

# Effects of Asphalt Viscosity on Physical Properties of Asphaltic Concrete

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This laboratory study investigated the effects of variations of mixing viscosity and compacting viscosity of asphalt on the physical properties of asphaltic concrete as measured by Marshall testing apparatus. The effects of varying the mineral filler content were also determined. Mixing temperatures were varied between 260 and 350 F in increments of 30 F. Marshall stability specimens were compacted by a mechanical compactor at temperatures in increments of 30 F ranging from 200 F to a temperature 30 F below the corresponding mixing temperature.

The viscosity-temperature relationship of the single 85-100 penetration grade asphalt cement used was established and each of the mixing and compacting temperatures was related to the asphalt viscosity. The same aggregates were used throughout the investigation, but two filler-bitumen ratios were investigated with the same asphalt content. The asphaltic concrete was of coarse-graded aggregate type for surface course conforming to gradation limits of Wisconsin State Highway Commission specifications.

The experimental results showed that variations in the mixing and compacting viscosities of asphaltic concrete produced changes in Marshall stability, flow value, specific gravity, and voids of the compacted mixtures. Some of these differences were large enough to warrant attention to selection and control of proper mixing and compacting viscosities. "Optimum" mixing viscosity and "optimum" compacting viscosity are suggested for the asphaltic concrete mixtures investigated. The results showed that changes in the ratio of mineral filler to asphalt cement affect the optimum mixing and compacting viscosities of asphalt for the asphaltic concrete paving mixtures investigated.

•THE IMPORTANCE of proper viscosity of asphalt during both mixing and compacting operations of hot-mix asphaltic concrete pavements is recognized. For improved qualitative control of pavement construction, it is essential that the asphalt be at proper viscosity at the times of mixing the asphalt and aggregates in the plant and of compacting the paving mixture by paving and finishing machines and rollers on the paving project.

A fundamental measure of fluidity of asphalt in hot mixes is on the basis of viscosity which is the inverse of fluidity. Viscosity also varies inversely with temperature, i. e., the higher the temperature, the lower the viscosity.

## PURPOSE AND SCOPE

The purpose of this investigation is:

1. To study the effects of variations in mixing viscosity and in compacting viscosity of the asphalt on physical properties of compacted asphaltic concrete by the Marshall test;

2. To determine the effects of filler-bitumen (F/B) ratio on the results obtained;
3. To establish "optimum" mixing viscosity and "optimum" compacting viscosity for the asphaltic concrete mixtures investigated.

The experimental work reported consisted of the mixing, compacting, and testing of specimens of Wisconsin State Type 3 bituminous concrete surface course mix (1) using the Marshall test apparatus. The mixing was done at 30 F increments through a 260 to 350 F range. Both asphalt and aggregate were heated to the same mixing temperature. Five different compaction temperatures at 30 F increments were chosen between 200 and 320 F to simulate a range of temperature that might occur during pavement construction at the commencement of knockdown rolling on hot-mix projects where 85-100 penetration grade asphalt cements are used. The compaction temperature varied from a minimum of 200 F to a peak value 30 F below the corresponding mixing temperature (Table 1). No reheating was done after the materials were mixed.

The viscosity-temperature relationship of the asphalt cement used was established and each of the mixing and compaction temperatures was related to the asphalt viscosity. Four specimens were molded at each of the combinations of mixing and compacting temperatures. Two filler-bitumen (F/B) ratios were used with the same asphalt content.

## SELECTION OF MATERIALS

### Aggregates

Pit run gravel from Brown Pit, Baraboo, Wis., was used. The gravel was crushed; about 66 percent of coarse aggregate consisted of dolomite and 34 percent was igneous material. The sand was a mixture of igneous and dolomite material.

Pulverized limestone dust from the Waukesha Limestone Company was used as mineral filler. It had 81.7 percent passing the No. 200 sieve and a specific gravity of 2.823 by ASTM Designation: D854-58. Limestone dust passing the No. 200 sieve had a specific gravity of 2.844.

### Bitumen

The bitumen was an 85-100 penetration grade asphalt cement produced by the Texas Company at Casper, Wyo. At 77 F, it had a specific gravity of 1.030 and a ductility of 110+ cm. The viscosity-temperature relationship is shown in Figure 1. A Saybolt Furol viscometer was used

TABLE 1

Mixing Temp (° F)	Mixing Viscosity (SSF)	Compacting Temp (° F)				
		320	290	260	230	200
350	34.5	x	x	x	x	x
320	54.0	—	x	x	x	x
290	105	—	—	x	x	x
260	250	—	—	—	x	x
Compacting Vis- cosity (SSF)		54	105	250	640	2000

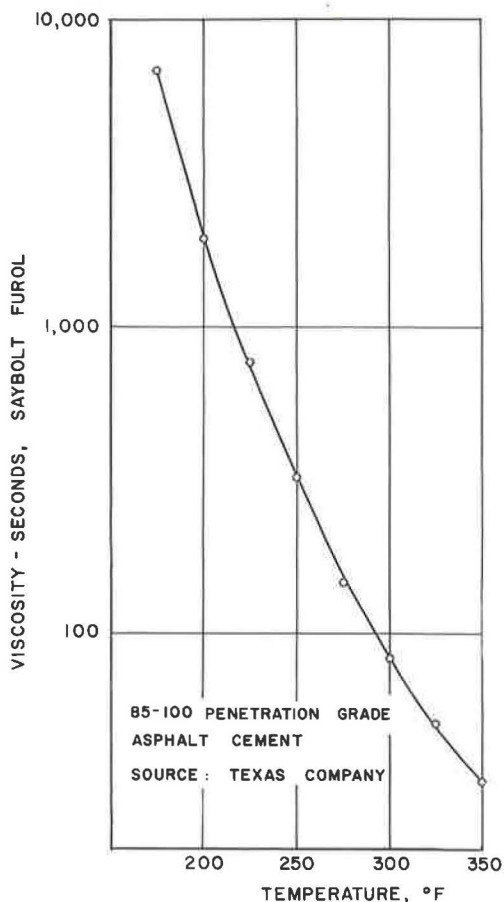


Figure 1. Viscosity-temperature relationship for asphalt cement.

TABLE 2  
VISCOSITY OF ASPHALT CEMENT  
BY SAYBOLT FULOL VISCO-  
METER METHOD<sup>a</sup>

Test Temp (° F)	Viscosity (SSF)		
	Test 1	Test 3	Avg.
250	318.0	322.5	320.3
275	148.5	144.5	146.5
300	83.0	82.5	82.8
325	52.0	50.0	51.0
350	33.5	32.5	33.0
375	23.5	23.5	23.5

<sup>a</sup>Viscosity at 77° F by sliding plate microviscometer,  $1.212 \times 10^6$  poises at FS = 1,000 ergs/sec/cu cm.  
<sup>b</sup>By ASTM Method E102-62.

TABLE 3  
VISCOSITY OF ASPHALT CEMENT VACUUM CAPILLARY  
VISCOMETER METHOD<sup>a</sup>

Test Temp (° F)	Capillary Tube No.	Diam Tube (cm)	Vacuum (cm Hg)	Time (sec)	K	Viscosity (poises)	Avg. Viscosity (poises)
175	2	0.1004	30	67.8	2.172	147.50	—
	4	0.0987	30	69.0	2.120	146.00	146.75
200	1	0.1141	10	44.0	0.919	40.40	—
	1	0.1141	10	45.0	0.919	41.30	40.85
225	2	0.1004	10	22.2	0.705	15.65	—
	4	0.0987	10	21.2	0.685	14.55	15.10
250	1	0.1141	10	7.5	0.917	6.87	—
	1	0.1141	10	7.0	0.917	6.42	6.65

<sup>a</sup>Viscosity at 77° F by sliding plate microviscometer,  $1.212 \times 10^6$  poises at FS = 1,000 ergs/sec/cu cm.

for viscosity determination (Table 2) in the high temperature range (250 to 350 F), and the viscosity between 175 and 250 F was measured by a vacuum capillary viscometer (Table 3). The mixing and compacting viscosities were interpolated from Figure 1 for the various mixing and compacting temperatures investigated.

#### MIXING AND COMPACTING VISCOSITIES (TEMPERATURES)

The mixing and compacting viscosities investigated (with corresponding temperature values) are given in Table 1. The "x" marks indicate the combinations of mixing viscosities and compacting viscosities at which Marshall specimens of asphaltic concrete were molded and tested.

#### PAVING MIXTURE

A coarse-graded aggregate type of mix for surface course conforming to gradation limits of Specification No. 3, 1957, Wisconsin State Highway Commission (1), was used. The aggregate gradation curves are shown in Figure 2. Two designed gradations were investigated: one with a limestone dust content of 8.0 percent by weight of total aggregate, which corresponds to usual practice, and a second with a limestone dust content of 11.5 percent by weight of total aggregate. These values correspond to 8.6 and 11.3

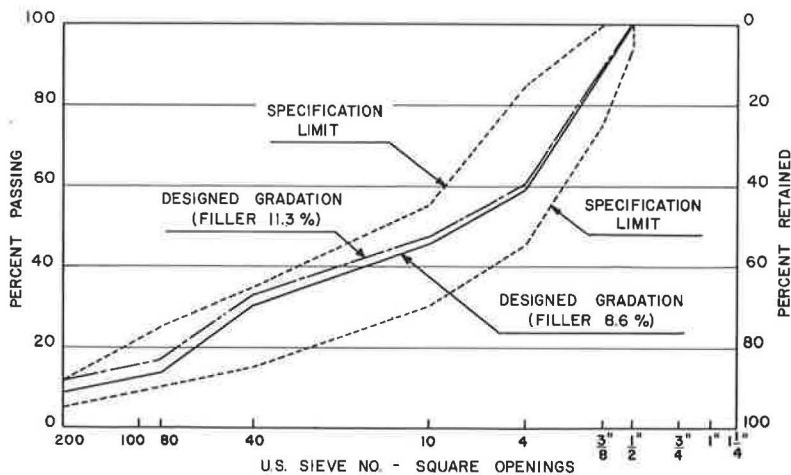


Figure 2. Aggregate gradation curves for asphaltic concrete mixtures.

percent mineral filler passing No. 200 sieve by weight of total mix, respectively, considering the blended aggregate. The F/B ratios by weight were 1.81 and 2.38, respectively, when filler is taken as material passing No. 200 sieve. The corresponding F/B ratios by volume were 0.66 and 0.87, respectively. The maximum size of coarse aggregate was  $\frac{1}{2}$  in. Controlled grading of the aggregate was maintained during the molding of the specimens by separating the aggregate into different size fractions and then recombining according to the design proportions.

An asphalt content of 4.75 percent by weight of the total mixture was used throughout the investigation on the basis of previous studies using the same aggregate and mix gradation. This asphalt content also conforms to current practice of the Wisconsin State Highway Commission for these materials and results in a mixture that yields test values satisfying the established criteria of the Commission.

### PREPARATION OF MARSHALL SPECIMENS

The method of mixing, molding and testing Marshall specimens conformed in general to ASTM Designation: D1559-60T (2), except for variations in mixing viscosity and compaction viscosity and except that a compaction machine, built for the Wisconsin State Highway Commission testing laboratory, was used in place of hand compaction. Compaction was by 50 blows of the hammer of each side of the specimen at the rate of approximately 50 blows in 66 sec. The specimen molds were rotated during compaction at a rate of one revolution for each 50 blows of the hammer. The hammer weighed 10 lb and had a flat horizontal striking face. The height of drop was 18 in. During compaction, the specimen molds rested on a steel plate mounted on a concrete pedestal. Careful attention was paid to mixing and compacting temperatures in molding the specimens. No reheating of the mix was done after mixing. The standard test temperature of 140 F was carefully controlled.

### DATA AND DISCUSSION OF RESULTS

#### Effects of Mixing Viscosity on Mixture Containing 8.6 Percent Mineral Filler

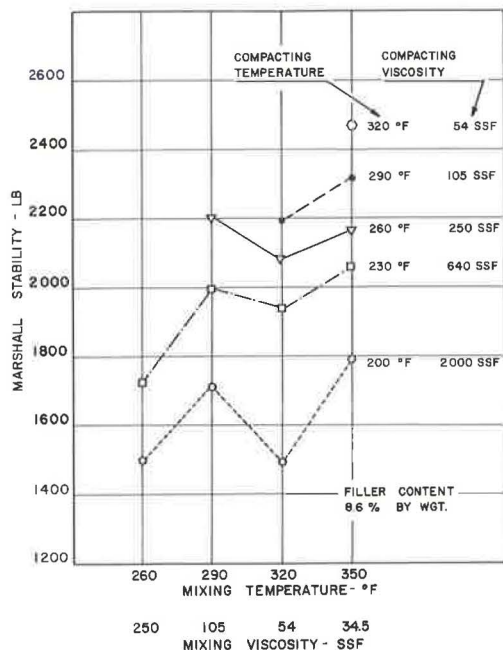


Figure 3. Effects of mixing viscosity (mixing temperature) on Marshall stability.

**Stability.**—Figure 3 shows the relationship of mixing viscosity (in seconds, Saybolt Furol (SSF)) to stability and also the relationship of mixing temperature to stability. The trend of all curves is the same at different compaction viscosities from 2,000 to 54 SSF (compaction temperatures from 200 to 320 F). Each curve has a peak and a trough when the mixing viscosity is decreased from 250 to 34.5 SSF (mixing temperature from 260 to 350 F).

Each peak is assumed to indicate the optimum mixing temperature for the corresponding compacting temperature. The stability increases as the mixing temperature is increased from 260 to 290 F (viscosity decreasing from 250 to 105 SSF). The stability decreases when the mixing temperature is raised to 320 F (viscosity 54 SSF). Further rise in mixing temperatures from 320 to 350 F (viscosity decreasing from 54 to 34.5 SSF) results in increased stability values.

The peaks and troughs in Figure 3 for 8.6 percent filler asphaltic concrete com-



pare favorably with the peaks and troughs shown by Lehmann and Adam (3, Figs. 3 and 4), especially for 137 penetration asphalt from Talco crude. The viscosity-temperature curve (Fig. 1) for the Texas Company 85-100 penetration grade asphalt also compares closely with one for 137 penetration asphalt from Talco crude (3, Fig. 2). Lehmann and Adam also give an explanation concerning these relationships involving peaks and troughs. In a similar manner, the results of this investigation for the 8.6 percent filler asphaltic concrete mixture may be explained: At a mixing temperature of 260 F (viscosity 250 SSF) the asphalt is not fluid enough for proper coating and mixing with aggregate particles so the lowest values of stability are obtained. However, the aggregate and asphalt temperatures are high enough at 290 F (asphalt viscosity 105 SSF) to permit droplets of asphalt to envelop particles of aggregates on contact resulting in intimate coating and uniform dispersion of materials. This increases the stability values. Further rise in the mixing temperature to 320 F (viscosity 54 SSF) makes the asphalt extremely fluid so that instead of coating the particles to uniform thickness it merely lubricates the particles, causing excessive movements under dynamic impact of the compaction hammer. This results in a drop in stability at mixing temperature of 320 F as compared with 290 F. Further rise in stability value when the mixing temperature is increased to 350 F (viscosity 34.5 SSF) could well be attributed to the hardening or oxidizing of asphalt which results in change in consistency.

From this discussion it follows that a proper control over the mixing viscosity and compacting viscosity should be exercised for asphaltic concrete. The asphalt must be at proper viscosity (or fluidity) at the time of mixing to promote intimate mixing and coating (not lubricating) and proper dispersion of materials. The viscosity of the contained binder at time of compaction must be low enough so that a considerable portion of compactive effort exerted is not expended in overcoming the greater resistance offered by the higher viscosity of binder at lower temperatures.

Considering the stability values up to a compaction temperature of 260 F, the highest value of stability (2,200 lb) is obtained when the mixing is done at 290 F (viscosity 105 SSF) with compaction at 260 F (viscosity 250 SSF). This appears to be an excellent combination of mixing temperature and compacting temperature. A value of 2,184 lb is obtained for a mixing temperature of 320 F (mixing viscosity of 54 SSF) and a compacting temperature of 290 F (compacting viscosity of 105 SSF), which appears also to be a satisfactory practical combination of mixing and compacting temperatures.

Figure 4 shows the contours of stability values at intervals of 100 lb with mixing tem-

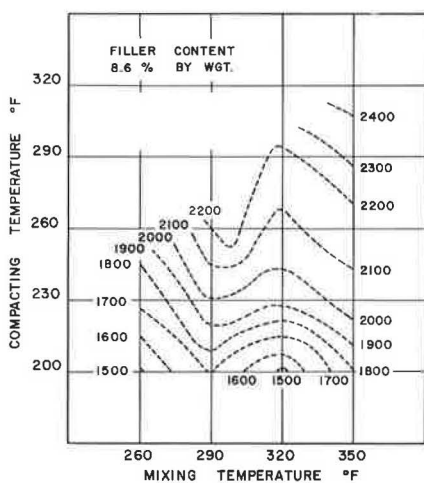


Figure 4. Stability contours showing effects of variations in mixing and compacting temperatures.

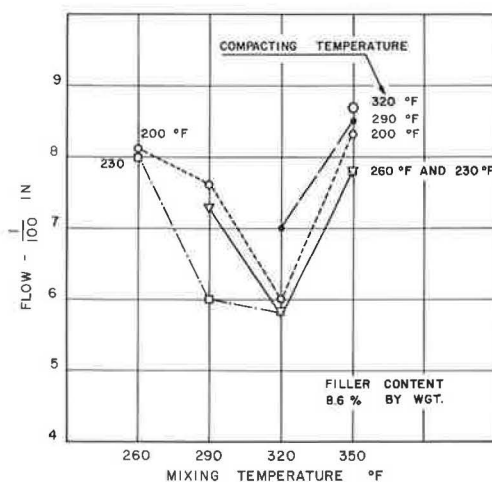


Figure 5. Effects of mixing temperature on flow.

perature and compacting temperature as the coordinate axes. In the drawing of these contours it is assumed that the stability varies linearly between two different stability levels. These contours indicate that higher compaction temperatures are required at mixing temperatures of 260 and 320 F to provide the same stability values as at a mixing temperature of 290 F. Thus, a compaction temperature of 210 F is required with mixing at 290 F to give the same stability (1,800 lb) as obtained at compaction temperatures of 245 and 220 F with mixing done at temperatures of 260 and 320 F, respectively. There is not much difference in the compaction temperatures for mixing temperatures of 290 and 350 F for equal stabilities, the compaction temperatures at 350 F being slightly lower than those at 290 F.

**Flow.**—Figure 5 gives the relationship between mixing temperature and flow. The general trend of all curves is the same. Each curve has a trough at a mixing temperature of 320 F. Within the limits of compacting temperatures from 200 to 290 F, the lowest values of flow are obtained at a mixing temperature of 320 F.

**Specific Gravity.**—In Figure 6 mixing viscosity and mixing temperature are plotted against specific gravity. The specific gravity values are not appreciably affected by variations in the mixing viscosity. The specific gravity values peak at mixing viscosity of 105 SSF for compacting viscosities of 250, 640 and 2,000 SSF. An interesting comparison may be made between these peak values and those shown by Lehmann and Adams (3, Fig. 6).

For compacting temperatures up to 260 F (viscosity 250 SSF), the highest value of specific gravity is obtained at a mixing temperature of 290 F (viscosity 105 SSF). An equal value is also obtained for compacting temperature of 290 F (viscosity 105 SSF) with a mixing temperature of 320 F (mixing viscosity 54 SSF).

Figure 7 shows the contours of specific gravity at intervals of 0.005 with mixing temperature and compacting temperature as the coordinate axes. It has been assumed that the specific gravity varies linearly between two different specific gravity levels. These contours indicate that the specific gravity increases as the mixing temperature is increased from

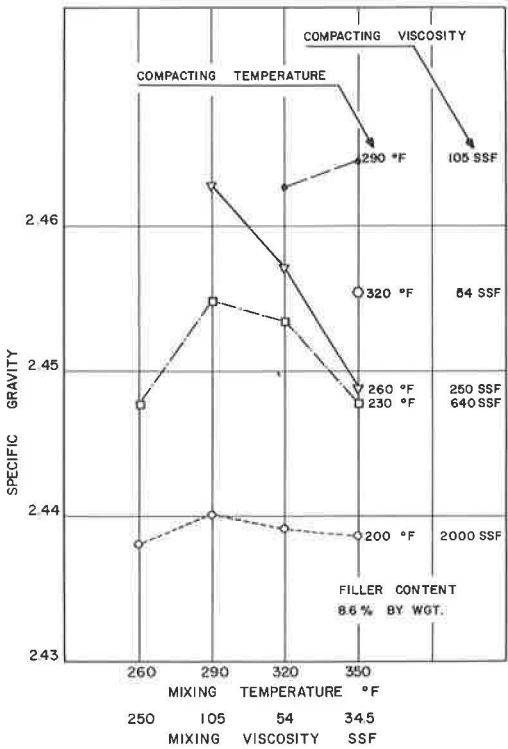


Figure 6. Effects of mixing viscosity (mixing temperature) on specific gravity of asphaltic concrete.

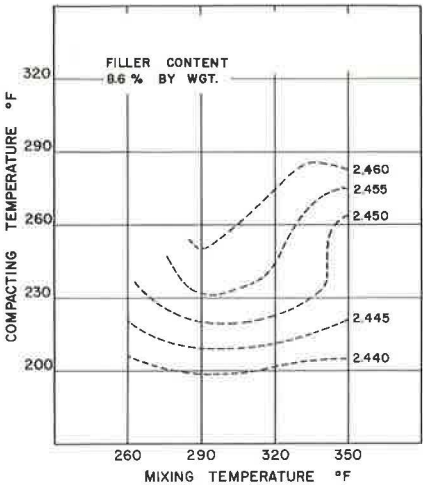


Figure 7. Specific gravity contours of asphaltic concrete showing effects of variations in mixing and compacting temperatures.

260 to 290 F (viscosity 250 to 105 SSF). Further rise in mixing temperatures from 290 to 350 F results in a decrease in specific gravity values. This is in contrast to stability values shown in Figures 3 and 4 where the values increase as the mixing temperature is increased from 320 to 350 F. Thus, an increase in stability value may not be related to increase in density.

**Voids in Total Mix.** —Figure 8 gives the plot of mixing temperature vs percent voids in total mix. Apparent specific gravity of the aggregate was used for the computation of voids. The discussion of specific gravity values pertains also to voids in total mix.

**Voids in Mineral Aggregate.** —The percentage of voids in mineral aggregate (VMA) is an important criterion to study in design of mixtures because it indicates the amount of space available for asphalt in compacted mixtures. Minimum VMA values are significant because they indicate the combination of materials and methods of fabrication at which the mineral particles are arranged to occupy the smallest volume for a given amount of compaction. For compaction temperatures up to 260 F, the lowest values of VMA are obtained at a mixing temperature of 290 F (viscosity 105 SSF), the curves forming a trough (Fig. 9). Because low values of VMA are desirable, the combination of 290 F mixing temperature with 260 F compacting temperature is good; also, 320 F mixing temperature with 290 F compacting temperature gives a similar value.

**Voids Filled with Bitumen.** —Figure 10 shows the relationship between mixing temperature and percent voids filled with bitumen (VFB). Within the limits of mixing temperatures (260 to 350 F) and compacting temperatures (200 to 320 F), the VFB lie between 75.0 and 80.8 percent. An increase in VFB when the mixing temperature is raised from 260 to 290 F is followed by a decrease in values up to a mixing temperature of 350 F, excepting at a compaction temperature of 290 F and where there is a slight increase in VFB at a mixing temperature of 350 F over that obtained at mixing temperature of 320 F.

For compaction temperatures up to 260 F, the highest values of VFB are obtained at a mixing temperature of 290 F, the curves peaking at this temperature. The highest value of VFB is obtained at mixing and compacting temperatures of 350 and 290 F, respectively. This value (80.8 percent) is only 0.4 higher than the value at the mixing temperature of 290 F with compaction done at 260 F or the value obtained at the 320 F mixing temperature with 290 F compacting temperature.

#### Effects of Compacting Viscosity on Mixture Containing 8.6 Percent Mineral Filler

Graphs showing the relationship between compacting viscosity (or compacting temperature) and physical properties of asphaltic concrete by the Marshall test method are shown in Figures 11 to 16. These graphs are based on the same data as plotted in Figures 3 to 10 or where mixing viscosity (or mixing temperature) was plotted as abscissa.

Compaction studies by Parker (11) for a similar asphaltic concrete wearing course mixture gave similar trends for Marshall stability, specific gravity, percent voids in total mix, and percent voids filled with bitumen for increases in compaction temperature.

**Stability.** —Figure 11 gives the plot of compacting viscosity as abscissa vs Marshall stability as ordinate, as well as that of compacting temperature as abscissa against Marshall stability. All curves follow the same pattern. There is an increase in the stability value as the compacting temperature is increased from 200 to 320 F (viscosity decreased from 2,000 to 54 SSF). This increase is the greatest from a compacting temperature of 200 to 230 F (viscosity 2,000 to 640 SSF). As the compaction temperature is raised, the binder viscosity is reduced. Therefore, less resistance is offered to the compactive effort, resulting in higher stability values.

Neglecting the mixing temperature of 350 F, which is considered high for present-day practice, the highest value of stability is obtained at a compaction temperature of 260 F (viscosity 250 SSF) with mixing at 290 F (viscosity 105 SSF). This value is higher than stability obtained at a mixing temperature of 350 F (viscosity 34.5 SSF) with compaction at 260 F (viscosity 250 SSF). It can also be seen from Figure 11 that compaction temperature at 290 F (viscosity 105 SSF) is satisfactory with mixing temperature of 320 F (mixing viscosity of 54 SSF).

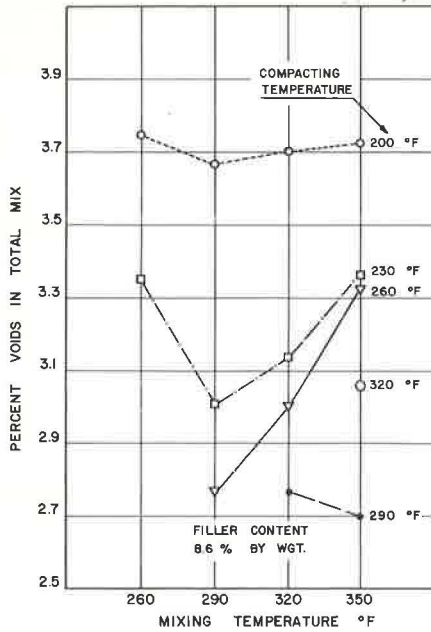


Figure 8. Effects of mixing temperature on percent voids in total mix.

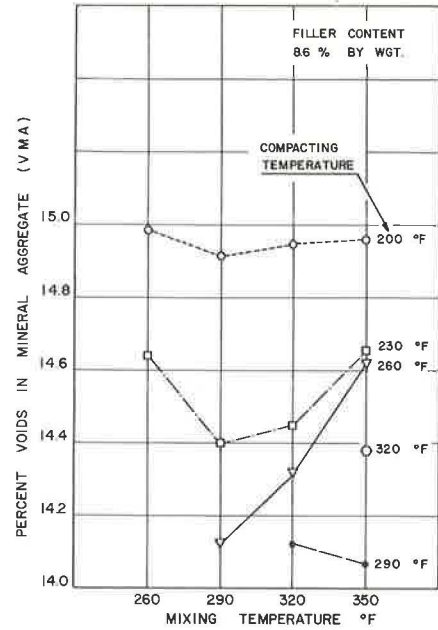


Figure 9. Effects of mixing temperature on percent VMA.

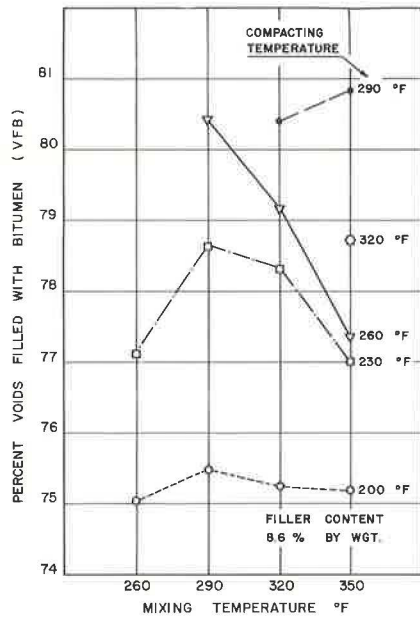


Figure 10. Effects of mixing temperature on percent VFB.

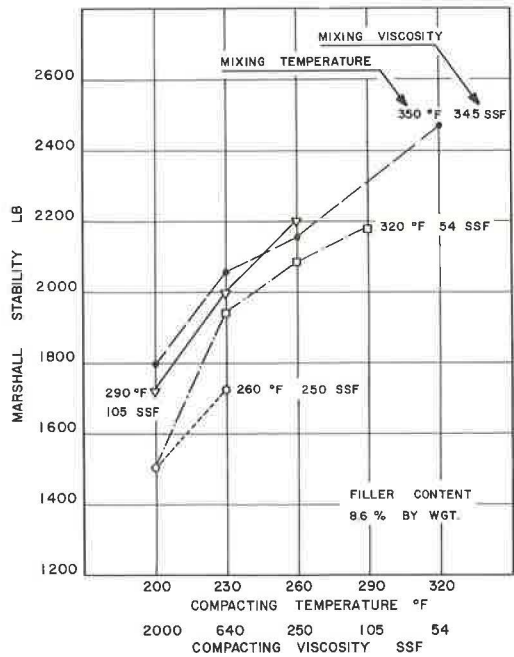


Figure 11. Effects of compacting viscosity (compacting temperature) on Marshall stability.



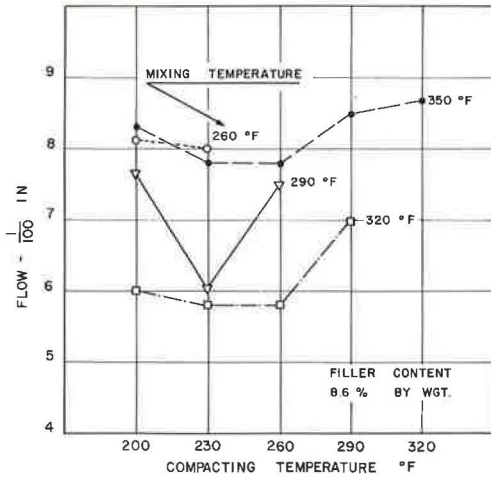


Figure 12. Effects of compacting temperature on flow.

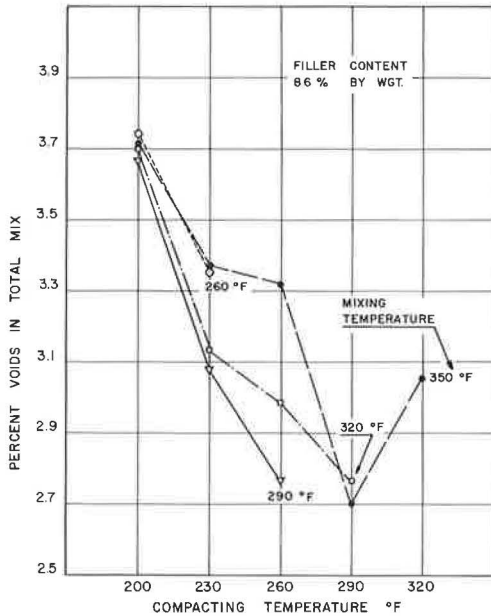


Figure 14. Effects of compacting temperature on percent voids in total mix.

**Flow.**—The relationship between compacting temperature and flow is given in Figure 12. At any mixing temperature, there is no appreciable change in flow values (in units of 0.01 in.) within the limits of compacting temperatures, the maximum variation being 1.7 for a mixing temperature of 290 F. Within the limits

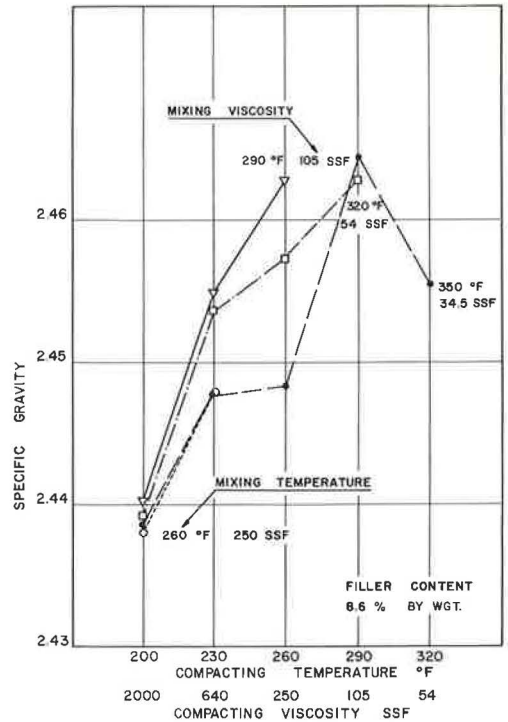


Figure 13. Effects of compacting viscosity (compacting temperature) on specific gravity of asphaltic concrete.

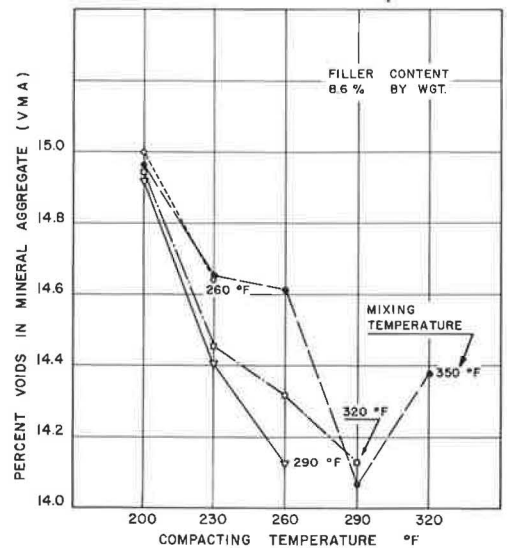


Figure 15. Effects of compacting temperature on percent VMA.

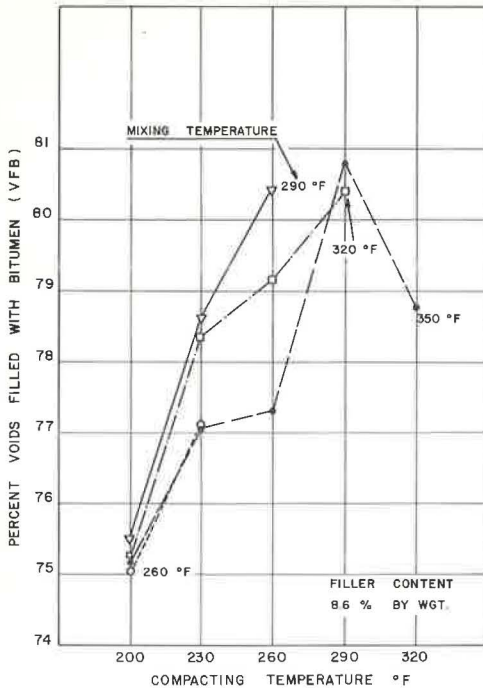


Figure 16. Effects of compacting temperature on percent VFB.

temperature of 320 F (with mixing at 350 F), viscosity of the contained asphalt appears to be very low (54 SSF), so that the mix displaces under the compactive effort, and the compaction is, therefore, not fully effective. This results in a decrease in specific gravity when the compacting temperature is increased from 290 to 320 F (viscosity decreased from 105 to 54 SSF).

The practice of many highway organizations is to specify roadway density requirements as a function of laboratory density, such as 98 percent of laboratory density. In view of the variation of specific gravity values of laboratory compacted mixtures with compacting viscosity of the asphalt (Fig. 13), it is suggested that a requirement should be placed in specifications to control the compacting viscosity of asphalt when forming laboratory briquets for use in checking pavement density. This would eliminate errors caused by employing too high a compacting viscosity (too low a compacting temperature) when molding the laboratory briquets (3).

**Voids in Total Mix.**—Figure 14 shows the relationship of the compacting temperature to percent voids in total mix. There is no appreciable change in the voids for the mixture tested as the compacting temperature is increased from 200 to 320 F. For the mixing temperatures (260 to 350 F) and compacting temperatures (200 to 320 F) used in molding specimens, the void values range between 2.70 and 3.74 percent, giving a total variation of about 1.0 percent only. As the compacting temperature is increased from 200 F there is a decrease in voids up to a compacting temperature of 290 F, after which there is a slight increase (0.35 percent voids) as the compacting temperature is raised to 320 F at a mixing temperature of 350 F.

The decrease in voids is due to the ability of the less viscous asphalt to fill up more of the aggregate voids as the compacting temperature is raised, the compactive effort remaining the same throughout the series. At high compacting temperatures, however, there may be excessive movement of the mix due to lubricating action of the binder. The full compactive effort may not, therefore, be effective. This increases the void contents at high compacting temperatures.

of mixing and compacting temperatures investigated, the flow values lie between 5.8 and 8.7. Minimum values of flow are obtained at the mixing temperature of 320 F.

**Specific Gravity.**—In Figure 13 the plot of compacting viscosity vs specific gravity is given as well as the relationship of the compacting temperature to specific gravity for the same data. There is an increase in specific gravity values as the compacting temperature is increased to 290 F (viscosity decreased to 105 SSF). This increase is steepest for compacting temperatures between 200 and 230 F (viscosity 2,000 to 640 SSF). As the compacting temperature is increased to 320 F (viscosity 54 SSF) there is a decrease (0.009) in specific gravity at mixing temperature of 350 F (viscosity 34.5 SSF). These results can be explained as follows: At low compacting temperatures, the viscosity of the contained asphalt is very high (viscosity at 200 F of 2,000 SSF). A considerable portion of the compactive effort is expended in overcoming the resistance offered by high binder viscosity and does not contribute to the compaction of the mix. This results in decreased densities at low compacting temperatures. However, at a compacting

**Voids in Mineral Aggregate.**—Figure 15 shows the plot of compacting temperature vs percent VMA. As the compacting temperature is increased from 200 to 290 F, there is progressive decrease in VMA. Further rise in compacting temperature to 320 F with mixing at 350 F results in a slight increase (0.31 percent VMA). Lowest value of VMA is obtained at a compacting temperature of 290 F with mixing at 350 F. This percent value is only 0.06 lower than the VMA at mixing and compacting temperatures of 290 and 260 F, respectively, or the VMA at mixing and compacting temperatures of 320 and 290 F, respectively.

**Voids Filled with Bitumen.**—Figure 16 gives the relationship between compacting temperature and percent VFB. As the compacting temperature is increased from 200 to 230 F, there is an average increase of 2.55 percent VFB. This is followed by further increase in VFB as the compacting temperature is raised to 290 F. At the mixing temperature of 350 F, a further increase in compacting temperature from 290 to 320 F results in a decrease of 2.05 in percent VFB values. With a mixing temperature of 350 F and compaction at 290 F, the highest VFB value of 80.8 percent is obtained. This value is 0.4 higher than percent VFB obtained at mixing and compacting temperatures of 290 and 260 F, respectively.

### Effects of Mixing Viscosity on Mixture Containing 11.3 Percent Mineral Filler

Properties of the mixture containing 11.3 percent mineral filler are discussed, as well as the effects on the results of a relatively high F/B ratio.

**Stability.**—Figure 17 gives the plots of mixing viscosity and mixing temperature vs Marshall stability for 11.3 percent mineral filler. The general trend of all curves is the same. There is an increase in the stability values as the mixing temperature is raised from 260 to 350 F (viscosity decreased\*from 250 to 34.5 SSF). This increase is at a low rate from 260 to 290 F (viscosity from 250 to 105 SSF), but the values increase more rapidly when the mixing temperature is increased from 290 to 350 F (viscosity from 105 to 34.5 SSF).

It may be noted that this increase in the stability value as the mixing temperature is increased from 260 to 350 F at filler content of 11.3 percent is in contrast to the results obtained with filler content of 8.6 percent (Fig. 3). For 8.6 percent filler, the curves have a peak at 290 F and a trough at 320 F as the mixing temperature is increased from 260 to 350 F. These results may be explained as follows: As the filler content is increased from 8.6 to 11.3 percent (asphalt content being the same), the viscosity of asphalt-filler binder is increased. Higher mixing temperatures are, therefore, required for proper coating, good mixing and uniform dispersion of materials. Thorough mixing is evidently not obtained at low mixing temperatures of 260 and 290 F (asphalt viscosities of 250 and 105 SSF), resulting in lower stabilities than at mixing temperatures of 320 and 350 F (viscosities of 54 and 34.5 SSF). The increased stabilities at 350 F may be attributed to hardening of asphalt.

It is also seen from Figure 17 that at very low compaction temperatures (or high compaction viscosities) there is no

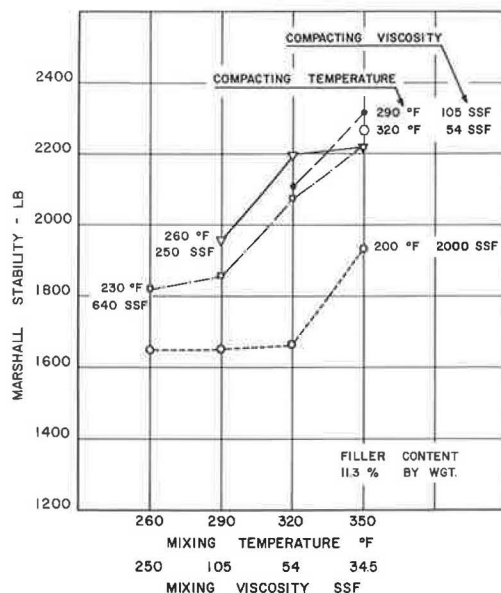


Figure 17. Effects of mixing viscosity (mixing temperature) on Marshall stability.



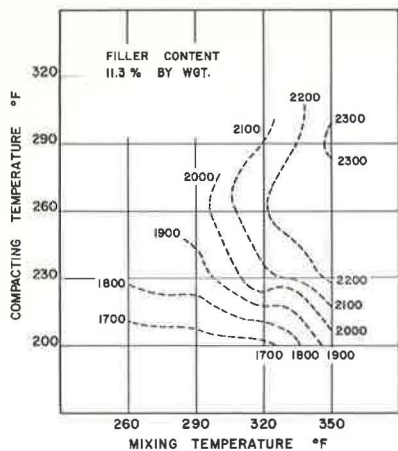


Figure 18. Stability contours showing effects of variations in mixing and compacting temperatures.

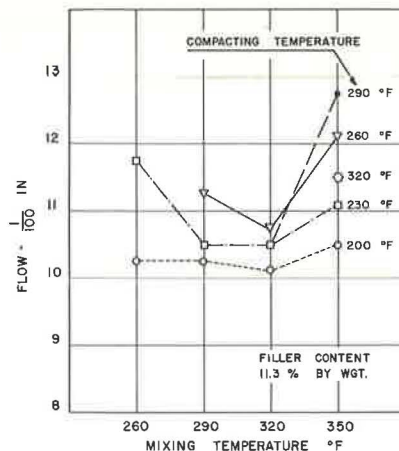


Figure 19. Effects of mixing temperature on flow.

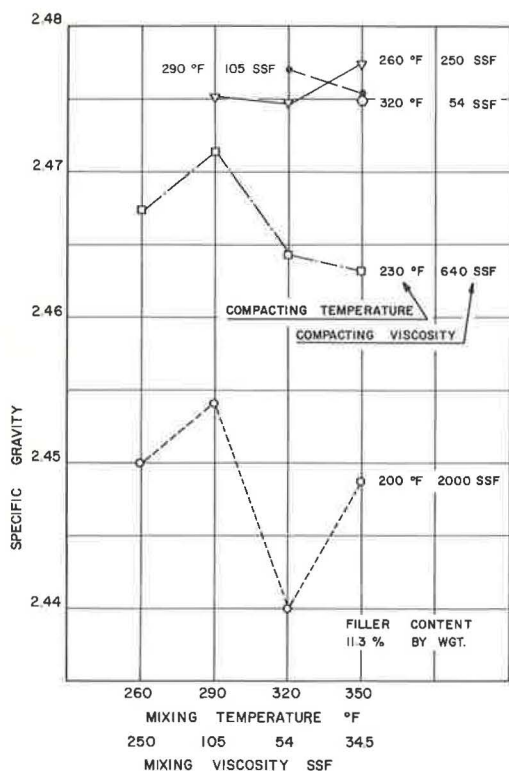


Figure 20. Effects of mixing viscosity (mixing temperature) on specific gravity of asphaltic concrete.

appreciable difference in the stability values as the mixing temperature is increased from 260 to 290 F (viscosity from 250 to 105 SSF).

Up to a mixing temperature of 320 F, the highest stability value is obtained at a mixing temperature of 320 F (viscosity 54 SSF) with compaction done at 260 F (viscosity 250 SSF). This value is 20 lb lower than at mixing and compacting temperatures of 350 and 260 F, respectively.

Figure 18 shows the stability contours at 100-lb intervals with filler content of 11.3 percent. These contours show that for a constant compacting temperature, the stability values increase as the mixing temperatures are increased. The lower portion of this figure indicates that for equal stability, the compaction temperatures should be progressively increased as the mixing temperature is decreased from 350 to 260 F. Thus, compaction temperatures of 211, 222, and 227 F are required for same stability (1,800 lb) at mixing temperatures of 320, 290, and 260 F, respectively. Also, with mixing temperatures of 350 and 320 F, a stability value of 2,000 lb is obtained when compaction is done at temperatures of 290 and 224 F, respectively. The upper portion of the figure indicates that for a constant mixing temperature of 320 F, there is a peak in stability values at about 260 F compacting temperature. Above this peak, there is a reversal be-



cause increased compacting temperature produces a lower stability value when the mixing temperature is kept constant (e. g., the stability values at 260 and 290 F for a mixing temperature of 320 F).

**Flow.**—In Figure 19 the graph showing the relationship between mixing temperature and flow is given. The general trend of all curves is the same as noted with 8.6 percent filler content in Figure 5, but the flow values are greater for the 11.3 percent filler mixture.

**Specific Gravity.**—Figure 20 gives the plots of mixing viscosity and mixing temperature vs specific gravity. The general trend of all curves is the same up to a mixing temperature of 320 F (viscosity 54 SSF). The specific gravity increases as the mixing temperature increases from 260 to 290 F (viscosity from 250 to 105 SSF) after which there is a decrease in the values as the mixing temperature is raised to 320 F (viscosity 54 SSF). Further increase in mixing temperature to 350 F (viscosity 34.5 SSF) produces variable results. It is interesting to compare the peak in curves obtained at 290 F (105 SSF mixing viscosity) with results published by Lehmann and Adam (3, Fig. 6), where a peak is shown at 85 SSF mixing viscosity for percent theoretical specific gravity for laboratory compacted briquets.

Figure 21 shows the contours for specific gravity for the 11.3 percent filler mixture at intervals of 0.005 with mixing temperatures and compacting temperatures as the coordinate axes. For a constant mixing temperature, specific gravity is increased as the compacting temperature is raised.

**Voids in Total Mix.**—Figure 22 shows the relationship between mixing temperature and percent voids in total mix for 11.3 percent mineral filler. The change in voids as the mixing temperature is varied between 260 and 350 F is slight, less than 0.6 percent at equivalent compaction temperatures. A decrease in voids as the mixing temperatures are increased from 260 F (viscosity 250 SSF) to 290 F (viscosity 105 SSF) is followed by some increase up to 320 F (viscosity 54 SSF). It is interesting to compare this trough in values of percent voids in total mix with the peak of values given by Lehmann and Adam (3, Fig. 6).

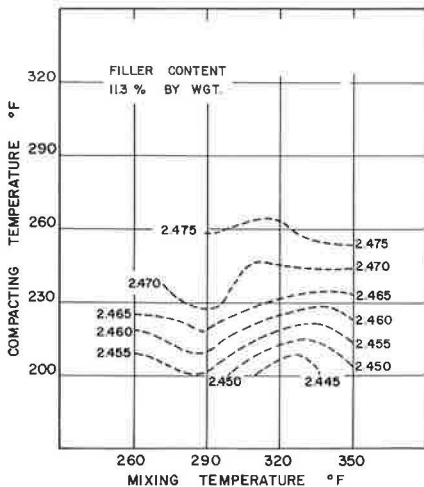


Figure 21. Specific gravity contours of asphaltic concrete showing effects of variations in mixing and compacting temperatures.

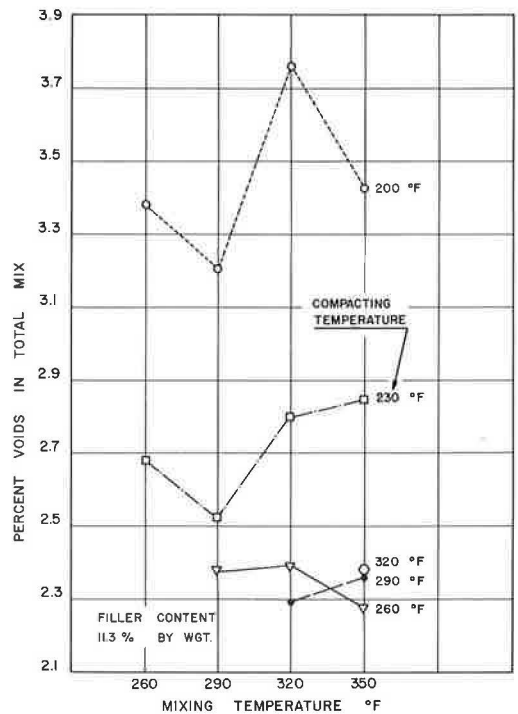


Figure 22. Effects of mixing temperature on percent voids in total mix.

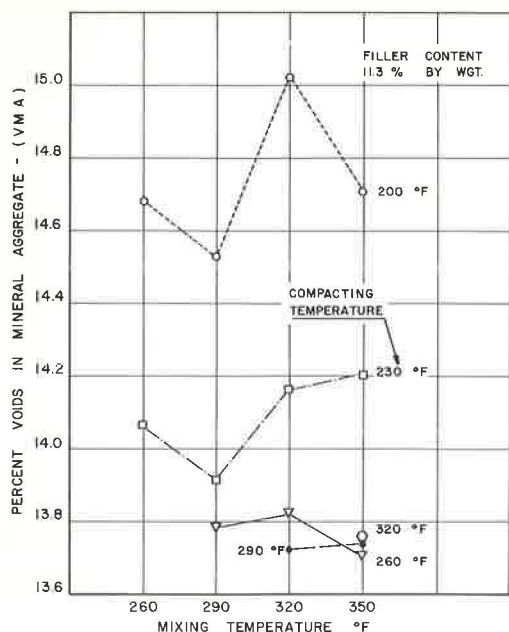


Figure 23. Effects of mixing temperature on percent VMA.

There is very little difference in values as the mixing temperature is further increased to 350 F, excepting at a compaction temperature of 200 F where the percent voids decreases by 0.25.

**Voids in Mineral Aggregate.** — Figure 23 gives the plot of mixing temperature vs percent VMA. The maximum change in percent VMA at the same compaction temperature is only 0.5 as the mixing temperature is varied between 260 and 350 F. For compacting temperatures up to 260 F, a trough of low values of VMA occurs at 290 F. The combination of 320 F mixing temperature with 290 F compaction temperature gives a low value of VMA of 13.72.

**Voids Filled with Bitumen.** — The relationship between mixing temperature and percent VFB is shown in Figure 24 for 11.3 percent mineral filler. The total variation in VFB values is about  $1\frac{1}{2}$  times the variation at filler content of 8.6 percent, the values varying between 74.9 and 83.4 percent. As the mixing temperature is increased from 260 to 290 F, there is an increase in VFB. Further rise in mixing temperature up to 320 F results in a decrease in values. For further increase in mixing temperature up to 350 F, the trends are variable. For compaction temperature equal to or greater than 260 F the percent VFB values lie within 0.7 as the mixing temperature is varied between 290 and 350 F.

#### Effects of Compacting Viscosity on Mixture Containing 11.3 Percent Mineral Filler

Graphs for the mixture containing 11.3 percent mineral filler are considered where the compacting viscosity (or compacting temperature) is plotted against the various physical properties. These graphs are based on the same data as plotted in Figs. 17 to 24 where mixing viscosity (or mixing temperature) was plotted as abscissa.

**Stability.** — Figure 25 shows the relationship of compacting viscosity and temperature as abscissa against Marshall stability as ordinate for the 11.3 percent mineral filler mixture. There is an appreciable increase in the stability as the compacting tempera-

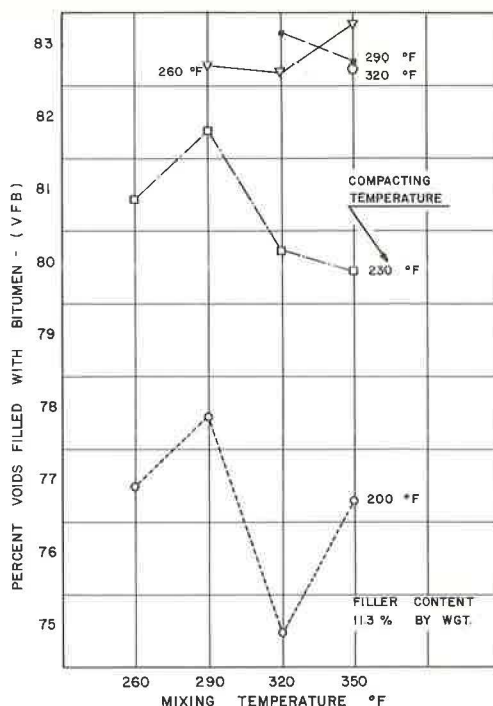


Figure 24. Effects of mixing temperature on percent VFB.

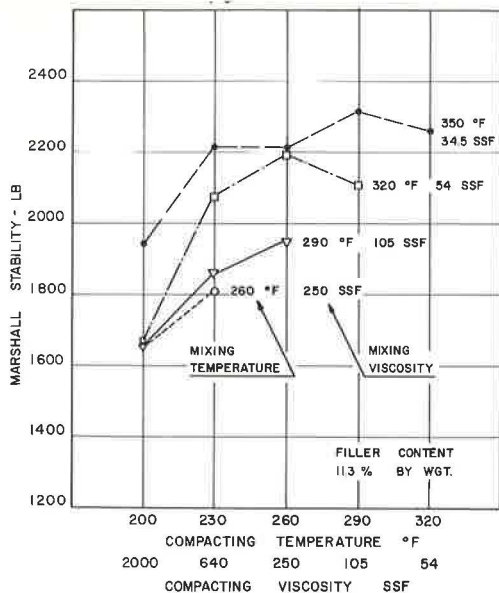


Figure 25. Effects of compacting viscosity (compacting temperature) on Marshall stability.

of 350 F (viscosity 34.5 SSF), the stability is highest at a compacting temperature of 290 F (viscosity 105 SSF) after which there is a decrease in stability of 54 lb as the compacting temperature is increased to 320 F (viscosity 54 SSF). There is a decrease of 90 lb in stability at a mixing temperature of 320 F when the compacting temperature is raised from 260 to 290 F (viscosity decreased from 250 to 105 SSF).

**Flow.**—The results for the mixture containing 11.3 percent mineral filler for compacting temperature vs flow are plotted in Figure 26. Within the limits of mixing and compacting temperatures, the variation in flow is less than 2.7, the values lying between 10.1 and 12.8. There is an increase in the flow as the compacting temperature is increased from 200 to 260 F. This is followed by a slight decrease in flow at a mixing temperature of 320 F. At a mixing temperature of 350 F, there is a decrease in flow of 1.2 as the compacting temperature is raised from 290 to 320 F. Minimum values of flow are obtained at the mixing temperature of 320 F, as is also the case for the mixture with the filler content of 8.6 percent (Fig. 12).

**Specific Gravity.**—Figure 27 gives the relationship between compacting viscosity and specific gravity as well as between compacting temperature and specific gravity. As the compacting temperature is increased from 200 to 260 F (viscosity decreased from 2,000 to 250 SSF), there is an increase in specific gravity values. Further rise in compacting temperature to 320 F (viscosity 54 SSF) results in a slight decrease in specific gravities at a mixing temperature of 350 F (viscosity 34.5 SSF).

The reasons for this increase in specific gravities as the compacting temperature is increased to a certain value followed by decrease in the values with further rise in compacting temperature have already been explained in the discussion on the mixture with 8.6 percent filler content.

It may be noted from comparison of Figures 25 and 27 that although there is a slight increase in specific gravity when the compacting temperature is increased from 260 to 290 F with mixing at 320 F, the corresponding stability decreases by 90 lb. Also at mixing temperature of 350 F, an increase in compacting temperature from 260 to 290 F results in a very slight decrease in specific gravity (0.0023) but the stability increases by 100 lb. These show a lack of direct stability-density correlation.

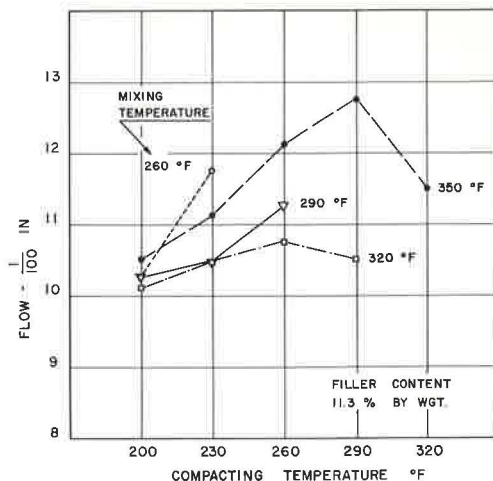


Figure 26. Effects of compacting temperature on flow.



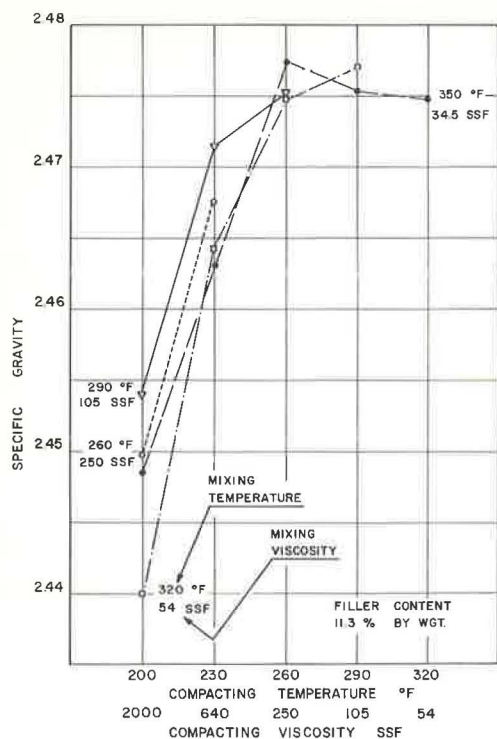


Figure 27. Effects of compacting viscosity (compacting temperature) on specific gravity of asphaltic concrete.

shown for 11.3 percent mineral filler. Within the limits of mixing and compacting temperatures, the void values lie between 2.3 and 3.8 percent, giving a maximum variation of about 1.5 percent voids. There is a steep decrease in voids as the compacting temperature is raised from 200 to 230 F, the average decrease being 0.7 percent voids. The amount of change in voids reduces with further rise in compacting temperatures to 320 F. At the mixing temperature of 350 F there is practically no difference in voids as the compacting temperature is increased from 260 to 320 F.

**Voids in Mineral Aggregate.**—Figure 29 gives the plot of compacting temperature against percent VMA for 11.3 percent mineral filler. The VMA values lie between 13.7 and 15.0 percent, giving a maximum variation of 1.3 percent within the range of mixing and compacting temperatures used in this study. There is a decrease in the VMA as the compacting temperature is increased from 200 to 290 F, excepting for the mixing temperature of 350 F where there is a very slight increase (0.09 percent VMA) as the compacting temperature is raised from 260 to 320 F. The combination of 290 F compacting temperature with 320 F mixing temperature gives a low value of VMA.

**Voids Filled with Bitumen.**—Figure 30 shows the relationship between compacting temperature and percent VFB. The VFB values range between 74.9 and 83.4 percent, as the compacting temperature is varied between 200 and 320 F with the mixing temperature ranging between 260 and 350 F. The increase in VFB values is greatest when the compacting temperature is increased from 200 to 260 F. An increase in compacting temperature from 260 to 320 F results in a small decrease in VFB (0.6 percent VFB) at the mixing temperature of 350 F. Relatively high values of VFB are obtained at a mixing temperature of 320 F with a compacting temperature of 290 F, as well as at temperatures of 290 and 260 F, respectively.

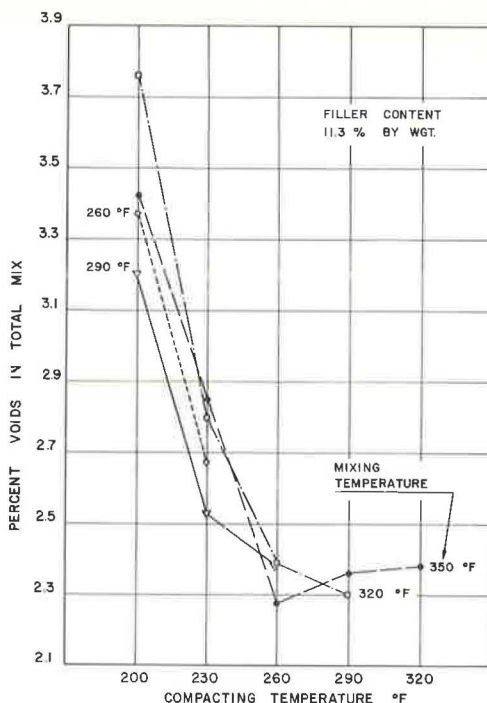


Figure 28. Effects of compacting temperature on percent voids in total mix.

**Voids in Total Mix.**—In Figure 28 the relationship between compacting temperature and percent voids in total mix is



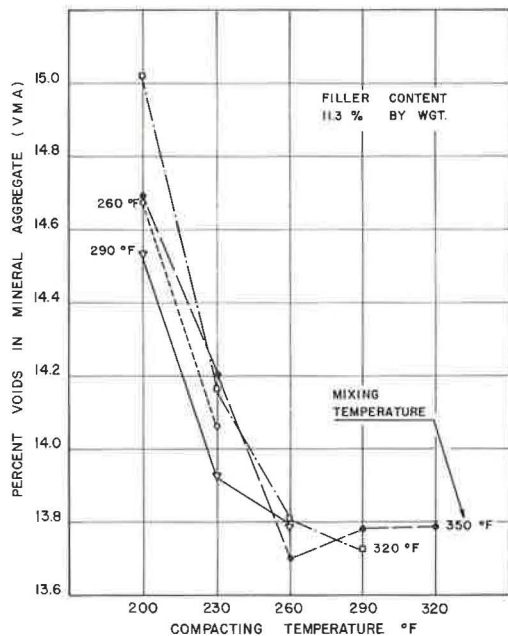


Figure 29. Effects of compacting temperature on percent VMA.

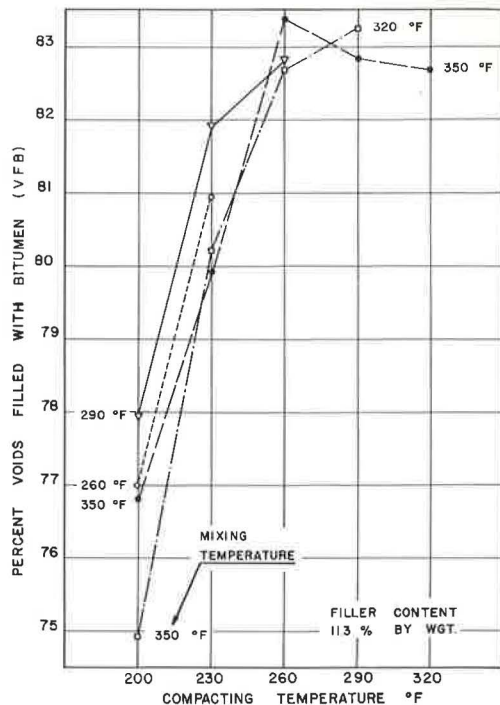


Figure 30. Effects of compacting temperature on percent VFB.

### Effects of Increasing Filler-Bitumen Ratio

As mentioned before, the effects of mixing and compacting viscosities on the properties of asphaltic concrete were studied with two filler contents, keeping constant the asphalt content of 4.75 percent by weight of total mix. A filler content of 8.6 percent by weight of total mix (considered normal in the asphaltic concrete mix investigated) was used in one set of specimens, whereas the filler content of 11.3 percent (considered relatively high) was used in the other set of specimens.

**Stability.**—The increase in F/B ratio by weight from 1.81 to 2.38 (filler content from 8.6 to 11.3 percent by weight of total mixture) results in an increase in the stability values at mixing temperatures of 260, 320, and 350 F, and a decrease at mixing temperature of 290 F. This is readily seen in Figure 31 (see also Figs. 3 and 17). Taking the average of the stability values at different compacting temperatures at specified mixing temperatures, this increase is 119 lb (7.1 percent), 86 lb (4.5 percent), and 32 lb (1.5 percent) at mixing temperatures of 260, 320, and 350 F, respectively. At a mixing temperature of 290 F, there is a decrease of 150 lb (7.6 percent) in the value. The increase in stability may be due to the increase in the binder viscosity as the filler content is increased from 8.6 to 11.3 percent. Also, filler properties such as particle shape and particle-size distribution may affect the Marshall stability (4, p. 16). For the mixing temperature of 290 F, however, it is not clear as to why there is a decrease in stability values for the 11.3 percent filler mixture. Kallas and Puzinauskas (5, Fig. 12) reported variable results in Marshall stability values due to different concentrations of limestone dust mineral filler.

It is also seen from a study of Figure 25 for the 11.3 percent filler mixture that with high mixing and compacting temperatures (or low mixing and compacting viscosities) there is a drop in stability values. Thus, at a mixing temperature of 320 F (viscosity 54 SSF), the stability decreases by 91 lb as the compacting temperature is increased from 260 to 290 F. Also at a mixing temperature of 350 F (viscosity 34.5 SSF), the drop in stability is 54 lb as the compacting temperature is increased from 290 to 320

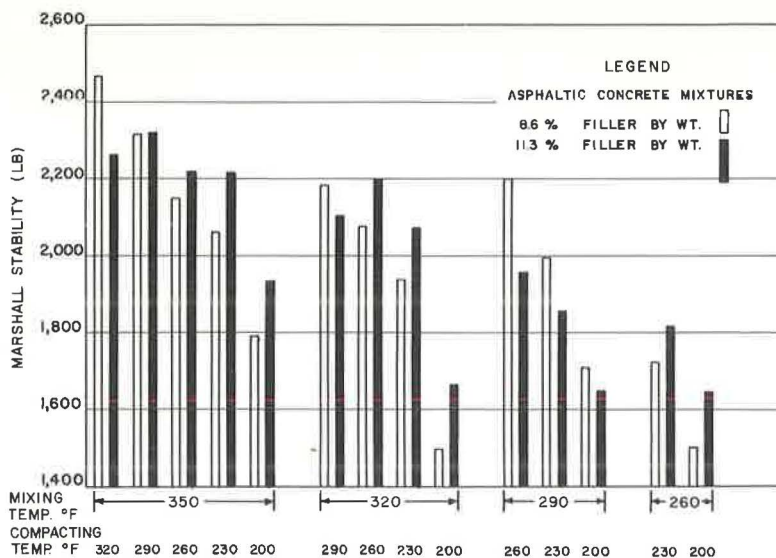


Figure 31. Comparison of Marshall stability values for asphaltic concrete mixtures with different filler contents for different mixing and compacting temperatures.

F. This is in contrast to the results shown in Figure 11 for the 8.6 percent filler mixture where at high mixing temperatures of 350 and 320 F, there is an increase in stability values as the compacting temperatures are increased from 260 to 320 F (compacting viscosities are decreased from 250 to 54 SSF).

The tendency of the Marshall stability-mixing viscosity curve to show a peak and a trough (Fig. 3) for 8.6 percent filler as the mixing viscosity is decreased (or mixing temperature increased) is eliminated when the filler content is increased to 11.3 percent. In the latter case (Fig. 17), there is a progressive rise in stability as the mixing viscosity is decreased from 250 to 34.5 SSF (or mixing temperature is increased from 260 to 350 F).

Lower mixing viscosities (or higher mixing temperatures) are desirable at high filler content so that there may be thorough mixing and uniform dispersion of the materials. The "optimum" mixing viscosity and the "optimum" compacting viscosity for stability depend on filler content.

**Flow.** —The flow values are considerably affected by the F/B ratios. The flow values increase as the filler content is increased from 8.6 to 11.3 percent (Figs. 5 and 19).

**Specific Gravity.** —Increase in mineral filler content from 8.6 to 11.3 percent by weight increases the specific gravity values. This increase in density indicates the void-filling property of the mineral filler (Figs. 6 and 20).

**Voids in Total Mix.** —The increase in mineral filler content results in a slight decrease in the voids in total mix (Figs. 8 and 22).

**Voids in Mineral Aggregate.** —At identical mixing and compacting temperatures, the VMA decrease as the mineral filler content is increased with one exception (Figs. 9 and 23).

**Voids Filled with Bitumen.** —At identical mixing and compacting temperatures, the VFB at the mineral filler content of 11.3 percent are higher than at the filler content of 8.6 percent with one exception (Figs. 10 and 24).

#### OPTIMUM MIXING AND COMPACTING VISCOSITIES

Within the range of mixing viscosities and compacting viscosities investigated in this study, a mixing temperature of 290 F (mixing viscosity of 105 SSF) is satisfactory at the filler content of 8.6 percent for the given gradation of aggregate and the given asphalt cement. For the mixing temperature of 290 F (viscosity 105 SSF), highest stabil-

ity and specific gravity values are obtained at the compacting temperature of 260 F (viscosity 250 SSF).

For comparison, a set of four specimens was prepared at a mixing temperature of 300 F (viscosity 82 SSF), with compaction done at 250 F (viscosity 335 SSF). The results are shown in Table 4. There is not much difference in the stability and density values when the mixing is done at temperatures of 290 and 300 F with compaction at 260 and 250 F, respectively; the stability and density are very slightly higher in the former, the difference being 10 lb for stability and 0.5 pcf for density values.

From this discussion it is seen that a mixing temperature range of 290 F (viscosity 105 SSF) to 300 F (viscosity 82 SSF) is satisfactory at a filler content of 8.6 percent with the aggregate gradation and asphalt cement used in this study.

At a filler content of 11.3 percent, the stability values at the mixing temperature of 320 F (viscosity 54 SSF) are higher than the values obtained when mixing is done at temperature of 290 F (viscosity 105 SSF) (Figs. 17 and 25). However, the average density with mixing temperature of 320 F is slightly lower than at the mixing temperature of 290 F.

A study of Figures 25 and 27 shows that at the filler content of 11.3 percent, mixing and compacting temperatures of 320 and 260 F (viscosity 54 and 250 SSF), respectively, are most satisfactory. However, mixing and compacting temperatures of 320 and 290 F (viscosity 54 and 105 SSF) are also satisfactory because the stability is only 91 lb smaller. At the compacting temperature of 260 F, the stability with mixing done at 320 F is 240 lb higher than the value at mixing temperature of 290 F, and 18 lb lower than at mixing temperature of 350 F. Mixing temperatures above 320 F are not recommended because of the danger of overheating and hardening the asphalt cement. However, there is not much difference in the density at mixing temperatures of 290, 320, and 350 F with compaction done at 260 and at 290 F (Fig. 20).

It is thus observed that an increase in filler content requires use of lower mixing viscosity (higher mixing temperature) for optimum stability and density values. In other words, the F/B ratio should be considered before arriving at an optimum mixing viscosity in the design and construction of asphaltic concrete. Also, the F/B ratio should be considered in selecting an optimum compacting viscosity for the design and construction of asphaltic concrete.

At the filler content of 8.6 percent by weight, the optimum mixing viscosity range of 82 to 105 SSF (300 to 290 F) is within the range of 75 to 150 SSF suggested by the Asphalt Institute (6). The corresponding mixing temperature range lies between 277 and 303 F for the asphalt cement used in this study for this viscosity range, the average temperature being 290 F.

At the mixing viscosity of  $85 \pm 10$  SSF suggested in the Marshall stability test of ASTM Designation: 1559-60T (2), the temperature range varies between 293 and 303 F (Fig. 1). This mixing temperature range is satisfactory at the filler content of 8.6 percent, as can be seen from the previous discussion of results obtained by the Marshall test.

At the compacting viscosity of  $140 \pm 15$  SSF suggested in the Marshall stability test of ASTM (2), the temperature varies between 275 and 283 F for the asphalt cement used in this investigation (Fig. 1). For the materials used in this investigation and for the mixture with 8.6 percent filler, a compacting temperature of about 260 F gave good results as measured by the Marshall test. The higher value between 275 and 283 F according to ASTM (2) would appear to be satisfactory (Figs. 3, 4, and 11).

At the filler content of 11.3 percent by weight, the optimum mixing viscosity as discussed previously is 54 SSF (or optimum mixing temperature of 320 F). This is outside the limits of 75 to 150 SSF suggested by the Asphalt Institute (or temperature range be-

TABLE 4  
MARSHALL TEST RESULTS FOR MIX CONTAINING 8.6 PERCENT FILLER

Property	At Mixing Temp 290 F and Com- pacting Temp 260 F	At Mixing Temp 300 F and Com- pacting Temp 250 F
Stability (lb)	2,200	2,190
Flow (0.01 in.)	7.5	6.8
Specific Gravity	2.463	2.456
Density (pcf)	153.67	153.22
Percent Voids in Total Mix	2.77	3.05
Percent VMA	14.02	14.38
Percent VFB	80.98	78.77



tween 277 and 303 F). This optimum mixing viscosity is also below the ASTM value of  $85 \pm 10$  SSF (or above temperature range of 293 to 303 F). However, Vokac (7) has noted that sheet asphalt with higher filler content required 50 to 100 SSF for mixing, whereas one-sized aggregate mixes, plant-mix macadam or sand asphalt could be mixed at temperatures corresponding to 125 to 250 SSF.

By comparing against the ASTM (2) compacting viscosity of  $140 \pm 15$  SSF (temperature range 275 to 283 F), it is noted that the optimum compacting viscosity for the 11.3 percent filler mixture investigated is 250 SSF (optimum compacting temperature of 260 F). However, good results were also obtained for a compacting viscosity of 105 SSF (compacting temperature of 290 F). It appears that the ASTM compacting viscosity requirement falls within a range of compacting viscosities that would be suitable for this high filler content mixture.

Further research is required using a variety of aggregate types and gradations, different types of asphalts, and different F/B ratios to establish optimum mixing viscosity and optimum compacting viscosity for asphaltic concrete mixes.

### CONCLUSIONS

Based on the materials and methods employed in this investigation, the following conclusions may be stated:

1. Variations in mixing viscosity of asphalt over a range of 34.5 to 250 SSF (temperature range from 350 to 260 F) gave significant differences in test results on asphaltic concrete specimens for Marshall stability, flow, specific gravity, percent voids in total mix, percent voids in mineral aggregate, and percent voids filled with bitumen.
2. Variations in compacting viscosity of asphalt over a range from 54 to 2,000 SSF (temperature range of 320 to 200 F), also gave significant differences in test results for the same properties.
3. Variations in the filler-bitumen ratio by weight from 1.81 to 2.38 in asphaltic concrete specimens gave some significant differences in the test values of physical properties for identical combinations of mixing viscosity and compacting viscosity of asphalt.

### RECOMMENDATIONS

1. Selection of mixing viscosity and compaction viscosity values of asphalt for molding asphaltic concrete specimens should be based on optimum conditions consistent with practical paving plant and construction operations requirements for the production of durable pavements.
2. The filler-bitumen ratio should be considered in selecting optimum mixing viscosity and optimum compacting viscosity for the design and construction of asphaltic concrete.
3. The mixing viscosity and compacting viscosity of asphalt should be stated in reports giving results obtained by the Marshall stability test.
4. Control of the mixing and compacting viscosities of asphalt in the heating and mixing of materials and molding of asphaltic concrete specimens for the Marshall stability test should be required to obtain consistent and significant values of physical properties of asphaltic concrete mixtures.
5. A requirement should be placed in specifications to control the compacting viscosity of asphalt when forming laboratory briquets for use in checking pavement density to eliminate errors caused by employing too high a compacting viscosity (too low a compacting temperature) when molding laboratory briquets.

### ACKNOWLEDGMENTS

Acknowledgment is made to the International Cooperation Administration and the Agency for International Development of the U. S. Government for the support given to Dr. Gandharv Raj Bahri of India as a participant in the teacher training program at the University of Wisconsin. The use of the facilities of the testing laboratory of the State Highway Commission of Wisconsin in conducting this investigation is also appreciated.



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*Discussion*

CHARLES F. PARKER, W. S. Hinman, Inc., Westbrook, Me. —The studies made by Dr. Bahri and Prof. Rader are in many ways similar to those shown by the writer (11). The purpose of this latter paper was slightly different and is more closely related to actual construction procedures, whereas Prof. Rader's paper is more closely associated with laboratory control.

The results of the compaction temperature studies shown (11) were presented to show the importance of this relationship and how critical this could be during actual construction. It was recommended that the diameter of steel-tired rollers be increased and widened to permit rolling at higher temperatures with less displacement or decompaction.

The procedure used by Bahri and Rader was similar to that used by the writer and was the standard Marshall procedure as has been described by Prof. Rader. The mix comprised 6.3 percent (of total mix) asphalt and the following gradations of aggregate: passing  $\frac{1}{2}$  in. sieve, 100 percent; No. 4, 68 percent; No. 10, 44 percent; No. 20, 31 percent; No. 40, 23 percent; No. 80, 13 percent; No. 200, 4.7 percent. The minimum mixing temperature was that required in the standard procedure, except when the tests were performed at higher temperatures than the standard; in this case all materials were brought to the temperature of the test before mixing. The results obtained by Bahri and Rader appear to support those we obtained.

In a paper (9) reporting on results using a Hveem kneading compactor rather than the Marshall method of compaction, Kiefer stated:

A comparison of the results of this experimental program using kneading compaction with those of Parker...using impact compaction, shows that although the curves follow the same general trend....The changes in specific gravity, percent voids, stabilometer value and cohesimeter value using kneading compaction were about one half of those using impact compaction.

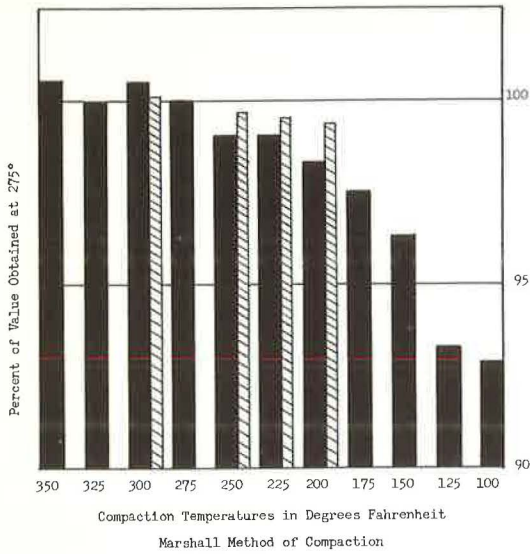


Figure 32. Effect of compaction at various temperatures on specific gravity; Rader results shown by hatched bars at 350F mixing temp. with filler content 8.6% by wt.

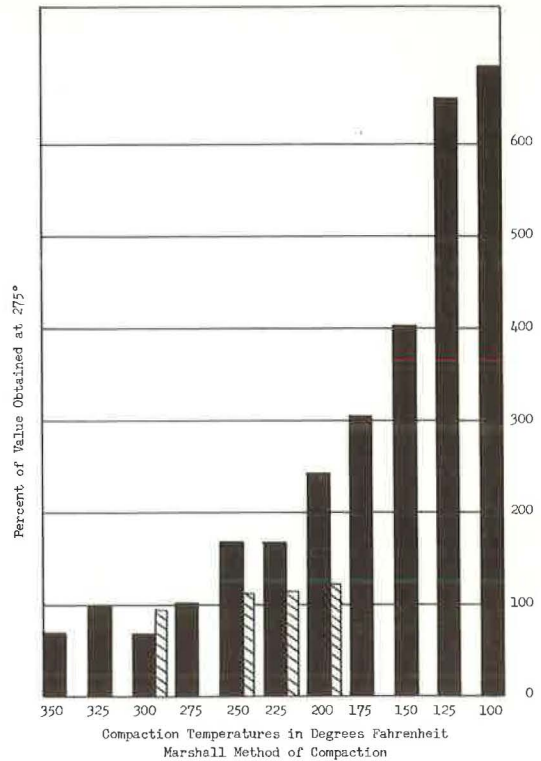


Figure 33. Effect of compaction at various temperatures on percent voids; Rader results shown by hatched bars at 350F mixing temp. with filler content 8.6% by wt.

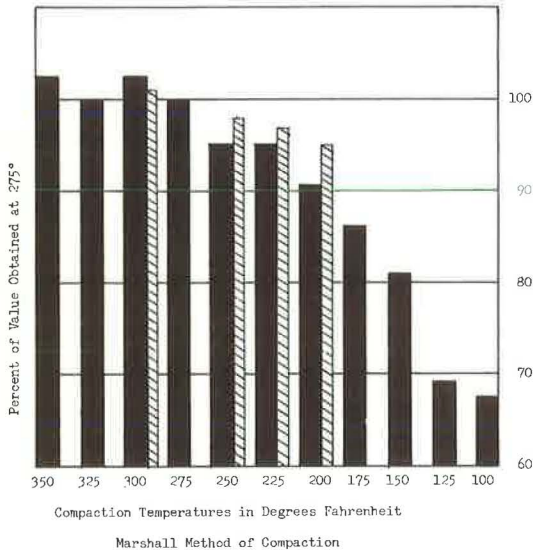


Figure 34. Effect of compaction at various temperatures on voids filled; Rader results shown by hatched bars at 350F mixing temp. with filler content 8.6% by wt.

In Figure 32, the values of Bahri and Rader for specific gravity are shown by the hatched bars; the shape of this curve corresponds very closely to the results obtained by the writer though the temperature range is not as broad as that investigated by the writer. In Figure 33, Prof. Rader's results for percent voids are again shown by the hatched bars and the trend is not quite as great as shown by our results. However, studies were made by the writer over a temperature range from 350 to 100 F as compared to the much narrower range of 300 to 200 F of Prof. Rader's paper. This low range (100 to 200 F) would seem to be of considerable importance in that it reflects

to a great extent the results that may be obtained during cold weather construction, such as was described previously in a paper (12). In Figure 34, again the trend of our results for voids filled is very similar to those of Bahri and Rader and more extreme temperatures are covered by the writer. In Figure 35, the Bahri-Rader results for

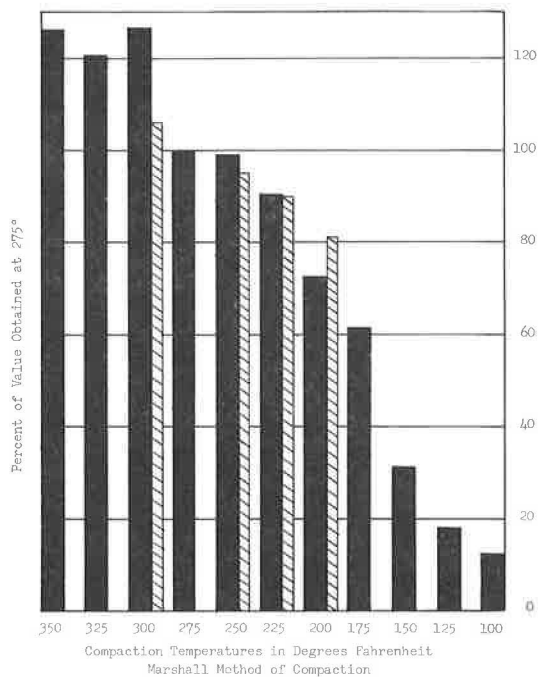


Figure 35. Effect of compaction at various temperatures on Marshall stability; Rader results shown by hatched bars at 350°F mixing temp. with filler content 8.6% by wt.

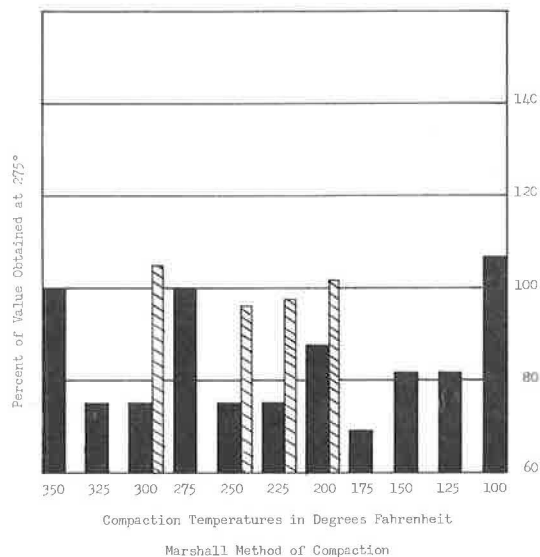


Figure 36. Effect of compaction at various temperatures on Marshall flow; Rader results shown by hatched bars at 350°F mixing temp. with filler content 8.6% by wt.

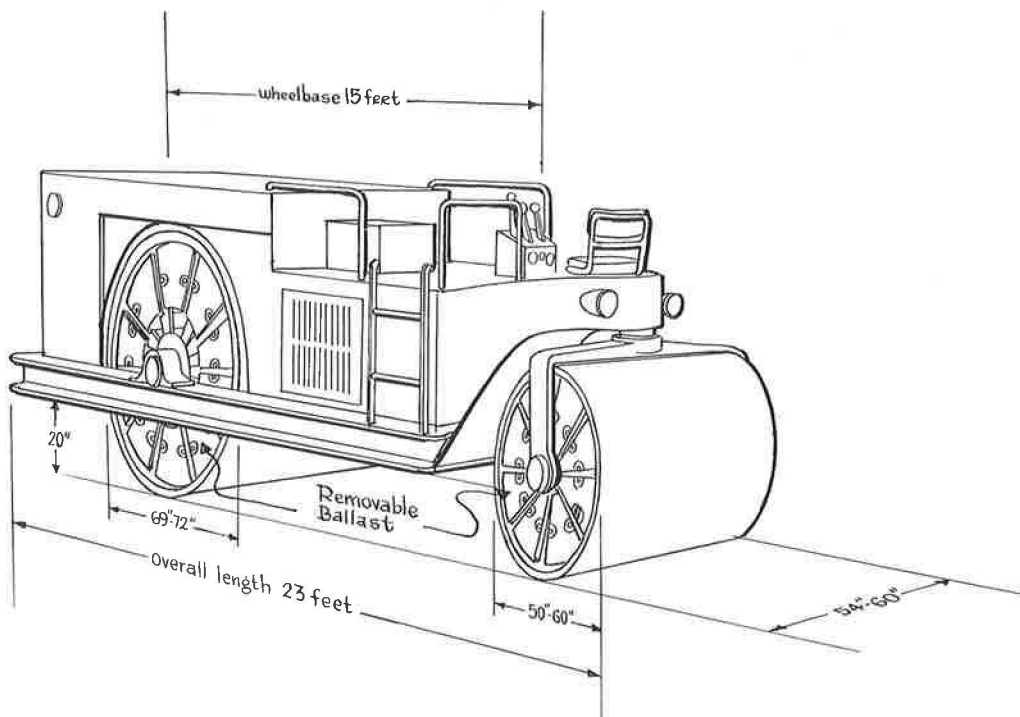


Figure 37. Artist's conception of roller.



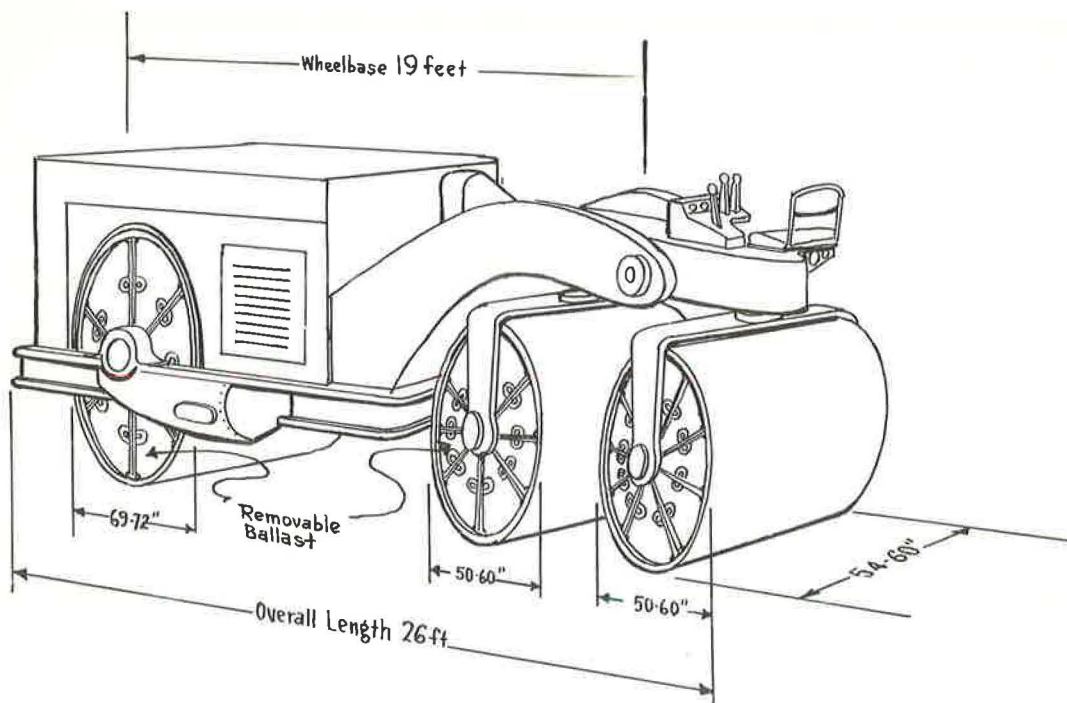


Figure 38. Artist's conception of roller.

Marshall stability, shown by the hatched lines are very similar to the results obtained by the writer, except in the high range of 300 F and the low range of 200 F. However, the general trend is practically identical. As shown in Figure 36, our results were somewhat erratic on this study of Marshall flow and nearly as much so in the results of the Bahri-Rader investigation.

Bahri and Rader have stated in their paper that for a mixture containing 8.6 percent mineral filler, "Considering the stability values up to a compaction temperature of 260 F, the highest value of stability (2,200 lb) is obtained when the mixing is done at 290 F (viscosity 105 SSF) with compaction at 260 F (viscosity 250 SSF). This appears to be an excellent combination of mixing temperature and compaction temperature." Our investigation indicated that the ideal compaction temperature was 275 F (11).

The writer agrees with Dr. Bahri and Prof. Rader that a selection of mixing viscosity and compaction viscosity values of asphalt for molding asphaltic concrete specimens should be based on optimum conditions consistent with the practical paving plant and construction operations and that a requirement should be placed in specifications to control the compaction viscosity of asphalt when forming laboratory briquettes for use in checking paving density.

Looking again at the practical side or the actual construction, it is important to have a requirement for compaction temperatures in the specification. This brings up the point that it is difficult to roll many of the so-called tender-type mixes by the conventional method of compaction, and that by increasing the diameter of the rollers, compaction may be completed at higher temperatures with less displacement or decompaction. Much the same effect is accomplished by pneumatic-tire rolling. In reality, changes in tire pressure varies the contact diameter of the rolls.

Figures 37 and 38 show an artist's conception of changes in design of steel-tired rollers that would permit compaction at higher temperatures by increasing the diameter of the rolls.



In conclusion, according to F. N. Hveem, "If more of our compaction rollers had six-foot wheels, many of our asphalt-compaction troubles would disappear" (13).

#### References

12. Parker, C. F., "Effect of Mix Temperature." HRB Spec. Rept. 54, pp. 28-33 (1960).
13. Day, Ray, "Pick Your Rollers for Top Blacktop Profit." Constr. Equip. and Mater. (Oct. 1963).