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Effect of Mixing and Compaction Temperature on Dynamic Modulus of Modified Binder Bituminous Mixtures

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Abstract

Modified binders are increasingly used to cater to the high tire pressure and frequency of loading. The use of modified binders poses considerable challenges in terms of material characterization and distress prediction. However, one area which is least explored is related to the mixing and compaction temperature to be used for mix production using modified binders.

In this investigation, the influence of mixing and compaction temperature on the dynamic modulus of bituminous mixtures produced using two modified binders is studied. A polymer modified binder (PG70-16) and an improved crumb rubber modified binder (CRMB-IMP) was used with Bituminous Concrete Grade 2 of the Indian Specification. Samples were fabricated with two sets of mixing and compaction temperature. In the first set, the samples were produced with the mixing and compaction temperature used in the current field practice (20°C higher than that of unmodified binder). In the second set, samples were mixed at a temperature corresponding to the non- Newtonian to Newtonian transition regime. To establish such regime, a shear rate sweep was carried out on the binder using a rotational viscometer. The AASHTO protocol was followed for fabricating the samples of bituminous mixtures and dynamic modulus was determined as a function of frequency and temperature. The collected dynamic modulus values were used to fit a master curve and it was found that considerable differences exist in the master curve between the dynamic modulus values of mixtures produced using these two protocols though the volumetric properties of these mixtures were identical. It is clearly seen from this exercise that when it comes to modified binders, even rudimentary issues related to mixing and compaction temperature are not resolved.

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1. Introduction

Selection of appropriate mixing and compaction temperature is very critical in producing bituminous mixtures with the required mechanical and volumetric properties. The choice of the mixing and compaction temperature depends on the binder viscosity. In current practice, for unmodified binders, the mixing temperature is selected based on viscosity limits of 0.17±0.02 Pa.s and the compaction temperature is determined based on viscosity limits of 0.28±0.03 Pa.s (Asphalt Institute, 2003). In the extensive survey carried out by NCHRP (West et al., 2010), it was found that most countries follow manufacturer specified mixing and compaction temperature in case of modified binders. Typical manufacturer specification suggests increasing the mixing and compaction temperature up to 20°C when compared to unmodified binders (West et al., 2010).

Various researchers have used different techniques to determine mixing temperature for modified binder. Yildrim et al., 2000, used viscosity-temperature chart and the temperature corresponding to the viscosity of 0.17±0.02 Pa.s and 0.28±0.03 Pa.s was taken as the mixing and compaction temperature respectively. Here, the same viscosity range that is used for the unmodified binder was used. Bahia et al., 2001, used zero shear viscosity in determining the mixing and compaction temperature. The mixing and compaction temperature obtained using zero shear viscosity was found to be less than that obtained from conventional viscosity chart. Recently, NCHRP in a provisional standard suggested a test methodology for determining the mixing temperature based on Newtonian response of the material. From the oscillatory shear test conducted at 50, 60, 70 and 80 ºC, they captured the phase lag to construct a master curve and the mixing temperature was determined from the frequency corresponding to the phase angle of 86 º (West et al, 2010).

Determination of compaction temperature is even more challenging when compared to mixing temperatures. At these temperatures, the material exhibits transition from Newtonian to a non-Newtonian fluid and hence the determination of a viscosity at any specific temperature will be non-unique. The decrease in viscosity due to the shear thinning behavior of the modified binder due to shearing and the increase in viscosity due to temperature drop rather complicates the issue. In real life, since the compaction density is the only quality control parameter used for checking the compaction of pavement, most of the contractors and modified binder manufacturers set a compaction temperature and roller passes to get the required density. However, it is possible that for a given density (or air voids), the possibility of a widely varying mechanical properties exists and unless one understands the issues related to compaction mechanics, it is not possible to arrive at an unique compaction temperature range for a given binder and mix (Saradhi et al., 2008).

Added to the above issues is the aging that happens to the mix during mixing and compaction. During the transport of mix from hot mix plant and during compaction considerable aging occurs to the binder and this also influences the manner in which compaction could be carried out. To simulate the short term aging of the mix, the current AASHTO protocol prescribes that the mix be kept in an oven for a specific temperature for 4 hours before compaction (AASHTO PP2, 1994). Prior to compaction, the sample is then transferred to another oven which is kept at the compaction temperature for 30 minutes and immediately thereafter the sample is compacted. While there is considerable discussion and debate in the technical literature (Bahia et al., 2001 and West et al., 2010) about compaction temperature for mixes with modified binders, it is not clear whether the short-term aging protocol for mixes with unmodified binders could be identically adopted for mixes with modified binder.

In this investigation, test protocols were established to determine the mixing and compaction temperature for modified binders. Using this protocol, samples were cast. In addition, the mixing and compaction temperature as adapted by Indian Highway Engineers (20 °C more than unmodified binder) was also used and samples were cast. Dynamic modulus measured at different temperatures and frequencies were used to compare the difference in the properties.

2. Determination of Mixing and Compaction Temperature of Modified Binders

2.1 Materials

In this work, a polymer modified binder (PG 70-16) and an improved crumb rubber modified binder (CRMB-IMP) was used for fabricating samples satisfying the Bituminous Concrete grade-2 (BC-2) specification of the Ministry of Road Transport and Highways, India (MoRTH, 2001). These modified binders were produced using VG 30 binder at the R&D facility of Bharat Petroleum Corporation Limited (BPCL). The PG 70-16 and the CRMB-IMP are the nomenclatures proposed by BPCL. The material properties of the modified asphalt used in this investigation are listed in Table 1.

Table 1: Properties of modified materials

Tests	PG70-16	CRMB-IMP
Penetration at 25 ºC	46	52
Softening Point (R&B) (ºC)	55	51
Elastic recovery of half thread in ductilometer at 15 ºC (%)	58	50
Temperature corresponding to G*/sin δ for 1.0 kPa at 10 rad/s (ºC)	82.3	93.7
Separation, difference in softening point, R&B (ºC)	0.1	1.5
Viscosity at 150 ºC (Poise)	6.09	17.6
Loss in mass on short-term aging (%)	0.04	0.87
Increase in softening point on short -term aging (ºC)	5	6
Reduction in penetration after short- term aging	5	13.33
Elastic recovery of half thread in ductilometer at 25 ºC of short-term aged binder (%)	72.5	69.5
Temperature corresponding to G*/sin δ for 2.2 kPa at 10 rad/s (ºC)	83.4	86.5

2.2 Experimental Investigations on binder

The main focus of this investigation is to find the mixing temperature of modified binder and it is hypothesized here that the non-Newtonian – Newtonian transition temperature holds the key to determining such temperatures (see for instance a similar assumption made by Bahia et al. 2001). Several experimental protocols are available to determine such transitions. Padmarekha and Krishnan (2011) used three different experimental protocols to determine the on-set of Newtonian regime for unmodified binders. In the first test protocol, the temperature and shear rate during the test was simultaneously varied and the viscosity was measured by them. In the second test protocol, the binder was subjected to shear rate ramp at constant temperature and in the third test protocol, the material was tested at a constant temperature and shear rate. In all these test protocols, the temperature corresponding to shear rate independent viscosity was used to determine on-set of Newtonian behavior. The transition from Newtonian to non-Newtonian behavior was found to be dependent on the test protocol. In this investigation, the shear rate sweep test protocol that was conducted at constant temperature was used to determine the mixing temperature (Newtonian temperature). Brookfield HA DV-II rotational viscometer with the

thermosel apparatus was used for characterizing the rheological response of the binder. The SC4- 21 spindle of 16.77 mm diameter and 35.15 mm effective length was used. The sample preparation was carried out as per ASTM D4402, 2006. The sample in the rotational viscometer was subjected to incrementing shear rate at constant temperature. The material was initially pre-sheared for 5 min at an angular velocity of 10 rpm and then gradually increased to 20 rpm at a rate of 0.02 rpm/sec and decreased at the same rate to 10 rpm. Figure 1 shows the imposed angular velocity as a function of time. Fresh samples were used while conducting tests at different temperatures. The absolute viscosity as a function of shear rate at different temperatures was recorded. The details of the experiment conducted are listed in Table 2.

Figure 2 shows the variation of apparent viscosity as a function of shear rate for PG 70-16 binder. It is clearly seen that at 140 ºC, during shear rate increase ramp, the apparent viscosity of the binder decreases as the shear rate increases exhibiting shear thinning response. Due to the history of deformation to which the binder was subjected, the change in the apparent viscosity as a function of shear rate was not predominant during the downward ramp. At 150 ºC, though the effect of shear thinning behaviour was not that considerable as compared to 140 ºC, one could notice the difference in viscosity due shear rate increase and decrease ramp. The viscosity of the binder at 160 ºC was fully and completely independent of shear rate and also the viscosity during shear rate increase and decrease ramp were identical. From this, one can conclude that the PG 70-16 binder exhibited Newtonian response at 160 ºC. Figure 3 shows the shear rate sweep test results of CRBM-IMP binder and one could see that the CRMB-IMP material exhibited Newtonian response at 180 ºC. We hasten to add here that it is possible for the material to show Newtonian response at temperatures between 150 and 160 ºC for PG70-16 and between 170 and 180 ºC for CRMB-IMP. To determine that one needs to run several experiments and such exercise was not attempted here.
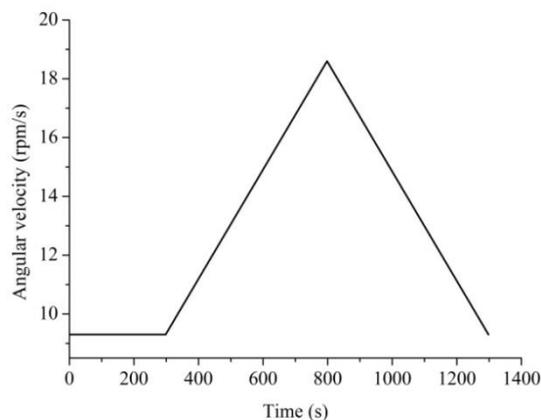

Fig 1. Angular velocity as a function of time

Table 2. Binder testing conditions

Materials	Temperature (°C)	Angular velocity range (rpm)
PG70-16	140, 150, 160	10-25
CRMB – IMP	160, 170, 180	10-20

As discussed earlier, the temperature corresponding to the on-set of Newtonian response of the binder was considered as the mixing temperature. The compaction temperature was considered 10 ºC less than the mixing temperature following the accepted practice and the conditioning temperature for short-term aging was kept at 135 °C as per the AASHTO practice (AASHTO PP2, 1994 and Bahia et al., 2001). Table 3 details the mixing,

conditioning and compaction temperature determined as per the new protocol as discussed here (Protocol II). The mixing and compaction temperature that were used in the current practice were determined from that of unmodified VG 30 binder. The mixing and compaction temperature for unmodified binder determined as per Asphalt Institute, 2003 is listed in table 3. Protocol I in Table 3 corresponds to the current field practice wherein 20 °C is added to the unmodified binder mixing, conditioning and compaction temperatures.

3. Effect of Mixing and Compaction Temperature on Dynamic Modulus of Modified Binder Mixtures

The bituminous mix pertaining to BC grade 2 were fabricated using unmodified binder and the modified binders. Two sets of bituminous mix samples were fabricated with different mixing and compaction temperature mentioned against protocol I and protocol II in Table 3. All the BC mixes were prepared for a 4±0.5% target air voids with 5% bitumen content. After mixing, the mix was kept in the oven for 4 hours to simulate aging that occurs due to mixing and compaction process. For unmodified binder, the temperature during this process is maintained at 135 °C for 30 min. The mix temperature after short term aging is increased to compaction temperature before compaction. The sample was compacted using Superpave gyratory compactor and the number of gyration used corresponded to 30 million standard axles. The cylindrical specimens of 165 mm height and 150 mm diameter were produced and cored to the size of 150 mm height and 100 mm diameter for testing. Totally 16 set of samples were casted and cored for testing. Table 4 lists the air voids of the samples fabricated. Gmb in the table represents bulk specific gravity, Gmm represents maximum specific gravity, VMA represents percentage voids in mineral aggregate, VFA represents percentage voids filled by asphalt and $|E^*|_{max}$ represents maximum limiting dynamic modulus. The data related to unmodified binder is not shown here for brevity.
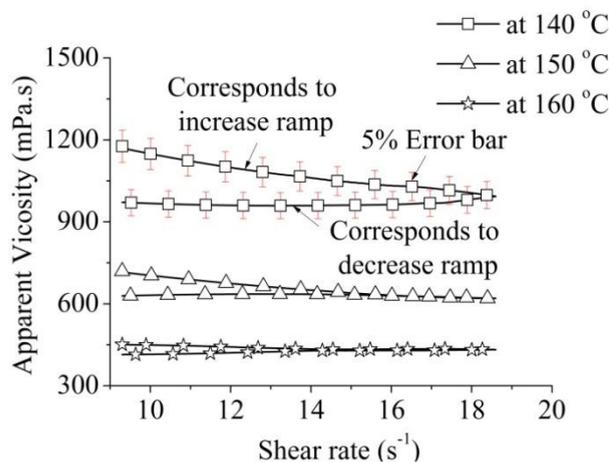

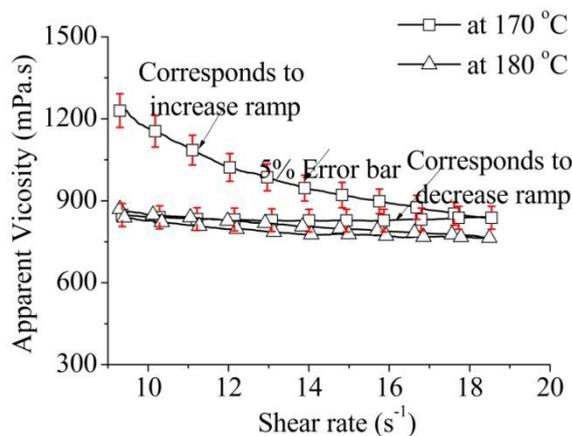Fig 2. Shear rate sweep results of unaged PG-70/16 binder   Fig 3. Shear rate sweep results of unaged CRMB-IMP binder

Table 3. Mixing and compaction temperatures

Test Protocol	Binder	Temperature (°C) for		
		Mixing	Aging	Compaction
AI, 2003	Unmodified Controlled Binder (VG 30)	165	135	150
Protocol I	All modified binder	185	155	170
Protocol II	PG 70-16	160	135	150
	CRMB – IMP	180	135	170

Table 4. Air voids and maximum limited dynamic modulus of the entire samples tested

Sample Details		Air voids (%)	Gmb	Gmm	VMA (%)	VFA (%)	$|E^*|_{max}$ (kPa)
Binder and Test Protocol	Sample Number						
PG 70-16 (Protocol I)	PG-1	4.44	2.472		11.949	62.841	2.26E+07
	PG-2	4.47	2.473	2.587	11.918	62.494	2.25E+07
	PG-3	4.54	2.470		12.041	62.295	2.27E+07
	PG-4	4.52	2.470		12.022	62.403	2.25E+07
PG 70-16 (Protocol II)	NPG-1	4.04	2.501		10.931	63.040	2.31E+07
	NPG-2	3.64	2.511	2.606	11.918	69.458	2.33E+07
	NPG-3	4.09	2.499		10.977	62.741	2.31E+07
	NPG-4	3.57	2.513		10.494	65.982	2.33E+07
CRMB-IMP (Protocol I)	CI-1	4.19	2.491		11.275	62.837	2.29E+07
	CI-2	4.65	2.479	2.600	11.918	60.983	2.27E+07
	CI-3	4.27	2.489		11.349	62.375	2.29E+07
	CI-4	4.27	2.489		11.349	62.375	2.29E+07
CRMB-IMP (Protocol II)	NCI-1	3.79	2.508		10.664	64.461	2.32E+07
	NCI-2	4.18	2.498	2.607	11.918	64.927	2.30E+07
	NCI-3	4.56	2.488		11.379	59.927	2.28E+07
	NCI-4	4.18	2.498		11.027	62.091	2.30E+07

The maximum dynamic modulus was determined from

$$|E^*|_{max} = P_c \left[4,200,000 \left(1 - \frac{VMA}{100} \right) + 435,000 \left(\frac{VFA \, x \, VMA}{10,000} \right) \right] + \frac{1 - P_c}{\left[\frac{1 - \frac{VMA}{100}}{4,200,000} + \frac{VMA}{435,000(VFA)} \right]}, \tag{1}$$

where, P_c is given by $P_c = \frac{\left(20 + \frac{435,000 \, (VFA)}{VMA} \right)^{0.58}}{650 + \left(\frac{435,000 \, (VFA)}{VMA} \right)^{0.58}}$. It can also be seen that there is not considerable difference in the air voids of samples fabricated with both the protocols.

All the samples were subjected to compressive haversine load with a contact load of 5 kPa magnitude. The test was conducted in the unconfined loading condition as per AASHTO TP 79, 2010. The load amplitude during testing was adjusted so as to maintain the resulting axial strain between 75 and 125 micro-strains. This is carried out automatically by the equipment. The experiments were conducted at different frequencies of 0.01, 0.1, 0.2, 0.5, 1, 2, 5, 10, 20 and 25 Hz and at 5, 25, 45 and 55 ºC. The data acquisition system recorded the axial deformation due to haversine load using three displacement transducers and dynamic modulus and phase lag were calculated. The sample data for the stress applied and the resultant strain at a frequency of 2 Hz for a bituminous mix prepared with PG 70-16 binder as per protocol I is shown in figure 4.
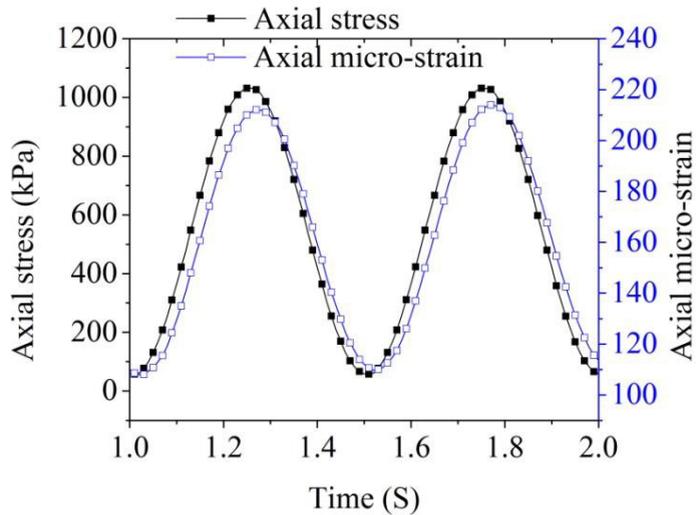
Fig 4. Stress - strain response due to compressive haversine loading of PG 70-16 bituminous mix

Figure 5 compares the dynamic modulus of the mix producing using PG 70-16 binder for two different mixing and compaction temperature. The dynamic modulus of the mix produced using CRMB-IMP is show in Figure 6. As can be seen, the dynamic modulus values of two sets of samples were identical with the variation not exceeding the acceptable statistical limit of 9.2% (AASHTO TP 79, 2010). The dynamic modulus master curve was constructed appealing to time-temperature superposition principle. The master curve construction was carried as per the requirement of mechanistic empirical pavement design approach (NCHRP, 2004). The dynamic modulus data at different temperature were shifted suitably so as to fit the function given in equation 2. The shift factor used for shifting the dynamic modulus was obtained from equation 3.

$$\log|E^*| = \delta + \frac{(|E^*|_{max} - \delta)}{1 + e^{\beta + \gamma\left\{\log\omega + \frac{\Delta E_a}{19.14714}\left[\left(\frac{1}{T}\right) - \frac{1}{T_r}\right]\right\}}}, \tag{2}$$

$$\log[a(T)] = \frac{\Delta E_a}{19.14714}\left[\frac{1}{T} - \frac{1}{T_r}\right]. \tag{3}$$

Here, $|E^*|$ represents dynamic modulus, ω is the frequency at the temperature at the temperature T, T_r is the reference temperature in °K, ΔE_a is the activation energy (treated as a fitting parameter), $a(T)$ represents shift factor at temperature T and $|E^*|_{max}$ represents maximum limited dynamic value of the mix. This shifting is carried out using Rhea software (RHEA, 2012) and the master curve was obtained for the reference temperature of 21°C. The master curve with the respective shift factor is shown in Figure 7 and 8.

From the master curve, it can be seen that the dynamic modulus near the testing frequency for both the sets of sample were the same. However, one can observe that there exists considerable difference in dynamic modulus at lower and higher frequencies. One can also notice that the dynamic modulus of the protocol II sample is consistently lower than protocol I. Also, the maximum limited dynamic modulus value (listed in Table 4) for protocol II is lesser than the protocol I. The reason might be due to different aging temperature to which the mix was subjected to. In protocol I, the aging of mix was carried out at higher temperature which might have resulted

in higher dynamic modulus. It should be noted that AASHTO recommends the use of this master curve in the mechanistic empirical pavement design. It is possible that if a different master curve method is used, there may not be this much variation at the higher and lower frequencies.
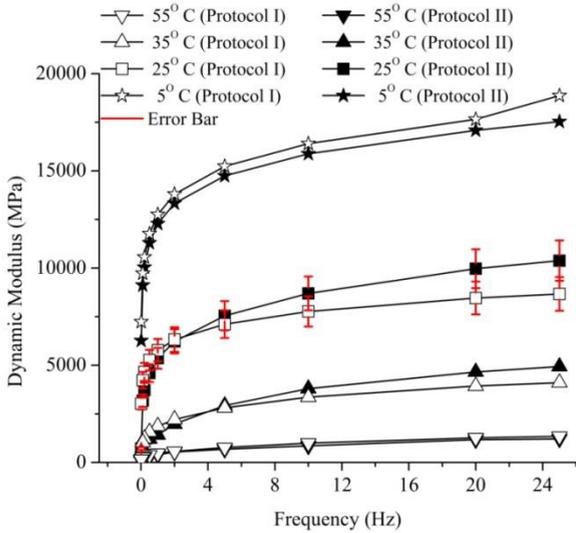

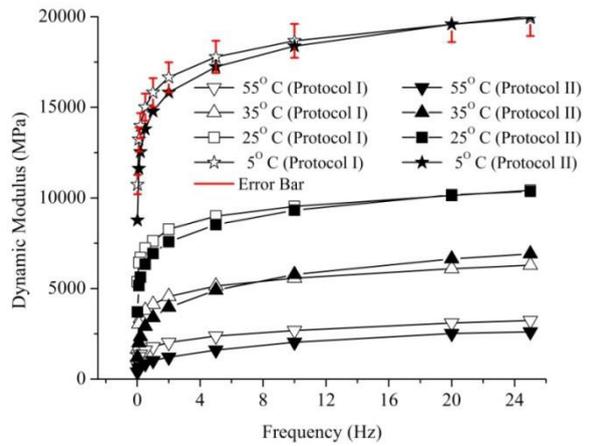Fig 5. Dynamic modulus of the bituminous mix produced using PG 70-16

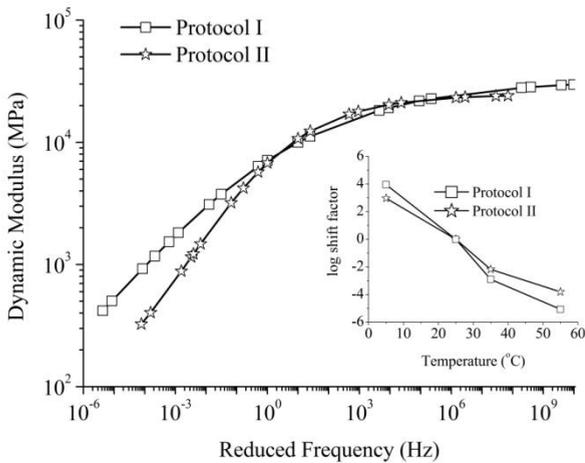Fig 6. Dynamic modulus of the bituminous mix produced using CRMB - IMP

Fig 7. Master curve and shift factor for mix produced using PG 70-16 binder
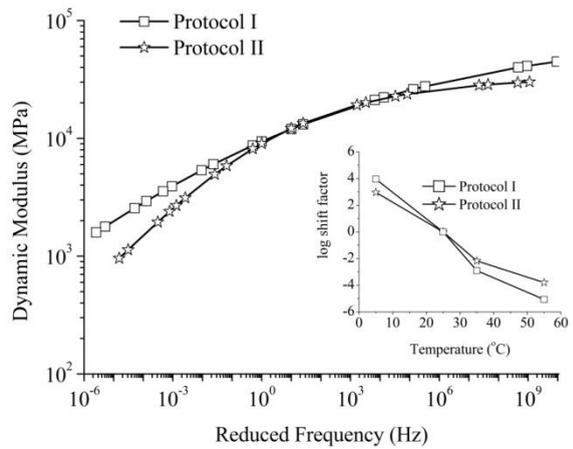

Fig 8. Master curve and shift factor for mix produced using CRMB - IMP binder

4. Conclusion

Ever increasing traffic volume and traffic load demands the use of modified binder. The full benefits of the use of modified binder can be obtained only if one understands the intricacy in selecting mixing and compaction temperature of mixture produced using modified binder. The mixing and compaction temperature for the mix plays a key role in controlling the mechanical properties of the mix. This investigation focused on two different

approaches for the mixing and compaction temperature for modified binders. While the first approach used 20 °C in excess of unmodified binder, the second approach determined the mixing and compaction temperature based on the rheological response of modified binders. The dynamic modulus values of bituminous mixes were within experimental error range, however, the master curves differed at lower and higher frequencies.

References

AASHTO PP2. (1994). *Standard practice for mixture conditioning of Hot-Mix Asphalt (HMA).* American Association of State Highway and Transportation Officials, Washington D.C.,

AASHTO TP 79. (2010). *Standard method of test for determining dynamic modulus and flow Number for hot mix asphalt using the Asphalt Mixture Performance Tester (AMPT).* American Association of State Highway and Transportation Officials*,* Washington, D.C.

Asphalt Institute (2003). *Superpave mix designs, superpave series no. 2. (SP-2).* Asphalt Institute, Lexington, KY, USA.

ASTM-D4402. (2006). *Standard test method for viscosity determination of asphalt at elevated temperatures using a rotational viscometer.* ASTM International, West Conshohocken, PA.

Bahia H. U., Zeng D. I. H. M., Zhai H., Khatri M. A. and Anderson R. M. (2001). *Characterization of modified asphalt binders in superpave mix design.* Transportation Research Board, National Research Council, Washington, D.C.

IS 15462. (2004). Polymer and rubber modified bitumen - specification. The Bureau of Indian Standards, New Delhi, India.

MoRTH. (2001). *Specification for roads and bridge work.* 4th revision, Ministry of Shipping, Road Transport and Highways, New Delhi, India.

NCHRP, (2004). *Guidelines for the mechanistic-empirical design for new and rehabilitated pavement structures*, Transportation Research Board, Washington, D.C.

Padmarekha A. and Krishnan J. M. (2011). Experimental investigations on high temperature transition of asphalt. *Construction and Building Materials*, 25, 4221-4231.

RHEA. (2012). *Rheology Analysis Software*, *Version 1*. ABATECH, Philadelphia, USA, http://www.abatech.com/RHEA.htm.

Saradhi, K., Eyad M. and Rajagopal K. R. (2008). A thermomechanical framework for modeling the compaction of asphalt mixes. *Mechanics of Materials*, 40(10), 846–864.

West R. C., Watson D.E., Turner P. A. and Casola J. R. (2010). *Mixing and compaction temperatures of asphalt binders in hot-mix asphalt.* Transportation Research Board, Washington, D.C.

Yildrim Y., Solaimanian M., Kennedy T. W. (2000). Mixing and compaction temperatures for Superpave mixes, *Journal of the Association of Asphalt Paving Technologist,* 69, 34-72.