CHAPTER 5. TRIBOLOGICAL ASSESSMENT OF WMA TECHNOLOGY

5.1 Preamble

Warm mix asphalt (WMA) offers a more sustainable alternative to traditional hot mix asphalt by enabling production at reduced temperatures, typically below 140°C [2]. This is made possible through the incorporation of various technologies such as organic additives, chemical agents, or water-based foaming methods. The use of such energy-efficient technology has replaced traditional hot mix asphalt (HMA), which requires mixing temperatures between 140°C and 180°C. The implementation of such technology can lead to significant enhancements in energy consumption and the release of pollutant gases. The use of WMA resulted in reductions in emissions across the board during the plant's production process. In addition, the WMA reduces the polycyclic aromatic hydrocarbons and asphalt aerosols/fumes. WMA was also found to use 30% less energy than conventional methods [113]. Along with WMA, the use of polymer modified binder (PMB) is common in pavement industry to enhance the performance of the pavement. The successful implementation of WMA and PMB depends on the accurate determination of production temperatures (mixing and compaction temperature) [117]. Inappropriate determination of mixing and compaction temperature leads to premature failure of the pavement [341]. Lower mixing temperature may lead to the insufficient coating of the asphalt binder over the aggregates, whereas lower compaction temperature can cause difficulty during field compaction, and may lower the in-field density [343]. On other hand, the higher production temperatures may result in oxidative hardening of asphalt binder and degradation of polymeric network in PMB, leading to premature failure of the pavement [131]. Past studies have shown that there are no standards available for the determination of production temperatures (mixing and compaction temperature) of WMA technology. The use of equi-viscous criteria for the determination of production temperatures of WMA and PMB may give unrealistic results. The NCHRP 648 study provides an overview of numerous techniques described in (chapter 4) for calculating the MT and CT for modified binders. The use of these procedures results in extremely low or high temperatures for several modified asphalt binders, which may cause a problem with compaction, emissions and deterioration of the asphalt binders' properties [143,267]. Recent studies have demonstrated that the conventional viscosity criteria cannot be used for justification of reduced temperature in the case of WMA technology [15,194]. These studies also shown 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. 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 help of tribology.

Tribology can be defined as the study of lubrication, friction, and contact zone between particles in relative motion [185]. Mixing and densification of WMA asphalt mixture lead to the reduction in friction, wherein mineral aggregate particles are in relative motion with a thin film of asphalt binder acting as the lubricating medium. Recently, the fundamentals of tribology have been successfully used to describe such mechanism. Being a new area of exploration, there are no guidelines available currently to explain the tribological characteristics of WMA technology. Along with this, the frictional characteristics of polymer modified binder using tribology has been unexplored in the literature. Therefore, for their successful implementations, it is necessary to conduct a detailed study on the use of WMA and polymer modified asphalt binders. This forms the motivation for this chapter. In this chapter, tribology test has been carried out on WMA and polymer modified binders to determine their mixing and compaction temperature. This chapter discuss the applicability of this tribological approach for determination of MT and CT of WMA technology used in viscosity grade binder and polymer modified binders. All the analysis was carried out by taking base binders (VG30 and PMB40 mentioned in Chapter 3) 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. Finally, in this chapter, a criterion based on the coefficient of friction has been proposed to determine the production temperatures for WMA and polymer modified binders. These criteria will encourage pavement engineers to implement sustainable WMA technology in field with better confidence.

5.2 Review of Tribological Studies Related to WMA Technology

The use of tribological concepts in WMA studies emerged from the argument that the reduction in production temperatures is a function of the improvement in the lubrication between the aggregates and asphalt binder, and therefore the traditional methodology of using viscosity as the guiding criteria may not always be applicable. Recent investigations have shown that the process responsible for the compaction and densification of warm mix additives can be attributed to two physical characteristics [117,376]. These include the lubricating properties of warm mix modified asphalt binder and the altered frictional characteristics at the interface between the binder and the aggregate. The concept of lubricity was coined in the pavement industry in 2007 by Reinke et al [12,188]. Thereafter, various tribological experiments, such as the asphalt boundary lubrication test, four-ball lubricity test, and ball-on-three-plates test (BOTP), have been performed on asphalt binders to understand the lubrication properties of different WMA technologies. The details of these studies have been discussed in Chapter 2. A representative list of previous studies is shown in Table 5-1.

Table 5-1. Review of tribology studies related to WMA technology

Organic Technology		
References	**Additive (dosage)**	**Tribology test**
[188]	Sasobit (0.5 w/b)	BOTP
[15]	Wax additive (0.5 w/b)	BOTP
Chemical Technology		
[12,188]	Revix (0.5% w/b)	Tribo-rheometry
[17]	Revix (0.5% w/b)	Four-ball lubricity test
[191]	• Oxidized polyethylene Lubricant (1% to 4% w/b) • Amine-based surfactant (1% to 2% w/b)	Four-ball lubricity test
[160]	• Rediset WMX (1%, 2% and 3% w/b) • Functionalized Polyolefin Polymer (FPE) (3.5% w/b) • Cecabase RT (0.7% w/b)	• Four-ball lubricity test • BOTP • Asphalt Boundary Lubrication Test
[188]	Evotherm (0.5 w/b)	BOTP
[15]	Chemical additive (0.4% and 0.8% w/b)	BOTP
[194]	Evotherm (0.25%, 0.50%, and 0.75% w/b)	BOTP
Foaming Technology		
[17]	Foaming (Foaming water content 1.0% to 2.0% w/b)	Four-ball lubricity test
[186]	Foaming (Foaming water content 1.0% – 3.5%)	BOTP

Previous research works have shown that incorporating warm mix additives into asphalt binder improves the coefficient of friction, irrespective of the type of WMA technology. The improved lubricating behaviour of asphalt binder is a function of various variables such as sliding speed, normal load, temperature, nature of interacting surface, etc., employed during the tribological test. The details of these variables can be found in Chapter 2. Majority of the previous studies have used ball-on-three-plates geometry to simulate the lubrication phenomena in the asphalt mixture. Additionally, this geometry ensures less contact stress as compared to other geometries. The present study used the ball-on-three-plates test to assess tribological behaviour of WMA additives and polymer modified binders, the details of which are described in the subsequent section.

5.3 Methodology

The current chapter is divided into two major phases. The first phase involves the evaluation of mixing and compaction temperatures based on rotational viscometer (RV) and tribology test. During first phase, various viscosity grade binders have been tested using RV to determine their MT and CT. These MT and CT have been used as the reference temperatures for tribology study. In initial phase, during tribology test, suitable combination of normal load and sliding speed has been identified. After that tribology test has been conducted on WMA and polymer modified binders using suitable normal load and sliding speed to determine their MT and CT. During tribology test, criteria based on coefficient of friction has been proposed for determination of MT and CT. The second phase includes the validation of MT and CT using workability test, coating ability test, and compactibility test. In this phase, the workability test has been developed and used for determination of MT and CT of WMA and polymer modified binders. These MT and CT obtained from workability test have been used for comparison and validation of MT and CT obtained from tribological approach. Finally, the MT and CT obtained from tribological approach have been validated using coating ability test and compactibility test.

Within this context, fourteen viscosity grade binder, four polymer modified binders, and four different warm mix additives were selected for the study. To estimate the production temperatures, various tests such as the rotational viscosity, workability, and BOTP, were performed in different phases. The findings obtained from multiple methods were subjected to further analysis to elucidate the mechanisms underlying the reduction of MT and CT as a result of implementing WMA technology. The research plan adopted for this chapter is shown in Figure 5-1.

The major objectives of the work are as follows:

1) To study the effect of sliding speed and normal load on the coefficient of friction in the BOTP experimentation.
2) To standardize tribological parameters (sliding speed and normal load) for determination of production temperatures of asphalt binders.
3) To study the effect of different plates (Steel, Granite, and Dolerite) on determination production temperatures of asphalt binders.
4) To establish ranges of coefficient of friction for estimating the production temperature using BOTP test.
5) To validate the MT and CT obtained from tribological approach using workability, coating ability and compactibility test.

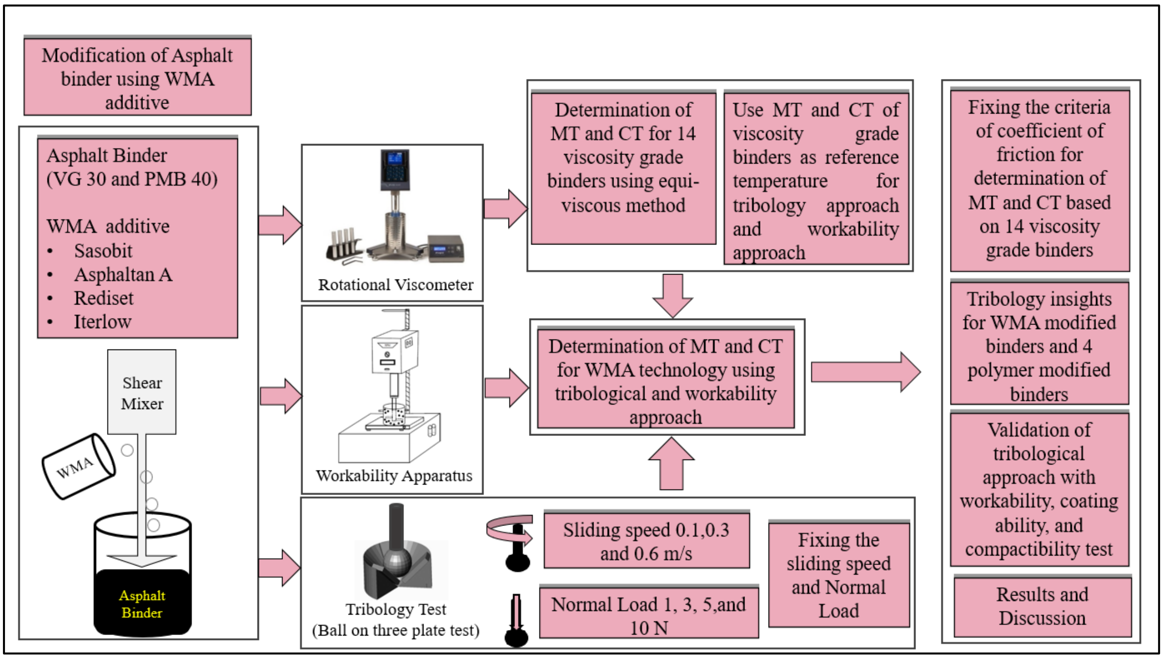


Figure 5-1. Research methodology adopted in this chapter.

5.4 Materials

In this study, fourteen viscosity grade asphalt binder and four polymer modified binders (PMB) from different sources were used for assessment of production temperature using tribological approach. The viscosity grade binders were classified using absolute viscosity at 60° C whereas penetration value at 25° C was used for classification of polymer modified binders. Four different warm mix additives (WMA): Sasobit, Asphaltan A, Rediset, and Iterlow were selected for the research work. The additives were blended with one of the viscosity grade binder i.e. VG30 (mentioned in Chapter 3) in accordance with manufacturer recommendations. The Sasobit and Asphaltan A which are organic additives were added in base asphalt binders (V8 i.e. VG30 and P1 i.e. PMB40 mentioned in Chapter 3) at dosage of 1,2, and 3% by weight of asphalt binder. The chemical additives Rediset and Iterlow were added in base asphalt binder (V8 and P1) at dosage of 0.4, 0.5, and 0.6% and 0.3, 0.4, and 0.5% by weight of asphalt binder, respectively. In this chapter, the V8 and P1 are the same base binders mentioned in Chapter 3. Due to use of many viscosity grade binders and polymer modified binders, they have designated as V8 and P1 in this Chapter. Table 5-2 summarizes the material selected for the study.

Table 5-2. Material selection summary

	Viscosity Grade Binders		
	Type	**Viscosity at 60°C (Pa.s)**	**Designation**
Asphalt Binder	VG30	250	V1
	VG30	251.6	V2
	VG30	254.8	V3
	VG30	260.1	V4
	VG30	265.5	V5
	VG30	271.1	V6
	VG30	275.6	V7
	VG30 (mentioned in Chapter 3 as base binder)	280	V8
	VG40	370	V9
	VG40	391.1	V10

	VG40	400.1	V11
	VG40	407.6	V12
	VG40	420.6	V13
	VG40	426	V14
	Polymer Modified Binders		
	Type	**Penetration value at 25ºC (dmm)**	**Designation**
	PMB40 (mentioned in Chapter 3 as base binder)	49	P1
	PMB40	45	P2
	PMB40	43	P3
	PMB40	50	P4
Warm Mix Additives	Sasobit (Organic)		S1 (V8+1% Sasobit by weight of binder) S2 (V8+2% Sasobit by weight of binder) S3 (V8+3% Sasobit by weight of binder)
	Asphaltan A (Organic)		A1 (V8+1% Asphaltan A by weight of binder) A2 (V8+2% Asphaltan A by weight of binder) A3 (V8+3% Asphaltan A by weight of binder)
	Rediset (Chemical)		R0.4 (V8+0.4% Rediset by weight of binder) R0.5 (V8+0.5% Rediset by weight of binder) R0.6 (V8+0.6% Rediset by weight of binder)
	Iterlow (Chemical)		I0.3 (V8+0.3% Iterlow by weight of binder) I0.4 (V8+0.4% Iterlow by weight of binder)

		I0.5 (V8+0.5% Iterlow by weight of binder)

Note: In viscosity graded binder, VGXX, the number XX in VGXX indicates that the asphalt binder's dynamic viscosity (at 60°C) falls between the range of XX × (100 ± 20) Poise. In polymer modified binder, PMB40, the number 40 indicates penetration value at 25°C.

5.5 Phase 1: Determination of MT and CT using RV and Tribology Test

5.5.1 Rotational Viscometer Test

In this study, rotational viscometer test was performed on all viscosity grade binders (V1 to V14) to evaluate their production temperatures. The test used Equi-viscous (EQ) method for the estimation of MT and CT of all binders according to the ASTM D2493. For the purpose of determining the MT and CT, the viscosity at two distinct temperatures (135°C and 165°C) were measured using rotational viscometer. The determination of MT and CT was based on the linear relationship between viscosity and temperature. The temperature ranges corresponding to the viscosity values of 0.170 ± 0.02 Pa.s and 0.280 ± 0.03 Pa.s, were referred to as mixing and compaction temperatures, respectively.

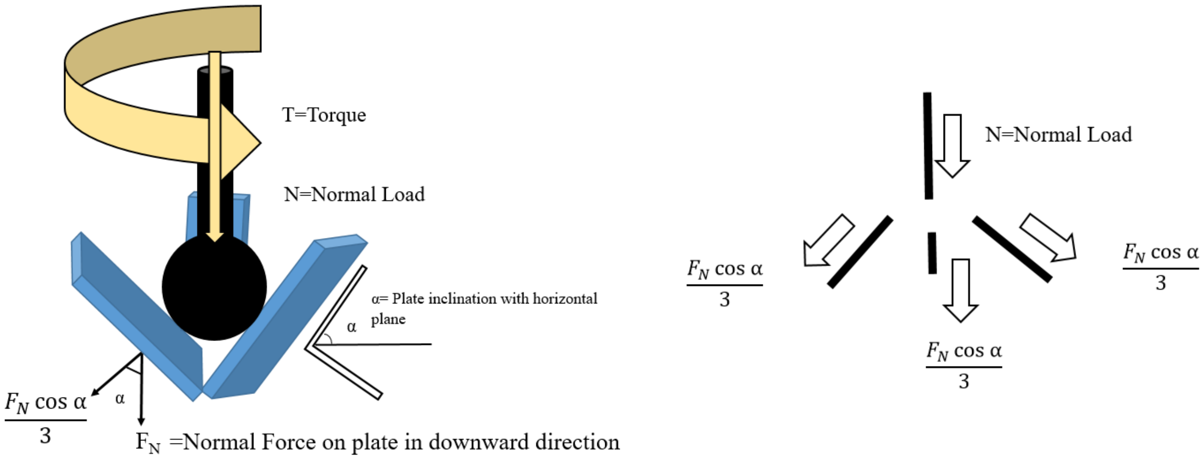
5.5.2 Tribology Test

The tribology test was performed through a tribological fixture fixed on the MCR 102 DSR (Anton Paar) ©. The fixture consisted of a ball-on-three-plates geometry (also known as ball-on-pyramid), as shown in Figure 5-2. The radius of the ball was 6.35 mm with a plate dimension of $3\times6\times16$ mm^3. Figure 5-5 shows a pictorial view of the ball and plates used in the study. This test was conducted to measure the coefficient of friction (CoF) for studying the lubricating behavior of the asphalt binders. CoF (μ) was determined using Equation 5-10, as discussed in subsequent section. The value of μ was determined by imposing axial load and sliding speed of different magnitudes.

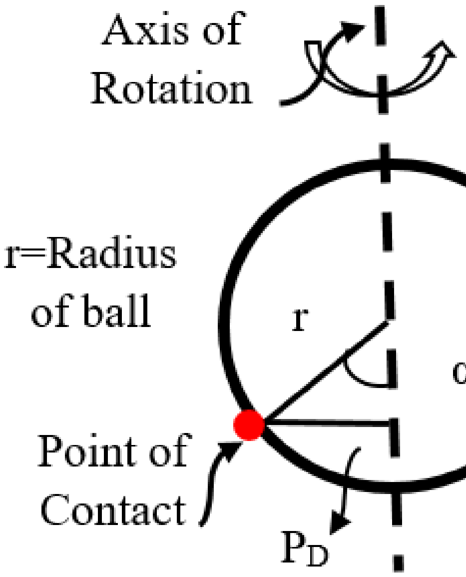
Figure 5-2. Ball-on-three-plates arrangement mounted on DSR

5.5.2.1 Calculation of CoF for Ball-on-Three-Plates (BOTP)

The BOTP geometry is generally mounted on a dynamic shear rheometer (DSR) [15]. To do the test, the device applies a torque T and a normal load N on the sample. The applied normal load is divided among the three plates (Figure 5-3b). F_N is the normal force acting on plates in the downward direction as shown in Figure 5-3.



a) (b)



(c)

Figure 5-3. a) Free body diagram b) Distribution of normal force among the plates c) determination of frictional force

To keep force balance across the axis of rotation and to hold contact between plates and the ball, the normal load acting through the spindle (shaft) should be equal to the normal force acting perpendicular to the plates. Therefore,

$$N = 3 \times \frac{F_N \cos \alpha}{3} \tag{5-1}$$

$$N = F_N \cos \alpha \tag{5-2}$$

$$F_N = \frac{N}{\cos \alpha} \tag{5-3}$$

To calculate the coefficient of friction (μ), it is necessary to calculate the frictional force between the plates and the ball. Due to the application of torque, the ball slides on the plate and generates a frictional force (F_F), which can be described mathematically as:

$$T = F_F \times P_D \tag{5-4}$$

Where, P_D (perpendicular distance) is the distance between the axis of rotation and the point of contact (see Figure 5-3c). From Figure 5-3 (c),

$$Sin\,\alpha = \frac{P_D}{r} \tag{5-5}$$

$$T = F_F \times r\sin\alpha \tag{5-6}$$

$$\mu = \frac{F_F}{F_N} \tag{5-7}$$

$$\mu = \frac{\frac{T}{r\sin\alpha}}{\frac{N}{\cos\alpha}} \tag{5-8}$$

$$\mu = \frac{T\cos\alpha}{\mathrm{N}\,r\sin\alpha} \tag{5-9}$$

For $\alpha = 45^{\circ}$, $\sin\alpha = \cos\alpha$

$$\mu = \frac{T}{\mathrm{N}\,r} \tag{5-10}$$

5.5.2.2 Parameters Considered During the Study

The value of μ is a tribo-system property comprising at least two bodies in contact, along with the surrounding environment and the interface (referred to as lubricant). In HMA, asphalt binder acts as the interface (lubricant) between mineral aggregates. The frictional behavior of asphalt binder during the test is influenced by various parameters such as normal load, sliding speed, surface roughness, temperature, etc. The list of influencing parameters has been discussed earlier. To study the effect of primary parameters on the value of μ, varying normal loads (1N, 3N, 5N, and 10 N), and sliding speeds (0.05 m/s, 0.1 m/sec, and 0.3 m/sec) were selected. The testing temperature was varied from 90°C to 160°C with an increment of 10°C. The selection of these temperatures covered the entire domain of the production temperatures for the selected asphalt binders. To neglect the effect of surface roughness, the test was performed using aggregate plates of constant surface roughness. Atomic force microscopy (AFM) was used to measure the surface roughness of the plates and details of surface roughness are mentioned inTable 5-3. The surface roughness of the plates was quantified using two key parameters: the average roughness (R_a) and the root mean square (RMS) roughness. The average roughness (R_a) is the arithmetic mean of the absolute values of the surface height deviations from the centerline, providing an overall measure of the surface texture. The RMS roughness (R_q) is the square root of the average of the squared deviations from the mean height, which emphasizes larger deviations and provides a more sensitive measure of surface irregularity. These parameters are commonly used to characterize the micro-texture of surfaces and are critical in understanding the tribological behavior in contact systems. Finally, the effect of these parameters was analyzed and used for the determination of production temperatures.

5.5.2.3 Preparation of Aggregates Plates

The study used two different types of aggregate plates for the tribology test. For the preparation of plates, the aggregates were collected from the local quarry. The two types of aggregates were selected for plate preparation: Granite, and Dolerite. The collected aggregates were cut using a stone cutter in such a way that it should give enough plates. The aggregates were cut into samples of size 3 × 16 × 6 mm. After cutting, the aggregates plates were polished using 280 silicon carbide (SiC) grit which is one of the polishing standards followed in the pavement industry [239,378]. The polishing was done to remove surface irregularities on surface due to cutting. The detailed procedure of aggregates plates preparation is shown in Figure 5-4. The polished substrate was then cleaned using an ultrasound bath at 60^{o}C for 30 minutes and placed in an oven for drying at 110^{o}C for 24 hours. The prepared plates were used for the tribology test.

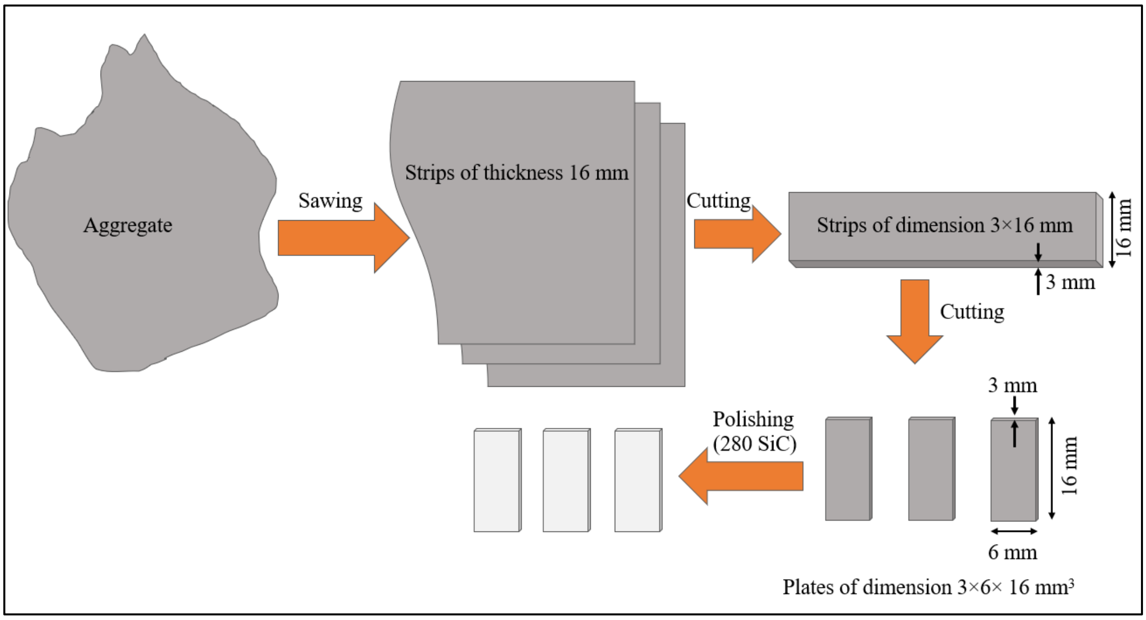
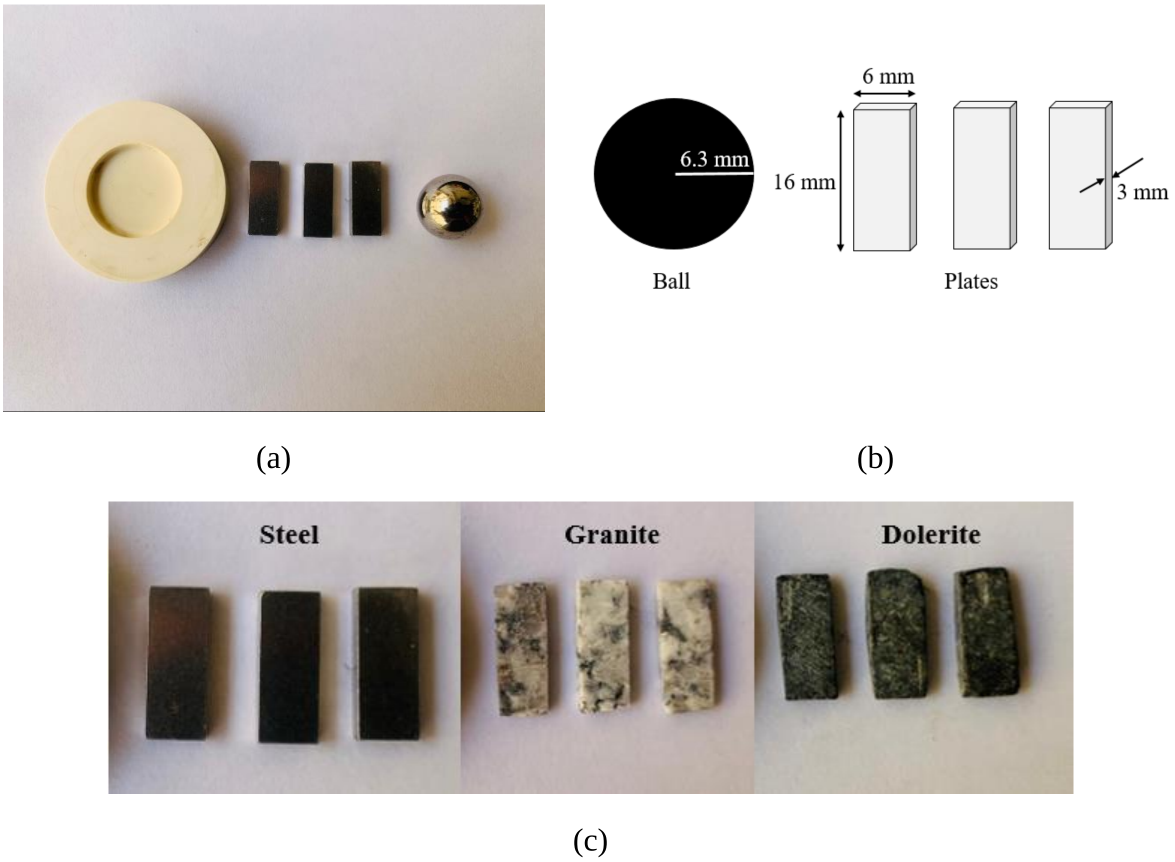


Figure 5-4. The procedure adopted for the preparation of aggregates plates



(a)

(b)

(c)

Figure 5-5. Plates and ball used in the study a) Pictorial view b) Schematic view c) Different plates used in the study

Table 5-3. Surface roughness details of the plates

Type of Plates	Surface Roughness Parameters	
	Average Value (R_a), µm	Root Mean Square (RMS) Value (R_q), µm
Steel	163.32	214
Granite	271	369
Dolerite	261.9	355

5.5.2.4 Testing Procedure

Following steps were used to perform the tribology test on the WMA binders:

a) The tribology cup, which accommodates the asphalt binder, was preheated to 160° C

b) Approximately 1gm sample was collected using a silicon mould. The asphalt binder was placed in the preheated tribology cup for the test.

c) The ball-on-three-plates geometry was attached to the DSR, the sample was loaded and tared to zero.

d) Normal load and sliding speed were selected to run the test.

e) The value of CoF was obtained corresponding to the input parameters at the desired test temperature.

f) The test involved a pre-run at 160° C. CoF was measured at a range of temperature, which was varied from 160° C to 90° C in the first run and 90°C to 160°C in the second run.

g) Step (f) was performed three times for each binder to obtain the average value of CoF.

h) After completion of each run, the tribology cup, plates, and ball were dismounted and cleaned for the next run.

5.5.2.5 Approach for the Determination of Production Temperatures

The current study covered the assessment of the production temperature of warm mix and polymer modified asphalt binders. The estimation of production temperatures for these binders may not be possible using viscosity-based approaches. At lower temperatures, it is anticipated that WMA will offer a similar degree of lubricating behaviour (workability) to viscosity grade binders i.e. HMA. On other hand, polymer modified binders at their production temperatures exhibits same lubricating behaviour as that of viscosity grade binders at their production temperatures. To ensure the same workability or lubricating behaviour, a reference point is necessary to predict the production temperatures. According to available literatures [132,134], viscosity-based methods, particularly the conventional EQ method, give suitable mixing and compaction temperatures for unmodified asphalt binders (i.e. viscosity grade binders used in this study). From this perspective, the production temperatures of 14 viscosity grades binders were evaluated first using EQ method and these temperatures were used as a reference in this study.

At these reference temperatures, the μ for all viscosity grades binders were determined using tribological test. The μ values were averaged over all viscosity grade binders corresponding to their mixing and compaction temperatures. These average μ values with standard deviation were used as reference value for determination of the production temperatures of polymer modified and warm mix modified asphalt binders. To determine the production temperatures, tribological test was performed on WMA and PMB binders with specified normal load and sliding speed. The test resulted into μ versus temperature profile for these binders. The temperatures corresponding to reference μ values were considered as the production temperatures.

5.6 Phase 2: Validation Using Workability, Coating ability, Compactibility test

5.6.1 Background, Need and Development of Workability Prototype

Measuring the workability of asphalt mixtures is not new. One of the earliest workability device was developed in 1979 by Marvillet and Bougalt [379]. This device measured the workability in terms of the torque value required to rotate the spindle through a loose mix inside a cylindrical bowl. Since 1979, various workability devices have been developed with different operational mechanisms and complexities. A brief review of developed workability prototypes together with their working procedures can be found elsewhere [9]. Few literature [380,381] specified a need for refinement in the existing workability prototypes in terms of torque measurement and maintaining test temperatures within the testing bowl.

Previously developed workability prototypes can be compared through two categories, based on their design arrangements [151,380,382,383]. The first one comprises a fixed container with a rotating shaft [147,151,380], while the second consists of a rotating container and a fixed shaft setup [150,383]. The current study implemented the first approach and developed a new workability device that measures workability in terms of torque. The first approach is adopted owing to its better reliability and accuracy, as stated in past studies [147,151,380]. Though the developed prototype is operated using a similar mechanism as adopted by past researchers, some changes have been incorporated in this study. These include the installation of a heating element and a power meter for obtaining accurate results at any specific temperature. However, the primary objective of the present study is not to assess the workability, but to use the workability parameter for predicting the production temperatures of WMA mixtures.

The fabricated workability device consists of six components: a rotating metal container, a spindle with sharp blades, a digital speed drive, a heating mantle with a temperature controller unit, a power meter, and an electric motor. The line diagram of the workability prototype is presented in Figure 5-6. To ensure consistent mixing, the size of the metal container was selected such that it completely accommodates the asphalt mixture. Different studies have prepared different types of blade attachments (in the spindle) as per their convenience and usefulness. An ideal blade setup should ensure continuous mixing of the mixture and thereby eliminating the creation of a shear plane within the asphalt mixture. Gudimettla et al. [380]

observed that the creation of a shear plane gives a constant value of torque over the range of temperature. The study also identified that the lack of resistance provided by the asphalt mixture is the probable reason for such shear planes. To overcome this issue in this study, the spindle blades were attached in a way that it restricts the creation of a shear plane. The height of the spindle is made adjustable through an adjusting head. It has to be noted that the change in height of the spindle within the asphalt mixture also changes the torque value and may lead to inappropriate results. Thus, in the present study, height of the spindle was kept constant throughout the testing. A speed drive was attached to the setup to operate the test at variable speeds. However, in this study, a constant speed was used to maintain consistency. Digital sensors were used to frequently monitor the power and speed of the shaft. These sensors were directly attached to the motor and measures the power required to rotate the mixture at a selected speed and specific temperature. In this study, the torque values were measured indirectly using power (obtained from power meter) and speed of the shaft (indicated by speed drive display). A heating mantle was also installed and supports the metal container for maintaining the test temperature of asphalt mixtures. A digital thermometer was used to measure the temperature of the asphalt mixture during the testing operations. The configuration of the workability prototype is illustrated in Table 5-4.

Table 5-4. Configuration of workability prototype

Technical Details	
Capacity of motor	1 Horsepower
Volume of container	4276 cm^3 (4.27 Liter)
Number of blades	2
Length of blade	120 mm
Height of blade	25 mm
Distance between both the blades	25 mm
Spindle speed	600 rpm

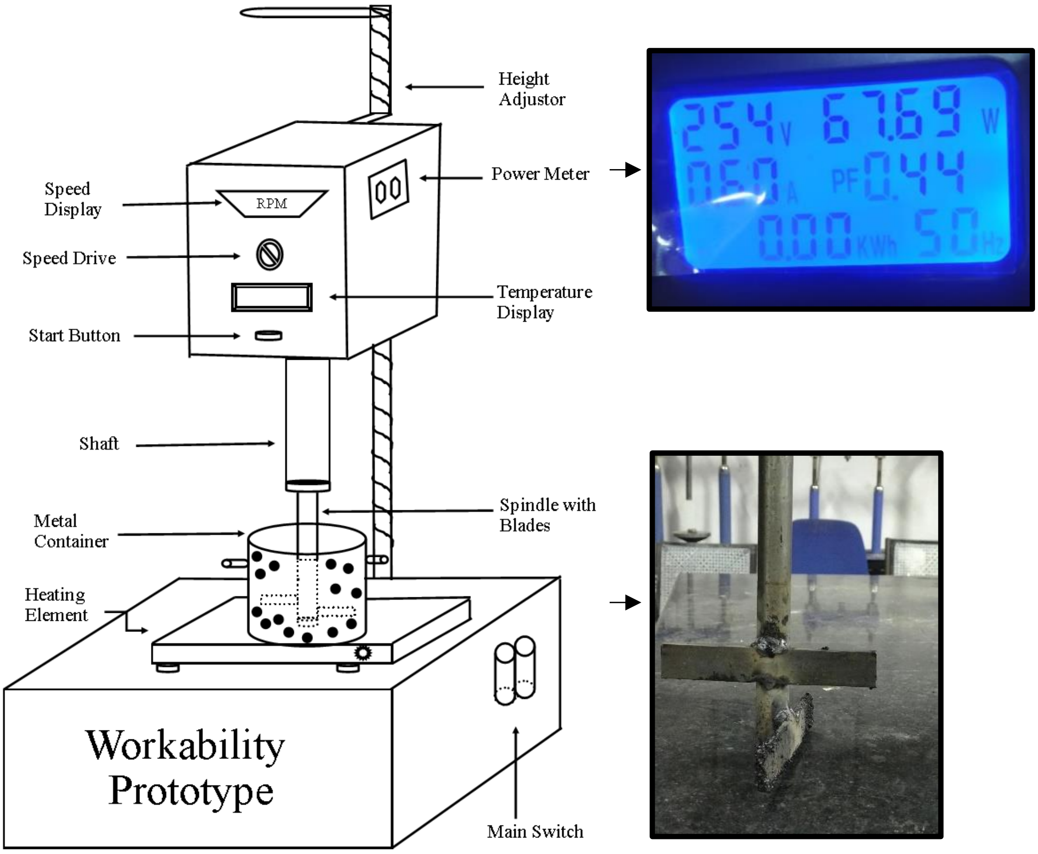


Figure 5-6. Line diagram of developed workability prototype

5.6.1.1 Steps for the Quantification of Workability

To determine the workability of asphalt mixture, the following procedure was adopted.

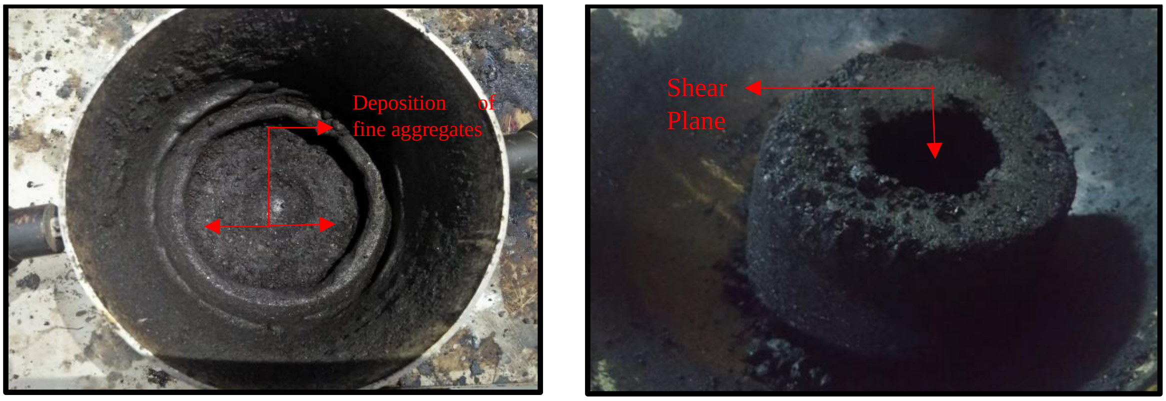
1) The aggregates and asphalt binder were placed in the oven at a temperature range of 160˚C-165˚C for 2 hours prior to the mixing process [140]. This step was undertaken to ensure that the materials reach the anticipated mixing temperature before the start of the mixing process. Thereafter, a fixed quantity of heated aggregate was batched and mixed with heated asphalt binder to produce asphalt mixtures. The aggregate weight of 3 kg was selected based on the container volume (4276 cm^3) and the capacity of the mixing motor to ensure efficient and uniform mixing.
2) Following the mixing process, the asphalt mixture was kept in the oven for conditioning at 5˚C higher than the actual testing temperature for a period of 2 hours. This was done to account for the reduction in temperature during transferring of asphalt mixture from

the mixing pan to the workability container. The container and spindle were also heated to the test temperature till the start of the testing procedure.

3) After mixing and conditioning, the asphalt mixture was transferred to a container, placed on a heating mantle. Then the spindle was inserted into the container filled with asphalt mixture.
4) The test was performed by rotating the spindle at a constant speed. The speed should be enough such that the motor easily rotates the mixture without any difficulty.
5) The spindle was allowed to rotate at the above-mentioned speed for a period of one minute to achieve uniformity in the asphalt mixture. In order to drop the temperature of the asphalt mixture, heating was not applied initially.
6) The resistance of the asphalt mixture to the rotation of the spindle was evaluated using the power required to rotate the spindle. Power was determined using a power meter attached to the apparatus. The measured power was indirectly represented in terms of torque using a mathematical relationship between torque, power, and rotation speed, as given in Eq.3.2 [384].
7) Initially, power readings were taken as the temperature dropped from 160°C to 130°C. Once the temperature dropped to 130°C, the heating mantle was started to increase the temperature of the asphalt mixture. Power readings were retaken as the temperature increased from 130°C to 160°C. Readings were taken at 5°C intervals. Finally, an average of these two readings reported for analysis purposes.
8) The workability test timing depends upon the capacity of the heating mantle, and it approximately takes one and half hours to complete the test. At the end of the test, the spindle was dismounted from the shaft, and subsequently, the spindle and container were cleaned to avoid disturbances in readings during the next test.

5.6.1.2 Challenges and Refinements in the Workability Attributes

While using the workability device on the mixture of graded mineral aggregates and asphalt binder, it was observed that the finer aggregates particles tend to deposit on the wall of the container as agglomerations (shown in Figure 5-7). It was initially hypothesized that this formation is due to the high speed of the motor, which creates a shear plane while the spindle rotates within the asphalt mixture. Changes in the measurement process, such as variation in speed of the motor, quantity of material used, and adjustment in the spindle height, were made to resolve this issue. However, all such changes resulted in the reoccurrence of a similar problem. It was later found that the use of graded mineral aggregates results in such occurrence. Therefore, 3 kg of single-sized aggregates (9.5 mm passing and 6.3 mm retained) were blended with 120 g of asphalt binder corresponding to 4% binder content by total weight of aggregate. These proportions were selected to ensure consistency and improve repeatability in the results. Also, a gap of 25 mm was maintained between the spindle and the container.



(a) (b)

Figure 5-7. Deposition of material (a) fine aggregate on the walls of the container and (b) agglomerated chunk

5.6.1.3 Feasibility and Validation of Fabricated Workability Prototype

The relationship between torque and temperature was plotted to check the feasibility of the fabricated workability setup, as shown in Figure 5-8. The torque reading was noted at each temperature, and the process was repeated 5 times to observe the variation in results. As is expected, the torque decreases gradually with the increase in temperature. This ensures the applicability and adaptability of the developed prototype for the measurement of workability. As can be seen, multiple torque values were observed corresponding to any tested temperature. A similar kind of scattering effect was reported in previous studies [151,380]. Average data at the required temperatures are shown in the present study for better and clear recognition of the asphalt mixture behaviour with change in temperature. The line shown in Figure 5-8 indicates the average values of torque with a change in temperature. The procedure of finding the production temperature is discussed in the subsequent section.

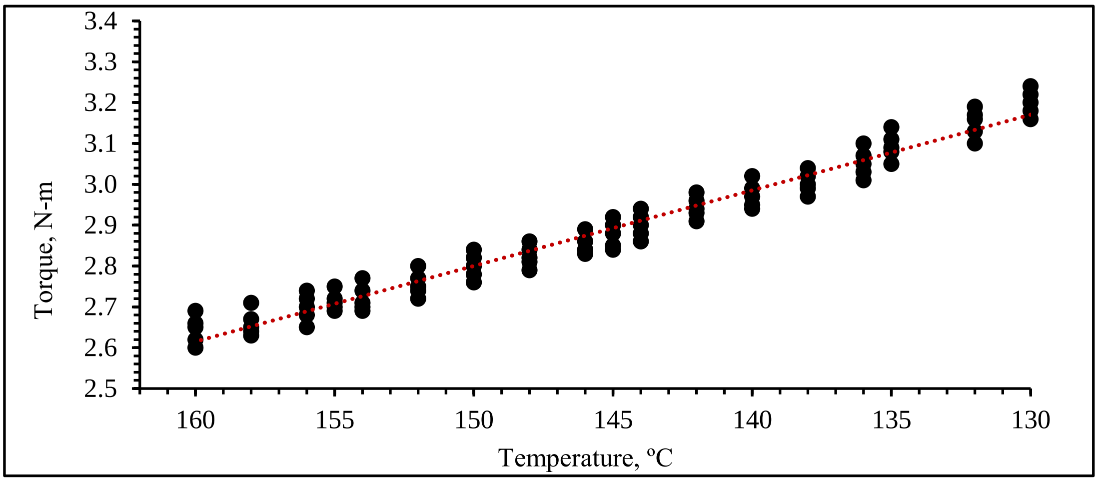


Figure 5-8. Example of the raw data obtained from workability test along with the average trend

5.6.1.4 *Approach for Finding Production Temperatures*

The present study involves the use of WMA technologies, where the viscosity-based methods may not be applicable for the quantification of production temperatures. It is expected that WMA will offer similar workability as that of HMA at lower temperatures. Although workability can be used for WMA mixtures, there is a requirement for a reference point to determine the production temperatures. As per the available literature [12,13,132,273], viscosity-based methods, especially the traditional EQ method, provides appropriate mixing and compaction temperatures for unmodified asphalt binders (such as VG30 used in this study).

From this perspective, the production temperature obtained for VG30 (as obtained from EQ method) was taken as a reference. The torque values obtained with VG30 at the temperatures obtained using EQ method were used to evaluate production temperatures for WMA mixtures.

5.6.2 Validation of Tribology Approach Using Coating Ability and Compactibility Test

In general, at the mixing temperature, a satisfactory aggregate coating by the asphalt binder is expected [385]. On the other hand, an adequate compaction temperature signifies appropriate packing density of the asphalt mixtures at in-situ conditions [386]. The purpose of adopting the WMA technology is to yield equivalent coating and percentage of voids as that of HMA, when mixed and compacted at their estimated mixing and compaction temperatures, respectively. Therefore, coating ability and compactibility tests were carried out to demonstrate the validity of the predicted mixing and compaction temperatures. All these validations were performed by taking HMA as the reference asphalt mixture.

To validate mixing temperature, a test was conducted on loose asphalt mixtures. On the other hand, compacted asphalt mixtures were tested to verify the compaction temperature. The first test evaluates the coating ability for assessing the correct range of mixing temperature [387], whereas the latter determines the volumetric characteristics of the compacted sample to validate the proposed compaction temperature [127]. Results obtained for the conventional HMA mixture are taken as reference. The adopted methodology and procedure for the validation of production temperatures are presented in the next section. To do this, asphalt mixes were prepared using the Marshall mix design, in accordance with Asphalt Institute specification (MS-2) [140], utilizing bituminous concrete (BC) gradation with a nominal maximum size of aggregate of 19 mm, mentioned in Ministry of Road Transport and Highways (MoRTH) [388]. Figure 5-9 shows the design aggregate gradation used in the study. Initially, the optimum binder content (OBC) was evaluated for samples prepared using V8, P1, P2, P3, and P4. The same OBC was used to prepare WMA samples for each base binder. A few literatures stated that WMA has a minor influence on the OBC and volumetric characteristics of asphalt mixtures. Since the present study aims to evaluate the production temperatures of asphalt mixtures, the obtained OBC was used to prepare WMA and polymer modified binder mixtures. Here, it should be noted that all the samples were prepared at the mixing and compaction temperatures obtained using the tribological approach, explained in the previous section. The summary of mix design results for utilizing bituminous concrete (BC) with V8, P1, P2, P3, and P4 are presented in Table 5-5.

Table 5-5. Summary of mix design

Binder Type	**OBC (%)**	**Air Voids (%)**	**VMA (%)**	**VFB (%)**	**Stability (kN)**	**Flow (mm)**
V8	5.41	4.04	14.71	72.5	13.15	3.84
P1	5.51	3.998	14.66	71.7	16.9	3.71
P2	5.55	4.05	14.76	72	17.2	3.7
P3	5.5	4.01	14.75	72	18.1	3.8
P4	5.52	4.03	14.18	72.5	17.1	3.9
Specification Limit	Minimum 5.2	3-5	Minimum 12	65-75	>9	2-4

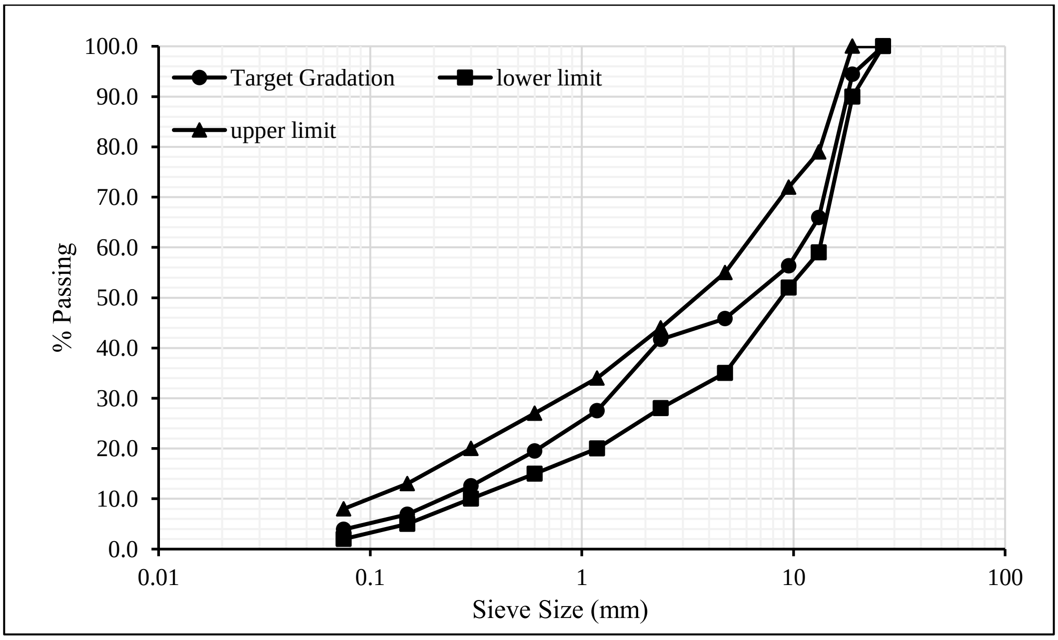


Figure 5-9. Aggregate gradation used in the study

5.6.2.1 Coating Ability of Asphalt Mixture

IRC SP 101 [389] has recommended using the test method specified in AASHTO T195 [93] to evaluate coating over the aggregates. This method quantifies the degree of asphalt coating based on visual assessments. The major challenge in this test method is its dependency on manual qualitative visual inspection, which may be subjective [390]. It is suggested that the image processing techniques offer better accuracy [391,392]. In order to assess the coating ability using image processing, a simple experimental setup was designed and fabricated. Figure 5-10 shows the line diagram of the developed experimental setup. A camera was attached at the top of box to capture the image of the asphalt mixture. A diffused light source was installed along the boundary at the top of the setup to capture clear details of the coated and uncoated aggregates. All the images were captured under uniform lighting conditions to reduce the subjectivity in this study. The quantity of test samples was also kept constant, and the image was captured from the same height and alignment to maintain consistency throughout the testing procedure. Therefore, all sources of variability were minimized to obtain reliable results.

1200 gm of asphalt mixture samples (cooled at room temperature) prepared at their respective mixing temperature were placed on the tray inside the experimental setup. For each sample, multiple images were taken by changing the orientation of the placed sample. For each sample, five images were captured by rotating the sample tray approximately 60° between each capture, covering a total of 360° to account for surface variability and ensure comprehensive assessment of the coating. This approach was adopted based on practices in image-based material studies where multiple orientations are used to minimize bias due to heterogeneous surface distribution [393,394]. The images were analysed using an android based software (Color Analysis (Version 4)), developed by Roy Leizer. The details of the software are shown in Figure 5-11. While there are various software’s available for image analysis, the authors found this software to be simple, and yet robust for the required analysis. Researchers may also use other image analysis tool following the proposed procedure. The software converts the colours of the image in the form of Red-Green- Blue (RGB) bands. The percentage of each pixel's colour is directly obtained using the software.

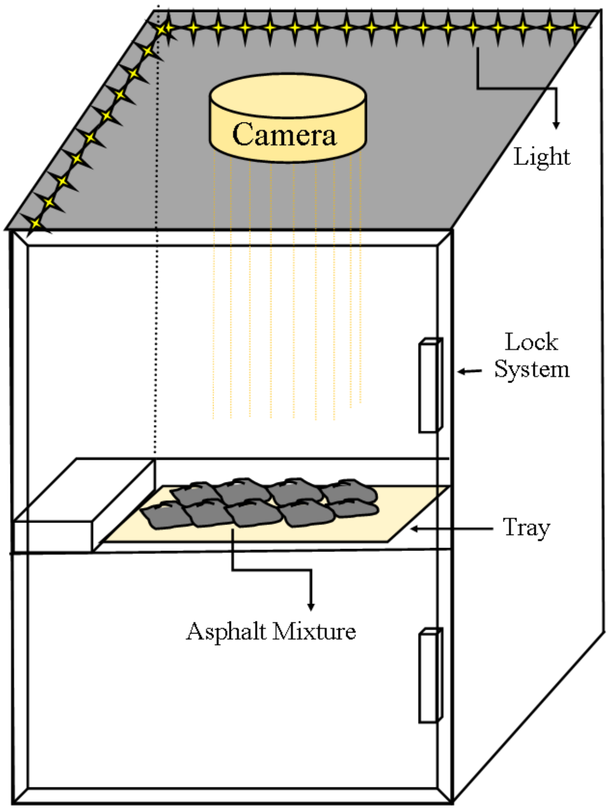
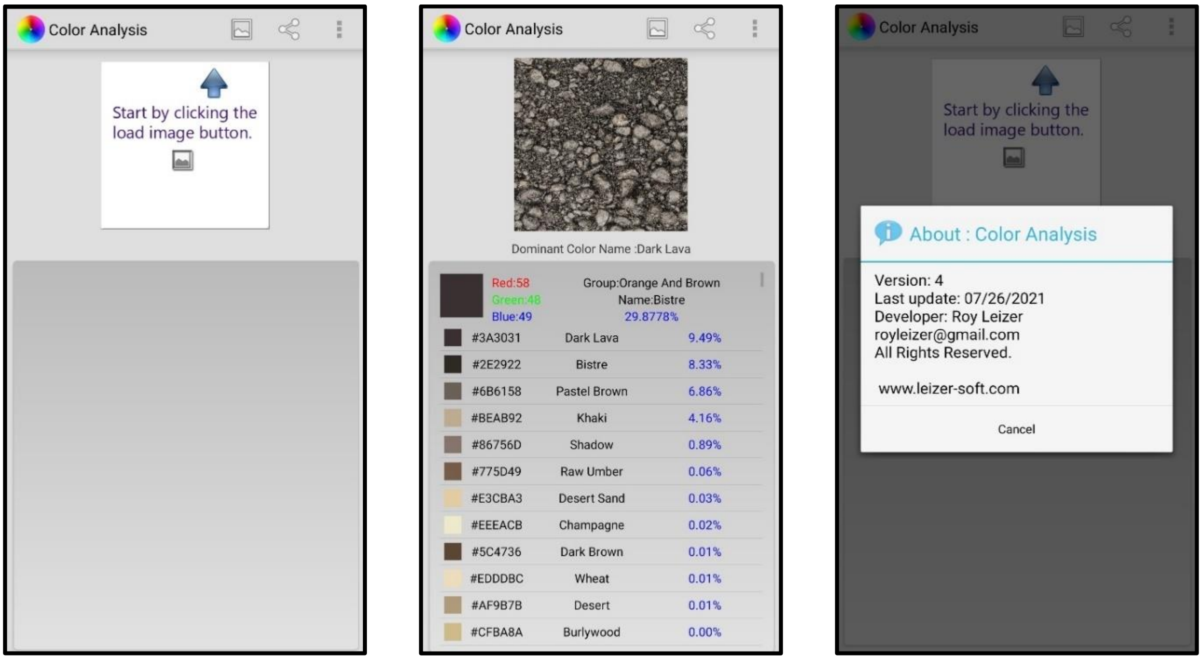


Figure 5-10. Schematic representation of experimental setup for coating.

The coating was quantified using a parameter, denoted as coating index (CI). CI is defined as the absolute difference between the magnitude of colours obtained in uncoated and coated aggregates mixtures. For better coating, a higher value is desirable. To ensure the applicability of this software, initial images were taken on control mixtures prepared using VG 30 at three different mixing temperatures (100°C, 130°C, and 160°C). Here, 160°C is the actual mixing temperature for VG 30 obtained from the EQ method. Figure 5-12 shows the variation in coating index. As is expected, with increase in temperature, CI increases. At 160°C the value of coating index obtained was 65 % (indicating 35% similarity). This is attributed to the effect of light, and presence of dark colour on the aggregates taken during this study. To better understand the effect of WMA, irrespective of base bitumen and aggregate, the measured CI was normalized with respect to the CI of base bitumen. This was done because the reference value CI changes for different binder and aggregate sources. The new proposed parameter is defined as "Normalized Coating Index" (CI_N).



Start by clicking the load image button.

Dominant Color Name :Dark Lava

Red:58
Green:48
Blue:49
Group:Orange And Brown
Name:Bistre
29.8778%

■	#3A3031	Dark Lava	9.49%
■	#2E2922	Bistre	8.33%
■	#6B6158	Pastel Brown	6.86%
■	#BEAB92	Khaki	4.16%
■	#86756D	Shadow	0.89%
■	#775D49	Raw Umber	0.06%
■	#E3CBA3	Desert Sand	0.03%
■	#EEEACB	Champagne	0.02%
■	#5C4736	Dark Brown	0.01%
■	#EDDDBC	Wheat	0.01%
■	#AF9B7B	Desert	0.01%
■	#CFBA8A	Burlywood	0.00%

Start by clicking the load image button.

About : Color Analysis

Version: 4
Last update: 07/26/2021
Developer: Roy Leizer
royleizer@gmail.com
All Rights Reserved.

www.leizer-soft.com

(a) (b) (c)

Figure 5-11. Details of software (a) Front Interface, (b) Colour sample in RGB format, and (c) About the developer

(a) (b) (c) (d)

Figure 5-12. Image captured (a) Uncoated Aggregates, (b) Coating at 100˚C, (c) Coating at 130˚C, and (d) Coating at 160˚C.

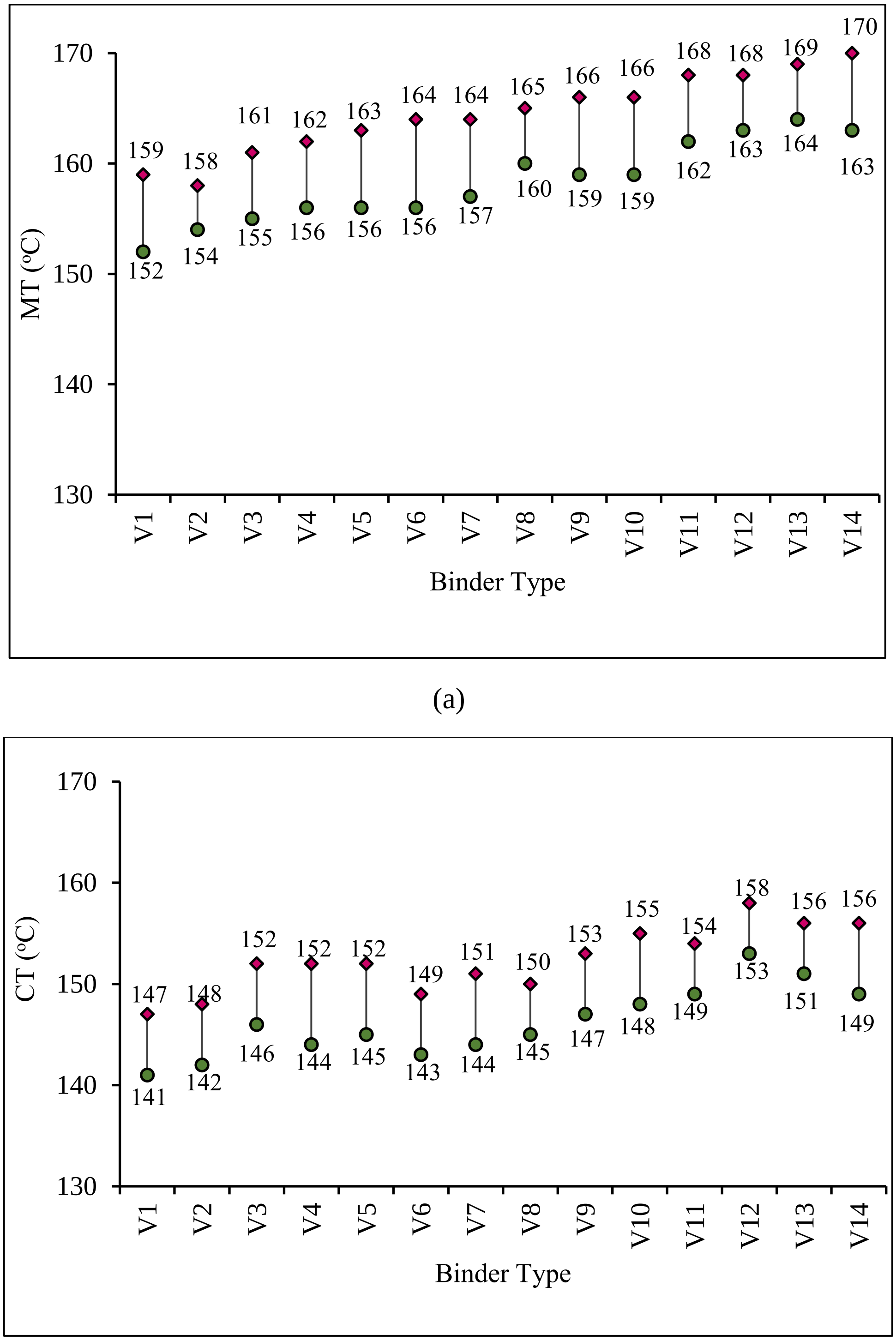
5.6.2.2 Compactibility Test

All the HMA and WMA mixtures were mixed and compacted at their respective mixing and compaction temperatures. Compaction was done using a Marshall hammer with 75 blows on each side of the sample. The bulk specific gravity (G_{mb}) for all the compacted specimens was determined in accordance with AASHTO T166 [395]. In general, the theoretical specific gravity (G_{mm}) depends on the asphalt binder content and aggregate composition [127]. The value of G_{mm} determined as per AASHTO T209 [396] was the same for HMA and WMA mixtures. Thereafter, the air voids for both the type of asphalt mixtures were calculated and compared for verification.

5.7 Results and Discussion: Phase 1

5.7.1 Rotational Viscometer Test

Figure 5-13 shows the appropriate temperature ranges of MT and CT for all binders used in the study. The minimum and maximum values of MT and CT were included in temperature ranges. It can be seen that different values of MT and CT were obtained for different viscosity grade binders. MT and CT of all VG40 binders were higher than VG30. This can be due to the higher viscosity of VG40 as compared to VG30 asphalt binders. It can be seen that the MT and CT of all viscosity grade binders were found to be within a specified limit, according to MoRTH [397]. The findings of Chapter 4 showed that the EQ method could not be used to determine the production temperatures of modified binders (PMBs, and WMA binders in the present study). Same can be observed from past study [12]. However, EQ method works well for viscosity grade binders. To overcome the drawbacks of EQ methods, the recent hypothesis of reduction in friction between mineral aggregates and asphalt binder can be used for the evaluation of production temperature of PMB and WMA technologies. Results of these friction study (tribological study) are discussed in subsequent section. The MT and CT of fourteen viscosity grade binders obtained using EQ method has been used as a reference temperature for tribological evaluation of WMA and PMB modified binders.



(a)

(b)

Figure 5-13. Production temperature using EQ method a) MT b) CT

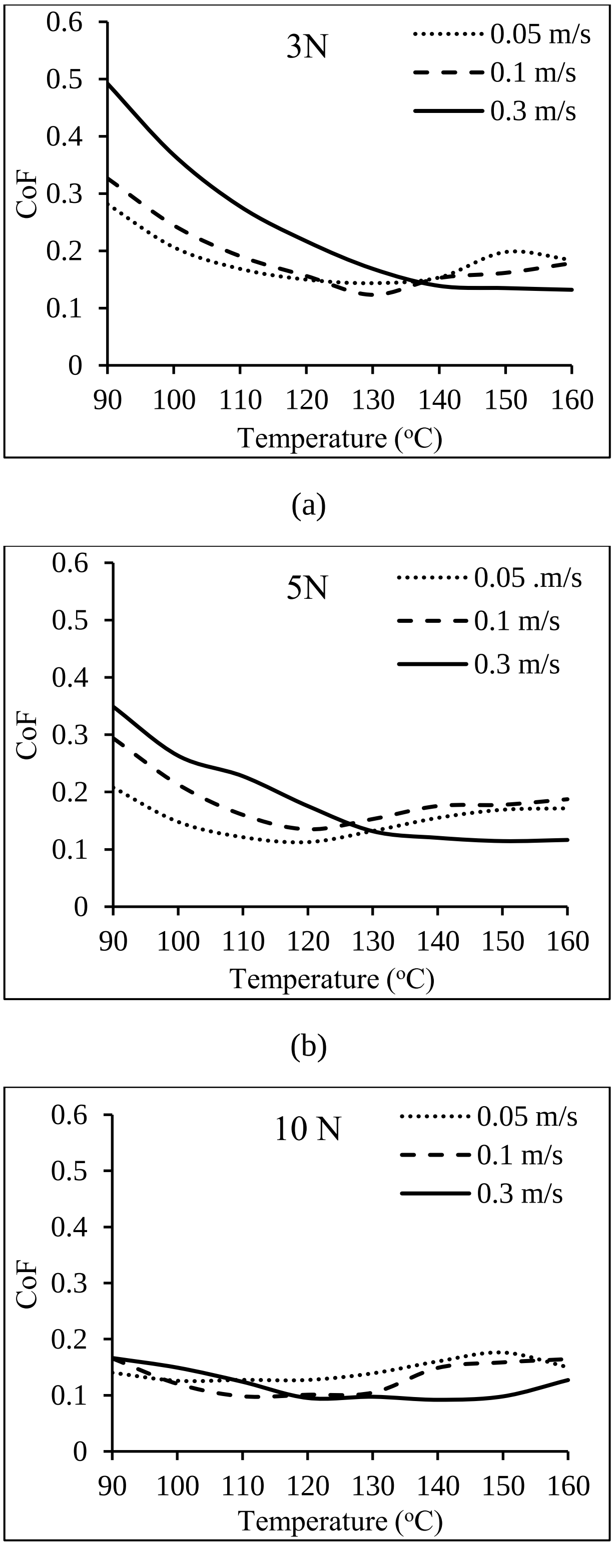
5.7.2 Tribology Test

5.7.2.1 Fixing Tribological Parameters

Figure 5-14 shows the variation of CoF (of V8 which is VG30 in this study) with temperature for different values of normal load and sliding speed. In this study, the main task was to decide the normal load and sliding speed that will characterize the asphalt binder for the determination of their production temperatures. In addition, the selected parameters will also differentiate the effect of WMA technology on the base asphalt binder (V8). To characterize the asphalt binder, it is anticipated that the CoF should be decreased with temperature for the characterization of WMA modified asphalt binders. This is due to the fact that the lubrication effect of asphalt binder increases with temperature [41]. This trend was necessary to capture the effect of temperature on CoF in the case of viscoelastic material like asphalt binder.

To decide the appropriate tribological parameters, initially, the different combinations of sliding speed and normal load were chosen for the test. Most previous tribology studies suggested a normal load of 10 N for tribological characterization. Therefore, the trial began with a normal load of 10 N with three different sliding speeds of 0.05, 0.1, and 0.3 m/sec for V8 asphalt binder. This speed values were falling in the elasto-hydrodynamic regime where lubricants (asphalt binder in this study) exhibit lower CoF. From Figure 5-14, it can be observed that the CoF was increased with the temperature above 130^{o}C. This was due to the loss of bearing capacity of lubricant (asphalt binder) at such high temperatures where the binder exhibits a loss of film thickness [398,399]. This loss of film thickness allows the ball to directly slide over the plates and results in higher CoF. This phenomenon was observed due to higher Hertzian stresses generated at contact for such load and speed combinations [400]. To avoid this loss of film, the normal load was reduced to 5N and 3N for the same combination of sliding speed and these loads were arbitrarily decided. Again, test was conducted on the V8 asphalt binder using these combinations of sliding speed and normal load. From Figure 5-14, it can be seen that the CoF was decreased with temperature for a normal load of 3N and 5N for a sliding speed of 0.3 m/sec. This showed that the lubricant film was formed with these combinations of loads and sliding speeds. The normal load with a lower sliding speed was not suitable to characterize the asphalt binder. This was again due to the incapability of lower speed to maintain appropriate film at the contact [401,402]. Figure 5-14 also showed that the CoF was higher for 3 N followed by 5N and 10 N. This phenomenon was predominant for temperatures below 130°C. At temperature >130°C, the asphalt binder was highly viscous so it was easy to shear such fluid using a high load whereas a low load required more torque to shear such highly viscous fluid. This was the reason for getting high CoF for lower loads at a temperature below 130°C. If it is true for lower load, then it has been true for lower speed and lower load. From Figure 5-14, it can be seen that the lower speed with lower load showed higher CoF as compared to higher speed and load.

Thereafter, the normal load of 3N and 5N with a sliding speed of 0.3 m/sec were selected for the characterization of WMA modified asphalt binders. For purpose of characterization, the mid dosages of WMA additives (S2 and R0.4) were selected for the test. Figure 5-15 shows the variation of CoF with temperature for WMA modified asphalt binders using the normal load of 3N and 5N and sliding speed of 0.3 m/sec. From Figure 5-15 (a), it can be observed that the the normal load of 5N was considered unsuitable as it did not show a smooth decreasing trend in CoF with temperature, indicating inadequate film formation and unstable lubrication behavior due to the influence of WMA additives. This was due to the different mechanisms associated with WMA additives. The Sasobit act as a viscosity reducer whereas Rediset act as a surface tension reducer. The addition of Sasobit to the base binder reduces the viscosity and this reduced viscosity caused a loss of bearing capacity (lack of lubricant support) of the binder and resulted in higher CoF for this normal load. The same was also observed in the case of Rediset due to the reduction of surface tension. From Figure 5-15 (b), it can also be observed that the normal load of 3N was appropriate to characterize the Rediset modified asphalt binder but fails to characterize the Sasobit modified asphalt binder. This was due to the incapability of the normal load of 3N to form sufficient lubricant film at sliding contact in the case of the Sasobit modified asphalt binder. To overcome this problem, the normal load was reduced to 1N and used for the characterization of WMA modified asphalt binders. Figure 5-15 (c) shows the variation of CoF with temperature for a normal load of 1N. It can be seen that the CoF has reduced with temperature for the base and WMA modified asphalt binders. This combination of normal load and sliding was able to differentiate between the WMA additives as seen in Figure 5-15 (c). This showed that the combination of 1N and 0.3 m/sec was suitable for forming the lubricating film of sufficient thickness for both the WMA additives. The combination also minimized the ball and plate contact and the same was also reported by the previous study [403]. Therefore, the normal load of 1N and sliding speed of 0.3 m/sec were considered for testing the WMA technology and polymer modified binders. From Figure 5-15 (c), it can also be observed that the CoF was greater than 1 for a temperature below 110^{o}C. This was due to the stick-slip phenomenon where asphalt binder was shifted from viscous media to adhesive media [404–406]. After the finalization of the tribological parameter, the tribology test was conducted on WMA modified and polymer modified binders using the normal load of 1N and sliding speed of 0.3 m/sec. The determination of mixing and compaction temperature using the tribological approach and its validation are described in the subsequent section.



(a)

(b)

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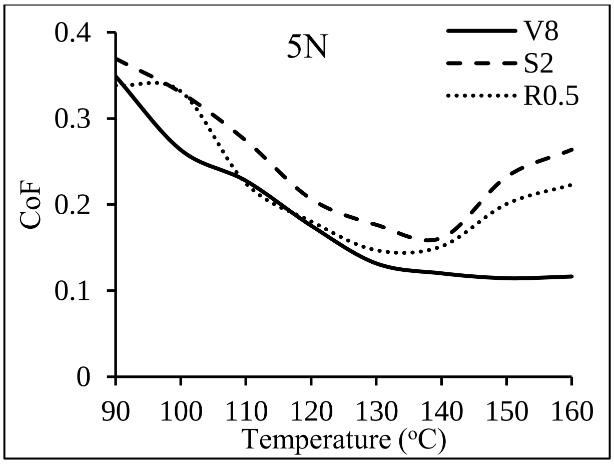
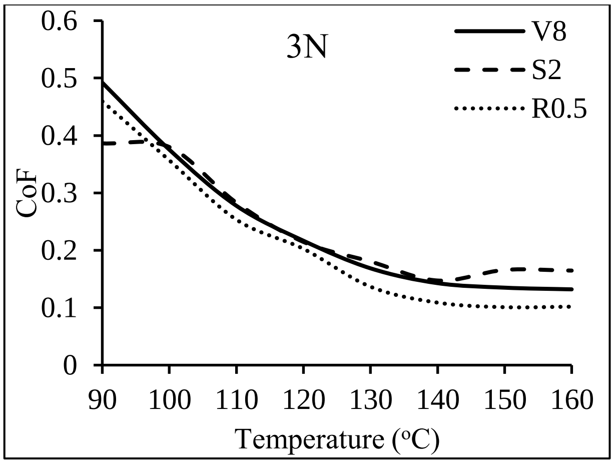
Figure 5-14. Variation of CoF with temperature for different speed a) 3N b) 5N c) 10N



(a)



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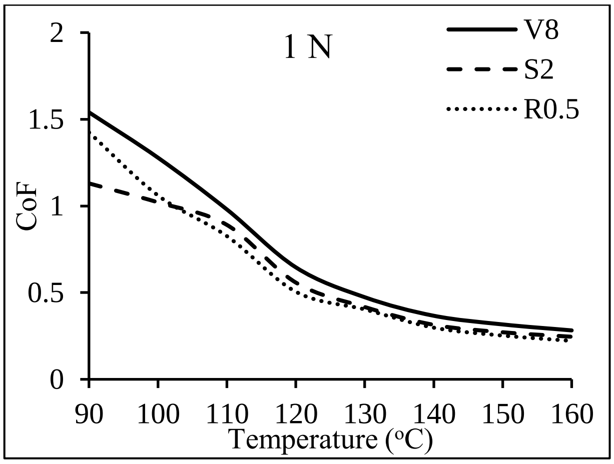
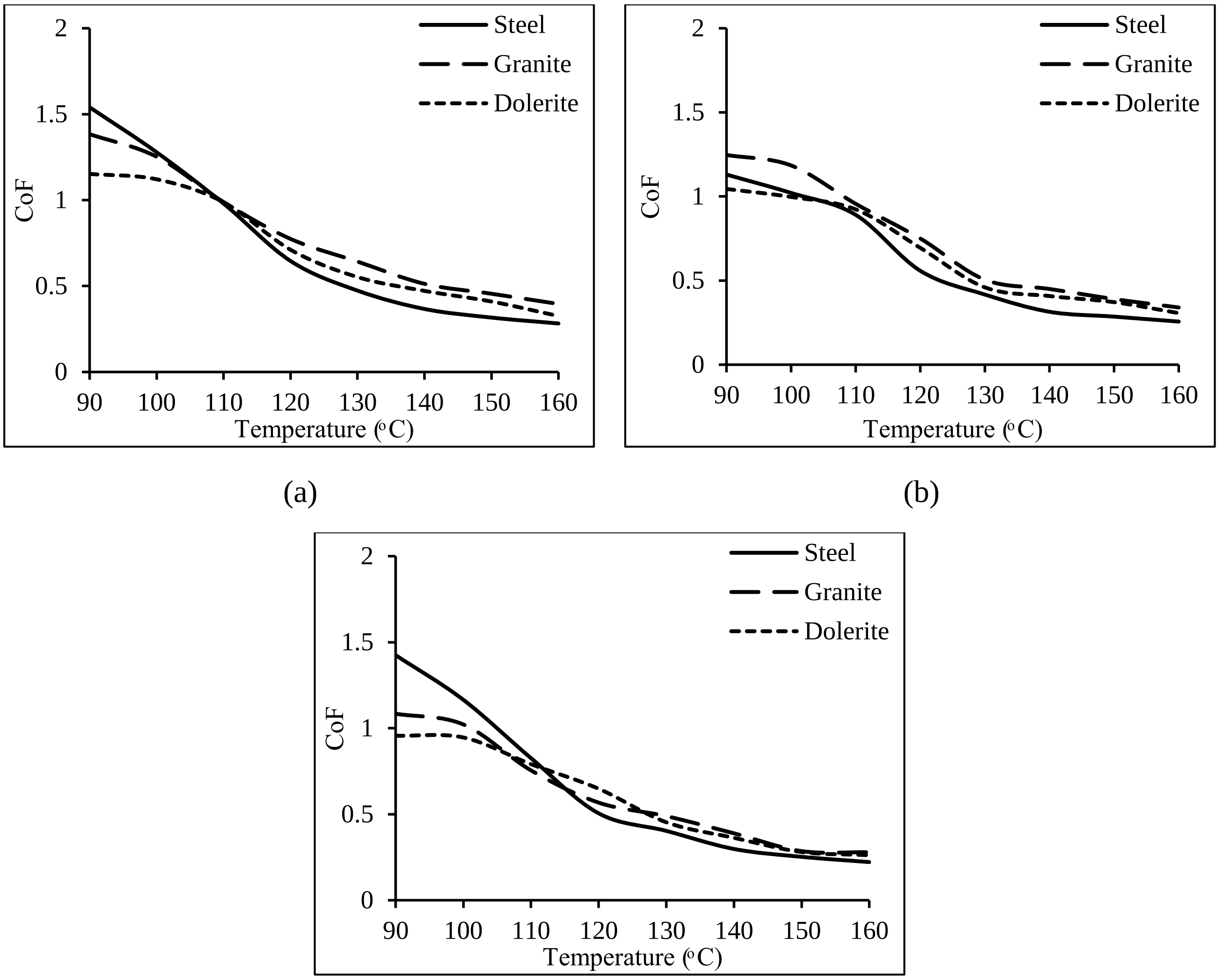


(c)

Figure 5-15. Variation of CoF with temperature for WMA modified asphalt binder at 0.3 m/s a) 5N b) 3N c) 1N

5.7.2.2 Effect of Plates on Frictional Characteristics of Asphalt Binders

Figure 5-16 shows the variation of CoF with the temperature at a normal load of 1N and sliding speed of 0.3m/sec for different plates used in the study. The variation is only shown for VG 30 and mid dosages of well-known WMA additives (Sasobit and Rediset), other data has not been shown for brevity. The frictional behaviour of binders was decreased with temperature, irrespective of WMA additive and plates used. It can be due to decreasing viscosity of the binder with temperature. The rate of reduction in CoF was higher for steel plates at lower temperatures, while at higher temperatures, the rates of reduction were similar for all plate types. This behavior may be attributed to the differing surface characteristics of the plates and their interaction with the binder at varying temperatures. The higher rate of reduction in CoF for steel plates can be due to the lower surface roughness of steel plates as compared to Granite and Dolerite plates as can be seen in Table 5-3. The surface with higher surface roughness exhibits higher CoF. This behaviour holds true when the temperature was above 120^{o}C. Below 120^{o}C, the asphalt binder showed complex behaviour where it is moved from viscous media to adhesive media [187]. The addition of WMA additives showed improved frictional behaviour (reduction in friction) as compared to VG 30 binder as can be seen in Figure 5-17. This observation was the same for different plates used in the study. This can be attributed to better lubrication of behaviour of WMA modified asphalt binders as compared to VG 30. The Sasobit provides better lubrication by reducing viscosity whereas Rediset improved lubrication by reducing the surface tension of the binder. The WMA modified binders demonstrated similar frictional characteristics (in terms of CoF) as compared to VG30 at relatively lower temperatures. This frictional characterization has been used in the study for determining the production temperatures of WMA technology at which all binders exhibit the same value of CoF.



(a)

(b)

(c)

Figure 5-16. Variation of CoF with temperature for different plates a) VG 30 b) S2 c) R0.5

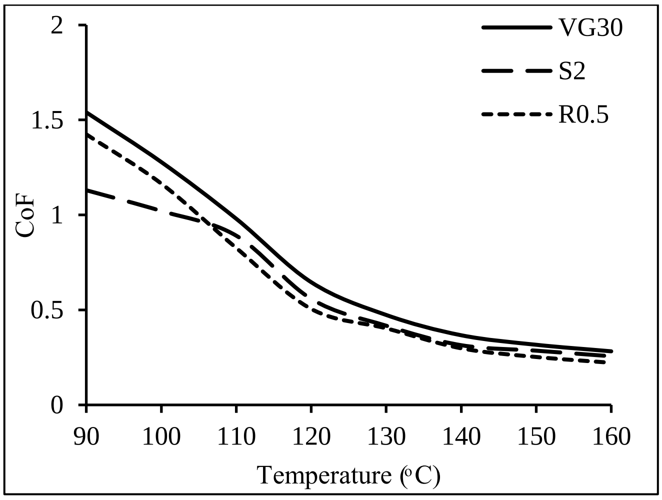


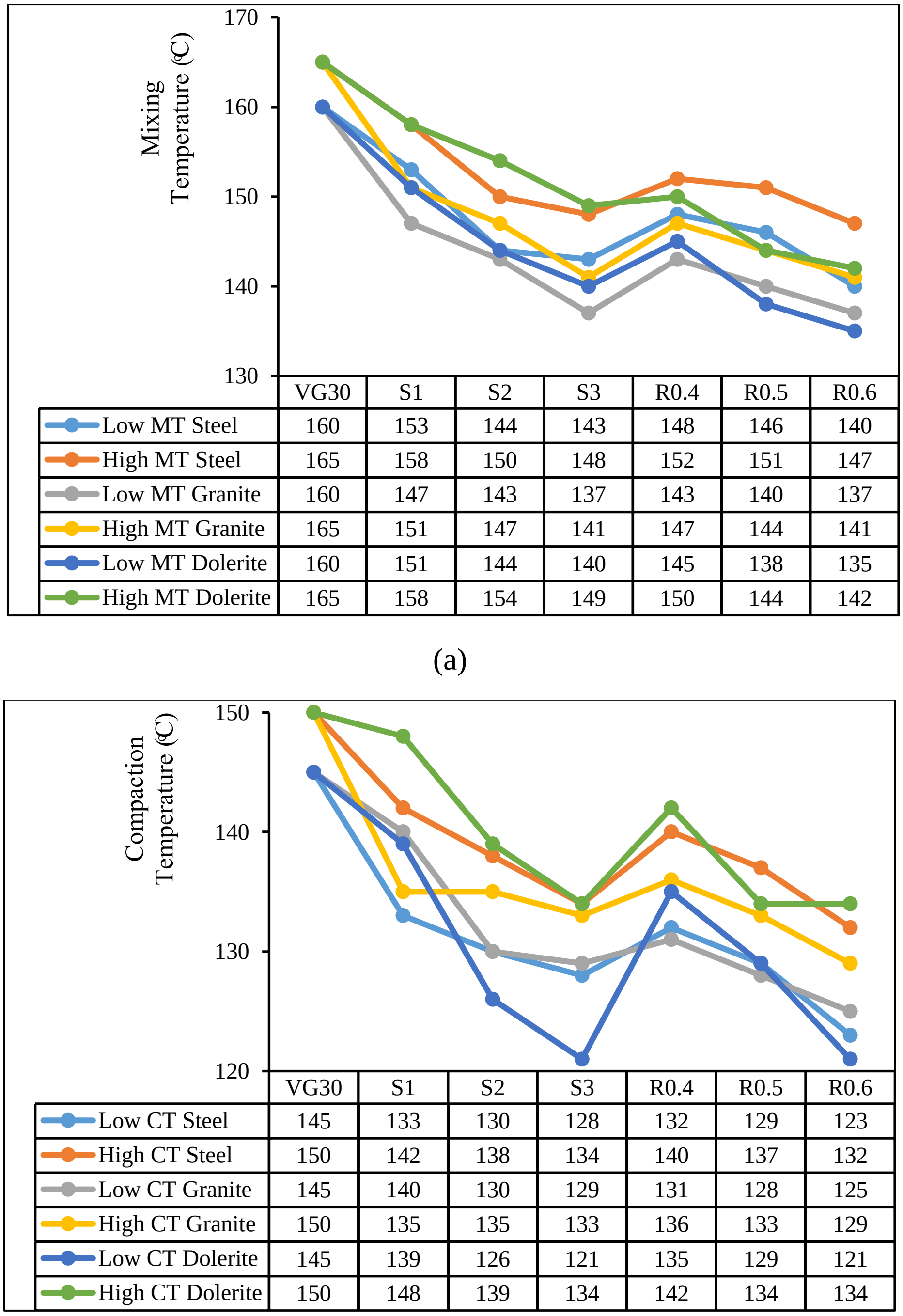
Figure 5-17. Variation of CoF with temperature for various WMA modified binders using steel plates

In this study, effect of different plates on MT and CT determined from tribological approach has been evaluated. To check this effect, the study was performed on well-known warm mix additives such Sasobit and Rediset. Initially, only single binder VG30 (V8) was used as reference binder to determine the MT and CT of WMA modified binders. It is expected that all WMA modified binders at their MT and CT should show similar frictional characteristics. It means that all WMA binders should have the same CoF at their respective MT and CT. In this tribological study, a similar concept has been used for the determination of MT and CT as adopted in the workability study. To determine the production temperatures of WMA modified binders, the reference range of CoF has been needed. In this study, CoF values corresponding to MT and CT (as obtained from the EQ approach) of the VG30 binder were taken as the reference value. The three reference values of CoF have been calculated corresponding to three different types of plates used in the study. The reference CoF corresponding to MT and CT for Steel, Granite, and Dolerite plates are shown in Table 5-6. The CoF value at 165°C for VG 30 was extrapolated using a simple power function. At these CoF values all WMA modified binders showed similar frictional behaviour (same level of lubrication). The temperature corresponding to these CoF was referred to as MT and CT of WMA modified binders using a tribological approach. From Table 5-6, it can be seen that the ranges of CoF for steel plates were lower than actual plates (Granite and Dolerite). This can be attributed to the lower surface roughness of steel plates as compared to actual plates. The ranges of CoF for actual plates were found to be close to each other due to the same level of roughness. This means that the CoF ranges are not sensitive to plate type if they exhibit the same level of roughness. This uniqueness of CoF over different plates of the same roughness makes it an important parameter for the determination of the production of WMA modified binders. Therefore, it can be concluded that the use of steel plates are sufficient to carry out the tribological study and evaluate the mixing and compaction temperatures.

Table 5-6. Ranges of coefficient of friction for determination of production temperature

Binder Type	**Plate Type**	**Mixing temperature (°C)**	**CoF**	**Compaction temperature (°C)**	**CoF**
VG30	Steel	160	0.282	145	0.350
		165	0.255	150	0.317
	Granite	160	0.396	145	0.49
		165	0.365	150	0.455
	Dolerite	160	0.38	145	0.47
		165	0.34	150	0.415

Figure 5.18 shows ranges of MT and CT determined using the tribological approach for different plates. The ranges were found to be approximately the same for all plates used in the study. The little variation in ranges may be attributed to the difference in their ranges of CoF. The steel plates showed higher average values as compared to Granite and Dolerite plates. This can be due to the higher rate of change of CoF with temperature in the case of Steel plates as compared to Granite and Dolerite plates (refer to Figure 5-16). However, Granite and Dolerite plates showed approximately similar value of MT and CT. This again showed that the MT and CT are not sensitive to plate type if they exhibit the same level of roughness. Therefore, this study suggested the use of steel for evaluating the MT and CT of WMA modified asphalt binders as these plates are universally available and subjected to uniform surface roughness as used in this study. Thus the results of Granite and Dolerite plates are not discussed further. After confirming this hypothesis regarding the effect of type of plates on CoF of WMA modified binders, the frictional behaviour of Asphaltan A, Iterlow and polymer modified binders has been studied using steel plates. The results of frictional behaviour of WMA and polymer modified binders are discussed in subsequent section.



	VG30	S1	S2	S3	R0.4	R0.5	R0.6
Low MT Steel	160	153	144	143	148	146	140
High MT Steel	165	158	150	148	152	151	147
Low MT Granite	160	147	143	137	143	140	137
High MT Granite	165	151	147	141	147	144	141
Low MT Dolerite	160	151	144	140	145	138	135
High MT Dolerite	165	158	154	149	150	144	142

(a)

	VG30	S1	S2	S3	R0.4	R0.5	R0.6
Low CT Steel	145	133	130	128	132	129	123
High CT Steel	150	142	138	134	140	137	132
Low CT Granite	145	140	130	129	131	128	125
High CT Granite	150	135	135	133	136	133	129
Low CT Dolerite	145	139	126	121	135	129	121
High CT Dolerite	150	148	139	134	142	134	134

(b)

Figure 5-18. Ranges of production temperature determined using tribological approach a)Mixing temperature b) Compaction temperature

5.7.2.3 *Effect of WMA and Polymer Modified Binders on Frictional Characteristic*

In this study, coefficient of friction (CoF) represents the workability of asphalt mixture. An asphalt mixture with a higher CoF value will indicate poor workability and vice-versa. The

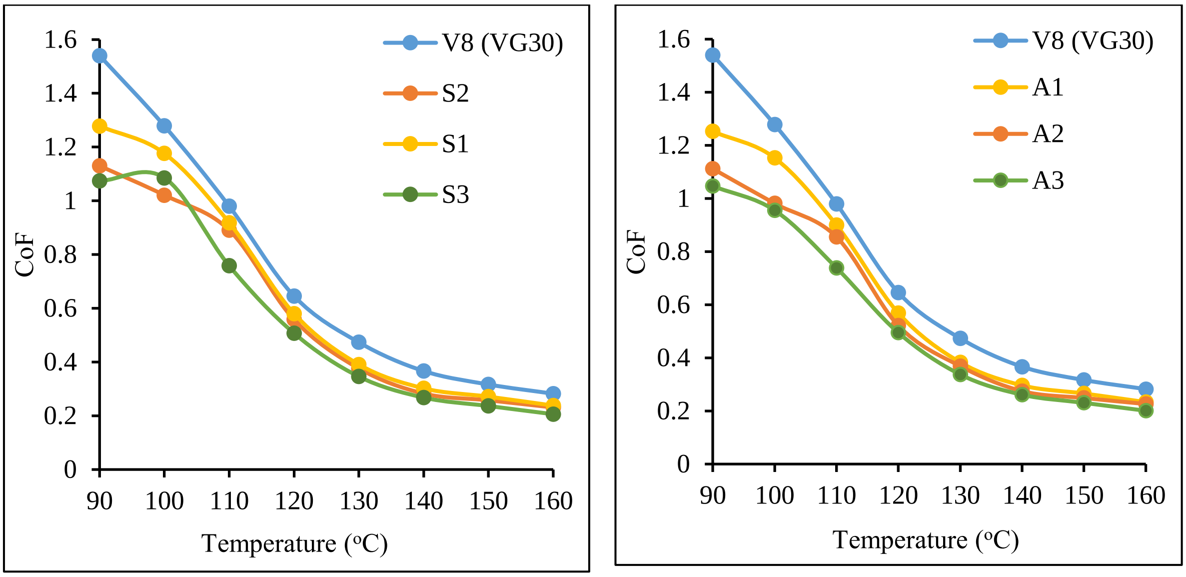
CoF readings were measured over a series of temperatures ranging from 90˚C - 160˚C. Figure 5-19 shows the variation of CoF with the temperature at a normal load of 1N and sliding speed of 0.3m/sec for WMA additives in VG30 (as base binder). The CoF of binders was decreased with temperature, irrespective of WMA additive. It can be due to the reduction in stiffness (viscosity) of the binder with temperature. Although all binders exhibited a decrease in CoF with increasing temperature, the rate of reduction was largely comparable between the WMA-modified binders and the base binder (VG30). Slightly lower CoF values observed for WMA-modified binders at temperatures above 120°C may suggest marginal improvements in lubrication behaviour due to the presence of WMA additives. This behaviour holds true when the temperature was above 120^{o}C. Below 120°C, the asphalt binder displayed complex behaviour, transitioning from a viscous medium to an adhesive medium [187]. The addition of WMA additives showed improved reduction in friction as compared to base binder as can be seen in Figure 5-20 and Figure 5-22. This can be attributed to lubrication action of WMA additives added in base binder. The Sasobit provides better lubrication by reducing viscosity whereas Rediset improved lubrication by reducing the surface tension of the binder [58]. From Figure 5-19, it can also be found that the rate of improvement in CoF was increased with increase in dosages of WMA additives. This can be due to the increase in lubrication effect of binder due to addition of more amount of WMA additives. This observation was generally true across all types of WMA additives within the tested dosage ranges although minor deviations were noted at higher dosages of certain chemical additives may be due to reduction in lubrication effectiveness of chemical additive. The WMA modified binders demonstrated similar frictional characteristics (in terms of CoF) as compared to VG 30 at relatively lower temperatures.

Figure 5-20 shows the variation of CoF with the temperature for various polymer modified binder used in this study. It can be observed that the polymer modified binders (P1, P2, P3, and

P4) showed higher CoF as compared to VG30 binder. This can be attributed to the higher stiffness of polymer modified binder due to presence of polymeric network in their structure. The different polymer modified binder showed different frictional characteristics due to the variation in their source (mechanical properties). Polymer modified binder P3 showed higher CoF values while P4 showed lower CoF values. This can due to higher stiffness of P3 as compared to other polymer modified binders whereas P4 showed lower stiffness among all PMBs. Finally, it can be revealed that the PMB showed similar frictional behaviour (in terms of CoF) as compared to VG30 at higher temperatures. Figure 5-21 shows the variation of CoF with the temperature for WMA additives in PMB40 as base binder. Similar to WMA modification in VG30, the addition of WMA additives showed improved reduction in friction as compared to polymer modified binder (PMB40). This improved reduction in friction helps in reduction in production temperature of polymer modified binders.

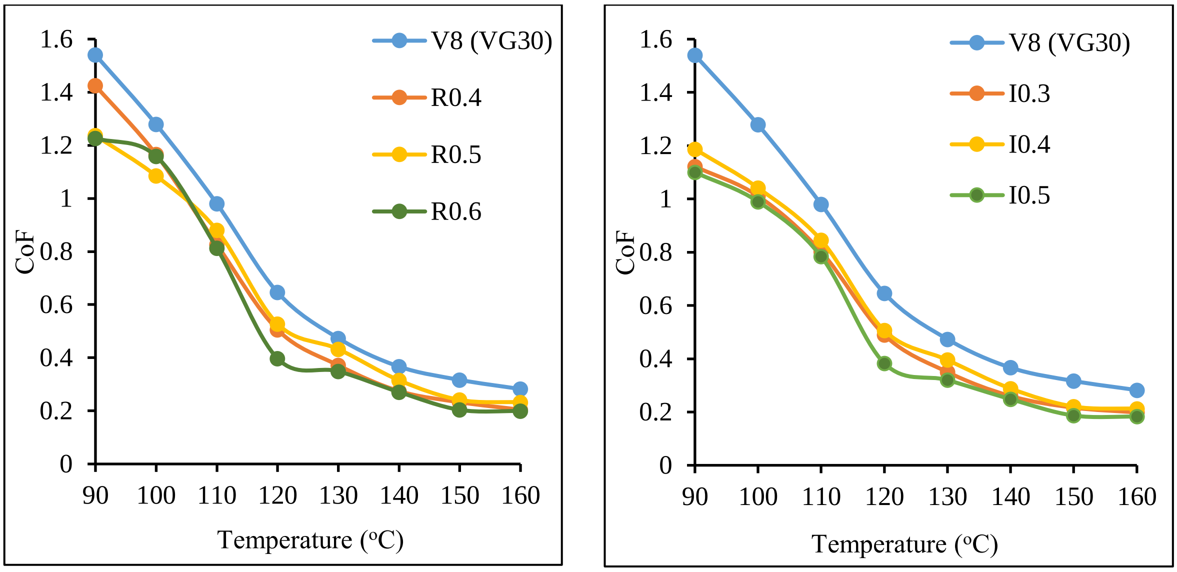
Finally, it can be concluded that the application of warm mix technologies lowers the CoF values and results in a better frictional characteristic. However, the reduction in CoF values and corresponding improvement in frictional behaviour of binder is highly dependent on the type of warm mix additives and their respective dosages. The CoF values follows a decreasing trend with the increase in dosage of warm mix, irrespective of the technology, as shown in Figure 5-19 and Figure 5-21. Notably, for VG30 with chemical additives and PMB40 with Iterlow, the reduction in CoF with increasing dosage is relatively less pronounced. Finally, it can be revealed that the WMA modified binders demonstrated similar frictional behaviour (in terms of CoF) as compared to V8 at relatively lower temperatures whereas PMB showed similar behaviour at higher temperature. This phenomenon can be adopted to compare and predict the production temperatures of WMA mixtures corresponding to the same level of friction (lubrication behaviour) as obtained for HMA (VG30) mixture. The resulting temperatures at which the CoF of WMA modified binders is similar to the conventional HMA

(VG30) may be considered as appropriate production temperatures. This frictional behaviour has been used for determining the production temperatures of WMA and polymer modified asphalt binders.



(a) Sasobit (S)

(b) Asphaltan A (A)



(c) Rediset (R)

(d) Iterlow (I)

Figure 5-19. Effect of WMA additives on frictional characteristics of VG30 as base binder (a) Sasobit (S),(b) Asphaltan A (A) (c) Rediset (R), (d) Iterlow (I)

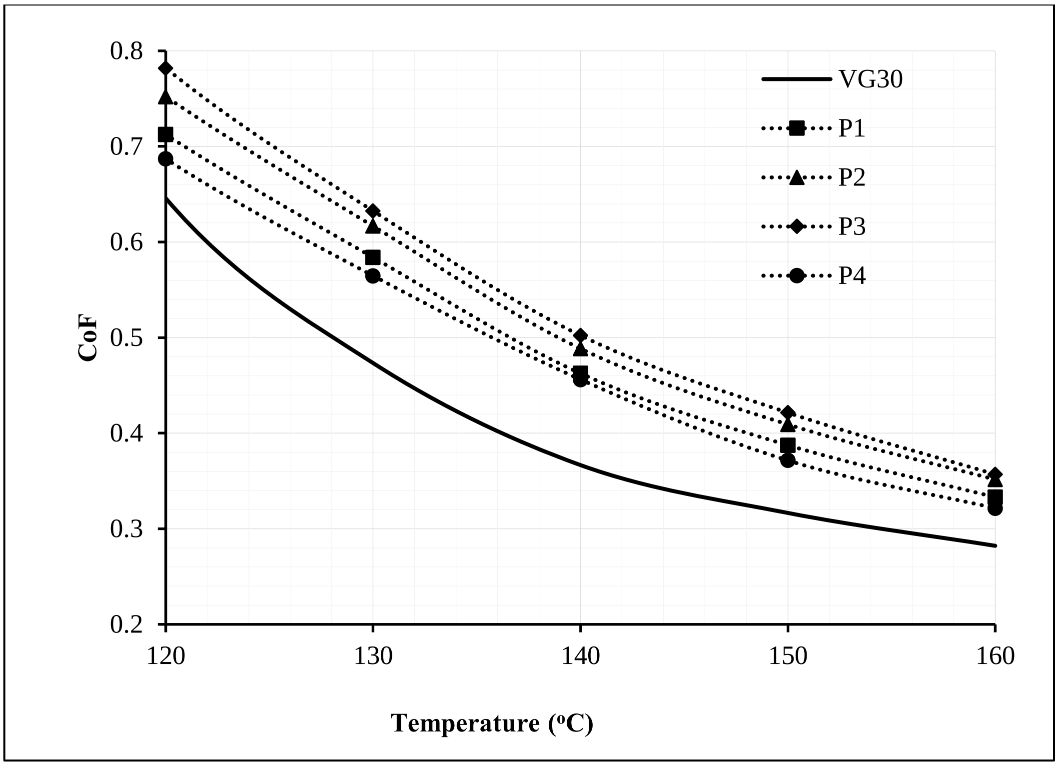
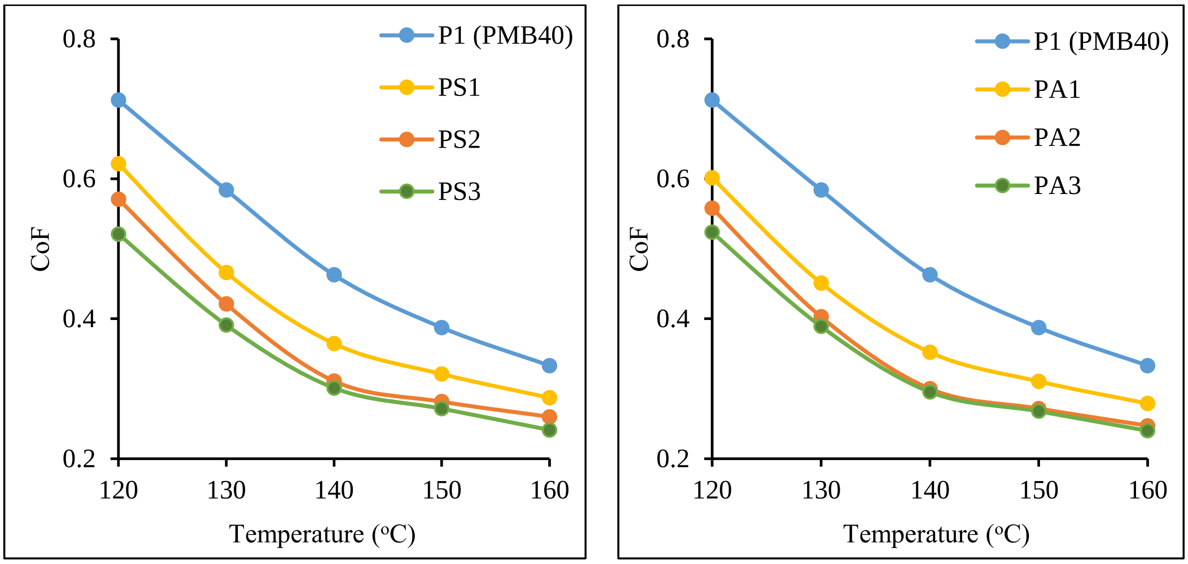
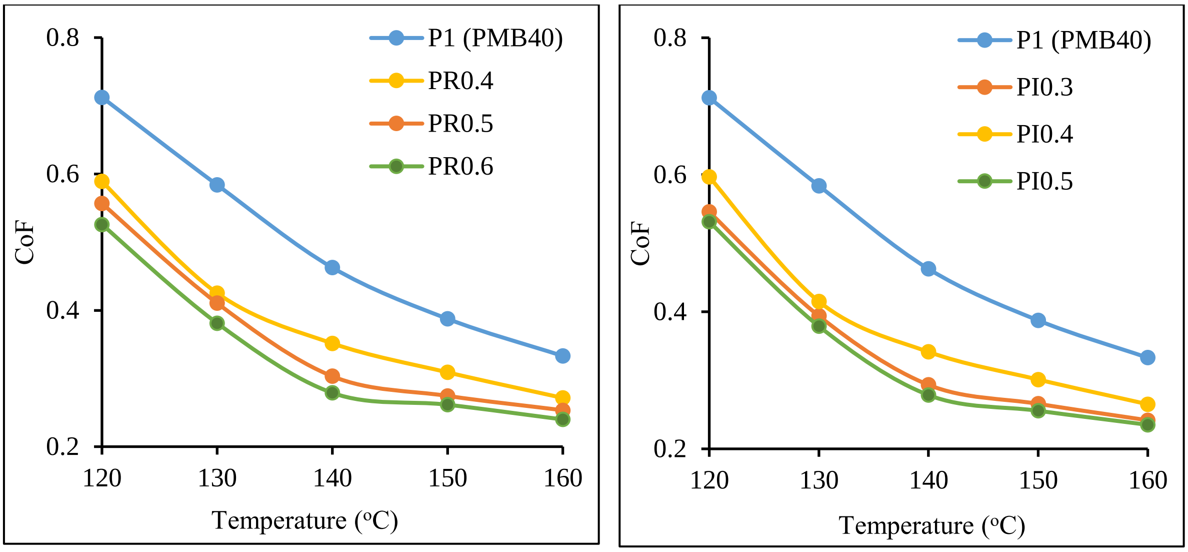


Figure 5-20. Variation of CoF with temperature for various polymer modified binders using steel plates



(a) Sasobit (S)

(b) Asphaltan A (A)



(c) Rediset (R) (d) Iterlow (I)

Figure 5-21. Effect of WMA additives on frictional characteristics of PMB40 as base binder (a) Sasobit (S), (b) Asphaltan A (A) (c) Rediset (R), (d) Iterlow (I)

5.7.2.4 Determination of Production Temperatures Using the Tribological Approach

As discussed in earlier section, the MT and CT of WMA modified binders using various plates has been determined by considering VG30 as a reference binder. But, the determination of MT and CT might vary depending on the type of reference binder used. So, in order to consider this variation and to propose reliable ranges of MT and CT, various binders has been used for determination of MT and CT using tribological approach. Therefore, fourteen binders have been considered for this study.

It is expected that WMA and polymer modified binders at their MT and CT should show similar frictional characteristics as that of viscosity grade binders. It means that all WMA and polymer modified binders should have the same CoF at their respective MT and CT. To determine the production temperatures of modified binders, the reference range of CoF has been needed. As discussed earlier, the CoF values corresponding to MT and CT (as obtained from the EQ approach) of all viscosity grade binders were taken as the reference value. It can be seen that the CoF values corresponding to MT and CT (shown in Table 5-7) were found to be insensitive to the type of viscosity grade binders. This was also confirmed by the statistical analysis using one-way ANOVA test ($p>0.05$). This implies that the viscosity grades binders can have same ranges of CoF at their respective MT and CT. Therefore, it can be concluded that the CoF values corresponding to viscosity grade binders were used as reference values to evaluate the mixing and compaction temperatures These CoF values were average over 14 viscosity grade binders with respect to their MT and CT. The CoF for all viscosity grade are shown in Table 5-7. The average value of CoF (shown in Table 5-7) corresponding to MT and CT was found to be 0.26 and 0.33, respectively. The standard deviation of 0.021 and 0.023 in CoF was observed corresponding to MT and CT, respectively. At these CoF values all modified binders showed similar frictional behaviour (same level of lubrication). These average CoF with standard deviation (shown in Table 5-7) were used as reference values for determination of production temperature of modified binders. The temperature ranges corresponding to the CoF values of 0.26 ± 0.021 and 0.33 ± 0.023, were referred to as mixing and compaction temperatures, respectively. The determination using tribological approach has been illustrated in Figure 5-22.

Table 5-7. CoF at production temperature of viscosity grade binders

Binder Type	**MT**	**CoF**	**CT**	**CoF**	**Binder Type**	**MT**	**CoF**	**CT**	**CoF**
V1	152	0.299	141	0.37	V8	160	0.282	145	0.35
	159	0.266	147	0.345		165	0.255	150	0.317
V2	154	0.279	142	0.361	V9	159	0.249	147	0.335
	158	0.249	148	0.32		166	0.215	153	0.305
V3	155	0.28	146	0.347	V10	159	0.274	148	0.339
	161	0.256	152	0.31		166	0.221	155	0.302
V4	156	0.29	144	0.37	V11	162	0.261	149	0.321
	162	0.26	152	0.32		168	0.25	154	0.295

V5	144	0.271	134	0.332	V12	163	0.295	153	0.37
	151	0.251	138	0.315		168	0.27	158	0.345
V6	156	0.295	143	0.36	V13	164	0.27	151	0.329
	164	0.26	149	0.33		169	0.225	156	0.291
V7	157	0.27	144	0.345	V14	163	0.29	149	0.37
	164	0.25	151	0.31		170	0.27	156	0.34
Average CoF					**Standard Deviation**				
MT	0.26				0.021				
CT	0.33				0.023				

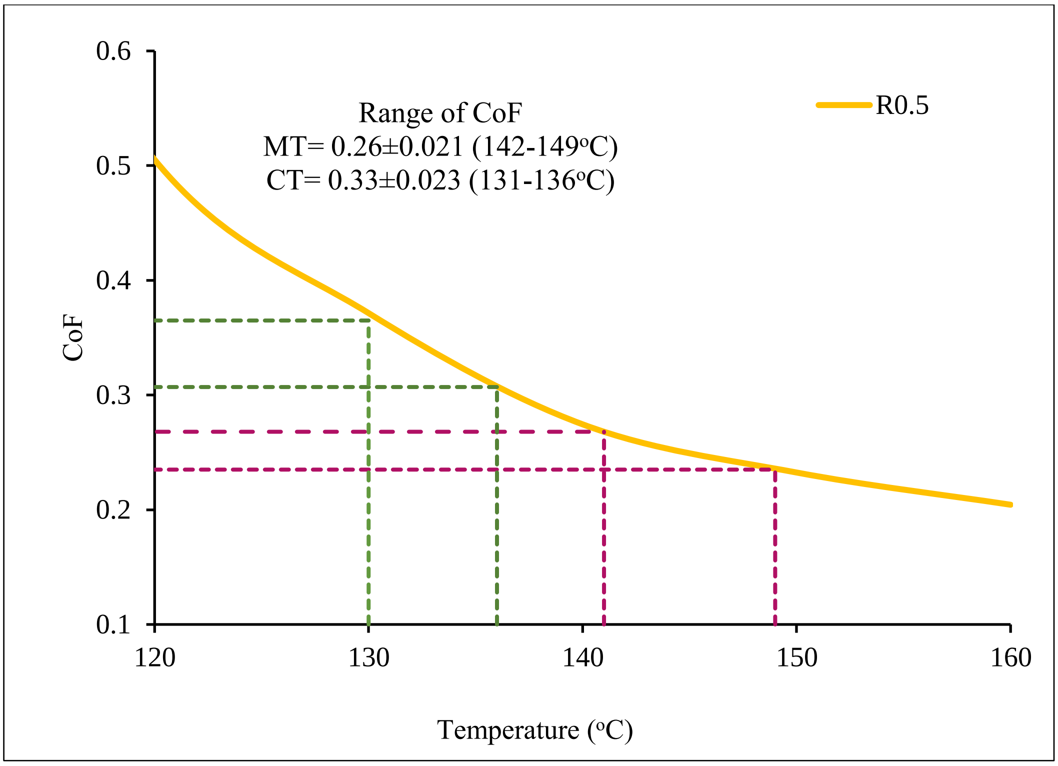
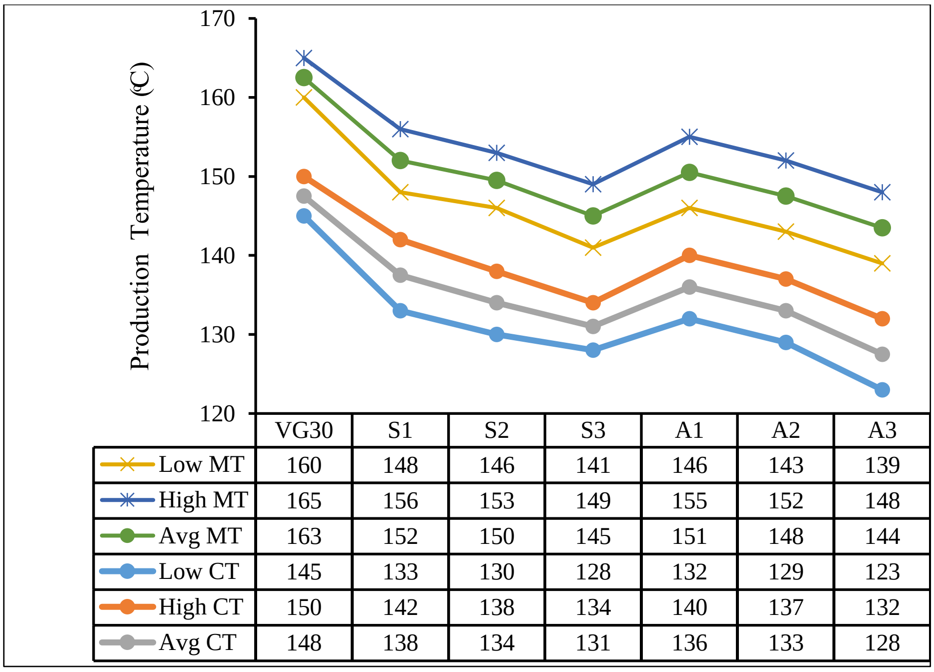


Figure 5-22. Determination of MT and CT using tribological approach for Rediset

Figure 5-23 and Figure 5-25 shows ranges of MT and CT of VG30 and PMB40 containing WMA additives determined using the tribological approach, respectively. The MT and CT of WMA modified binders were found to be lower than base binders, irrespective of type of WMA additive and base binder. The effect was increased with increase in dosages of WMA additives.

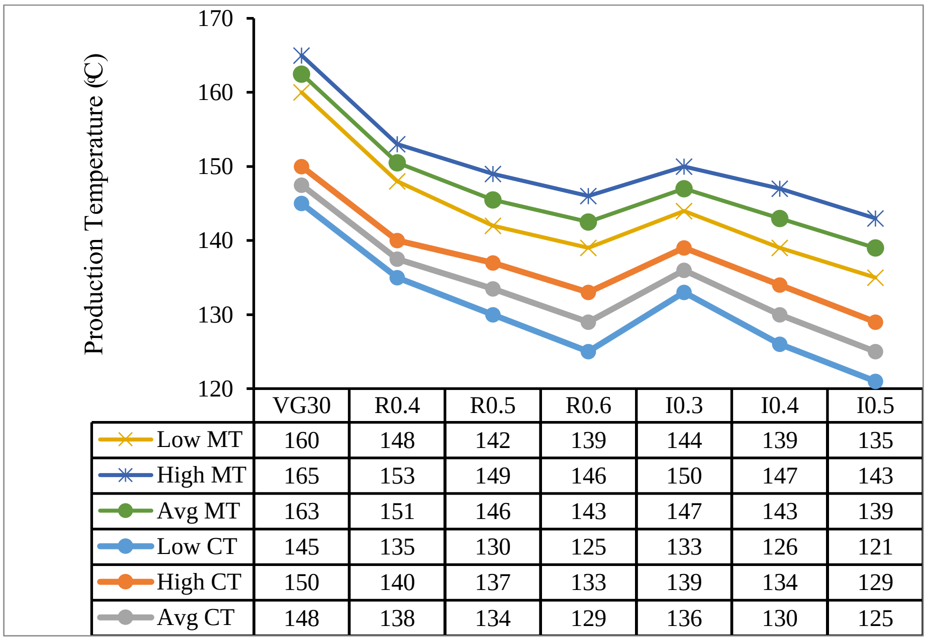
This can be due to a decrease in friction (improvement in lubrication) with the increase in dosages of WMA additives. It can also observe that the extent of reduction in MT and CT was function of type of base binder, WMA additives and their dosages. This showed that the approach was sensitive to the type of base binder, WMA additives and their dosages. The MT and CT of polymer modified binder (P1, P2, P3, and P4) were higher than VG30 as can be seen from Figure 5.24. This can be attributed to higher stiffness of polymer modified binder as compared to VG30 binder. The little variation in MT and CT among various polymer modified binders may be due to the difference in their sources. This implies that the approach was sensitive to source of the binder.

The addition of WMA additives lowered the MT and CT of base binders as can be seen in Figure 5-26 and Figure 5-27. The maximum reduction in MT and CT of VG30 for Sasobit was found to be 18°C and 17°C, respectively whereas it showed maximum reduction of 18°C and 17°C in MT and CT for PMB40, respectively. On the other hand, Asphaltan A showed maximum reduction of 20°C and 21°C in MT and CT for VG30 binder, respectively while reduction of 15°C and 19°C in MT and CT was observed with PMB40. This reduction in MT and CT of organic additive can be due to the improvement in lubricating behaviour of base binder due to their viscosity reducing function. The Asphaltan A showed higher reduction in MT and CT as compared to Sasobit. This can be attributed to the lower melting point of Asphaltan A, which allows for the early melting of wax in it, resulting in a significant reduction in production temperature. The Rediset showed maximum reduction of 21°C and 19°C in MT and CT of VG30, respectively whereas its addition to PMB40 showed maximum reduction of 21°C and 19°C in MT and CT, respectively. On the other hand, Iterlow showed maximum reduction of 24°C and 23°C in MT and CT for VG30 binder, respectively while reduction of 18°C and 21°C in MT and CT was observed with PMB40. This reduction in MT and CT of chemical additive can due to the improvement in lubricating behaviour of base binder due to their surface tension reducing function. The Iterlow showed higher reduction in MT and CT as compared to Rediset. In addition, it can be seen that chemical additives showed higher reduction as compared to organic additives. This can be attributed to the difference in mechanism associated with WMA additives for reducing the MT and CT. Considering all the warm mix additives and both base binders, the maximum reduction in MT and CT achieved was 24°C and 23°C, respectively. From the Figure 5-26 and Figure 5-27, it can also be observed that the reduction in MT and CT was increased with increase in dosages of WMA additives, irrespective of base binders and WMA additives. In addition, it was also found that the reduction in MT and CT was function of base binders. The addition of WMA additives to VG30 showed higher reduction in MT and CT as compared to their addition to PMB40. This can due to the dominance of polymeric structure in polymer modified binder which slightly affect the function of WMA additives. However, the reasonable amount of reduction in MT and CT of PMB40 was observed due to WMA additives. Overall, the reduction in MT and CT of base binder was found to be a function of base binder, type of WMA additives and their dosages. Unlike EQ method and conventional viscosity based approaches, these results revealed that the method (approach) was sensitive to base binder, source of binder, WMA additives and their dosages. In addition, the production temperatures of polymer modified binders were determined to be reasonable when compared to the conventional viscosity based approaches. Therefore, the method can be the best and most logical way to characterize the production temperature of WMA technology. To check the suitability of production temperature, their validation is necessary. In this study, the method was validated with the workability, coating ability and compactibility test. The results of validation are discussed in the subsequent sections.



	VG30	S1	S2	S3	A1	A2	A3
Low MT	160	148	146	141	146	143	139
High MT	165	156	153	149	155	152	148
Avg MT	163	152	150	145	151	148	144
Low CT	145	133	130	128	132	129	123
High CT	150	142	138	134	140	137	132
Avg CT	148	138	134	131	136	133	128

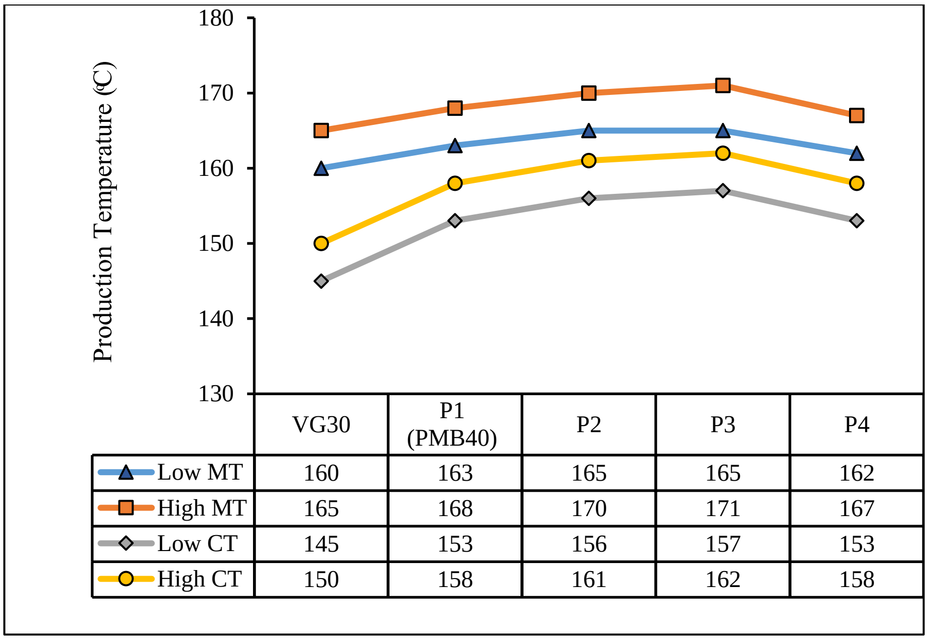
(a)



	VG30	R0.4	R0.5	R0.6	I0.3	I0.4	I0.5
Low MT	160	148	142	139	144	139	135
High MT	165	153	149	146	150	147	143
Avg MT	163	151	146	143	147	143	139
Low CT	145	135	130	125	133	126	121
High CT	150	140	137	133	139	134	129
Avg CT	148	138	134	129	136	130	125

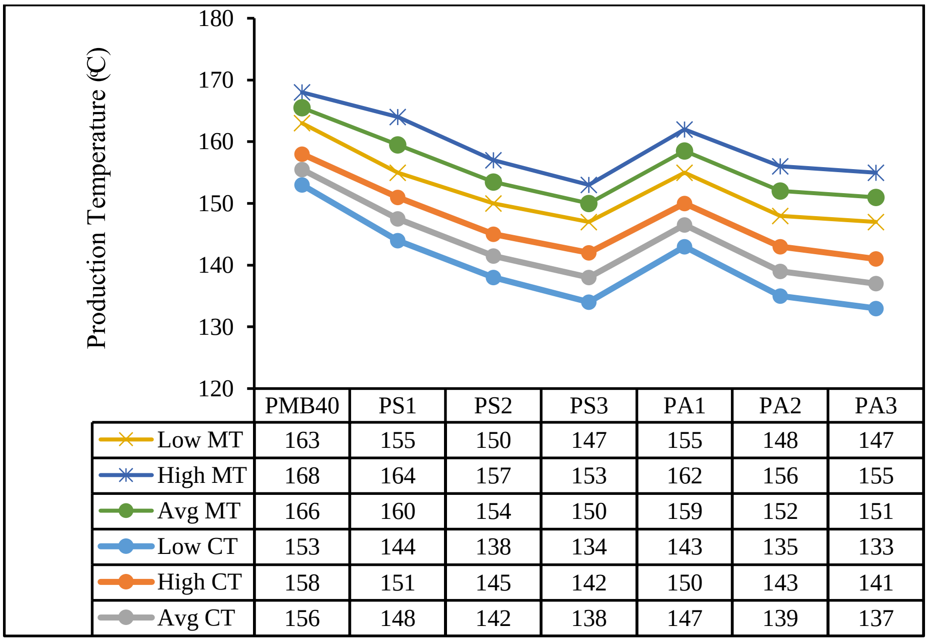
(b)

Figure 5-23. Production temperatures using tribological approach for WMA additives in VG30 as base binder a) Organic additives b) Chemical additives



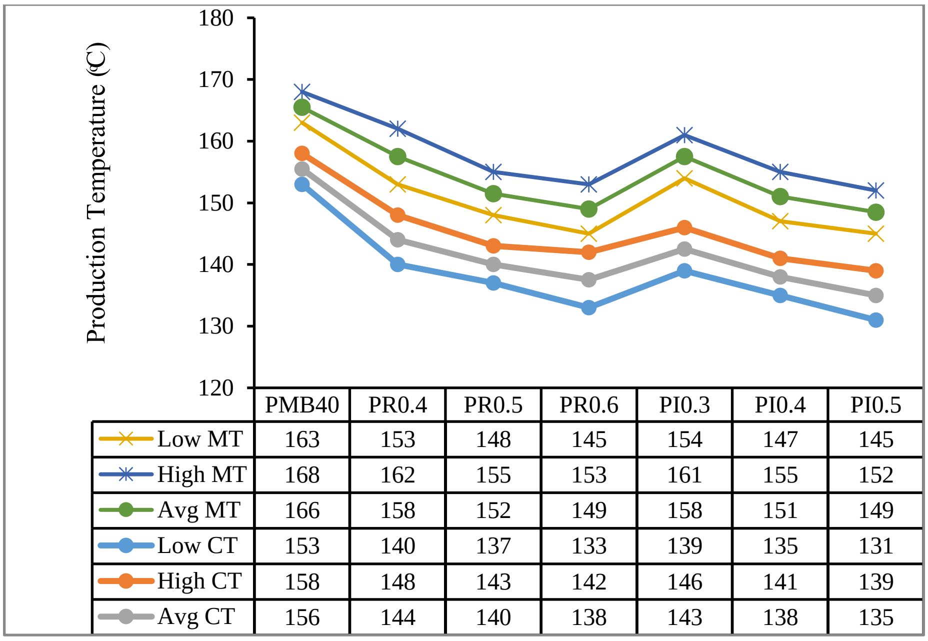
	VG30	P1 (PMB40)	P2	P3	P4
Low MT	160	163	165	165	162
High MT	165	168	170	171	167
Low CT	145	153	156	157	153
High CT	150	158	161	162	158

Figure 5-24. Production temperatures using tribological approach for various polymer modified binders



	PMB40	PS1	PS2	PS3	PA1	PA2	PA3
Low MT	163	155	150	147	155	148	147
High MT	168	164	157	153	162	156	155
Avg MT	166	160	154	150	159	152	151
Low CT	153	144	138	134	143	135	133
High CT	158	151	145	142	150	143	141
Avg CT	156	148	142	138	147	139	137

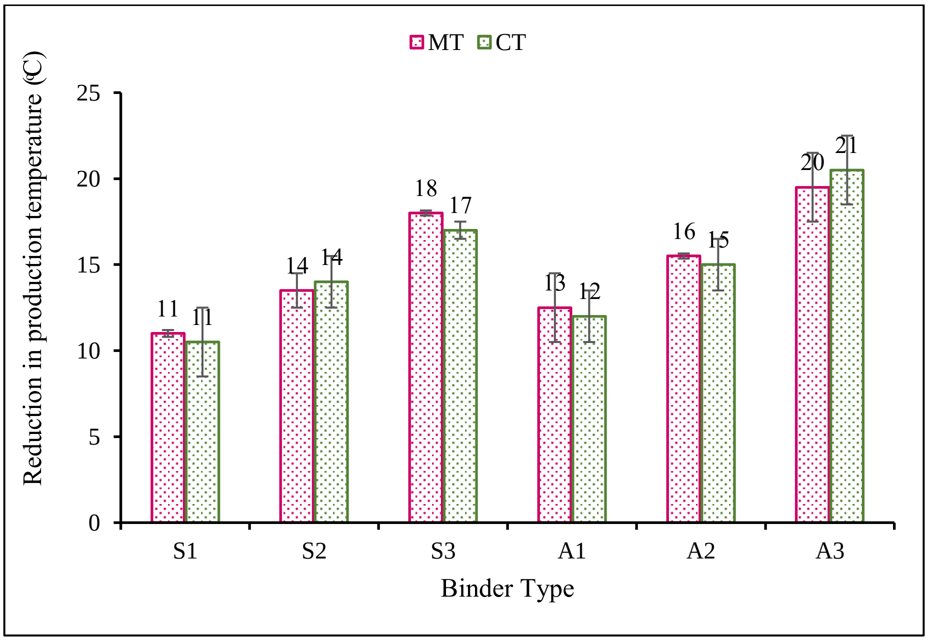
(a)



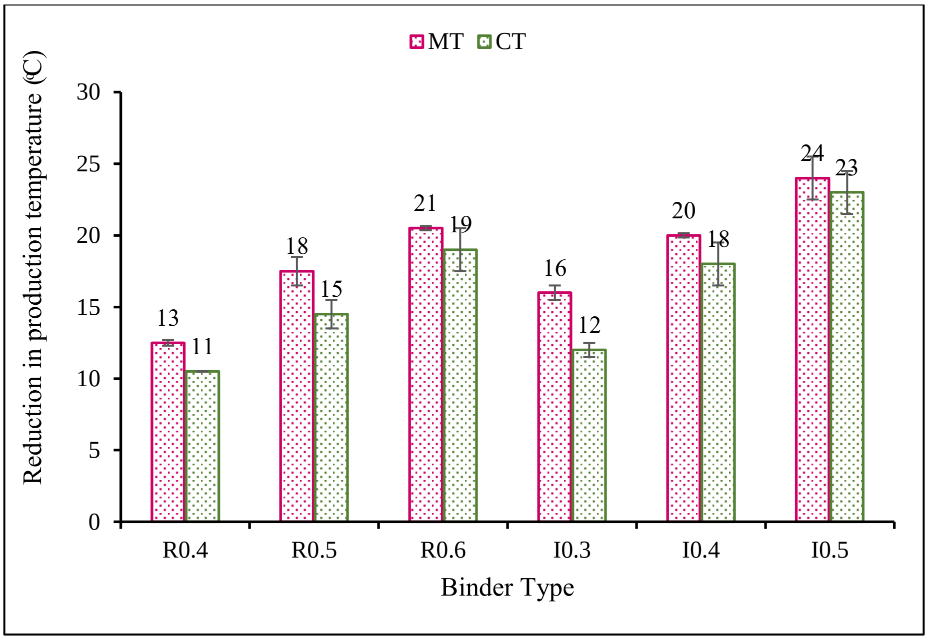
	PMB40	PR0.4	PR0.5	PR0.6	PI0.3	PI0.4	PI0.5
Low MT	163	153	148	145	154	147	145
High MT	168	162	155	153	161	155	152
Avg MT	166	158	152	149	158	151	149
Low CT	153	140	137	133	139	135	131
High CT	158	148	143	142	146	141	139
Avg CT	156	144	140	138	143	138	135

(b)

Figure 5-25. Production temperatures using tribological approach for WMA additives in PMB40 as base binder a) Organic additives b) Chemical additives

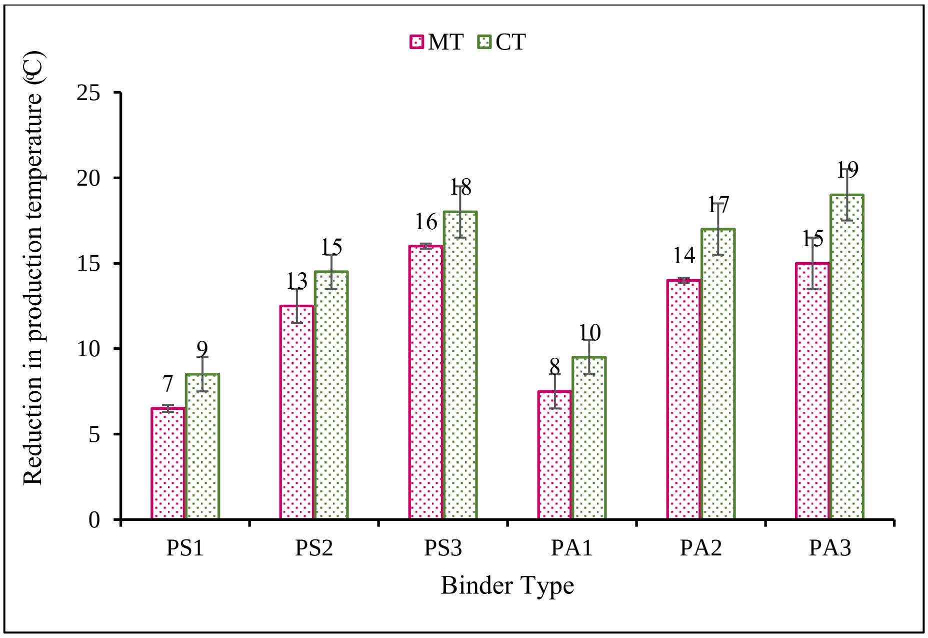


(a)

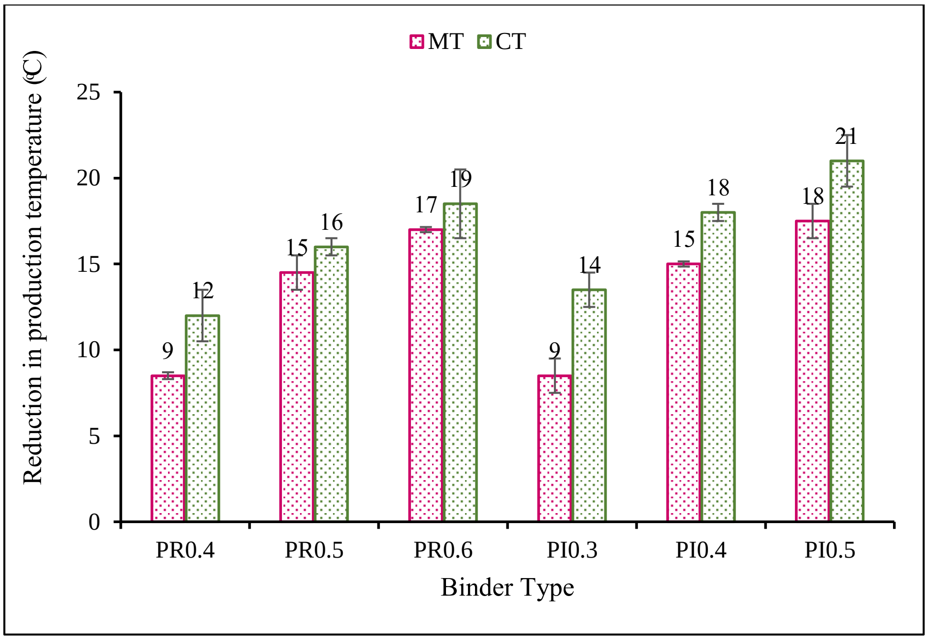


(b)

Figure 5-26. Reduction in MT and CT of VG30 a) Organic additives b) Chemical additives



(a)



(b)

Figure 5-27. Reduction in MT and CT of PMB40 a) Organic additives b) Chemical additives

5.8 Phase 2: Validation of Tribological Approach

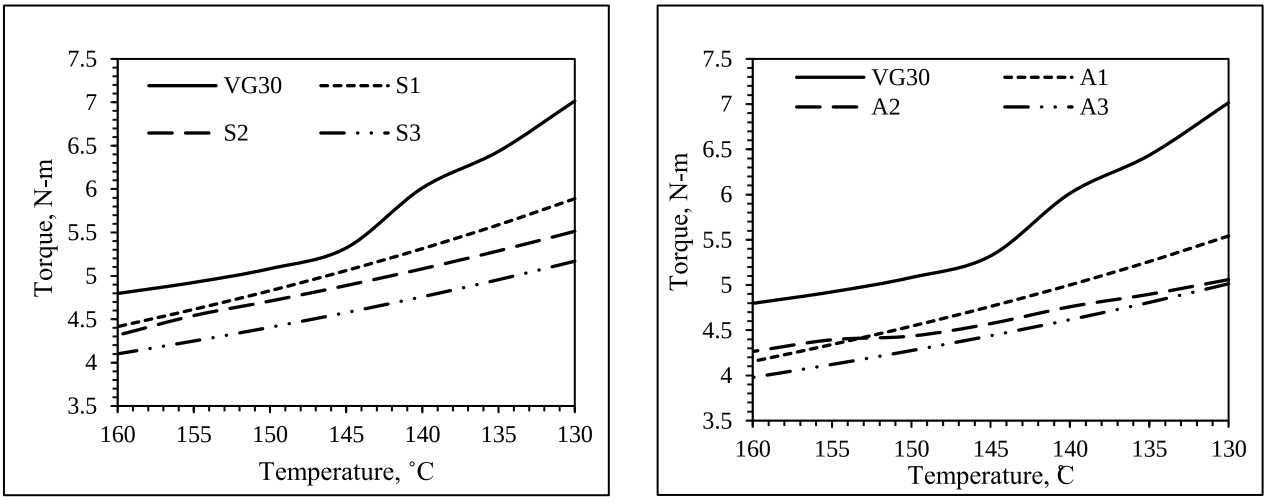
5.8.1 Workability Test

5.8.1.1 Discussion on Workability Characteristics

In this study, workability is represented indirectly by the value of torque. An asphalt mixture with a higher torque value will indicate poor workability and vice-versa. The torque readings were measured over a series of temperatures ranging from 130˚C - 160˚C. The temperature range was selected with the observation that the torque values show high variability at temperatures lower than 130˚C. This is attributed to the formation of agglomerated chunks due to the stiffening of asphalt binder at temperatures lower than 130˚C. On the other hand, an upper limit of 160˚C was chosen to avoid the aging of asphalt binder at high temperatures.

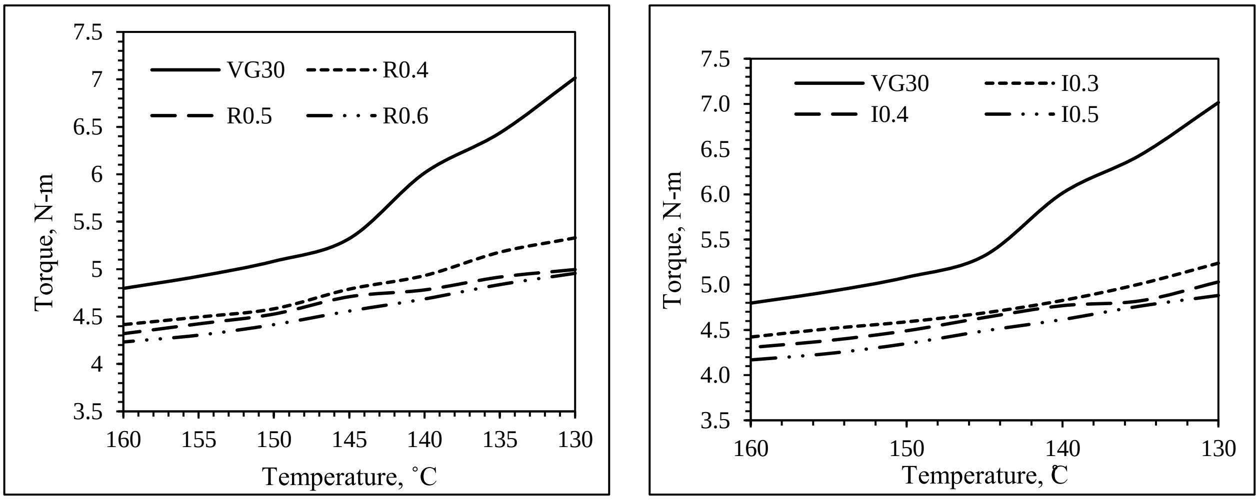
Figure 5-28 to Figure 5-32 shows the variation of torque values over a range of test temperatures for all the considered asphalt mixtures prepared using various combinations of binder, aggregates and WMA additives. As can be seen, the decrease in temperature increases the torque value. These trends are consistent for both HMA and WMA mixtures. However, the rate of increment in torque is higher for conventional HMA mixture in comparison to WMA mixtures. This observation indicates that the HMA mixture cools more rapidly with the drop in temperature, which may lead to a lower hauling distance than WMA mixtures. In addition, the reduced cooling rate in WMA mixtures would extend the paving time for the contractors and thereby shorten the overall construction period in comparison to conventional HMA mixtures [407,408]. Typically, the HMA mixture becomes harsher and less workable at low-temperature conditions (130-145˚C), as indicated by the upward hump in torque values. However, the addition of WMA technologies contradicts this behaviour and improves workability. As is evident, the application of WMA additives, irrespective of aggregate type, exhibited lower torque values (higher level of workability) than HMA mixtures (VG 30 and PMB 40). Similar trends were observed for all the WMA additives. Needless to say, workability of the asphalt mixtures was affected with change in base bitumen, aggregate type, and WMA additive and their dosage. In addition, it was observed that the increase in dosage of WMA additives proportionately lowers the torque, and thereby improves the workability as shown in Figure 5-28 to Figure 5-32. The extent of improvement in workability may be associated with the working mechanism of different WMA technologies with different aggregate type. It was also found that asphalt mixtures with Granite aggregate require higher torque to rotate the spindle and thereby resulted in lower workability compared to Dolerite inclusive asphalt mixtures as can be seen in Figure 5-33. This trend was evident for both the base binder (VG 30 and PMB 40). The higher torque values in case of Granite can be attributed to their higher surface roughness as compared to Dolerite. Therefore, aggregate mineralogy and surface characteristics can affect the workability characteristics of asphalt mixtures. Finally, it was also observed that the polymer modified binder showed higher torque values as compared to VG30. This trend was true for both the aggregate type. This can be due to higher stiffness of polymer modified binder which requires more torque to rotate the spindle through it.

In brief, WMA mixtures showed similar workability (in terms of torque) to that of HMA at relatively lower production temperatures. For PMB mixtures, slightly higher torque values may still be considered reasonable due to their inherently higher viscosity. Therefore, the estimated temperatures at which the torque is similar or slightly higher than that of conventional HMA can be regarded as appropriate for the production of WMA or PMB mixtures, respectively. In addition, the workability approach also considers the effect of aggregate type and binder type for the evaluation of production temperature, which is missing in IRC SP 101- 2019. This workability characteristics of various WMA modified binder have been used for determination of MT and CT. The details regarding the determination of MT and CT have been discussed in subsequent section.



(a) Sasobit (S)

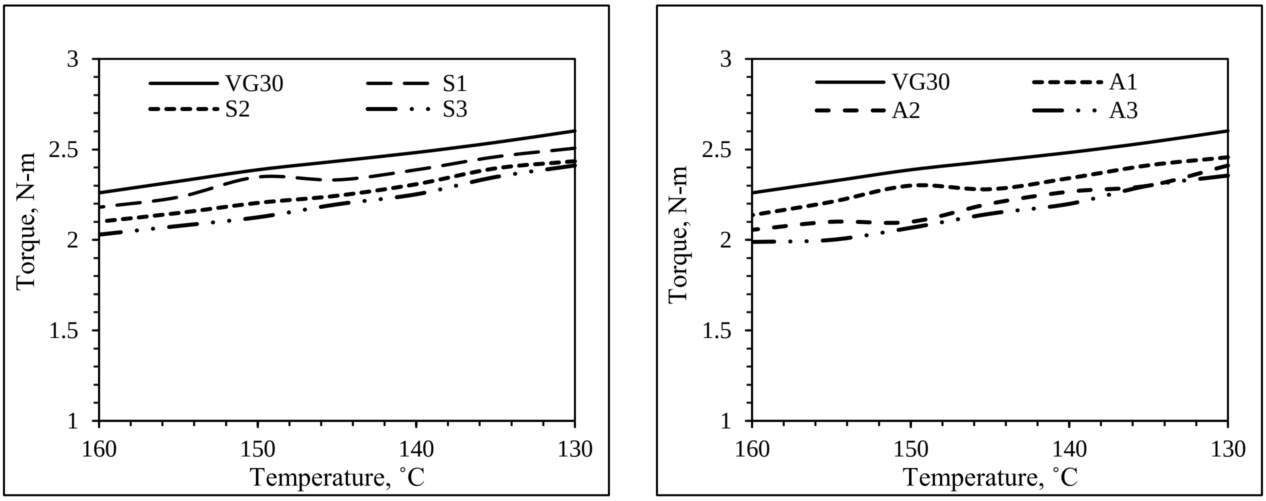
(b) Asphaltan A (A)



(c) Rediset (R)

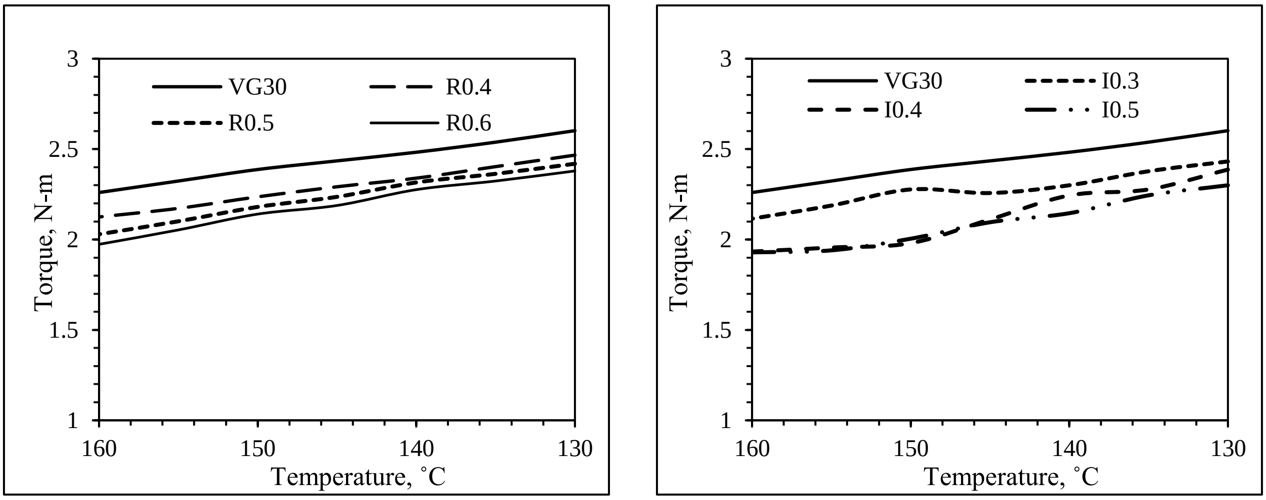
(d) Iterlow (I)

Figure 5-28. Torque values for different asphalt mixtures prepared with Granite and VG30 (a) Sasobit (S),(b) Asphaltan A (A) (c) Rediset (R), (d) Iterlow (I)



(a) Sasobit (S)

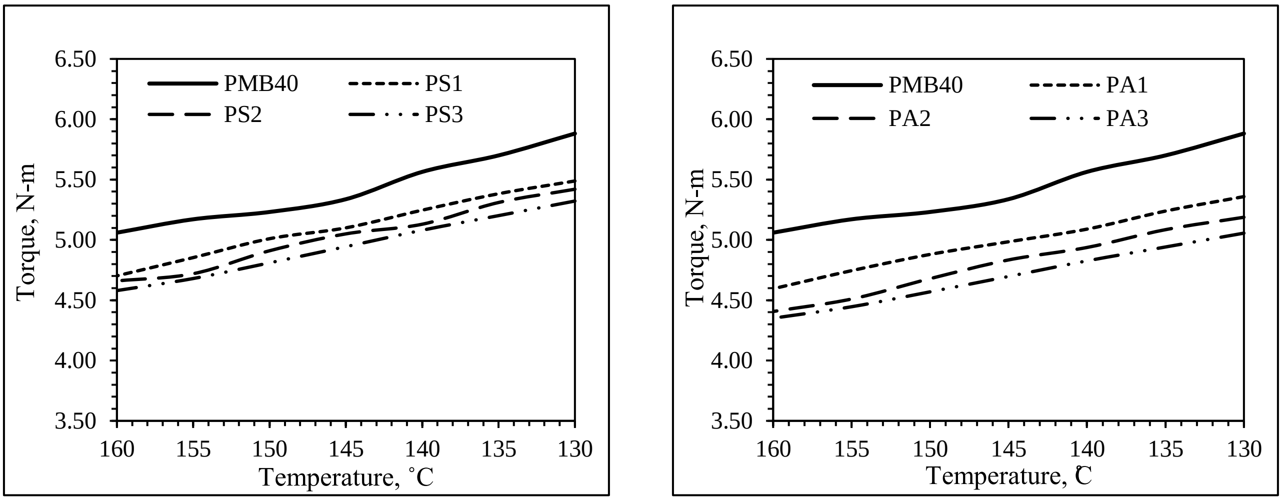
(b) Asphaltan A (A)



(c) Rediset (R)

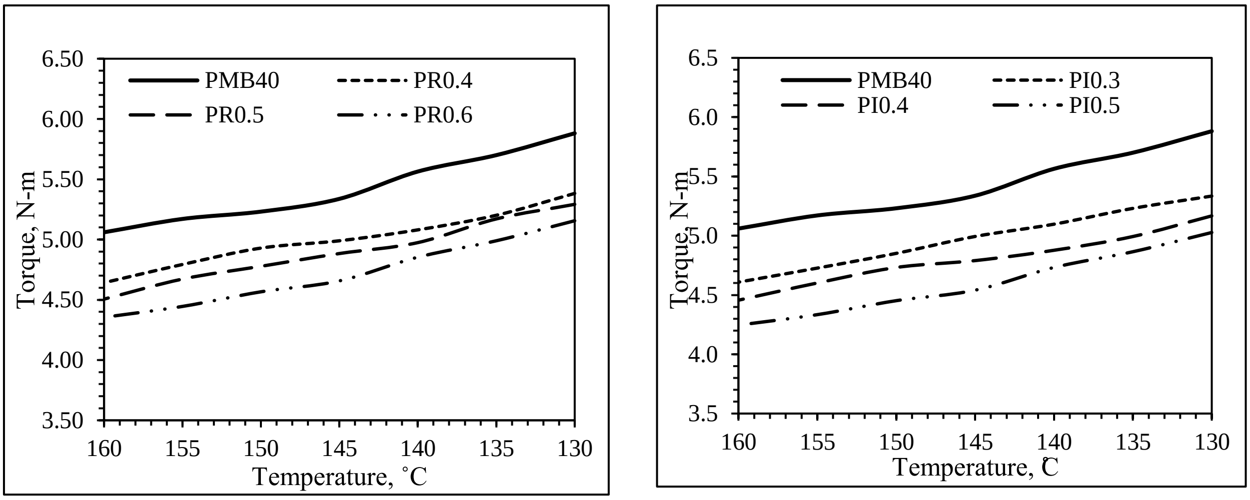
(d) Iterlow (I)

Figure 5-29. Torque values for different asphalt mixtures prepared with Dolerite and VG30 (a) Sasobit (S),(b) Asphaltan A (A) (c) Rediset (R), (d) Iterlow (I)



(a) Sasobit (S)

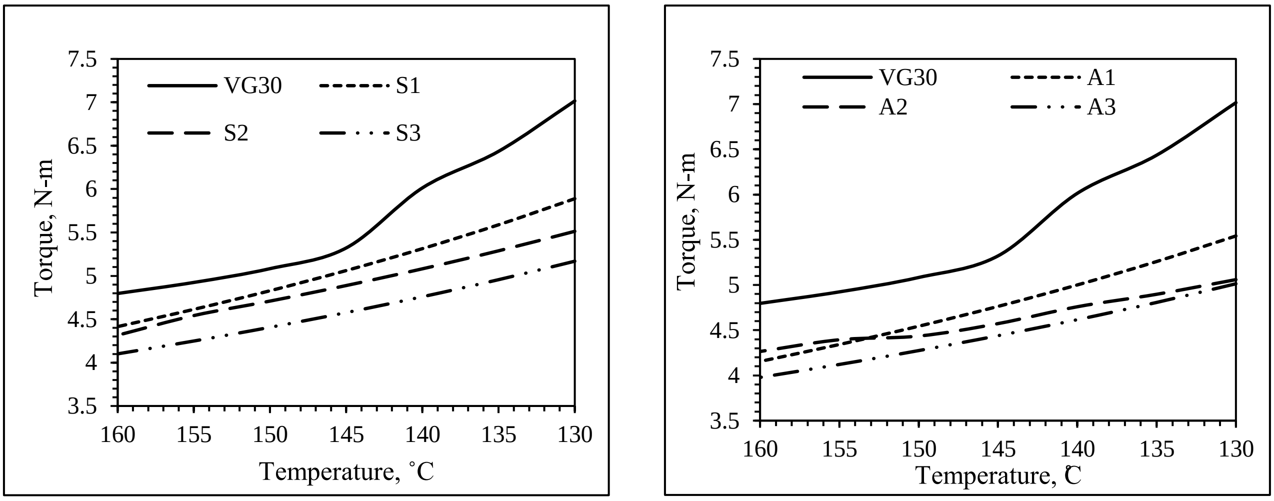
(b) Asphaltan A (A)



(c) Rediset (R)

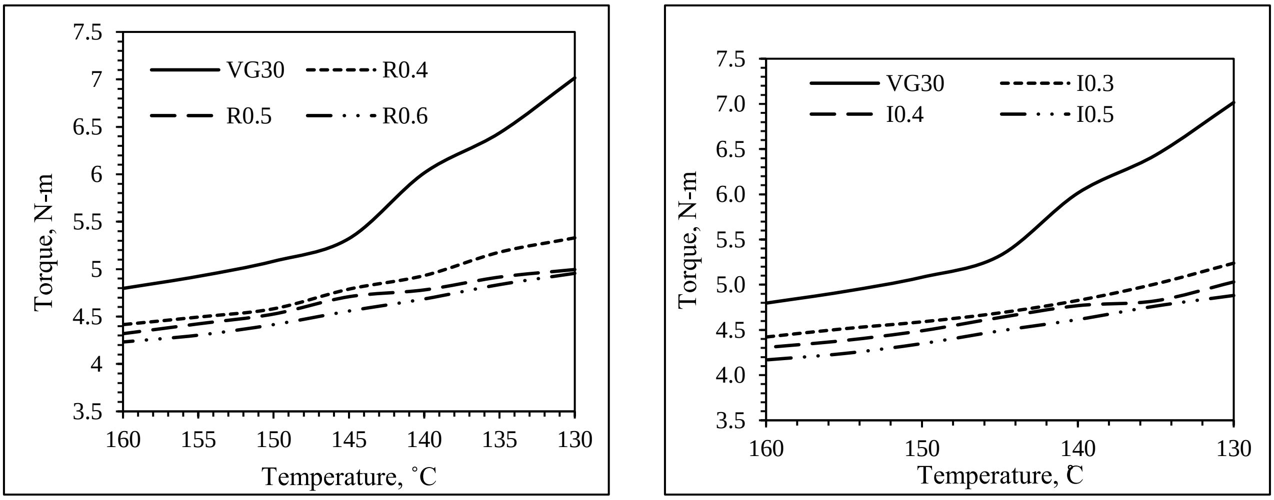
(d) Iterlow (I)

Figure 5-30. Torque values for different asphalt mixtures prepared with Granite and PMB40 (a) Sasobit (S),(b) Asphaltan A (A) (c) Rediset (R), (d) Iterlow (I)



(a) Sasobit (S)

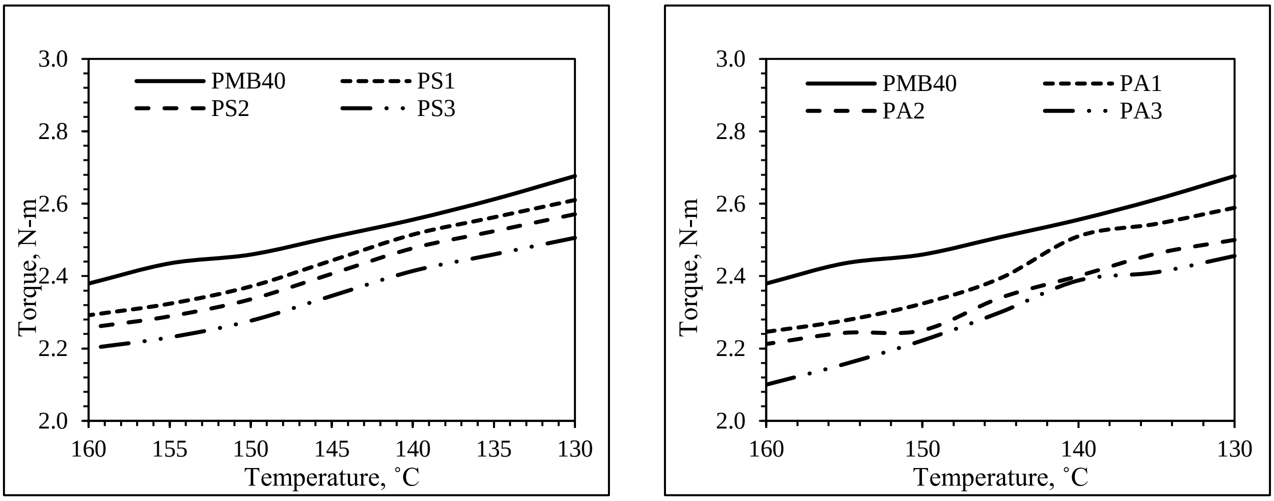
(b) Asphaltan A (A)



(c) Rediset (R)

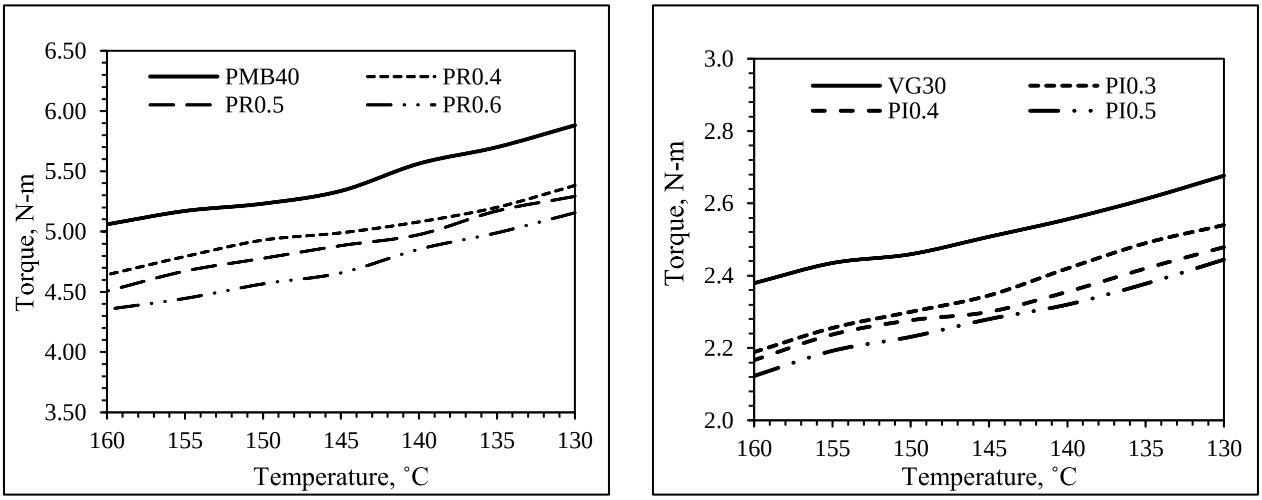
(d) Iterlow (I)

Figure 5-31. Torque values for different asphalt mixtures prepared with Granite and VG30 (a) Sasobit (S),(b) Asphaltan A (A) (c) Rediset (R), (d) Iterlow (I)



(a) Sasobit (S)

(b) Asphaltan A (A)



(c) Rediset (R)

(d) Iterlow (I)

Figure 5-32. Torque values for different asphalt mixtures prepared with Dolerite and PMB40 (a) Sasobit (S),(b) Asphaltan A (A) (c) Rediset (R), (d) Iterlow (I)

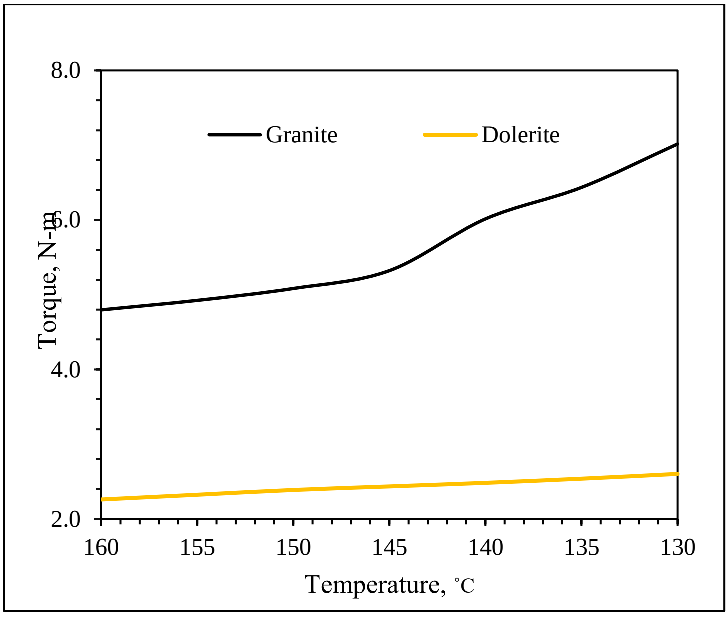


Figure 5-33. Effect of aggregate type on torque values of asphalt mixture

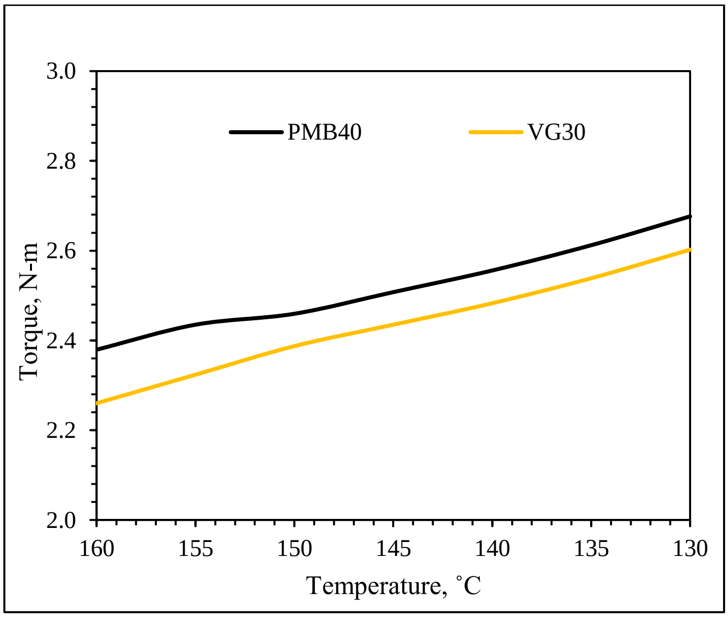


Figure 5-34. Effect of binder type on torque values of asphalt mixture

5.8.1.2 Determination of MT and CT Using Workability Approach

As discussed in the preceding sections, the torque values of HMA prepared with VG 30 were used as a reference to estimate the production temperatures of PMB and WMA based mixtures. The reference torque values corresponding to mixing and compaction temperature (as obtained from EQ approach) for different aggregate (Granite and Dolerite) type are provided in Table 5-8. In the present study, the torque values were determined over a selected range of temperatures (i.e. 130- 160°C). However, the upper range of the mixing temperature was found to be 165°C (EQ approach for VG 30). Therefore, a simple power model was used to predict the torque value at 165°C and the results are shown in Table 5-8. The production temperature corresponding to this reference torque value is referred to as mixing and compaction temperatures. The concept of equi-torque was used in the workability study to determine the production temperature of WMA modified asphalt binders.

Table 5-9 shows the mixing and compaction temperatures of all WMA modified binders determined using workability test. It can be found that the addition of WMA additives reduced the MT and CT of base binders (VG30 and PMB40). The amount of reduction in MT and CT was dependent upon the type of base binder, WMA additives and their dosages. The one-way ANOVA was carried out to check the effect of aggregate type on the amount of reduction due to the warm mix additives. The results of one-way ANOVA showed that the effect of aggregate type was insignificant to the amount of reduction achieved by warm mix additives (p-value>0.05). The maximum amount of reduction in MT of VG30 achieved by organic additives (Asphaltan A and Sasobit) was 25°C for Granite and Dolerite, respectively. On other hand, the maximum reduction of 29°C in CT was achieved with these organic additives. The chemical additive, Rediset showed maximum reduction of 26°C in MT for Granite whereas Iterlow showed maximum reduction of 23°C in MT for Dolerite. The maximum reduction in CT achieved by chemical additive (Rediset and Iterlow) was 23°C for Granite. Iterlow showed maximum reduction of 26°C in CT for Dolerite. From this study, it can be found that the Granite showed high reduction in MT and CT as compared to Dolerite, irrespective of type of base binders. In addition, among the organic additives the Asphaltan A showed higher reduction in MT and CT as compared to Sasobit. This can be due to lower melting point of Asphaltan A as compared to Sasobit. On the other hand, Iterlow as chemical additives showed higher reduction as compared to Rediset. Among all WMA additives, Iterlow showed highest reduction in MT and CT followed by Asphaltan A, Rediset, and Sasobit. The same trend has also been observed during tribology study. This can be due to their different mechanism and chemical structure associated with the reduction in MT and CT of base binders. From this study, it can also be observed that the amount of reduction achieved by the WMA was function of type of aggregate, base binder, WMA additives and their dosages.

Overall, it can be stated that the application of WMA technologies effectively reduces the mixing and compaction temperatures of conventional HMA mixtures and subsequently offers similar/improved workability characteristics. Also, the value of production temperatures, for all the considered bituminous mixtures, were found to be reasonable as compared to the temperatures obtained from conventional EQ approach. As workability study involves actual assessment of MT and CT based on asphalt mixtures. So, it can be used for validation of MT and CT obtained from tribological approach. In addition, this validation can be further complimented by coating ability test and compactibility test. The results regarding the validation have been discussed in subsequent section.

Table 5-8. Reference torque values for base asphalt binder (VG30) for different aggregate type.

Binder Type	**Aggregate type**	**Mixing temperature, ˚C**		**Torque corresponding to Mixing temperature, N-m**		**Compaction temperature, ˚C**		**Torque corresponding to Compaction temperature, N-m**	
		Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
VG30	Granite	160	165	4.78	4.35	145	150	5.32	5.08
	Dolerite	160	165	2.26	2.22	145	150	2.43	2.38

Table 5-9. MT and CT obtained from workability approach

Binder Type	Granite				Dolerite			
	MT (ºC)	CT (ºC)	Reduction in MT (ºC)	Reduction in CT (ºC)	MT (ºC)	CT (ºC)	Reduction in MT (ºC)	Reduction in CT (ºC)
VG30	160-165	145-150	-	-	160-165	145-150	-	-
S1	151-160	141-145	7	5	153-156	137-142	9	8
S2	148-159	134-140	9	10	145-148	130-134	16	15
S3	140-152	125-132	17	19	141-143	127-131	19	18
A1	145-155	134-139	13	11	149-152	133-137	13	13
A2	139-155	122-130	16	24	140-143	126-130	20	19
A3	135-148	120-127	21	24	137-139	124-127	22	22
R0.4	146-159	130-137	10	14	148-150	132-137	14	13
R0.5	139-158	117-127	14	25	143-145	130-133	16	16
R0.6	136-153	115-124	18	28	140-142	127-131	19	19
I0.3	143-160	124-133	11	19	147-150	130-134	16	16
I0.4	138-157	117-126	15	26	137-139	127-130	20	19
I0.5	133-151	112-122	21	31	133-135	120-123	26	26
Polymer modified binders								
PMB40	167-180	148-157	-	-	172-175	154-158	-	-
PS1	154-174	137-146	9	11	161-164	146-150	11	8
PS2	157-170	134-143	13	14	158-161	143-147	14	11
PS3	151168	130-140	15	18	153-156	137-141	19	17
PA1	153-170	132-141	13	16	157-159	143-147	15	11
PA2	145-162	126-135	21	22	153-156	137-141	19	17
PA3	141-159	119-129	25	29	147-150	134-137	25	21
PR0.4	154-173	131-142	11	16	159-162	143-148	13	11
PR0.5	149-166	128-138	17	20	157-157	138-142	18	16
PR0.6	142-158	123-132	25	25	151-154	134-139	21	19
PI0.3	152-170	131-141	13	17	154-156	139-143	18	15
PI0.4	145-164	122-132	20	26	151-154	133-138	21	20
PI0.5	138-154	118-127	29	30	147-150	130-135	25	24

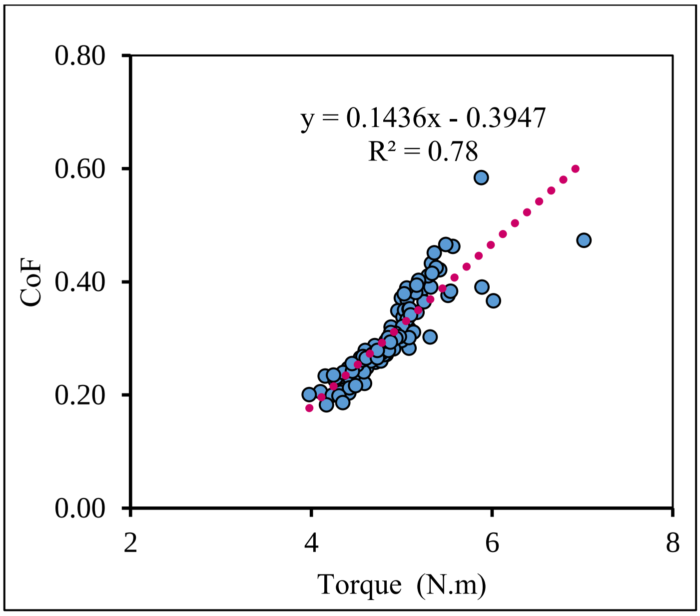
5.8.1.3 Validation of MT and CT of Tribology Approach Using Workability Approach

Figure 5-35 presents the correlation between CoF obtained from the tribology test and torque obtained from the workability study for both the aggregate types. A good correlation existed between CoF and torque for both the aggregates used in this study. This correlation was obtained for 104 data points. It was revealed that the CoF increased with torque, for both the aggregate types, indicating that it is possible to predict the CoF from the workability properties. It was due to the fact that both methods were based on the same principle i.e. based on the friction between aggregate and asphalt binder. The lower workability of the asphalt mixture can be attributed to the higher friction between the aggregate and the asphalt binder. The value of R^2 (coefficient of determination) was found to be higher (R^2=0.85) for Granite plates as compared to Dolerite plates (R^2=0.78). Both the values of R^2 were greater than 0.75 indicating a better correlation between CoF and torque [409]. The different R^2 values can be attributed to the difference in mineralogy and surface characteristics of both the aggregate type. These results showed that the tribological behaviour of binder was found to be well correlated with workability of the asphalt mixture. This also imparts that the steel plates can be used for tribology study instead of actual plates predicting the workability of asphalt mixture made of any aggregate type.

In this study, the tribological approach was validated with a workability approach. Figure 5-36 shows the comparison between the MT and CT determined from the tribology approach and workability approach. The equality lines (y = x) are also added to clearly show the similarity (or difference) between MT and CT determined from both approaches. The variations in the MT and CT were smaller when data points are closer to the equality line. For MT determined using Granite aggregates, the data points lie below the equality line indicating that the lower value of MT obtained using tribology as compared to MT determined using the workability approach. For other combination, the data points are close to the equality line as can be seen in Figure 5-36. The closeness of the point to the equality line was quantified in terms of mean absolute percentage error (MAPE). The lower MAPE values indicate the closeness of data points to the equity line i.e. better validation (comparison in this case) of the expected parameter with the actual parameter. It can be seen that for all combinations, the MAPE values were within 10% indicating the better validation of MT and CT determined from the tribological approach [410]. This showed that the MT and CT were similar for both approaches since the MT and CT values were very close to the equality line. The little variation in MAPE values can be due to the difference in the rate of change of CoF and torque with temperature corresponding to all plates and aggregates used in the study. This showed that the MT and CT determined from the tribological approach were appropriate and feasible to implement in the field for WMA technology. Finally, the results of validation indicate that the tribology can be used as a tool for evaluating the workability and production temperature of WMA modified asphalt mixture. Although tribological approach showed better correlation and validation with workability approach, but there is need to evaluate coating ability and compactibility at mixing and compaction temperatures, respectively. To validate mixing and compaction temperature obtained from tribological approach, coating ability test and compactibility test have been performed and results have been discussed in subsequent section.

5.8.2 Validation of MT and CT of Tribology Approach Using Phase Angle Method

In this study, the tribological approach was also validated with a phase angle method for polymer modified binders. For validation purpose, four different polymer modified binder (from different sources) were selected and their physical properties are shown in chapter 4. Figure 5-37 shows the comparison between the MT and CT determined from the tribology approach and phase angle method. It can be seen that considering all polymer modified binders, the MAPE values were within 10% indicating the better validation of MT and CT of PMBs determined from the tribological approach [410]. This showed that the MT and CT were similar for both approaches since the MT and CT values were very close to the equality line. This showed that the MT and CT polymer modified binder determined from the tribological approach were comparable with phase angle method. This again implies that the tribological approach works well for polymer modified binders.



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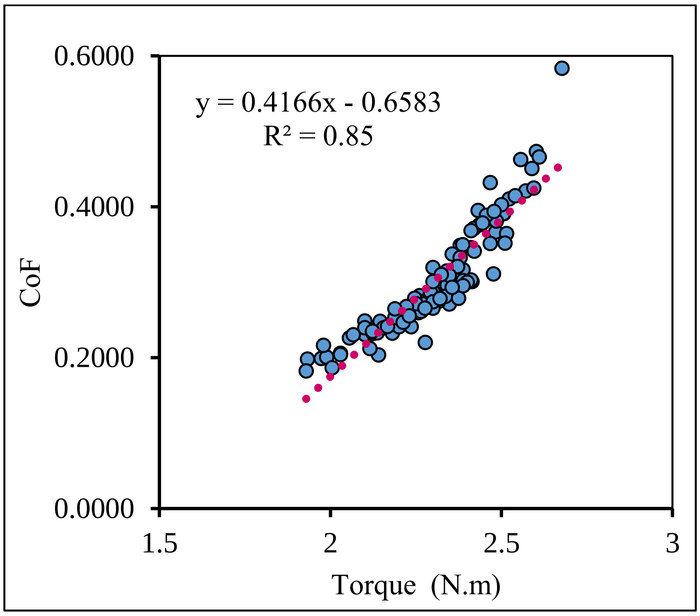
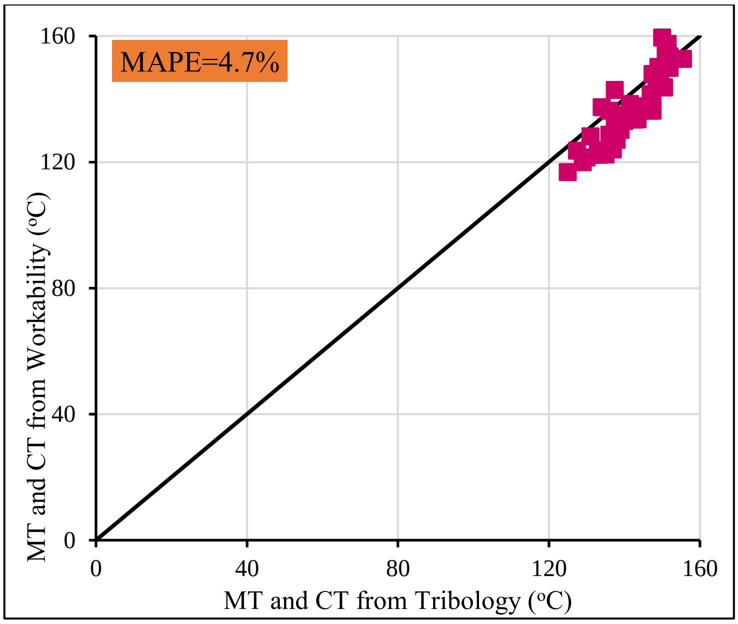


(b)

Figure 5-35. Correlation between CoF and torque a) Granite b) Dolerite



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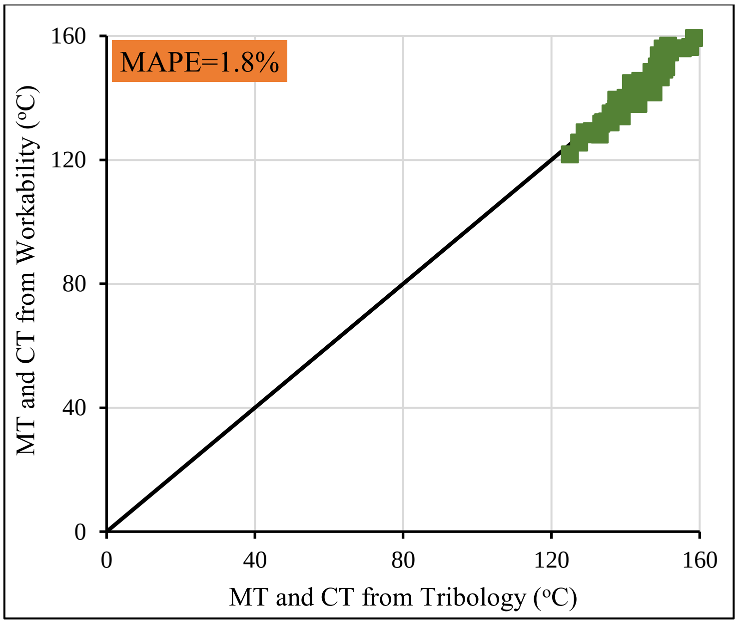


(b)

Figure 5-36. Validation of tribological approach with workability approach a) Granite b) Dolerite

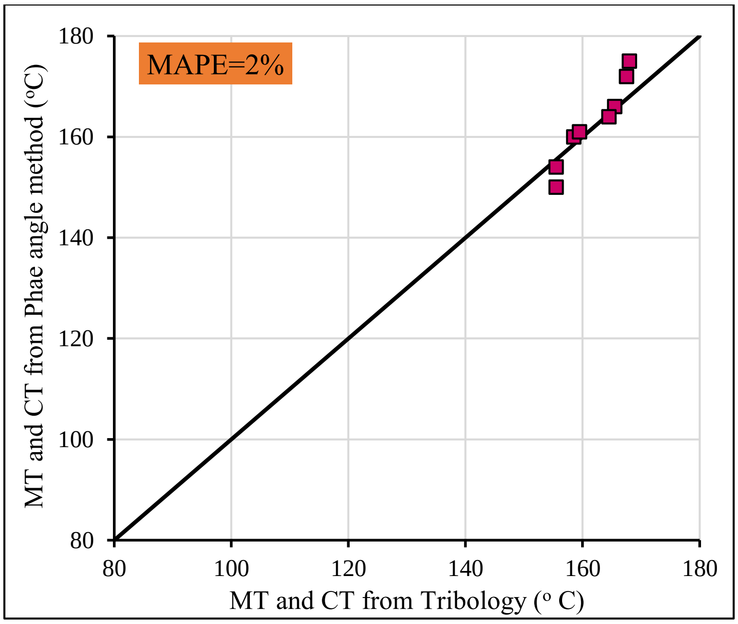


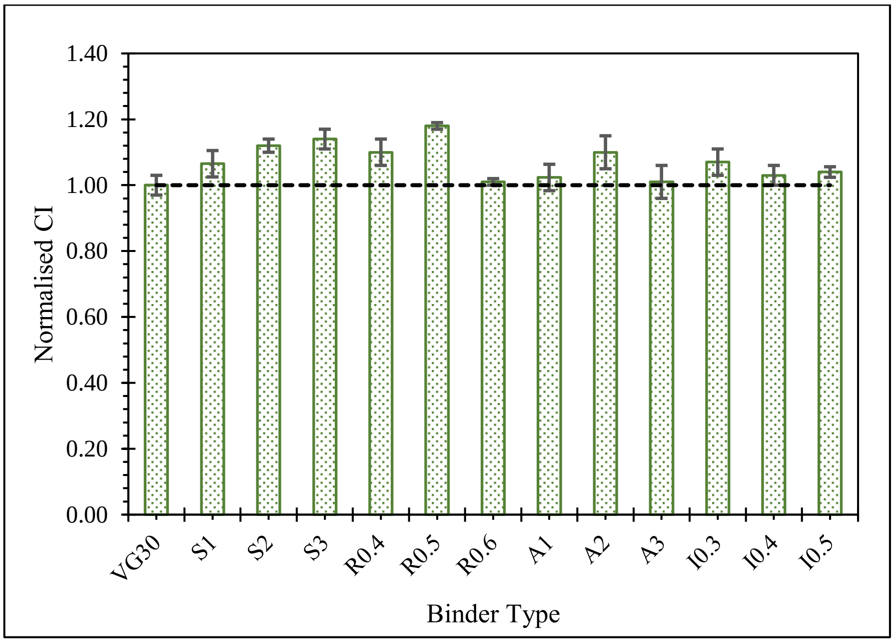
Figure 5-37. Validation of tribological approach with phase angle method

5.8.3 Validation of MT and CT using Coating Ability and Compactibility test

To check the suitability of MT and CT obtained from tribology approach, validation of approach is necessary. In this study, the validation was carried out in two steps. First, the mixing temperatures were validated using a coating ability test. At the mixing temperature, it is expected that the asphalt binder will sufficiently coat the aggregate particles. Secondly, for the validation of compaction temperature, air voids of compacted mixtures were evaluated. This was done to ensure that at the compaction temperature appropriate density in the bituminous mixtures is obtained. Air voids in a compacted mixture were taken as an indicator of compactibility. In both the validations, samples made with VG30 was used as the reference for their corresponding warm mix and polymer modified binder samples. The image analysis technique was used for checking the coating ability and the concept of air voids was used for checking the compactibility. The detailed methodology for the validation of MT and CT has been discussed in above mentioned section. This study used coating index (CI) for ensuring coating at mixing temperature. To better understand the effect of WMA, irrespective of base asphalt binder and aggregate, the measured CI was normalized with respect to the CI of the base binder. This was done because the reference value CI changes for different binder and aggregate sources. The newly proposed parameter is defined as the “Normalized Coating Index (CI_N)”. For better compactibility, the air voids for both types of asphalt mixtures were calculated and compared for verification. To do this, asphalt mixes were prepared using the Marshall mix design, in accordance with Asphalt Institute specification (MS-2), utilizing bituminous concrete (BC) gradation with a nominal maximum size of aggregate of 19 mm, mentioned in Ministry of Road Transport and Highways (MoRTH) specifications. The details about the mix design have been provided in above section (5.6.2).

5.8.3.1 Discussion on Coating Ability

Figure 5-38 (a) and (b) shows the value of normalized coating index (CI_N) for all the WMA mixtures prepared using VG30 and PMB40, respectively. In general, an appropriate mixing temperature should lead to proper coating of asphalt binder over the aggregates. In order to determine CI_N for WMA and polymer modified mixtures, the value of CI_N for asphalt mix (with VG30) was taken as unity. For polymer modified binders (PMB40), the normalized coating index (CI_N) was also calculated with respect to the VG30 control mixture ($CI_N = 1$), to enable consistent comparison of coating performance across all mixtures. A higher value of CI_N indicates better coating. Although CI_N increased with the increase in mixing temperature, the addition of WMA additives improved the coating ability of asphalt mixtures, even at reduced mixing temperatures. It can be seen that the CI_N values for both WMA and polymer modified binders were higher than 1 indicating better coating ability even at lower mixing temperatures. Similarly, the polymer modified binders (P1, P2, P3, and P4) showed similar coating as compared to VG30 indicating the better coating of binder over aggregates as can be seen from Figure 5-39. This showed that the addition of WMA additives improved the coating ability of asphalt mixtures, even at reduced mixing temperatures. This better coating can ensure better performance of the asphalt mixture. Finally, it can be concluded that the MT of WMA and polymer modified binders determined from tribological approach are appropriate and implementable in field.



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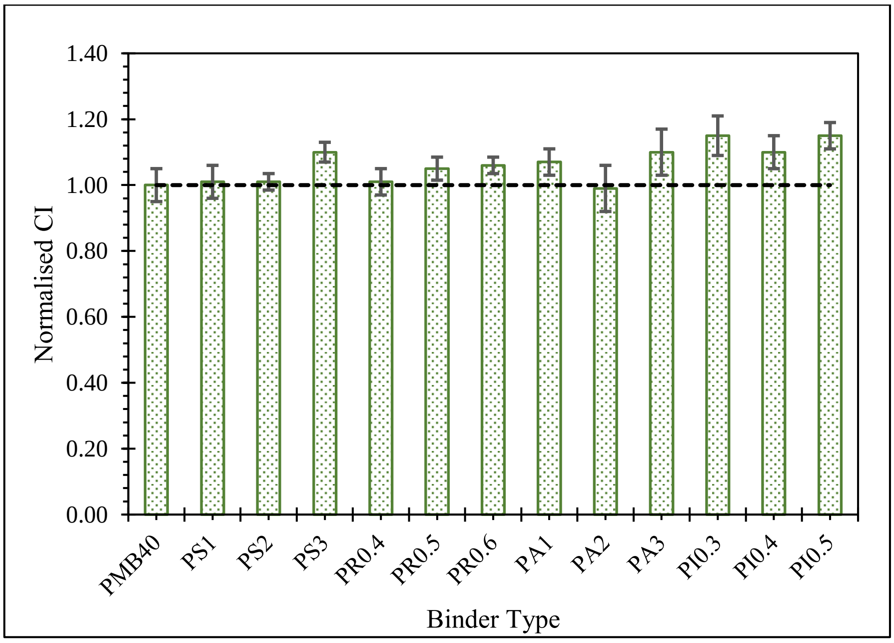


(b)

Figure 5-38. Validation of tribological approach with using coating ability test a) VG30 as base binder b) PMB40 as base binder

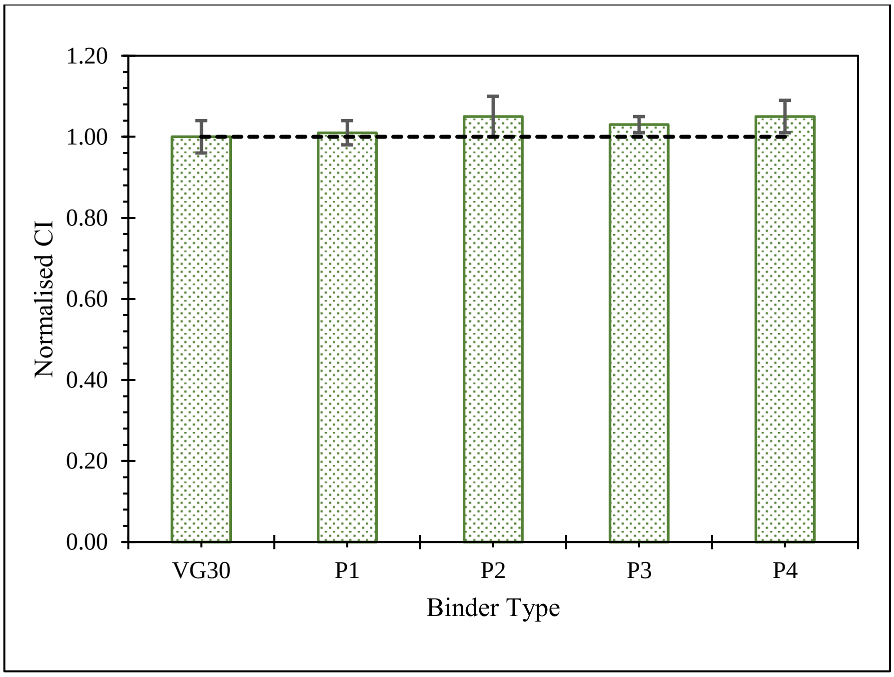
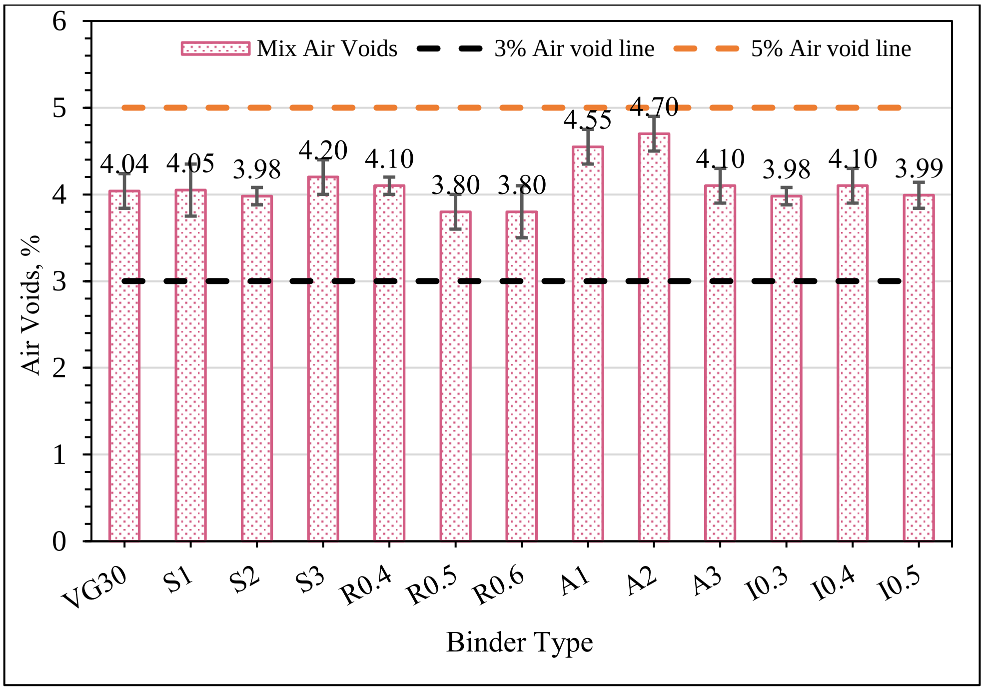


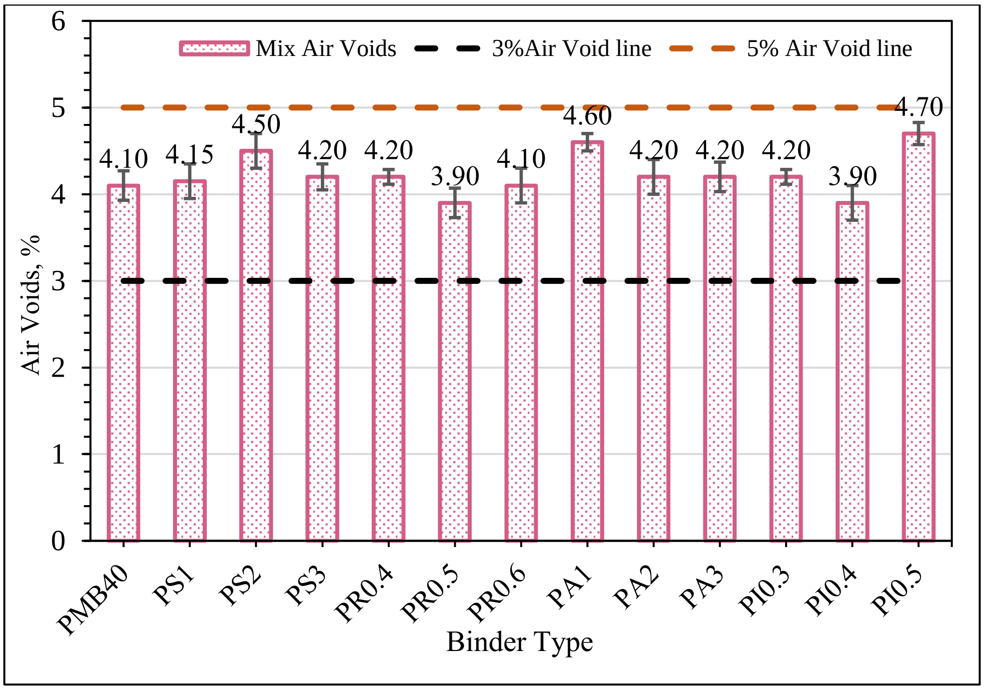
Figure 5-39. Validation of MT of PMBs obtained using tribological approach using coating ability test

5.8.3.2 Discussion on Compactibility

The value of air voids in compacted asphalt mixture was used to validate the compaction temperature. As per the guidelines given by MoRTH, the reference air void range was taken as 3-5% and shown in Figure 5-40 and Figure 5-41 with dotted line. Figure 5-40 presents the average air voids of WMA and polymer modified mixture compacted at the temperatures obtained through the tribological approach. The air voids for all the tested asphalt mixtures were found to be within the specified range of MoRTH (i.e., 3-5%). Results of compactibility revealed that the WMA and polymer modified mixture showed similar level of compactibility as that of VG30. No specific trend was observed with the change in dosage of warm mix additives. However, the air voids of all the WMA mixtures, even at reduced compaction temperature, were consistent with the results obtained for conventional HMA mixture. Finally, the results of compactibility revealed that all WMA and polymer modified mixtures were densified at lower compaction temperatures (showed a similar level of compactibility as that of VG 30) without sacrificing their mechanical performance. This indicates that the proposed methodology for the evaluation of compaction temperature can be considered more realistic and appropriate.



(a)



(b)

Figure 5-40. Validation of tribological approach with using compactibility test a) VG30 as base binder b) PMB40 as base binder

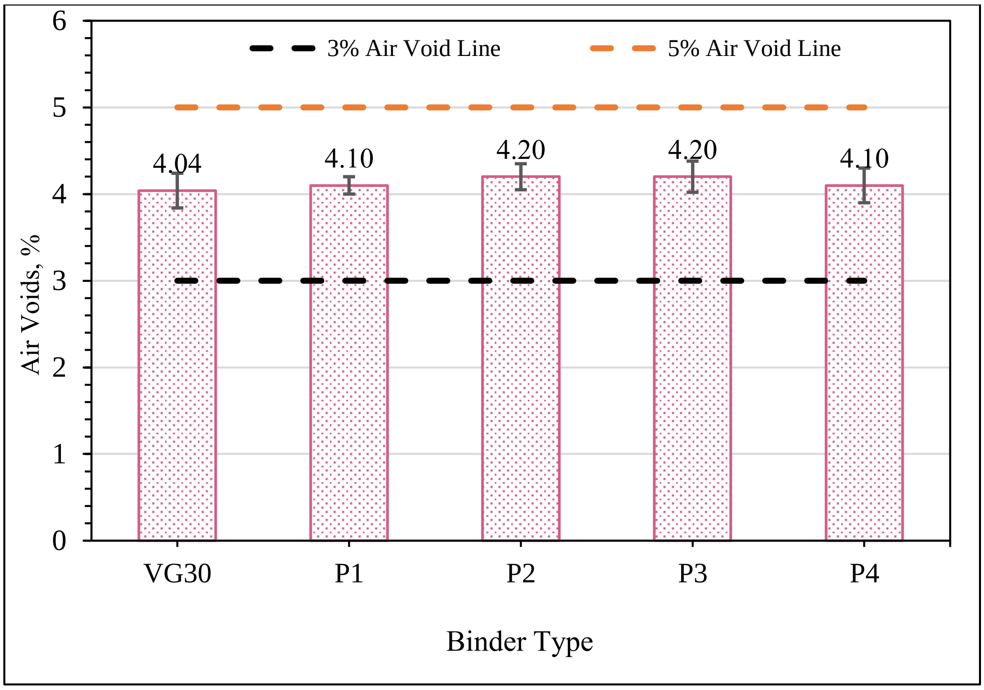


Figure 5-41. Validation of CT of PMBs obtained using tribological approach using compactibility test

5.9 Summary

This chapter demonstrated a tribology-based approach for evaluation of production temperatures of WMA modified asphalt binders. The procedure was applied to assess the reduction in mixing and compaction temperatures offered by different warm mix technologies. Further, the obtained mixing and compaction temperatures were validated using workability test, coating ability test and compaction ability test. The key conclusions derived from the different sections are as follows:

- Coefficient of friction for asphalt binder was found to be a function of normal load, sliding speed, temperature, and surface roughness of the plates.
- Ball-on-three-plates geometry mounted on DSR with the normal load of “1N” and sliding speed of “0.3 m/sec” can be successfully used for evaluating the effectiveness of WMA additives.

- The tribological approach was sensitive to WMA additives and their dosages. For all types of plates, the chemical additives showed the maximum reduction in MT and CT followed by organic additives.
- For steel plates, CoF ranges from 0.26 ± 0.021 and 0.33± 0.023 is used for evaluating mixing and compaction temperatures, respectively.
- The fabricated workability setup was successful to quantify the workability characteristics of asphalt mixtures which can further used for validation of MT and CT obtained from tribology approach. A suitable workability setup can be easily fabricated for workability assessment. The critical components of the set up includes an electric motor with speed control arrangement, appropriately designed spindle with blades, heating mantle for maintaining appropriate range of temperatures, a power meter for calculation of torque.
- Torque values of asphalt mixtures prepared using VG30 was used as the reference for evaluation of other mixtures. WMA mixtures showed lower mixing and compaction temperatures than conventional VG30 asphalt mixtures, depending on the dosage of WMA additives.
- The MT and CT determined from the tribological approach were well correlated and validated with the workability approach.
- The image analysis proposed in this study can be used to quantify the coating ability of binder over aggregate particles. Chemical additives showed higher values of normalized coating index (CI_N), followed by organic additives.
- Even at reduced compaction temperature, the air voids within WMA mixtures were consistent with the results obtained for conventional HMA mixture. No specific trend was observed with the change in dosage of warm mix additives.

- The analysis of coating ability and compactibility indicated that the proposed tribology approach for estimating the production temperatures is reliable and can be used to estimate the production temperatures of WMA mixtures.