Effects of Mixing Viscosity and Compacting Viscosity on Physical Properties of Tar Concrete

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This laboratory study investigated the effects of variations in mixing viscosity and compacting viscosity on the physical properties of tar concrete as measured by the Marshall testing apparatus. The effects of varying the mineral filler content were also determined. Mixing temperatures were varied between 170 and 250 F in increments of 20 F. Marshall stability specimens were compacted by a mechanical compactor at temperatures in increments of 20 F, ranging from 150 F to a temperature 20 F below the corresponding mixing temperature.

The viscosity-temperature relationship of the single straight-distilled coke-oven tar of RT-12 grade was established, and each of the mixing temperatures and compacting temperatures was related to kinematic viscosity of tar in centistokes (cs). The same aggregates were used throughout the investigation; two filler-tar ratios were investigated with the same tar content. The commercial mineral filler was limestone dust. The tar concrete of both gradations was a coarse-graded type for surface courses, conforming to gradation limits of ASTM designation D1753-64 for ½-in. nominal maximum size of aggregate and also to the producer's specifications. The method of mixing, molding, and testing Marshall specimens conformed in general to ASTM designation D1559-62T except for variations in mixing viscosity and compacting viscosity and for mechanical compaction. The standard test temperature of 100 F was carefully controlled. The tar content was 5.25 percent.

The experimental results showed that variations in the mixing viscosity and compacting viscosity of tar concrete produced significant differences in values of Marshall stability, flow, specific gravity, and voids of the compacted mixtures. Some of these differences in values were large enough to warrant attention to selection and control of proper mixing viscosity and compacting viscosity of tar. Optimum mixing viscosity and optimum compacting viscosity are suggested for the tar concrete mixtures investigated. Change in mineral filler content affected the stability values for all the temperature combinations investigated.

•ALTHOUGH the importance of maintaining proper viscosity in tar during both mixing and compacting operations of hot-mix tar concrete pavements is recognized, there have been insufficient data available on which to base qualitative control. This investigation

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TABLE 1

MIXING AND COMPACTING VISCOSITIES (TEMPERATURES)

Mixing Temp. (deg F)	Mixing Viscosity (cs)[a]	Compacting Temperature (deg F)				
		230	210	190	170	150
250	68	X	X	X	X	X
230	78		X	X	X	X
210	165			X	X	X
190	413				X	X
170	1, 282					X
		78	165	413	1, 282	4, 472
		Compacting Viscosity (cs)				

[a]Centistokes.

TABLE 2

VISCOSITY OF TAR BY VACUUM CAPILLARY VISCOMETER METHOD

Test Temp. (deg F)	Capillary Tube No.	Diam. Tube (cm)	Vacuum (cm hg)	Time (sec)	Viscosity (poises)	Avg. Viscosity (poises)
130	2	0. 1004	60	69. 50	307. 866	299. 325
	4	0. 0987	60	68. 00	290. 518	
	3	0. 0994	60	69. 00	299. 593	
150	2	0. 1004	20	37. 50	54. 242	54. 129
	3	0. 0994	20	37. 00	52. 458	
	2	0. 1004	20	38. 50	55. 688	
170	3	0. 0994	10	22. 50	15. 453	15. 445
	4	0. 0987	10	22. 20	15. 002	
	4	0. 0987	10	23. 50	15. 881	
190	4	0. 0987	5	16. 00	5. 058	4. 954
	2	0. 1004	5	14. 00	4. 589	
	4	0. 0987	5	16. 50	5. 216	
210	3	0. 0994	5	6. 00	1. 920	1. 969
	1	0. 1141	5	5. 00	2. 115	
	3	0. 0994	5	5. 80	1. 865	
230	2	0. 1004	2	8. 80	0. 924	0. 931
	3	0. 0994	2	9. 20	0. 947	
	2	0. 1004	2	8. 80	0. 924	
250	4	0. 0987	2	8. 80	0. 812	0. 810
	1	0. 1141	2	5. 80	0. 787	
	4	0. 0987	2	8. 20	0. 832	

TABLE 3

VACUUM CAPILLARY VISCOMETER TEST—COKE-OVEN TAR RT-12 GRADE

Test Temp. (deg F)	Absolute Viscosity (poises) a	Specific Gravity b	Kinematic Viscosity (stokes) a/b = c	Kinematic Viscosity (cs) cs x 100
130	299. 325[a]	1. 2164	246. 07	24607
150	54. 129	1. 2104	44. 72	4472
170	15. 445	1. 2044	12. 82	1282
190	4. 954	1. 1984	4. 13	413
210	1. 969	1. 1924	1. 65	165
230	0. 931	1. 1864	0. 78	78
250	0. 810	1. 1804	0. 68	68

[a]Average of three determinations

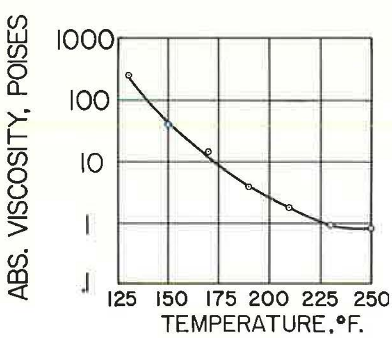

Figure 1. Viscosity-temperature relationship for coke-oven tar of RT-12 grade.

was planned to obtain detailed information concerning effects of variations in the mixing and compacting viscosities of tar on the physical properties of tar concrete, by means of the Marshall stability test.

The following purposes were covered:

1. To establish the temperature-viscosity relationship of tar in its complete temperature range for preparing the laboratory-mixed specimens of tar concrete.
2. To study the effects of mixing viscosity and compacting viscosity on the physical properties of tar concrete mixtures.
3. To determine the effects of filler-tar ratio on the foregoing results.
4. To establish optimum mixing viscosity and optimum compacting viscosity for the tar concrete mixtures investigated.
5. To compare the ASTM designation D1559-62T mixing and compacting viscosities with the optimum values obtained in this investigation.
6. To compare the results obtained for tar concrete with those for asphaltic-concrete.

The experimental work consisted of the mixing, compacting, the testing of specimens of tar concrete using the Marshall test apparatus. The mixing was done at 20-F increments through a 170- to 250-F range. Both tar and aggregate were heated to the same mixing temperature. Five different compaction temperatures at 20-F increments were chosen between 150 and 230 F. The compaction temperature varied from a minimum of 150 F to a peak value 20 F below the corresponding mixing temperature. The X marks (Table 1) indicate the combinations of mixing viscosities and compacting viscosities at which Marshall specimens of tar concrete were molded.

The viscosity-temperature relationship of the tar was established, and each of the mixing and compaction temperatures was related to the tar viscosity. Six specimens were molded at each of the combinations of mixing and compaction temperatures. Two filler-tar ratios were used with the same tar content.

SELECTION OF MATERIALS

Aggregates

Pit-run crushed gravel and sand from Brown Pit, Baraboo, Wis., were used. They consisted of a mixture of dolomite and igneous material. The apparent specific gravity and percentage water absorption of the material retained on No. 4 sieve were 2.713 and 1.730; for materials passing No. 4 sieve, these values were 2.730 and 1.120.

Limestone dust was used as mineral filler. It has a specific gravity of 2.823 and 80.2 percent passed No. 200 sieve. Calculated percentages of mineral filler correspond to material passing No. 200 sieve.

Bituminous Material

The bituminous material was a straight-distilled coke-oven tar of RT-12 grade; at 77 F it had a specific gravity of 1.235. The solubility in carbon disulfide determined according to ASTM method D4-52 was 88.6 percent. A vacuum capillary viscometer was employed to obtain the absolute viscosity values in the range of 130 to 250 F. Original viscosity data are given in Table 2. Kinematic viscosity values were calculated by dividing absolute viscosity in poises by specific gravity values for each temperature (Table 3). The relationship of absolute viscosity to temperature is plotted in Figure 1. The viscosity value of the tar at 77 F was determined by sliding plate microviscometer to be 2.225×10^5 poises at FS = 1,000 ergs/sec/cu cm.

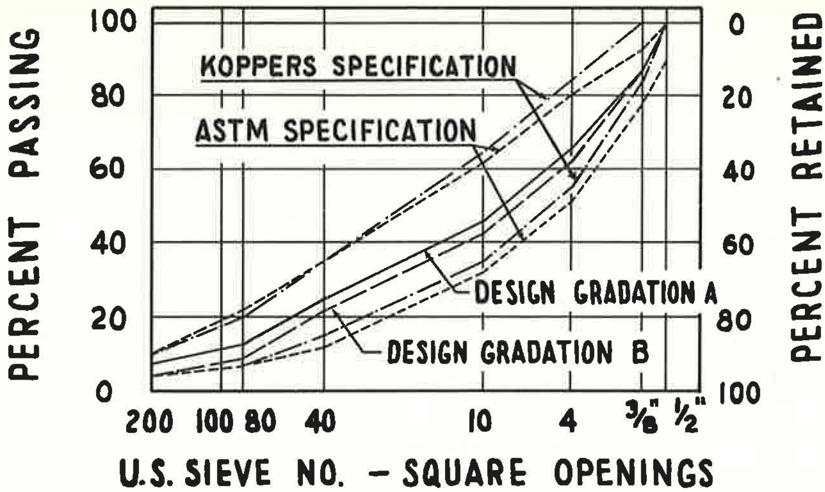

Figure 2. Aggregate gradation curves for tar concrete mixtures.

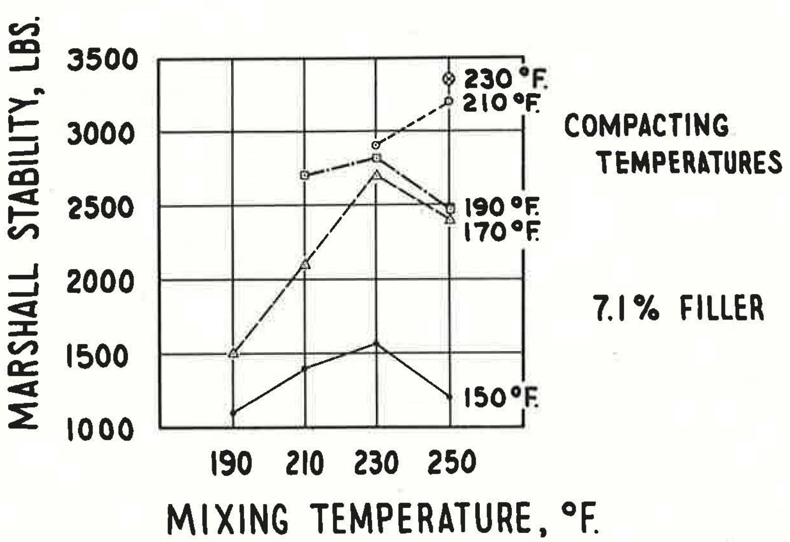

Figure 3. Effects of mixing temperature on Marshall stability of tar concrete.

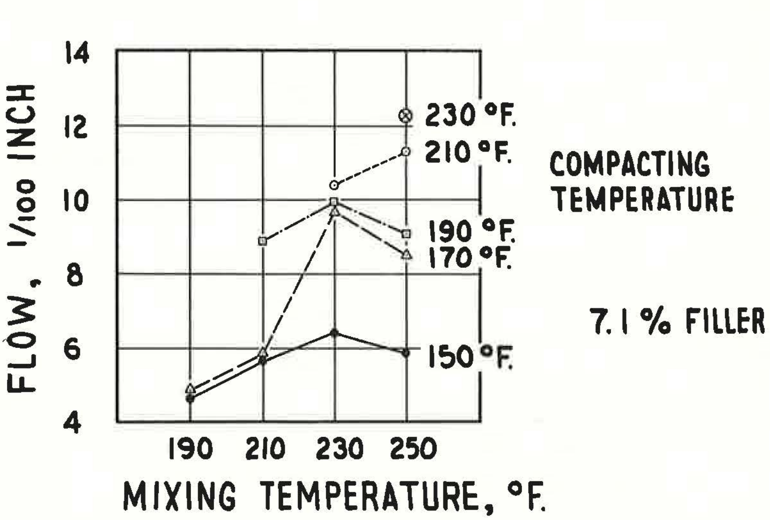

Figure 4. Effects of mixing temperature on flow.

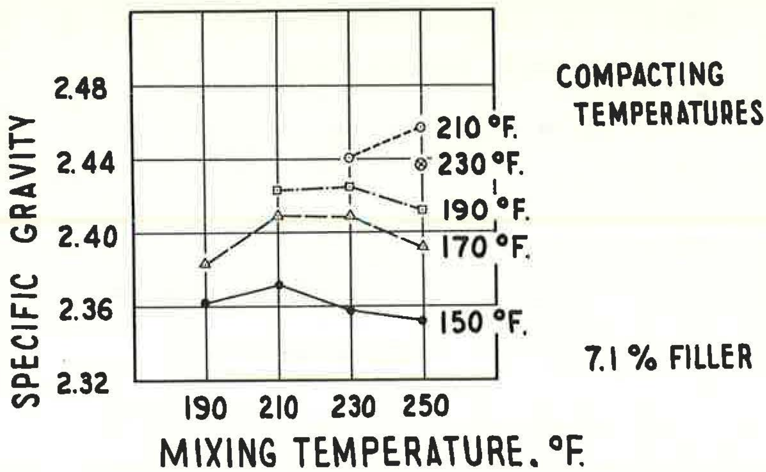

Figure 5. Effects of mixing temperature on specific gravity of tar concrete.

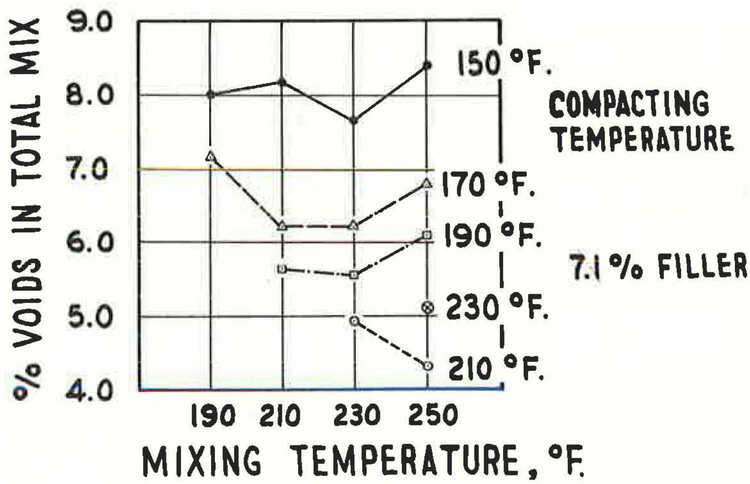

Figure 6. Effects of mixing temperature on percentage of voids in total mix.

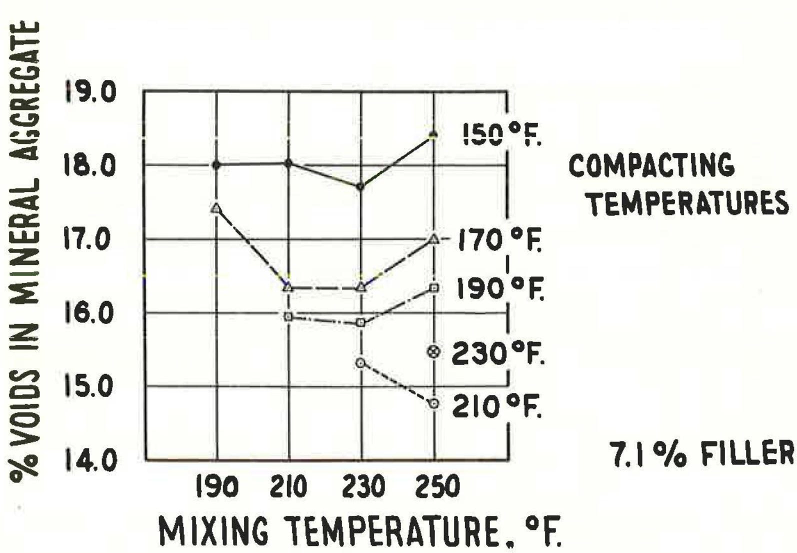

Figure 7. Effects of mixing temperature on percentage of voids in mineral aggregate.

PAVING MIXTURE

The aggregate gradation curves are shown in Figure 2. Two designed gradations, A and B, were investigated: A, a gradation with 7.10 percent mineral filler passing No. 200 sieve by weight of total mix and B, one with 3.75 percent mineral filler. A tar content of 5.25 percent by weight of the total mixture was obtained in designing the proportions of the A mixture by selecting the percentage corresponding to the peak of the Marshall stability curve for different tar contents. The same tar content was used for the B mixture. The filler-tar ratios were 1.352 and 0.714 by weight for mixtures A and B, respectively, and 0.59 and 0.31 by volume.

PREPARATION OF MARSHALL SPECIMENS

The method of mixing, molding, and testing Marshall specimens conformed in general to ASTM method of test, designation D1559-62T, except for variations in mixing viscosity and compacting viscosity and except that a compaction machine was used in place of hand compaction. Careful attention was paid to mixing and compacting temperatures in molding these specimens. No reheating of the mix was done after mixing. The standard test temperature of 100 F was carefully controlled.

EFFECTS OF MIXING VISCOSITY ON MIXTURES CONTAINING 7.1 PERCENT MINERAL FILLER

Stability

Figure 3 shows the relationship of mixing temperature to stability. High values of Marshall stability were obtained for mixing temperature of 250 F with compacting temperatures of 230 and 210 F. For the compacting temperatures of 150, 170, and 190 F, there is an optimum mixing temperature of 230 F. Mixing at 230 F gives stability values of 2,822 and 2,846 lb for compacting temperatures of 190 and 210 F, respectively. Also, the combination of 210 F mixing temperature with 190 F compacting temperature gives a good value of stability, i.e., 2,712 lb.

At the lower mixing temperatures, the tar binder is not fluid enough to coat the aggregates to provide sufficient interlocking; consequently, the resulting mixtures have low stability values. As the fluidity of the tar binder is increased by raising the mixing temperature, the physical binding of the tar improves. When the fluidity of the tar binder becomes sufficient to provide an intimate coating and uniform dispersion of materials, relatively high stability values are obtained.

The tar may be damaged by overheating at very high mixing temperatures. To determine the effects of employing a very high mixing temperature, the mixing temperature of 250 F was investigated; however, it is considered to be too high a mixing temperature from the standpoint of practical paving plant operation.

From the foregoing discussion, it follows that proper control over the mixing viscosity and compacting viscosity should be exercised for tar concrete. The tar should be at proper viscosity (or fluidity) at the time of mixing to promote intimate mixing and coating (not lubricating) and proper dispersion of materials. Besides this, the viscosity of the contained tar 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.

Flow. Figure 4 shows the relationship between mixing temperature and flow.

Specific Gravity. A plot of mixing temperature vs specific gravity is shown in Figure 5. For a compacting temperature of 190 F, the highest value of specific gravity is obtained at a mixing temperature of 230 F; approximately the same value of the specific gravity is obtained at a temperature combination of 210 F and 190 F mixing and compacting temperatures, respectively.

Voids in Total Mix. Figure 6 shows a plot of mixing temperature vs voids in total mix.

Voids in Mineral Aggregate. Figure 7 shows the effect of mixing temperature on voids in mineral aggregate.

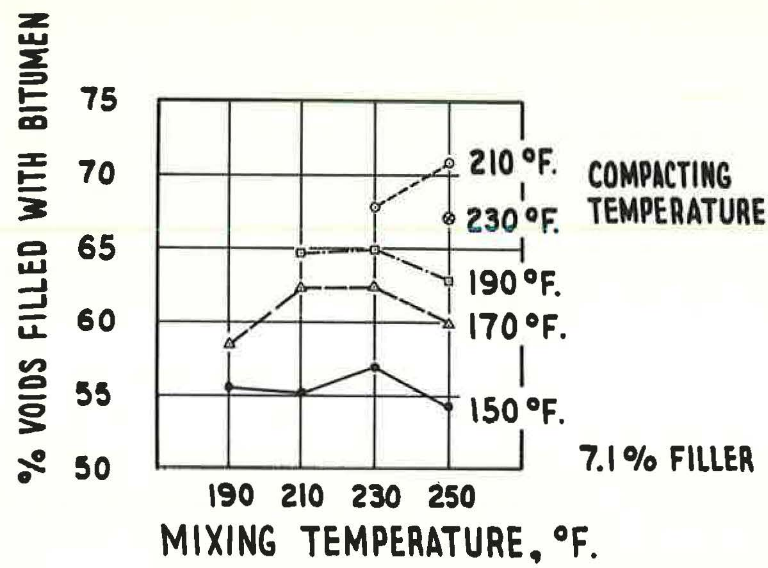

Figure 8. Effects of mixing temperature on percentage of voids filled with bitumen.

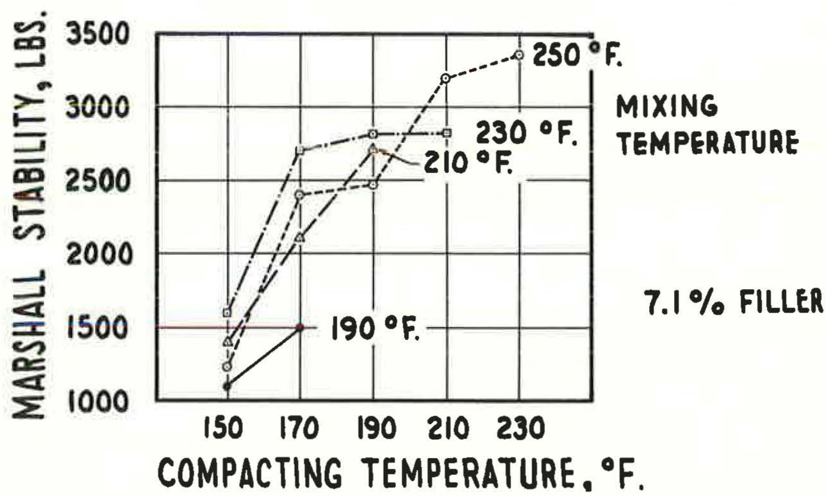

Figure 9. Effects of compacting temperature on Marshall stability of tar concrete.

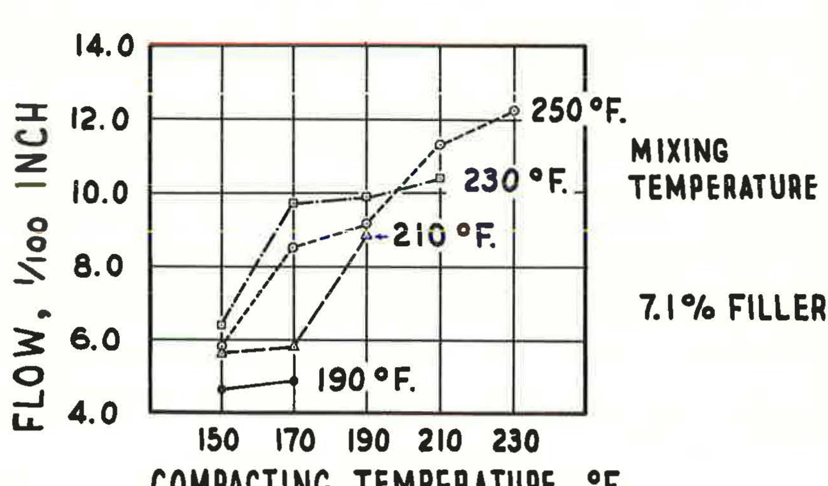

Figure 10. Effects of compacting temperature on flow.

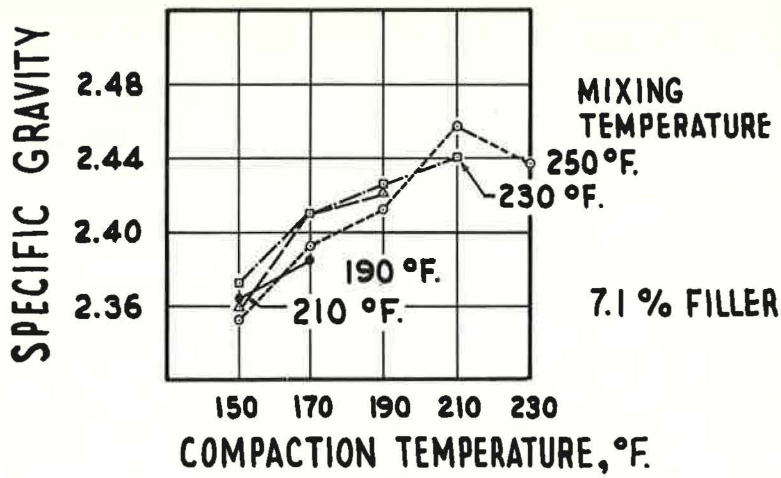

Figure 11. Effects of compacting temperature on specific gravity of tar concrete.

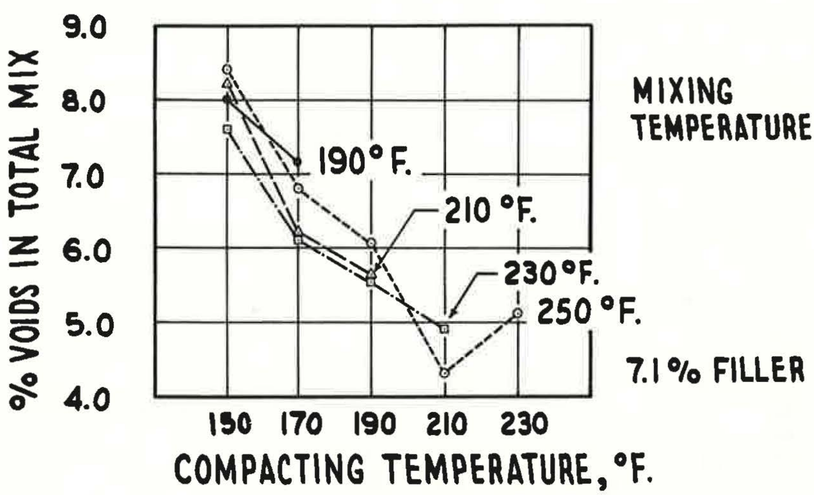

Figure 12. Effects of compacting temperature on percentage of voids in total mix.

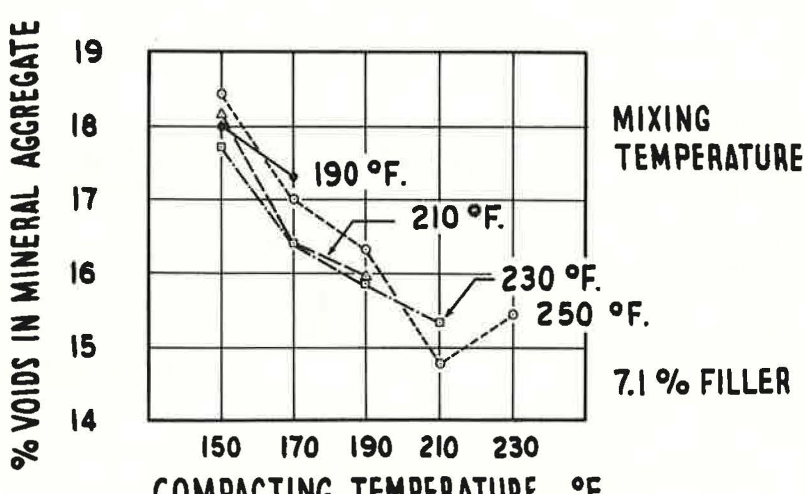

Figure 13. Effects of compacting temperature on percentage of voids in mineral aggregates.

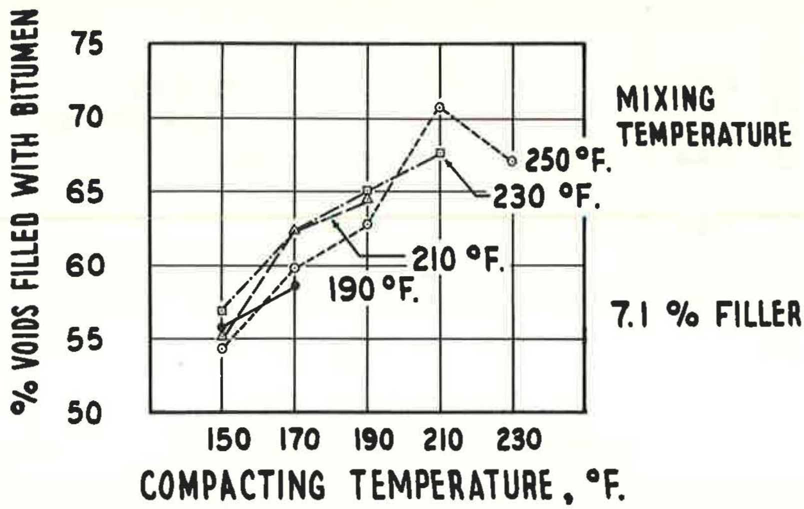

Figure 14. Effects of compacting temperature on percentage of voids filled with bitumen.

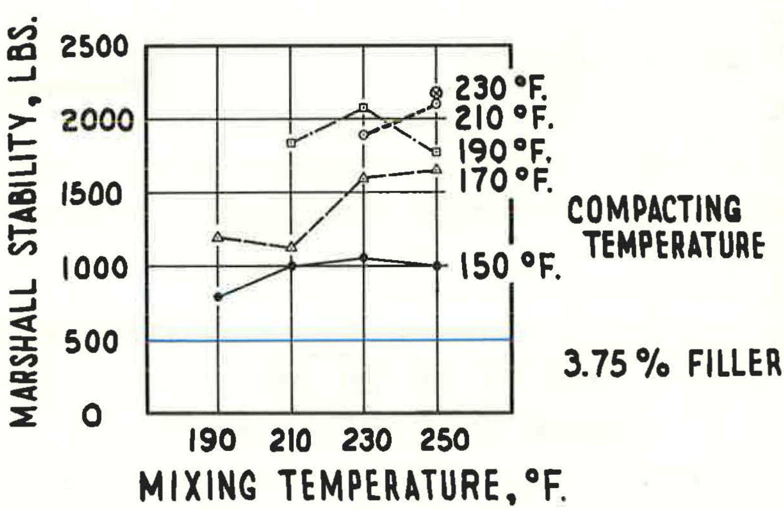

Figure 15. Effects of mixing temperature on Marshall stability of tar concrete.

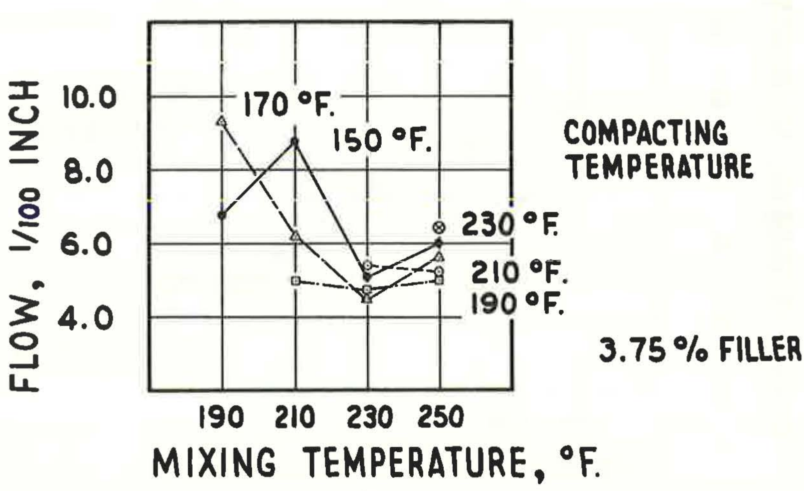

Figure 16. Effects of mixing temperature on flow.

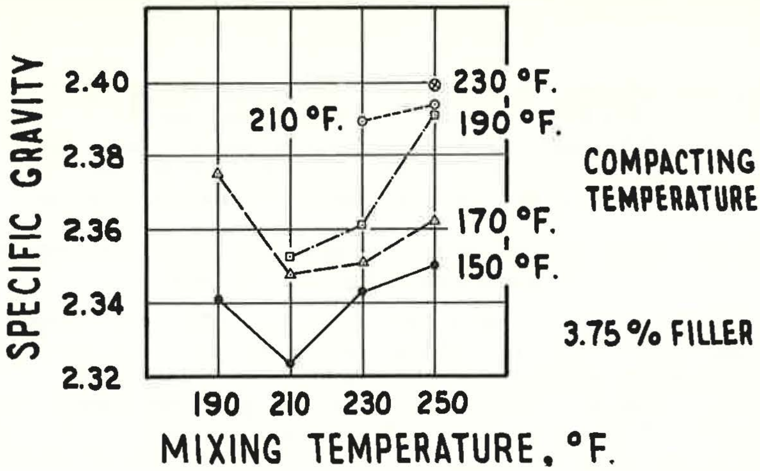

Figure 17. Effects of mixing temperature on specific gravity of tar concrete.

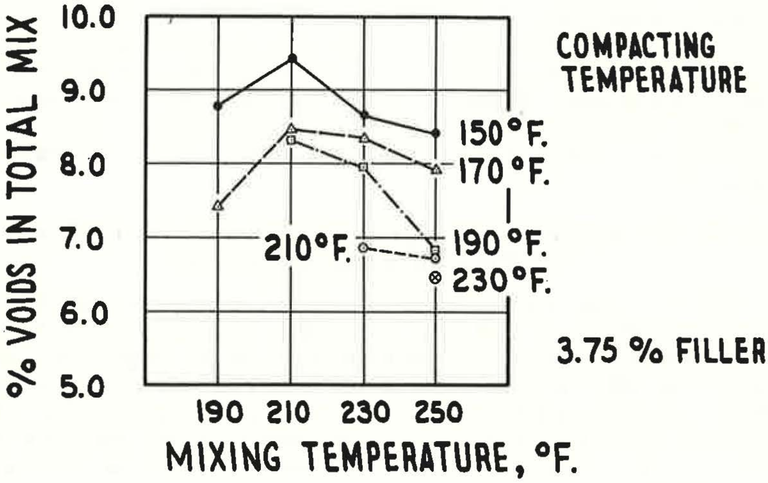

Figure 18. Effects of mixing temperature on percentage of voids in total mix.

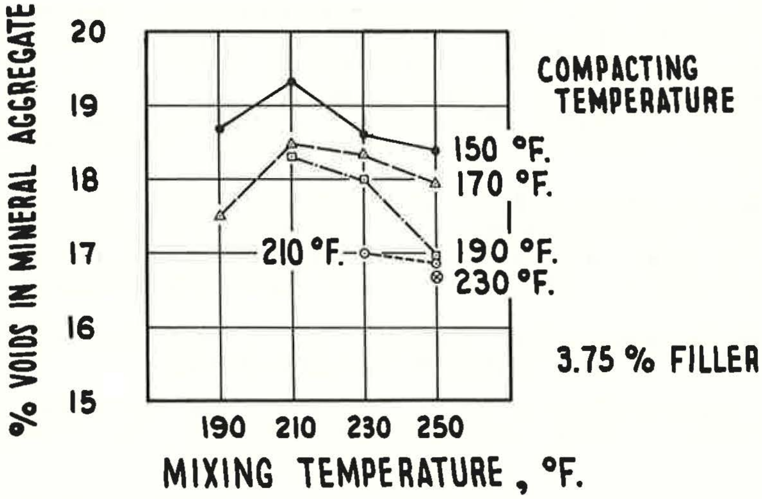

Figure 19. Effects of mixing temperature on percentage of voids in mineral aggregates.

Voids Filled with Bitumen. Figure 8 shows the relationship between mixing temperature and voids filled with bitumen (tar). The term "voids filled with bitumen" as employed in the original Marshall test development data has been used in this report, the term "bitumen" was intended to mean "bituminous material" or "tar" and no correction was made for the test value of 88.6 percent solubility in carbon disulfide.

EFFECTS OF COMPACTING TEMPERATURE ON MIXTURE CONTAINING 7.10 PERCENT MINERAL FILLER

Stability. Figure 9 shows the same data as Figure 3 plotted with compacting temperature as abscissa against Marshall stability. There is an increase in the stability values as the compacting temperature is increased from 150 to 230 F.

Flow. Figure 10 shows the relationship between compacting temperature and flow.

Specific Gravity. A plot of compacting temperature vs specific gravity is shown in Figure 11. With one exception, specific gravity values increase with increases in compacting temperatures.

Voids in Total Mix. Figure 12 shows the plot of compacting temperature vs percentage of voids in total mix. With one exception, the values of percent voids in total mix decrease as the compacting temperature is increased.

Voids in Mineral Aggregate. Figure 13 shows a plot of compacting temperature vs percentage of voids in mineral aggregate. With one exception, the percentage of voids in mineral aggregate decreases as the compaction temperature is increased.

Voids Filled with Bitumen. Figure 14 shows the relationship between compacting temperature and the percentage of voids filled with bitumen (tar). With one exception, the trend is that the percentage of voids filled with bitumen (tar) increases as the compacting temperature is increased.

EFFECTS OF MIXING TEMPERATURE ON MIXTURE CONTAINING 3.75 PERCENT MINERAL FILLER

Stability. Figure 15 shows a plot of mixing temperature vs Marshall stability for 3.75 percent mineral filler. A high value of stability was obtained for the mixing temperature of 230 F and the compaction temperature of 190 F. High values of stability were also obtained at 230 F mixing temperature and 210 F compacting temperature as well as at 210 F mixing temperature and 190 F compacting temperature. The very high mixing temperature 250 F with compacting temperatures of 230 and 210 F gave high stability values, but this mixing temperature is considered too high from a practical paving plant standpoint.

Flow. Figure 16 shows the relationship between mixing temperature and flow.

Specific Gravity. Figure 17 shows the relationship between mixing temperature and specific gravity. For all compacting temperatures the specific gravity values increased as the mixing temperature was raised from 210 to 250 F.

Voids in Total Mix. Figure 18 shows the relationship between mixing temperature and the percentage of voids in total mix for 3.75 percent mineral filler. For all compacting temperatures the percentage of voids in total mix decreases in value as the mixing temperature is increased from 210 to 250 F.

Voids in Mineral Aggregate. Figure 19 shows the relationship between mixing temperature and the percentage of voids in mineral aggregate. The trends are the same as in Figure 18.

Voids Filled with Bitumen. Figure 20 shows the relationship between mixing temperature and voids filled with bitumen (tar). The values of the percentage of voids filled with bitumen (tar) increase as the mixing temperature is increased for all mixing temperatures ranging from 210 to 250 F for all compacting temperatures.

EFFECTS OF COMPACTING TEMPERATURE ON MIXTURE CONTAINING 3.75 PERCENT MINERAL FILLER

Stability. Figure 21 shows the plot for compacting temperature against Marshall stability. With one exception, the trend is that the stability values increase as the

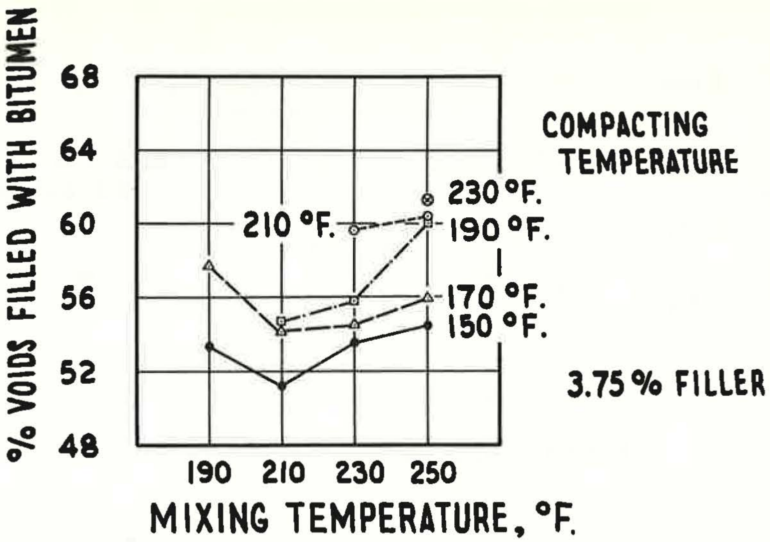

Figure 20. Effects of mixing temperature on percentage of voids filled with bitumen.

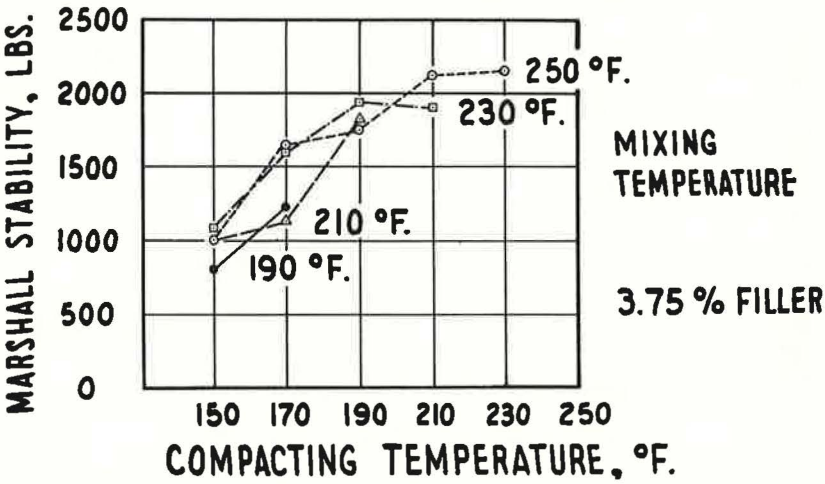

Figure 21. Effects of compacting temperature on Marshall stability of tar concrete.

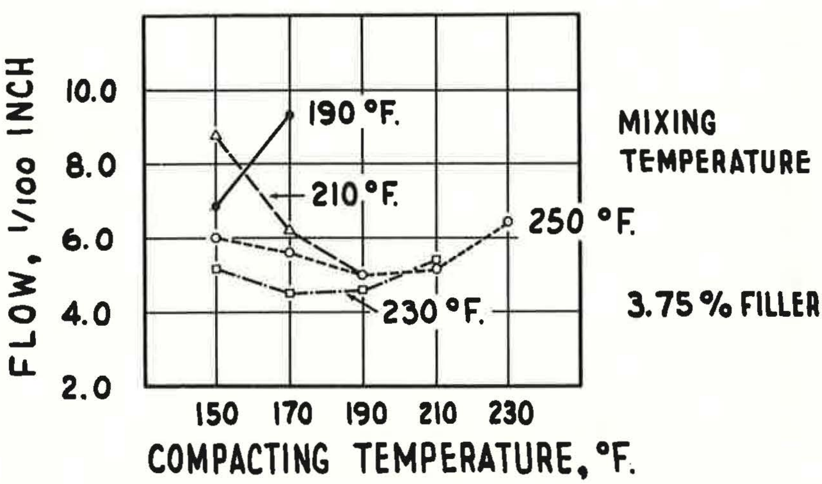

Figure 22. Effects of compacting temperature on flow.

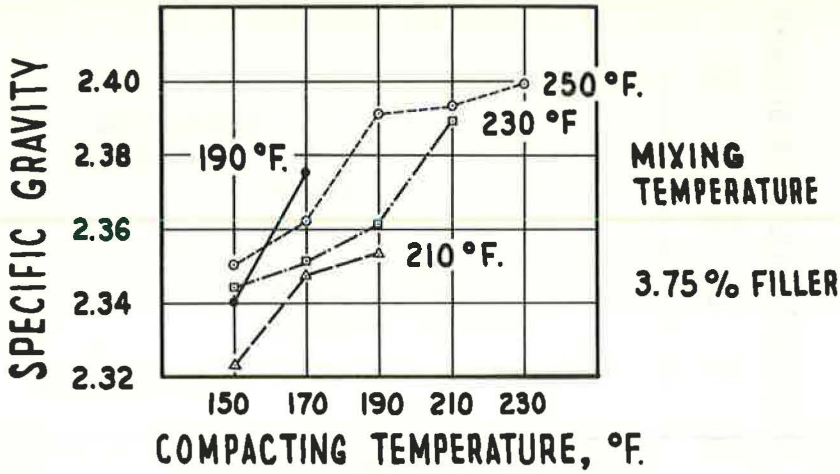

Figure 23. Effects of compacting temperature on specific gravity of tar concrete.

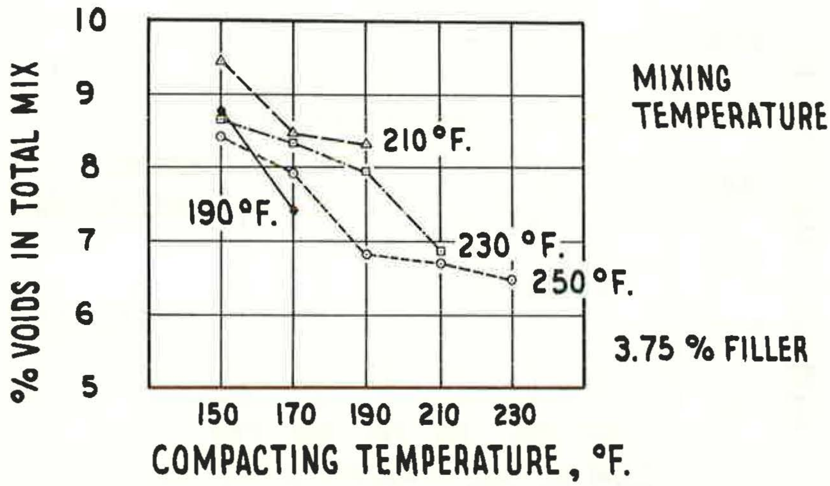

Figure 24. Effects of compacting temperature on percentage of voids in total mix.

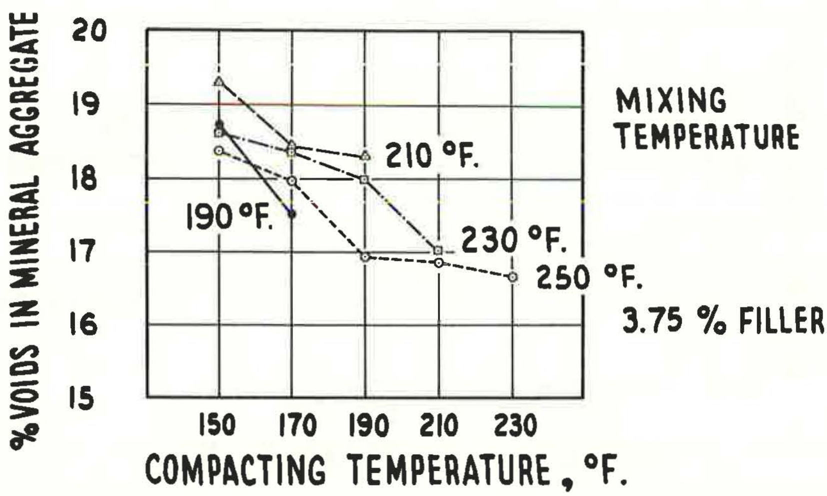

Figure 25. Effects of compacting temperature on percentage of voids in mineral aggregate.

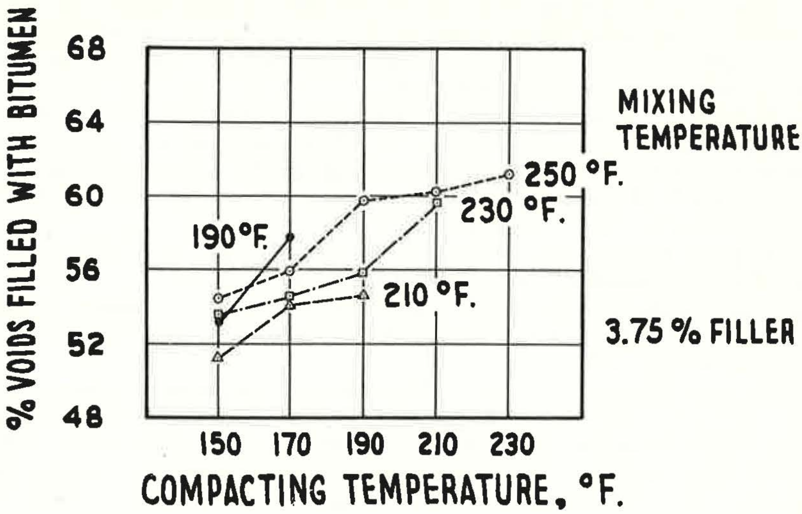

Figure 26. Effects of compacting temperature on percentage of voids filled with bitumen.

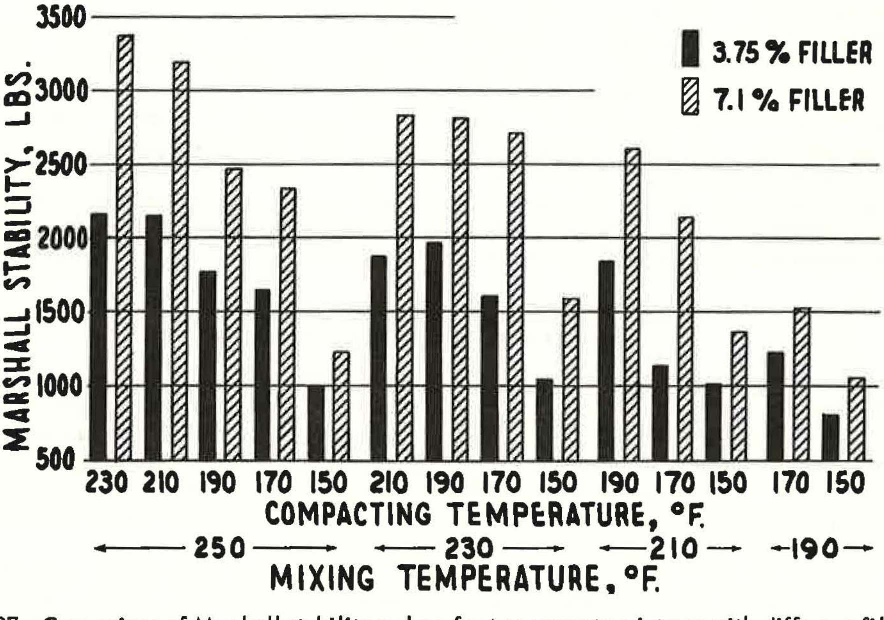

Figure 27. Comparison of Marshall stability values for tar concrete mixtures with different filler contents for different mixing and compacting temperatures.

compacting temperature is increased. This is true for all mixing temperatures. For the mixing temperature of 230 F, a high value of stability is obtained at 190 F compacting temperature.

Flow. Figure 22 shows the relationship between compacting temperature and flow. Flow values for 190 and 210 F compacting temperatures are lower for 3.75 percent than for 7.10 percent filler content specimens (Fig. 10).

Specific Gravity. Figure 23 plots compacting temperature vs specific gravity. In all cases, the values of specific gravity increase as the compacting temperature is

increased. The specific gravity is 2.389 for the mixing temperature of 230 F in combination with the compacting temperature of 210 F. Figure 11 shows that the specific gravity values are lower for 3.75 percent filler than for 7.10 percent filler content specimens for all temperature combinations.

Voids in Total Mix. Figure 24 plots compacting temperature and voids in total mix. For all mixing temperatures, the values of voids in total mix are decreased as the compacting temperature is increased. The voids in total mix are higher for 3.75 percent filler than for 7.10 percent filler content specimens (Fig. 12). This means that the increased amount of filler material has acted to fill up the voids in the mixture.

Voids in Mineral Aggregates. Figure 25 shows the effect of compacting temperature on voids in mineral aggregate. The percentage of voids decreases as the compacting temperature is increased from 150 to 230 F for all values of mixing temperature. The voids in mineral aggregate are higher for 3.75 percent filler than for 7.10 filler content specimens (Fig. 13).

Voids Filled with Bitumen. Figure 26 shows the relationship between compacting temperature and voids filled with bitumen (tar). The values of percent voids filled with bitumen (tar) increase as the compacting temperature is increased from 150 to 230 F for all mixing temperatures. The percentage of voids filled with bitumen (tar) is less for 3.75 percent filler than for 7.10 percent filler content specimens (Fig. 14).

EFFECTS OF FILLER-TAR RATIO

As previously discussed, the effects of mixing and compacting temperatures on the properties of tar concrete were studied with two mineral filler contents, keeping the tar content of 5.25 percent by weight of total mix the same.

Stability. Figure 27 shows the stability values for the two mineral filler contents. Specimens with a filler content of 7.10 percent show an increase in stability values for all the temperature combinations of mixing and compacting temperatures as compared to the specimens containing a filler content of 3.75 percent. Except for one temperature combination, i.e., 230 F mixing temperature with 190 F compacting temperature for the mixture containing 3.75 percent mineral filler, there is a decrease in stability values for each of the mixing temperatures as the compacting temperature is lowered. Generally speaking, this pattern of decrease in stability values is about the same for both the mixtures containing 3.75 percent and 7.10 percent mineral filler contents.

DETERMINATION OF OPTIMUM VALUES FOR MIXING AND COMPACTING VISCOSITY

One of the main objectives of this project was to determine the optimum mixing viscosity and the optimum compacting viscosity for the type of tar concrete investigated. The mixing temperature of 250 F is considered too high for paving plant operation owing to the danger of overheating the tar. A temperature combination of 230 F mixing temperature (viscosity 78 cs) with 190 F compacting temperature (viscosity 413 cs) is good; also satisfactory is 210 F mixing temperature (viscosity 165 cs) with 190 F compacting temperature for 3.75 percent filler.

For the tar concrete mixture containing the comparatively high filler content of 7.10 percent, 230 F mixing temperature (viscosity 78 cs) with the 210 F compacting temperature (viscosity 165 cs) gives the highest stability value of 2,846 lb (Fig. 27). A temperature combination of 230 F mixing temperature (viscosity 78 cs) with 190 F compacting temperature (viscosity 413 cs) gives a stability very close to the foregoing. However, a temperature combination of 210 F mixing temperature (viscosity 165 cs) with 190 F compacting temperature (viscosity 413 cs) gives a high stability value and may be preferable from a practical paving plant standpoint. These all give satisfactory values of flow, specific gravity, and voids. The foregoing optimum values are summarized in Table 4.

COMPARISON WITH ASTM REQUIREMENTS

ASTM designation D1559-62T (1) recommends the mixing viscosity and compacting viscosity of 25 ± 3 and 40 ± 5, respectively, in terms of Engler specific viscosity.

TABLE 4

OPTIMUM MIXING AND COMPACTING TEMPERATURES COMPARED WITH ASTM REQUIREMENTS

Filler Content (%)	Optimum Values		ASTM D1559-62T	
	Mixing Temp. (deg F)	Compacting Temp. (deg F)	Mixing Temp. (deg F)	Compacting Temp. (deg F)
3.75	210-230 (165-78 cs)	190 (413 cs)	203-212	190-196
7.10	210-230 (165-78 cs)	190-210 (413-165 cs)	203-212	190-196

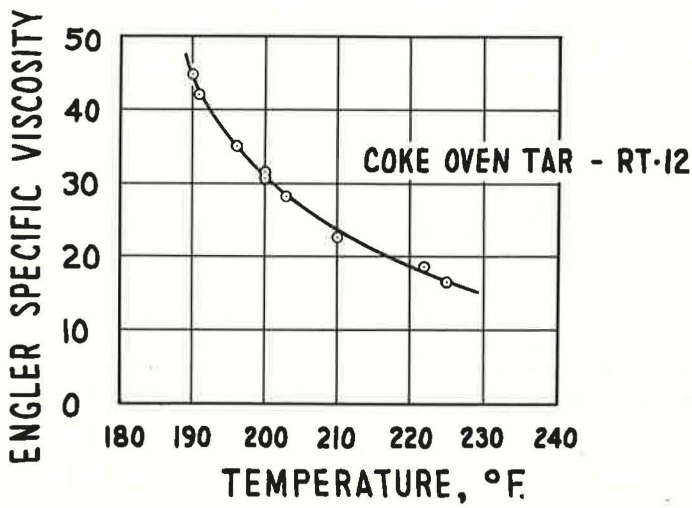

Figure 28. Relationship between temperature and Engler specific viscosity for coke-oven tar of RT-12 grade.

TABLE 5

OPTIMUM MIXING AND COMPACTING TEMPERATURES FOR ASPHALTIC-CONCRETE AND TAR CONCRETE WITH COMPARABLE FILLER CONTENTS

Type of Mixture	Filler Content (%)	Mixing Temperature (deg F)	Compacting Temperature (deg F)
Asphaltic-concrete (2)[a]	8.0	290 (105 SSF)	260 (250 SSF)
Tar concrete	7.10	210-230 (165-78 cs)	190-210 (413-165 cs)

[a]85-100 grade AC.

Figure 28 is a plot of Engler specific viscosity values vs temperatures in degrees F. The corresponding limits of mixing temperature and compacting temperature for the coke-oven tar of RT-12 grade according to ASTM requirements are 212 to 203 F and 196 to 190 F, respectively. These temperatures are compared with the temperatures obtained in this investigation corresponding to optimum viscosity values (Table 4). The results obtained in this investigation agree favorably with the requirements given in ASTM designation D1559-62T for the Marshall test.

COMPARISON OF RESULTS FOR TAR CONCRETE VS ASPHALTIC-CONCRETE

This study was an extension of the research project by Gandharv R. Bahri and Lloyd F. Rader (2). The type and gradation of the aggregates and mineral filler were similar in the two investigations. The asphalt content was 4.75 percent by weight. The asphalt binder was more viscous than the tar binder. At 77 F, the asphalt binder had a viscosity of 1.212 times 10^6 poises compared to 2.2225 times 10^5 poises for the tar binder. The corresponding temperatures for the values of optimum mixing viscosity and optimum compacting viscosity for asphaltic-concrete mixtures are higher than those for the tar concrete mixtures. The respective values for comparable filler contents are given in Table 5.

RECOMMENDATIONS

1. Selection of mixing viscosity and compacting viscosity values of tar for molding tar concrete specimens should be based on optimum conditions consistent with practical paving plant and construction operation requirements for the production of durable pavements.
2. Control of the mixing viscosity and the compacting viscosity of tar in the heating and mixing of materials and molding of tar concrete specimens for the Marshall stability test should be required in order to obtain consistent and significant values of physical properties of tar concrete mixtures.
3. The filler-tar ratio should be considered in designing tar concrete mixtures.
4. Use of kinematic viscosity values should be recommended instead of Engler specific viscosity values for establishing mixing and compacting temperatures for tar concrete mixtures in ASTM designation 1559-62T for the Marshall test.

REFERENCES

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4. Bahri, Gandharv Raj. Investigations of Viscous Properties of Bituminous Materials and Mixtures and Bitumen-Filler Mortars. PhD thesis, Univ. of Wisconsin, 1962.
5. Khanna, Sudarshan K. Effects of Viscosity Control of Bituminous Binders on Physical Properties of Bituminous Paving Mixtures. Dept of Civil Eng., Univ. of Wisconsin, 1965.

Discussion

P. B. COWAN, Asphalt Technologist, Standard Oil Co., Ohio—Professor Rader made the comment in his paper that as the fluidity of the tar binder increases with increasing temperature, the physical binding of the tar improves. In point of fact, what is happening is that the viscosity of the tar binder is increasing. This is well documented in Tingle and Wright's paper on the weathering of road tar (J. Appl. Chem., July 10, 1960, pp. 306-312). In this paper it was demonstrated that a tar increased rapidly in viscosity immediately after mixing. Tingle and Wright, in investigating the change in viscosity of a coke-oven tar, indicate that viscosity increases due to mixing are all due to evaporation of volatile matter. Thus the increasing stability of the mix with temperature is evidently due to the hardening of the tar binder. Also, only two specimens fall within the recommended range of 3 to 5 percent voids in the mix. This would indicate a higher tar content is needed. Marshall design is not based on the maximum stability value alone but on a range of controlling values in flow, percent voids, specific gravity, and voids in the mineral aggregate. Maximum stability in a mix is not a controlling factor, provided a minimum value of 500 lb is attained. The flow values with few exceptions are below the minimum values recommended. A flow below 8 is generally considered a brittle mix. I believe that this brittleness is caused by two factors, a low tar content causing a thin film of tar and the extreme temperature sensitivity of tar to hardening. This film thickness is appreciably less with tar than with asphalt because of the difference in specific gravities of the two materials. Hence a greater weight percent of tar would be required in identical mixes for equal voids contents.

Testing tar concrete specimens at 100 F is apparently done to equalize between asphalt and tar viscosities in the original cement. This appears to me to be in error. The selection of 140 F was to duplicate the maximum pavement service temperature. Examination of BPR thin film residues run at 225 F for RT-12 vs BPR TFOT residues of 85-100 penetration asphalts run at 325 F indicates that tar has a higher viscosity at 140 F than 85-100 penetration asphalt cement. In either case there is no valid justification for testing tar concrete at 100 F and asphaltic concrete at 140 F.

I would suggest both materials be run at their maximum service temperature (140 F) as intended in the original Marshall design. I agree with the recommendation that kinematic viscosity values should be used in establishing the optimum mixing and compacting temperatures. However, I suggest the compacting viscosity value should be determined on a TFOT residue for greater accuracy. In addition, the time duration for holding tar concrete samples at these temperatures must be closely controlled to avoid excessive hardening of the tar binder.

P. F. PHELAN, Technical Director, Road Materials, Kopper's Co., Inc., Verona, Pa.—Rader and Khanna are to be commended for this paper which illustrates the importance of viscosity control in the design and construction of bituminous mixtures—in this case, tar concrete. Certainly the control of mixing and compacting viscosities both in laboratory design and actual construction will result in more consistent paving mixtures, and in more uniform physical properties of the tar concrete obtained.

Both mixes A (7.10% filler) and B (3.75% filler) required approximately the same mixing and compacting temperatures for optimum values, as indicated by Marshall stability test results. In both cases the optimum mixing-compacting combinations were approximately 220 F to 190 F, whereas the proper temperatures based on the viscosities suggested in ASTM D-1559 would average a 208 F to 193 F combination. This would appear to be about as close as might practically be expected.

However, the tables indicate that the 250-F mixing, 210-F compacting combination always appeared to give better results, as shown by higher density, increased Marshall stability, lower voids, etc. The authors stated that the tar may be damaged by overheating at very high mixing temperatures. The authors considered 250 F too high from the standpoint of practical paving plant operations. With this I would agree, as tar grade RT-12 (at time of mixing) is usually not in excess of 225 F.

Perhaps this apparent contradiction, i. e., the best mixing-compacting temperature combination being somewhat too high for practical paving plant operations, is due to the fact that the mixes may be somewhat lean in tar content. The aggregate grading used was chosen to conform to the ½-in. (maximum aggregate size) surface course mixture in ASTM D-1753 (specifications for hot-mixed, hot-laid tar paving mixtures). In this specification the suggested range of tar content (by weight of total mixture) is 6-11 percent, with the aggregate containing 4-10 percent passing the No. 200 mesh sieve. Mix A contained 7. 10 percent filler and 5. 25 percent tar. The same percentage of tar was used in Mix B, containing 3. 75 percent filler.

Experience in Wisconsin (Milwaukee area) would indicate that aggregates of this nature with this type of grading would probably use 6. 5 to 7. 0 percent tar, if the mix were not intended to be sealed immediately. Should this somewhat higher (approximately 1. 5 percent additional) tar content have been used, we suspect that the optimum mixing and compacting viscosities (for density) would not have changed much, but that at the higher temperatures (above 225 F) the mix specimens might not have exhibited such apparently favorable Marshall characteristics.

That the mix is somewhat lean is attested to by the fact that Marshall stabilities of 2, 800 (7. 1% filler) and 2, 000 (3. 75% filler) are somewhat higher than normal. It would be interesting to see how these test results would have compared if another tar content, perhaps 6. 75 percent, had been used throughout these tests.

Throughout the paper, Professor Rader and Mr. Khanna referred to bitumen, voids filled with bitumen, etc. It is a small point, but it may be appropriate to point out that actually the term bituminous material or tar should be used to describe such characteristics. It is realized, of course, that the terminology was taken directly from that used in the original Marshall test development data, and that it is generally used throughout the United States.

It is especially interesting to note the authors' final recommendation that kinematic viscosity values should be recommended (or should be used) for establishing optimum mixing and compacting temperatures. This was advocated some 30 years ago by representatives of the Koppers Company, but apparently was not taken seriously at that time. At the present time, an ASTM task force is attempting to develop a dynamic viscosity test method which can be used for all grades of road tar. When such a method is found and adopted, the proper values will be substituted for the present Engler specific viscosity values given in ASTM D-1559.

LLOYD F. RADER, Closure—The discussions by Paul F. Phelan and Philip B. Cowan are sincerely appreciated. Mr. Phelan has taken an active interest in this project by supplying the tar and discussing the paper. He recognizes the importance of viscosity control in the design and control of bituminous mixtures.

Mr. Cowan discusses the increase in viscosity of tar immediately after mixing, stating that the increasing stability of the mix with temperature increase is evidently due to the hardening of the tar binder caused by evaporation of volatile matter. The authors agree with this concept of hardening of tar at high temperatures such as 250 F, and believe that such high mixing temperatures should be avoided. However, at the lower mixing temperatures investigated (see Fig. 3 for 190 F mixing temperature) the viscosity was so high that the tar binder was not fluid enough to coat the aggregates to provide sufficient interlocking; consequently the resulting mixtures had low stability values. Thus it is necessary to increase the fluidity of the tar binder by raising the mixing temperature to get improved physical binding of tar with the aggregates during mixing. At an optimum mixing temperature (Table 4), an intimate coating and uniform dispersion of materials may be achieved which results in relatively high stability values. One should not go much above this optimum mixing temperature because of detrimental hardening of the tar in the resulting paving mixture, as discussed previously.

Both Mr. Phelan and Mr. Cowan suggest that a higher tar content than the 5. 25 percent used in this project would be more in accordance with field practice. The authors

agree that a higher tar content would give greater durability and resistance to cracking. The value of 5.25 percent tar was selected as the percentage corresponding to the peak of the Marshall stability curve for different tar contents for the A mixture containing 7.1 percent filler.

Mr. Phelan suspects that if a somewhat higher tar content had been used, the optimum mixing and compacting viscosities would not have changed much. With this the authors agree. The authors also agree that it would be interesting to see how the test results would compare if a higher tar content had been used.

Mr. Cowan notes that the voids in total mix are rather high and that only two combinations fall within a range of 3 to 5 percent voids in total mix. This matter is related to tar content. However, for the A mixture containing 7.1 percent filler, the optimum combinations of mixing temperature (viscosity) and compacting temperature (viscosity) (Table 4) give lower values of voids in total mix than those obtained for lower mixing temperatures (Figs. 6 and 12). Thus, the data show the importance of proper viscosity control in achieving low percentages of voids in total mix.

Mr. Cowan comments that the flow values with few exceptions are below the minimum values recommended. He also states: "A flow below 8 is generally considered a brittle mix." The authors agree that it is not desirable to have too low a flow value and that it is not desirable to have a brittle mix. However, the data in Figures 4 and 10 for the A mixture containing 7.1 percent filler show that the optimum combinations of mixing temperature and compacting temperature (Table 4) give higher flow values (above 8) than those obtained by using lower mixing temperatures and lower compacting temperatures (below 8 in many cases).

With respect to the testing temperature of 100 F for tar concrete discussed by Mr. Cowan, this is the specified test temperature in ASTM method of test designation D-1559. Mr. Cowan's discussion should be referred to ASTM Committee D-4 on Road and Paving Materials for consideration.

Mr. Phelan is correct that the authors should have used the term "bituminous material" or "tar" instead of the term "bitumen" as for example in Figures 8, 14, 20, and 26 and accompanying discussions.

The authors are glad that both Mr. Phelan and Mr. Cowan agree with the recommendation that kinematic viscosity values should be recommended and used in establishing optimum mixing and compacting temperatures for tar concrete mixtures in ASTM Method of Test Designation D 1559 for the Marshall Test. I wish to thank Mr. Phelan and Mr. Cowan for their discussions.