CHAPTER 4. DETERMINATION OF MIXING AND COMPACTION TEMPERATURES OF WMA TECHNOLOGY: CONVENTIONAL APPROACHES

4.1 Preamble

The use of warm mix asphalt (WMA) is one of the energy efficient technology, which produced asphalt mixture at temperatures below 140°C [2]. The reduction in production temperature can be achieved by using one of the warm technologies, either organic, chemical, or foaming. The use of such energy efficient technology (Warm mix asphalt) has replaced traditional hot mix asphalt (HMA), which requires mixing temperatures between 150°C and 180°C [1]. The implementation of such technology can lead to significant enhancements in energy consumption and the release of pollutant gases. This makes WMA an attractive technology for building greener road, especially when the performance of the asphalt mix is not compromised despite of being produced at lower temperatures. WMA is produced by adding certain additives in the asphalt binder, or the asphalt mixture. These additives can be classified as foaming additives, organic additives, and chemical additives. The amount of temperature reduction achieved by technologies (additives) is dependent upon the mechanism by which technology reduces the production temperature [58]. The detailed description regarding their mechanism can be found in section 2.3 of Chapter 2. It is worth noting that although these technologies may exhibit different mechanism for temperature reduction, but the goal of this technology is to reduce the production temperatures of asphalt binder. However, the degree of temperature reduction depends on the specific type of WMA technology and its corresponding dosages.

The efficacy of WMA technology hinges on the precise determination of production temperatures. Inappropriate determination of production temperature lead to the premature failure of the pavement due to poor mixing and compaction. Numerous investigations [126,370] have been carried out to ascertain the effect of mixing and compaction temperatures

on the performance of asphalt mixtures. Lower mixing temperature may lead to an insufficient coating of asphalt binder over the aggregates, resulting in moisture-induced damage [2,341]. On the other hand, lower compaction temperature can cause difficulty during field compaction and result in lower field density [127]. Unlike lower production temperatures, excessively high temperatures during the production and placement of asphalt mixtures may result in severe consequences [125,342]. Sarnowski et al. [129] mentioned that overheating of asphalt mixtures leads to accelerated binder aging. According to Cheraghian and Wistuba [130], aging results in oxidative hardening of asphalt binder, leading to premature pavement cracking. Mo et al. [131] stated that 80% of premature failure of asphalt pavements is often due to inadequate compaction of asphalt mixtures. Over a period of time, several methodologies have been proposed to determine the mixing and compaction temperature of asphalt mixtures [11]. Though standard methods are available to determine the production temperatures of HMA, there are no standard methods to determine the mixing and compaction temperatures for WMA. In India, the guidelines are available for the implementation of WMA technology in field. These guidelines are mentioned in IRC SP 101-2019 [40]. The current guidelines are scanty in providing an adequate procedure for evaluating the mixing and compaction temperatures of asphalt mixtures produced using different warm mix technologies. The guideline recommends producing asphalt mixture at 30°C lower temperature than the conventional hot mix asphalt. The resulting mixture should undergo assessment for binder coating (qualitative evaluation), air voids criteria (determined by the volumetric of compacted specimens), and moisture susceptibility (assessed via the tensile strength ratio (TSR) value) at the lower temperature suggested by guidelines. Additionally, taking manufacturer's recommendation is suggested to decide appropriate reduction in the production temperature, and optimum dosage of the WMA additives. This process is too iterative and lacks fundamental quantification of production temperatures of WMA technology [132,342,343]. Therefore, there is a need to improve the

available specification by introducing a suitable process for assessing the production temperatures of WMA. This forms the motivation for this chapter. In this chapter, various methods mentioned in NCHRP 648 are employed to determine the mixing and compaction temperature of WMA modified asphalt binders [11]. These guidelines used viscosity based methods and dynamic shear rheometer based method (phase angle method) for determination of MT and CT. This chapter discuss the applicability of these methods for determination of MT and CT of WMA technology. All the analysis was carried out by taking base binders (VG30 and PMB40) as reference binder. The results obtained from various methods were further analysed to understand the mechanism involved in reduction of MT and CT due to WMA technology.

4.2 Methodology

The current chapter is divided into two major phases. The first phase involves the evaluation of mixing and compaction temperatures based on different techniques (approaches) using rotational viscometer (RV). The approaches based on RV include, Equi-viscous Method, Zero Shear Viscosity (ZSV) Approach, Simplified ZSV Approach, High Shear Rate Method (HSR-O), High Shear Rate Evolution Approach (HSR-E), Flow Behaviour Method. These approaches are employed to determine the MT and CT of WMA modified binders. The second phase includes the assessment of MT and CT using phase angle method employing dynamic shear rheometer. In this phase, the phase lag (phase angle) is used as an essential parameter to determine the mixing and compaction temperatures of WMA modified binders. The phase angle master curve is constructed at a reference temperature of 80°C, and the frequency (ω) corresponding to the phase angle of 86° is taken for further evaluation of production temperatures. Figure 4-1 illustrates the research framework followed in the present chapter.

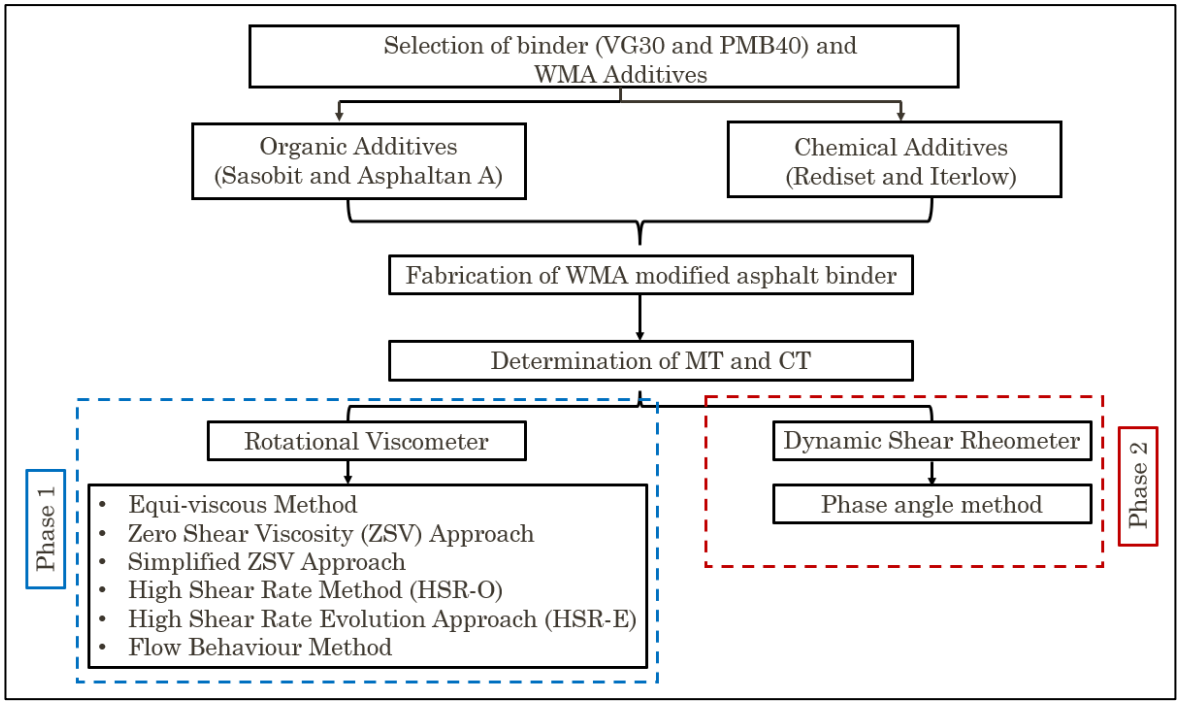

Figure 4-1. Research methodology adopted in this chapter.

4.3 Phase 1: Determination of MT and CT Using RV

The first part of the study consisted of finding the production temperatures based on the previously proposed test methods using RV. The tests were conducted on all the considered asphalt binders using RV at different test conditions, as presented in this Chapter. Since, some of the warm mix technologies, for example, chemical and foaming based processes, does not specifically reduce/influence the viscosity/rheology of the asphalt binder, the use of RV based methods are debatable [147]. To confirm this aspect, all these methods were used for evaluation of mixing and compaction temperatures of all the binder blends prepared in this study. The following section provide the determination of MT and CT using these approaches in graphical form.

- **Equi-viscous (EQ) method**

  ASTM D2493 [371] provides guidelines on evaluating the production temperatures using the equi-viscous (EQ) method [13]. As per the procedure, the temperature ranges

corresponding to 0.17±0.02 Pa.s and 0.28±0.03 Pa.s are taken as mixing and compaction temperatures, respectively, for the production of asphalt mixtures. Figure 4-2 present the determination of MT and CT for VG30 binder using EQ approach.

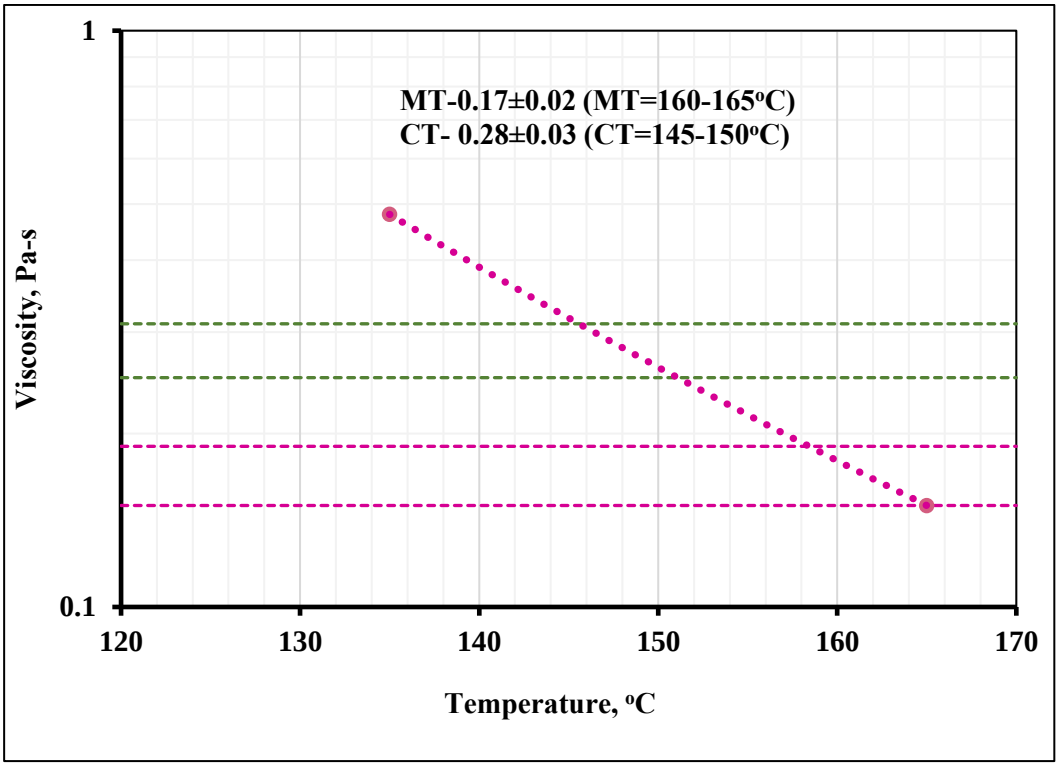

Figure 4-2. Determination of MT and CT using EQ method.

- **Zero Shear Viscosity (ZSV) Approach**

In this method, Brookfield viscometer is used to determine the viscosity of asphalt binder by varying shear rate at two temperatures 135°C and 165°C. The Cross-Williamson model is used to estimate the ZSV at 135°C and 165°C. Figure 4-3 illustrates the determination of ZSV using Cross-Williamson model. In this approach, the MT and CT temperature is determined by plotting the log-log of viscosity as a function of log temperature (in degrees Kelvin). The viscosity criteria of 3 Pa. s and 6 Pa. s is used for determination of MT and CT, respectively [141]. The power function was employed to predict MT and CT based on the criteria established in this approach. Figure 4-4 present the determination of MT and CT for VG30 binder using ZSV approach.

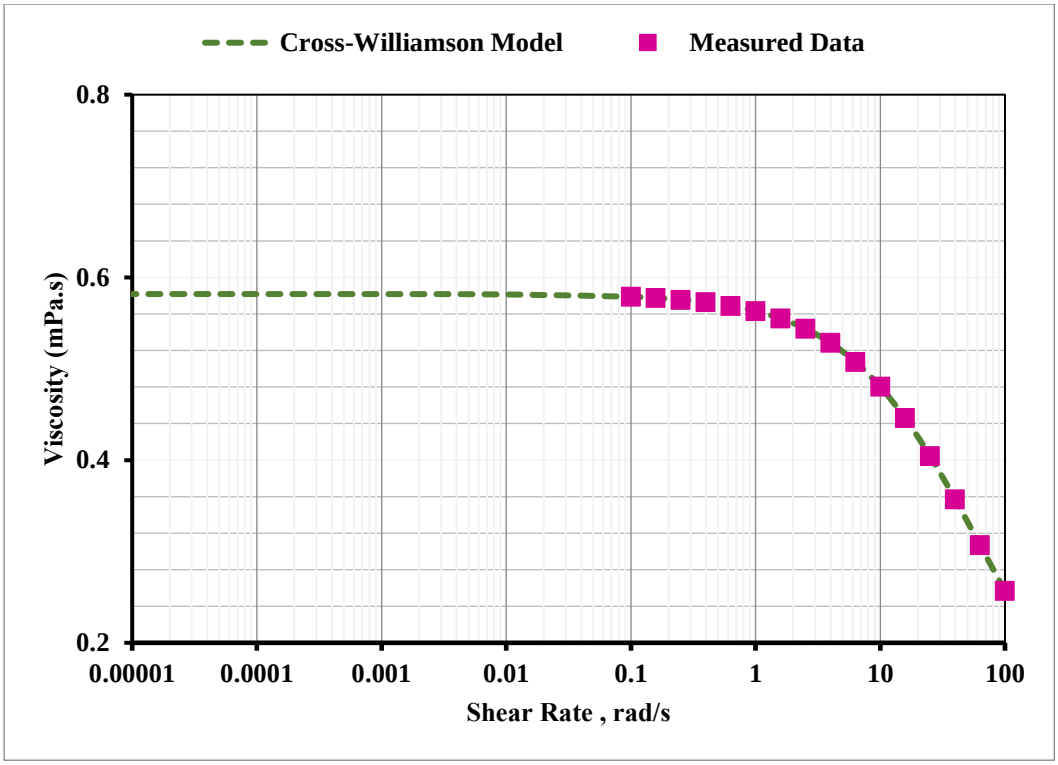

Figure 4-3. Determination of ZSV using Cross-Williamson model

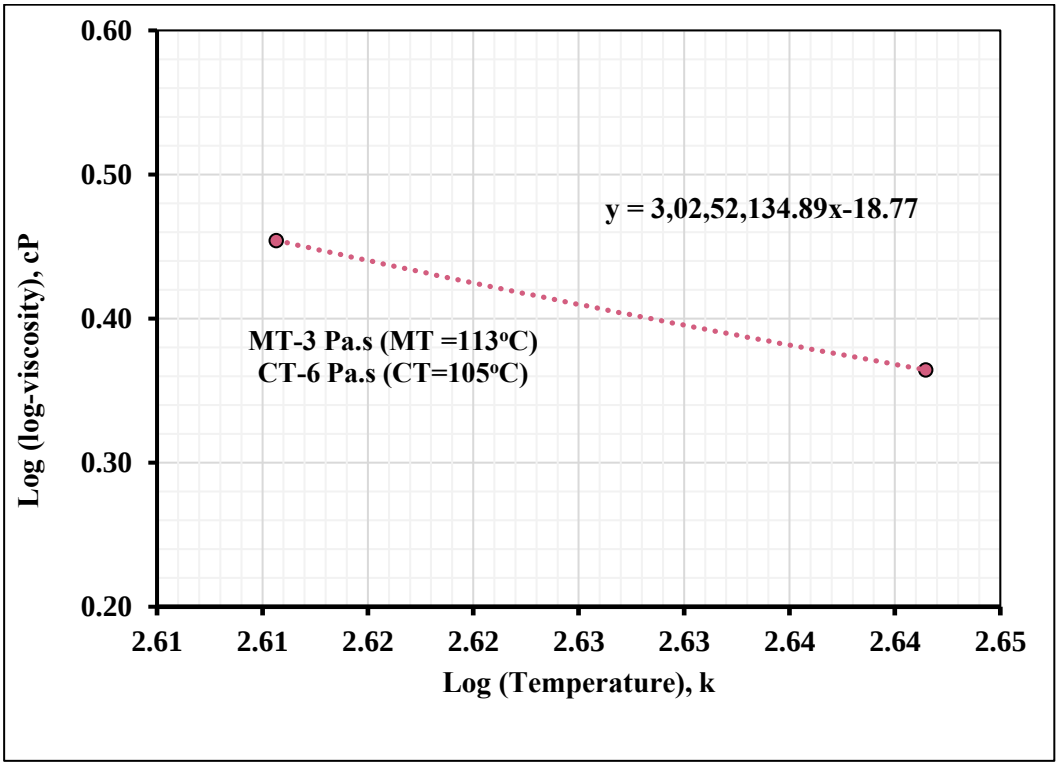

Figure 4-4. Determination of MT and CT using ZSV method.

- **Simplified Zero Shear Viscosity (S-ZSV) Approach**

In this approach the determination of ZSV is same as that of above-mentioned ZSV approach but only difference is in the viscosity criteria. In this approach, the MT and CT temperature is determined by plotting the log of viscosity as a function of temperature (in degrees Celcius). To determine mixing and compaction temperature, viscosity criteria of 0.75 ± 0.05 Pa. s and 1.4 ±0.10 Pa. s is used respectively [144]. The criteria used in this approach used power function to predict MT and CT of WMA modified binders. Figure 4-5 present the determination of MT and CT for VG30 binder using S-ZSV approach.

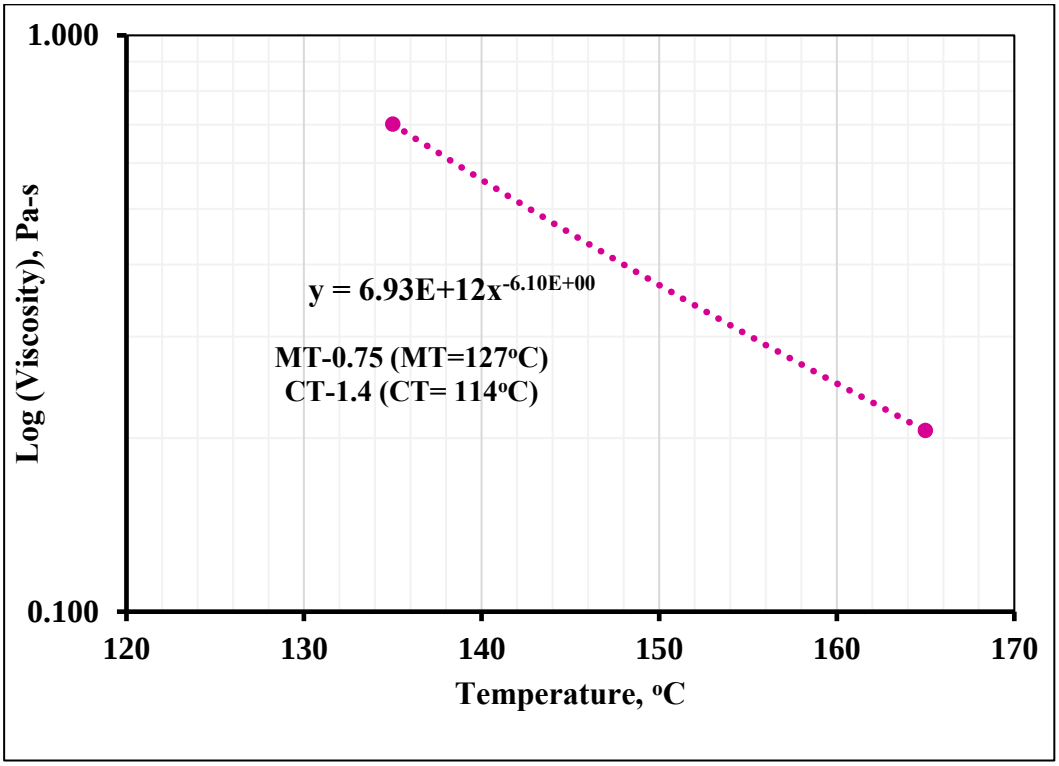

Figure 4-5. Determination of MT and CT using S-ZSV method.

- **High shear rate (HSR-O) Approach**

In this method, the viscosity using Brookfield viscometer is determining by varying shear rate at two temperatures 135°C and 165°C. The viscosity at shear rate of 500 1/s is extrapolated using power-law model at both temperatures 135°C and 165°C [125]. To determine MT and CT, EQ method viscosity criteria is used (0.17 ± 0.02 Pa. s and 0.28 ±

0.03 Pa. s). Figure 4-6 present the determination of MT and CT for VG30 binder using HSR-O approach.

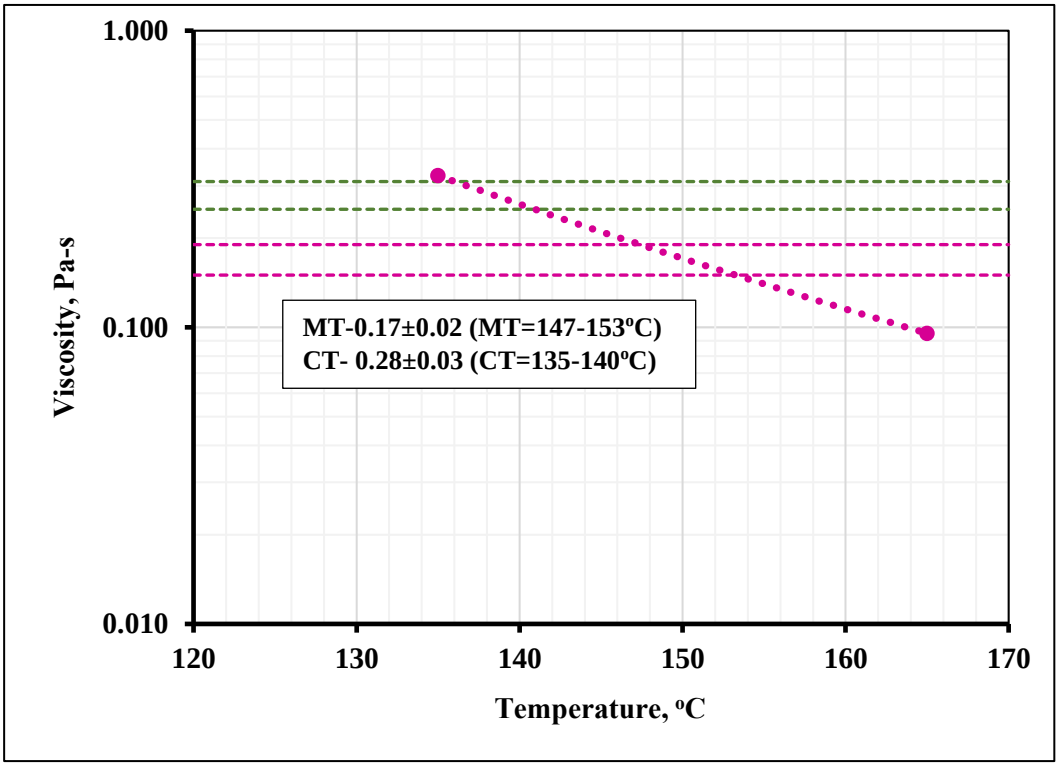

Figure 4-6. Determination of MT and CT using HSR-O approach.

- **Modified high shear rate (HSR-E) Approach**

This approach is similar to above-mentioned high shear rate method (HSR) but only difference is in the viscosity criteria used for determination of production temperatures. The viscosity criteria are changed due to underestimation of production temperatures by using EQ criteria [132]. In this method viscosity criteria is modified to 0.275 ± 0.03 Pa. s and 0.550 ± 0.06 Pa. s for mixing and compaction temperature respectively. The power function was used in this study to predict the CT using criteria employed in this approach. Figure 4-7 present the determination of MT and CT for VG30 binder using HSR-E approach.

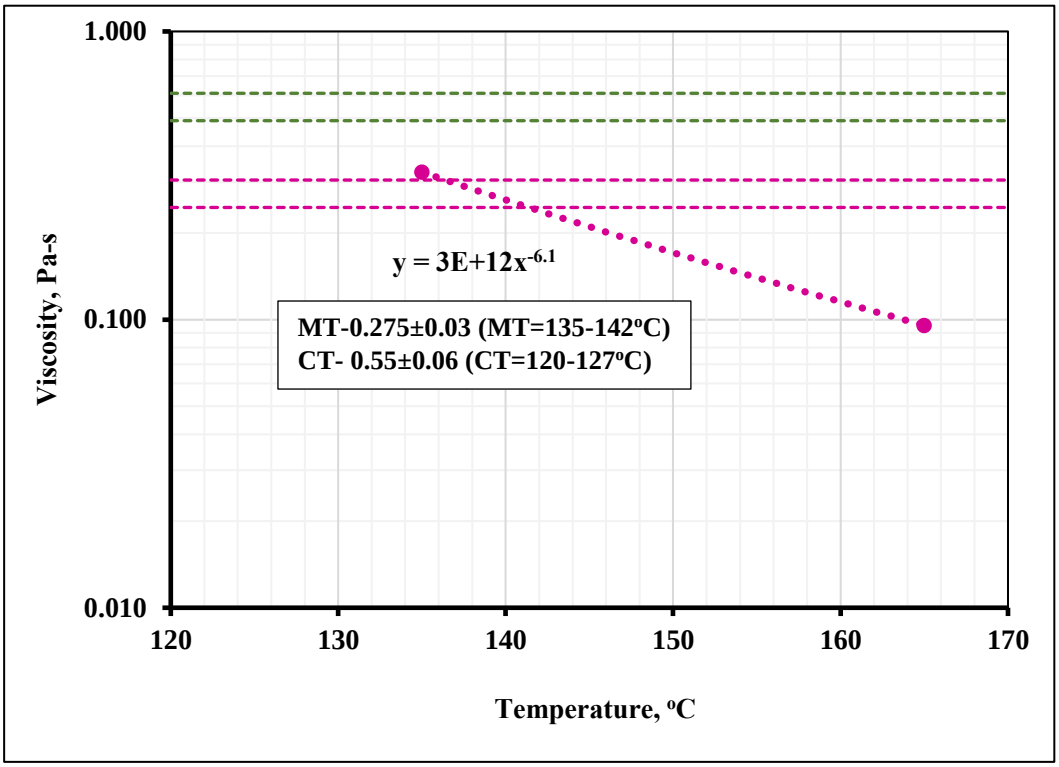

Figure 4-7. Determination of MT and CT using HSR-E approach.

- **Flow Behaviour Approach (FBA)**

Considering the shear rate in the mixing plant, Saboo et al.[138] recommended three different shear rates (1000, 10000, 100000 s^{-1}) for the estimation of mixing temperatures using same viscosities limit as given in ASTM D2493. For the prediction of mixing temperature, ZSV using rotational viscometer at suggested shear rates are plotted against temperatures and EQ method viscosity criteria of 0.17 ± 0.02 Pa. s is used for determination of mixing temperature. In this study ZSV is determined at 100000 s^{-1} for better results as suggested by authors of the study [138]. The power function was used in this study to predict the MT and CT using this approach. Figure 4-8 present the determination of MT and CT for VG30 binder using flow behaviour (100000 s^{-1}) approach.

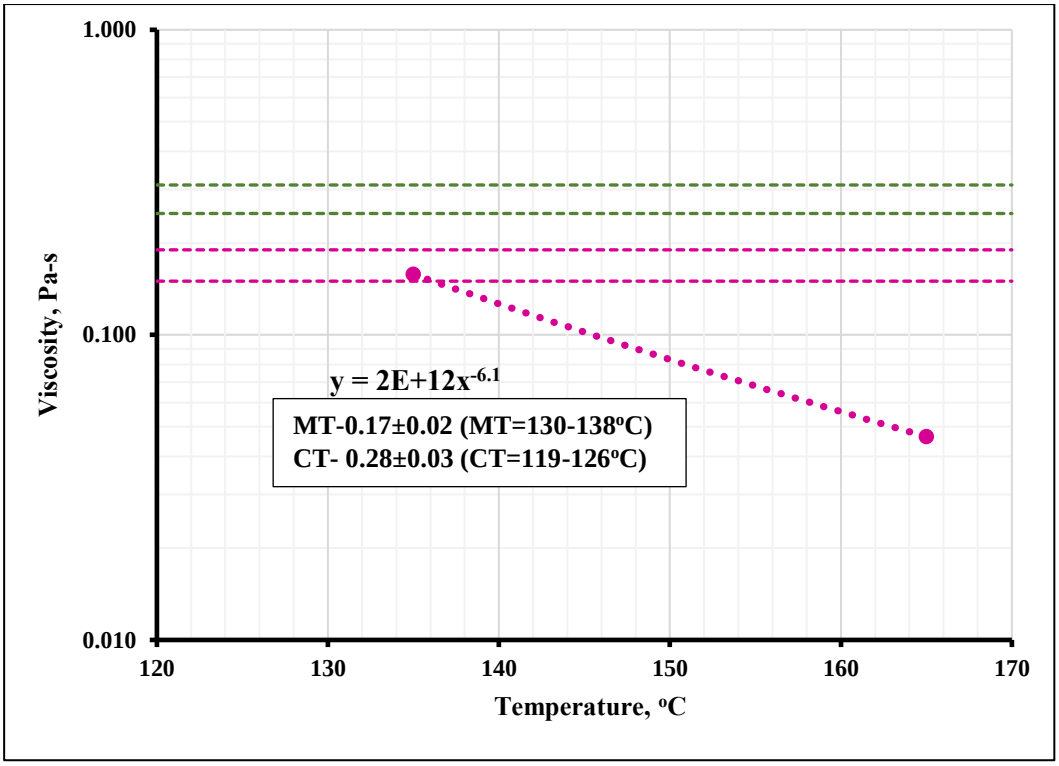

Figure 4-8. Determination of MT and CT using flow behaviour (100000 s^{-1}) approach.

4.4 Phase 2: Determination of MT and CT Using DSR

The second phase of the study consisted of finding the production temperatures using DSR. Two methods have been proposed in the previous literature to predict production temperatures using DSR [11]. These methods are steady state flow (SSF) method and phase angle method (PAM). The present study does not include the SSF method owing to the delamination (at higher temperatures, i.e., 76, 82 and 88˚C) of binder from the parallel plate geometry in the DSR. In addition, this method requires extrapolation of viscosity corresponding to a higher temperature range (around 180˚C). Also, many modified asphalt binders may not reach a steady-state at 500 Pa [372]. Therefore, the only phase angle method has been used in this study for determination of MT and CT of WMA modified binders. This method is based on non-Newtonian behaviour of asphalt binder. In this method, the frequency sweep test was carried out on WMA modified binders using 25 mm parallel plate geometry with 1 mm gap. Frequency of test was varied from 0.1 to 100 rad/sec whereas strain level was maintained at 12%. This

method involves the testing of asphalt binder under an oscillatory mode at temperatures of 50°C, 60°C, 70°C and 80°C. During the test, the phase lag between input and output response was recorded for all WMA modified binder at each temperature and frequency. The phase lag (phase angle) was selected as an important parameter to determine the mixing and compaction temperature and thus the method is popularly known as Phase angle method. In this method, temperature of 80°C was taken as a reference temperature for development of phase angle master curve based on time-temperature superposition (TTS). For construction of master curve, the sigmodal model has been used in this study and shift factors were obtained using free shifting approach. The details of this model can be found elsewhere [373]. The method involves the determination of frequency (ω in rad/sec) at reference temperature (T_{ref}) corresponding to phase angle of 86 degree using master curve where asphalt binder exhibits viscous behaviour. This frequency was used as an input for determination of mixing and compaction temperature. The following empirical equations are used for determination of mixing and compaction temperature. Figure 4-9 illustrates the determination of MT and CT of PMB 40 using phase angle method.

$$\text{Mixing temperature } (^{o}F) = 325\ (\omega)^{-0.0135} \quad (4\text{-}1)$$

$$\text{Compaction temperature } (^{o}F) = 300\ (\omega)^{-0.012} \quad (4\text{-}2)$$

Where, ω =frequency in rad/sec

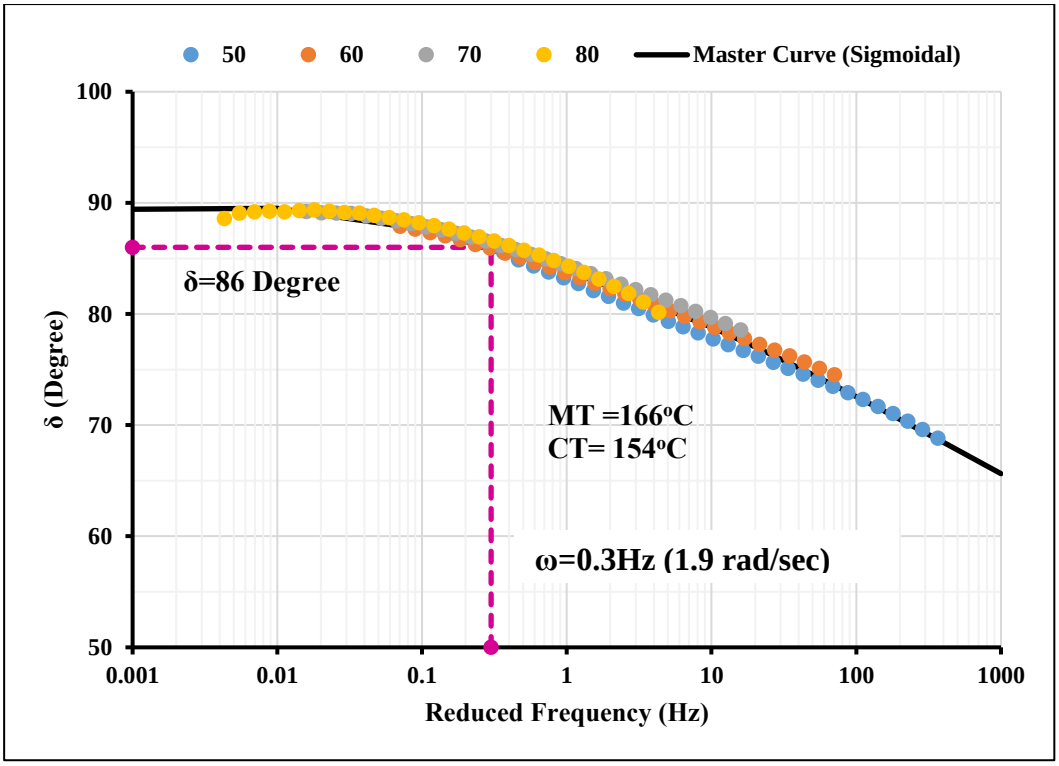

Figure 4-9. Determination of MT and CT of PMB40 using phase angle method.

4.5 Results and Discussion

4.5.1 Phase 1: Determination of MT and CT Using RV

Various RV-based approaches (as mentioned in above section) were used to assess the production temperatures of WMA modified binders and polymer modified binders. Mixing temperatures obtained from various approaches for VG30 and PMB40 are shown in Table 4-1 and Table 4-3, respectively. Table 4-2 and Table 4-4 presents the ranges of compaction temperatures for VG30 and PMB40, respectively. The variation in results between different methods is due to the methodology adopted in each method. As expected, the production temperatures of PMB 40 are higher than VG 30, irrespective of approach used. This higher value of MT and CT can be attributed to viscoelastic non-Newtonian fluid behaviour of modified asphalt binders at such elevated temperatures. The past literature also shows that the linear relationship between temperature and viscosity may not hold true for modified binders [117,132]. The relation is valid when the viscosity is independent of the shear rate, which is

impossible in modified binders. Notably, the MT and CT obtained for PMB 40 are excessively high (>180 ˚C), which may result in degradation of polymeric structure and accelerated aging of binder. This accelerated aging of binder may cause premature failure of pavement. The MT and CT of VG30 binder obtained from EQ method were found to be 160-160˚C and 145-150˚C, respectively. These ranges of MT and CT of VG30 binder were found to be appropriate as specified in Ministry of Road Transport and Highways (MoRTH) [344]. The production temperatures for VG30 binder calculated from other adopted methods are lower than the specified values [344] and hence not acceptable. Although VG30, being a conventional unmodified binder, shows limited sensitivity to shear rate, variations in mixing and compaction temperatures among different methods arise due to the fundamental differences in testing procedures such as the imposed shear conditions and temperature dependencies. These methodological differences can lead to slight variations in measured responses, even for binders with relatively Newtonian behavior. Similar observations have been reported in previous studies [13,273]. Considering all the test methods, ZSV yields a lower value of production temperatures, followed by S-ZSV, FBA, HSR-E, HSR-O, and EQ method. The similar trend was observed in case of polymer modified binder as can be seen from Table 4-3 and Table 4-4. Though the other methods were developed to overcome the shortcomings of the EQ method, the methodology for evaluating production temperatures is still based on the viscosity of the asphalt binder. Approaches based on shear rate did not work well for polymer modified binder even they exhibit shear susceptibility [132]. This shows the inadequacy of these approaches for the characterization of polymer modified binders. In addition, some additives, such as Rediset and Iterlow did not influence the viscosity of the base asphalt binder, so they may not be characterized using this viscosity based approaches [2,374]. Thus, the adopted methods may indicate inappropriate mixing and compaction temperatures for such warm mix additives and polymer modified binders.

In general, the application of warm mix additives lowers the mixing and compaction temperatures of asphalt mixtures. As shown in Table 4-1, 4.2, 4.3, and 4.4 the reduction in production temperatures is dependent on the type of WMA technology, dosages and test method adopted for determination of MT and CT. The maximum reduction in mixing temperatures for organic-based technologies (Sasobit and Asphaltan A) were found to be around 12°C (VG 30) and 10°C (PMB 40). The respective reduction using chemical-based agents (Rediset and Iterlow) were approximately 10°C (VG 30) and 8°C (PMB 40). The maximum reduction in compaction temperature was around 11°C (VG 30 and PMB 40) for organic based additives, whereas it reduced by approximately 8°C and 10°C with the addition of chemical-based WMA agents in VG 30 and PMB 40, respectively. The extent of reduction in production temperatures are regardless of WMA additives dosage. From the results, it can also be found that the addition of WMA additives to VG30 binder showed predominant effect than PMB40. The polymeric network present in PMB40 may impact the mechanism of WMA additives involved in reduction of MT and CT.

From the Table 4-1 to Table 4-4, it can be seen that the maximum reduction in MT and CT was obtained for organic based additives (viscosity reducers) in both the base binders (VG 30 and PMB 40). Since the production temperatures obtained from EQ approach are directly related to the viscosity values, the organic-based additives showed higher reduction compared to chemical based WMA agents. This can be due to the viscosity reducing behaviour of Sasobit which reduces the viscosity of base binder. On the other hand, this approach may provide inappropriate results/trends for chemical based WMA binders. It can be due to the surface tension reducing behaviour of chemical additives like Rediset and Iterlow. It was also found that the production temperatures for few warm mix additives either did not change with the variation in the dosage of WMA additives, or resulted in marginal temperature reduction. For example, the increase in dosage of Rediset from 0.4% to 0. 5% did not significantly change the

mixing temperature of VG 30 and PMB40 binders. On the other hand, Iterlow did not show any significant reduction in MT and CT of VG30 binder as dosages increases from 0.3% to 0.5%. Similar type of unexpected trends/observation were observed for PMB 40 as well.

Along with these observations, the outcome of other approaches showed that the results either did not change with an increase/decrease in dosage of warm mix additives or indicate unexpected trends. For example, in the HSR-E approach, adding 0.4% Rediset decreased the mixing temperature to 136 °C while 0.5% showed a slight statistically insignificant increase to 139 °C indicating no consistent trend with dosage. Similar observations were noted with other test approaches for different warm mix additives and dosages. In the case of ZSV and S-ZSV approaches, the MT and CT of all the binders were lower than 140 °C, which are considered unrealistic for field implementation as low temperatures can compromise aggregate coating and compaction, potentially leading to inadequate field density and premature pavement failure. In addition, no noticeable effect of dosage was found with the addition of any of the WMA additives in PMB40, and the methods consistently produced unrealistically low MT and CT values (<140 °C) indicating that ZSV and S-ZSV approaches may be limited in their applicability for determining production temperatures of WMA modified binders. Similarly, in HSR-O and HSRO-E approaches, the MT and CT of WMA modified binders were found to be lower than EQ method and higher than ZSV and S-ZSV approaches. The MT and CT obtained from these approaches were found to be inappropriate to implement in field. The use of these lower MT and CT can lead to insufficient densification (field density) of the asphalt mixture, resulting in the pavement's failure. While analysing the results obtained from different test methods, it was found that the addition of WMA additives rather increases the mixing and compaction temperatures. This effect was clearly seen in chemical additives (Rediset and Iterlow) evaluated using flow behaviour method. Since flow behaviour method is based on shear rate, the chemical additives are not characterized using flow behaviour approach as they

do not change their viscosity with shear rate. Similar observations were noted with PMB40 and different warm mix additives and their dosages. These several issues restrict the applicability of these approaches for WMA modified and polymer modified asphalt binders.

Overall, the results demonstrated the inapplicability of EQ approach and viscosity based approaches for determining the production temperatures of WMA and polymer modified binders. The results of this section proved that the conventional viscosity criteria cannot be used for justification of reduced temperature in the case of WMA technology.

Table 4-1. Range of mixing temperature using different test methods for VG30 as base binder.

Binder Type	**Test Methods (Temperature is in ˚C)**					
	EQ	**ZSV**	**S-ZSV**	**HSR-O**	**HSR-E**	**100000 S^{-1}**
VG30	165-160	112-114	125-128	147-159	136-141	131-136
S1	153-160	107-109	119-122	145-151	133-139	132-137
S2	152-159	104-106	116 -119	143-150	131-137	130-136
S3	150-157	105-107	117-119	143-149	132-137	132-137
A1	155-162	109-113	118-121	142-150	132-138	130-135
A2	154-160	105-109	117-121	143-151	130-135	129-134
A3	152-158	106-110	117-120	144-150	129-135	128-134
R0.4	155-161	109-111	121-124	145-151	134-139	129-134
R0.5	153-159	107-109	119-122	148-154	137-142	140-146
R0.6	148-155	102-104	113-116	142-149	130-136	132-138
I0.3	154-160	107-112	120-125	144-150	134-138	128-135
I0.4	152-158	106-110	118-122	147-152	132-140	134-140
I0.5	150-156	106-108	115-119	145-150	131-137	133-139

Table 4-2. Range of compaction temperature using different test methods for VG30 as base binder

Binder Type	**Test Methods (Temperature is in ˚C)**					
	EQ	**ZSV**	**S-ZSV**	**HSR-O**	**HSR-E**	**100000 S^{-1}**
VG30	145-150	145-150	113-116	136-141	122-126	121-125
S1	141-146	100-102	106-109	133-138	118-123	121-125
S2	139-144	96-98	103-106	131-136	115-120	119-124
S3	138-143	98-100	104-107	131-136	116-121	121-125
A1	140-147	101-105	108-112	132-139	115-120	118-122
A2	139-145	97-101	105-108	130-138	114-119	117-122
A3	139-144	99-102	105-109	131-137	114-120	118-123
R0.4	142-148	101-103	109-111	133-138	119-123	118-123
R0.5	140-146	100-102	107-110	136-141	121-126	129-133
R0.6	135-141	95-97	101-103	130-135	114-119	120-125
I0.3	140-146	100-105	107-112	130-135	120-125	115-120
I0.4	138-143	99-103	105-109	133-138	120-126	122-127
I0.5	137-143	96-101	100-105	128-132	118-123	120-126

Table 4-3. Range of mixing temperature using different test methods for PMB40 as base binder

Binder Type	Test Methods (Temperature is in ˚C)					
	EQ	ZSV	S-ZSV	HSR-O	HSR-E	100000 S^{-1}
PMB40	173-180	118-120	138-141	170-176	157-163	163-169
PS1	168-175	115-117	133-136	163-169	151-156	152-158
PS2	167-173	115-118	132-135	160-167	148-154	148-154
PS3	163-169	111-114	127-130	156-162	144-149	144-150
PA1	166-172	112-115	130-134	161-166	148-152	150-157
PA2	165-171	110-115	126-132	158-164	147-151	146-152
PA3	160-166	107-110	124-128	155-160	142-148	144-152
PR0.4	168-174	114-117	133-136	165-171	153-158	159-165
PR0.5	166-173	113-116	132-135	163-169	151-156	156-162
PR0.6	166-173	113-115	131-134	163-170	151-157	159-165
PI0.3	166-172	108-114	130-135	164-168	150-156	157-162
PI0.4	164-170	105-111	129-135	159-164	150-156	154-161
PI0.5	163-169	105-110	130-136	160-167	150-156	154-162

Table 4-4. Range of compaction temperature using different test methods for PMB40 as base binder

Binder Type	Test Methods (Temperature is in ˚C)					
	EQ	ZSV	S-ZSV	HSR-O	HSR-E	100000 S^{-1}
PMB40	160-166	109-111	125 -128	157 -162	141 -146	151 -156
PS1	155-161	106-108	120-123	150-156	134-139	140-145
PS2	154-159	106-109	119-122	148-153	132-137	137-142
PS3	150-155	103-105	114-117	143-149	128-133	133-138
PA1	156-162	105-109	122-126	148-155	136-141	141-146
PA2	155-160	104-108	120-124	147-153	134-139	138-143
PA3	152-156	104-109	117-121	144-151	130-138	134-139
PR0.4	155-160	106-108	121-123	152-158	137-142	147-152
PR0.5	154-159	105-107	119-122	150-156	135-140	144-149
PR0.6	153-159	105-107	118-121	151-156	135-140	146-152
PI0.3	154-159	105-109	120-124	150-155	135-141	144-151
PI0.4	153-157	104-108	118-123	148-154	134-141	142-148
PI0.5	153-158	104-108	117-120	148-152	134-141	143-150

4.5.2 Phase 2: Determination of MT and CT Using DSR

The phase angle method was developed to determine the mixing and compaction temperatures of polymer modified binders. In literature, it has been stated that the phase angle method works well for polymer modified binders. Therefore, to check the suitability of phase angle method, it has been performed on various polymer modified binder obtained from different sources. To

do this, four different polymer modified binder were selected, in which P1 is base binder used for WMA modification as stated in Chapter3. The physical properties of these binders are shown in Table 4-5. Determination of MT and CT using phase angle method is shown in Figure 4-9. The frequency corresponding to phase angle 86 degree determined at 80˚C was used for determination of MT and CT. All binder exhibits same viscous behaviour at phase angle of 86 degrees. Table 4-6 shows the MT and CT of different polymer modified binders determined from phase angle method. It can be seen that MT of different PMBs were ranging from 164-175˚C whereas CT were ranging from 150-161˚C. The variation in MT and CT can be attributed to their different sources. It can be seen that the MT and CT of PMBs was lower than 180-190°C. This indicates the production temperatures obtained from the phase angle method were realistic and implementable in field without any adverse effect (degradation of polymer and excessive aging) on pavement performance. These results were found to be consistent with past studies [13,143,375]. In addition, it also shows the applicability of the phase angle method for determining the production temperatures of PMBs binders. Although the production temperatures determined from the phase angle method were accurate, these were higher from an environmental perspective. This can be minimized by incorporating WMA additives into the polymer modified binders. After this, the evaluation of MT and CT of WMA modified binders has been explored using phase angle method. The MT and CT of polymer modified binder are further used for studying the correlation between tribology based approach and phase angle method. The results of correlation have been discussed in Chapter 5.

Table 4-7 shows the MT and CT of all WMA modified binders using phase angle method. The mixing and compaction temperatures for VG 30 were found to be 159˚C and 146˚C, respectively. These temperatures are approximately consistent with the temperatures predicted using the EQ method. On the other hand, MT and CT for PMB40 were found to be 166˚C and 154˚C, respectively. As discussed earlier, the MT and CT obtained from phase angle method

were appropriate and implementable in field and consistent with past studies. From Table 4-7, it can be seen that the production temperatures show inconsistent trends for warm mix modified asphalt binders. This observation is true for both the base binders (VG30 and PMB40). For asphalt binders modified with organic additives (Sasobit and Asphaltan), the increase in dosage increases the production temperatures, which is unlikely. This is because the phase angle measurements are made at temperatures lower than the melting point of organic additives, where they crystallize and forms a lattice structure. The crystallization increases the stiffness and lowers the value of reduced frequency corresponding to the phase angle of 86˚. This results in higher mixing and compaction temperatures compared to the base asphalt binder. On the contrary, chemical additives (Rediset and Iterlow) does not show any variation in production temperatures. The reason behind this behaviour is that the measurement of phase angle is taken near to the temperature at which chemical additives does not change the rheology of the asphalt binder [376,377]. Thus, they do not affect the phase angle values obtained at the reference temperature of 80˚C. Therefore, PAM does not indicate any change in mixing and compaction temperatures for the asphalt binders modified with chemical-based additives. The obtained temperatures are very similar to the production temperatures of the base asphalt binders. The same trend has been observed with addition of chemical additives to PMB40. The unexpected trends/observations indicate that PAM may not be a good method to predict the production temperatures for warm mix modified asphalt binders.

Table 4-5. Physical properties of different polymer modified binders used in phase angle method.

Type of Polymer modified binders	**Abbreviation**	**Penetration value at 25˚C**	**True failure temperature (High PG)**
PMB40 (base binder mentioned in Chapter 3 supply by Hincol)	P1	49	84.9 (PG82)
PMB40 (IOCL)	P2	45	85.9 (PG82)
PMB 40 (Shell Bitumen)	P3	43	87.5 (PG82)
PMB 40 (Local Supply)	P4	50	82.4 (PG82)

Table 4-6. MT and CT obtained using phase angle method for different polymer modified binders.

Type of Polymer modified binders	**Mixing Temperature (˚C)**	**Compaction Temperature (˚C)**
P1	166	154
P2	172	160
P3	175	161
P4	164	150

Table 4-7. MT and CT obtained using phase angle method for WMA modified binders.

Type of Binder	**Production Temperatures**		**Type of Binder**	**Production Temperatures**	
	MT (˚C)	**CT (˚C)**		**MT (˚C)**	**CT (˚C)**
VG30	158	146	PMB40	166	154
S1	163	149	PS1	171	158
S2	183	165	PS2	187	165

S3	290	241	PS3	280	246
A1	160	150	PA1	168	159
A2	178	163	PA2	180	163
A3	240	220	PA3	250	222
R0.4	158	145	PR0.4	165	152
R0.5	158	146	PR0.5	163	152
R0.6	158	145	PR0.6	163	153
I0.3	157	144	PI0.3	164	152
I0.4	156	144	PI0.4	163	152
I0.5	155	144	PI0.5	163	151

4.5.3 Drawback of Phase Angle Method for Organic and Chemical Additives

Approach for the phase angle method is based on non-Newtonian behaviour of asphalt binder, which is generally observed with polymer modified binders. The method evaluates the MT and CT using the viscous behavior of the binder at 80°C, represented by a phase angle of 86°. Binders exhibiting more viscous behavior (i.e., higher phase angle) typically require lower MT and CT while those with less viscous behavior (i.e., lower phase angle) require higher MT and CT.

Organic additive shows dual behaviour around their melting point. Generally melting point of organic additives lies between 80^{o}C-100 ^{o}C depending upon the length of carbon atoms in their structure. The organic additives reduces viscosity above the wax's melting point due to liquefaction of these waxes thereby facilitating the production of asphalt mixes at lower temperatures. During cooling of asphalt binder below melting point, these additives solidify into microscopically small particles dispersed evenly throughout the bitumen [10]. Consequently, this phenomenon leads to a stiffening of the binder, resembling the behaviour

of fiber-reinforced materials[79][80]. This behaviour of organic additives above and below the melting point can be clearly seen in Figure 4-10. To use phase angle method for organic additives, the phase angle measurements are made at temperatures lower than the melting point of organic additives, where they crystallize and forms a lattice structure. The crystallization increases the stiffness and lowers the value of reduced frequency corresponding to the phase angle of 86˚. This lower value of reduced frequency results into higher value of MT and CT which can be observed from Table 4-7. But the organic additives are WMA additive that lowers the MT and CT of base binders (generally by reducing viscosity). This showed that the prediction of MT and CT based on phase angle cannot be applied to the organic additives which exhibit dual nature around the temperature of 80^{o}C. On the other hand, chemical additives do not change/affect the rheology (stiffness) of the asphalt binder as can be seen from Figure 4-10. Since chemical additives do not change the rheology of the asphalt binder, same reduced frequency as that of base binder is obtained when the measurement of phase angle is taken near to the temperature at 80˚C. Therefore, phase angle does not indicate any change in mixing and compaction temperatures for the asphalt binders modified with chemical-based additives. Therefore, the temperature reduction due to chemical additives cannot be assessed using this method. Finally, it can be concluded that the phase angle method works well for polymer modified binder but inapplicable for WMA modified binders.

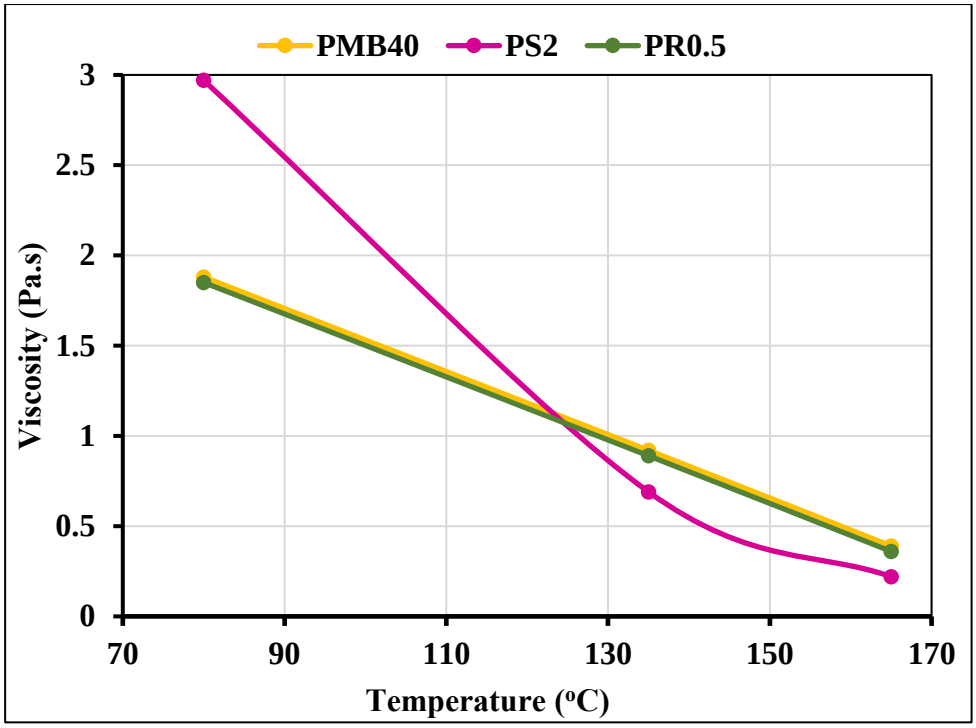

Figure 4-10. Behaviour of polymer and WMA modified binders over the range of temperatures.

4.6 Summary

This chapter discussed the applicability of various viscosity based approaches for evaluation of production temperatures of WMA modified binders. In addition, suitability of the phase angle method for polymer and WMA modified binders has also been discussed in this Chapter. These various approaches were used to assess the reduction in mixing and compaction temperatures offered by different warm mix technologies. It has been found that the conventional EQ method cannot be suitable for WMA modified binders due to its shear dependency. However, the EQ method was found to be suitable for viscosity grade binder i.e. VG30. In addition, other viscosity based approaches (ZSV, S-ZSV, HSR-O, HSR-E, Flow behaviour approach) also showed their inapplicability to characterize the WMA modified binders. The phase angle method was found suitable for polymer modified binders and MT and CT obtained from the method are feasible in field. However, the phase angle method also fails to determine the MT and CT of organic and chemical WMA additives. This can be due to their

different mechanism involved in reduction of production temperature. This chapter proved that the conventional viscosity criteria cannot be used for justification of reduced temperature in the case of WMA technology. Recently it has been hypothesed that the mechanism by which warm mix technologies reduce the production temperatures could be related to the reduction in friction at the contact zone of the mineral aggregates and asphalt binder [15,191,194]. This reduction in friction leads to improved workability in the asphalt mixture produced with WMA technology. The friction between mineral aggregate and asphalt binder can be studied using the science of tribology. The use of tribology for determination of MT and CT of WMA technology has been discussed in Chapter 5.