DETERMINATION OF THE TEMPERATURE FOR MIXING AGGREGATES WITH POLYMER-MODIFIED ASPHALTS

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Abstract

Mixing of aggregates and asphalt has to be done at an appropriately selected temperature. The mixing temperature controls the dryness of the aggregates, the quality of the mixture, the time it takes for the mix to cool down during laying and the ease of compaction during paving. A number of critical factors are to be considered when determining the mixing temperature. For unmodified asphalts, the procedure for determining the adequate mixing temperature is available. This is not the case for polymer-modified asphalts. In case the procedure recommended for unmodified asphalts is extended to polymer-modified asphalts, then unrealistically high mixing temperatures result. In the present work, a procedure is outlined for the determination of temperature for mixing aggregates with polymer-modified asphalts using a thermoplastic-modified asphalt (Novophalt) and a thermoplastic elastomer- modified asphalt (Styrelf) as case study materials.

INTRODUCTION

Aggregates and asphalt are combined in a mixing facility in which all of the constituent materials are heated, proportioned and mixed to produce the desired paving mixture [Epps et al (1991), Roberts et al (1991), Manual (1989)]. The asphalt hot-mix facilities could be of the batch or drum-mix type.

In the batch-type mixing facility, different size fractions of hot aggregate in desired amounts for a mixing batch are dumped into a mixing chamber called the pugmill. In most batch mixing facilities, a twin-shaft pugmill-type mixer is commonly used. When the aggregates are deposited into the pugmill, some dry mixing initially takes place till the weighed amount of asphalt gets added and the wet mixing begins.

The mixing time is carefully controlled so that it is long enough to give a uniform coating of asphalt to all aggregates but short enough to prevent any asphalt film hardening due to exposure to air and heat. There are, of course, set procedures laid down by AASHTO T 195 (ASTM D 2489) to establish the correct mixing time for a particular mix in a facility by observing the percentage of coarse particles that are completely coated with asphalt after the elapse of time. The test involves separating coarse aggregate particles from the mix on a selected sieve size. About 200 to 300 particles are examined under a strong light. Any speck of uncoated aggregate particle visible to the naked eye classifies that particle as uncoated. Usually, 90 to 95 percent coated particles are minimums for base and surface coarse mixes, respectively. The least time needed for the pugmill to achieve these minimums is taken as the most desirable mixing time.

Besides the mixing time, the other factors that govern the mixing efficiency are the speed of the mixer shafts as well as the paddles' arrangement, pitch and condition. The paddle faces can be set in a variety of combination. The

clearance between the paddle tips and the liner is normally maintained at less than half the maximum aggregate diameter. To ensure good uniform mixing, it is also important to fill the mixing chamber to the correct level, neither overfilled nor under filled.

Apart from the batch-type mixing facility, there is also the drum-mixing facility that is used. There is a difference in the method of operation between the two facilities. In the drum-mixing facility, required quantities of aggregate and asphalt enter through a cold-feed system and then the heating and blending are done simultaneously.

The cold aggregates enter the drum at the flame end where they are dried and heated. The aggregates and the heated air both flow in the same direction. As they move through the drum, asphalt is added and the blending with aggregates takes place. There are some variations of the drum-mix facility such as counter flow of heated air and midpoint recycled aggregate entry. Other variations include a change in the angle of inclination of the drum. However, in principle, the mixing process in the drum facility is essentially the same as that described above.

Whether batch mixing or drum mixing or variations of these, one important factor must be considered is the use of the appropriate mixing temperature. The correct temperature for aggregate-asphalt mixing is determined by the requirements for achieving dry aggregates, for good particle coating with asphalt, and for proper laying and compaction of the mixture. Determination of the mixing temperature for polymer-modified asphalts is not a trivial matter. The information available on the determination of mixing temperatures for unmodified asphalts is inadequate and hence there are ongoing efforts [(Bahia and Khatri (1999), Yildirim and Kennedy (1999), Yildirim et al (2000)] to address this issue.

Since the aggregates constitute 90 to 95% by mass (or equivalently, 77 to 87% by volume) of the mix, the temperature of the heated aggregate normally controls the temperature of the asphalt-aggregate mixture because the temperature of the asphalt rapidly adjusts to that of the aggregate when the two are mixed. The aggregate has to be heated to a high enough temperature to ascertain that they are sufficiently dry so that there is no foaming or slumping of the final mixture or other evidence of moisture which may adversely affect placement and service.

The temperature at which the asphalt mixture is produced affects both the ease of compaction and the time it takes for the mix to cool to $85^{o}C$ ($185^{o}F$). It is recommended that the temperature of the mixture immediately after discharge should be as low as can be demonstrated to get a good coating but then it has to be high enough to allow sufficient time for the mix to cool to $85^{o}C$ ($185^{o}F$) and compact with ease.

Basically, higher the temperature of the mix, greater is the fluidity of the asphalt and hence it is easier for the mix to compact. However, there is an upper limit on this temperature so that damage to the asphalt due to accelerated hardening is prevented. For unmodified asphalts, this upper limit on mixing temperature to prevent damage due to

accelerated hardening is indicated to be approximately 150°C (300°F), but certainly not more than 163°C (325°F). The Superpave mix design procedure specifies the mixing temperature based on the binder viscosity of 170±20 cSt measured on a capillary tube viscometer. The capillary tube viscometer has been replaced by the Brookfield viscometer as part of the improvement in the procedure.

Viscosity from the Brookfield viscometer is obtained in centipoise while the capillary viscometer gives kinematic viscosity in centistokes due to the inclusion of the density term. It is possible to convert from one viscosity to the other. In fact, the present practice based on the Superpave mix design procedure is to use the Brookfield viscometer to get data in terms of centipoise and then convert it to centistokes through a correction factor. A chart, which is based on kinematic viscosity data, is then used for determining the mixing temperatures.

It would, of course, be better to convert the existing chart which was developed through capillary viscometry and make it directly valid for Brookfield viscosity data. This can be easily done with some reverse calculations. The conversion equation is

$$\mu = \nu \, (G_b \times CF) \tag{1}$$

where μ is the steady-shear Newtonian viscosity from the rotational viscometer in centipoise, ν is the kinematic viscosity determined from the capillary tube viscometer in centistokes, G_b is the specific gravity of the unmodified asphalt at 25°C, CF is the correction factor defined as follows.
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The correction factor is given by the equation

$$CF = -0.0006(T_{test}) + 1.0135 \tag{2}$$

where T_{test} represents the test temperature. For test temperatures of 165°C and 135°C, the corresponding CF values are 0.9145 and 0.9325. If different values such as 185°C and 110°C are chosen instead, the CF values are 0.90 and 0.95 approximately. When calculations are done, using the conversion equation (1), then a new range is obtained for viscosity of 140-183cP (corresponding to 150-190cSt). The viscosity requirements specified above are, however, not valid for modified binders.

In the case of polymer-modified asphalts, a viscosity level of 140-183 cP is achievable only at high temperatures. At these high temperatures, there is likelihood of binder degradation. If lower temperatures are used, then it is quite likely that the polymer-modified asphalts would show a viscosity that is not constant but dependent on shear rate. If mixing is carried out at such temperatures where the viscosity is shear-dependent, then uniform mixing cannot be assured. This is because, during the entire mixing process, the binder sees a range of shear rates due to the variation

in the coating thickness of the aggregate as the mixing progresses with time. Since the mixing temperature has to be based on only one value of viscosity, it is important to decide which shear-rate value has to be chosen for assessing the viscosity. If an average shear rate value is used, then it is truly not representative of the differences in the viscosities that the mixture witnesses during the mixing process. If the viscosity at the maximum shear rate value is used, then again this value is reached only toward the end of the mixing process when the coating is as thin as it can possibly be. If the viscosity at the minimum shear rate or vanishing shear rate is used, then it is only representative of what happens in the mixing process at the start of the mixing process. Thus, trying to choose a mixing temperature in the range wherein the viscosity of binder shows shear-thinning behavior will not yield accurate results. A safe bet would therefore be to undertake the mixing in the temperature range wherein the binder is Newtonian or at least nearly Newtonian in behavior. By doing so, a great deal of complexity of the situation is alleviated. In the present work, therefore, shear rate independency of the binder viscosity is laid down as one of the constraints under which the mixing temperature is determined.

When dealing with polymer-modified asphalts, there are a number of additional constraints that are to be imposed when making a choice of the mixing temperature. All the critical factors that are to be considered are as follows.

1) The temperature should be high enough to ensure that

  (a) the binder viscosity is as shear-rate independent as possible,

  (b) the binder has good fluidity to provide uniform aggregate coating during mixing

(for unmodified asphalts, a viscosity range of 150-190 cSt or, equivalently, 140-183 cP is considered to be adequate),

  (c) the final mix discharge does not cool to below $85^{o}C$ during laying and compaction.

2) The temperature should be low enough to ensure that

  (a) polymer in the modified binder does not degrade,

  (b) accelerated hardening of the asphalt in the modified binder does not take place due to exposure to heat and air.

3) Most important, the temperature should be appropriate to ensure good quality of mixing.

OBJECTIVES

    The purpose of the present work is to systematically analyze the rheological properties of polymer-modified asphalts (in particular, two different types, which have been chosen for this case study) in order to recommend the correct mixing temperature for these two considered cases. During the study, there is a concerted effort made to lay down a procedure such that it could be generalized as more case studies are undertaken. This would then help in establishing a set of guidelines which could be used for determination of the mixing temperatures for all polymer-modified asphalts.

EXPERIMENTAL DETAILS

Binders

The polymer-modified asphalts chosen as binders for the present work are taken from two categories - (a) a thermoplastic (TP) - modified asphalt and (b) a thermoplastic elastomer (TPE) - modified asphalt. The specific TP - modified asphalt chosen in this study was Novophalt, while the specific TPE - modified asphalt chosen was Styrelf. These were used in the Accelerated Loading Facility (ALF) experiment [Stuart and Izzo (1999)] at the Turner-Fairbank Highway Research Center (TFHRC) of the Federal Highway Administration (FHWA). Some selected details about these polymer-modified asphalts are shown in Table 1.

TABLE 1

Selected Details about the Polymer-modified Asphalts Used

Asphalt ID	Base Asphalt	Modifier Type	Amount	Viscosity @135C, (cP)	@180C, (cP)	Performance Grade
Alf-Novophalt	AC-10	LDPE[+]	6.5%	1872	345	PG 76-22
Alf-Styrelf	AC-20	SBS[++]	6.0%	4270	367	PG 82-22

[+] Low Density Polyethylene

[++] Styrene-Butadiene-Styrene

Novophalt is manufactured by Advanced Asphalt Technologies (AAT), Sterling, VA. The base asphalt used for the ALF Novophalt is AC-10. The asphalt is mixed with a certain amount (probably about 6.5%) of low density polyethylene of an unknown grade as the information is proprietary. The mixing is done in a two-stage high shearing operation. The material is run through a high shear mixer at about 145^0C and then fed back into the mixer and run again to get a better dispersion. The final mixed material is not stabilized and tends to separate if correct handling procedures are not followed.

Styrelf is presently manufactured by Koch Materials, Wichita, KS. The base asphalt used for Styrelf is AC-20. This asphalt is first blown to AC-40 grade and then styrene-butadiene (SB) is added to it. Sulphur is added for the reactions to occur in order to achieve chemical links with asphaltenes and other reactive species in the asphalt.

Design

The process of mixing involves two components (aggregate and binder) and therefore, it is only logical that determination of the mixing temperature should not be based on understanding the rheological behavior of the binder alone. Hence, the experimental design involved a set of rheological characterization at different temperatures for neat

binders and also on binders filled with 30 volume per cent of diabase to assess the mixing behavior of aggregate with binder. The choice of using 30 volume per cent of diabase to prepare the asphalt mastic was based on the fact that the fines passing 200 mesh work out to about 27-28% by volume of the binder in most fully graded aggregate systems.

(a) On the neat binder, viscosity versus shear rate data were obtained from the Brookfield viscometer at seven to eight different temperatures between 115°C and 220°C. At each shear rate, the data points were collected under steady shear condition by allowing a reasonable lapse of time between each value.

(b) Various mixes of aggregate - binder were prepared using the following procedure. Measured quantity (97.98 gms) of binder was heated to a specified temperature for 80 minutes. At the same time, measured quantity (102.52 gms) of diabase (to make 30 volume percent mastic) was also heated to the same specified temperature for 80 minutes. The binder was removed from the oven and stirred for 1 minute at 600 rpm with a mechanical stirrer. Then diabase powder was added to it and it was further stirred for 2 minutes at 600 rpm. The mixture was then poured directly into the Brookfield viscometer for viscosity measurements at a selected temperature of 135°C for Novophalt and 150°C for Styrelf.

   The same procedure was followed exactly for generating a control blank sample without aggregates. 100 gms of binder were heated to the specified temperature for 80 minutes, stirred for (1+2=) 3 minutes and then poured for Brookfield viscosity measurement at 135°C for Novophalt and 150°C for Styrelf.

   Four different samples were prepared using the procedures described in the above two paragraphs. In each case only the temperature of mixing was changed. For Novophalt, the mixing was done at 150°C, 163°C, 180°C and 200°C. On the other hand, for Styrelf, the mixing was done at 163°C, 180°C, 200°C and 220°C.

    The viscosity data, however, was taken on all four mixtures at one single temperature. For Novophalt, this temperature for Brookfield viscosity measurement was 135°C, while for Styrelf, it was chosen to be 150°C. The choice of temperature is not stringent as long as the chosen temperature for viscosity measurement is lower than the temperatures at which the mixes are prepared. In case, the viscosity measurements for Styrelf were done at 135°C rather than at 150°C, the final conclusions would not have been different.

Equipment Used

The Brookfield Viscometer was used for obtaining viscosity versus shear rate data. The particular choice of this equipment was due to its appropriateness for mixing temperature study. During mixing process, the flow occurs in steady shear and not under unsteady dynamic conditions. Further, the temperatures of mixing are always going to be high enough where the elasticity of the material will not be significant. Hence, using the dynamic shear rheometer (DSR) for determining mixing temperatures would be meaningless. One could consider the use of the capillary viscometer but they would be inappropriate for polymer-modified asphalts whose viscosity levels would fall outside

the range of measurements of these devices. Therefore, the Brookfield viscometer becomes the preferred and apt choice for the determination of mixing temperatures.

In the present study, the Brookfield viscometer was used with various spindles (SC4-21, SC4-27 and SC4-34) for generating the data covering a reasonably wide shear rate range. A soak time of 20 minutes was prescribed for all samples. At each shear rate, a sufficient elapse of time was allowed to ensure that the data was at steady shear.

RESULTS AND DISCUSSION

Figure 1 shows the variation of steady shear viscosity with increasing shear rate at different temperatures for the neat (a) Novophalt and (b) Styrelf.
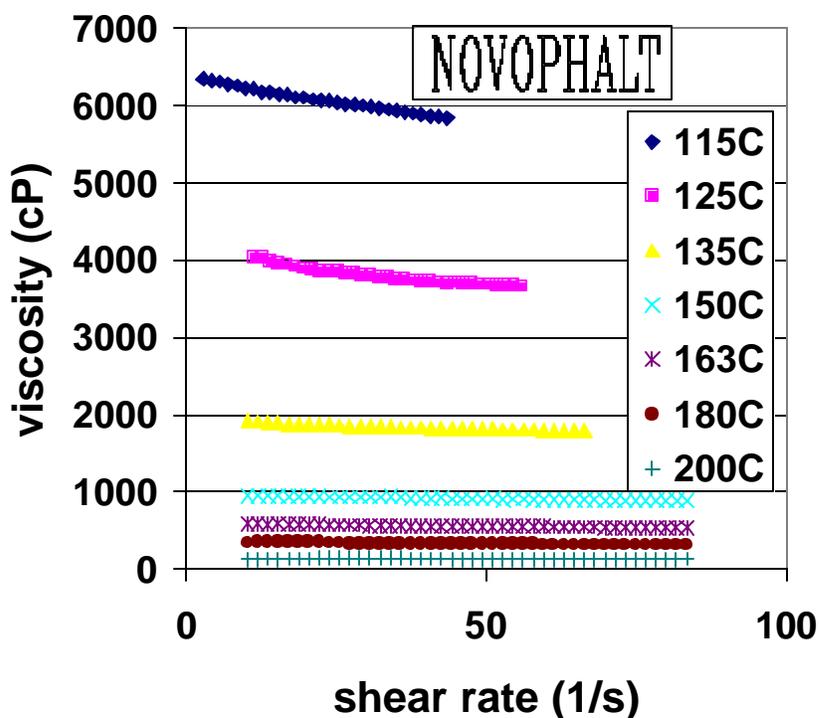
Figure 1 (a): Variation of steady shear viscosity with shear rate for neat Novophalt at various temperatures of 115°C, 125°C, 135°C, 150°C, 163°C, 180°C and 200°C.
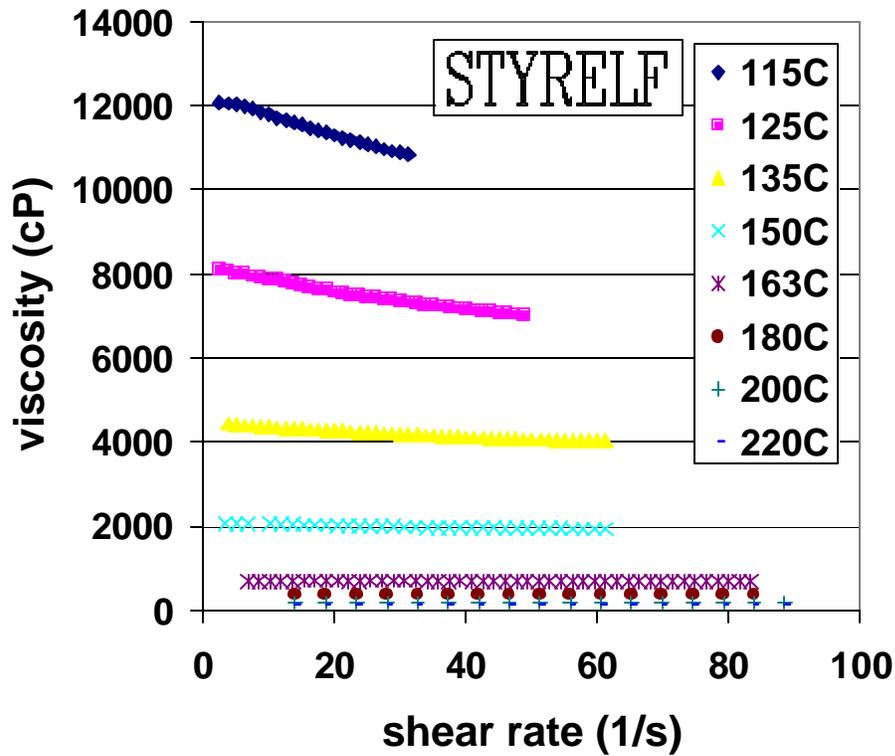
Figure 1 (b) : Variation of steady shear viscosity with shear rate for neat Styrelf at various temperatures of 115°C, 125°C, 135°C, 150°C, 163°C, 180°C, 200°C and 220°C.

It can be seen that, in both cases, the behavior is essentially Newtonian at higher temperatures especially those greater than 150°C. This satisfies criterion 1 (a) and gives us the first bound that the mixing temperature may have to be greater than 150°C. In order to take a closer look at the viscosity values in this temperature range, Figure 2 is plotted showing the variation of viscosity with shear rate for temperatures greater than 150°C for Novophalt and 163°C for Styrelf.
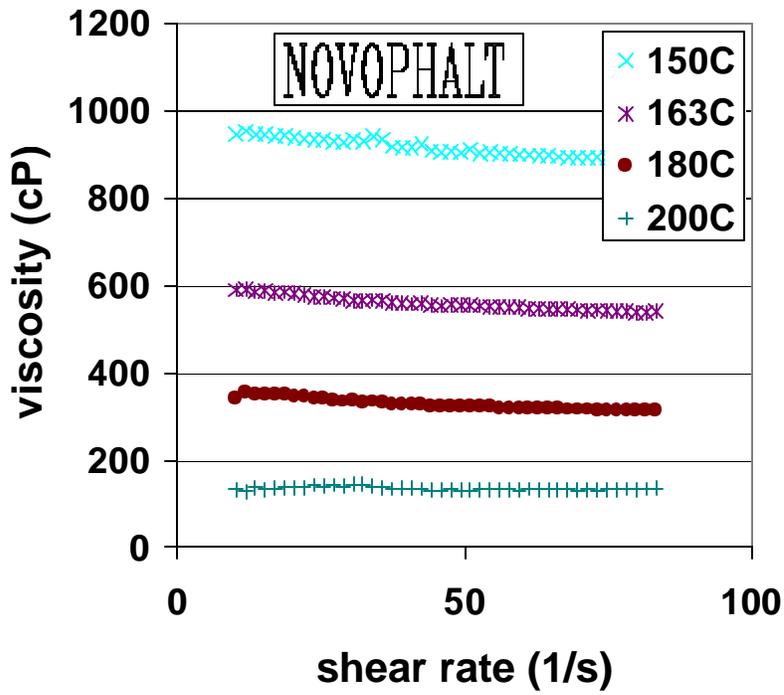
Figure 2 (a): Variation of steady shear viscosity with shear rate for neat Novophalt at four selected temperatures of 150°C, 163°C, 180°C and 200°C.
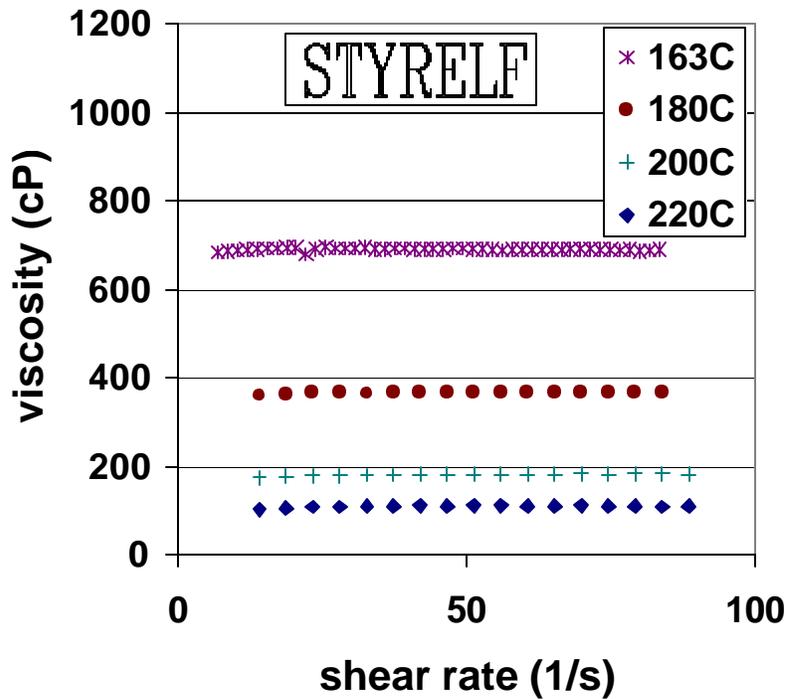
Figure 2 (b): Variation of steady shear viscosity with shear rate for neat Styrelf at four selected temperatures of 163°C, 180°C, 200°C and 220°C.

It can be seen that the temperature of 200°C alone satisfies criterion 1 (b) as it is the only one which shows a viscosity in the range of 140-183 cP which is considered adequate for unmodified asphalts. Moreover, the temperature of 200°C would also satisfy criterion 1 (c) because higher temperature would provide a larger differential for the temperature to cool down to 85°C. In the case of polymer-modified asphalts, though the temperature of 200°C falls in the acceptable range of good fluidity, the temperature may be too high to satisfy other criteria.

Taking the viscosity value at some fixed shear rate (say 20 /s), a plot is prepared to see the changes in viscosity with temperature as shown in Figure 3.
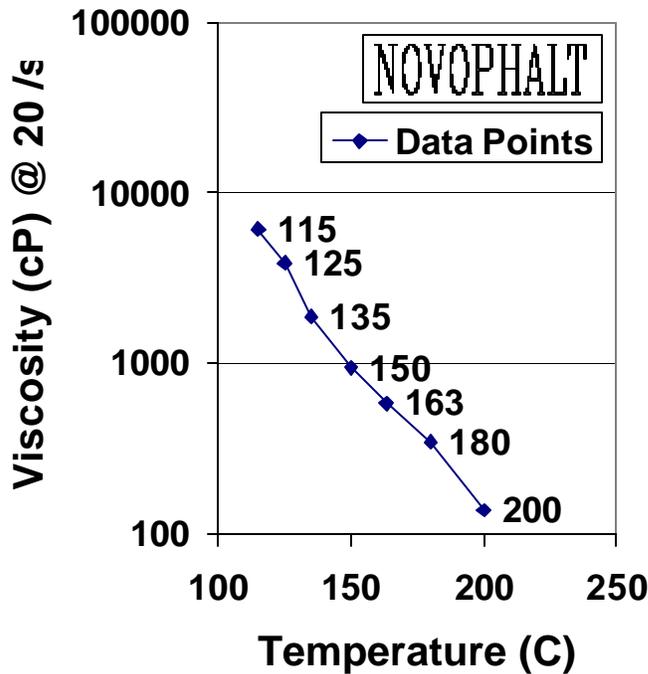

Figure 3 (a) : Variation of steady shear viscosity with temperature for neat Novophalt on an Arrhenius type of plot.

For Novophalt, it can be seen from Figure 3 (a) that there is a distinct change in the slope of the curve in two places. Below the temperature of 135°C, it can be seen that there is a sudden jump in the viscosity and the trend of increased level of viscosity continues from 125°C to 115°C. This sudden jump occurs because the mechanism of flow changes at around 125°C which happens to be the melting point of the polyethylene in the Novophalt. Thus, below that temperature the polyethylene behaves like solid particles in a matrix of fluid asphalt and hence, the mechanism of flow occurs at different activation energies. Again at 180°C, there is a change in the slope of the curve and the viscosity at 200°C shows a much greater drop in viscosity than what would have been if the straight line between

150°C and 180°C was extended. This is because at this temperature, the polymer in the Novophalt is likely to be subjected to degradation [Rokudai (1979), Shenoy et al. (1983), Shenoy and Saini (1996)]. Any thermal degradation would show a greater drop in viscosity than predicted by the straight on the viscosity versus temperature plot. Thus, though criteria 1 (b) and 1 (c) were satisfied by 200°C, it will have to be left out from further consideration because it fails the criterion 2 (a). Thus, the mixing temperature would have to be chosen to be less than 200°C or better still less than 180°C to be on the safer side.
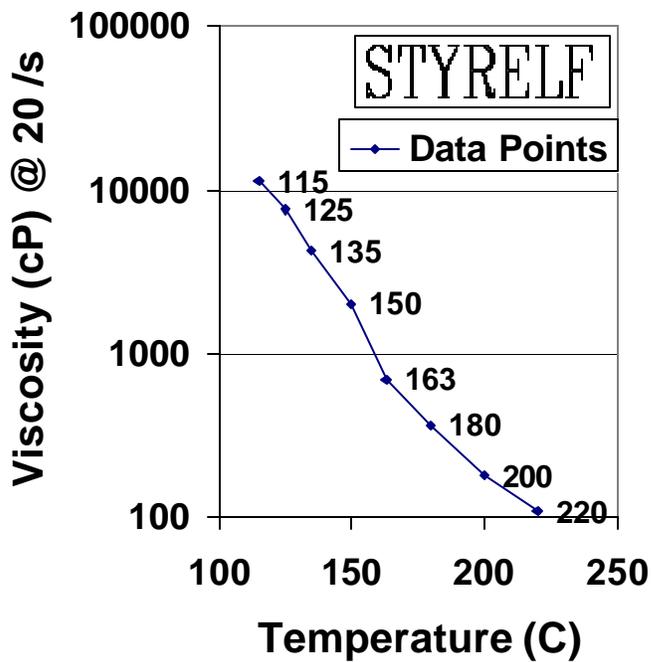

Figure 3 (b) : Variation of steady shear viscosity with temperature for neat Styrelf on an Arrhenius type of plot.

From Figure 3 (b), it can be seen that Styrelf follows a smooth straight line trend on an Arrhenius-type plot in two different ranges, namely, between the temperatures of 115°C and 150°C as well as between the temperatures of 163°C and 220°C. In the temperature range of 150°C to 163°C, it can be seen that there is a sudden drop in the viscosity. This sudden drop occurs because the mechanism of flow changes at around 150°C. Styrelf is basically a copolymer and hence has polymer chains comprising of more than one type of monomeric building blocks. Most block copolymers show microphase separation. Their melt viscosities are a manifestation of the existing two-phase structured system. When the temperature is increased, only one of the domains of the two-phase system melts. Between the temperatures of 115°C and 150°C, one of the domains in the Styrelf, namely, the polystyrene is in the melted form. But the system is able to flow as a whole due to the fluidity created by this domain, despite the fact that the two domains are not compatible. The viscosity follows the Arrhenius trend in this temperature region with an activation energy close to that of homopolystyrene. When the temperature is increased further, a stage is reached when both domains become fluid and the additional resistance to flow due to the presence of the unmelted domain is removed. In the case of Styrelf, this occurs at a temperature between 150°C and 163°C. Hence, beyond the temperature of 163°C, viscosity follows the Arrhenius trend but with an activation energy which is closer to that of polybutadiene. This explains why there is a discontinuity in the viscosity versus temperature plot for Styrelf. The curve in Figure 3 (b) thus suggests that it might be prudent to choose a mixing temperature greater than 163°C so as to make sure that both phases are completely melted. If both phases are not completely melted, then the unmelted domains will not disperse well within the system thereby leading to non-uniform properties in the mix.

At this stage, it is important to seek the most adequate mixing temperature by performing actual mixing and dispersion experiments and assessing the quality of the mixes. This is done along the lines followed by Dow et al (1988, 1990) and discussed in details by Shenoy (1999).

Figure 4 (a) for Novophalt and (b) for Styrelf shows the variation of viscosity with shear rate at one selected temperature when four samples of binder were mixed with the same quantity of diabase but at different mixing temperatures.
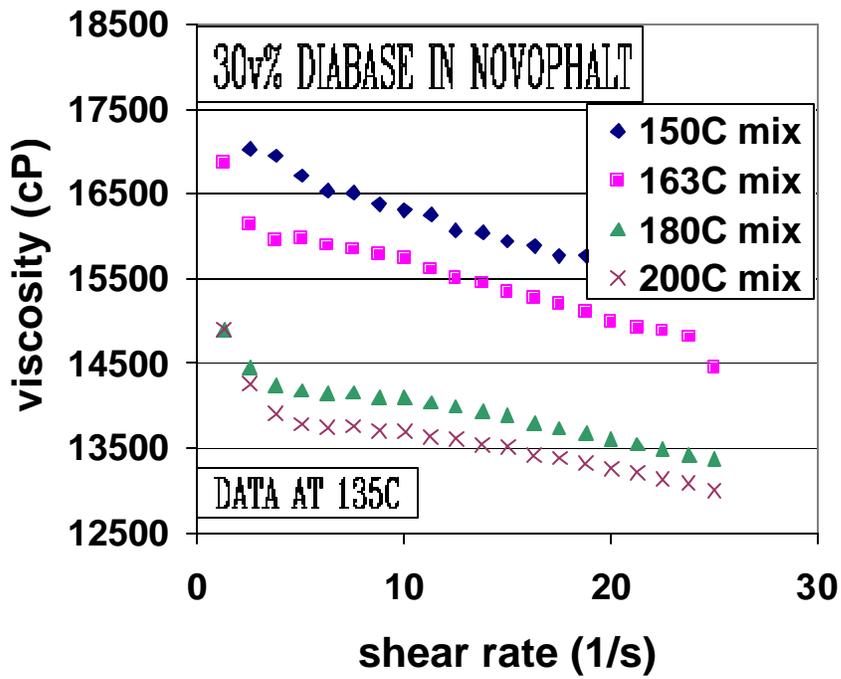
Figure 4 (a) : Variation of steady shear viscosity with shear rate at 135°C for Novophalt mixed with 30 volume percent diabase at four selected temperatures of 150°C, 163°C, 180°C and 200°C.
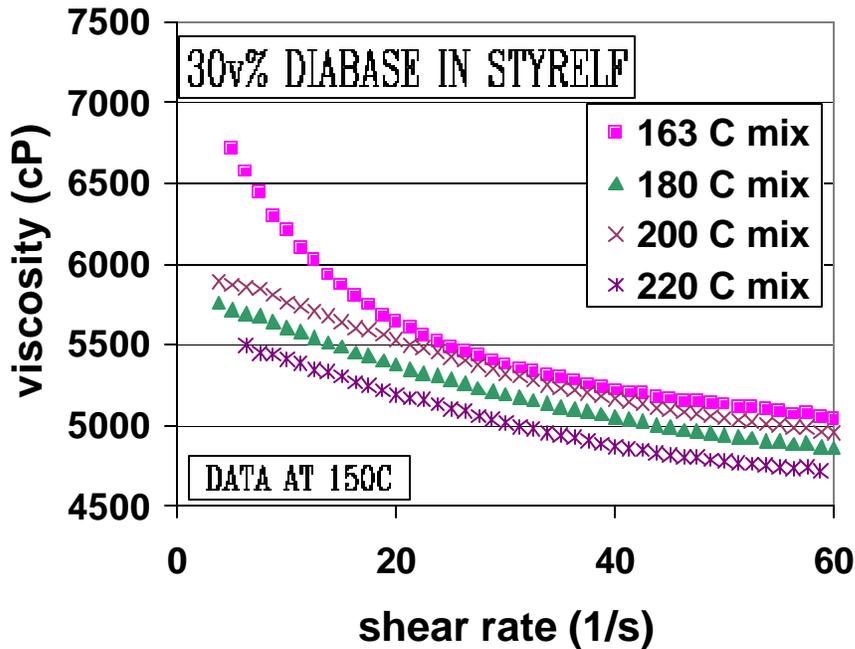
Figure 4 (b) : Variation of steady shear viscosity with shear rate at 150°C for Styrelf mixed with 30 volume percent diabase at four selected temperatures of 163°C, 180°C, 200°C and 220°C.

Since all the four samples in Figure 4 have the same quantity of diabase in the same binder [(a) Novophalt (b) Styrelf] and the viscosity measurements are taken at the same temperature, the curves in Figure 4 should have been identical. There should have been one curve in Figure 4 (a) for Novophalt and one curve in Figure 4 (b) for Styrelf. However, that is not the case. There is a practical significance of the differences in viscosity shown in these figures. The difference indicates that the dispersion level is not the same in each of the samples in Figures 4 (a) and (b) and that the mixing done at these different temperatures would lead to differences in properties of the mixed product.

Assessing dispersion by looking solely at the filled system data does not give the complete picture. It is important to see how the unfilled binder changed rheologically during the mixing operation. Figure 5 shows the viscosity versus shear rate curves for unfilled binder at the identical fixed temperature of 135°C for (a) Novophalt and 150°C for (b) Styrelf, but each has seen the identical thermal and shear history as the filled binders when mixed at four different temperatures between 150°C and 220°C.
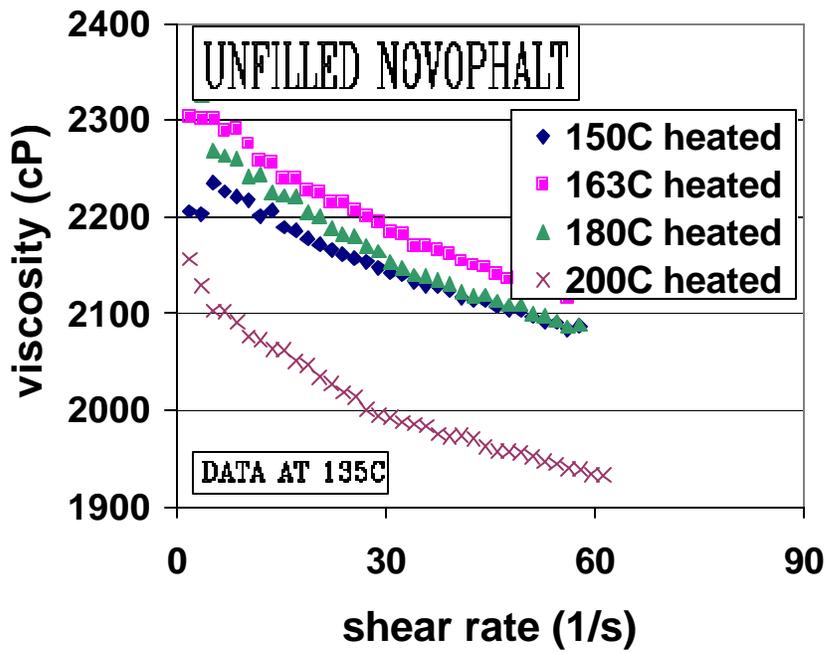
Figure 5 (a) : Variation of steady shear viscosity with shear rate at 135°C for unfilled Novophalt heat treated at four different temperatures of 150°C, 163°C, 180°C and 200°C.

In Figure 5 (a), at the lower temperature of 150°C, the effect of aging on the unfilled Novophalt is less and hence the viscosity of the material heat treated at 150°C is lower than that which was heat treated at 163°C. By the same argument, the viscosity of the unfilled Novophalt should have been progressively increasing when heat treated at higher and higher temperatures. However, this is not seen to be the case. In fact, the viscosity of the unfilled Novophalt heat treated at 180°C and 200°C are lower than that heat treated at 163°C. This is because there is a competing mechanism involved. Whereas on one hand, the asphalt in the Novophalt causes an increase in viscosity due to aging, the polymer in the Novophalt, on the other hand, causes a decrease in the viscosity due to thermal and mechanical degradation. These competing factors become more obvious at the higher temperatures.
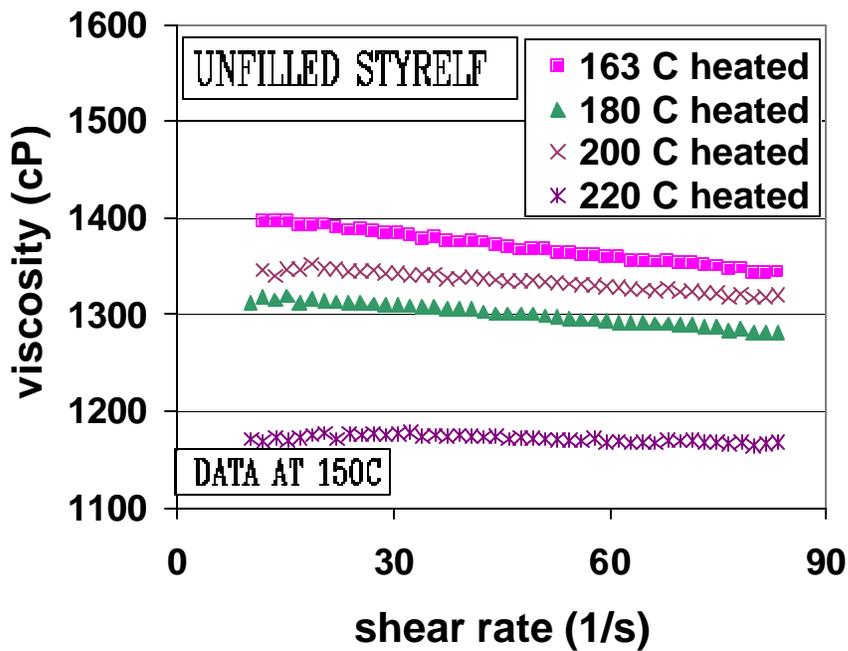

Figure 5 (b) : Variation of steady shear viscosity with shear rate at 150°C for unfilled Styrelf heat treated at four different temperatures of 163°C, 180°C, 200°C and 220°C.

It is to be understood that the two competing mechanisms are present even when Styrelf is exposed to high temperatures for a certain length of time. Whereas on one hand, the asphalt in the Styrelf causes an increase in viscosity due to aging, the polymer in the Styrelf, on the other hand, causes a decrease in the viscosity due to thermal and mechanical degradation. From Figure 5 (b) it can be seen that at the highest temperature of 220°C, the effect of degradation of the polymer is more dominant than the effect of aging of the asphalt in the Styrelf, hence the material heat treated at this temperature has the lowest viscosity. At temperatures between 163°C and 200°C, the effects of asphalt aging and polymer degradation in the Styrelf are comparable and hence the viscosities of the material heat treated at temperatures of 163°C, 180°C and 200°C are nearly identical.

When discussing filled system data, the above discussed factors must be taken into consideration. Simply by observing the filled system data as shown in Figure 4 does not give the entire information. Actually, it is the relative viscosity data that should be analyzed so that the effect of the matrix in the filled system is eliminated. This then gives a better representation of the dispersion level of the aggregates in the mix. Figure 6 shows the relative viscosity obtained by taking the ratio of the viscosity of the filled binder to the unfilled binder. For Novophalt, it can be seen from Figure 6 (a) that the relative viscosity goes through a minimum at around 180°C. Thus, in order to maintain good quality of mixing, it would be important to keep the mixing temperature to a level between 163°C and 180°C. In the case of Styrelf, there is no distinguishable minimum in Figure 6 (b). However, the lowest relative viscosity is again in the temperature range between 163°C and 180°C.
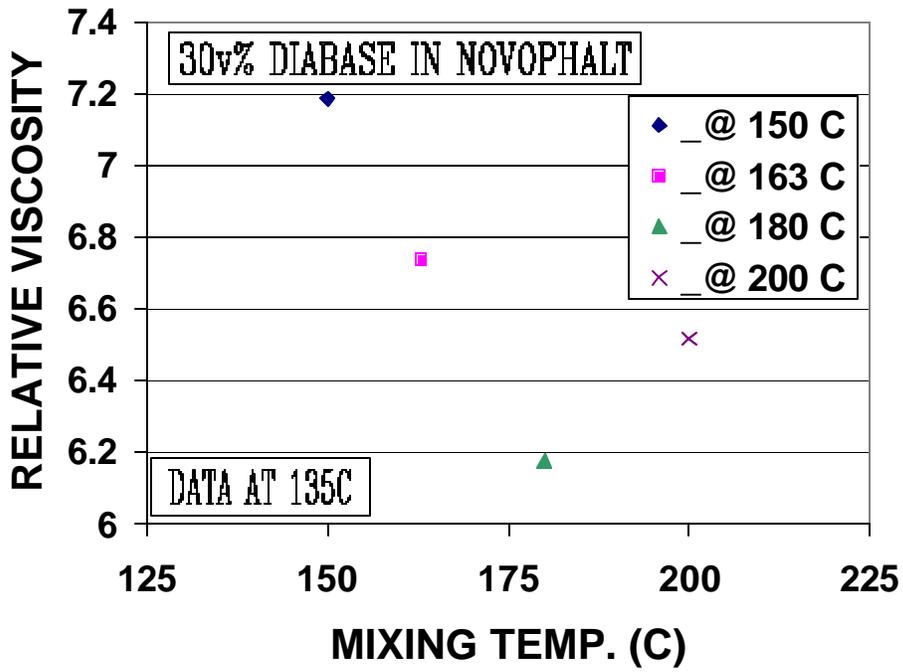
Figure 6 (a) : Variation of relative viscosity at 135°C versus mixing temperature for Novophalt mixed with 30 volume percent diabase at four different temperatures of 150°C, 163°C, 180°C and 200°C.
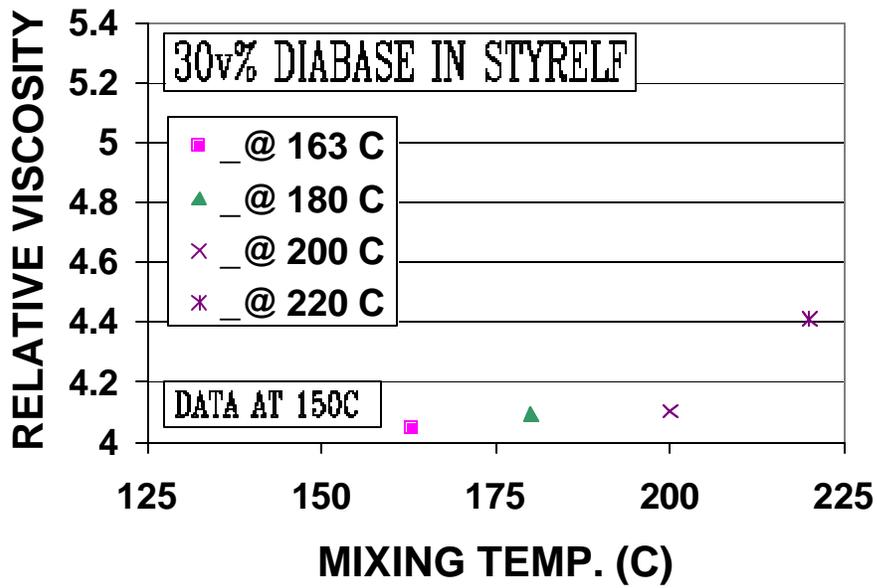
Figure 6 (b) : Variation of relative viscosity at 150°C versus mixing temperature for Styrelf mixed with 30 volume percent diabase at four different temperatures of 163°C, 180°C, 200°C and 220°C.

Based on the present work, it is concluded that the optimum mixing temperature for Novophalt and Styrelf can be chosen anywhere from163^{o}C to180^{o}C. From a practical viewpoint, it is preferable to specify a range rather than a single value when suggesting the appropriate mixing temperature. In this optimum mixing temperature range, the higher value should be preferred because it would then allow for any uncontrolled drop in temperature of a few degrees in practice without any significant loss in the mixing efficiency. However, it is essential to make sure that the chosen temperature from the suggested range is below the temperature at which the system may smoke. This is important from health and safety considerations, and may become the final driving force to use the mixing temperature more towards the lower end of the range.   In case, it is seen that the mixing components emit smoke even at the lower end of the suggested range, then it is prudent to drop the mixing temperature down in steps of few degrees, until a safe mixing temperature is reached. This mixing temperature would have fallen outside the optimum, but nevertheless would be close to it to ensure probably 90-95% mixing efficiency.

It should be noted that the present work attributes a great deal of importance to the quality of the mix and chooses the mixing temperature which would be optimum to give the best dispersion under the constraints of the equipment and process. This ensures that the mix quality is more uniform at all times. When the end point of mixing is governed by visual observation of the coated aggregates as prescribed in AASHTO T 195 (ASTM D2489), then the judgement becomes qualitative and there is no guarantee that the mixing temperature recommended will always give the same quality of the product. This is the reason why the present work follows the path of optimizing the quality of the mastic to determine the correct mixing temperature rather than using the criterion of the observation of the coated particles to determine it.

The deduction of the mixing temperature range was done by eliminating the temperatures which did not satisfy the criteria laid down earlier for optimizing the choice of the mixing temperature. Another method that can be used is to list the criteria and use pass/fail indicators (1/0) for the various temperatures as shown in Table 2. When this is done and the successes are totaled, it can be seen that 180°C comes out with the highest points for Novophalt in Table 2. The range to be selected should be that which lies between the highest and the second highest points, which in the present case, can be seen to be between 163°C and 180°C. Thus, the optimum mixing temperature range for the studied Novophalt can be taken to be between 163°C and 180°C. A similar exercise can be carried out for Styrelf and it can be seen that the mixing temperature range between 163°C and 180°C is also recommended for Styrelf from Table 2.

TABLE 2

Determination of the mixing temperature based on pass/fail indicators

Temp deg C	Shear-rate Independence	Good Fluidity	Arrhenius plot Smoothness	Min. Polym. Degrad.	Min. Asph. Aging	Min. Rel. Visc.	Total
(a) Novophalt							
115	0	0	0	1	1	0	2
125	0	0	0	1	1	0	2
135	0	0	1	1	1	0	2
150	1	0	1	1	1	0	4
163	1	0	1	1	0	1	4
180	1	1	1	1	0	1	**5**
200	1	1	0	0	0	1	3
(b) Styrelf							
115	0	0	0	1	1	0	2
125	0	0	0	1	1	0	2
135	0	0	0	1	1	0	2
150	0	0	0	1	1	0	2
163	1	0	1	1	0	1	**4**
180	1	1	1	0	0	1	**4**
200	1	1	1	0	0	0	3
220	1	1	1	0	0	0	3

After mixing the components at the appropriate mixing temperature, the mixed components are often stored at or near the mixing temperature for an extended length of time until the lay down and compaction is done. During this period of time, the rheological properties of the mix naturally change. The asphalt in the binder increases in viscosity while the polymer in the binder decreases in viscosity due to degradation. This does not affect the mixing efficiency as the mixing is already completed. However, it would affect the compaction depending on the net effect of the changes due to the system being held at the mixing temperature. At higher mixing temperatures, these effects are larger and this point must be borne in mind when determining compaction temperatures.

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