Effect of Asphalt Viscosity on Compaction of Bituminous Concrete

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A laboratory study was undertaken to determine the important variables that affect the densification of bituminous concrete during rolling. Of principal interest was the influence of asphalt viscosity on the compaction process; also examined were the effects of number of roller passes, type of roller (steel or rubber), hardness of the supporting medium, and environmental temperature. An attempt was made to simulate full-scale field rolling conditions insofar as possible in this study.

The measurements taken on the compacted mix included unit weights, voids, Marshall stabilities and flow. The results indicate that the effects of asphalt viscosity during compaction (between approximate mix temperatures of 300 F and 160 F) on stability is noticeable while the relative density and voids changes are small. The Marshall stability values, however, were found to be several times lower than those expected using a standard Marshall specimen compaction procedure.

The rubber-tire roller and rolling procedure used in this study gave a slightly less dense and less stable compacted mix than did a steel roller.

•COMPACTION of bituminous concrete is a stage of construction which transforms the mix from its very loose state into a more coherent mass, thereby permitting it to carry traffic loads.

Since compaction is a densification process involving the displacement of aggregate particles, the efficiency of the compactive effort will be a function of the internal resistance of the bituminous concrete. This resistance includes aggregate interlock, frictional resistance, and viscous resistance. The interlock and the frictional resistance are primarily functions of the geometry and surface characteristics of the aggregate. The viscous resistance is a function of the viscosity of the binding agent, asphalt.

An increase in density will result in an increase of the strength of the pavement. Previous publications (1, 2, 3) have indicated that the initial compaction during construction will give densities and stabilities that are below those measured in pavements after several years of exposure to traffic.

Theoretical and experimental work by Nijboer (4) divided the major variables in the process of compaction into two general categories: properties of the mix and properties of the roller. The properties of the mix include: (a) angle of internal friction and (b) viscosity of the bituminous mix. The properties of the roller include: (a) the weight of the roller, (b) the length of the roller, (c) the diameter of the roller, (d) the speed of rolling, and (e) the number of coverages. The work described here is an attempt to add to the present knowledge including parameters such as asphalt viscosity, various types of supports, different environmental compaction temperatures, and steel and rubber rollers.

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PURPOSE AND SCOPE

The general goal of this research project was to attempt to study, in the laboratory, compaction of a given bituminous-concrete mix under full-scale simulated steel and rubber-tire rollers. Specifically, the main purpose was to measure the effects of asphalt viscosity on the compaction process.

Massachusetts Type I surface mix with 6.5 percent of 85-100 Venezuelan asphalt was used for making 12- by 12-in. bituminous-concrete slabs, 2 in. thick (Fig. 1). Altogether about 400 specimens were compacted and the following primary measurements were made: (a) unit weights, (b) void contents, and (c) Marshall stabilities.

Constants and Variables

Steel Roller Compaction.—The roller diameter was 60 in. (in the form of a strip of curved steel plate, see Figs. 2 and 3).

The load was 250 lb per lin in.

Five initial mixing temperatures were used: 325 F, 277 F, 240 F, 217 F, 195 F (to correspond to asphalt viscosities of 100, 300, 900, 2000, and 5000 cps). Environmental placement and compaction temperatures were 80 F and 40 F.

Three hardnesses of supports under the specimen during compaction were K = 100 pci, K = 300 pci, and K = 2000 pci. (K = modulus of support reaction, in pounds per square in. per 1 in. deflection or in pounds per cubic inch.)

There were 1, 3, 6, and 18 coverages, and the time lapse between coverages was 2 min.

Figure 1. 12- by 12- by 2-inch specimen.

Figure 2. Compaction machine.

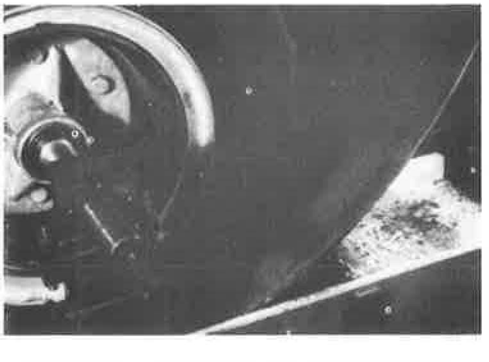

Figure 3. Close-up of steel roller.

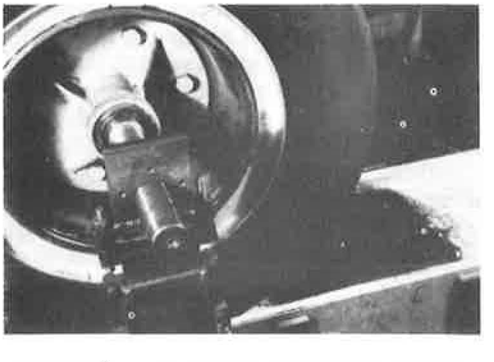

Figure 4. Close-up of rubber roller.

Rubber-Tired Roller Compaction.—The roller tire was 7.50 × 16 (Fig. 4) with a load of 3500 lb, and a 100-psi tire pressure. Initial mixing temperatures, and corresponding viscosities were the same as for steel roller compaction.

Environmental placement and compaction temperature was 80 F, with two hardnesses of supports: K = 100 pci and K = 2000 pci.

The same coverages and time lapse between coverages were used.

Miscellaneous.— Several additional trial tests were run to check the sensitivity of the results at extreme compaction temperatures, high base support values (concrete slab support), changes in roller loads and diameter, etc.

REASONS BEHIND VARIABLES

Before the actual test specimens were made, a number of preliminary experiments were conducted.

Dimensions of the Specimens

A simulation of road conditions was attempted. The thickness of 2 in. was chosen in order to use the Marshall procedure for strength measurements (in practice the Massachusetts Type I top course is usually compacted in layers thinner than 2 in.).

In order to reduce the size of the mix batches, trial experiments were conducted compacting the mix in various sized slabs, taking cores and comparing their density-void-stability values. The smallest specimen still simulating a "continuous" bituminous concrete mat was found to be in this case around 12 by 12 in. Thus all compacted specimens were made this size. They weighed about 22 lb each.

Choosing the Base Supports

Bituminous concrete may be placed on supports having different hardness or stiffness. To investigate the support values that would indicate differences in the compacted product, a series of preliminary compaction tests was conducted and it was found that supports with K values above 2000 gave similar results; there was a slight change in density-stability values at K values lower than 2000. This led to the choice of three supports: K = 100, K = 300, and K = 2000, which were simulated by 1-in. thick pads of foam rubber, urethane elastomer, and hard rubber, respectively. The K values, in pounds per cubic inch, were determined by compressing a 12.5 sq in. area of these pads, which were sandwiched between two steel plates, and measuring the load-deformation characteristics.

Rolling Frequency Procedure

Steel and rubber tire rollers with what were considered reasonable dimensions and unit pressures were chosen. A speed of 2 mph was assumed acceptable. In order to simulate the time interval between roller coverages a few field observations were made and it was decided that a 2-min interval between each coverage of the roller would closely approximate average field conditions. As will be shown later this time interval is not very critical; compaction results using the 2-min data can be calculated for other time intervals if necessary.

Other Variables

The materials, mix proportions, mix temperatures during mixing, placing, and compaction were selected according to observations and judgment, simulating conditions in Massachusetts. Added were some extreme conditions, such as mixing and compaction at mix temperatures below 200 F.

The compaction with the steel roller was conducted at two environmental temperatures, 40 F and 80 F, to observe cooling rates of the mix and their effect on compaction.

Figure 5. Mixing machine.

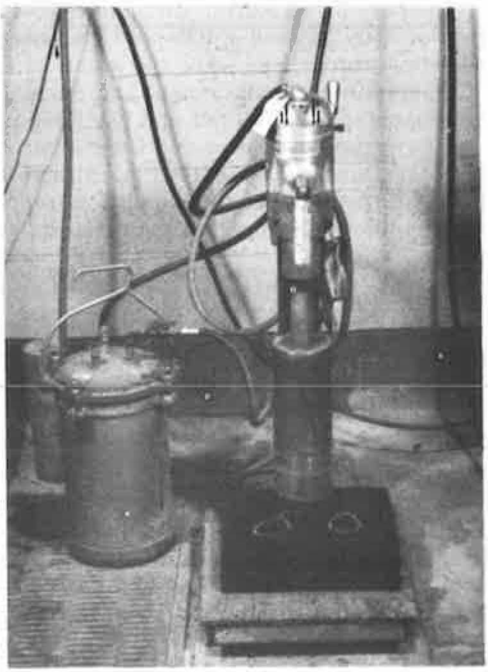

Figure 6. Core drill.

SPECIMEN PREPARATION

The aggregates (22 lb) were heated in an oven overnight to the desired temperature before the asphalt was added. Prior to mixing, the asphalt was heated to the same temperature as the aggregates. Both components were combined and mixed in a covered and Styrofoam-insulated mixing bowl (Fig. 5) for one min. The hot mix was then placed in the compaction box. The following sequence was carried out:

Time Sequence (min)	Action
0- 1	Mixing
1- 8	Transporting, placing and knock-down coverage
at 8	First coverage with roller
8-10	Wait
at 10	Second coverage
10-12	Wait (repeating coverages to completion)

In the case of the steel wheel roller, a knock-down coverage (of 50 lb/in.) was used before the standard 250 lb/in. compaction load was applied. In the case of the rubber roller, a knock-down coverage (50 lb/in.) using a steel roller was applied. Then the standard compactive load of 3500 lb and 100-psi tire pressure was used.

The procedure for the compaction with the rubber roller had to be modified, because the tire traversed only half the width of the specimen with each coverage. One full coverage in 2 min for all points of the specimen was achieved by applying one coverage per min on alternate halves of the specimen.

In all cases, continuous readings of the temperatures of each specimen were taken. After the specimens had reached room temperature, they were removed from the compaction box. The specimens were allowed to stay overnight after which they were placed at 40 F for three hours before the coring operations were performed (Fig. 6). Two cores, 4 in. in diameter and 2 in. thick, were cut out of each compacted specimen. After drying and obtaining specific gravities (and by inference void contents), Marshall stability-flow measurements on both cores were taken (ASTM D-1559-60T).

TEST RESULTS—VISCOSITY MEASUREMENTS

Viscosity of Asphalt

Since the major variable in the entire program was the asphalt viscosity, measurements were made on the fresh and the extracted asphalt.

Fresh Asphalt.—The absolute visocity as a function of temperature was determined experimentally using a Brookfield "Synchro-Lectric" HAT model (range 0-16,000,000 cps) Viscometer. The asphalt to be tested was placed in a 600-ml beaker and suspended in a constant-temperature oil bath. When the desired temperature was reached uniformly in the beaker, the viscometer with spindle No. 1 in place was lowered into the asphalt. Shear stress readings were taken covering a range of 0.5-100 rpm. Stress at each shear rate was plotted on a graph of log (shear stress) vs log (shear rate) and a straight line was drawn through the points. Viscosity at each temperature was calculated at the intersection of these lines with a line of constant energy (RPM x shear stress = constant). The asphalt behaved in a Newtonian fashion with only slight tendencies to be thixotropic (in the range investigated, viscosity decreased with increasing shear rate by only 7%). The results could be plotted as a straight line on a log-log (viscosity) vs log (absolute temperature F) basis (Fig. 7). The final results, after curve fittings by the least squares method, were:

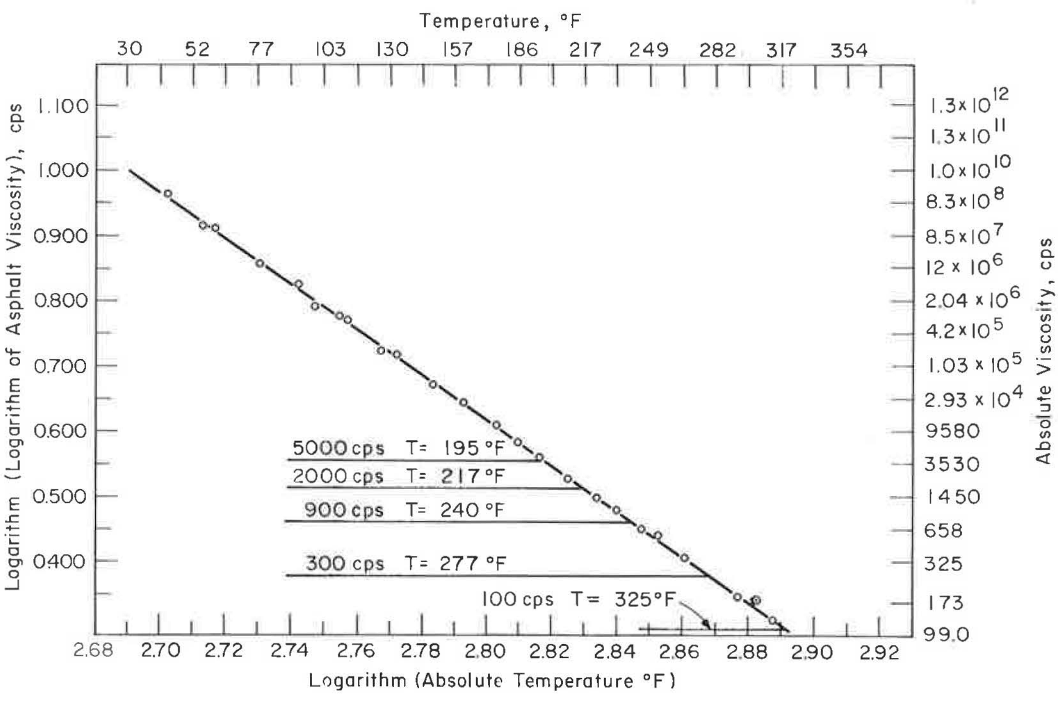

Figure 7. Initial asphalt viscosities and temperatures used in compaction experiments.

$$\log (\log \eta) = 10.1497 - 3.4030 \log (T_{abs}) \pm 0.0042$$

where

η = viscosity, cps; and
$T_{abs} = 560 + °F$.

This equation holds for temperatures ranging from 40 F to 377 F.

The above results were checked using the Saybolt-Furol viscosity method. Five points were obtained between 210 F and 168 F. Using the approximate relation that absolute viscosity (cps) equals 2 times the Saybolt-Furol time (in sec), the results checked very well with the Brookfield measurements. Additional points to 40 F were obtained by the Shell sliding plate viscometer.

Extracted Asphalt.—Since the viscosity of the asphalt was the single most important variable of the research project, it was clear that the variations in the viscosity of the asphalt due to hardening during mixing and compaction had to be checked. After compaction the asphalt was extracted and distilled using the modified Abson procedure ASTM D-762-49. The viscosity of the extracted asphalt was then determined between 40 and 325 F. The Saybolt-Furol viscometer was used from 325 to 160 F, and to complete the cycle, the Shell sliding plate microviscometer was employed from 160 to 40 F.

The results obtained are shown in Figure 8: one curve gives the viscosity-temperature relationship for the asphalt before heating-mixing and the other two curves, viscosities for the asphalt extracted from mixes which were heated and prepared at 325 F and 195 F.

Cooling of the Mix

The procedure called for heating both the mix and the aggregates to the desired temperature, mixing and compaction. During these various operations the temperature

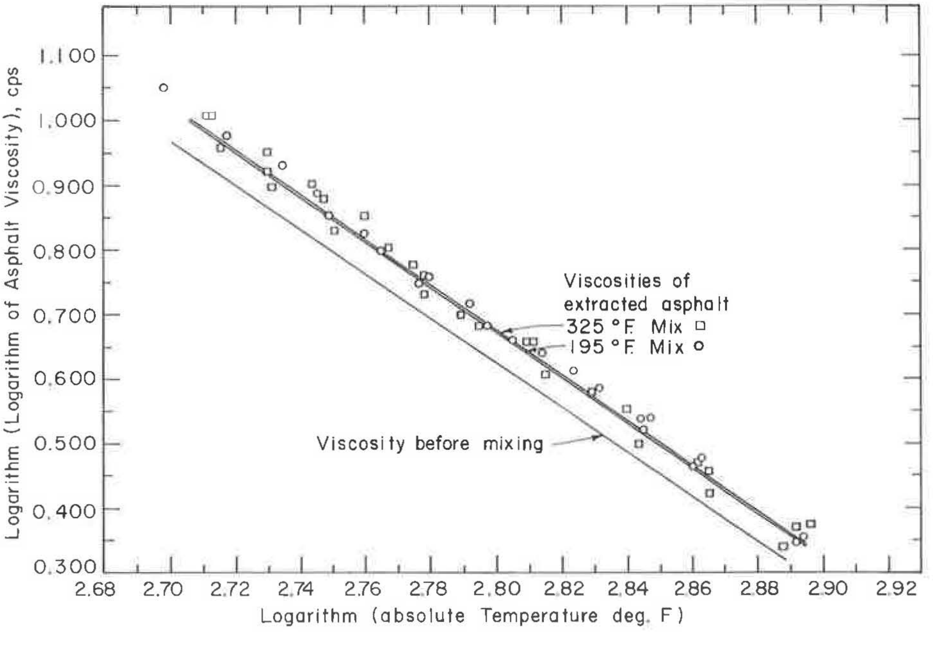

Figure 8. Logarithm of the logarithm of the asphalt viscosity vs the logarithm of the temperature in deg F absolute.

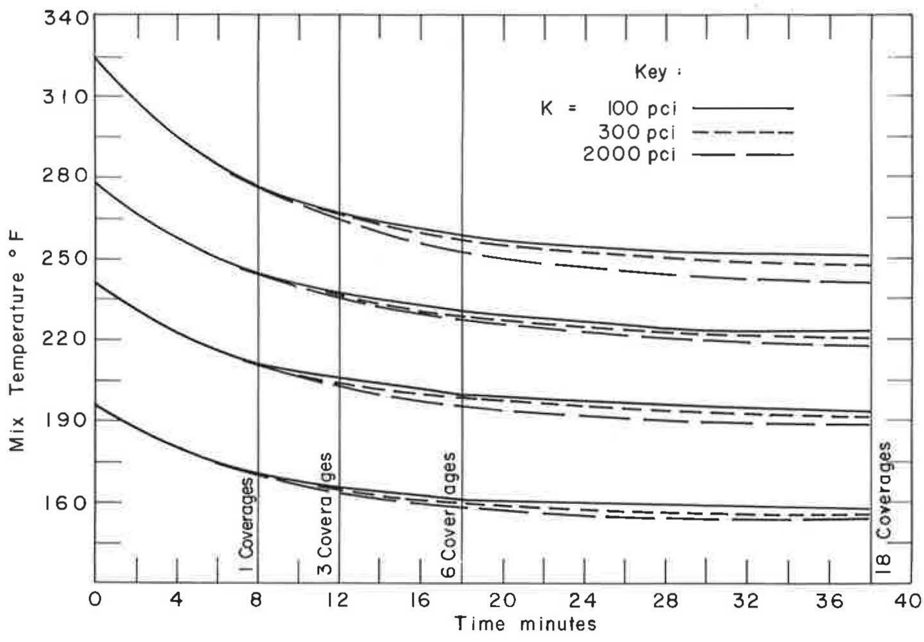

Figure 9. Temperature decay with time at 80 F environmental temperature, steel and rubber rollers, various initial mix temperatures.

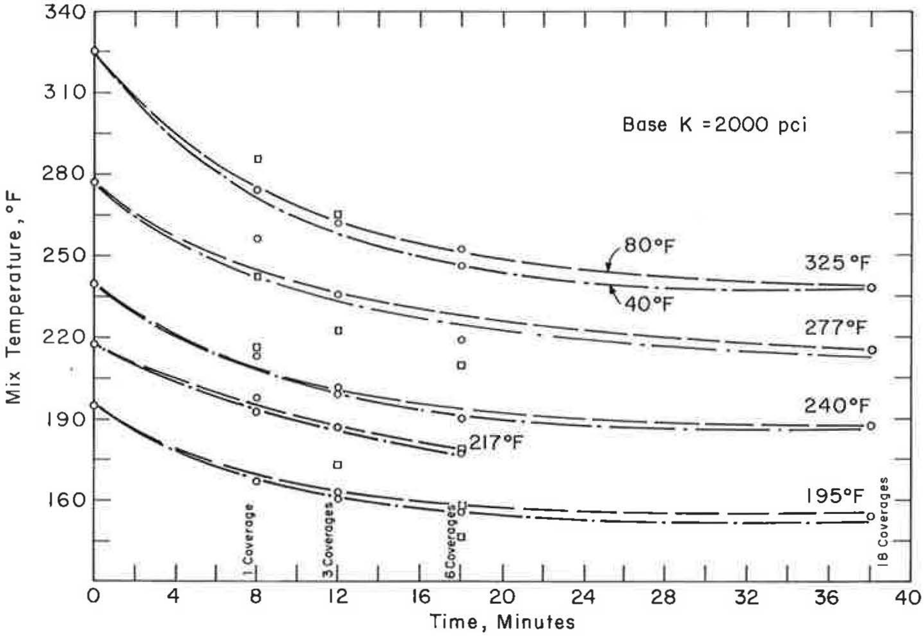

Figure 10. Temperature decay vs time, for steel-rolled specimen.

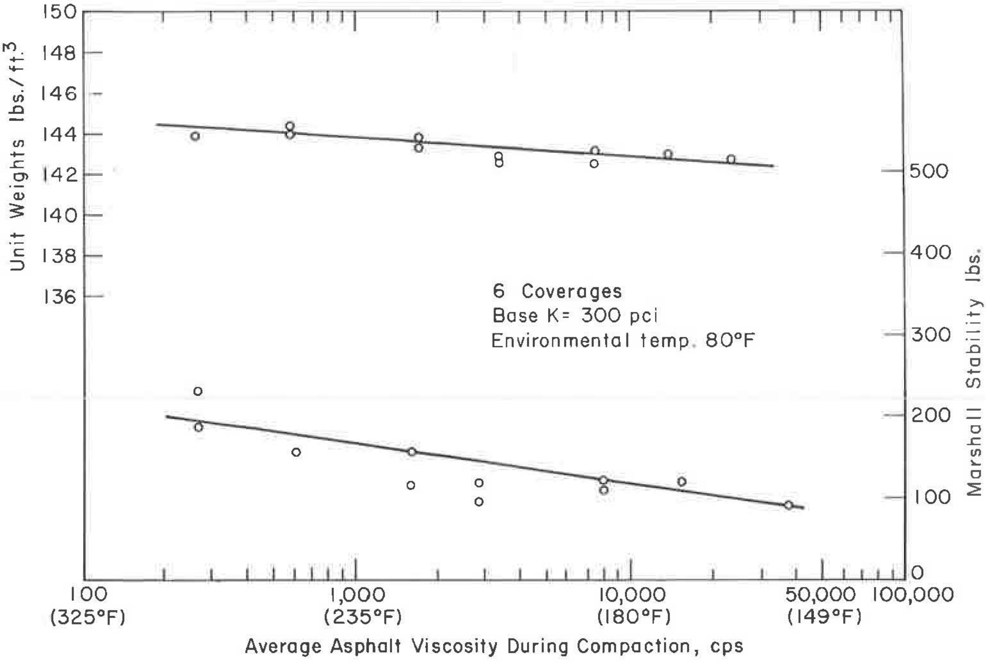

Figure 11. Unit weights and Marshall stability vs average asphalt viscosity, steel roller.

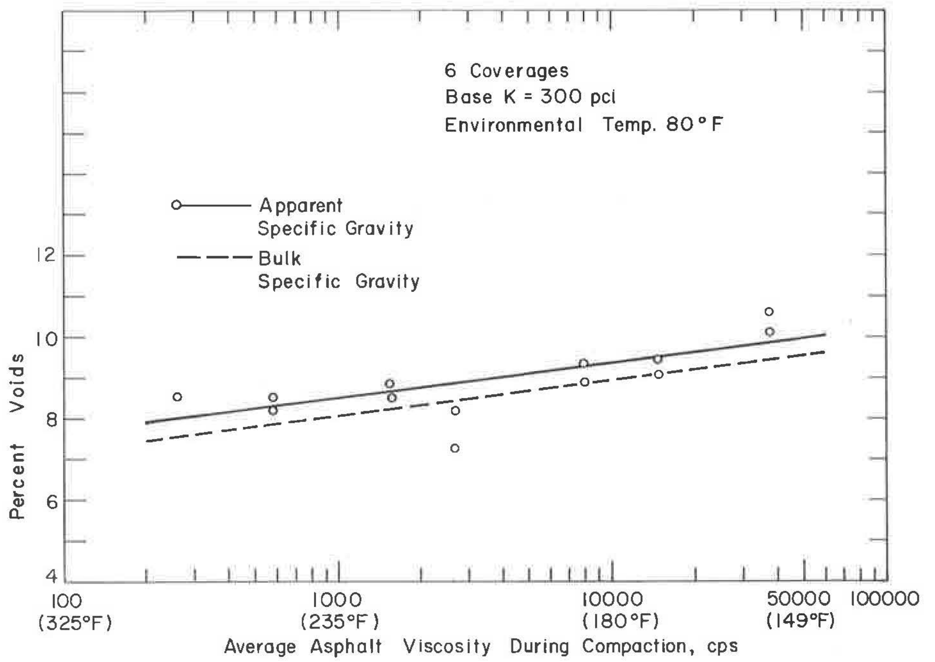

Figure 12. Percent voids vs average asphalt viscosity, steel roller.

of the mix was decreasing and the viscosity of the asphalt was increasing. The temperature-time curves for the various initial mix conditions and types of supports are given in Figure 9.

The cooling rate of the mix was slightly different for various types of base supports used (Fig. 9). This was due to the better conductivity of solid rubber, for example, (K = 2000) as compared to foam rubber (K = 100).

The cooling during the compaction depends also on the environmental compaction temperature (40 or 80 F) as indicated in Figure 10.

Because the viscosity (the temperature) of the mix was changing during the compaction, a certain "average compaction viscosity" had to be used for presentation of data. This was done by taking the temperature of the mix at the time of the first coverage and the temperature at the last coverage, and obtaining the average of these two; the corresponding viscosity was then calculated and designated as "average asphalt viscosity during compaction, cps."

This average compaction viscosity will not be exactly the viscosity of the fresh asphalt because some hardening during the mixing and compaction has taken place. The amount of hardening or increase in viscosity would be reflected by a curve somewhere between the viscosity of the fresh asphalt and the viscosity of the extracted asphalt shown in Figure 8. This amount of hardening was of little importance in the results (the unit weights would change by about 0.2 percent), and therefore, for convenience, the viscosity of the fresh asphalt was always used in the various figures presented in this paper.

Typical Examples

To maintain uniformity in the figures, the average asphalt viscosity during compaction is usually plotted against the other three measurements: density, voids and stability of the mixes. This is illustrated in Figures 11 and 12 for steel roller, 6 coverages, K = 300 and environmental compaction temperature of 80 F. One of the significant findings is that the physical properties of this mix altered proportionally to the logarithm of the average asphalt viscosity during compaction.

TEST RESULTS—COMPARISON OF STEEL AND RUBBER ROLLERS

In the following, the effect of different variables on the density-voids-stability characteristics for each type of roller is discussed.

Effect of Environmental Compaction Temperature

In the series of experiments with the steel roller, two environmental compaction temperatures were used: 40 F and 80 F. The room was brought to the designated temperature and then the mix was placed and compacted.

Figure 13 gives an example of what happens to the unit weight and the stability of the mix when compacted during cold and warm environmental temperatures. The main difference is that the average asphalt viscosity during the compaction is lower in the case of the 40 F temperature compared with the 80 F, other variables being equal. This simply results in slightly lower densities and stabilities, and both curves should follow the same line.

Some deviations from this pattern are expected due to the fact that simple average temperatures (viscosities) are used from the average asphalt viscosity during compaction.

This observation is of practical importance because it indicates that bituminous concrete can be placed and rolled in cold weather at temperatures below 40 F, provided that the needed number of coverages is applied within a short time. Heating the mix to unusually high temperatures is not as promising as repetitious rolling at normal mix laying temperatures (say 325 to 250 F).

The effect of environmental temperature on rubber-wheel rolling was not investigated on the assumption that the trends would be similar to the case previously discussed.

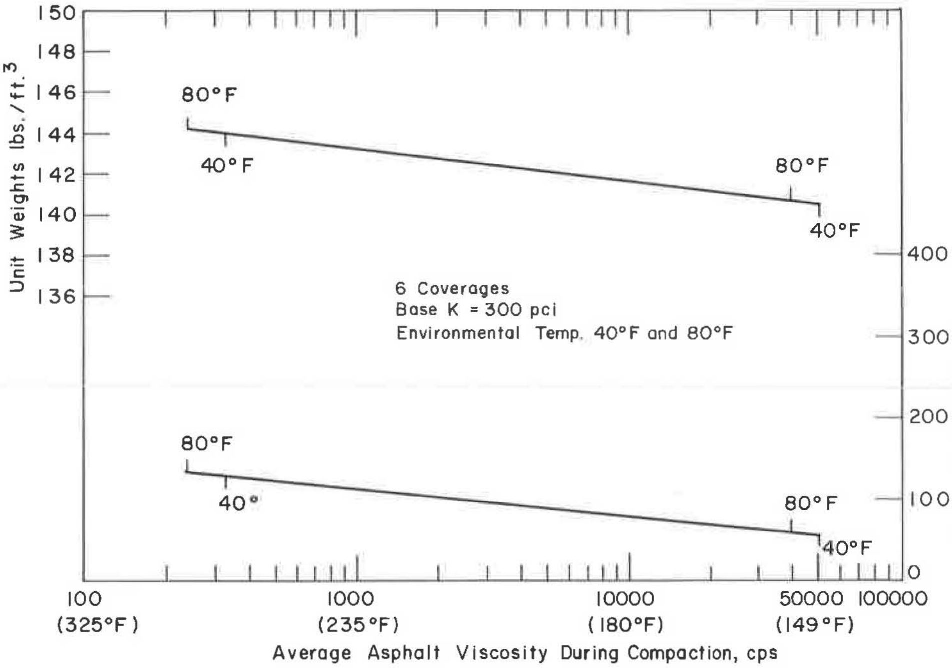

Figure 13. Unit weights vs average asphalt viscosity, steel roller.

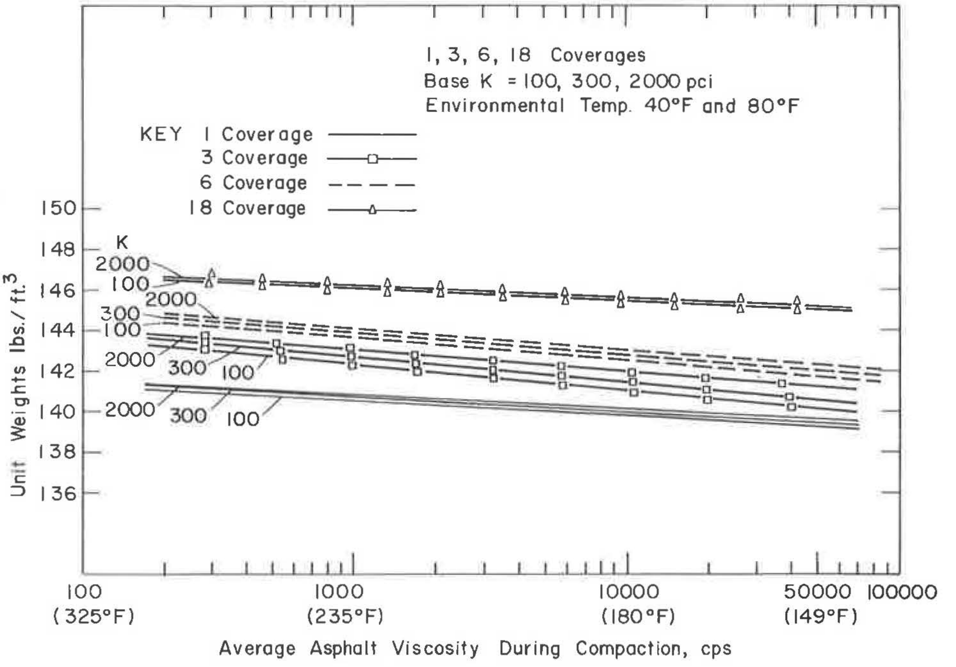

Figure 14. Unit weights vs asphalt viscosity, steel roller.

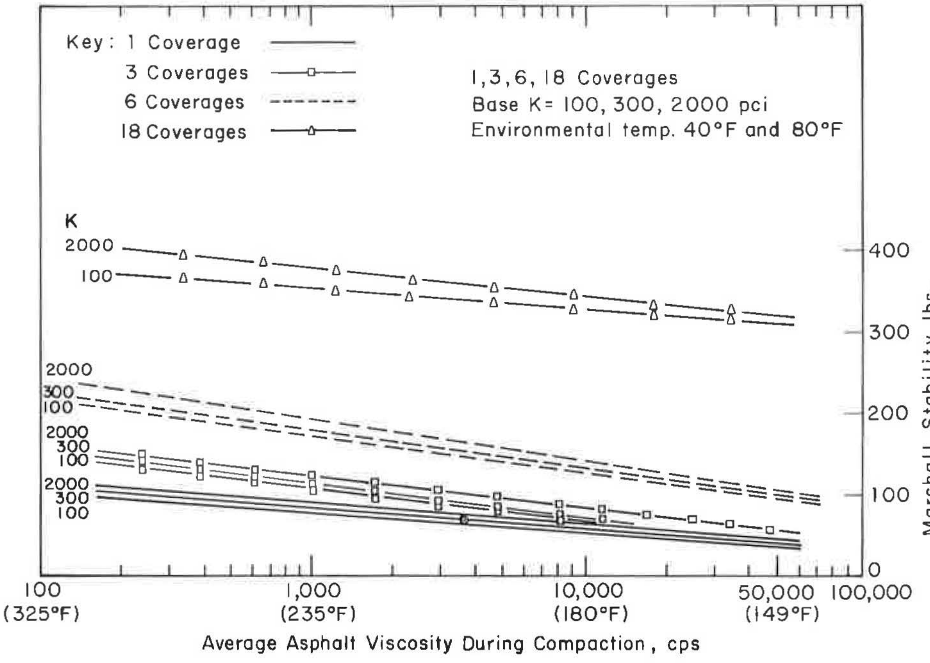

Figure 15. Marshall stability vs average asphalt viscosity, steel roller.

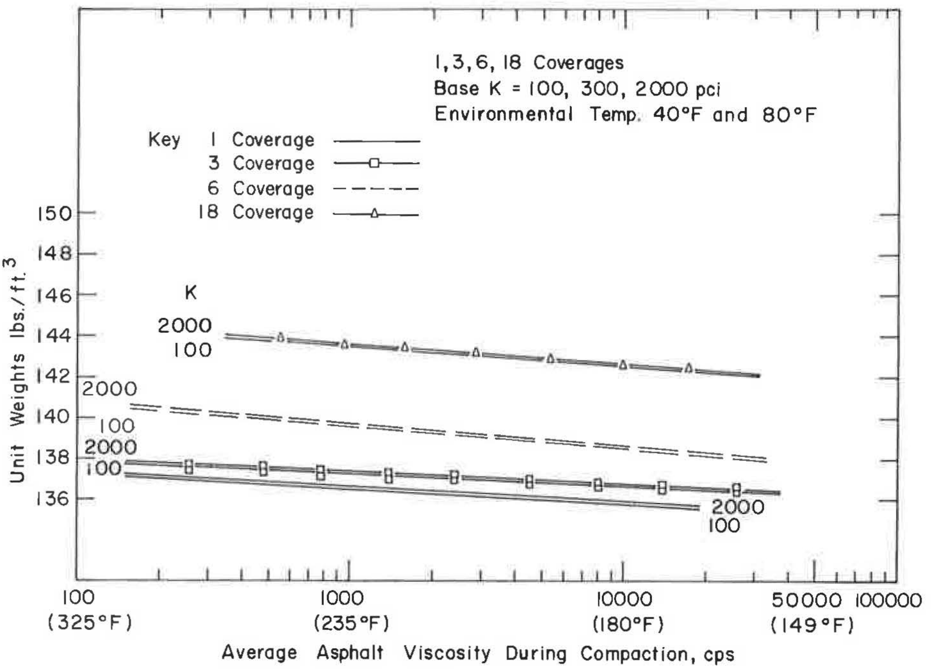

Figure 16. Unit weights vs average asphalt viscosity, rubber roller.

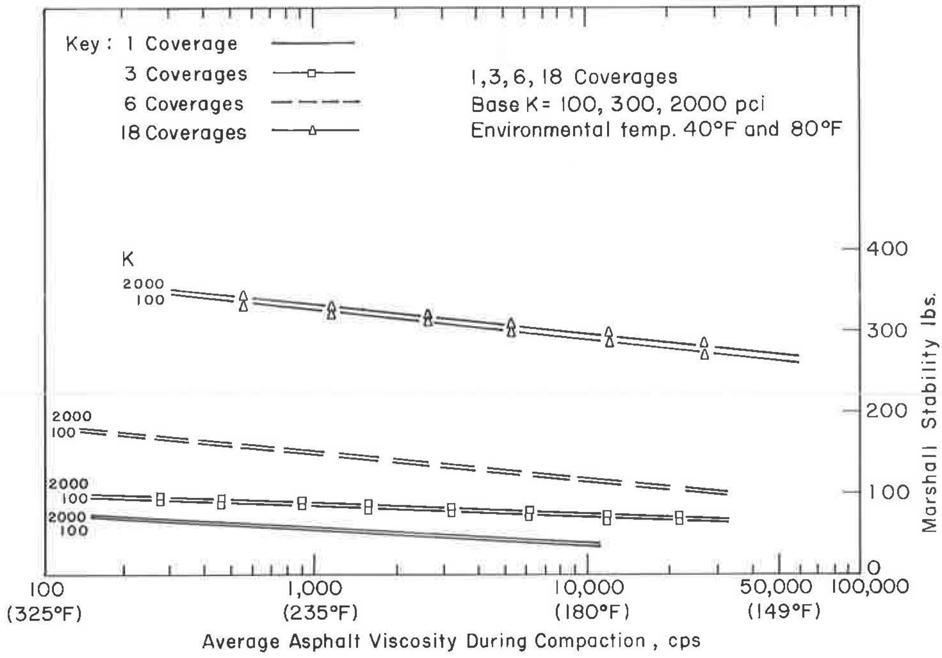

Figure 17. Marshall stability vs average asphalt viscosity, rubber roller.

Effect of Base Support Stiffness

Three types of base supports were used with reactions K equal to 100, 300 (in steel roller series only), and 2000 pci. Although the K = 100 (and maybe K = 300) base is seldom encountered in practice, it was chosen as an extreme case.

Figures 14 and 15 summarize the comparisons for the steel roller and Figures 16 and 17 for the rubber tire. There are only slight differences in the densities and stabilities, the harder base giving the higher values. Compaction checks using a concrete base (both smooth and rough) with K = 4,000,000 gave similar results to those of the K = 2000 base (solid rubber). In other words, the effect of base course stiffness or smoothness on density-stability of a 2-in. thick layer under compaction conditions described in this report was found to be small from a practical point of view.

Master Curves

From the previous findings it became apparent that the effects of the environmental compaction temperature and the base support stiffness were small. This permitted a compounding of the various curves to obtain about 80 points for plotting unit weight, stability, and void curves for the steel roller compaction as shown in Figures 18 to 25. Although a slight error is introduced due to compounding the points from various base supports, more reliable trend curves are obtained.

In Figure 20, the density-stability values are plotted against the average asphalt viscosity during compaction for 6 coverages of a steel roller. The curves are based on about 80 points each and the following trends can be observed:

1. For the unit weights, if a variation on both sides of the average curve ± 1.5 percent is accepted, 95 percent of all points will lie within this range (Fig. 20).

2. For the Marshall stabilities, assuming a range of ± 25 percent, about 80 percent of the points are inside the limits. This indicates that the variability in the Marshall stability values is considerable.

3. For the voids (based on apparent specific gravity) about 95 percent of the points lie within ± 15 percent of the average curve.

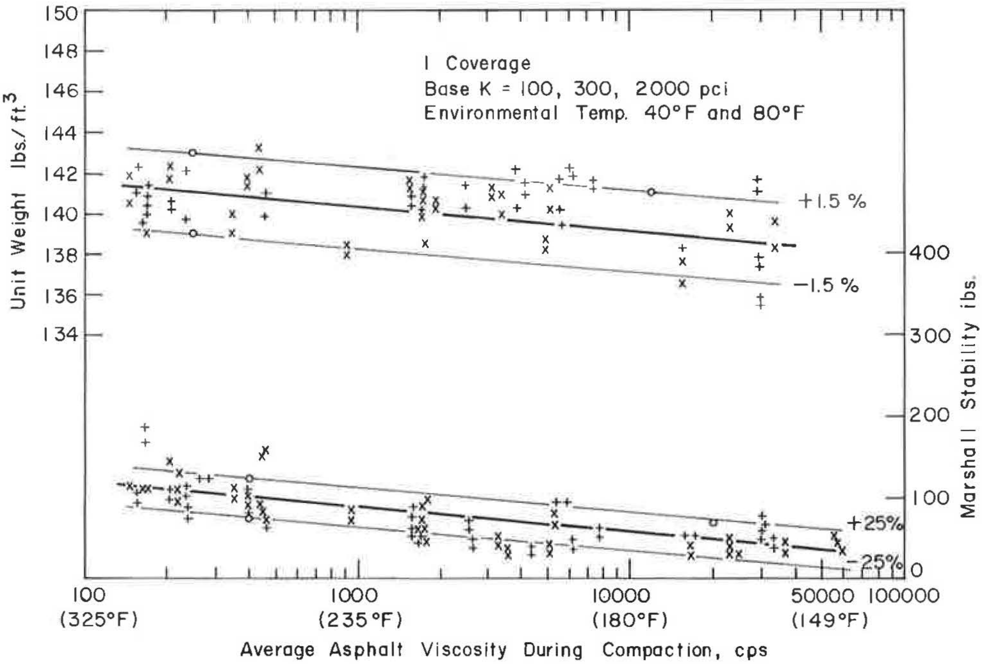

Figure 18. Unit weights and Marshall stability vs average asphalt viscosity, steel roller.

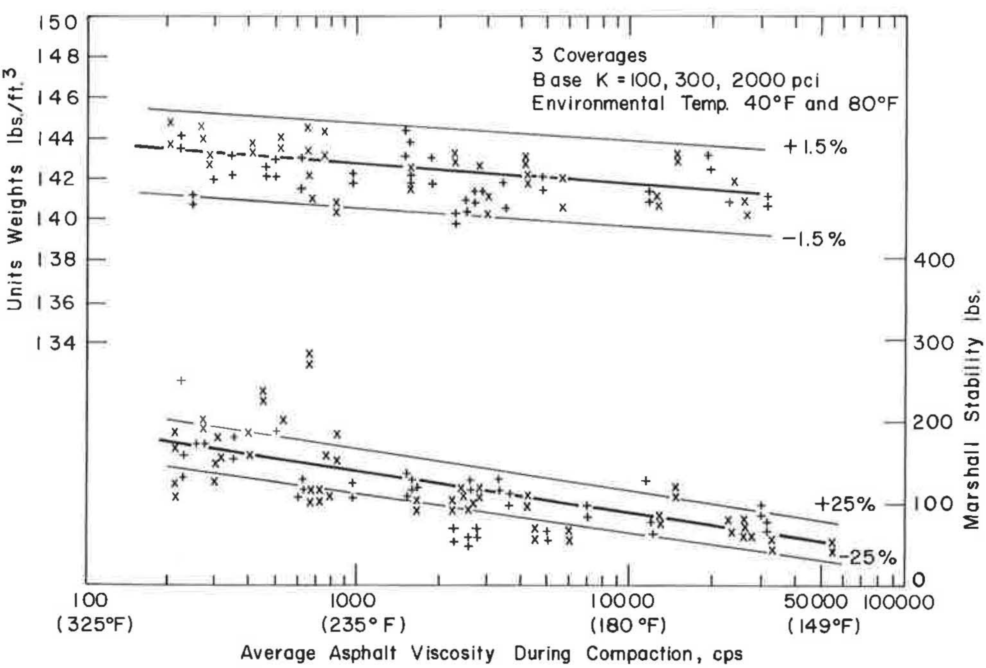

Figure 19. Unit weights and Marshall stability vs average asphalt viscosity, steel roller.

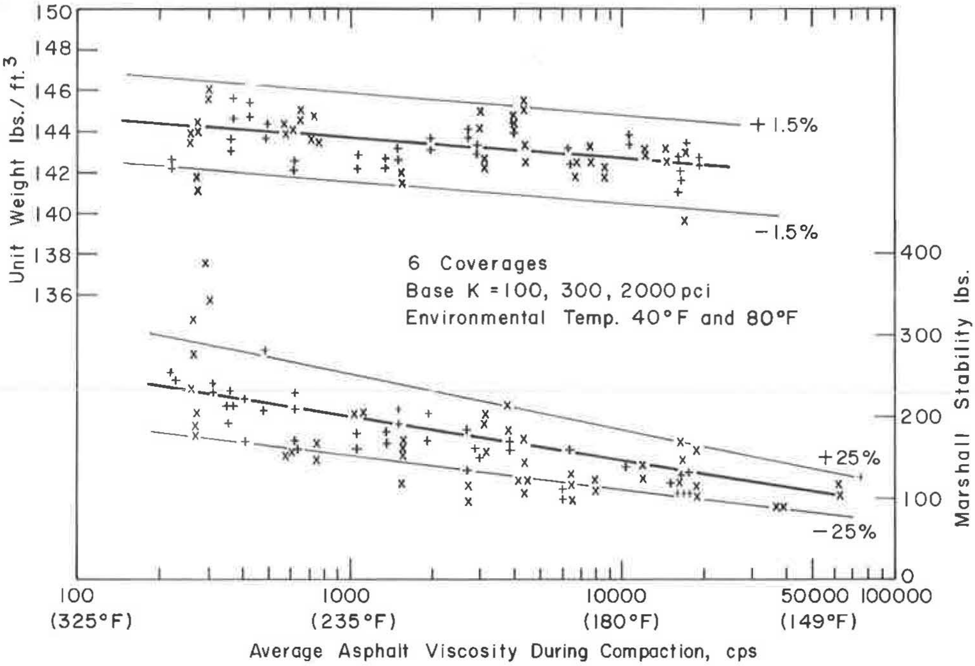

Figure 20. Unit weights and Marshall stability vs average asphalt viscosity, steel roller.

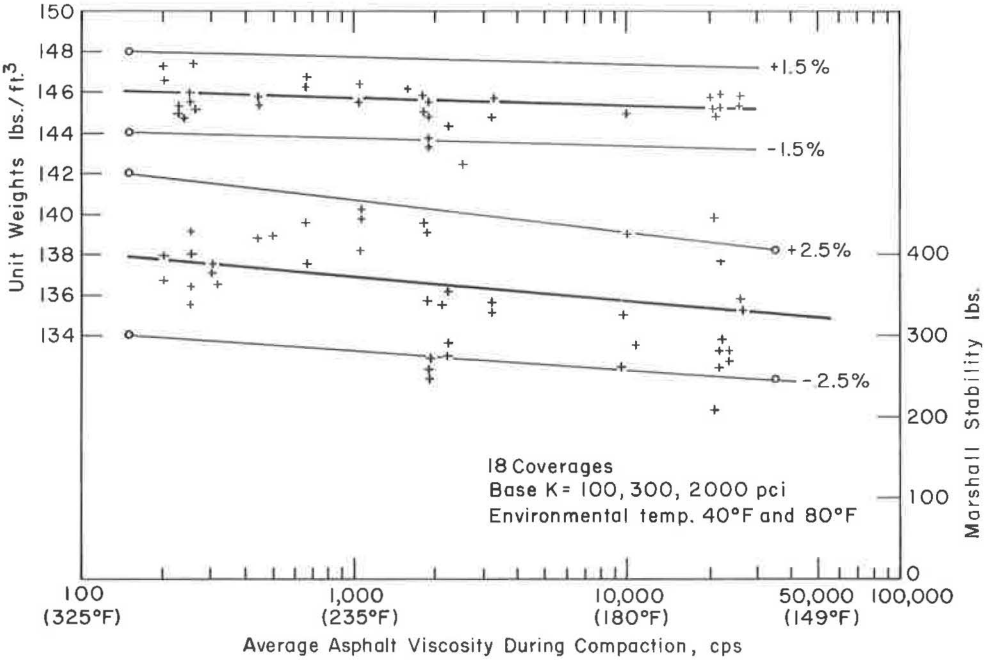

Figure 21. Unit weights and Marshall stability vs average asphalt viscosity, steel roller.

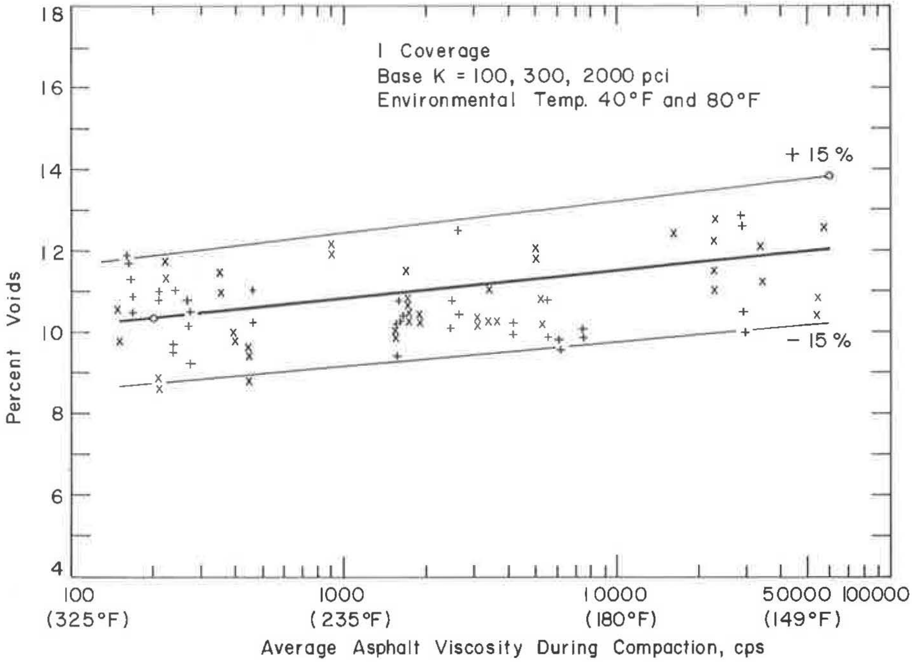

Figure 22. Percent voids vs average asphalt viscosity, steel roller.

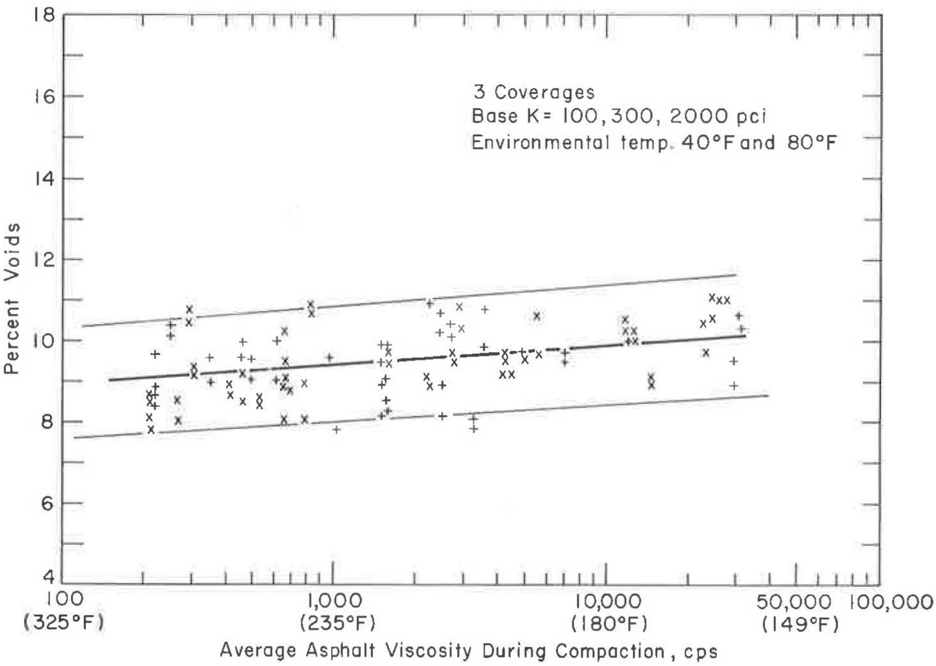

Figure 23. Percent voids vs average asphalt viscosity, steel roller.

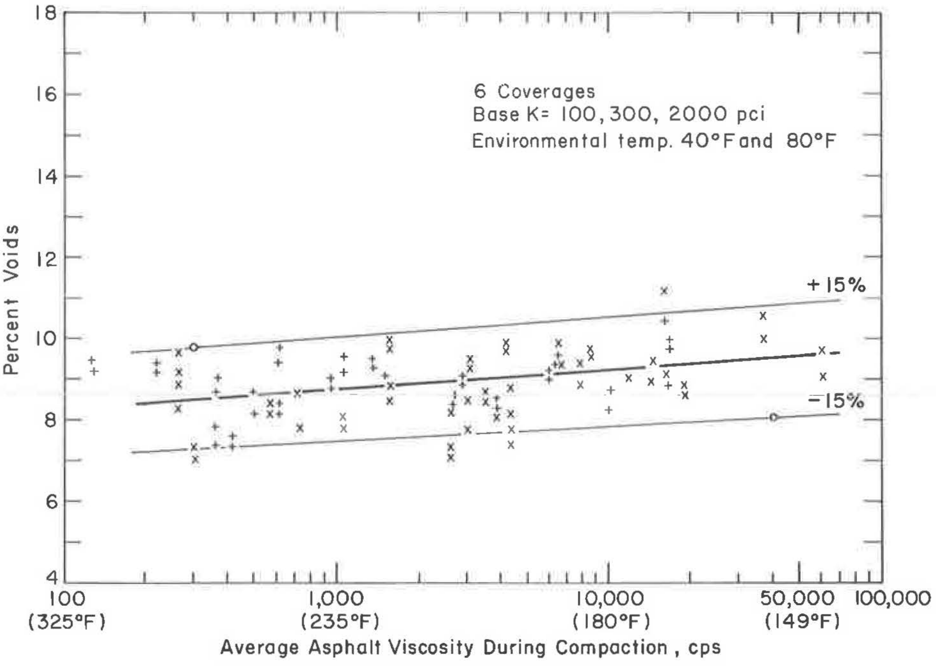

Figure 24. Percent voids vs average asphalt viscosity, steel roller.

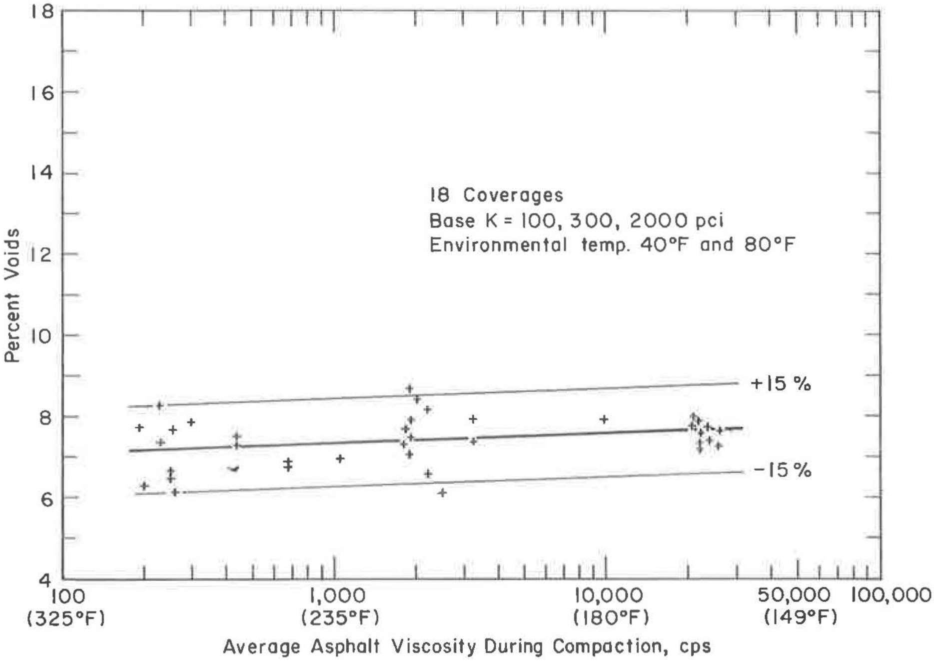

Figure 25. Percent voids vs average asphalt viscosity, steel roller.

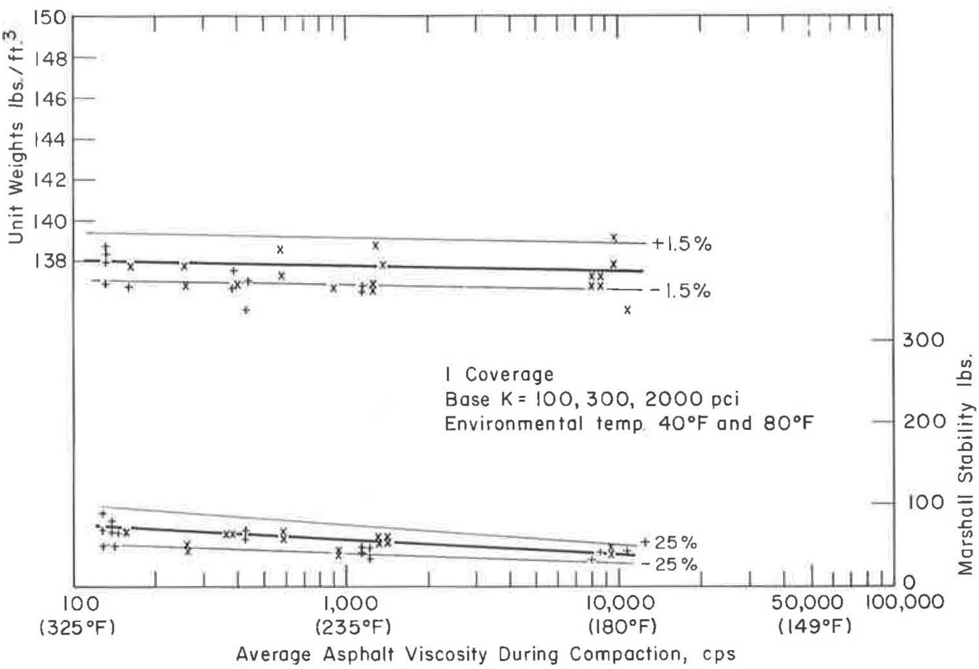

Figure 26. Unit weights and Marshall stability vs average asphalt viscosity, rubber roller.

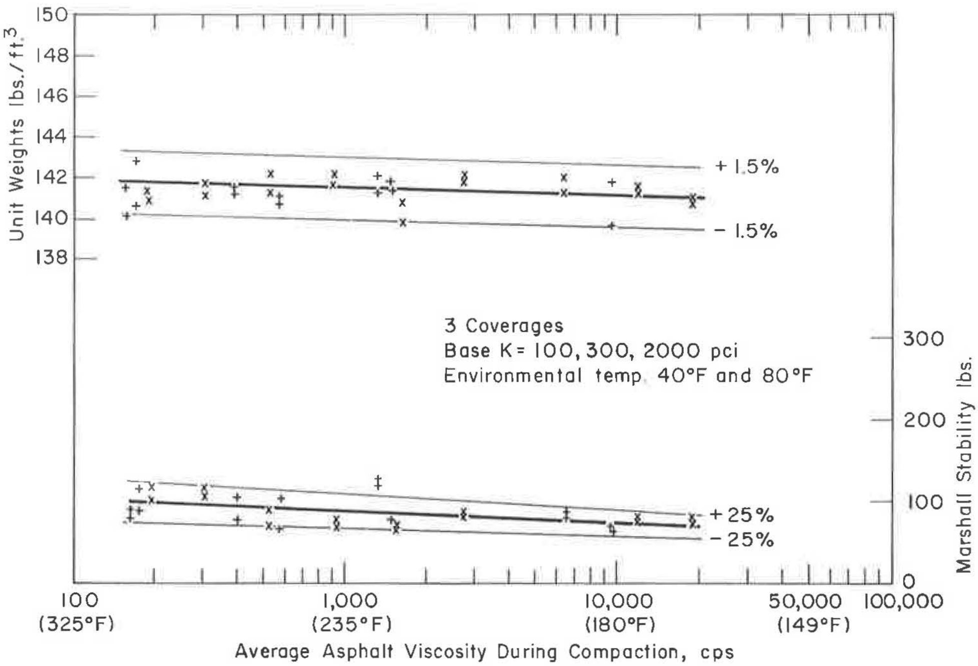

Figure 27. Unit weights and Marshall stability vs average asphalt viscosity, rubber roller.

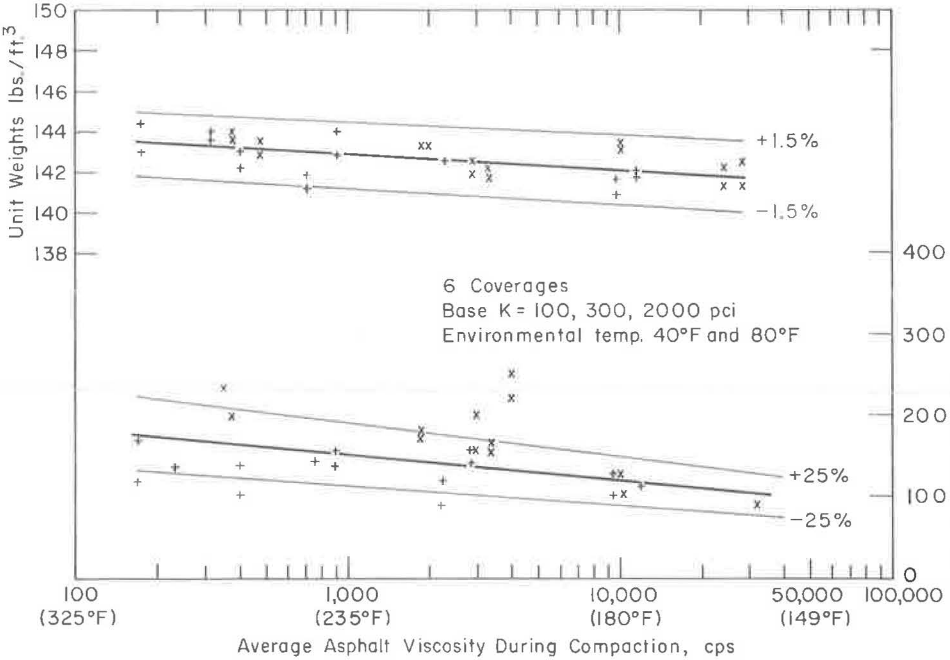

Figure 28. Unit weights and Marshall stability vs average asphalt viscosity, rubber roller.

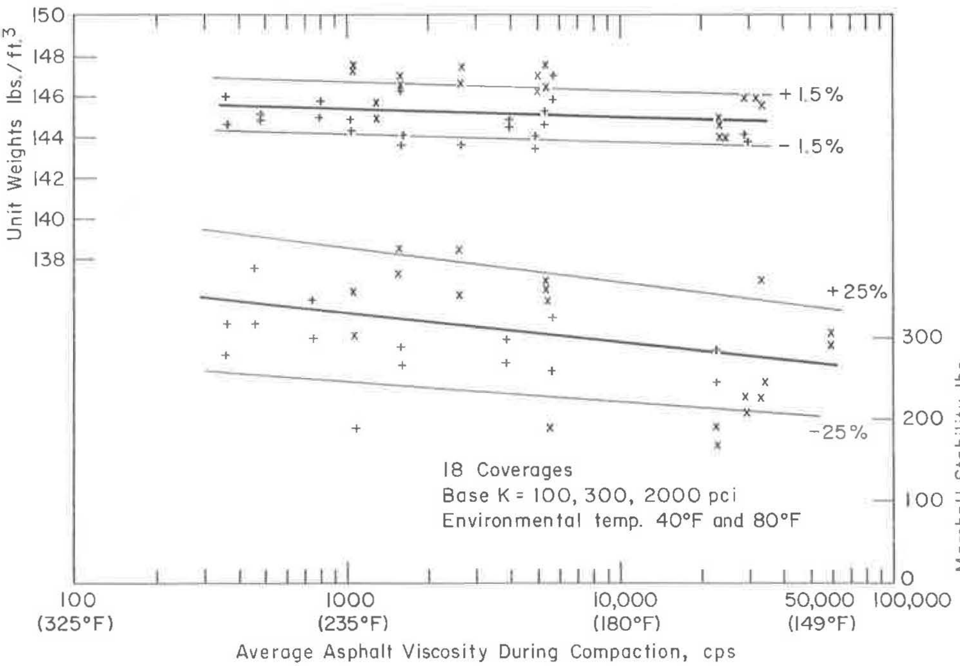

Figure 29. Unit weights and Marshall stability vs average asphalt viscosity, rubber roller.

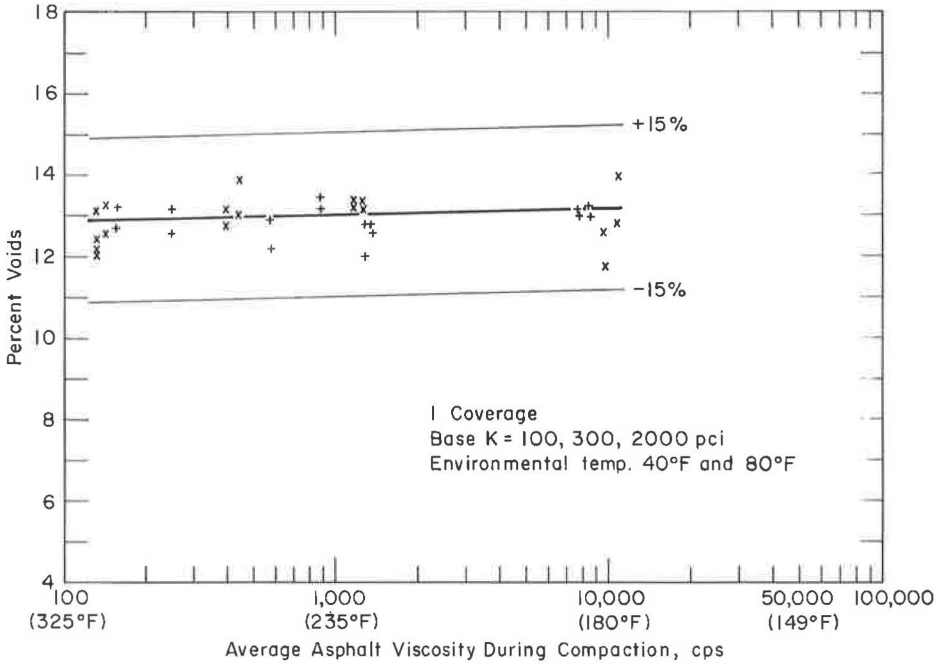

Figure 30. Percent voids vs average asphalt viscosity, rubber roller.

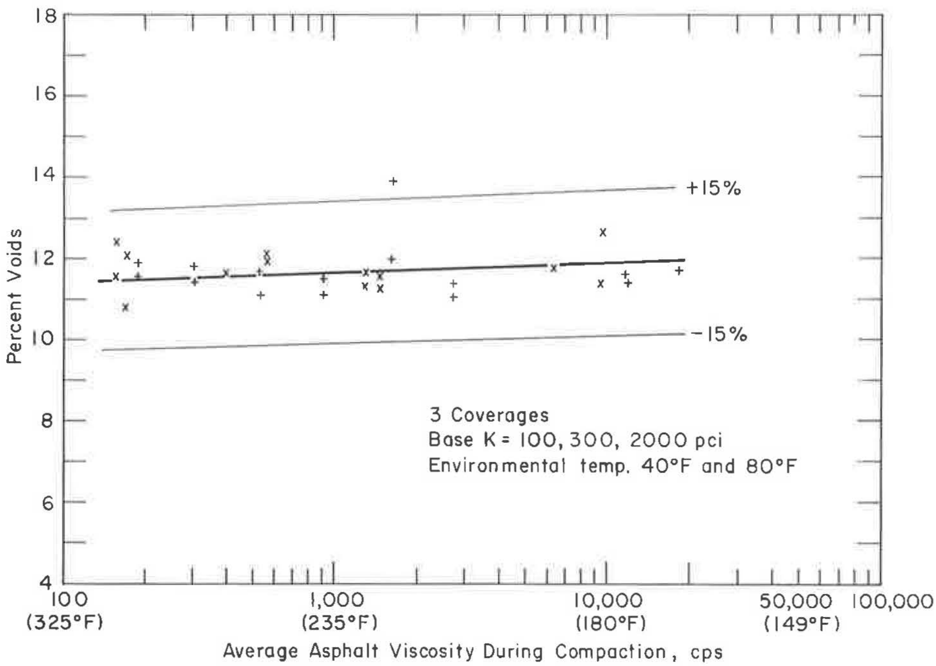

Figure 31. Percent voids vs average asphalt viscosity, rubber roller.

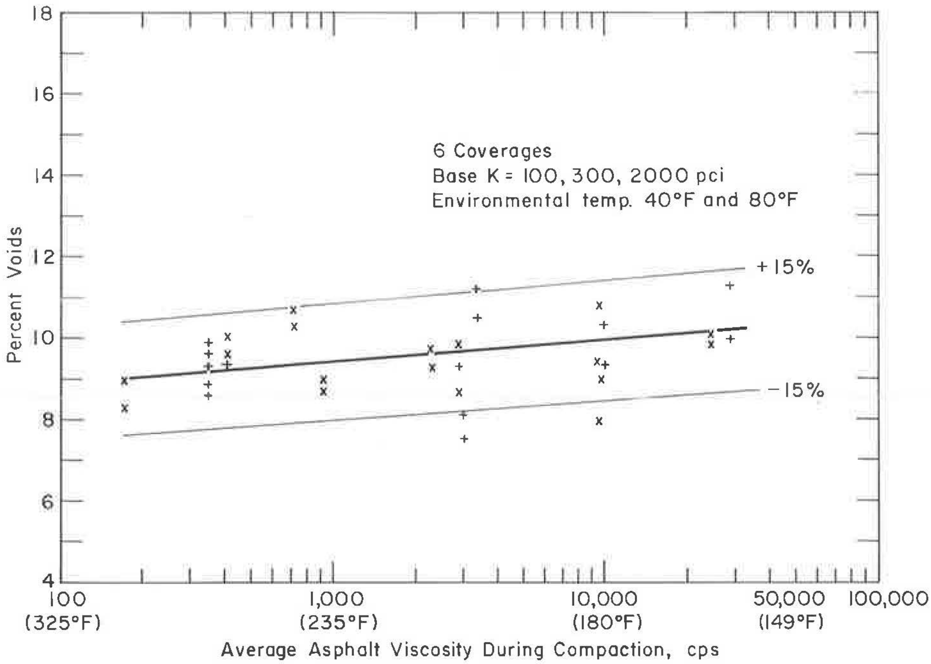

Figure 32. Percent voids vs average asphalt viscosity, rubber roller.

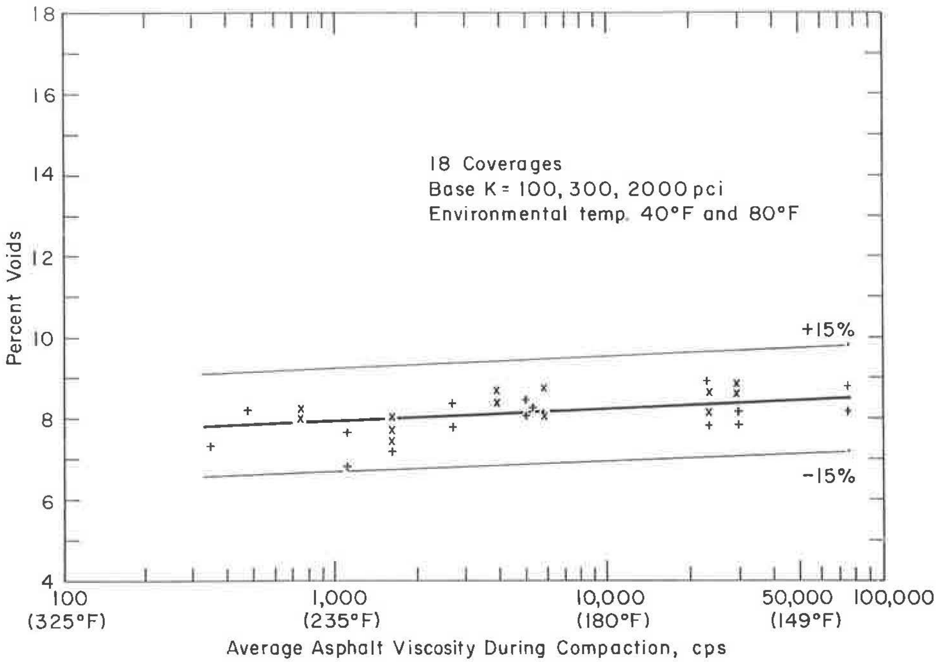

Figure 33. Percent voids vs average asphalt viscosity, rubber roller.

Similar trends are observed for the other coverages and the rubber roller. The number of specimens was less in the rubber roller series (Figs. 26 through 33).

Steel Versus Rubber Rolling

Figures 34 to 41 compare the effectiveness of a steel wheel roller (60-in. diameter, 250 lb/lin in.) and a rubber-tired roller (3500-lb load, 100-psi pressure). The main conclusion is that the specific rubber tire roller used was slightly less effective in compaction than the steel roller. Although from the surface it appeared that the rubber roller gave a more densely compacted mix, this apparently was not true inside the specimen. However, the differences between the two are not great, especially at larger number of coverages.

Several compaction experiments were conducted applying 9 coverages with steel roller and 9 with rubber. The resulting densities and stabilities were about the same as with the steel roller after 18 coverages.

Effect of Coverages

So far, all presentations have been made on the basis of viscosity vs density-stability for a given number of compaction coverages. Figures 42, 43 and 44 are plotted to compare the effect of coverages on the properties of the compacted mix.

It is emphasized that these curves are tied in and influenced by the particular 2-min time interval between each coverage. If, say, ½-min intervals between the coverages had been used, slightly different curves would be obtained.

Unit Weights.—Figure 42 shows the effects of number of coverages on unit weights approximating a semilogarithmic function. This is apparently due to the decreasing efficiency in densification of each successive coverage. At the beginning of the compaction, the bituminous mix is in a loose state; as more roller coverages are applied, the particles are pushed closer together, establishing more contact and the densification rate decreases rapidly.

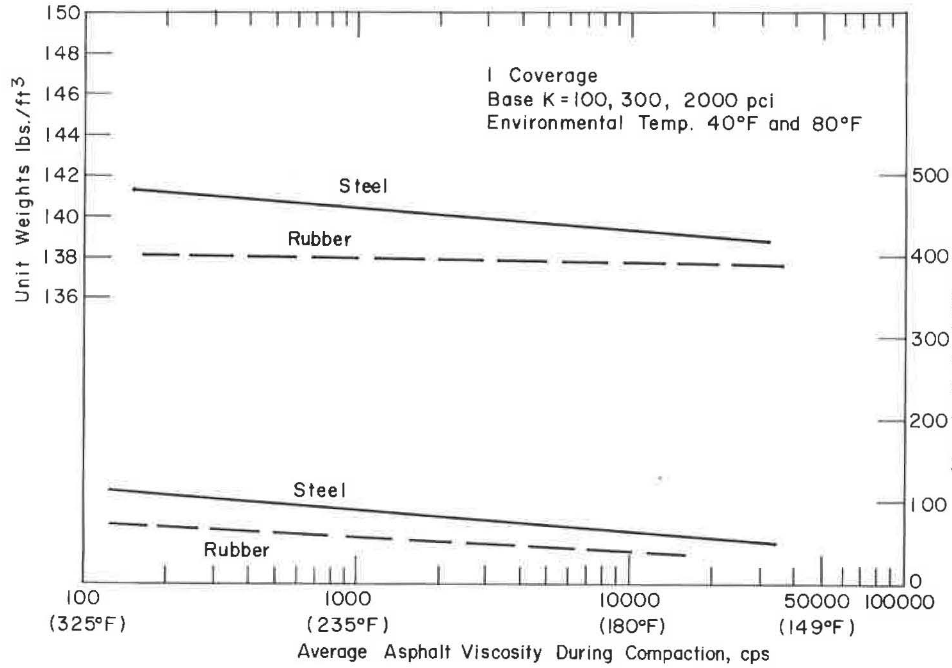

Figure 34. Unit weights and Marshall stability vs average asphalt viscosity, steel and rubber rollers.

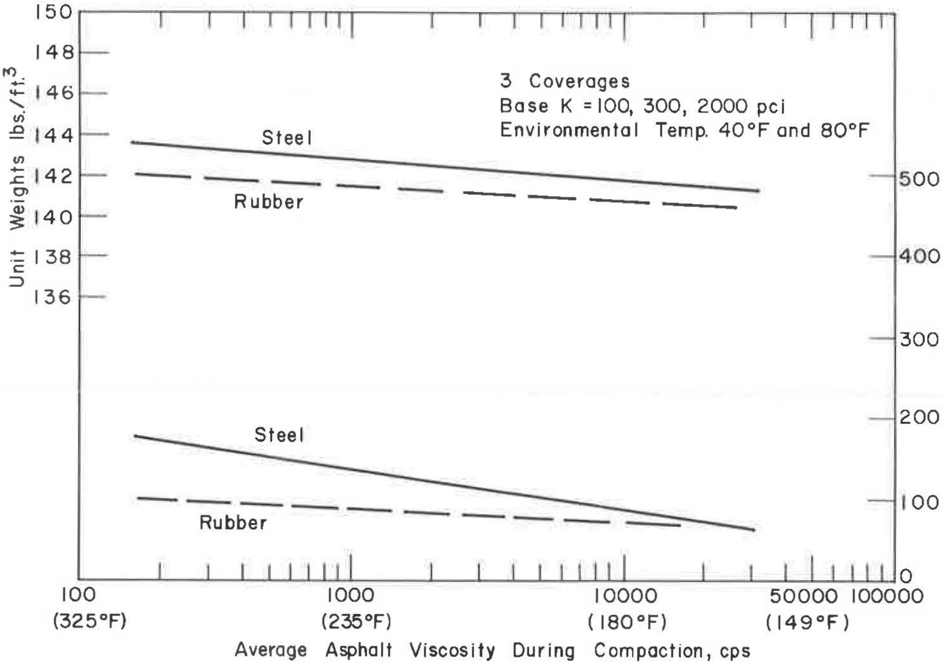

Figure 35. Unit weights and Marshall stability vs average asphalt viscosity, steel and rubber rollers.

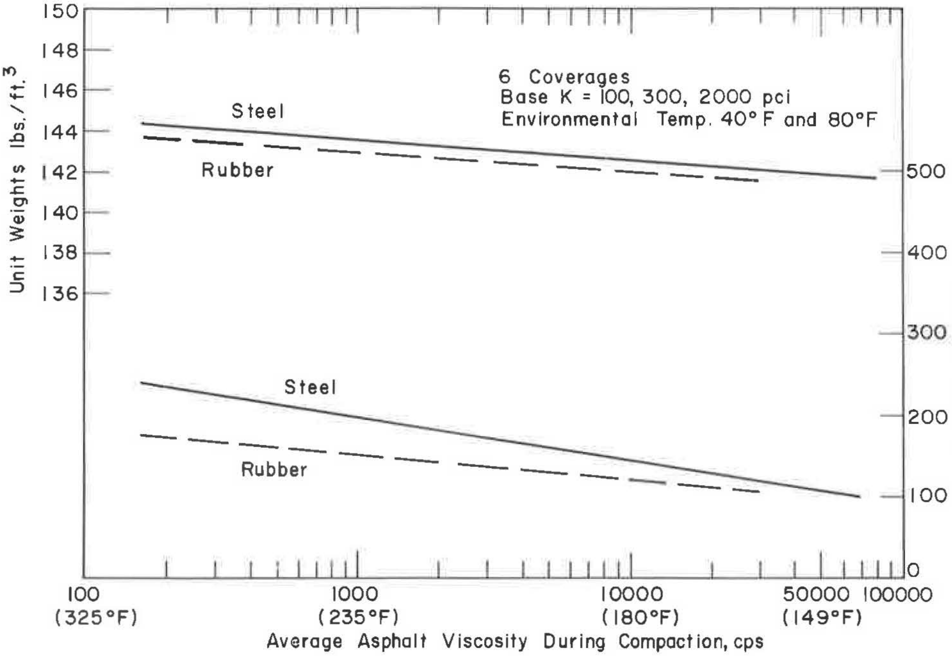

Figure 36. Unit weights and Marshall stability vs average asphalt viscosity, steel and rubber rollers.

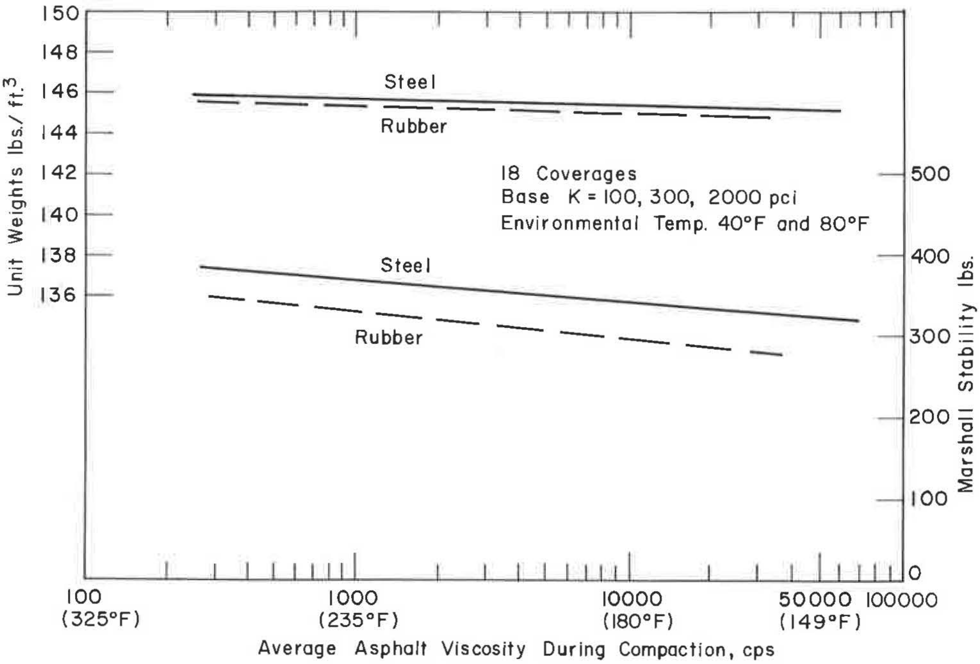

Figure 37. Unit weights and Marshall stability vs average asphalt viscosity, steel and rubber rollers.

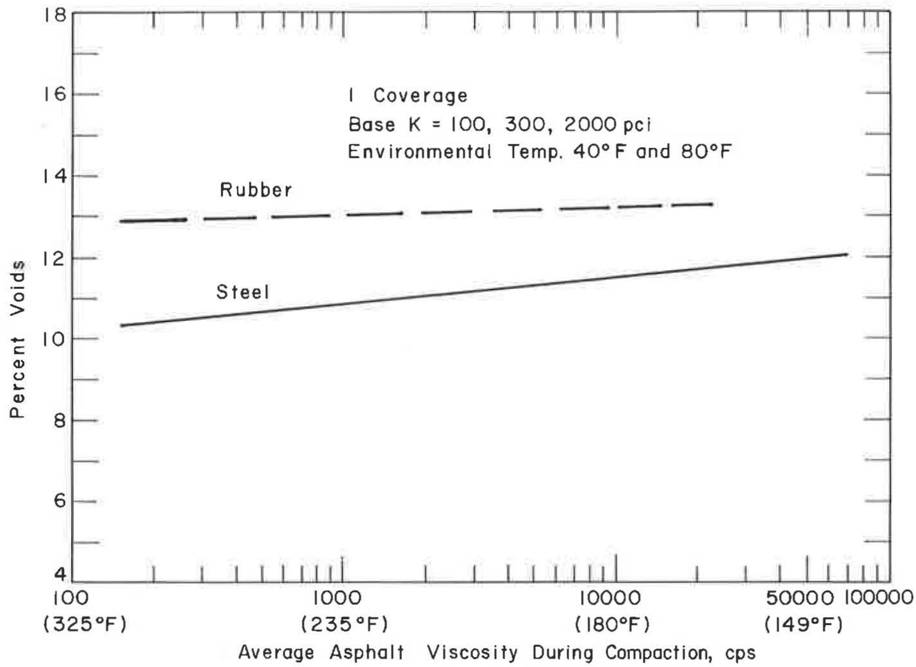

Figure 38. Percent voids vs average asphalt viscosity, steel and rubber rollers.

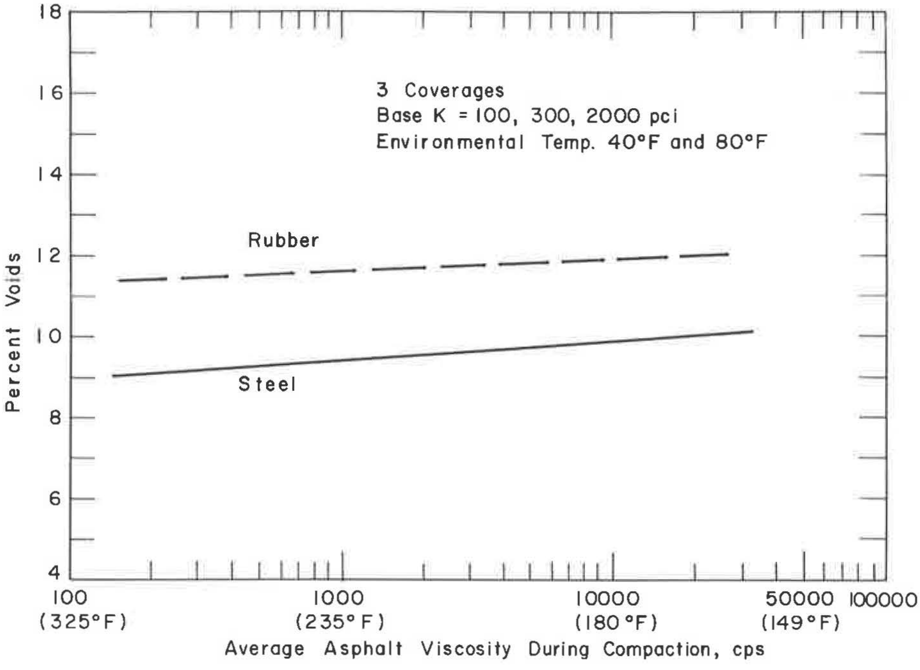

Figure 39. Percent voids vs average asphalt viscosity, steel and rubber rollers.

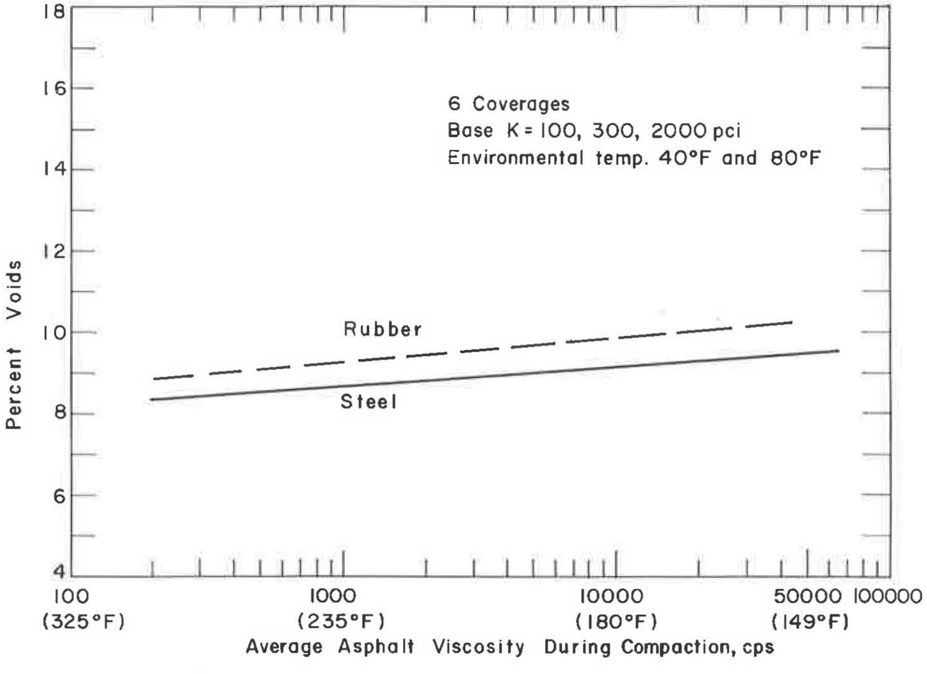

Figure 40. Percent voids vs average asphalt viscosity, steel and rubber rollers.

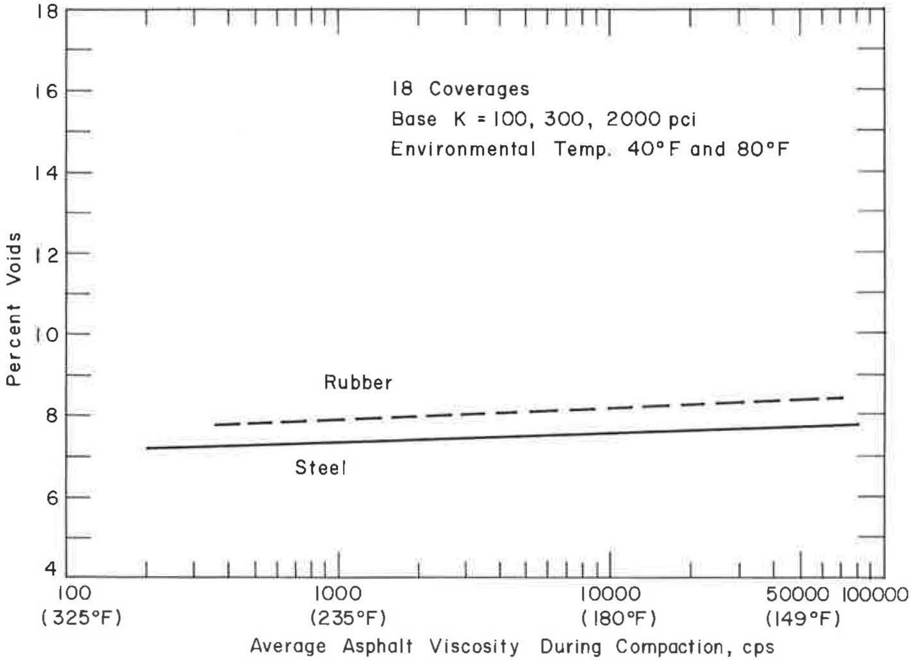

Figure 41. Percent voids vs average asphalt viscosity, steel and rubber rollers.

Figure 42 has been plotted for two average asphalt viscosities during the compaction—200 cps and 2000 cps, corresponding to 283 F and 217 F, respectively.

Marshall Stabilities.—Figure 43 shows the increase in stability with coverages. If plotted on a linear scale, an asymptotic curve is obtained showing less and less effect on strength with each coverage. The most significant observation is the low Marshall stability values even at 36 coverages (few specimens were compacted with 36 coverages). Cores taken from a freshly compacted similar mix from a pavement in Massachusetts gave values between 350 and 550, and pavements a few months old gave values in the range of 550 to 1150, indicating that the laboratory compaction values are probably reasonable. The laboratory mix, compacted by the Marshall method (50 blows) gave stability values of 1500 lb and more. Thus the stabilities are increased with the use of the pavement by traffic, possibly reaching the 50-blow Marshall values after several years of service. This presents a problem to the designer: should he work with a 350-lb stability or a 1500-lb stability in the design?

Void Content.—Figure 44 shows void content vs number of roller coverages. This again is a semilogarithmic function and the explanation for this relationship is similar to that presented in the discussion of density. These voids are based on apparent specific gravity of the aggregate. If bulk specific gravity is used, the void content would be about ½ percent lower (see Fig. 12); if effective specific gravity is used, the void contents would be between the apparent and the bulk values.

Guide for Field Compaction

The compaction experiments were set up in an attempt to simulate certain field compactions as closely as possible. Although the values obtained apply to one particular standard mix, it is possible that the general principles apply to other practical mixes in use.

Present Massachusetts specifications call for field compaction 95 percent or better of Marshall 50-blow density. Figure 45 shows a comparison between this minimum required density and the densities obtained with a steel roller in the laboratory. If

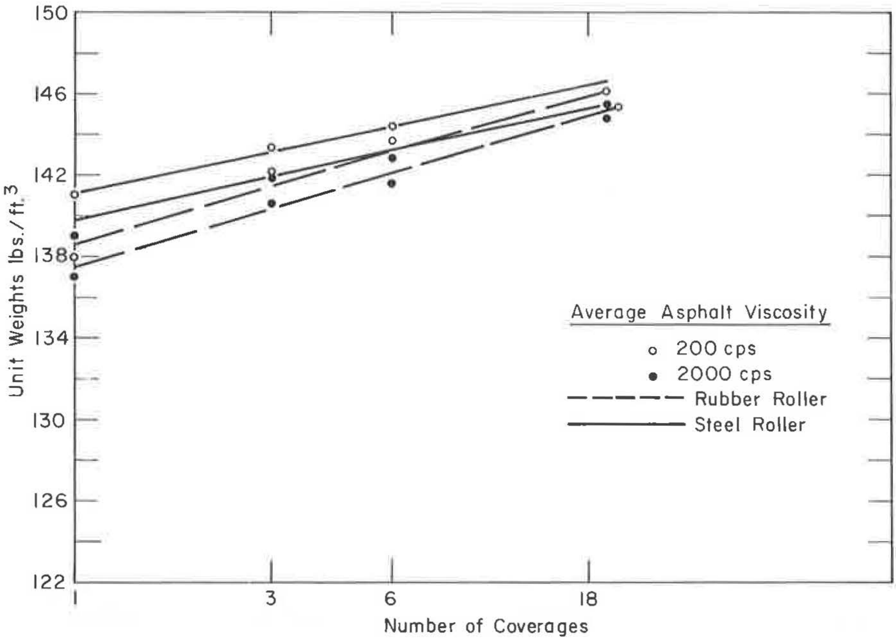

Figure 42. Unit weights vs number of coverages, steel and rubber rollers.

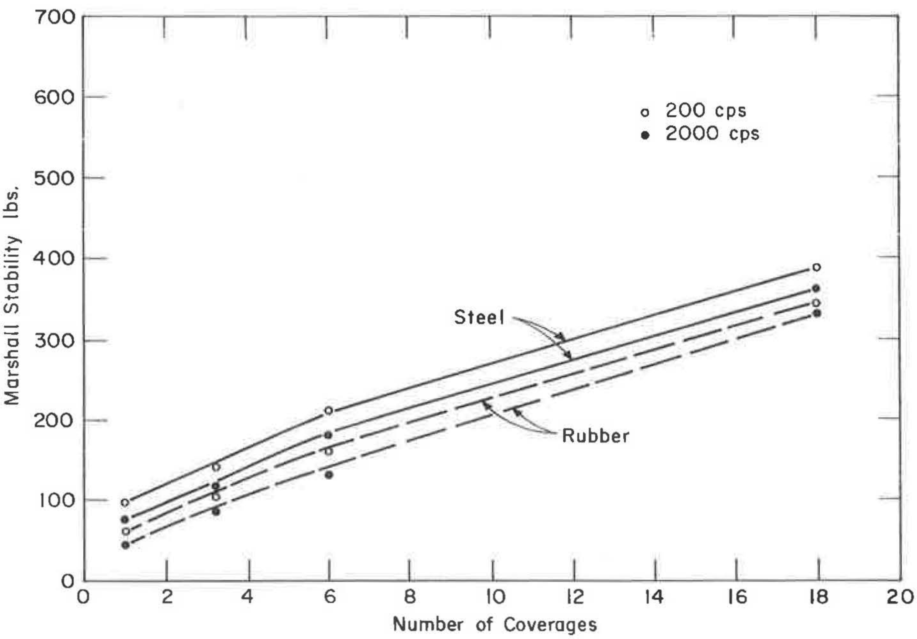

Figure 43. Marshall stability vs number of coverages, steel roller.

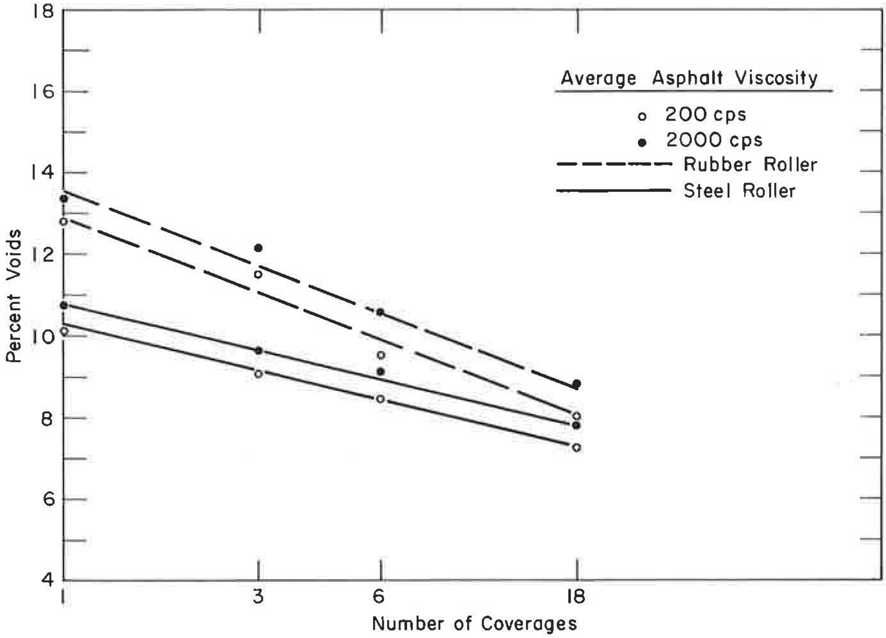

Figure 44. Percent voids vs number of coverages, steel and rubber rollers.

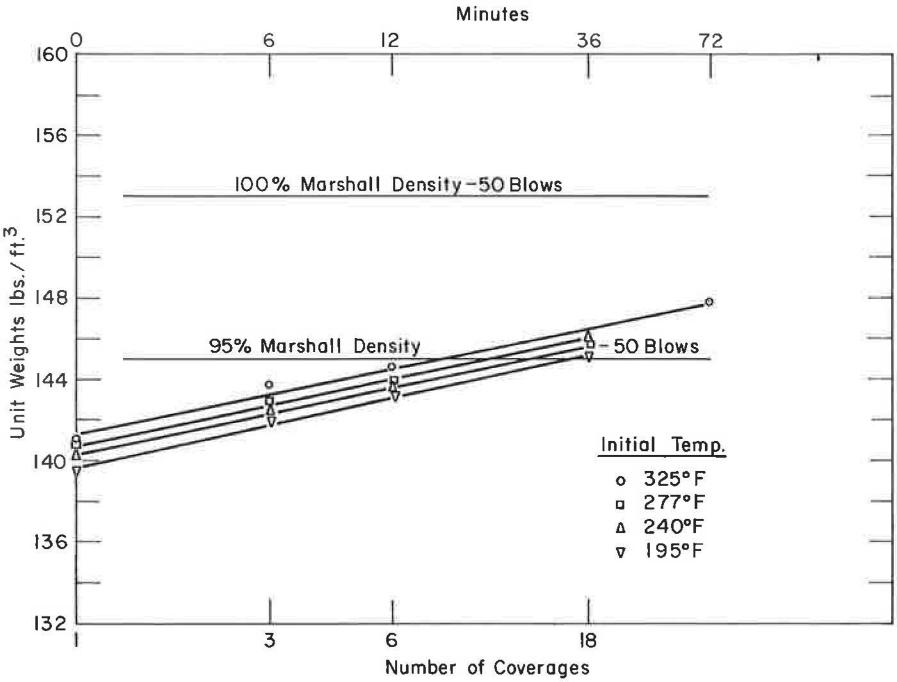

Figure 45. Unit weights vs number of coverages, steel roller, showing specified densities.

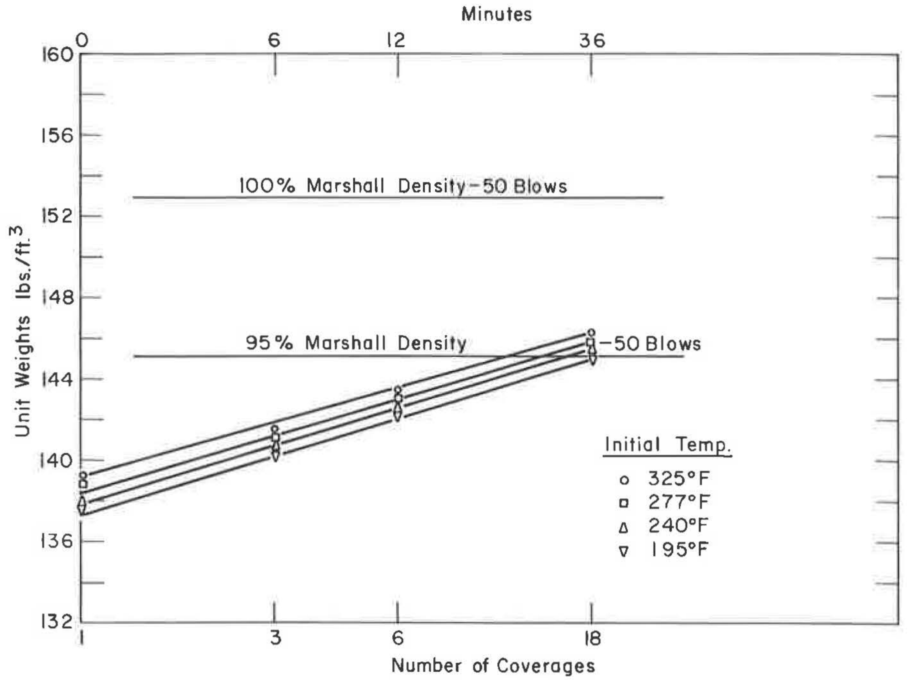

Figure 46. Unit weights vs number of coverages, rubber roller, showing specified densities.

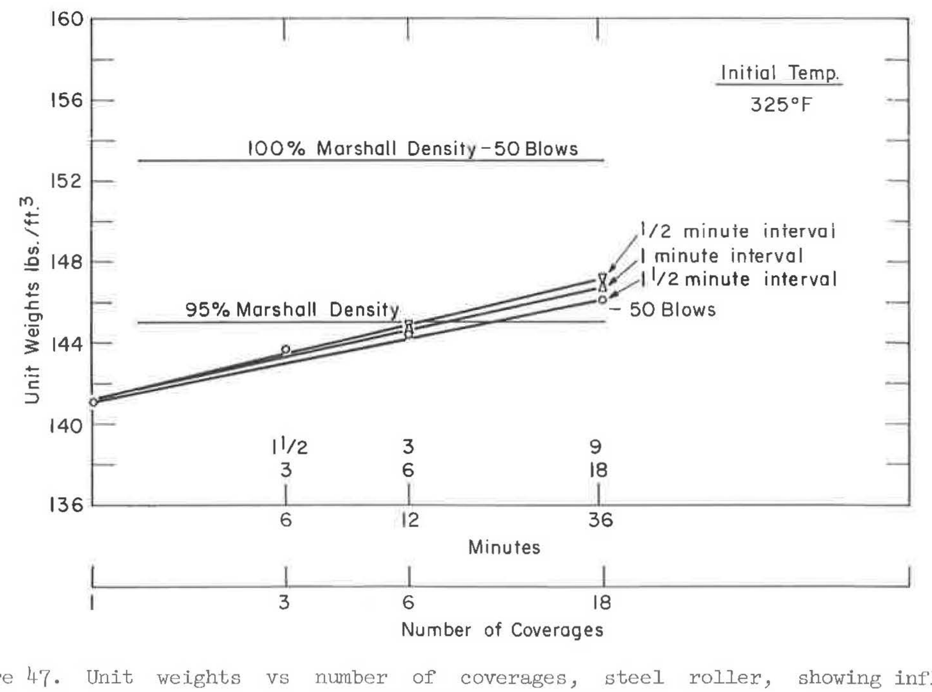

Figure 47. Unit weights vs number of coverages, steel roller, showing influence of frequency of coverages.

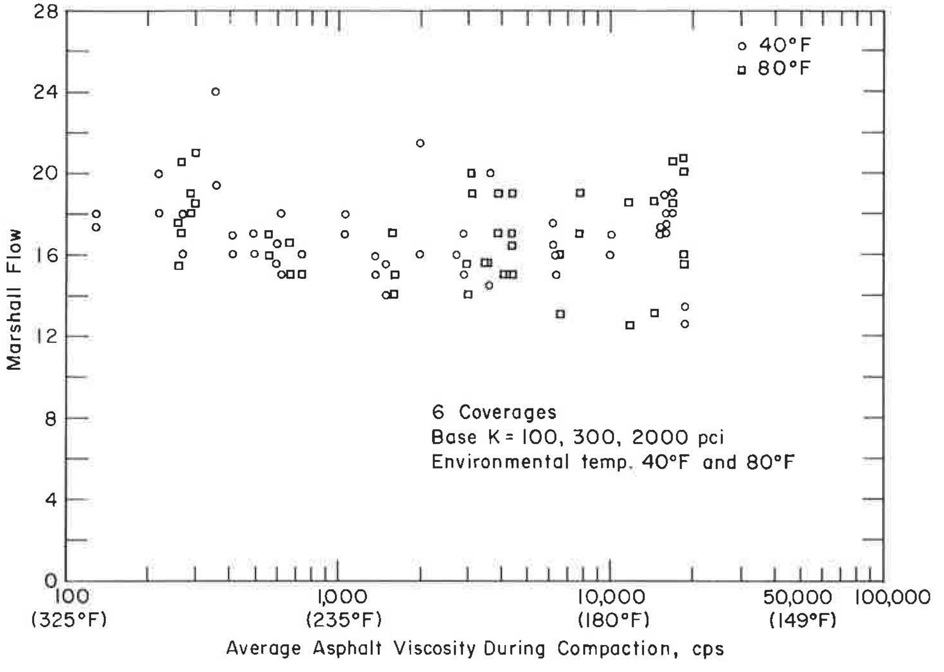

Figure 48. Marshall flow vs average asphalt viscosity during compaction, steel roller.

this laboratory compaction is assumed to be realistic, about 8 coverages are needed to get this density on the road provided that a 325 F mixing temperature is used and other conditions are similar to those used in the laboratory. If the initial mixing temperature is 195 F, about 17 coverages are needed. With a rubber roller, 11 and 20 coverages are needed for the same results (Fig. 46).

The time lapse between mixing and placing of the mix may be greater in the case of field work. However, the drop in temperature of the mix during the transport of a large bulk may very well compare with the heat losses of the 22-lb laboratory batch. If this is not true, temperature of the mix can be measured on the road and adjustments made to compare the results with Figures 45 or 46.

Changing Time Interval Between Coverages

All the curves presented so far are based on 2-min intervals between coverages. If this time is shortened, say, to 1 min or ½ min or less, the number of coverages needed to obtain a given density is reduced.

The effect of the variation of the rolling interval is shown in Figure 47 for the steel roller.

From the cooling curves (Figure 9) the temperatures were obtained for 1-min and ½-min intervals. From the compounded (master) curves of unit weights, Marshall stabilities and voids, the new values of the properties of the mix were obtained using the higher average asphalt temperatures during mixing. There is an increase in the unit weights depending upon the number of coverages (about 1 lb for 18 coverages). The Marshall stabilities would also be slightly increased. It is apparent that an increase would occur with an increased number of roller coverages. The difference (in Fig. 47) between 1 and 18 coverages means an increase of about 6 lb in unit weight (½-min coverage interval).

The results of rubber wheel compaction and those at other than 325 F initial temperatures show similar trends.

Other Physical Measurements

In addition to unit weights, voids, and Marshall stabilities, measurements of Marshall flow were taken. The Marshall flow values were somewhat erratic. This was probably due to the relatively low Marshall stability values encountered all through the study. Figure 48 gives an example for flow values.

CONCLUSIONS

The results of this study are based on laboratory compaction and testing of one specific dense graded bituminous-concrete mix. Attempts were made to simulate compaction on the road. The following conclusions appear warranted:

1. The effect of asphalt viscosity in the mix during compaction on density-voids was found to be relatively small. For instance, Figure 20 shows that the same mix compacted at temperatures at which the asphalt viscosity ranged between 200 and 20,000 cps had average unit weights of 144.4 and 142.3 lb, respectively, or a difference of 1.5 percent.
2. The effect of asphalt viscosity in the mix during compaction on Marshall stability was found to be noticeable. For instance, Figure 20 shows that the same mix compacted at temperatures equal to asphalt viscosity of 200 and 20,000 cps had average stabilities of 235 and 130, or a difference of 80 percent.
3. A semilogarithmic relationship appears to exist between the density-voids and Marshall stability of the compacted mix and the average asphalt viscosity during compaction (for a given number of roller coverages).
4. A semilogarithmic relationship appears to exist between the density and voids and the number of coverages.
5. An asymptotic relationship appears to exist between the Marshall stability and the number of coverages.
6. The Marshall stabilities obtained during the rolling compaction were much lower than those obtained by a 50-blow standard Marshall compaction.
7. The effect of the stiffness of base support on the compaction process of a 2-in. bituminous concrete mat was found to be small, although the harder bases gave slightly higher densities and stabilities.
8. In this study, the steel roller was more effective per coverage than the rubber roller, giving about 2 to 3 percent higher densities.

RECOMMENDATIONS

The results described in this report are primarily applicable to a given type of "standard" bituminous mix. Therefore, the following investigations would be of interest:

1. The high temperature rheological properties of the mix tested in this project should be determined. This may lead to simple ways of predicting the behavior of any mix under a roller.
2. Whether other gradations and asphalt contents give similar results should be investigated.
3. The low Marshall stabilities of a compacted mix are not desirable. Increasing the number of coverages before the mix cools appears to be the most effective way to get higher density and stability. Research on a theoretical and practical level should be attempted to find methods by which better initial compaction can be attained.

ACKNOWLEDGMENT

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