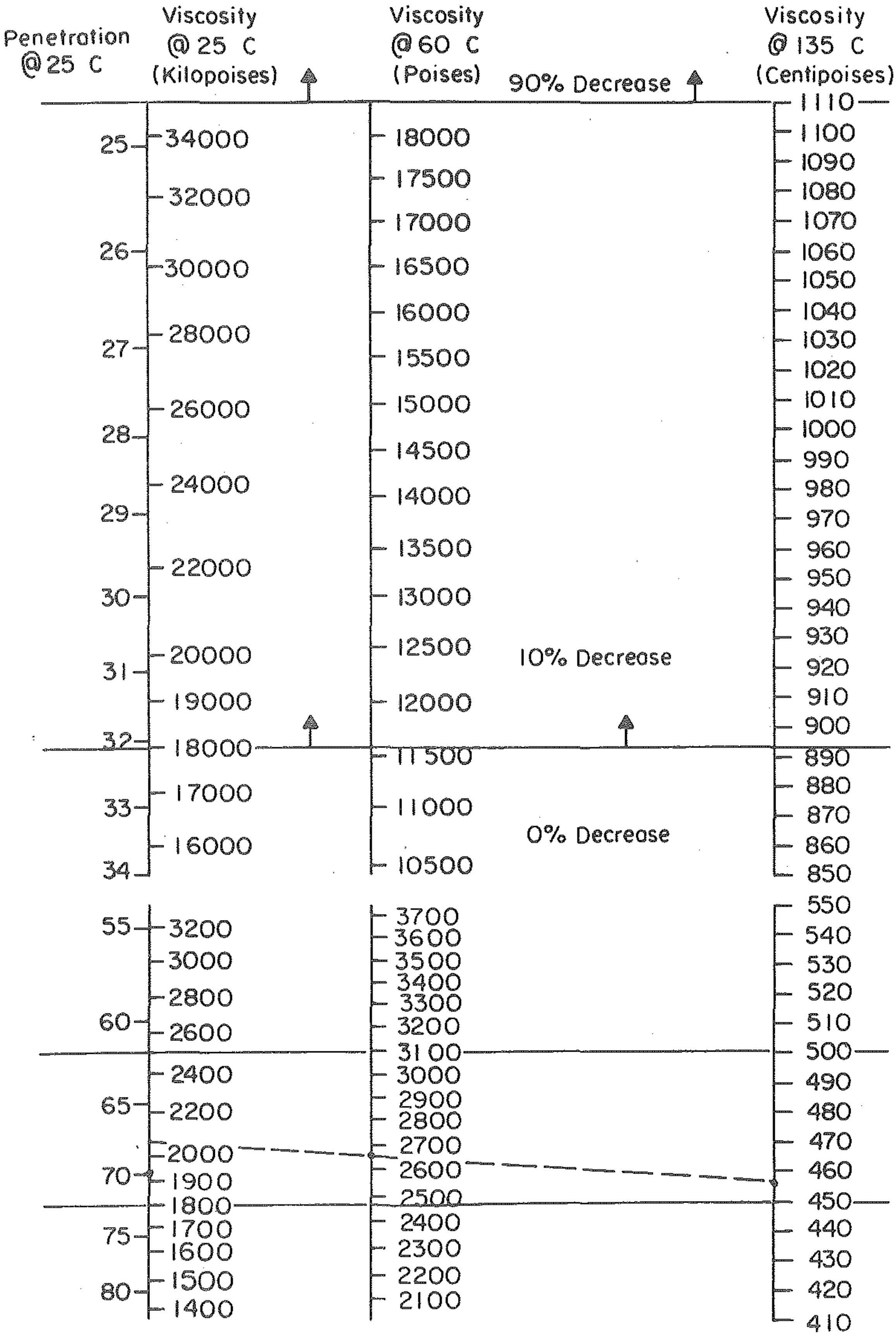


Figure 20. Viscosity grading chart for 1800-2500 kilopoises asphalt at 25 C, source G-'74.

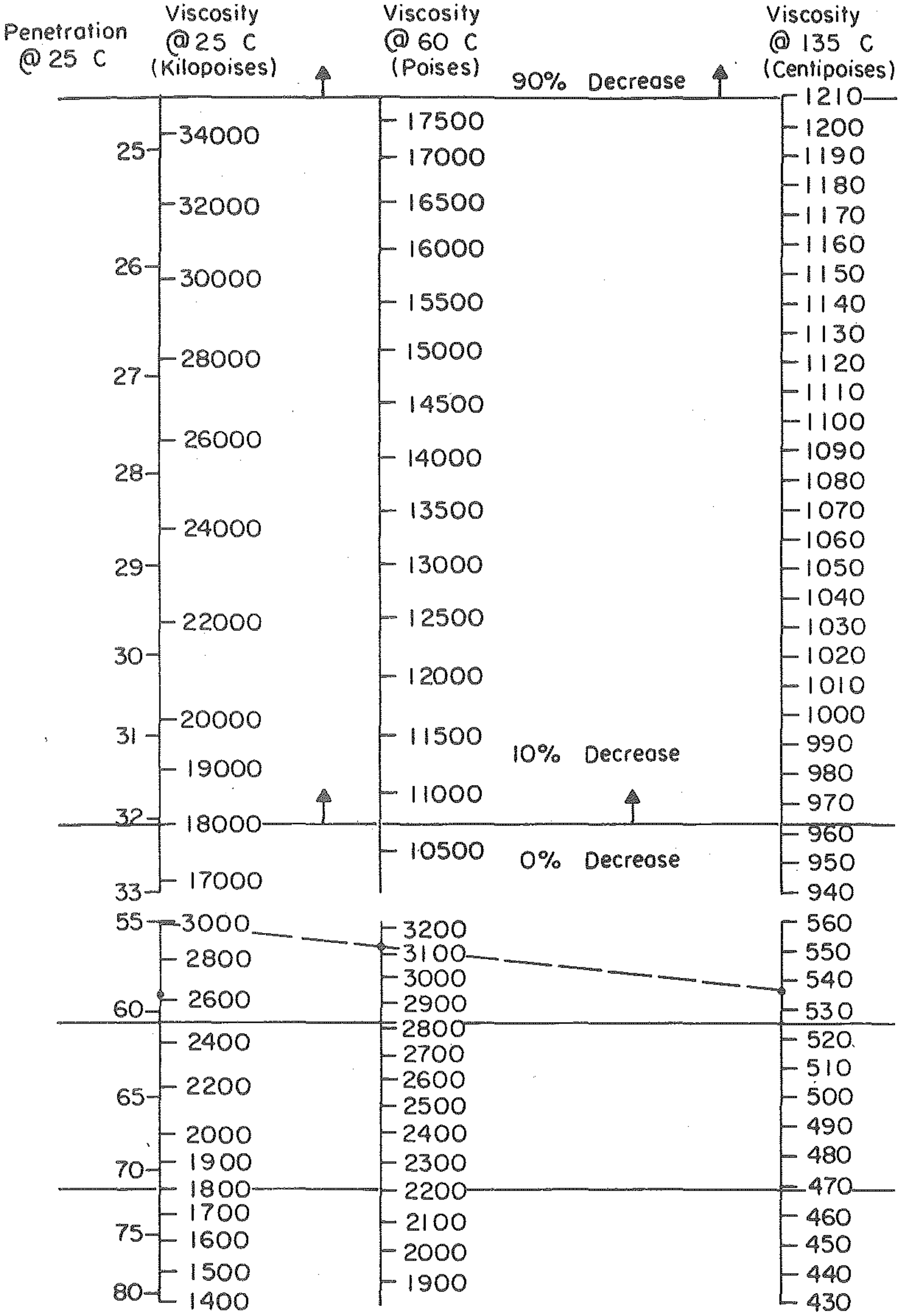


Figure 21. Viscosity grading chart for 1800-2500 kilopoises asphalt at 25 C, source I-'74.

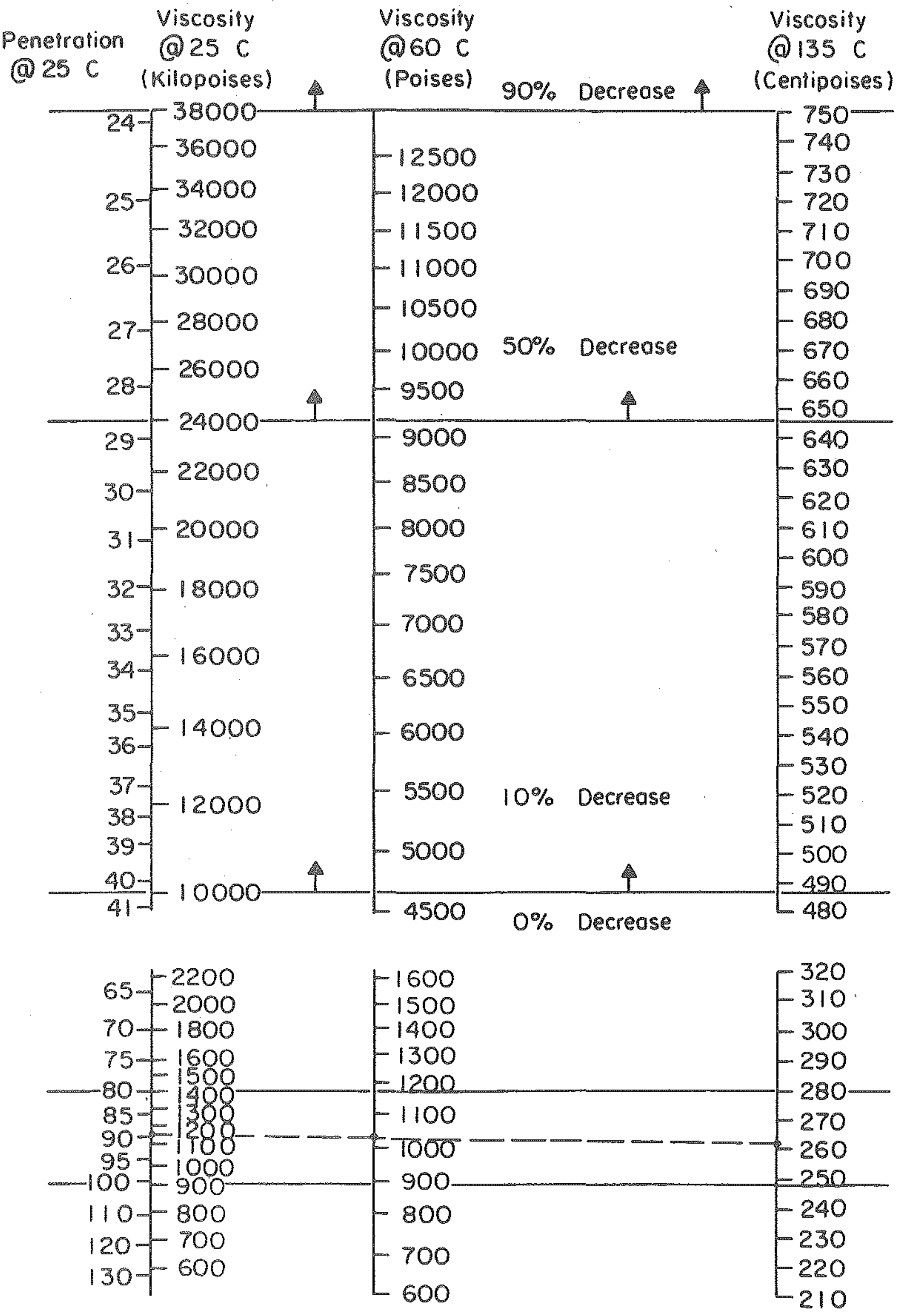


Figure 22. Viscosity grading chart for 900-1400 kilopoises asphalt at 25 C, source A-'75.

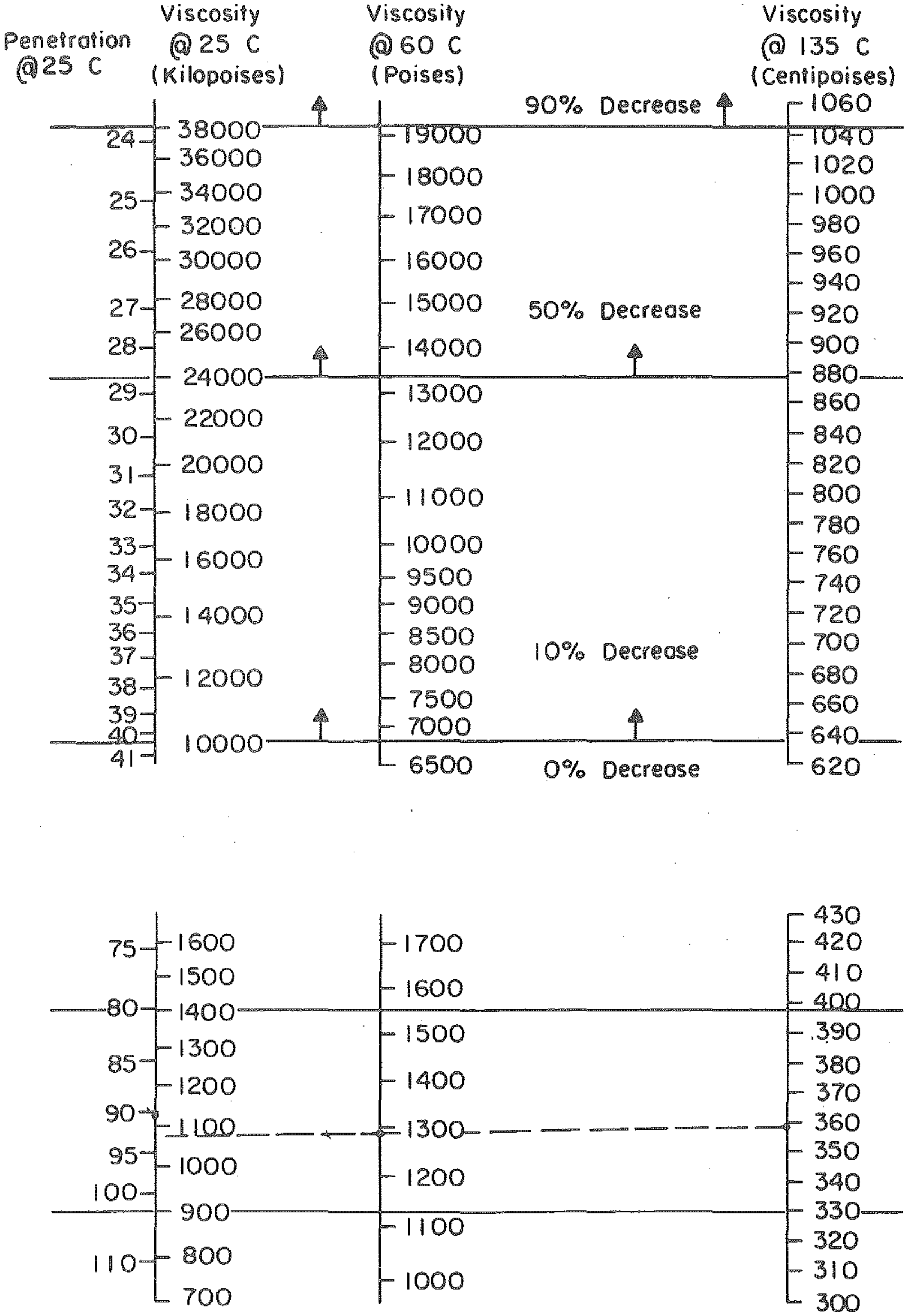


Figure 23. Viscosity grading chart for 900-1400 kilopoises asphalt at 25 C, source J-'75.

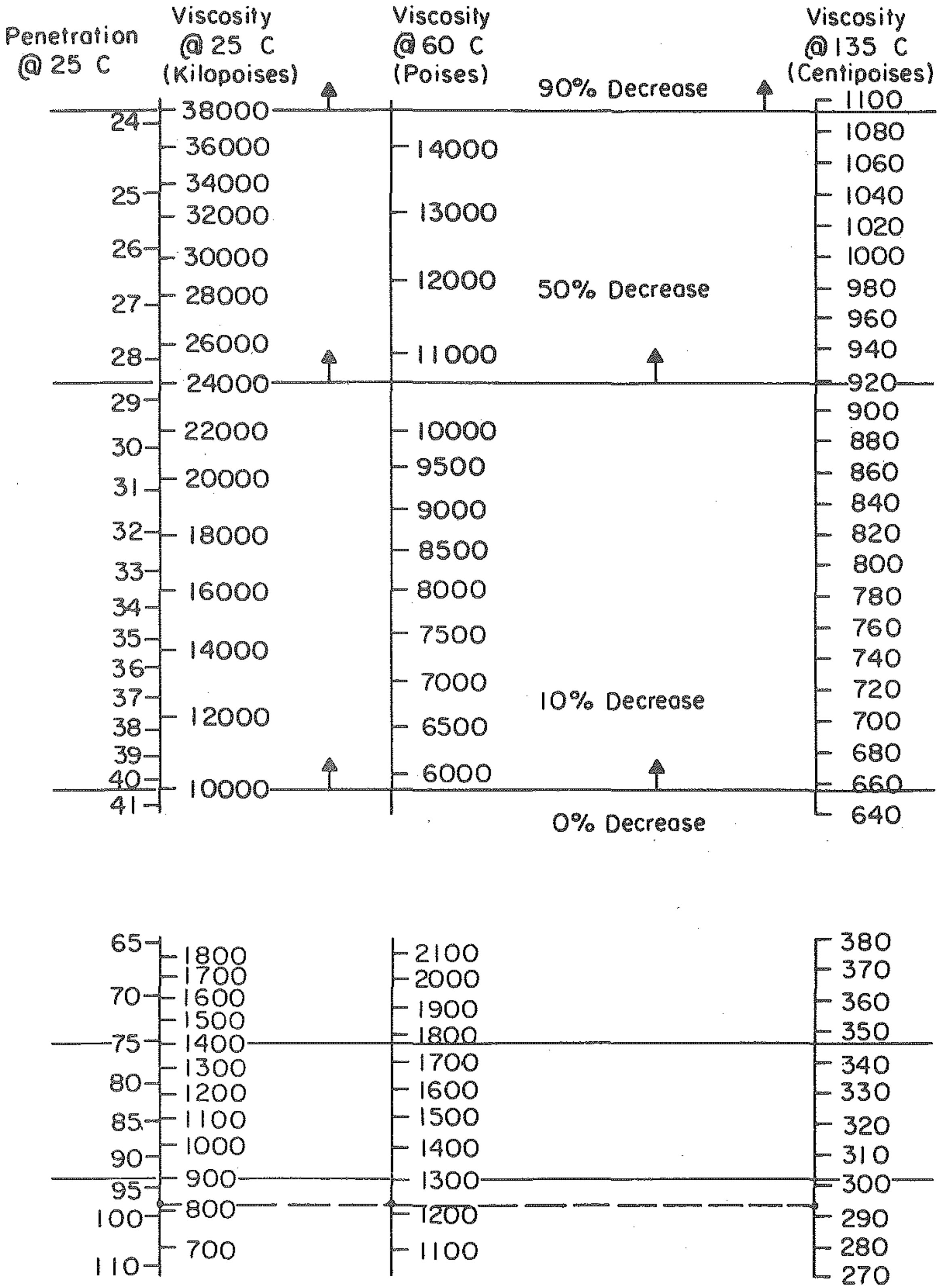


Figure 24. Viscosity grading chart for 900-1400 kilopoises asphalt at 25 C, source N-'75.

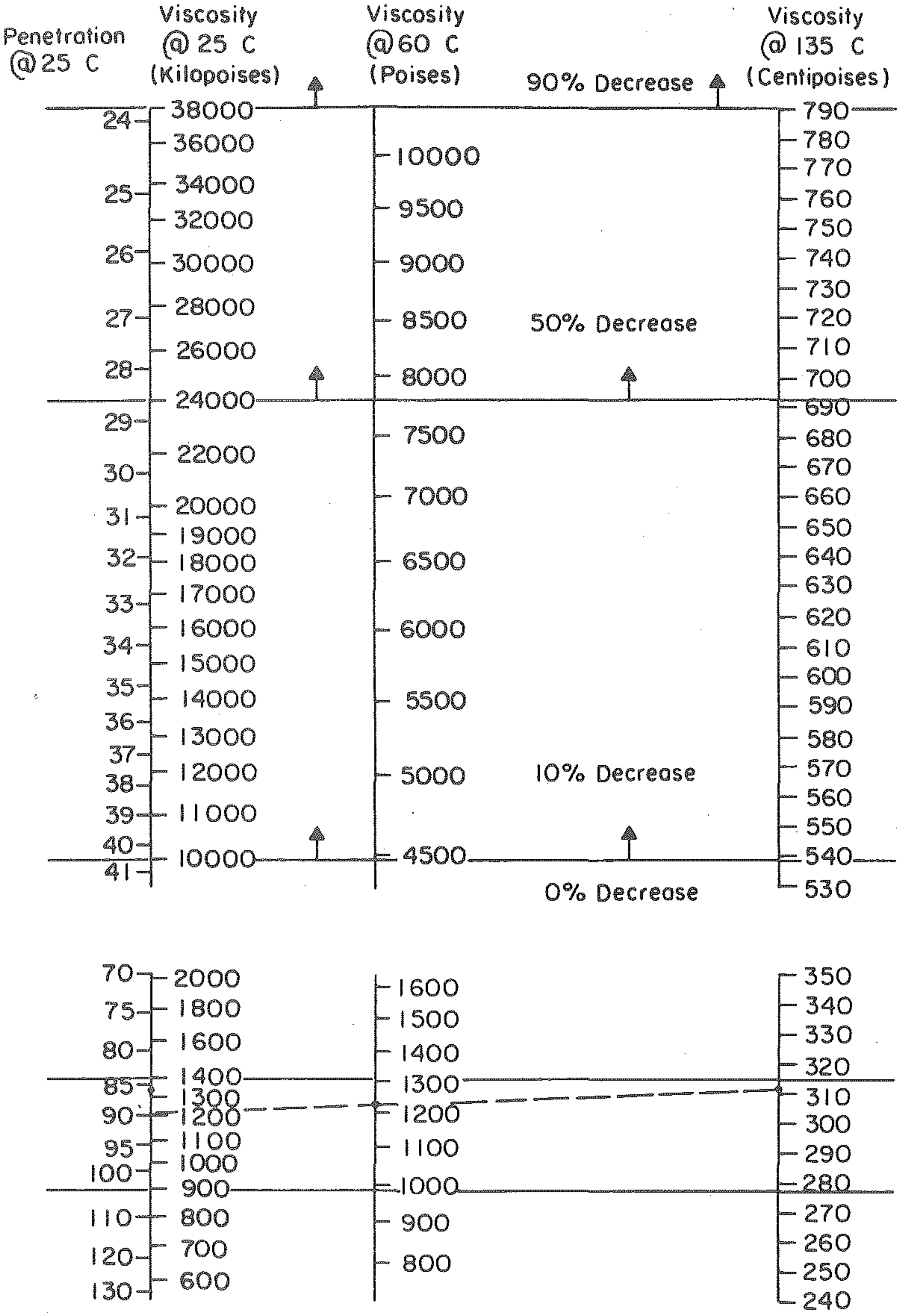


Figure 25. Viscosity grading chart for 900-1400 kilopoises asphalt at 25 C, source E-'74.

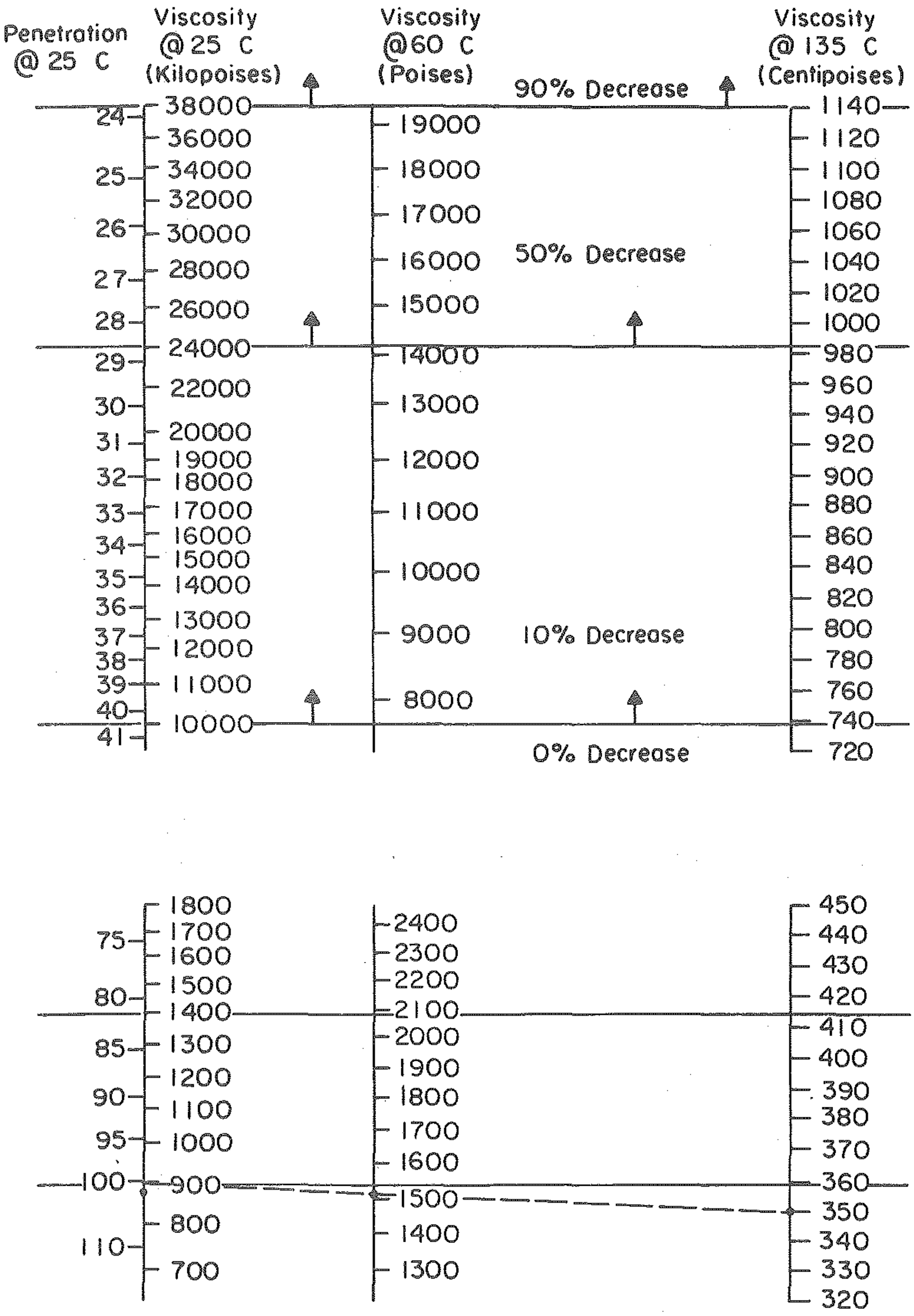


Figure 26. Viscosity grading chart for 900-1400 kilopoises asphalt at 25 C, source G-'74.

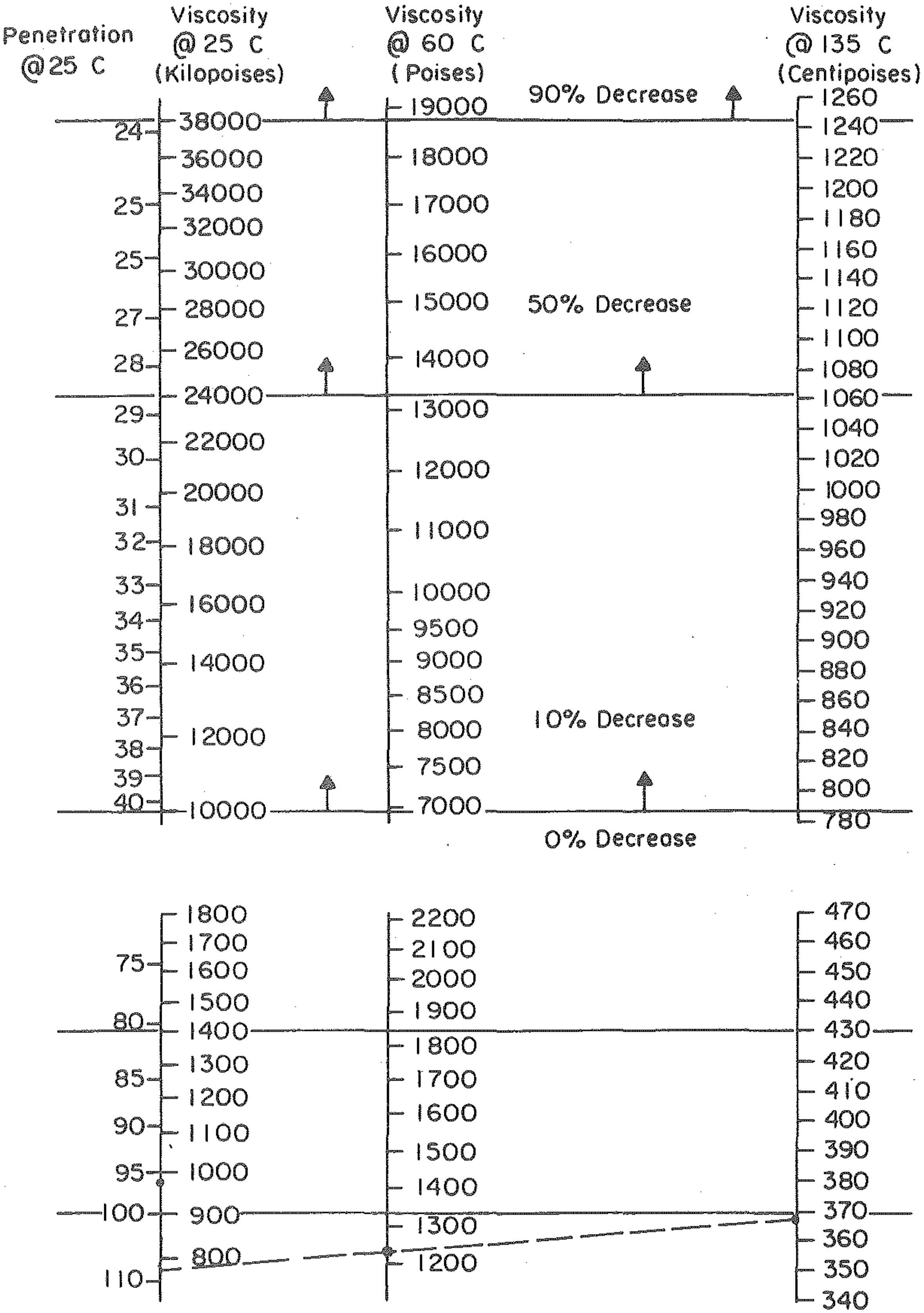


Figure 27. Viscosity grading chart for 900-1400 kilopoises asphalt at 25 C, source I-'74.

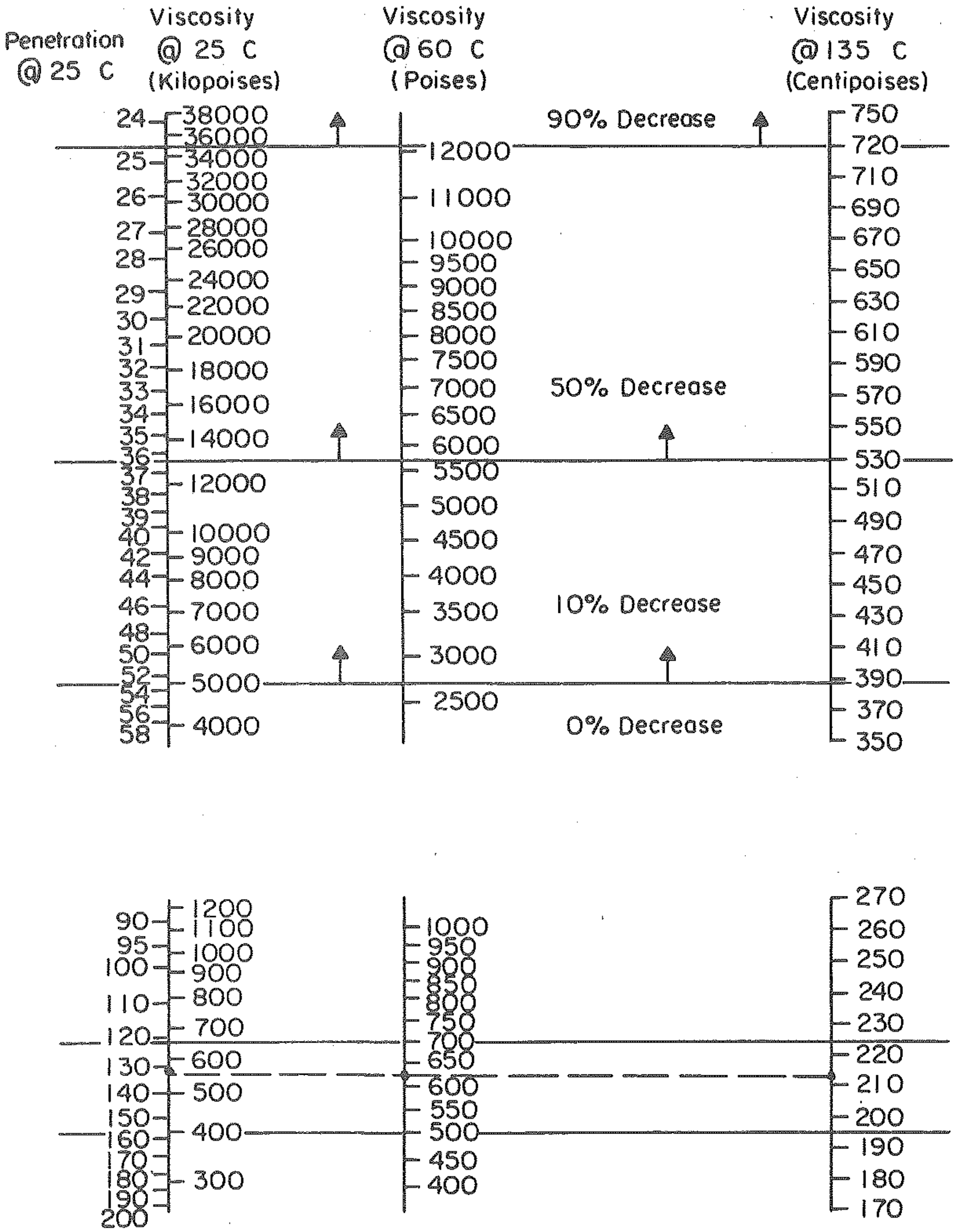


Figure 28. Viscosity grading chart for 400-650 kilopoises asphalt at 25 C, source A-'75.

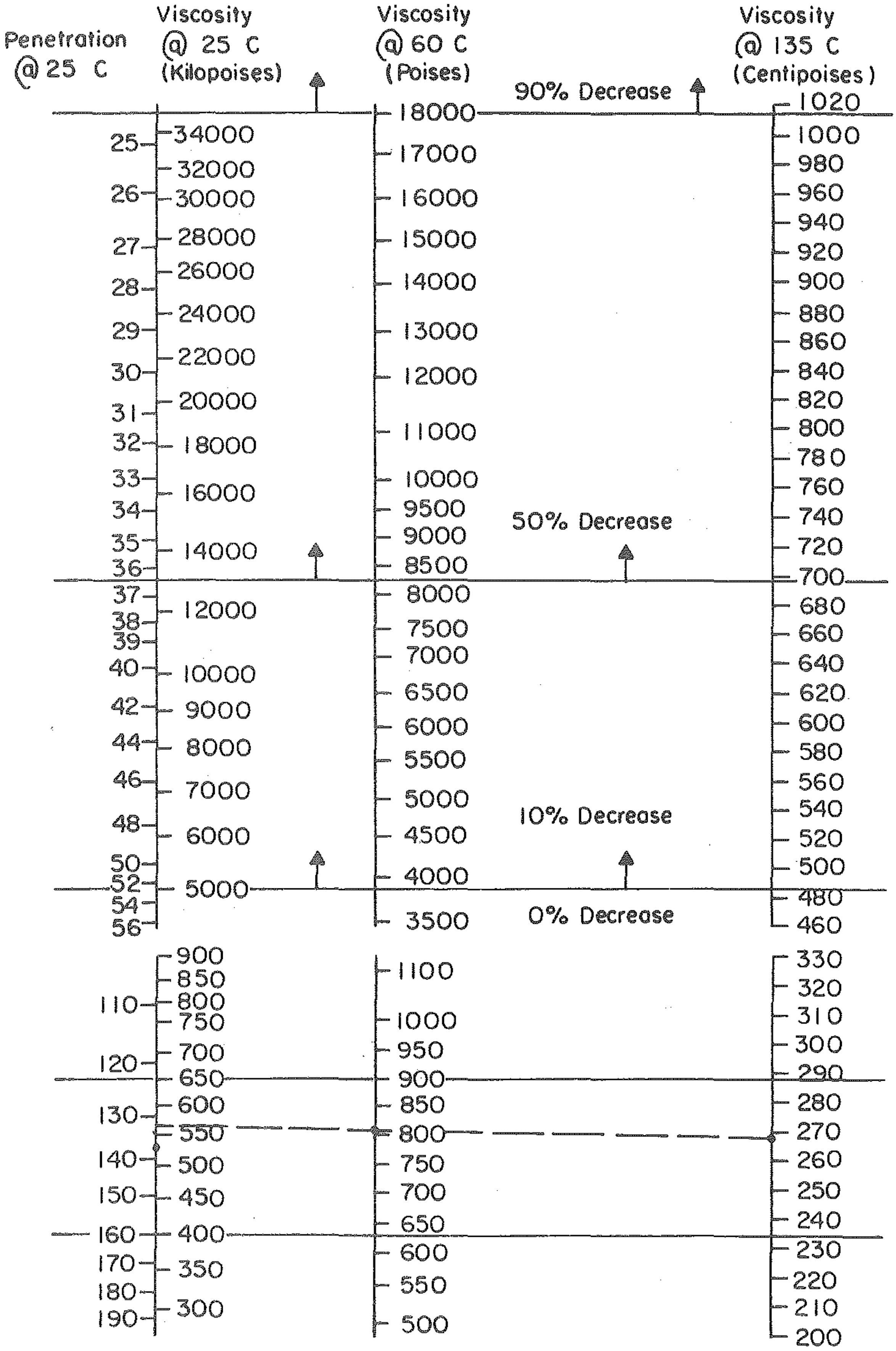


Figure 29. Viscosity grading chart for 400-650 kilopoises asphalt at 25 C, source J-'75.

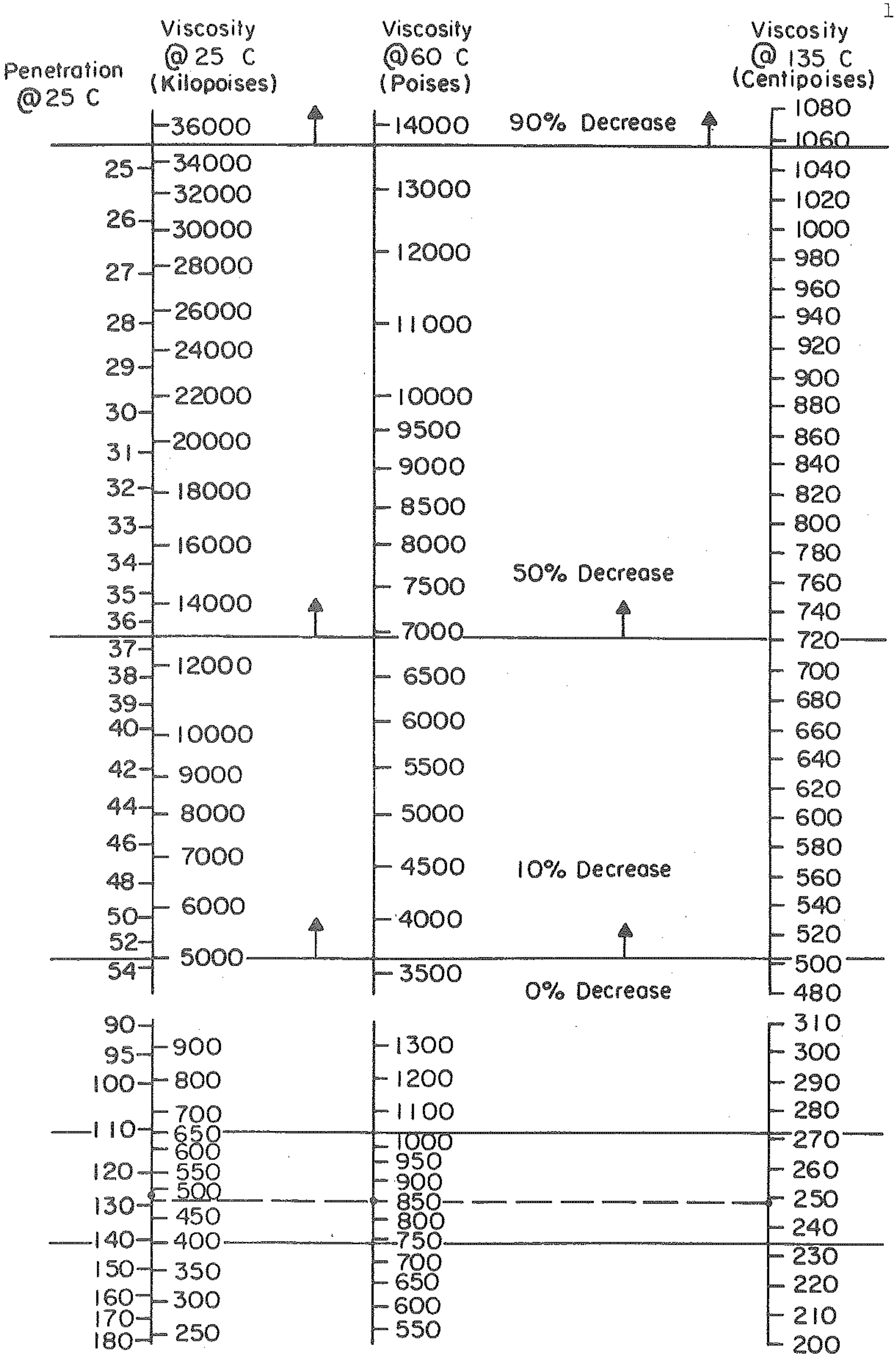


Figure 30. Viscosity grading chart for 400-650 kilopoises asphalt at 25 C, source N-'75.

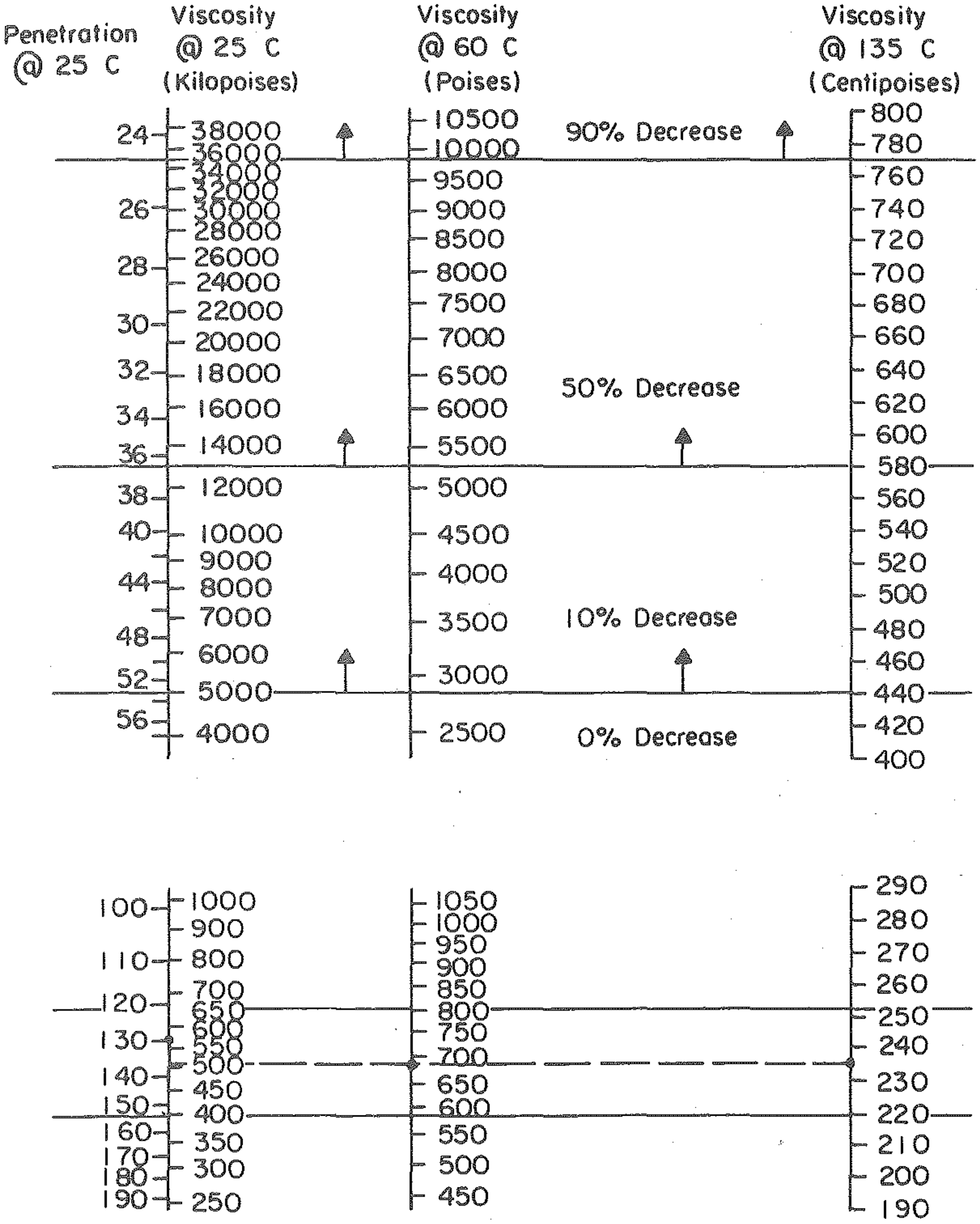


Figure 31. Viscosity grading chart for 400-650 kilopoises asphalt at 25 C, source E-'74.

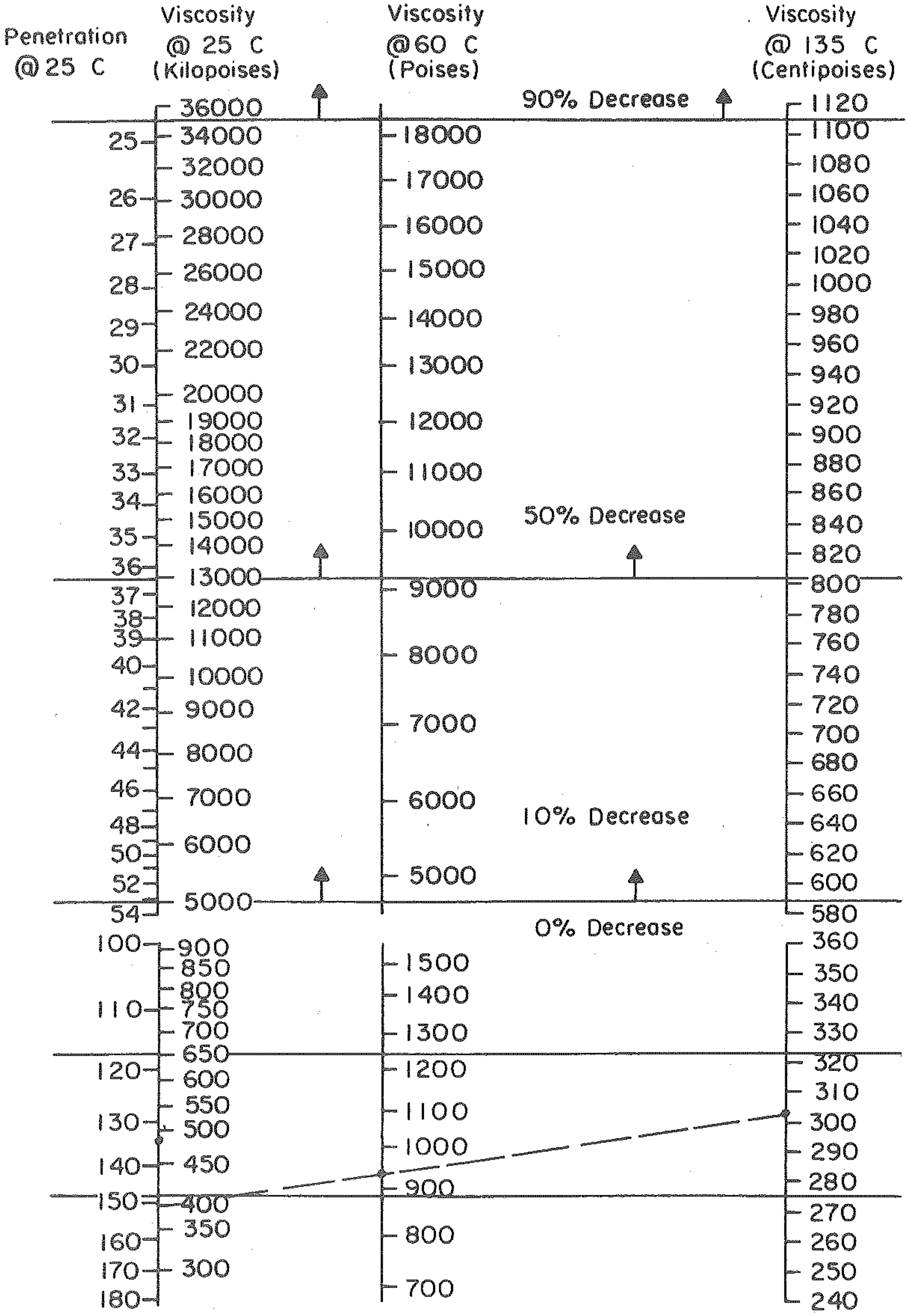


Figure 32. Viscosity grading chart for 400-650 kilopoises asphalt at 25 C, source G-'74.

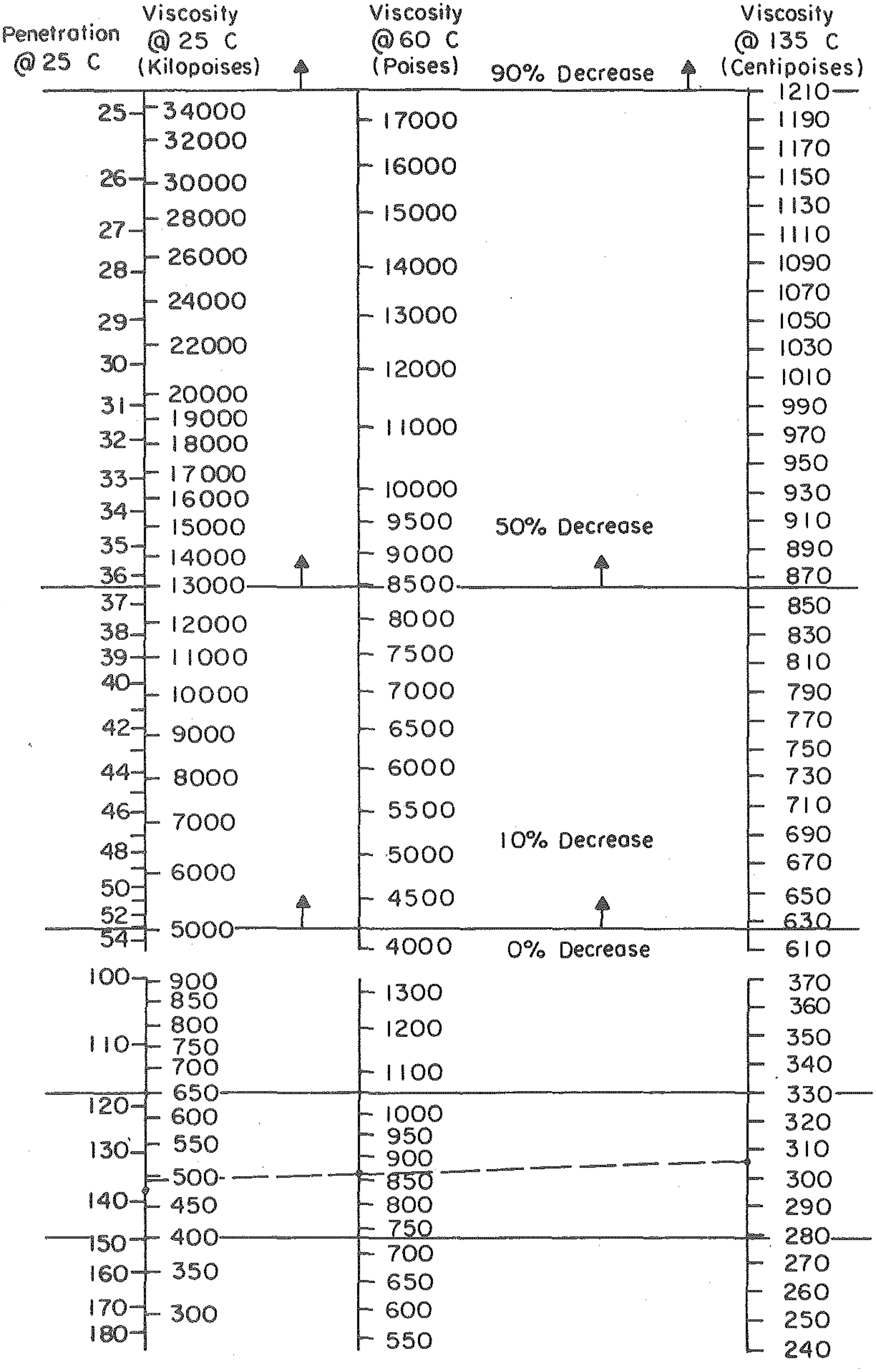


Figure 33. Viscosity grading chart for 400-650 kilopoises asphalt at 25 C, source I-'74.

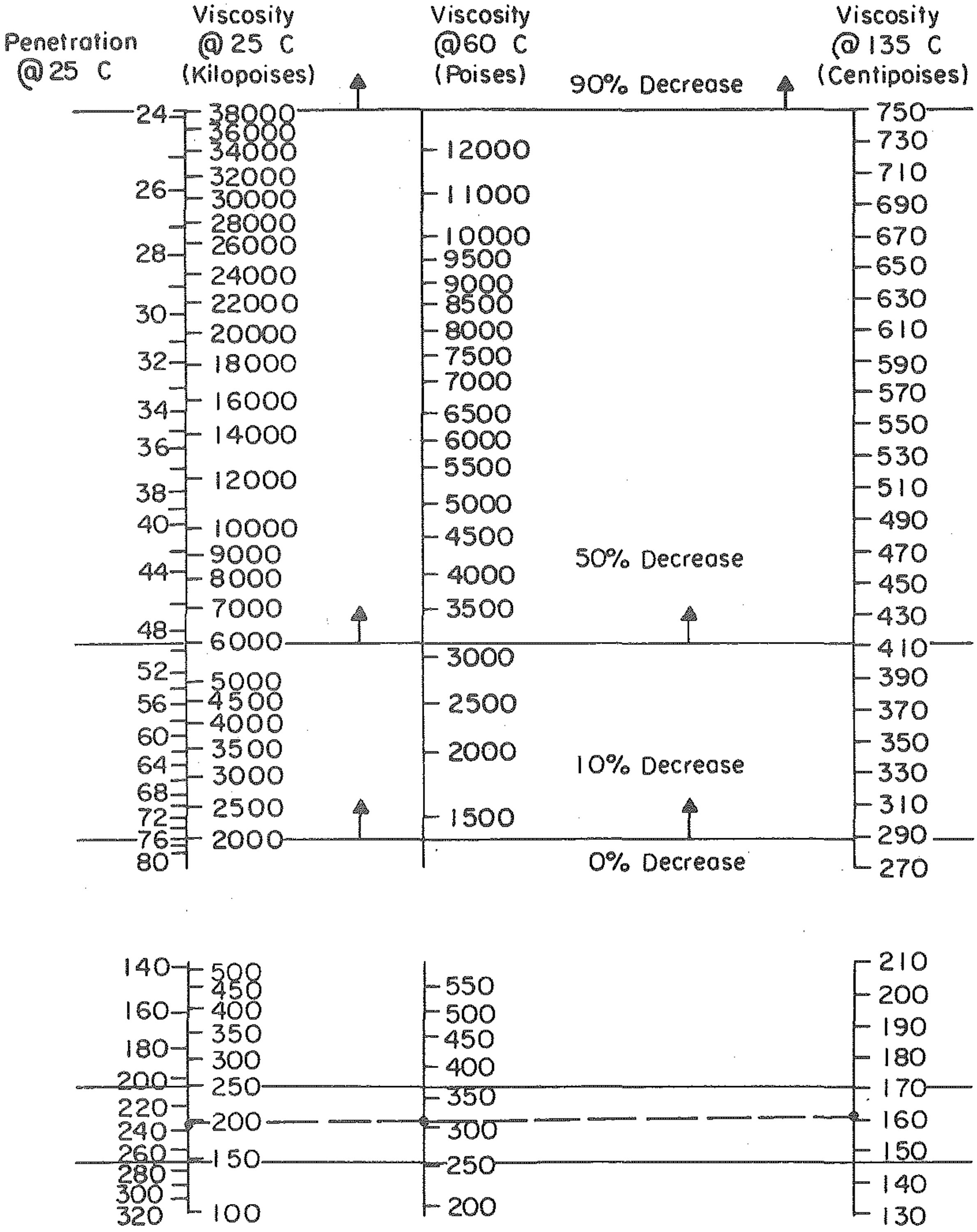


Figure 34. Viscosity grading chart for 150-250 kilopoises asphalt at 25 C, source A-'75.

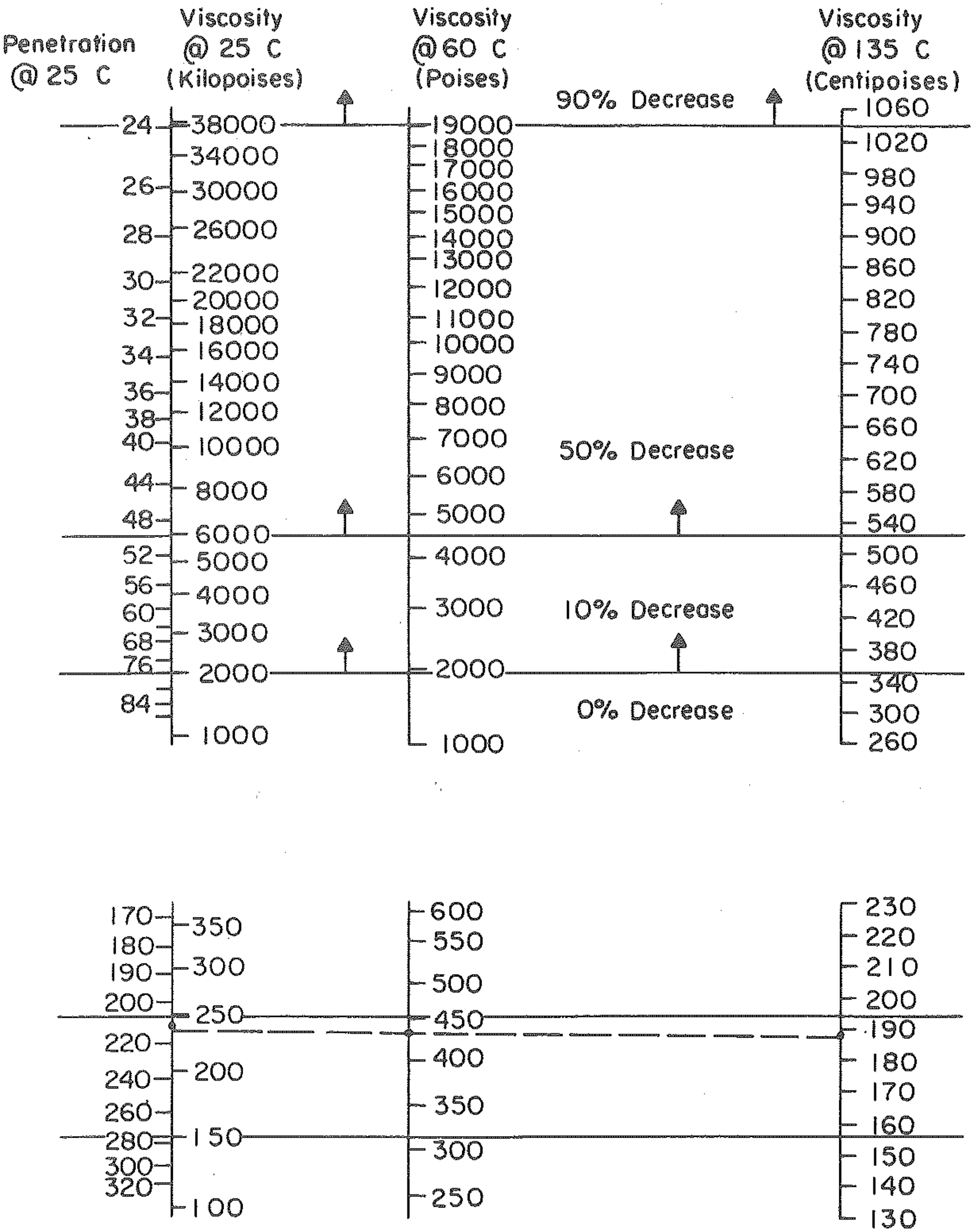


Figure 35. Viscosity grading chart for 150-250 kilopoises asphalt at 25 C, source J-'75.

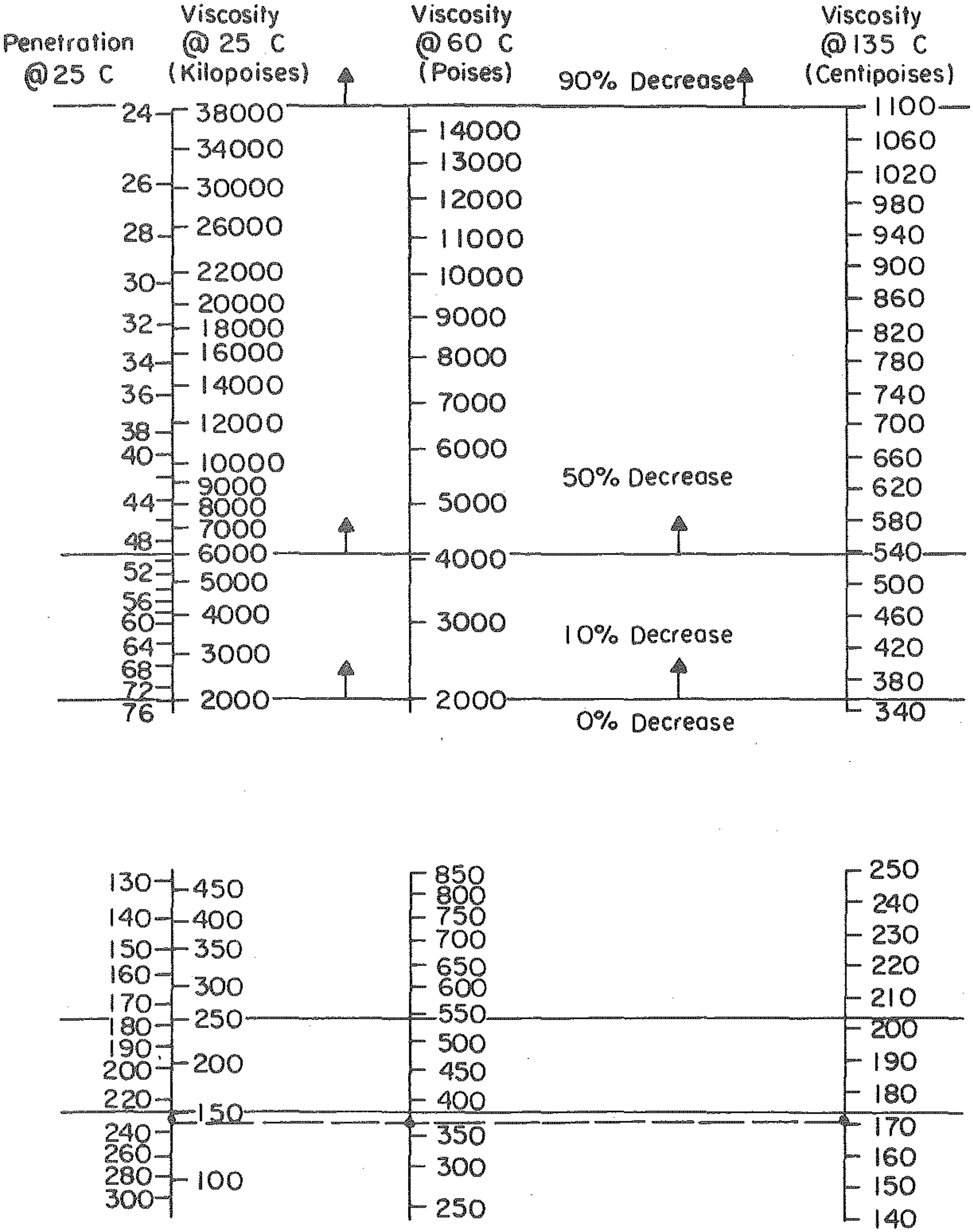


Figure 36. Viscosity grading chart for 150-250 kilopoises asphalt at 25 C, source N-'75.

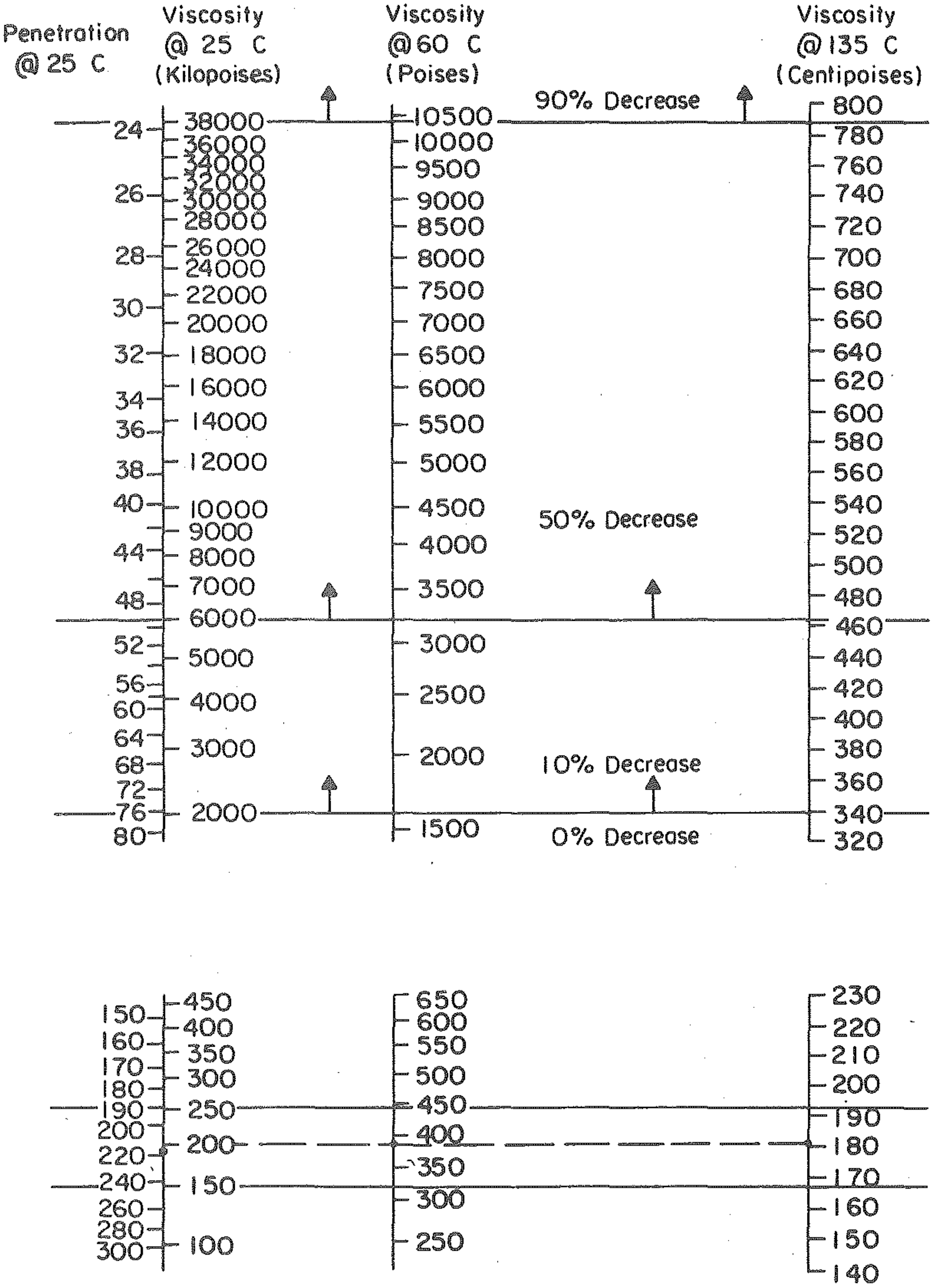


Figure 37. Viscosity grading chart for 150-250 kilopoises asphalt at 25 C, source E-'74.

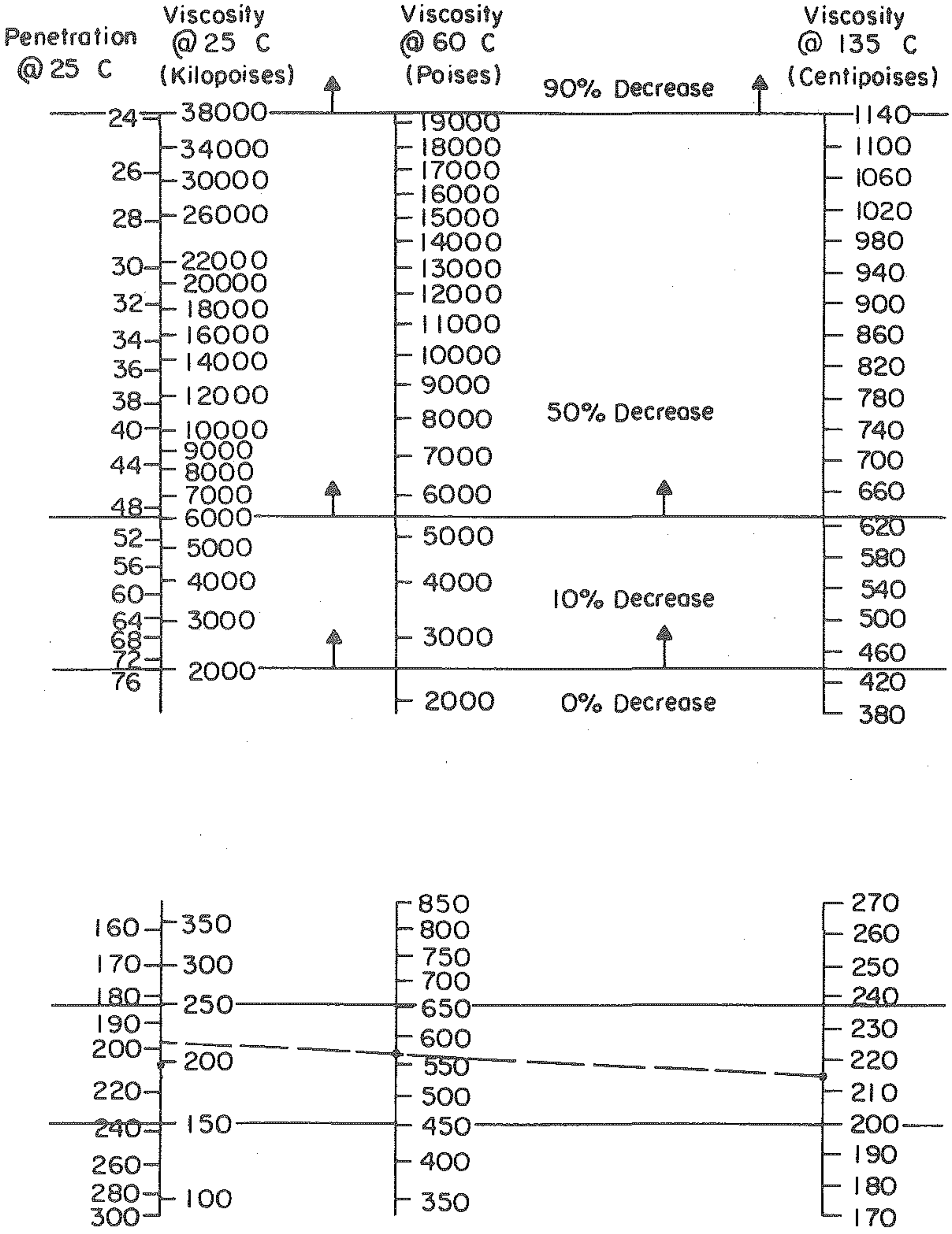


Figure 38. Viscosity grading chart for 150-250 kilopoises asphalt at 25 C, source G-'74.

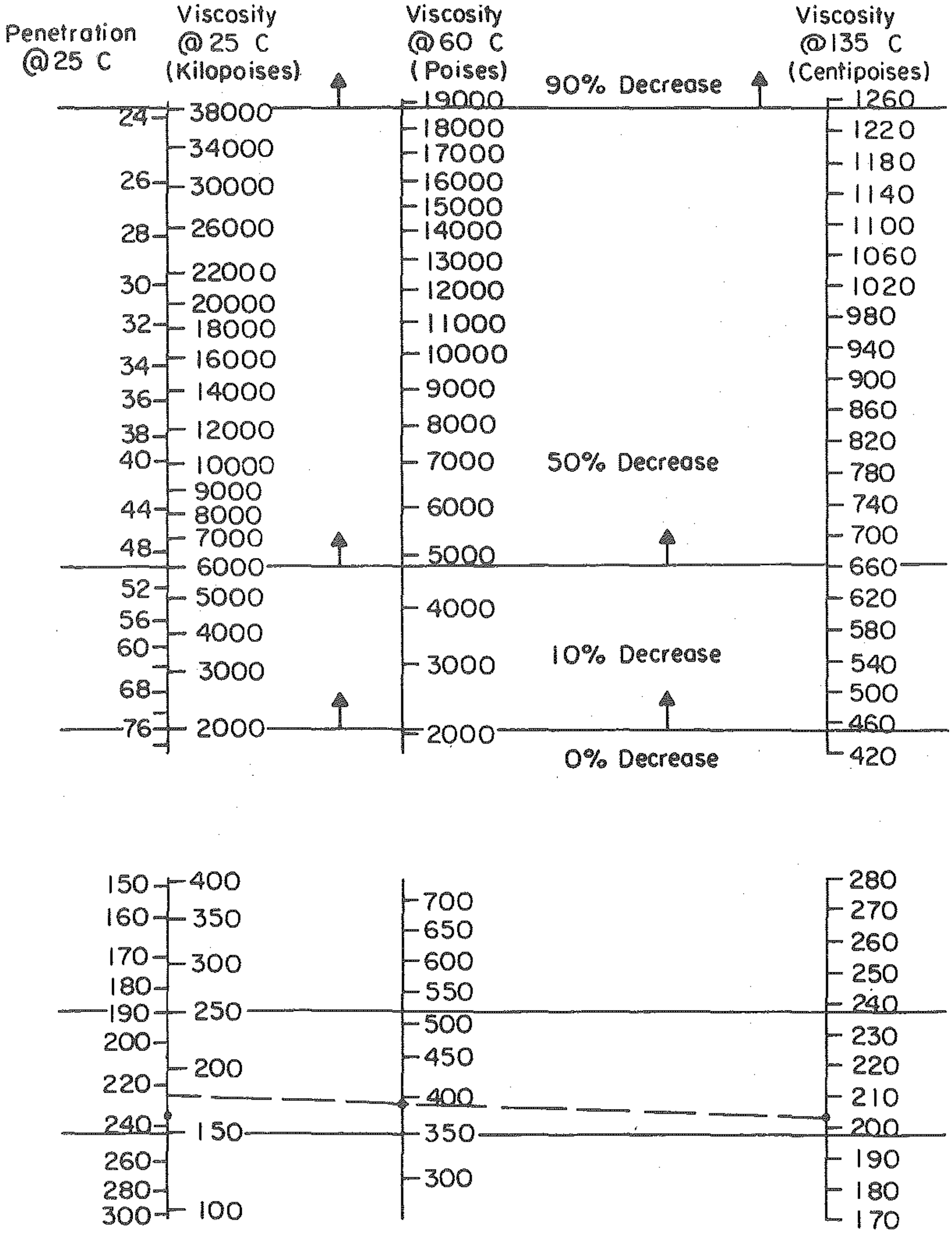


Figure 39. Viscosity grading chart for 150-250 kilopoises asphalt at 25 C, source I'74.

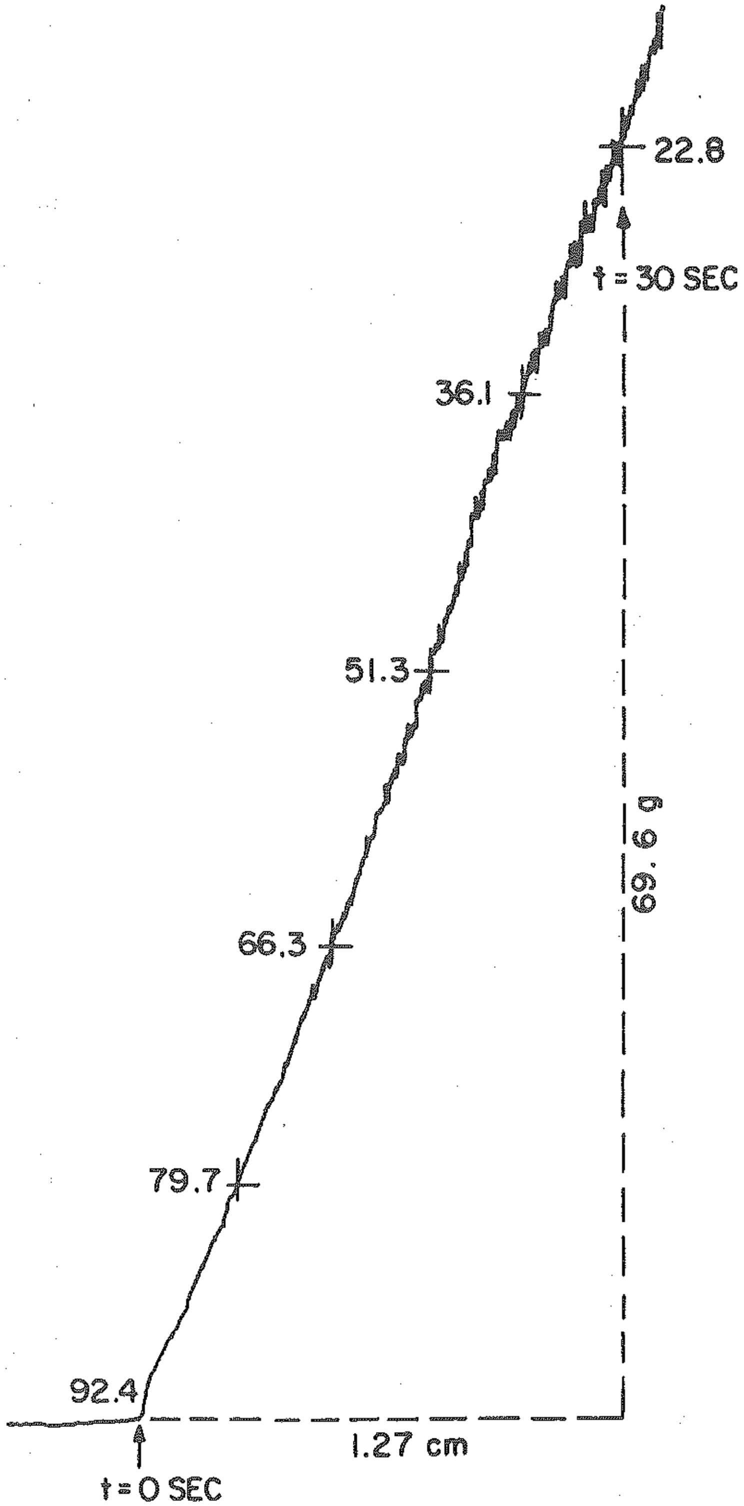


Figure 40. Tracing from a strip chart recorder (example).

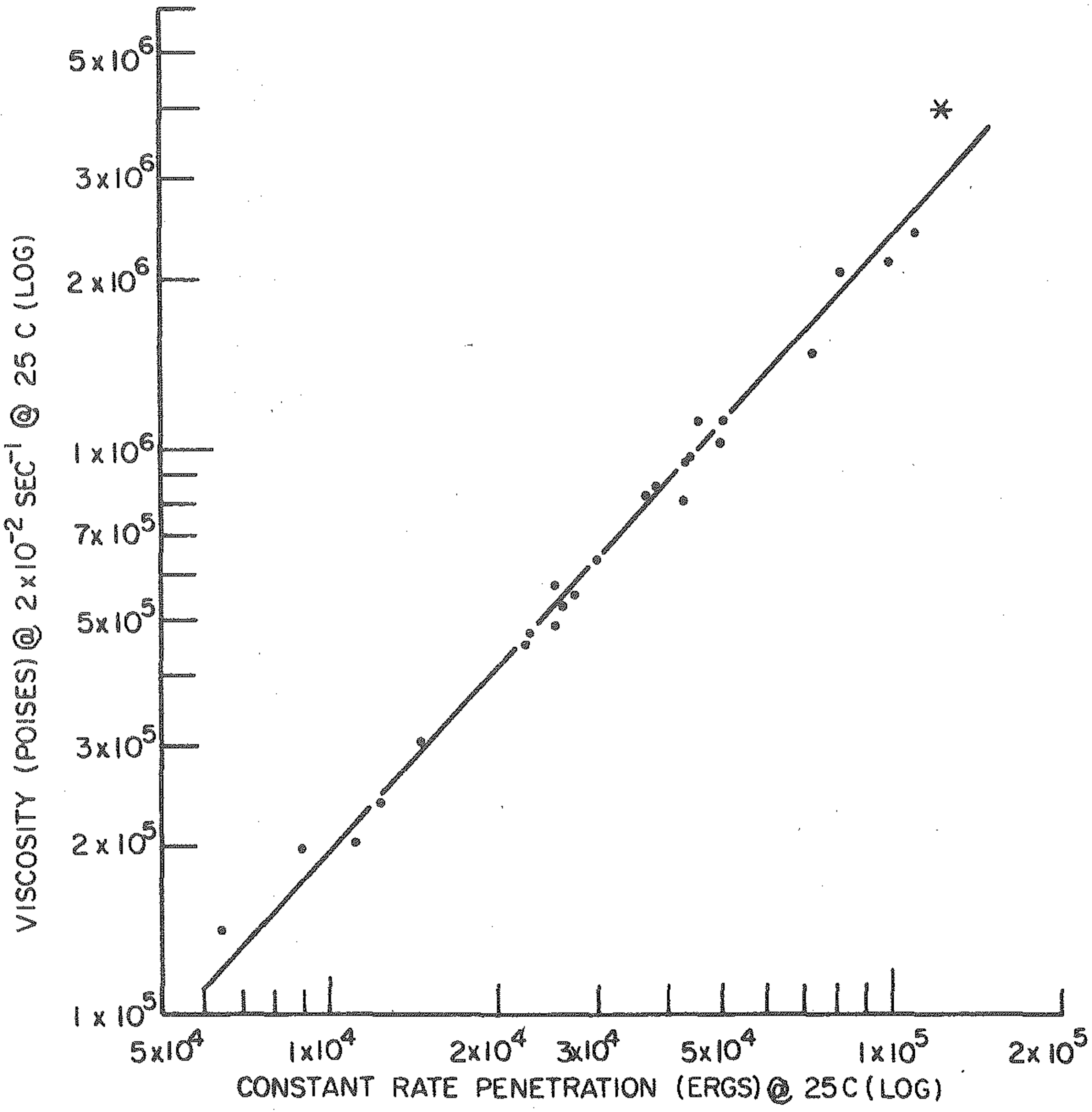


Figure 41. Regression analysis curve for viscosity and constant rate of penetration data.

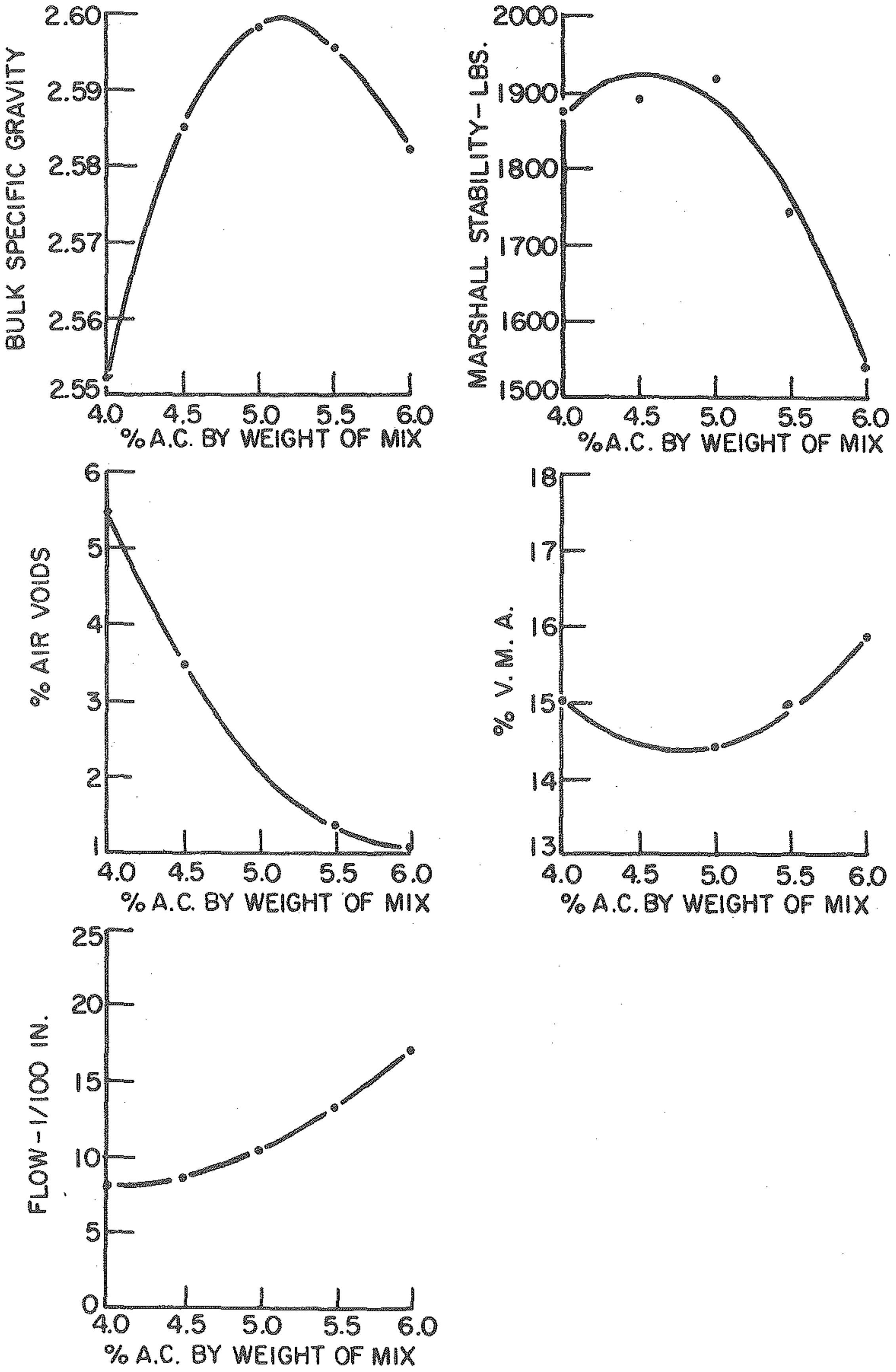


Figure 42. Example of Marshall mix design curves using regression analysis, AIMIX procedure.

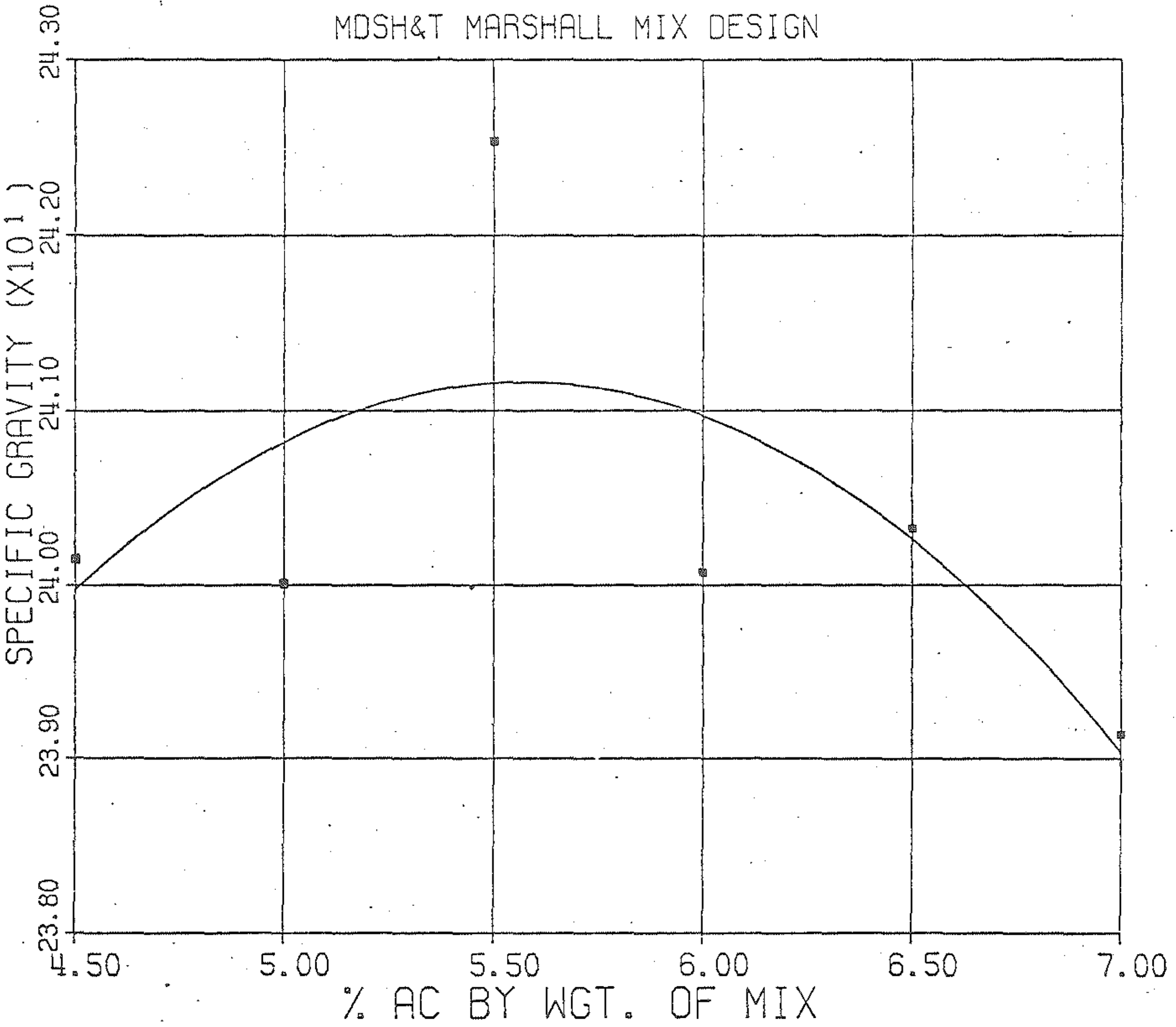


Figure 43. Specific gravity vs. asphalt content for MICHMIX example.

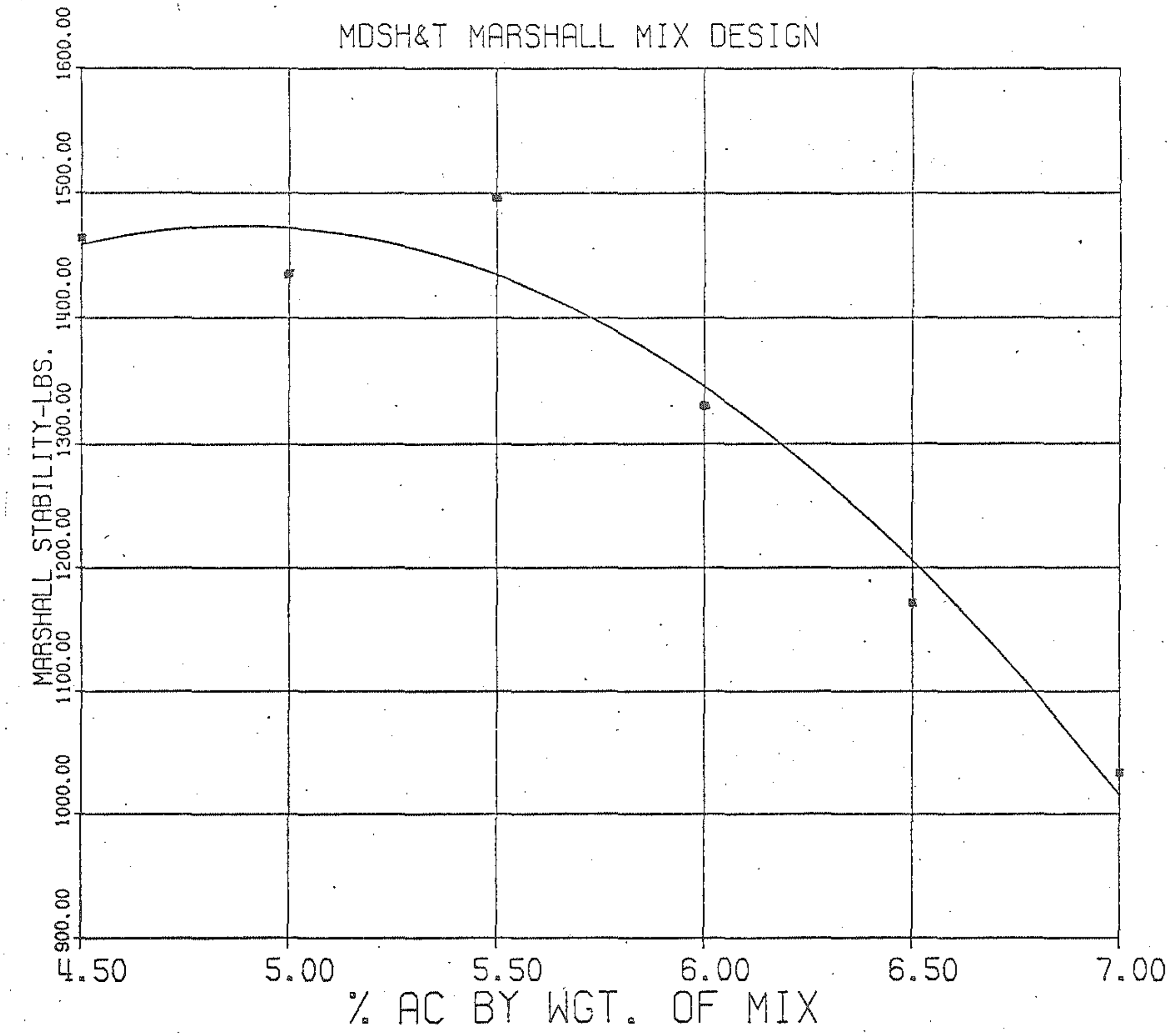


Figure 44. Marshall stability vs. asphalt content for MICHMIX example.

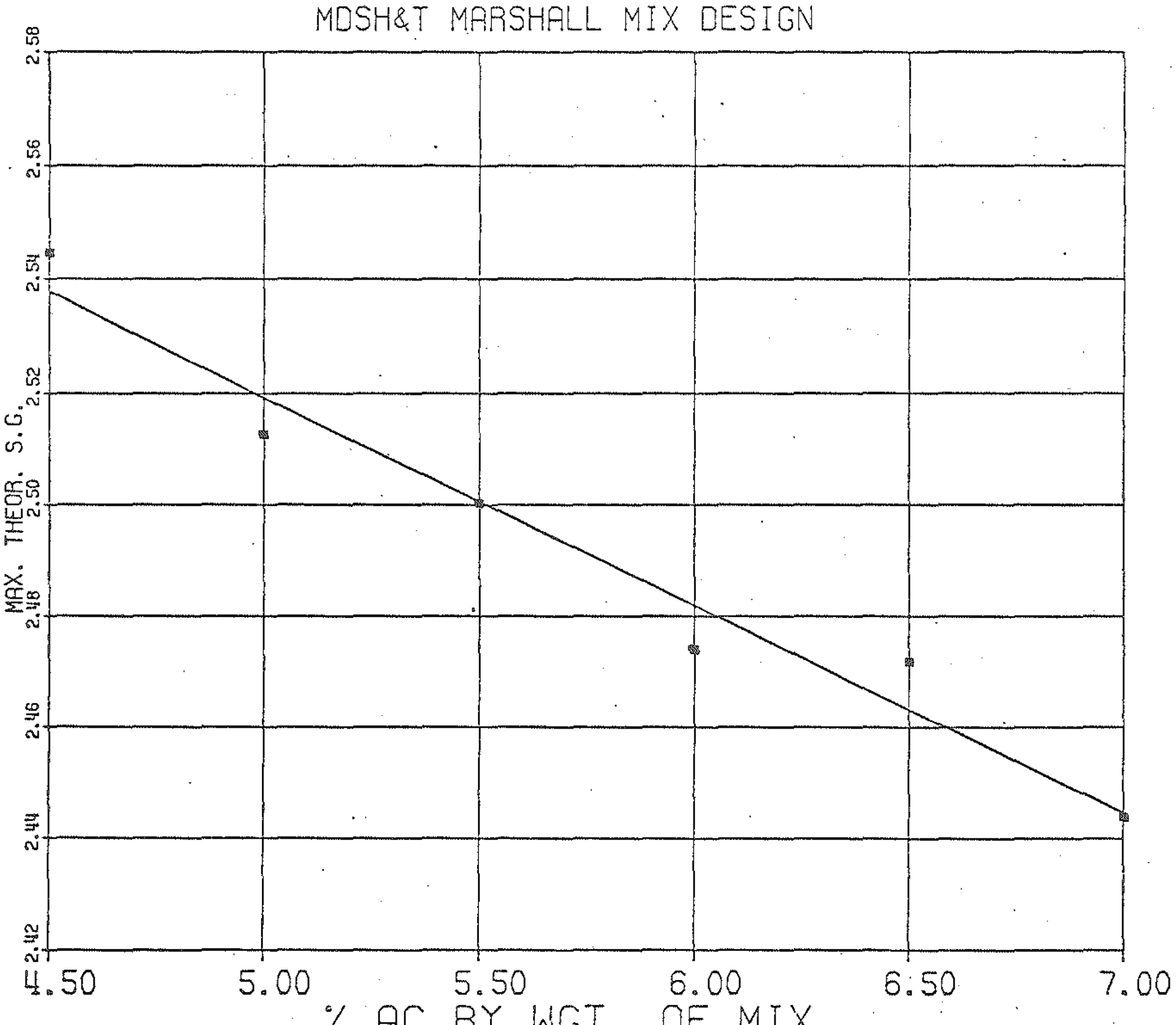


Figure 45. Maximum theoretical specific gravity vs. asphalt content for MICHMIX example.

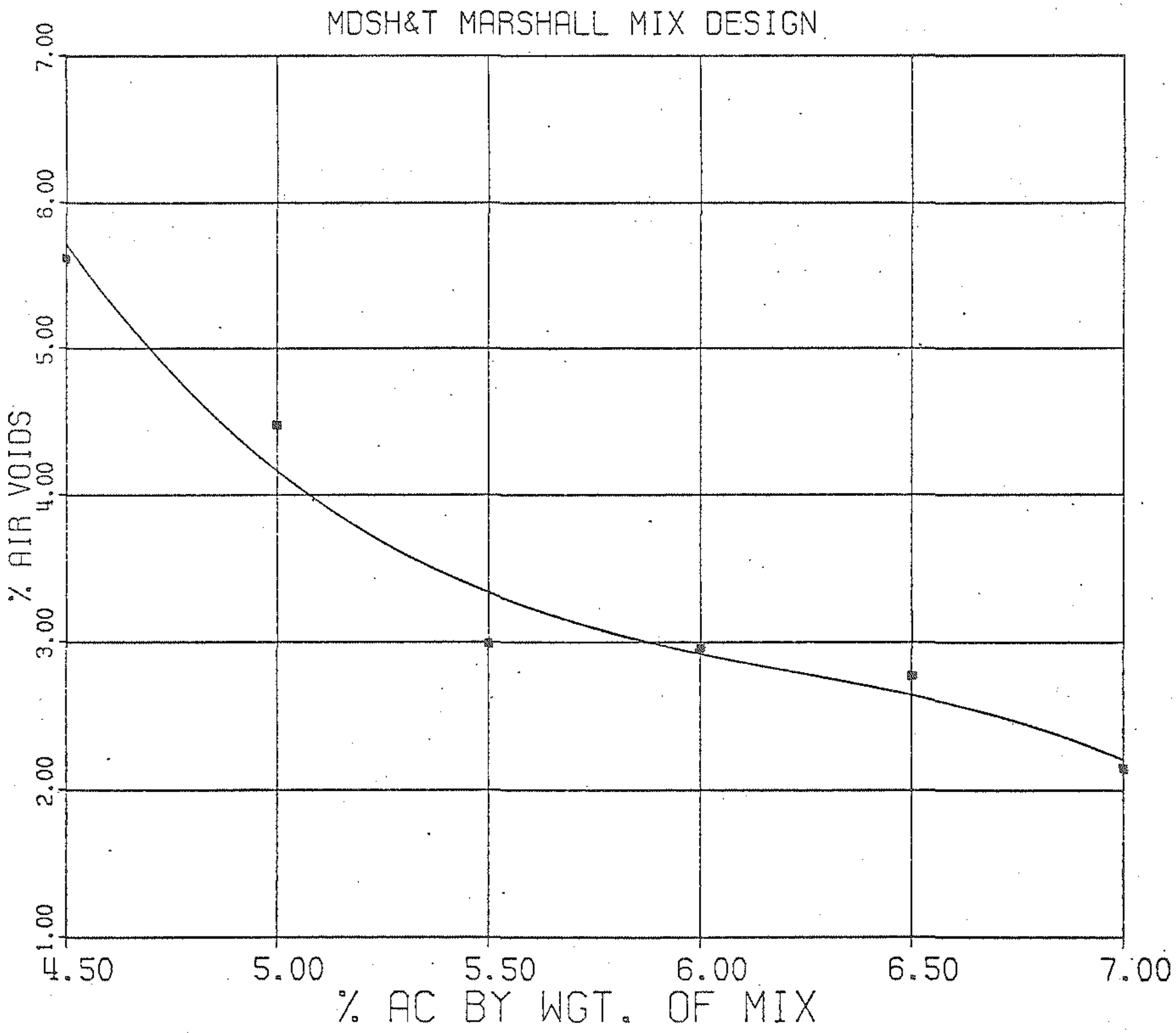


Figure 46. Air voids vs. asphalt content for MICHMIX example.

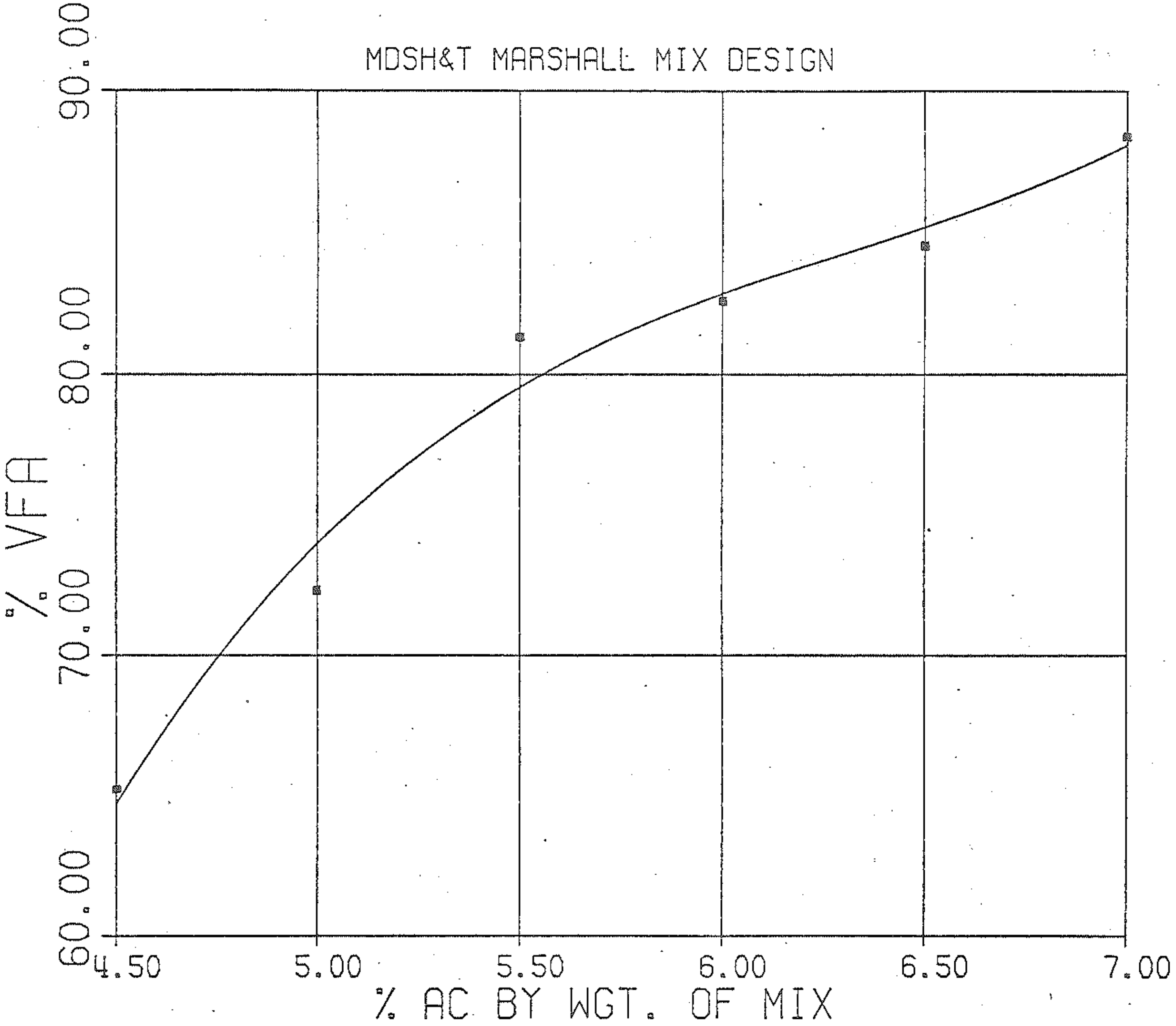


Figure 47. Voids filled with asphalt vs. asphalt content for MICHMIX example.

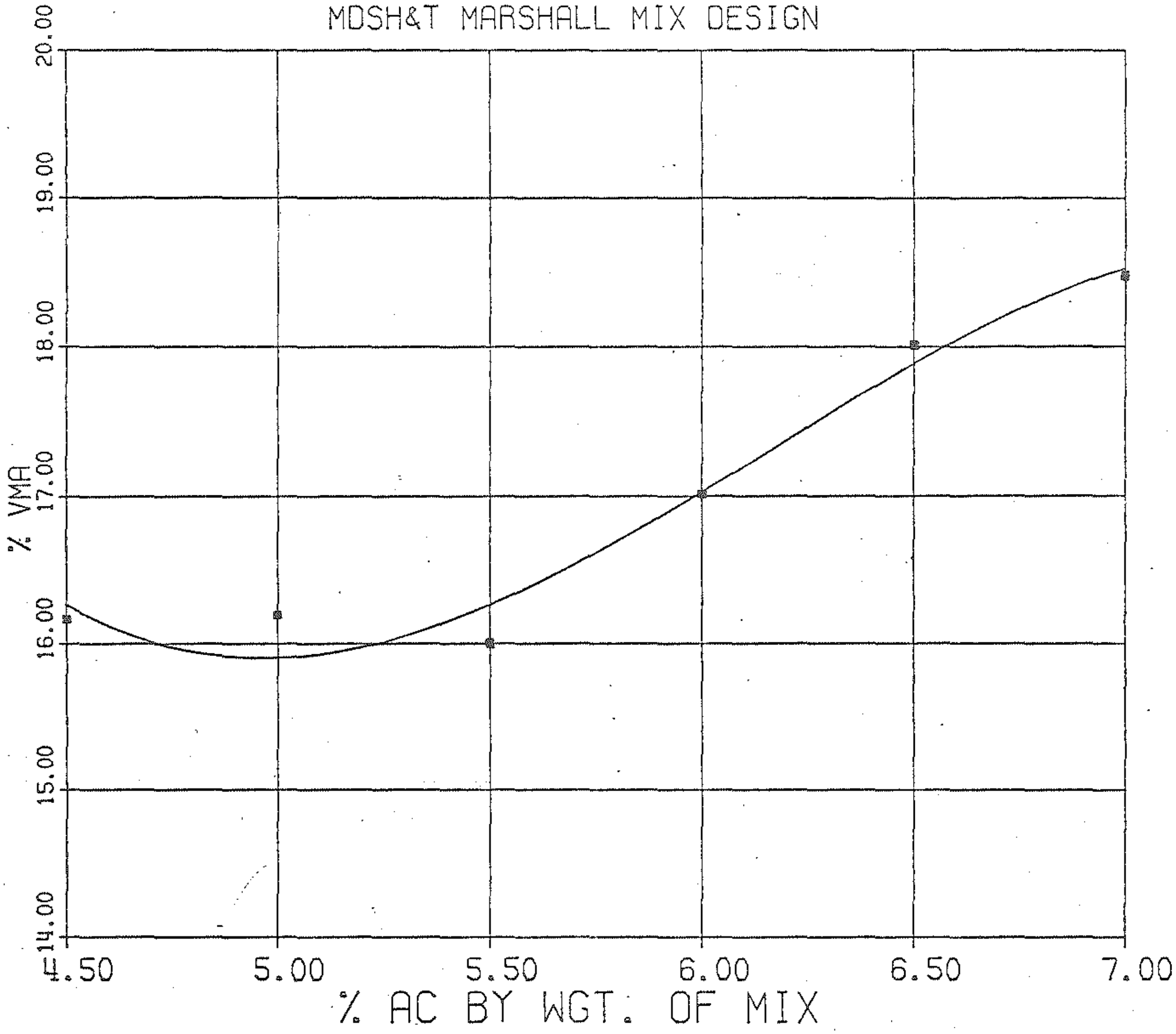


Figure 48. Voids in mineral aggregate vs. asphalt content for MICHMIX example.

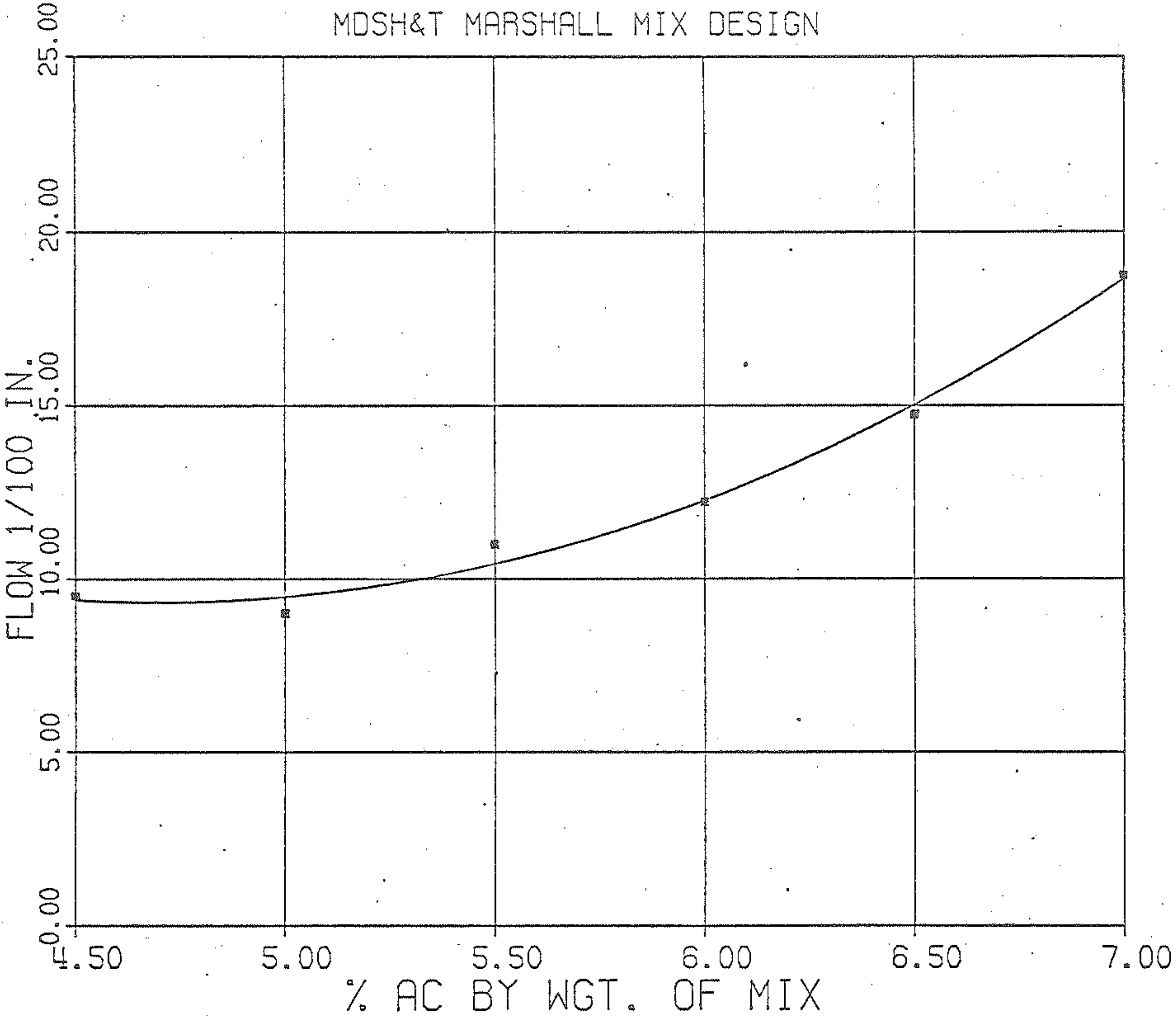


Figure 49. Marshall flow vs. asphalt content for MICHMIX example.

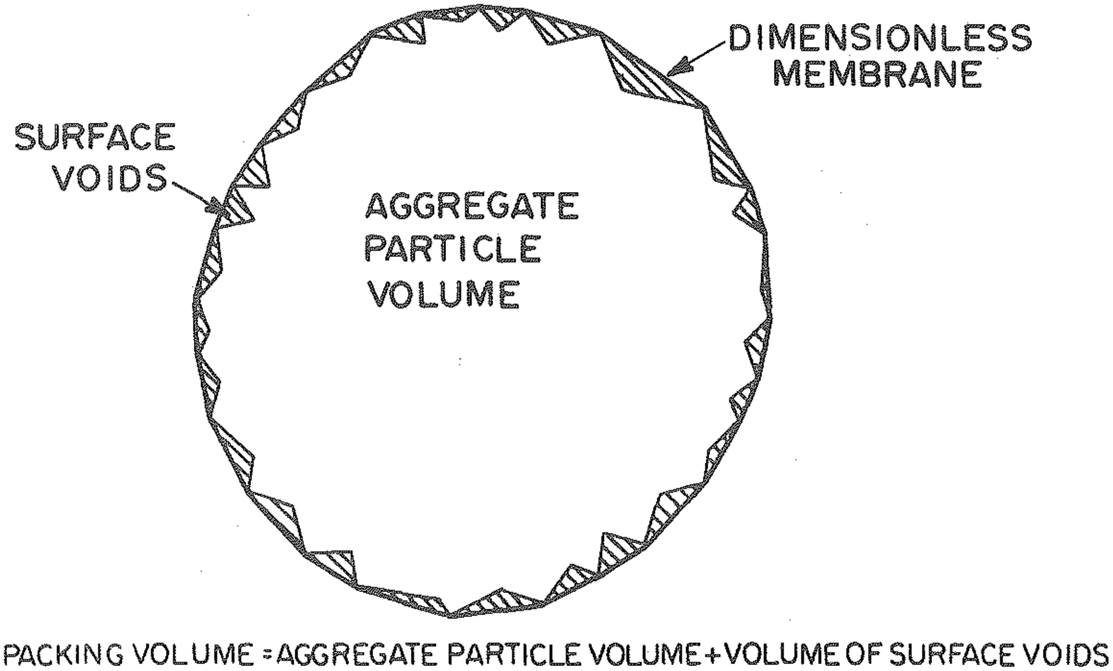


Figure 50. Illustration of particle packing volume.

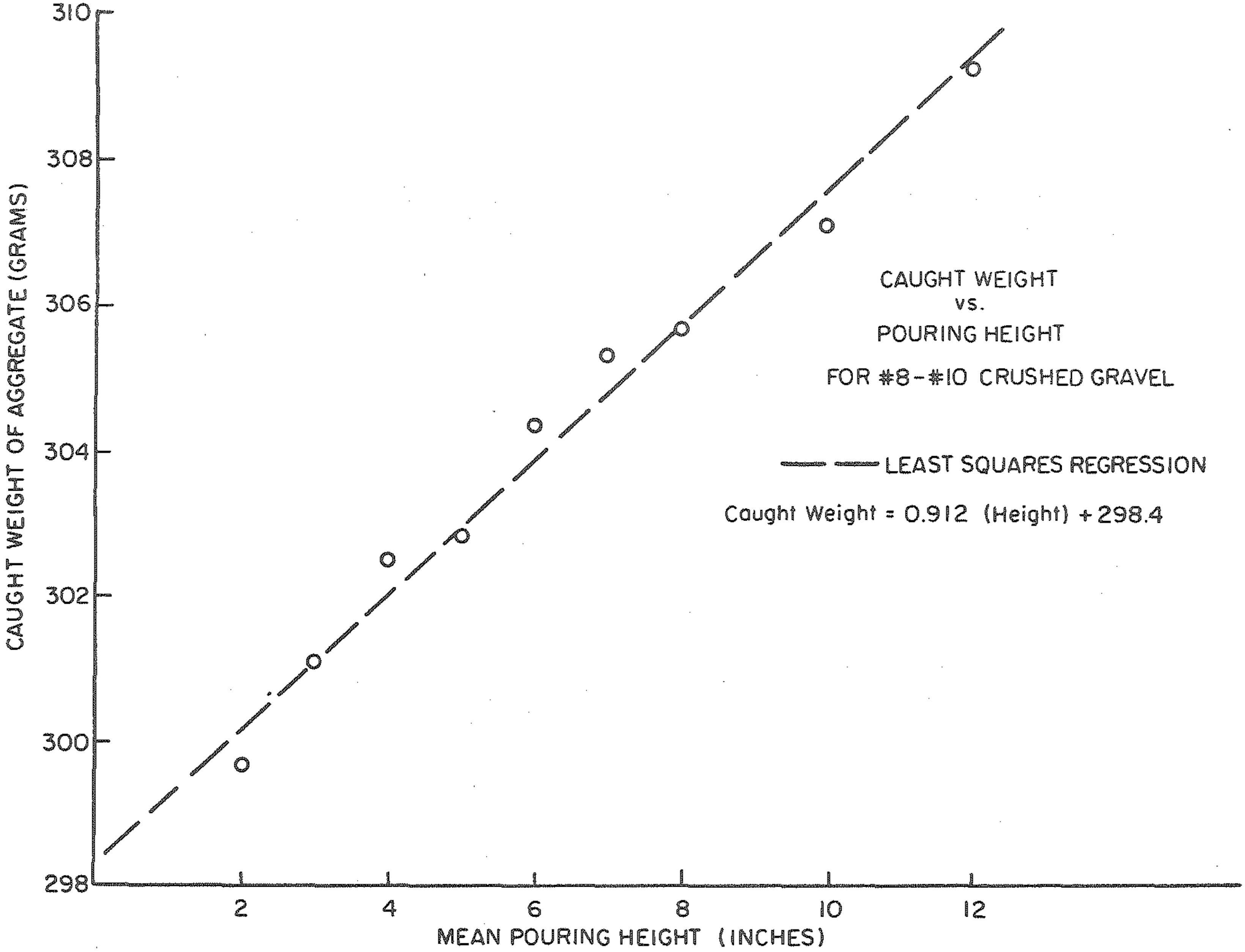


Figure 51. Caught weight vs. mean pouring height for #8-#10 crushed gravel.

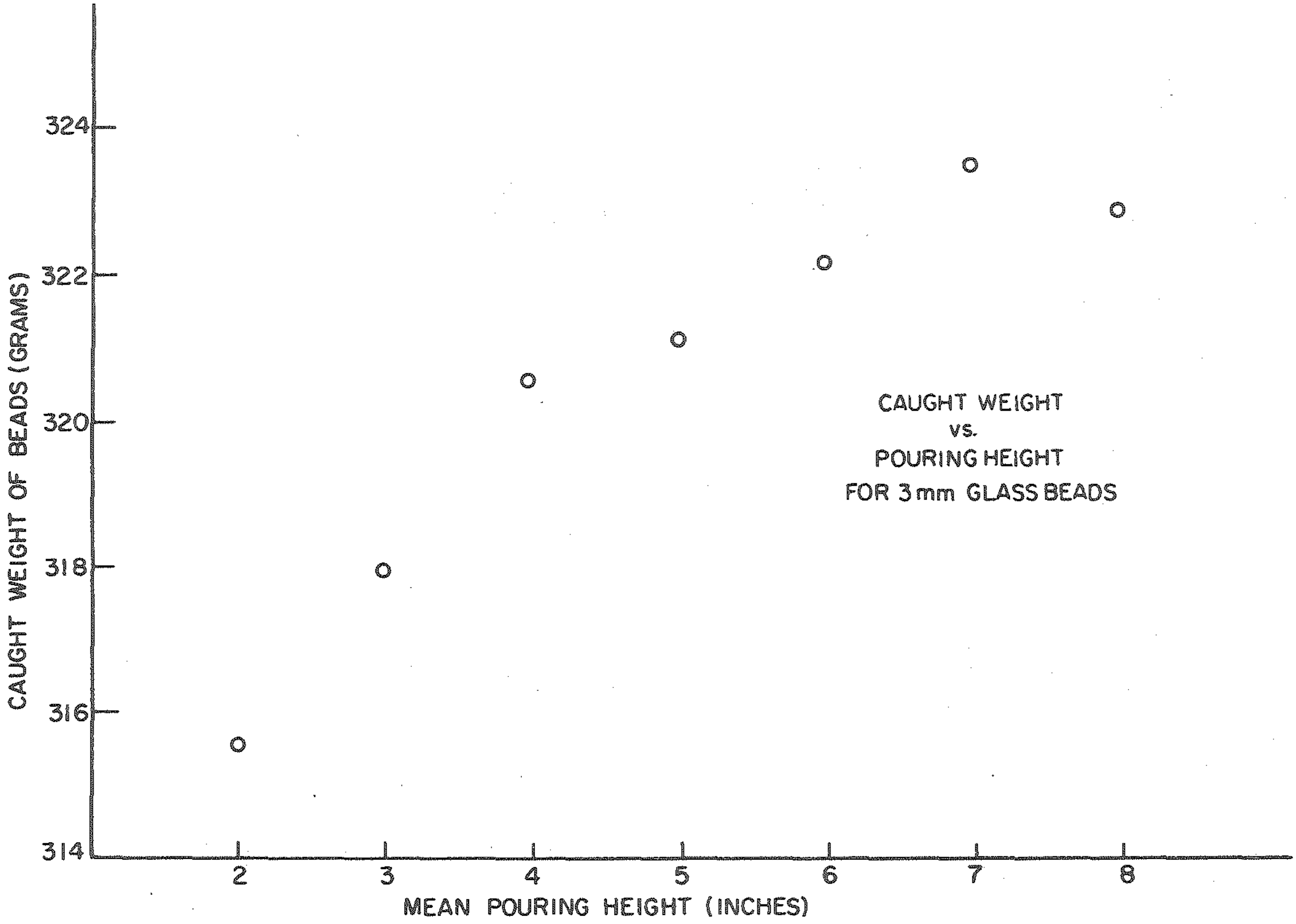


Figure 52. Caught weight vs. mean pouring height for 3 mm glass beads.

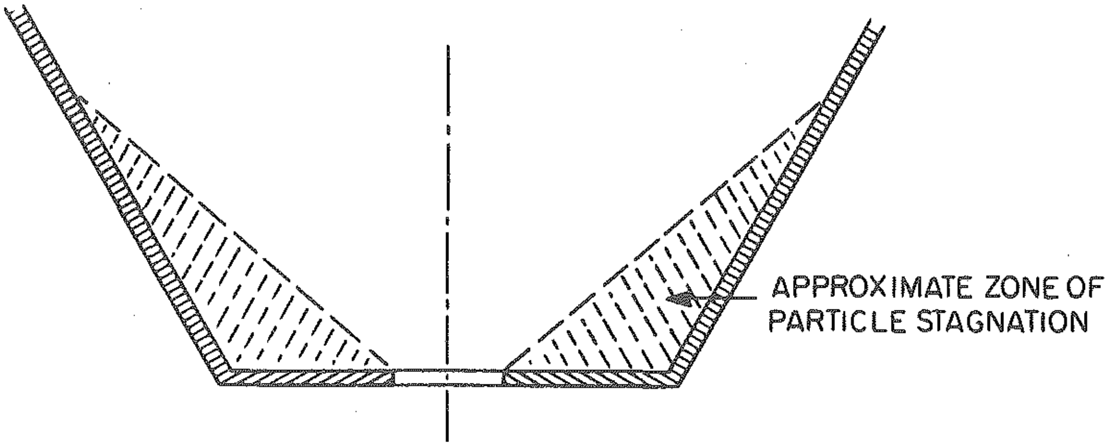
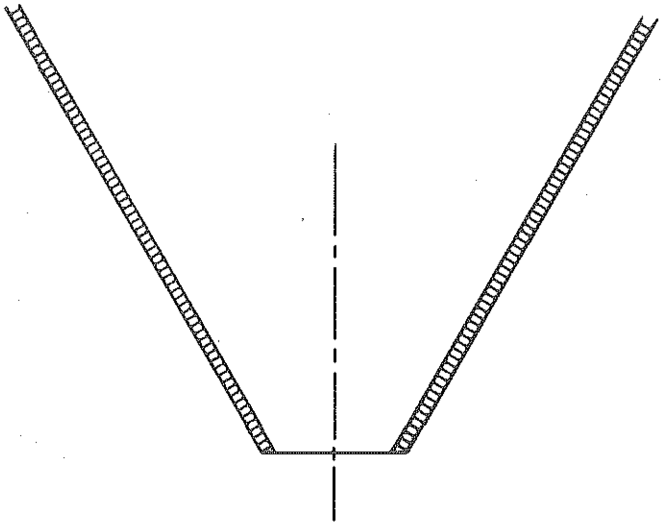


PLATE TYPE ORIFICE



CONE TYPE ORIFICE

Figure 53. Comparison of cone type and plate type orifices.

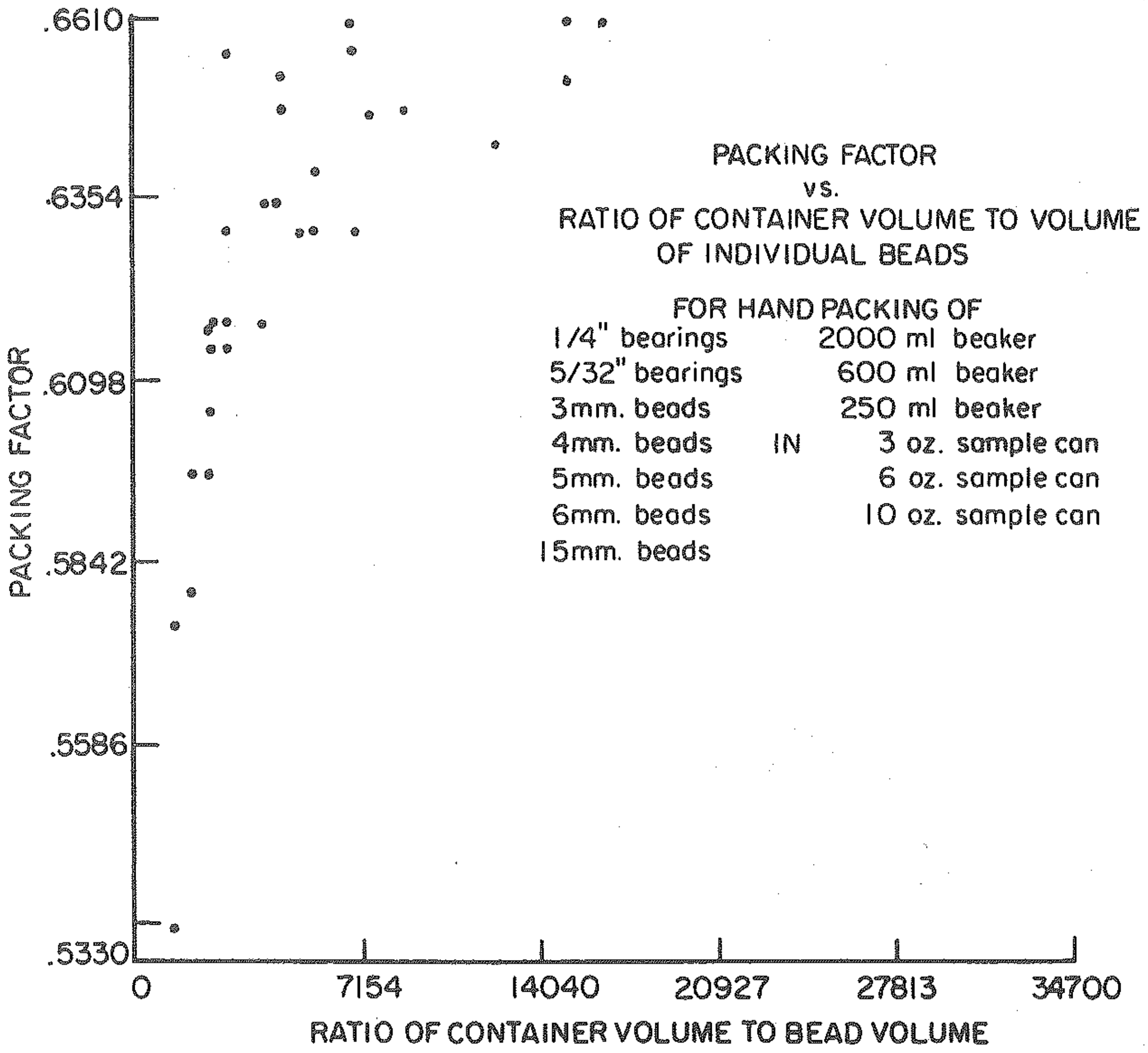


Figure 54. Packing factor vs. ratio of container volume to individual bead volume for selected beads and containers.

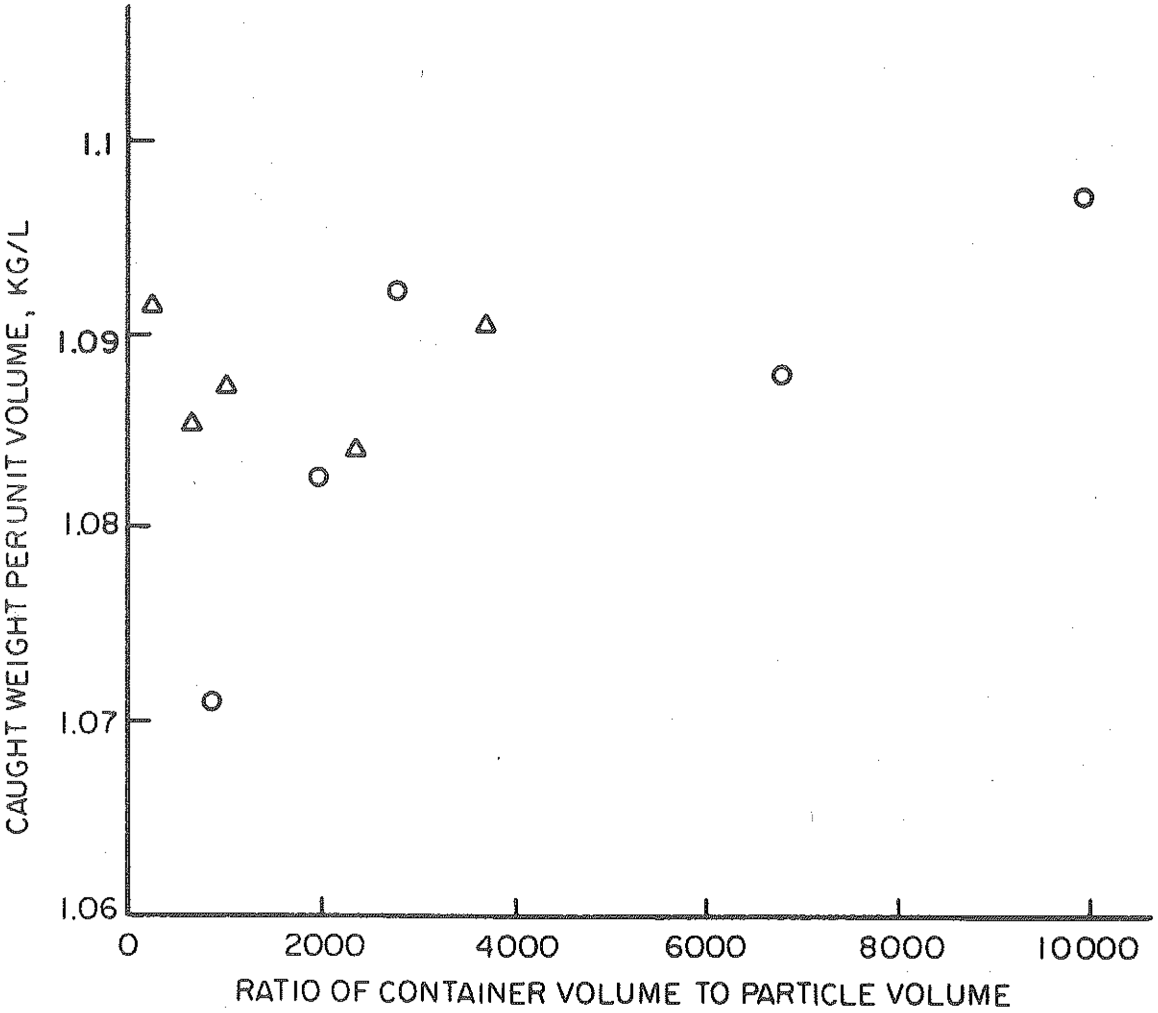


Figure 55. Caught weight per unit volume vs. ratio of container volume to individual particle volume for two slag fractions.

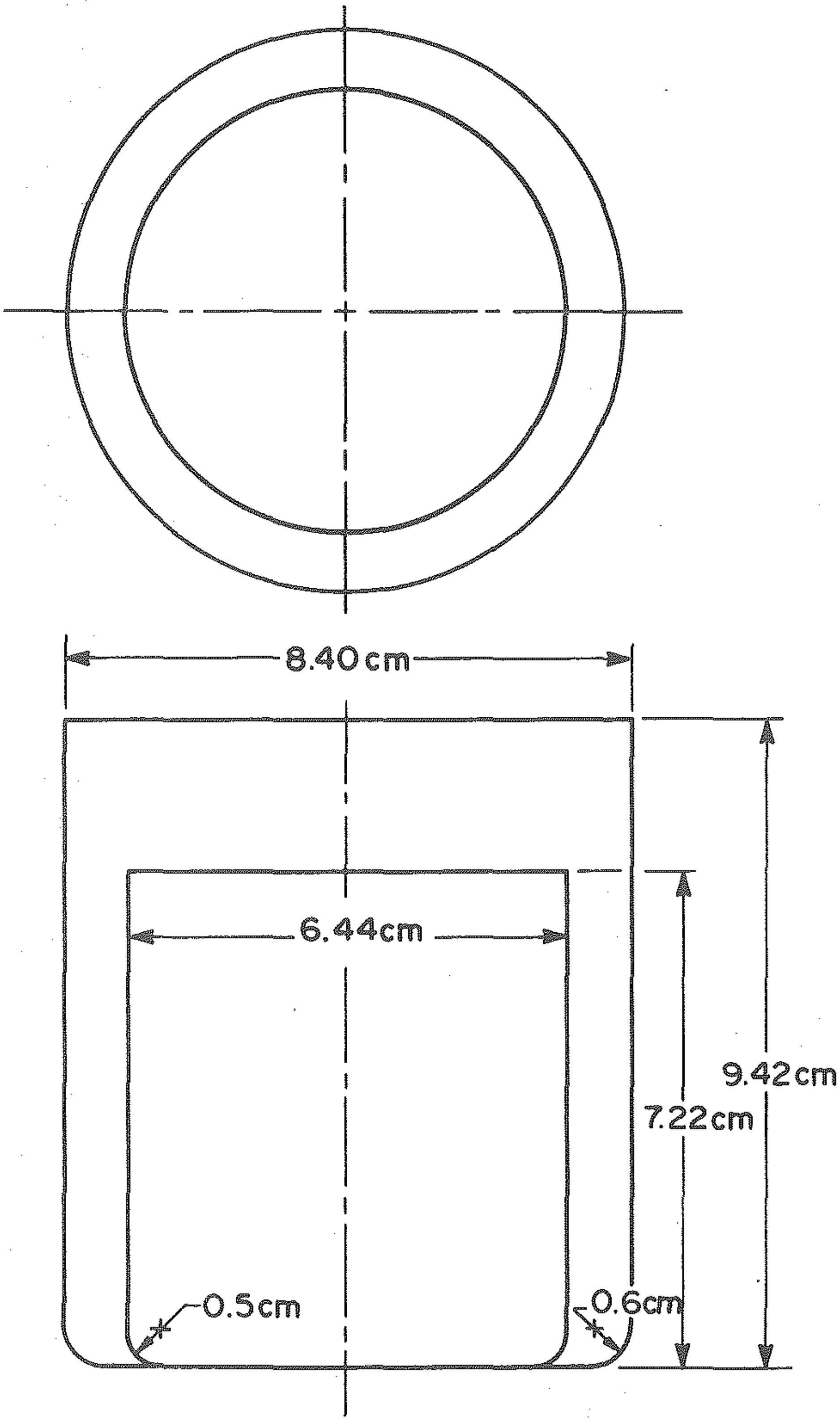


Figure 56. Inside dimensions of "250 ml" and "600 ml" containers.

APPENDICES

APPENDIX A

AGGREGATE PARAMETER PROGRAM

The program shown on the following pages calculates and tabulates aggregate parameters using pouring test data and data for bulk specific gravity, water absorption, maximum theoretical specific gravity, and asphalt content for each aggregate fraction and each aggregate fraction-bitumen mix. The factor to correct packing specific gravity as calculated in Appendix D is also included.

The procedure for determination of input aggregate parameters can be as follows:

(a) Select the sieve sizes to be used in analyzing the aggregate composition.

(b) Obtain sieved fractions and perform the pouring test for each fraction. If a fraction encompasses a large range of aggregate sizes, the fraction should be sub-sieved to provide a one-size[1] aggregate fraction for the pouring test. Results of this test may represent the whole fraction.

(c) Obtain packing specific gravity adjustment factor as described in Appendix D based on standard beads and their relation to the catch container

---

[1] Tons and Ishai (8) defined a one-size fraction as one in which the passing-retained sieves differ by a factor of 2.

employed.

(d) Obtain bulk specific gravity and water absorption values for each fraction.

(e) Produce an aggregate-bitumen mix for each fraction. Calculate its theoretical maximum specific gravity and associated asphalt content.

TABLE A-1

AGGREGATE PARAMETER PROGRAM

```
C
C
C     ****"AGGREGATE FACTURS' IN BITUMINOUS MIX DESIGN, STAGE 2"****
C     ****                 TESTING DATA ANALYSIS                  ****
C
C
   10 READ(5,200,END=99) SIZE1,SIZE2,FACTOR
      READ (5,202) N
      WRITE (6,100) SIZE1,SIZE2
      WRITE (6,101)
      WRITE (6,102)
      WRITE (6,103)
      I=0
C
C                      ACTUAL PROGRAM
C
20    I=I+1
      IF (I.GT.N) GO TO 10
      READ(5,201) AGG,W,GAG,WAB,GPE,GMM,ACT
C
C     ADJUST PACKING SPECIFIC GRAVITY FOR V-RATIO , DBEADWT
C
      GPE=GPE/FACTOR
      GAC=1.02
      VPE=W/GPE
      DIA=(6.*VPE/3.1416)**(1./3.)
      GAP=1./(1./GAG-WAB/100.)
      SRV=(GAP-GPE)*100./GAP
      GEO=GPE/GAP
      TEM=(ACT-100.*GAC/GMM)*100./(100.-ACT)
      BRW=TEM+100.*GAC/GPE
      BRV=BRW*GPE/GAC
      SAT=BRV*100./SRV
      SUR=(GAG-GPE)*100./GAG
C
C
      WRITE (6,104) AGG,W,DIA,GAG,GAP,WAB,BAB,VPE,GPE,SRV,GEO,BRW,BRV,SA
     1T,SUR
      GO TO 20
C
C                 OUTPUT FORMATS
C
100   FORMAT ('1',50X,'FRACTION SIZE: ',A4,'-',A4)
101   FORMAT ('-',20X,'CONVENTIONAL PARAMETERS',42X,'PACKING VOLUME PARA
     1METERS')
102   FORMAT ('0','AGG.',5X,'AVERAGE',5X,'EQUIVALENT',4X,'BULK',4X,'APP.
     1',4X,'WAT.',3X,'ASP.',7X,'PACKING',4X,'PACK.',2X,'SPEC.',2X,'GEOM.
     2',3X,'ASP.',3X,'ASP.',3X,'ASP.',3X,'SURF.')
103   FORMAT (' ',7X,'PAR. WEIGHT',3X,'SPHERE DIA.',3X,'SP.GR',3X,'SP.GR
     1',3X,'ABS.',3X,'ABS.',8X,'VCLUME',4X,'SP.GR',2X,'RUG.V',2X,'FACTOR
     2',2X,'RUG.W',2X,'RUG.V',2X,'SAT.',3X,'RUG.V')
104   FORMAT ( 1X,A5,2X,E11.5,3X,E11.5,3X,F5.3,3X,F5.3,3X,F4.2,3X,F4.2,5
     1X,E11.5,2X,F5.3,2X,F5.2,2X,F6.4,4(F7.2),/)
C
C                 INPUT FORMATS
C
200   FORMAT(2A4,F10.0)
201   FORMAT(A4,E10.5,5F10.0)
202   FORMAT (I2)
C
```

TABLE A-1 (Continued)
Page 2

```
 99     STOP
        END

                     VARIABLE LIST

C       N       = NUMBER OF AGGREGATES TO BE ANALYZED AND
C                 TABULATED .
C       SIZE1   = DESIGNATION OF UPPER SIEVE SIZE
C       SIZE2   = DESIGNATION OF LOWER SIEVE SIZE
C       AGG     = TYPE OF AGGREGATE
C       W       = AVERAGE PARTICLE WEIGHT
C       GAG     = BULK SPECIFIC GRAVITY
C       WAB     = PERCENT WATER ABSORPTION
C       GPE     = PACKING SPECIFIC GRAVITY
C       GMM     = MAXIMUM SPECIFIC GRAVITY OF THE MIXTURE
C       ACT     = ASPHALT CONTENT (PERCENT OF TOTAL MIXTURE WEIGHT)
C       GAC     = SPECIFIC GRAVITY OF THE ASPHALT
C       VPE     = AVERAGE PACKING VOLUME OF THE PARTICLES
C       GAP     = APPARENT SPECIFIC GRAVITY
C       SRV     = PERCENT SPECIFIC RUGOSITY
C       GEO     = GEOMETRIC IRREGULARITY NUMBER
C       BAB     = PERCENT ASPHALT LOST BY ABSORPTION
C       BRW     = PERCENT ASPHALT LOST BY RUGOSITY (WEIGHT BASIS)
C       BRV     = PERCENT ASPHALT LOST BY RUGOSITY (VOLUME BASIS)
C       SAT     = PERCENT ASPHALT SATURATION
C       SUR     = PERCENT MACRO SURFACE VOIDS

C                          OPERATING INSTRUCTIONS

C       I)  FORTRAN IV PROGRAM LANGUAGE IS USED
C       II)  INPUT DATA
C             A)  THERE ARE THREE TYPES OF DATA CARDS FOR
C                 EACH ONE-SIZE FRACTION
C                  1)  ONE CARD TO SPECIFY THE UPPER AND
C                      LOWER SIEVE SIZES FOR THE FRACTION AND
C                      THE PACKING SPECIFIC GRAVITY ADJUSTMENT
C                      FACTOR FOR THE FRACTION UNDER CONSIDERATION.
C                  2)  ONE CARD TO SPECIFY THE AGGREGATE TYPES
C                      TO BE ANALYZED WITHIN EACH FRACTION (N).
C                      FORMAT IS GIVEN IN STATEMENT 202.
C                  3)  A GROUP OF N CARDS TO SPECIFY THE
C                      AGGREGATE TYPE AND THE MEASURED ONE-SIZE
C                      AGGREGATE FACTORS.  FORMAT IS GIVEN
                       IN STATEMENT 201.
C             B)  THE PROGRAM CAN HANDLE ANY NUMBER OF FRACTIONS
C                 AND ANY NUMBER OF AGGREGATE TYPES WITHIN
C                 THE FRACTION.  THE FACTOR TO ADJUST PACKING
C                 SPECIFIC GRAVITY IS ALSO INCORPORATED.
C                 THIS FACTOR SHOULD BE SET TO 1.0 FOR
C                 FRACTIONS PASSING A #10 SIEVE.
```

APPENDIX B

COMPUTER PROGRAM FOR MIXTURE DESIGN TABLES

The program shown on the following pages uses input from aggregate analysis and from the aggregate parameter program to construct design tables for prediction of optimum asphalt content. Procedure for use of the design tables is outlined in Appendix E.

TABLE B-1

PROGRAM FOR MIX DESIGN

```
      **** REVISED DESIGN TABLE PROGRAM ****

      ARRAYS DIMENSIONED TO HANDLE UP TO 10 ONE-SIZE FRACTIONS

      DIMENSION ACWM(151),GMIX(91),X(10),GP(10),BRW(10),GAG(10),BAG(10),
     1VP(10),Y(10),VAG(10),VBAG(10),CFV(10),FR(10),BRV(10)
      GMIX(1)=1.800
C      A MINIMUM VMA IS ESTABLISHED TO LIMIT OUTPUT
      VMAMIN=0.
C      THE ACTUAL PROGRAM
      DO 2 I=1,90
    2 GMIX(I+1)=GMIX(I)+0.01
    3 READ(5,200,END=91)N,GB,AGG,ASMIN,ASMAX
      ACWM(1)=ASMIN
      DO 1 I=1,150
      ACWM(I+1)=ACWM(I)+0.1
      IA=I+1
      IF(ASMAX-ACWM(IA))15,15,1
    1 CONTINUE
   15 CONTINUE
      DO 10 I=1,N
      READ AGGREGATE DATA FOR EACH FRACTION
   10 READ(5,201)X(I),GP(I),BRW(I),BRV(I),GAG(I),BAG(I)
      WRITE(6,100)AGG,GB
      WRITE(6,101)N
      WRITE(6,102)(X(I),I=1,10)
      WRITE(6,103)
      VPT=0.
      VAGT=0.
      BAGT=0.
      DO 20 I=1,N
      VP(I)=X(I)/GP(I)
      VPT=VPT+VP(I)
      VAG(I)=X(I)/GAG(I)
      VBAG(I)=BAG(I)*X(I)/(100.*GB)
      VAGT=VAGT+VAG(I)
      BAGT=BAGT+X(I)*BAG(I)/100.
   20 CONTINUE
      DO 21 I=1,N
   21 Y(I)=100.*VP(I)/VPT
      GPT=100./VPT
      GAGT=100./VAGT
      DO 90 L=1,IA
      ACWA=ACWM(L)/(1.-ACWM(L)/100.)
      ACVA=ACWA*GPT/GB
      CACWAE=ACWA-BAGT
      VBT=ACWA/GB
      M=N-1
      DO 50 I=1,M
      VPTT=0.
      LL=I+1
      DO 30 J=LL,N
```

TABLE B-1 (Continued)
Page 2

```
   30 VPTT=VPTT+VP(J)
      VBAGTT=0.
      DO 40 K=1,I
   40 VBAGTT=VBAGTT+VBAG(K)
      CFV(I)=VPTT/(VBT-VBAGTT)
      FR(I)=GP(I)*(BRW(I)-BAG(I))/(100.*GB*(1.+1./CFV(I)))
   50 CONTINUE
      FR(N)=0.
      ACVAL=0.
      DO 60 I=1,N
   60 ACVAL=ACVAL+Y(I)*(BRV(I)-100.*FR(I))/100.
      ACVAE=ACVA-ACVAL
      ACWAE=ACVAE*GB/GPT
      FRT=0.
      DO 70 I=1,N
   70 FRT=FRT+FR(I)*Y(I)/100.
      EVP=(VPT-VPT*FRT)*100./VPT
      ACVEF=ACVAE*100./EVP
      ID=0
      DO 80 I=1,91
      VMIX=(100.+ACWA)/GMIX(I)
      AIRV=(VMIX-(100./GAGT+CACWAE/GB))*100./VMIX
      IF(AIRV-7.0)6,6,80
    6 IF(AIRV-2.0)90,7,7
    7 CVMA=(VMIX-100./GAGT)*100./VMIX
      IF(CVMA-VMAMIN)90,8,8
    8 EVPGT=VMIX-VMIX*AIRV/100.-ACWAE/GB
      EPVMA=(VMIX-EVPGT)*100./VMIX
      IF(ID)4,4,5
    4 WRITE(6,104)ACWM(L),ACVEF
      ID=1
    5 WRITE(6,105)GMIX(I).AIRV,CVMA,EPVMA
   80 CONTINUE
   90 CONTINUE
      GO TO 3
   91 STOP
C           .   OUTPUT FORMATS
  100 FORMAT('1',//,4X,'AGGREGATE TYPE - ',A2,3X,'ASPHALT S.G.= ',F6.3)
  101 FORMAT('0    NUMBER OF FRACTIONS N =',I2)
  102 FORMAT('0    X(1),....X(N)=',9(F4.1,','),F4.1,2X,'(FRACTIONS - WEIGH
     1T BASIS)',/)
  103 FORMAT('% ASPHALT',3X,'% FLOW',6X,'SPECIFIC',3X,'% AIR',10X,'%',
     110X,'%'/'CONTENT',5X,'ASPHALT',5X,'GRAVITY',4X,'VOIDS',7X,
     2'STANDARD',3X,'PACKING'/'BY WEIGHT',3X,'BY VOLUME',3X,'OF MIX',5X,
     3'BY VOLUME',5X,'VMA',8X,'VMA')
  104 FORMAT(F7.2,8X,F5.2)
  105 FORMAT(25X,F5.2,6X,F5.2,6X,F6.2,6X,F6.2)
C               INPUT FORMATS
  200 FORMAT(I2,1X,F5.3,1X,A2,1X,F4.1,1X,F4.1)
  201 FORMAT(F4.1,1X,F5.3,1X,F5.2,1X,F5.2,1X,F5.3,1X,F4.2)
      END
                VARIABLE LIST
C     ACWM   = ASPHALT CONTENT (PERCENT OF TOTAL MIXTURE WEIGHT).
```

TABLE B-1 (Continued)
Page 3

```
      ASMIN  = MINIMUM ASPHALT CONTENT TO BE CONSIDERED.
      ASMAX  = MAXIMUM ASPHALT CONTENT TO BE CONSIDERED.
C      GMIX   = SPECIFIC GRAVITY OF THE COMPACTED MIXTURE.
C      N      = NUMBER OF ONE-SIZE FRACTIONS IN THE MIX.
C      GB     = SPECIFIC GRAVITY OF ASPHALT.
C      AGG    = AGGREGATE TYPE DESIGNATION.
C      X(I)   = PERCENT BY WEIGHT OF THE I-TH FRACTION IN THE MIXTURE.
C      GP(I)  = PACKING SPECIFIC GRAVITY OF THE I-TH FRACTION.
C      BRW(I) = PERCENT ASPHALT LOST BY RUGOSITY FOR THE I-TH
C               FRACTION (WEIGHT BASIS).
C      BRV(I) = PERCENT ASPHALT LOST BY RUGOSITY FOR THE I-TH
C               FRACTION (VOLUME BASIS).
C      GAG(I) = BULK SPECIFIC GRAVITY FOR THE I-TH FRACTION.
C      BAG(I) = PERCENT ASPHALT LOST BY ABSORPTION FOR THE I-TH FRACTION.
C      VP(I)  = TOTAL PACKING VOLUME OF THE I-TH FRACTION.
C      Y(I)   = PERCENT BY VOLUME OF THE I-TH FRACTION IN THE
C               MIXTURE (PACKING VOLUME UNITS).
C      VAG(I) = TOTAL BULK VOLUME OF THE I-TH FRACTION.
C      VBAG(I)= TOTAL VOLUME OF THE ASPHALT ABSORPTION WITHIN
C               THE I-TH FRACTION.
C      CFV(I) = FINES CONCENTRATION OF THE I-TH FRACTION IN THE
C               MIXTURE.
C      FR(I)  = FINES LOST BY RUGOSITY FOR THE I-TH FRACTION IN
C               THE MIXTURE.
C      VPT    = TOTAL PACKING VOLUME OF THE AGGREGATE IN THE MIXTURE.
C      VAGT   = TOTAL BULK VOLUME OF THE AGGREGATES IN THE MIXTURE.
C      BAGT   = AVERAGE ASPHALT LOST BY ABSORPTION IN THE MIXTURE.
C      ACWA   = ASPHALT CONTENT (PERCENT OF TOTAL AGGREGATE WEIGHT).
C      ACVA   = ASPHALT CONTENT (PERCENT OF TOTAL PACKING VOLUME
C               OF THE AGGREGATES).
C      CACWAE = EFFECTIVE ASPHALT CONTENT (PERCENT OF TOTAL AGGREGATE
C               WEIGHT).
C      VBT    = TOTAL VOLUME OF ASPHALT IN THE MIXTURE.
C      FRT    = TOTAL FINES LOST BY RUGOSITY IN THE MIXTURE (PERCENT
C               OF TOTAL PACKING VOLUME OF AGGREGATES).
C      EVP    = ACTIVE PARTICLES IN THE MIXTURE (PERCENT OF TOTAL
C               PACKING VOLUME OF AGGREGATES).
C      ACVAL  = ASPHALT LOST IN THE MACRO SURFACE VOIDS OF AGGREGATES
C               (PERCENT OF TOTAL PACKING VOLUME OF AGGREGATES).
C      ACWAL  = ASPHALT LOST IN THE MACRO SURFACE VOIDS OF AGGREGATES
C               (PERCENT OF TOTAL WEIGHT OF AGGREGATES).
C      ACWAE  = FLOW ASPHALT CONTENT (PERCENT OF TOTAL AGGREGATE
C               WEIGHT).
C      ACVAE  = FLOW ASPHALT IN THE MIXTURE (PERCENT OF TOTAL
C               PACKING VOLUME OF AGGREGATES).
C      ACVEF  = FLOW ASPHALT CONTENT (PERCENT OF PACKING VOLUME
C               OF THE ACTIVE PARTICLES IN THE MIXTURE).
C      VMIX   = TOTAL VOLUME OF THE COMPACTED MIXTURE.
C      ATRV   = PERCENT AIR VOIDS IN THE COMPACTED MIXTURE.
C      CVMA   = PERCENT VMA (CONVENTIONAL).
C      EPVMA  = PERCENT PACKING VMA.

                 OPERATING INSTRUCTIONS

      I)  INPUT DATA
          A) RANGE OF ASPHALTS DETERMINED BY ASMIN, ASMAX.
          B) THERE ARE TWO GROUPS OF DATA CARDS FOR EACH AGGREGATE MIX
               1) ONE CARD TO SPECIFY THE AGGREGATE TYPE, NUMBER
                  OF FRACTIONS, AND ASPHALT RANGE.
               2) A GROUP OF N CARDS TO SPECIFY AGGREGATE
                  PARAMETERS FOR EACH FRACTION.
          C) THE PROGRAM WILL PRODUCE DESIGN TABLES SIMILAR
             TO THOSE SHOWN IN TABLE B-1 FOR ANY NUMBER OF
             MIXES, ANY RANGE OF ASPHALT CONTENTS FOR EACH MIX,
             AND ANY NUMBER OF FRACTIONS PER MIX.
```

TABLE B-2

PARTIAL MIX DESIGN TABLE OUTPUT FOR MIX I

```
   AGGREGATE TYPE - X1   ASPHALT S.G.=  1.025

   NUMBER OF FRACTIONS N =10

   X(1),...X(N)=10.4,11.4,20.0,10.6, 6.6, 5.2,18.8, 9.6, 1.7, 5.7  (FRACTIONS - WEIGHT BASIS)

  ASPHALT    % FLOW      SPECIFIC    % AIR          %          %
 CONTENT     ASPHALT     GRAVITY     VOIDS       STANDARD    PACKING
 BY WEIGHT   BY VOLUME   OF MIX      BY VOLUME      VMA        VMA
   4.00         3.00
                           2.40        6.68        12.40       9.40
                           2.41        6.29        12.03       9.03
                           2.42        5.90        11.67       8.65
                           2.43        5.52        11.30       8.27
                           2.44        5.13        10.94       7.89
                           2.45        4.74        10.57       7.52
                           2.46        4.35        10.21       7.14
                           2.47        3.96         9.84       6.76
                           2.48        3.57         9.48       6.38
                           2.49        3.18         9.11       6.01
                           2.50        2.79         8.75       5.63
                           2.51        2.41         8.38       5.25
                           2.52        2.02         8.02       4.87
   4.10         3.21
                           2.39        6.93        12.85       9.83
                           2.40        6.54        12.49       9.45
                           2.41        6.15        12.12       9.07
                           2.42        5.76        11.76       8.70
                           2.43        5.37        11.39       8.32
                           2.44        4.98        11.03       7.94
                           2.45        4.59        10.67       7.56
                           2.46        4.20        10.30       7.19
                           2.47        3.81         9.94       6.81
                           2.48        3.42         9.57       6.43
                           2.49        3.03         9.21       6.06
                           2.50        2.64         8.84       5.68
                           2.51        2.25         8.48       5.30
   4.20         3.43
                           2.39        6.78        12.94       9.88
                           2.40        6.39        12.58       9.50
                           2.41        6.00        12.22       9.12
                           2.42        5.61        11.85       8.74
                           2.43        5.22        11.49       8.37
                           2.44        4.83        11.12       7.99
                           2.45        4.44        10.76       7.61
                           2.46        4.05        10.39       7.24
                           2.47        3.66        10.03       6.86
                           2.48        3.27         9.67       6.48
                           2.49        2.88         9.30       6.10
                           2.50        2.49         8.94       5.73
                           2.51        2.10         8.57       5.35
   4.30         3.65
                           2.39        6.63        13.03       9.92
                           2.40        6.24        12.67       9.55
                           2.41        5.85        12.31       9.17
                           2.42        5.46        11.94       8.79
                           2.43        5.07        11.58       8.42
                           2.44        4.68        11.22       8.04
```

APPENDIX C

POURING TEST AND PROPOSED STANDARD APPARATUS

The pouring test is used to directly measure the packing specific gravity of an aggregate fraction. This test was developed by Tons and Ishai (8) for six one-size fractions. The basic pouring test assembly is shown in Figure C-1, and the two stages of modification prior to the present proposed standard apparatus are detailed in Table C-1. Table C-1 also presents the proposed standard apparatus based on current knowledge of the pouring test. The following should be noted in connection with the proposed apparatus:

(a) A conical bin is used for all aggregate sizes. This is accepable because aggregate head within the aggregate holding bin was found to be insignificant in determining packing efficiency of the caught sample.

(b) Orifice diameter is variable to allow selection of an orifice for each fraction and each aggregate type within the fraction for greatest test efficiency.

(c) A fraction range, rather than a specific fraction, is specified for each container assembly. The entire range of aggregate size likely to be encountered in bituminous mix design is considered, and the individual user may tailor his sieving and any necessary sub-sieving, as explained in Appendix A, to his own needs.

Equipment

Equipment necessary to perform the pouring test is as follows:

(a) Pouring apparatus as shown in Figure C-1, including:

  (1) aggregate bin with adjustable orifice,

  (2) catch container of standard volume,

  (3) pan to contain particle overflow.

(b) Metal straightedge to level aggregate in catch container.

(c) Balance, 5 kg. capacity, sensitive to 0.1 g.

(d) Standard beads of known size, specific gravity, and with known coefficient of deviation of individual bead weight. Beads should be free of oil and dirt.

Testing Procedure

The following testing procedure may be used for each aggregate fraction and each standard bead size:

(a) Select an orifice which will allow particles to flow slowly out of the cone without bridging.

(b) Fill the aggregate bin with enough material to fill the chosen catch container about 1.3 to 1.5 times.

(c) Open the bin shutter and allow particles to flow into the catch container.

(d) Carefully level particles to the top edge of the container with the metal straightedge.

(e) Weigh the contents of the container and record this as the test response.

(f) Repeat this procedure for as many replications as desired.

(g) Repeat for as many different aggregate fractions as necessary.

Calculations

Calculation of packing specific gravity can be performed as follows:

(a) Perform the desired number of replications of the pouring test for standard smooth particles. Average the test results. Divide the apparent specific gravity of the beads by average caught weight and obtain the packing specific gravity factor, Q.

(b) Using the same container, perform the pouring test for the aggregate fraction represented by the standard beads. Average the test responses for the replications performed and multiply this average by the packing specific gravity factor to obtain the packing specific gravity of the test aggregate.

(c) In equation form:

$$Q = \frac{G_{ps}}{\Sigma W_s} \qquad G_{px} = \frac{G_{ps}}{\Sigma W_s} \Sigma W_x = Q \Sigma W_x,$$

where

G_{px} = packing specific gravity of the test aggregate,

G_{ps} = packing specific gravity of the standard beads, (packing specific gravity = apparent specific gravity for perfectly smooth particles),

ΣW_x = caught weight of test aggregate filling the catch container,

ΣW_s = caught weight of standard particles filling the catch container,

Q = packing specific gravity factor.

TABLE C-1

POURING TEST ASSEMBLY: 1ST STAGE TO PRESENT[1]

First Stage

Dimension	Fraction			
	1/2 in.- 5/8 in.	#3- #4	#8- #10	#20- #30
Aggregate Bin Diameter (cm.)	10.0	10.0	7.5	7.5
Orifice Diameter (cm.)	7.5	5.5	1.5	1.5
Aggregate Height in Bin (cm.)	12.5	15.0	9.0	9.0
Pouring Height (cm.)	20.0	17.5	20.0	20.0
Catch Container Diameter (cm.)	12.5	10.0	5.0	5.0
Catch Container Height (cm.)	6.5	7.5	9.5	9.5
Glass Bead Diameter (mm.)	6.0	6.0	3.0	3.0

Second Stage

Dimension	Fraction					
	1/2 in.- 5/8 in.	#3- #4	#8- #10	#20- #30	#60- #80	#200- #270
Aggregate Bin Diameter (cm.)	16.0	16.0	16.0	8.5	8.5	8.5
Orifice Diameter (cm.)	7.6	3.6	1.6	1.1	0.9	0.8
Aggregate Height in Bin (cm.)	12.0	12.0	12.0	12.0	12.0	12.0
Pouring Height (cm.)	21.0	21.0	21.0	21.0	21.0	21.0
Catch Container Diameter (cm.)	12.2	10.3	8.4	6.4	6.4	6.4
Catch Container Height (cm.)	15.2	11.8	9.5	7.3	7.3	7.3
Glass Bead Diameter (mm.)	16.0	6.0	3.0	0.5	0.25	0.075

TABLE C-1 (Continued)
page 2

Proposed Standard

Dimension	Fraction Range						
	1 in.- 5/8 in.	5/8 in.- 3/8 in.	3/8 in.- #4	#4- #16	#16- #50	#50- #100	P#100
Orifice Diameter (cm.)	-----------variable, choose to match material flow[2]----------						
Pouring Height (cm.)	21.0	21.0	21.0	21.0	21.0	21.0	21.0
Catch Container Diameter (cm.)	15.4	12.2	10.2	8.4	6.4	6.4	6.4
Catch Container Height (cm.)	18.0	15.2	12.0	9.5	7.6	7.6	7.6
Glass Bead Diameter (mm.)	20	16	6	3	0.5	0.25	0.075
Catch Container Volume (ml.)	4000	2000	1200	600	250	250	250

[1] First and second stage tables given in "Design Factors for Bituminous Concrete" by Tons and Ishai.

[2] About 6-8 times the diameter of the largest particle.

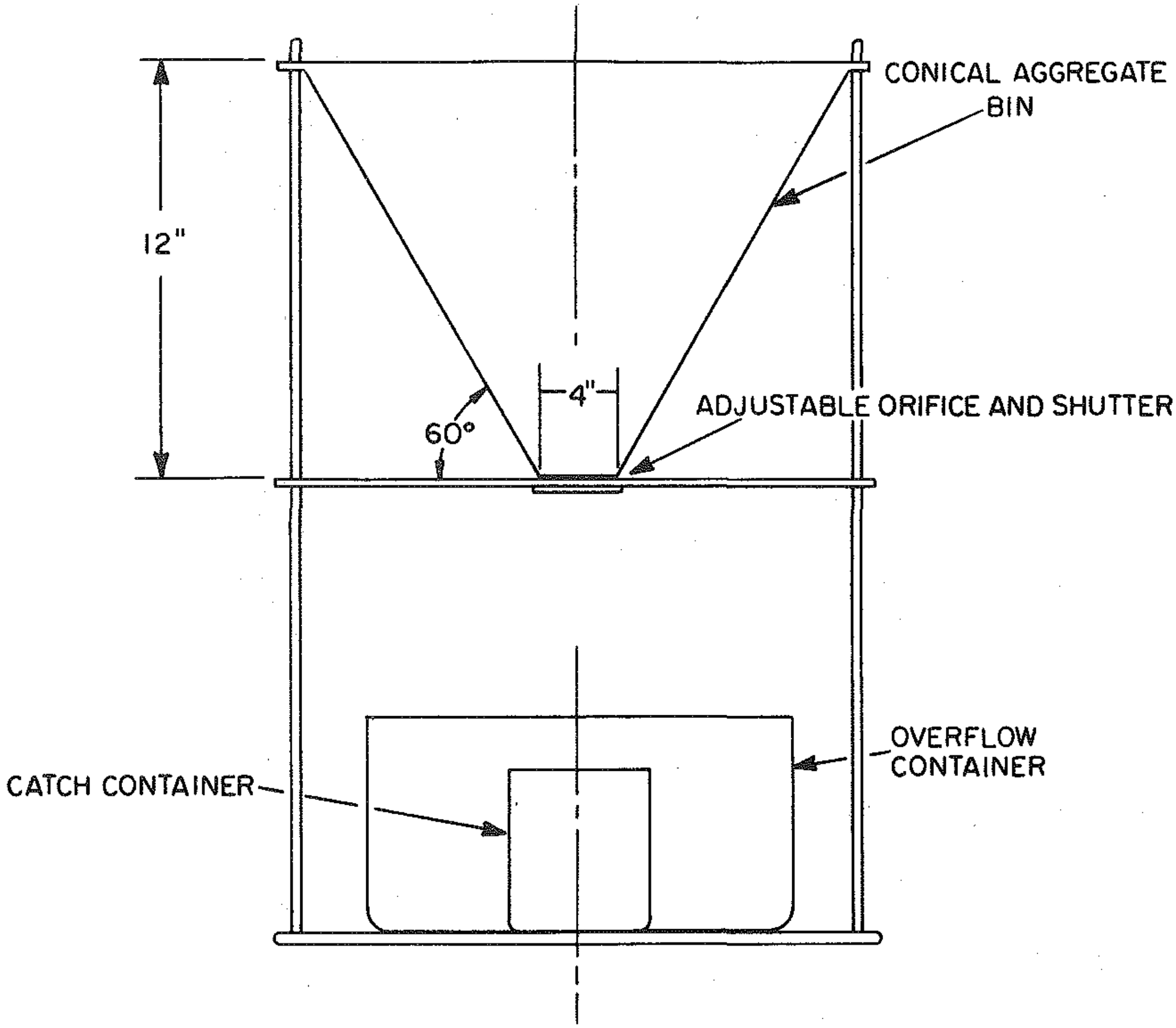


Figure C-1. Proposed standard pouring test apparatus.

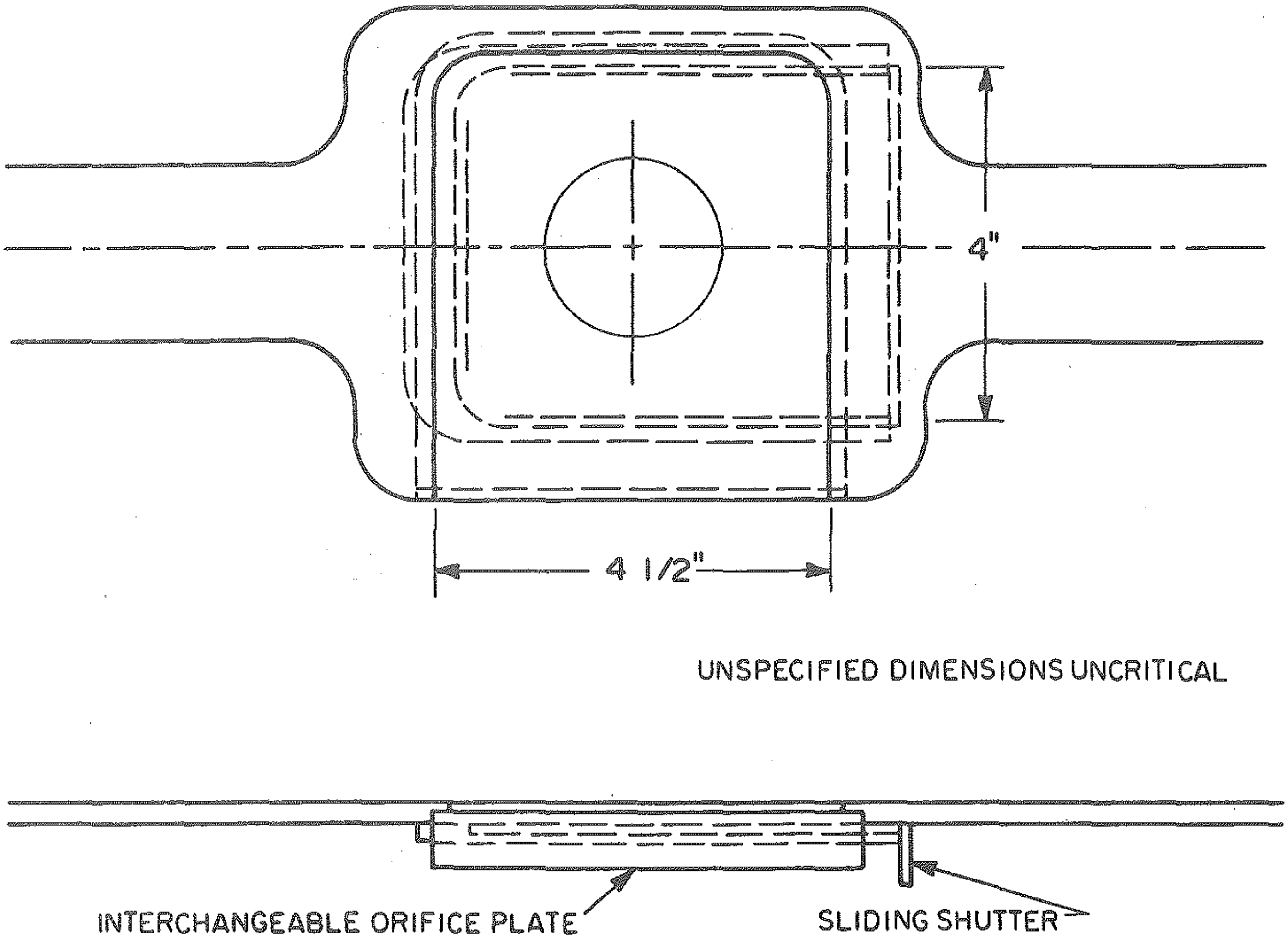


Figure C-2. Possible orifice-shutter arrangements.

APPENDIX D

CORRECTIONS TO PACKING SPECIFIC GRAVITY

The following factors were found to be significant in determining porosity of the caught sample in the pouring test:

(a) Pouring height.

(b) Pouring time.

(c) Ratio of container volume to individual bead volume.

(d) Variability of bead size within a single nominal bead size.

An additional factor was the ratio of container area to container volume. It was not known whether or not this factor was significant. This factor was included as a variable and will be shown to be insignificant within the range encountered.

The variables of pouring height and pouring time were held constant by using the same pouring height for all tests and by choosing an orifice size which would just preclude bridging of beads in the cone.

A variety of bead types and sizes was employed to provide a wide range of container-bead volume ratios, bead variability values (defined as the coefficient of deviation of bead weight), and container area-volume ratios. Table D-1 shows the containers and beads used. Note that three small non-standard sample cans were used in this test to increase the range of container-bead volume ratios considered. Table D-2 shows the appropriate data values from the twenty-eight tests used to predict the regression equation.

The Michigan Interactive Data Analysis System (MIDAS) was used to predict a multivariate regression equation to fit the data points (9). In particular, the SELECT command was used to select the relevant variables in order of their importance. Table D-3 shows output from this process. Note that a parameter for container-bead volume ratio is selected first, followed by selection of the parameter representing bead size variability. The parameter representing volume-area ratio of the container was not selected at any confidence level.

Based on this analysis, the following equation was used to predict packing:

$$P = 0.6169 + 0.01079(\ln(V/v\text{x}10^{-4})) + 0.001382(D_{bead})$$

where

P = the ratio of total caught bead volume to container volume

V = container volume

v = volume of a single bead

D_{bead} = coefficient of deviation of bead weight, percent.

Any combination of bead variability and container-bead volume ratio could have been chosen as a standard. Since the pouring test and allied packing theory assumes perfect beads, a bead variability of 0.0 was chosen as the standard. In addition, observation of many pouring tests indicated that container-bead volume ratios had little effect at values greater than 15,000, so that value was chosen as a standard.

With these corrections available, any standard bead can be used in conjunction with any catch container and the results modified to negate container size effects and bead imperfection. We may illustrate the procedure with an example. In the "second stage" pouring apparatus used by Tons and Ishai (8), 15 mm. glass beads were used as standard beads for the P5/8"-R1/2" aggregate fraction. With the catch container and beads used, container-bead volume ratio is 922. Coefficient of deviation of bead weight for the 15 mm. glass beads was found to be 6.5%. Using the regression equation, predict packing for this situation as:

$$P = 0.6169 + 0.01079(\ln(0.0922)) + 0.00138(6.5) = 0.6001$$

and the predicted packing for the standard case is,

$$P = 0.6169 + 0.01079(\ln(1.5)) + 0.00138(0) = 0.6212.$$

Dividing the second by the first, we get a correction factor:

$$CF = \frac{0.6212}{0.6001} = 1.0352.$$

Now, the adjusted packing specific gravity for aggregates may be obtained by dividing the unadjusted packing specific gravity by this factor. Aggregate parameter tables are shown in original and adjusted form in Table D-4.

It should be noted that the correction factor will not always be greater than 1.0. If container-bead volume ratio is greater than 15,000, no correction should be made for that parameter, but generally a correction will be necessary for bead variability.

TABLE D-1

COMPILATION OF BEAD AND CONTAINER PARAMETERS FOR STATISTICAL TEST

Beads

Bead Diameter (mm.)	Bead Type	Individual Bead Volume (cc.)	Coefficient of Deviation of Bead Weight (Percent)
6	glass	0.133	4.4
5	glass	0.065	6.5
4	glass	0.034	9.9
3	glass	0.014	11.4
6.35	steel	0.134	0.02
3.70	steel	0.033	0.03

Containers

Nominal Size	Height (cm.)	Inside Diameter (cm.)	Calibrated Volume (cc.)
250 ml	7.6	6.4	234.1
600 ml	9.5	8.4	519.9
3 oz	3.5	5.4	77.9
6 oz	4.8	7.0	184.8
10 oz	5.2	7.9	249.5

TABLE D-2
DATA FOR PACKING REGRESSION

Packing	V-ratio	Varatio	D-bead
.6223	4480.	1.4761	4.4
.6164	2020.	1.1323	4.4
.6102	2190.	1.1026	4.4
.6041	1600.	1.0087	4.4
.5916	690.	.7407	4.4
.6275	9450.	1.4761	6.5
.6262	4260.	1.1323	6.5
.6210	4610.	1.1026	6.5
.6162	3380.	1.0087	6.5
.6095	1460.	.7407	6.5
.6317	15300.	1.4761	9.9
.6311	6890.	1.1323	9.9
.6256	7460.	1.1026	9.9
.6216	5470.	1.0087	9.9
.6180	2360.	.7407	9.9
.6345	34700.	1.4761	11.4
.6317	16900.	1.1026	11.4
.6296	12400.	1.0087	11.4
.6294	5340.	.7407	11.4
.6056	3880.	1.4761	.02
.5970	1747.	1.1323	.02
.5900	1890.	1.1026	.02
.5860	1390.	1.0087	.02
.5687	598.	.7407	.02
.6190	7095.	1.1323	.031
.6150	7680.	1.1026	.031
.6124	5630.	1.0087	.031
.6100	2430.	.7407	.031

Packing = Total volume of caught beads/Volume of container
V-ratio = Volume of container/Volume of a single bead
Varatio = Volume of container(cc.)/Surface area of container(sq.cm.)
D-bead = Coefficient of deviation of bead weight.

TABLE D-3

REGRESSION ANALYSIS FROM MIDAS:SELECT

```
< SELECT V=1,2-6 MAX=5 LEVELS=.05,.15 OPT=STEPWISE,FORWARD >

SELECTION OF REGRESSION


ANALYSIS OF VARIANCE OF PACKING            N= 28        EQN= 1

SOURCE                DF   SUM OF SQRS  MEAN SQUARE  F-STATISTIC SIGNIF

REGRESSION             1   .50575 -2    .50575 -2    70.043      .0000
ERROR                 26   .18773 -2    .72205 -4
TOTAL                 27   .69348 -2

MULTIPLE R= .85398  R-SQR= .72929   SE= .84974 -2


VARIABLE         PARTIAL   COEFFICIENT   STD ERROR   T-STATISTIC SIGNIF

CONSTANT                   .62755        .22507 -2   278.83      .0000
LNVRED           .85398    .14326 -1     .17118 -2   8.3692      .0000

REMAINING        PARTIAL    SIGNIF

VRATIO          -.41486     .0314
VARATIO         -.23447     .2391
DBEADWT          .60128     .0009
V2/104          -.41486     .0314




ANALYSIS OF VARIANCE OF PACKING            N= 28        EQN= 2

SOURCE                DF   SUM OF SQRS  MEAN SQUARE  F-STATISTIC SIGNIF

REGRESSION             2   .57362 -2    .28681 -2    59.822      .0000
ERROR                 25   .11986 -2    .47944 -4
TOTAL                 27   .69348 -2

MULTIPLE R= .90948  R-SQR= .82716   SE= .69242 -2


VARIABLE         PARTIAL   COEFFICIENT   STD ERROR   T-STATISTIC SIGNIF

CONSTANT                   .61690        .33732 -2   182.88      .0000
DBEADWT          .60128    .13823 -2     .36739 -3   3.7626      .0009
LNVRED           .78886    .10792 -1     .16816 -2   6.4180      .0000

REMAINING        PARTIAL    SIGNIF

VRATIO          -.61910     .0007
VARATIO          .00861     .9667
V2/104          -.61910     .0007
```

TABLE D-4

AGGREGATE PARAMETER TABLES FOR ORIGINAL AND ADJUSTED PACKING SPECIFIC GRAVITY FOR 1/2"-5/8" FRACTION

ORIGINAL

FRACTION SIZE: 1/2- 5/8

	CONVENTIONAL PARAMETERS						PACKING VOLUME PARAMETERS							
AGG.	AVERAGE PAR. WEIGHT	EQUIVALENT SPHERE DIA.	BULK SP.GR	APP. SP.GR	WAT. ABS.	ASP. ABS.	PACKING VOLUME	PACK. SP.GR	SPEC. RUG.V	GEOM. FACTOR	ASP. RUG.W	ASP. RUG.V	ASP. SAT.	SURF. RUG.V
NG	0.46070E+01	0.15203E+01	2.616	2.736	1.69	0.37	0.18399E+01	2.504	8.49	0.9151	2.11	5.17	60.83	4.26
DL	0.49510E+01	0.15542E+01	2.802	2.829	0.33	0.21	0.19659E+01	2.519	10.98	0.8902	4.31	10.55	97.04	10.13
SS	0.38440E+01	0.15071E+01	2.179	2.568	6.94	2.45	0.17925E+01	2.144	16.49	0.8351	3.21	6.76	40.98	1.61
CG	0.45110E+01	0.15236E+01	2.691	2.752	0.81	0.51	0.18516E+01	2.436	11.48	0.8652	4.48	10.71	93.31	9.49
SL	0.36430E+01	0.15399E+01	2.229	2.467	4.32	3.69	0.19115E+01	1.906	22.77	0.7723	11.47	21.44	94.12	14.53
MR	0.49600E+01	0.15570E+01	2.839	2.931	1.11	0.05	0.19765E+01	2.509	14.39	0.8561	4.77	11.73	81.49	11.59
LS	0.46090E+01	0.15501E+01	2.644	2.697	0.74	0.36	0.19501E+01	2.363	12.36	0.8764	4.94	11.44	92.60	10.61
BP	0.51810E+01	0.15556E+01	2.656	2.694	0.53	0.32	0.19711E+01	2.628	2.45	0.9755	0.73	1.89	77.30	1.65

ADJUSTED

FRACTION SIZE: 1/2- 5/8

	CONVENTIONAL PARAMETERS						PACKING VOLUME PARAMETERS							
AGG.	AVERAGE PAR. WEIGHT	EQUIVALENT SPHERE DIA.	BULK SP.GR	APP. SP.GR	WAT. ABS.	ASP. ABS.	PACKING VOLUME	PACK. SP.GR	SPEC. RUG.V	GEOM. FACTOR	ASP. RUG.W	ASP. RUG.V	ASP. SAT.	SURF. RUG.V
NG	0.46070E+01	0.15379E+01	2.616	2.736	1.69	0.37	0.19046E+01	2.419	11.61	0.8839	3.54	8.40	72.34	7.52
DL	0.49510E+01	0.15723E+01	2.802	2.829	0.33	0.21	0.20351E+01	2.453	14.00	0.8600	5.74	13.69	97.76	13.19
SS	0.38440E+01	0.15246E+01	2.179	2.568	6.94	2.45	0.18556E+01	2.072	19.33	0.8067	4.89	9.93	51.36	4.95
CG	0.45110E+01	0.15413E+01	2.691	2.752	0.81	0.51	0.19170E+01	2.353	14.49	0.8551	5.96	13.75	94.88	12.57
SL	0.36430E+01	0.15577E+01	2.229	2.467	4.32	3.69	0.19791E+01	1.841	25.40	0.7460	13.36	24.11	94.91	17.44
MR	0.49600E+01	0.15751E+01	2.839	2.931	1.11	0.05	0.20451E+01	2.434	17.20	0.8270	6.20	14.73	85.13	14.60
LS	0.46090E+01	0.15680E+01	2.644	2.697	0.74	0.36	0.20187E+01	2.283	15.34	0.8466	6.46	14.45	94.24	13.65
BP	0.51810E+01	0.15737E+01	2.656	2.694	0.53	0.32	0.20405E+01	2.539	5.76	0.9424	2.10	5.23	90.69	4.42

APPENDIX E

SELECTION OF OPTIMUM ASPHALT CONTENT FROM DESIGN TABLES

An acceptable procedure for selection of optimum asphalt content using the design tables produced by the design table program is as follows:

(a) Obtain actual mix specific gravities for a variety of asphalt contents. Specimens made in conformance with Marshall specifications are convenient for this purpose. The range of asphalt contents considered should ideally have as its mean the optimum content. A good estimation for optimum asphalt content can be made from analysis of the design tables alone.

(b) Enter the design tables at the respective asphalt contents and mix specific gravities as obtained from the experimental specimens. At these points, note and record the packing V.M.A. calculated by the design table program.

(c) Plot packing V.M.A. versus asphalt content. Tests to date have shown that optimum asphalt content is indicated at minimum packing V.M.A.

(d) In some cases, packing V.M.A. will not reach a minimum, but will continue to decrease as asphalt content is increased. In such cases, asphalt optimum prediction should be made based on the value chosen for minimum air voids. This value may vary. The air void value used herein is the value used by the Michigan Department of State Highways and Transportation, 4%.

Figure E-1 shows a typical example of the relationship between Marshall data and computed packing V.M.A.

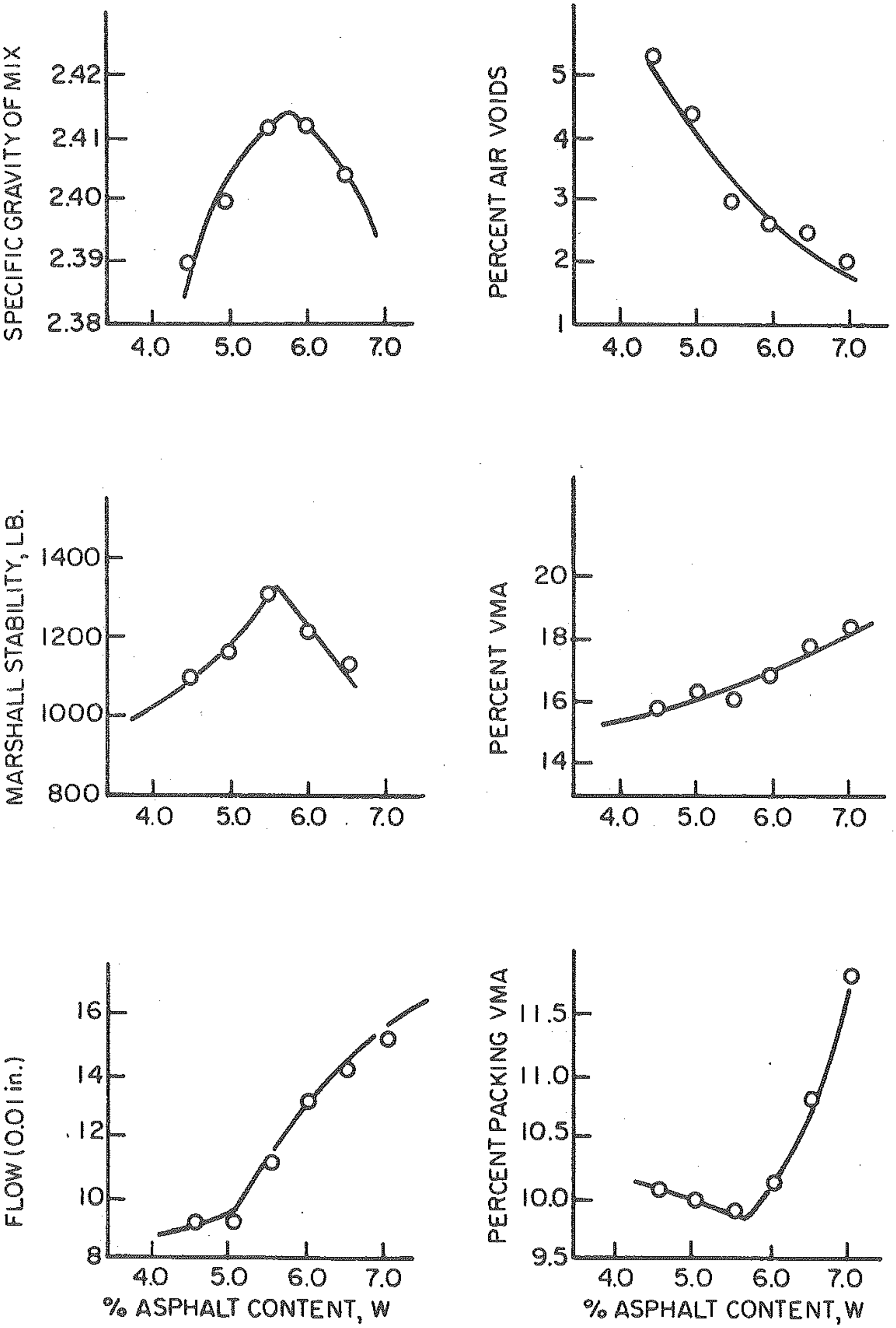


Figure E-1. Marshall data for Mix I.