CHAPTER 4

MIXING AND COMPACTION TEMPERATURES OF ASPHALT MIXTURES

4.1 Preface

Indian road industry and research have seen a sudden leap since the last decade. Government has sanctioned a major percentage of the annual budget for building and improving road infrastructure. This impetus has led to the adoption of various new technologies in pavement construction [9,10]. Use of warm mix asphalt (WMA) is one such technology, which enables the production and compaction of asphalt mixtures at relatively lower temperatures (ranging from 10 °C to 40 °C) than the conventional HMA [16–21]. This makes WMA an attractive technology for building greener road, especially when the performance of the asphalt mix is not compromised despite of being produced at lower temperatures. WMA is produced by adding certain additives in the asphalt binder, or the asphalt mixture [39,40]. The in-depth details on all the working mechanism of WMA additives can be found in previous chapters. Needless to say, the working mechanism of these technologies may be different, but the primary aim is to lower the production temperatures of asphalt mixtures. However, the reduction in production temperatures depends on WMA technology and their respective dosages. Despite the fact that the application of WMA results in various environmental and technical benefits, it has not been examined and/or implemented, with enough rigor, for pavement construction.

Numerous investigations [512,513] have been carried out to ascertain the effect of mixing and compaction temperatures on the performance of asphalt mixtures. Lower mixing temperature may lead to insufficient coating of the asphalt binder over the aggregates, thus increasing the chances of moisture-induced damage [43,77]. On the other hand, lower compaction temperature can cause difficulty during field compaction, and may lower the in-field density [514]. Unlike lower production temperatures, excessively high temperatures during production and placement of the asphalt mixtures may result in various other performance related concerns [137,138]. Sarnowski et al. [515] mentioned that overheating of asphalt mixtures leads to accelerated binder ageing. According to Cheraghian and Wistuba [516], ageing results in oxidative hardening of asphalt binder, leading to premature pavement cracking. Mo et al. [130] stated that 80% of premature failure of asphalt pavements is often due to inadequate compaction of asphalt mixtures. Over a period of time, several methodologies have been proposed to determine the mixing and compaction temperatures of asphalt mixture [139]. Though standard methods are available to determine the production temperatures of HMA, there are no standard methods to determine the mixing and compaction temperatures for WMA.

In India, IRC SP 101-2019 [27] is available as a guideline on use of WMA. In the present form, the guideline fails to describe a suitable procedure for assessing the mixing and compaction temperatures of asphalt mixtures produced using different warm mix technologies. The guideline recommends producing asphalt mixture at 30 °C lower temperature than the conventional HMA. The mix so produced is checked for asphalt binder coating (using qualitative assessment), air voids criteria (based on the volumetrics of compacted specimens), and moisture susceptibility (based on the value of tensile strength ratio (TSR)). Additionally taking manufacturer's recommendation is suggested to decide appropriate reduction in the production temperature, and optimum dosage of the WMA additives. This process is too iterative and lacks rational quantification of production temperatures [135,137,138]. Therefore, there is a need to improve the available specification by introducing a suitable process for assessing the production temperatures of WMA. This forms the motivation of the present objective.

This chapter discusses the applicability of different methods used for evaluating the mixing and compaction temperatures of WMA mixtures. It also includes the demonstration of a systematic process to evaluate the production (mixing and compaction) temperatures of WMA. In this part of the study, a workability measuring apparatus was fabricated, and the torque required to blend the aggregate-asphalt mixture at a fixed shear rate (rotations per minute) was used to quantify the workability of the asphalt mixtures. A new procedure, based on workability, was proposed and validated for rational evaluation of production temperatures. The obtained mixing and compaction temperatures were validated using coating ability and compactability checks, respectively, performed on each WMA mixture. The coating ability was assessed using a new experimental setup (as shown in Figure 3.27a) developed in the laboratory, while the compactability characteristic was examined using an impact compactor (as shown in Figure 3.27d). On the other hand, the comparison of air-void in the compacted asphalt mixture (Figure 3.27c) was selected as the parameter for the validation of compaction temperature. All the checks were performed by taking conventional HMA as the reference mixes. The results obtained from the comprehensive testing program were further used to optimize the dosage of WMA additives for both the aggregate sources. The results of this study can be directly used to revise the present guidelines (IRC SP 101 2019) [27] on the use of WMA in pavement construction.

4.2 Experimental Plan

This chapter is divided into three sections. The first section involves the evaluation of mixing and compaction temperatures based on different techniques (discussed in Table 3.6) employing RV/DSR. The second section included the assessment of asphalt mixtures. This section provides details about fabrication of a new workability prototype for asphalt mixtures. The workability attributes were indirectly used for the evaluation of production temperatures of WMA mixtures. The last section of the chapter explains the validation of the obtained production temperatures, using two different approaches. This phase included the development of an experimental setup to assess the coating ability of the asphalt binder over the aggregates, followed by the evaluation of compactability of asphalt mixtures at their respective compaction temperature. The details regarding the optimization of WMA additive dosages is also covered in the last section. Figure 4.1 illustrates the research framework followed in this chapter.

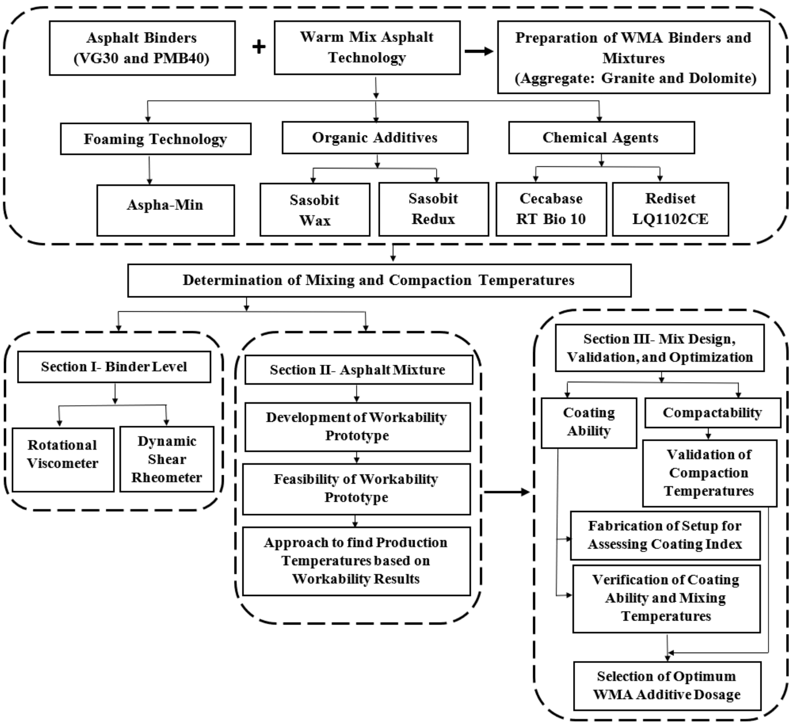


Figure 4.1. Research framework followed in this chapter

Section I

4.2.1 Different Approaches for Determining Mixing and Compaction Temperatures

The first part of the study consisted of finding the production temperatures based on the previously proposed test methods. The tests were conducted on all the considered asphalt binders using RV/DSR at different test conditions, as presented in Table 3.6. Since, some of the warm mix technologies, for example, chemical and foaming based processes, doesnot specifically reduce/influence the viscosity/rheology of the asphalt binder, the use of RV/DSR based methods are debatable [75]. To confirm this aspect, all these methods were used for evaluation of mixing and compaction temperatures of all the binder blends prepared in this study.

Section II

4.2.2 Background, Need, and Development of Workability Prototype

The term "workability" has been used to define various characteristics of asphalt mixtures associated with the construction of asphalt pavements. In particular, workability is defined as an intrinsic property that elucidates the ease with which the asphalt mixture can be mixed, laid, and compacted. This definition provides a term that applies to the movement of asphalt mixture through construction equipment to the field and its compactability [152]. Measuring the workability of asphalt mixtures is not new. One of the earliest workability device was developed in 1979 by Marvillet and Bougalt [155]. This device measured the workability in terms of the torque 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 in chapter 2 (Section 2.4). Few literatures [152,157] 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 divided into two categories based on their design arrangements [152,154,156,164]. The first one uses a fixed container with a rotating shaft [75,152,154], while the second consists of a rotating container and a fixed shaft setup [159,164]. In this study, the first approach was used to develop a new setup for measuring the workability in terms of torque. The first approach was adopted owing to its better reliability and accuracy, as stated in past studies [75,152,154]. Though the developed prototype was operated using a similar mechanism as adopted by past researchers, some changes were incorporated in this study. These included 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 was not to assess the workability, but to use the workability parameter for predicting the production temperatures of WMA mixtures. There are various factors that affect the workability including aggregate type, NMAS, gradation, shape, binder type, test temperatures, etc. Thus, to evaluate the production temperatures of WMA, all these variables were kept constant throughout the study.

The fabricated workability device consisted of six components: (i) a metal container, (ii) a spindle with sharp blades, (iii) a digital speed drive, (iv) a heating mantle with a temperature controller unit, (v) a power meter, and (vi) an electric motor. Figure 4.2 shows the schematic representation of the workability setup used in this study. To ensure consistent mixing, the size of the metal container was selected such that it completely accommodates the asphalt mixture. Different studies have prepared blade attachments (in the spindle) as per their convenience and usefulness. An ideal blade setup should ensure continuous mixing of the mixture, and thereby eliminate the creation of a shear plane within the asphalt mixture. Gudimettla et al. [152] observed that the creation of a shear plane gives a constant value of torque at different temperatures. To overcome this issue, in this study, the spindle blades were attached such that it restricts the creation of a shear plane. The height of the spindle was made adjustable using an adjusting head. The height of the spindle was kept constant throughout the testing. A speed drive was attached to the setup for operating 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 to measure the power required for rotating the mixture at the selected speed and temperature. In this study, the torque was measured indirectly by using the value of power (obtained from power meter), and speed of the shaft (indicated by speed drive display). A heating mantle was also installed for maintaining the test temperature of asphalt mixtures. A digital thermometer was used to measure the temperature of the asphalt mixture during the test. Operational details of the fabricated workability setup are presented in Table 4.1.

It should be noted that the fabricated workability set up is one of many such models which previous researchers have used [152,154–156,164]. This study doesnot stress on building a similar model, rather, the procedure proposed for the quantification of workability is the main novelty of this work. Therefore, the proposed method can be applied for any fabricated workability setup, if it is able to deliver consistent mixing of mineral aggregates with the asphalt binder under controlled temperature condition, and has an arrangement to measure the torque required to rotate the spindle in the asphalt mixture at any fixed shear rate.

Table 4.1. Operational details of workability prototype

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

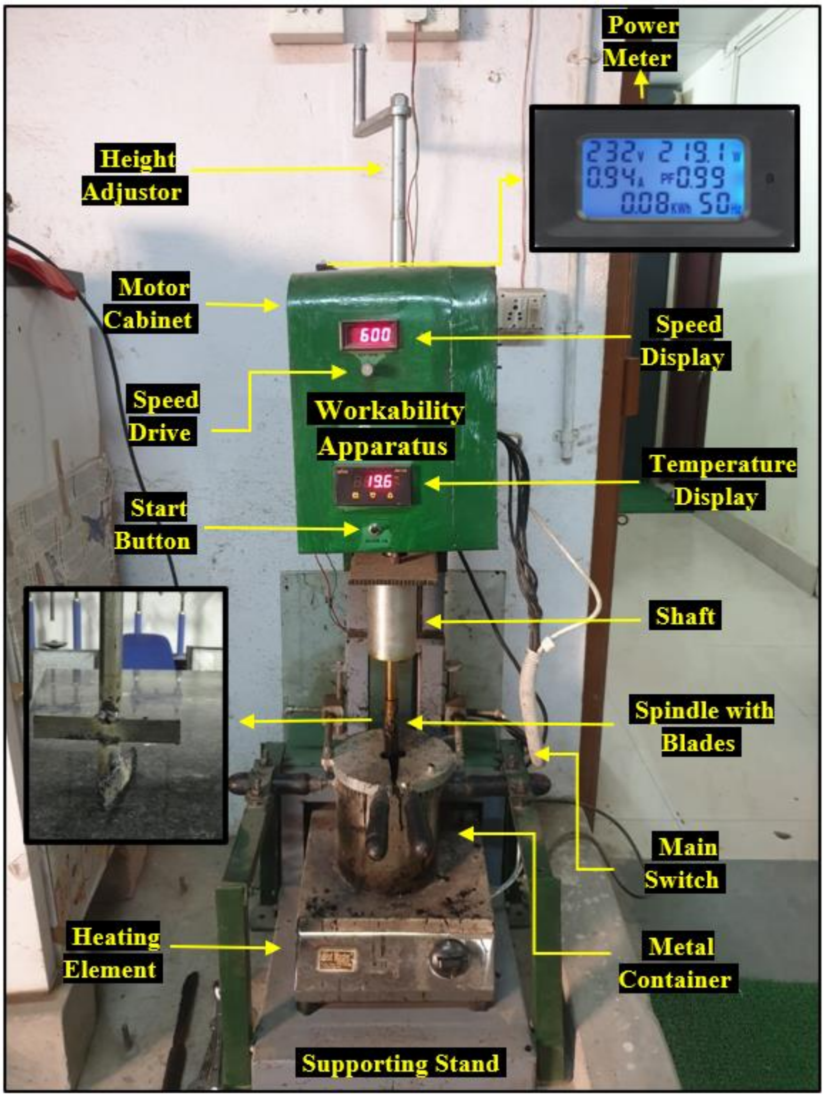


Figure 4.2. Workability apparatus fabricated in this study

4.2.2.1 Estimation of Workability

The workability of asphalt mixtures is quantified indirectly using the torque required to move the submerged spindle of the workability setup at a fixed rotational speed. The following steps, as shown in Figure 4.3, were followed and is proposed for estimation of workability:

1) The aggregates and asphalt binder were placed in the oven (160˚C-165˚C) for 2 hours prior to the mixing process. 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 aggregates was batched and mixed with the heated asphalt binder to produce asphalt mixtures. The weight of the aggregates was selected based on the size of container and capacity of motor.
2) Following the mixing process, the asphalt mixture was kept in the oven for conditioning (actual testing temperature + 5°C) 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 before the start of the testing procedure.
3) After mixing and conditioning, the asphalt mixture was transferred to a container, placed on the heating mantle. 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 was kept such that the motor easily rotates within the mixture without any difficulty.
5) The spindle was allowed to rotate for a period of one minute to achieve uniformity in the asphalt mixture. The temperature was allowed to drop under natural conditions.

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 speed of rotation, as given in Equation 4.1 [517].
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 turned on 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 interval. Average of these two readings was reported for further analysis.
8) The workability test timing depends upon the capacity of the heating mantle, and it approximately took one and half hours to complete the test in this study. 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.

$$\tau = \frac{60 \times P}{2 \times \pi \times N} \tag{4.1}$$

Where,

τ = Torque generated in N-m

P = Power in watt

N= Speed of the shaft in rotation per minute (rpm)

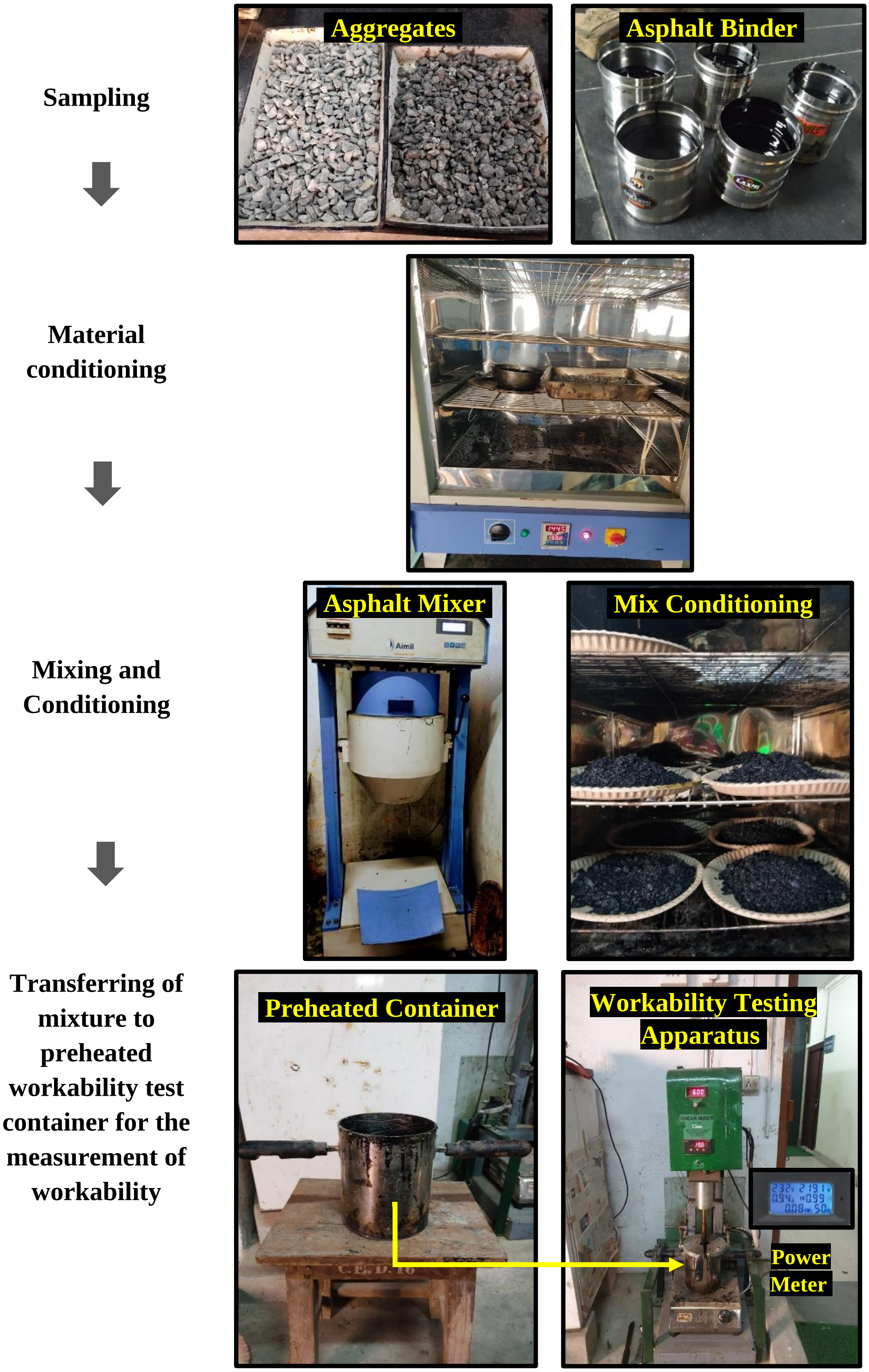
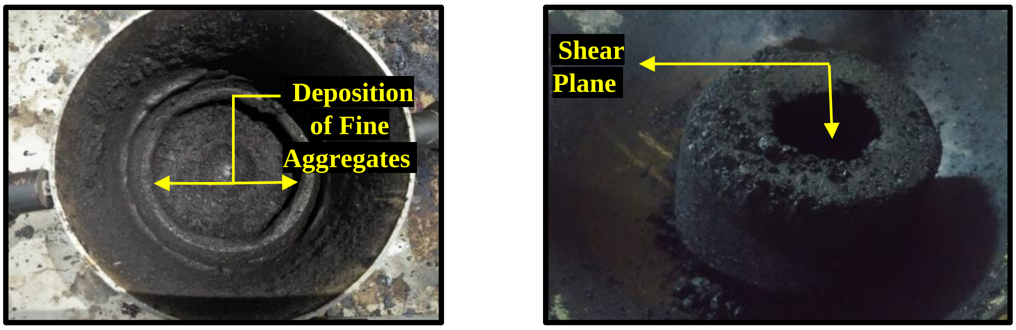


Figure 4.3. Stepwise measurement of workability of asphalt mixtures

4.2.2.2 Challenges and Refinement in the Workability Setup

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 4.4). 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, single-sized aggregates (9.5 mm passing and 6.3 mm retained) were incorporated and blended with a fixed amount of asphalt binder (4% by weight of aggregate) for further testing. The quantity of material was also reduced from 5 kg to 3 kg for better repeatability in the results. Also, a gap of 25 mm was maintained between the spindle and the container.

It should be, however, noted that alternate spindle geometry can be used for actual aggregate gradations, given that it is able to appropriately mix the sample without formation of shear plane.



(a) (b)

Figure 4.4. Deposition of material (a) fine aggregate on the walls of the container and (b) agglomerated chunk

4.2.2.3 Feasibility and Validation of Fabricated Workability Setup

The relationship between torque and temperature was plotted to check the feasibility of the fabricated workability setup, as shown in Figure 4.5. The torque reading was noted at each temperature, and the process was repeated 5 times to observe the variation in results. As expected, the torque decreased gradually with the increase in temperature. This ensured the applicability and adaptability of the developed prototype for the measurement of workability. As can be seen in Figure 4.5, multiple torque values were observed corresponding to any tested temperature. These results are in agreement with the results reported in past studies [152,154]. Average data at each temperature was taken in this study, as shown by the dotted line in Figure 4.5, for further analysis. The procedure of finding the production temperatures is discussed in the subsequent section.

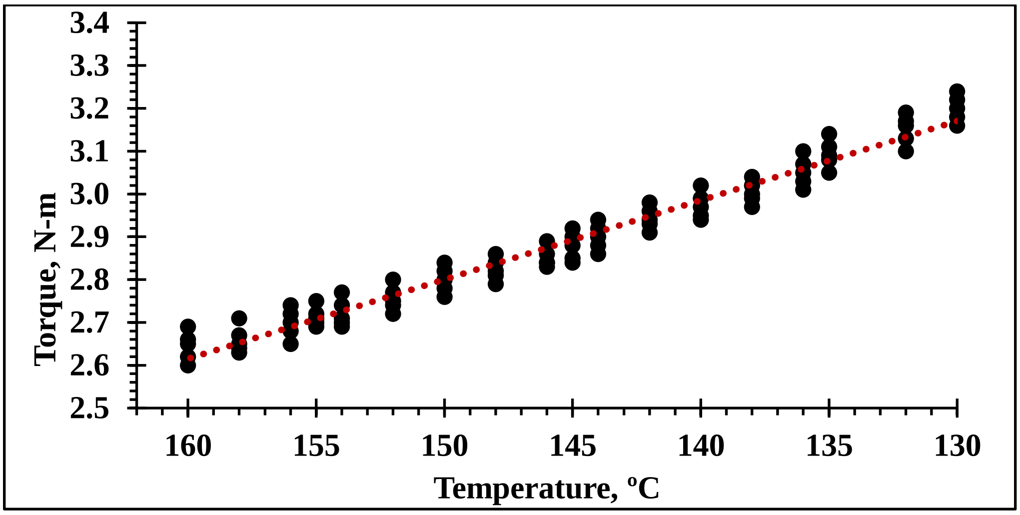


Figure 4.5. Example of the raw data obtained from workability test along with the average trend

4.2.2.4 Assessment of Production Temperatures

The present study involved 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. To develop an appropriate workability-based approach, there was a need for establishing a reference point to forecast the production temperatures. As per the available literature [132,135,160,518], 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). Therefore, the production temperatures obtained for VG30 (as obtained from EQ method) were taken as a reference. The torque values obtained for asphalt mixture prepared with VG30, at the temperatures (mixing and compaction) obtained using EQ method, were used to evaluate the production temperatures for WMA and PMB40 mixtures (prepared in this study).

In general, at the mixing temperature, a satisfactory aggregate coating by the asphalt binder is expected [519]. On the other hand, an adequate compaction temperature signifies appropriate packing density of the asphalt mixtures at in-situ conditions [520]. It signifies that coating of the asphalt binder over the aggregates and air-voids in the asphalt mixtures are representation of the workability at the mixing and compaction temperatures, respectively. It is expected that WMA and PMB40 mixtures will produce equivalent coating and percentage of voids in comparison to the reference mix prepared using VG30, when mixed and compacted at their forecasted mixing and compaction temperatures, respectively. Therefore, coating ability and compactability tests were carried out in this study to demonstrate the validity of the predicted mixing and compaction temperatures. For both the validation, samples prepared using VG30 and PMB40 were taken as the reference for their respective WMA samples.

Section III

4.2.3 Mix Design

Marshall mix design as per Asphalt Institute specification (MS-2) [136], was used to prepare asphalt mixtures using a bituminous concrete (BC) gradation having a nominal maximum size of aggregate as 13.2 mm (Figure 3.32). At first, the optimum binder content (OBC) was evaluated for granite and dolomite-based asphalt mixtures prepared using VG30 and PMB40. The same OBC was used to prepare WMA samples for each base binder. This is in agreement to previous studies that have demonstrated that the volumetric parameters of WMA and base asphalt mixtures are not considerably different [77,173,504]. Here, it should be noted that all the samples were prepared at the mixing and compaction temperatures obtained using the workability approach. The mix design results of BC-2 with VG30 and PMB40 corresponding to both the aggregate sources are presented in Table 3.7.

4.2.3.1 Validation of Production Temperatures

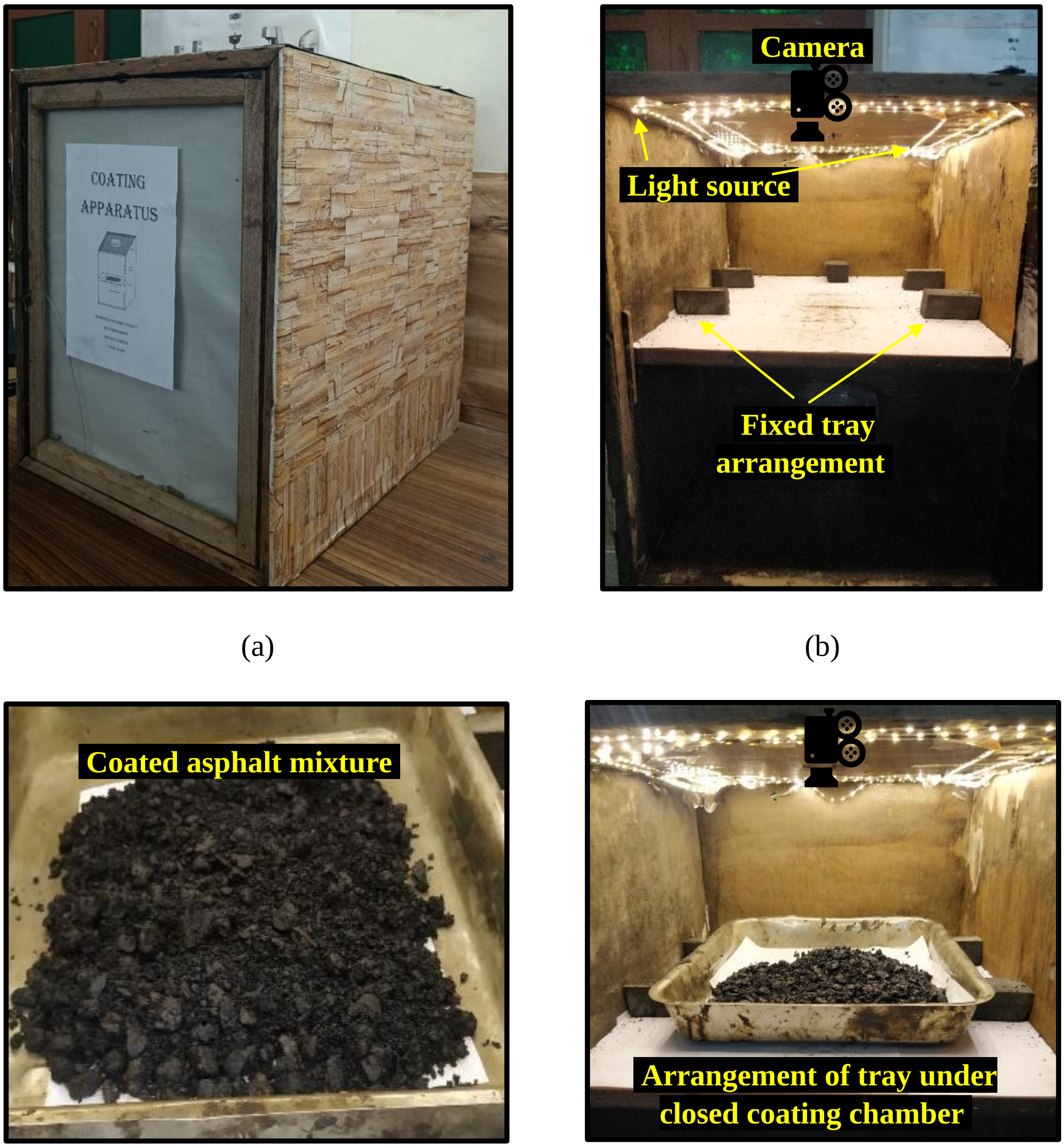
To validate the mixing temperature, a test (described in the following section) was conducted on loose asphalt mixtures. On the other hand, compacted asphalt mixtures were tested to verify the compaction temperature. The first test evaluates the coating ability of the asphalt mixture for assessing the correct range of mixing temperature, whereas the latter determines the volumetric characteristics of the compacted sample to validate the proposed compaction temperature. Results obtained for the conventional HMA mixtures (VG30 and PMB40), irrespective of aggregate sources, are taken as reference. The adopted methodology and procedure for the validation of production temperatures are presented in the next section.

4.2.3.1.1 Coating Ability of Asphalt Mixtures

In this study, the concept of coatability was used to validate the mixing temperatures of WMA mixtures. This approach measures the degree of asphalt coverage around the aggregate particles. IRC SP 101 [27] 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 [521]. It is suggested that the image processing techniques offer better accuracy [522,523].

In order to assess the coating ability using image processing, a simple experimental setup was designed and fabricated. Figure 4.6 shows the schematic representation of the developed experimental setup and its components. 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.

Velasquez et al. [524] recommended the quantification of coating by using coarser aggregates. This approach may not always indicate a complete assessment of asphalt mixtures which is a matrix of fine aggregates, coarse aggregates and asphalt binder. Thus, the present study attempted to assess the coating ability of asphalt binder, at a given mixing temperature, by incorporating a complete asphalt-aggregate mixture. This approach is expected to provide a better simulation of in-field condition.



(a) (b)

(c) (d)

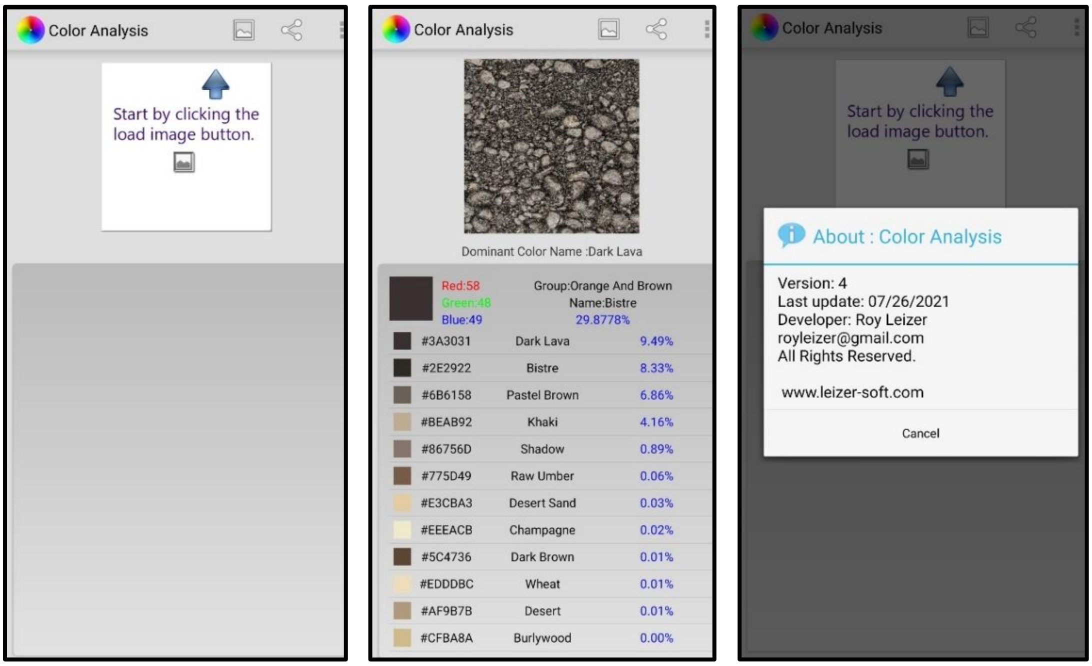
Figure 4.6. Components of coating apparatus (a) Experimental setup, (b) Inside arrangement, (c) Prepared asphalt mixture in tray, and (d) Image capturing using camera

Procedure of coating assessment and its verification

Initially, 1200 grams of aggregates were taken, conforming to the selected proportions for a fixed gradation (BC II in this study). Thereafter, the aggregates and asphalt binder were mixed at their OBC at the evaluated mixing temperature. The prepared samples were then allowed to cool at room temperature prior to any further investigation. The coated asphalt mixture was further placed in a tray attached inside the developed experimental setup. The arrangement of the tray was fixed, ensuring similar orientation and alignment for all the asphalt mixtures. After successful placement of the asphalt mixture, the images were taken using the attached camera. For each sample, multiple images were taken by changing the orientation of the placed sample. This was done to observe variability during image analysis. An overview of the complete procedure for coating analysis is shown in Figure 4.6. A total of three images were taken for each asphalt mixture for further investigation.

Image analysis was carried out using a simple android based software, Color Analysis (Version 4), developed by Roy Leizer [525]. The details regarding the software can be found elsewhere [525]. This software could be a viable tool for quick and approximate assessment of the asphalt binders coating over the aggregates. While there are various software's available for image analysis, it was found that the adopted software is 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. These colours are the combination of several different colour pixels, which are not visible with the naked eye [526]. The software provides the percentage of each pixel's colour, determined by the combination of RGB at different brightness levels, present in the considered image. An illustration of a random tested sample is given in Figure 4.7.

To ensure the applicability of this software, initial images were taken on control mixtures prepared using VG30 at three different mixing temperatures (100˚C, 130˚C, and 160˚C). After the preparation of samples, the images were captured inside the experimental setup and the percentage of each colour was determined. 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 (Figure 4.8a) and coated (Figure 4.8 (b-d)) aggregates mixtures. In general, an aggregate mixture with higher CI is desirable for signifying a better coating of asphalt binder over the aggregates.



(a) (b) (c)

Figure 4.7. Details of software (a) Front interface, (b) Colour sample in RGB format, and (c) About the developer [525]

Figure 4.8 (b-d) shows the images of asphalt mixtures at 100˚C, 130˚C, and 160˚C, respectively. A temperature of 160˚C was selected for the assessment as it is the actual mixing temperature for VG30 obtained from the EQ method. As is expected, with increase in temperature, CI increases. It was found that the absolute difference between uncoated and the asphalt mixture prepared at 100˚C is approximately 50%. This might be attributed to the partial coating of aggregates with the asphalt binder at this particular temperature. The asphalt mixture prepared at 160˚C indicated a CI of 65%, showing

35% similarity with uncoated aggregates. This may be associated with the presence of common colours between the uncoated and coated aggregates and the effect of light that is kept uniform throughout the process.

Since two aggregate sources and two base asphalt binders were used in the present study, there was a need to normalize CI of WMA mixtures with respect to the CI of conventional HMA mixtures (VG30 and PMB40) prepared either with granite or dolomite aggregates. 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)".

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

Figure 4.8. Image captured (a) Uncoated Aggregates, (b) Coating at 100˚C, (c) Coating at 130˚C, and (d) Coating at 160˚C

4.2.3.1.2 Compactability Test

HMA (with VG30 and PMB40) and WMA mixtures were prepared using standard Marshall compaction (75 blows) (Figure 3.27d). These mixes were prepared at their respective mixing and compaction temperatures. The bulk specific gravity (G_{mb}) of these mixtures were measured as per AASHTO T166 [527]. The theoretical maximum specific gravity, G_{mm}, was measured for HMA mixtures (with VG30) as per AASHTO T209 [528]. Since G_{mm} is primarily a function of amount of asphalt binder and aggregate gradation [514]., similar value was assumed for HMA and WMA mixtures. Air void was calculated using the value of G_{mb} and G_{mm}. Air voids of HMA and WMA mixtures were compared to quantify the compactability characteristics of WMA mixtures.

4.3 Results and Discussion

SECTION I

4.3.1 RV Approach

Various RV-based methods (as described in Table 3.6) were used to assess the production temperatures of PMB40 and WMA binders. Table 4.2 – Table 4.3 and Table 4.4 - 4.5 presents the obtained mixing and compaction temperatures, respectively, derived from various methods. The variation in results between different methods is due to the methodology adopted in each method. As expected, the production temperatures of PMB40 were higher than VG30, irrespective of the test method. On the other hand, the mixing and compaction temperatures of the VG30 derived from the EQ method were within a reasonable range, as specified in MoRTH [1]. The production temperatures for VG30 calculated from other adopted methods were found to be lower than the specified values [1]. This is due to the fact that the viscosity of the base asphalt binder did not change with the shear rate; however, all the alternative test methods involved the effect of shear rate to determine the production temperatures. Similar observations were reported by previous researchers [132,518]. Though the other methods were developed to overcome the shortcomings of the EQ method, the methodologies for evaluating production temperatures in these methods are also based on the viscosity of the asphalt binder.

In general, it was found that the application of WMA additives lowered the mixing and compaction temperatures. As shown in Tables 4.2, 4.3, 4.4, and 4.5, the reduction in production temperatures is dependent on the type of base asphalt binder, WMA technology, dosages, and test methods. It was observed that the traditional EQ method yielded higher values of production temperatures as compared to other test methods, irrespective of the type of WMA technology. The reduction in production temperatures after incorporating WMA additives was found in the range of 1-14˚C and 1-19˚C, when the additives are blended in VG30 and PMB40, respectively. On an average, the maximum reduction was obtained for organic based additives (viscosity reducers) in both the base binders (VG30 and PMB40), irrespective of the test methods. Since the production temperatures obtained from all the test methods are directly related to the viscosity values [131], the organic-based additives showed higher reduction compared to chemical-based WMA agents. This is because the chemical agents do not influence the viscosity of the base asphalt binder [77,92] and hence the adopted methods may indicate inappropriate mixing and compaction temperatures for asphalt binders blended with Cecabase and Rediset (chemical-based WMA agents adopted in this study). Interestingly, in some methods, the results either did not change with an increase/decrease in dosage of WMA additives, or resulted in marginal temperature reduction. For example, as per ZSV method, no noticeable effect of dosage was found with the addition of any of the WMA additive in PMB40, regardless of mixing and compaction temperatures. Similarly, in HSR-O method, the increase in dosage of Sasobit from 1% to 2% did not change the mixing temperature of VG30, whereas, there was only 1°C reduction in compaction temperature with the addition of 0.2% and 0.35% Cecabase in VG30. While analysing the results obtained from different test methods, it was found that the addition of WMA additives rather increases the mixing and compaction temperatures (for example: addition of Cecabase in VG30 as per flow behavior method). In addition, few methods indicated that unexpected effect of additive dosages, for example, in the HSR-E approach, adding 0.4% Rediset in VG30 decreased the mixing temperature to 136˚C, whereas adding 0.5% Rediset increased the temperature to 139˚C. Similar discrepancies in trends/observations were noted with other test methods for different WMA additives and dosages as well as for different base asphalt binders. Additionally, these approaches are not applicable for the WMA technologies which are directly added during the preparation of asphalt mixtures, such as Aspha-Min (Am).

Overall, the results demonstrated the inapplicability of EQ as well as other proposed approaches for finding the production temperatures of modified binders (PMB, and WMA binders in the present study). Therefore, this study attempted to develop a rational approach for the quantification of production temperatures, irrespective of the type of base asphalt binder, WMA technology, and their respective dosages. The proposed method incorporates the effect of aggregate source as well.

Table 4.2. Mixing temperature using different methods for VG30 base asphalt binder

Binder Type	**Test Methods (Temperature is in ˚C)**											
	EQ		**ZSV**		**S-ZSV**		**HSR-O**		**HSR-E**		**100000 S^{-1}**	
	Max	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
PMB40	165	160	114	112	128	125	153	147	141	136	136	131
PS1	160	153	109	107	122	119	151	145	139	133	137	132
PS2	159	152	106	104	119	116	150	143	137	131	136	130
PS3	157	150	107	105	119	116	149	143	137	132	137	132
PSR0.7	161	155	113	111	125	123	153	148	142	137	141	136
PSR1.35	156	150	110	107	120	117	148	142	136	131	134	128
PSR2	152	146	106	104	116	113	146	140	134	128	134	128
PC0.2	162	155	111	109	125	122	152	146	140	135	138	132
PC0.35	161	154	110	108	124	121	153	147	140	135	141	135
PC0.5	159	153	110	108	123	121	156	150	144	139	152	146
PR0.4	161	155	111	109	124	121	151	145	139	134	134	129

PR0.5	159	153	109	107	122	119	154	148	142	137	146	140
PR0.6	155	148	104	102	116	113	149	142	136	130	138	132

Table 4.3. Compaction temperature using different methods for VG30 base asphalt binder

Binder Type	**Test Methods (Temperature is in ˚C)**											
	EQ		**ZSV**		**S-ZSV**		**HSR-O**		**HSR-E**		**100000 S^{-1}**	
	Max	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
PMB40	150	145	106	104	116	113	141	136	126	122	125	121
PS1	146	141	102	100	109	106	138	133	123	118	125	121
PS2	144	139	98	96	106	103	136	131	120	115	124	119
PS3	143	138	100	98	107	104	136	131	121	116	125	121
PSR0.7	148	143	106	104	113	111	141	136	127	122	130	125
PSR1.35	143	138	102	101	108	105	135	130	121	116	123	118
PSR2	139	134	99	97	103	101	133	128	118	113	122	118
PC0.2	148	143	104	102	112	110	140	135	125	120	126	122
PC0.35	147	142	103	101	111	108	140	135	125	120	129	125
PC0.5	146	141	103	102	111	109	143	138	128	124	140	135
PR0.4	148	142	103	101	111	109	138	133	123	119	123	118
PR0.5	146	140	102	100	110	107	141	136	126	121	133	129
PR0.6	141	135	97	95	103	101	135	130	119	114	125	120

Table 4.4. Mixing temperature using different methods for PMB40 base asphalt binder

Binder Type	**Test Methods (Temperature is in ˚C)**											
	EQ		**ZSV**		**S-ZSV**		**HSR-O**		**HSR-E**		**100000 S^{-1}**	
	Max	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
PMB40	180	173	120	118	141	138	176	170	163	157	169	163
PS1	175	168	117	115	136	133	169	163	156	151	158	152
PS2	173	167	118	115	135	132	167	160	154	148	154	148
PS3	169	163	114	111	130	127	162	156	149	144	150	144
PSR0.7	176	169	117	115	138	135	173	167	160	155	168	162
PSR1.35	174	167	115	113	135	132	169	163	156	150	162	156
PSR2	171	165	115	113	133	130	165	159	152	147	155	149
PC0.2	177	170	119	116	138	135	171	165	158	152	160	154
PC0.35	176	169	117	114	136	133	171	165	158	152	163	157
PC0.5	175	168	116	113	135	132	168	161	155	149	157	151

PR0.4	174	168	117	114	136	133	171	165	158	153	165	159
PR0.5	173	166	116	113	135	132	169	163	156	151	162	156
PR0.6	173	166	115	113	134	131	170	163	157	151	165	159

Table 4.5. Compaction temperature using different methods for PMB40 base asphalt binder

Binder Type	**Test Methods (Temperature is in ˚C)**											
	EQ		**ZSV**		**S-ZSV**		**HSR-O**		**HSR-E**		**100000 S^{-1}**	
	Max	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
PMB40	166	160	111	109	128	125	162	157	146	141	156	151
PS1	161	155	108	106	123	120	156	150	139	134	145	140
PS2	159	154	109	106	122	119	153	148	137	132	142	137
PS3	155	150	105	103	117	114	149	143	133	128	138	133
PSR0.7	162	157	109	107	125	122	160	154	144	139	155	150
PSR1.35	160	154	107	105	122	119	155	150	139	134	149	144
PSR2	157	152	107	105	120	117	152	147	136	131	142	137
PC0.2	163	157	109	107	125	122	157	152	141	136	147	142
PC0.35	162	156	108	106	123	120	157	152	141	136	150	145
PC0.5	160	155	107	105	121	119	154	149	138	133	144	139
PR0.4	160	155	108	106	123	121	158	152	142	137	152	147
PR0.5	159	154	107	105	122	119	156	150	140	135	149	144
PR0.6	159	153	107	105	121	118	156	151	140	135	152	146

4.3.2 DSR Approach

Two methods have been proposed by past researchers to predict the production temperatures using DSR [139]. These methods are steady shear flow (SSF) and phase angle method (PAM). The present study did not use the SSF method, owing to the delamination (which was observed at higher temperatures, i.e., 76, 82 and 88˚C) of binder from the parallel plate geometry in the DSR. Therefore, the results obtained through PAM for VG30 are shown in Figure 4.9. The mixing and compaction temperatures for VG30 were found to be 159˚C and 146˚C, respectively. These temperatures are approximately consistent with the temperatures predicted using the EQ method, as shown by the straight lines in Figure 4.9. On the other hand, the production temperatures showed inconsistent trends for WMA binders. For asphalt binders modified with organic additives, such as Sasobit, the increase in dosage increased the production temperatures, which is unlikely. This is because the phase angle measurements were made at temperatures lower than the melting point of Sasobit, where it crystallizes and forms a lattice structure. The crystallization might have increased the stiffness and lowered the value of reduced frequency corresponding to the phase angle of 86˚. This resulted in higher mixing and compaction temperatures, compared to the base asphalt binder. On the contrary, Sasobit Redux, being an organic additive, did not show any variation in production temperatures. The reason behind this behavior is that the measurement of phase angle was taken near to the temperature at which Sasobit Redux wax ceases to flow. At the testing temperature range, the phase transition of Sasobit Redux occurs, and thus it did not affect the phase angle values obtained at the reference temperature of 80˚C. PAM did not indicate any change in mixing and compaction temperatures for the asphalt binders modified with chemical-based additives (Cecabase and Rediset). The obtained temperatures were very similar to the production temperatures of the base asphalt binder. Apparently, the addition of chemical agents does not influence the rheological properties. The inaccurate trends/observations indicate that PAM may not be an appropriate method to predict the production temperatures for WMA binders.

On the other hand, the phase angle master curves of WMA binders prepared with PMB40 showed inconsistent trends or wavy nature (due to the presence of transition and plateau region) at higher temperature (80°C), as shown with an example in Figure 4.10. The wavy nature in phase angle master curve of PMB is attributed to the presence of dominative polymer network. Therefore, this method was not further applied for quantifying the mixing and compaction temperatures of PMB based WMA binders. Similar observations were reported by previous researchers [148,529].

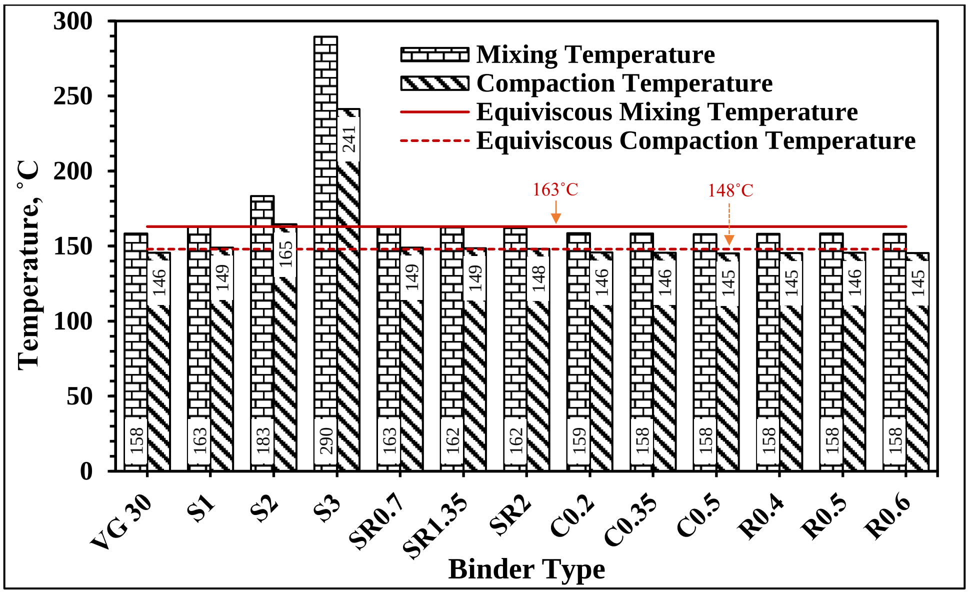


Figure 4.9. Mixing and compaction temperatures using PAM

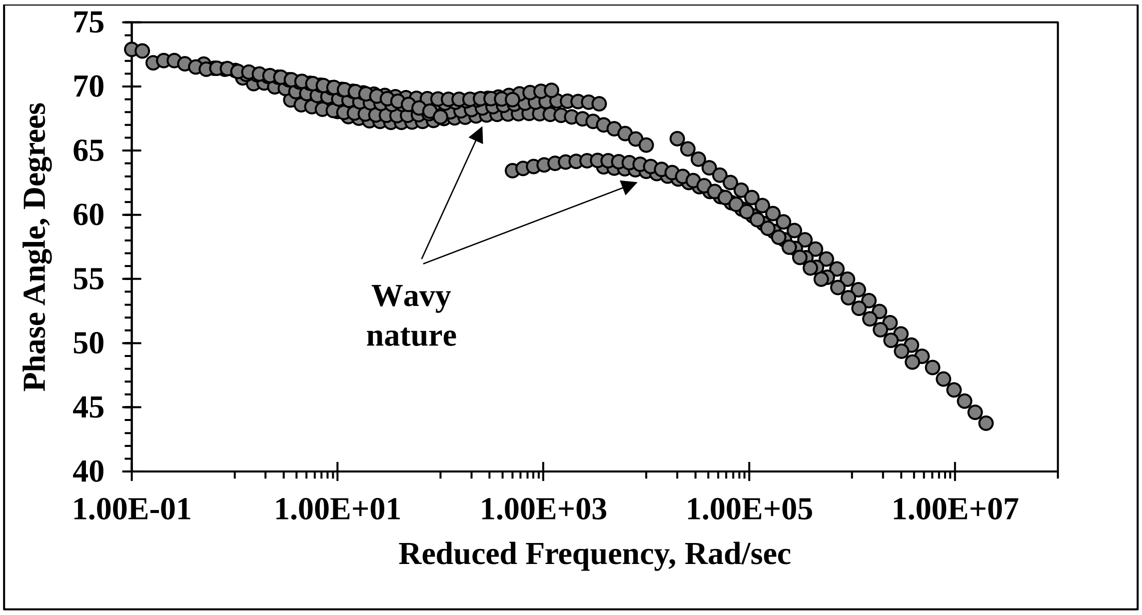


Figure 4.10. Phase angle master curve of PMB40

SECTION II

4.3.3 Discussion on Workability Characteristics

As mentioned previously, the value of torque was used to indirectly characterize the workability of asphalt mixtures. Lower torque values signify better 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 ageing of asphalt binder at high temperatures. Figure 4.11 shows the variation of torque with temperature for conventional HMA mixtures (VG30 and PMB40). In general, torque value increases with decrease in production temperature. This is attributed to the reduction in stiffness of asphalt binder from 160°C to 130°C.

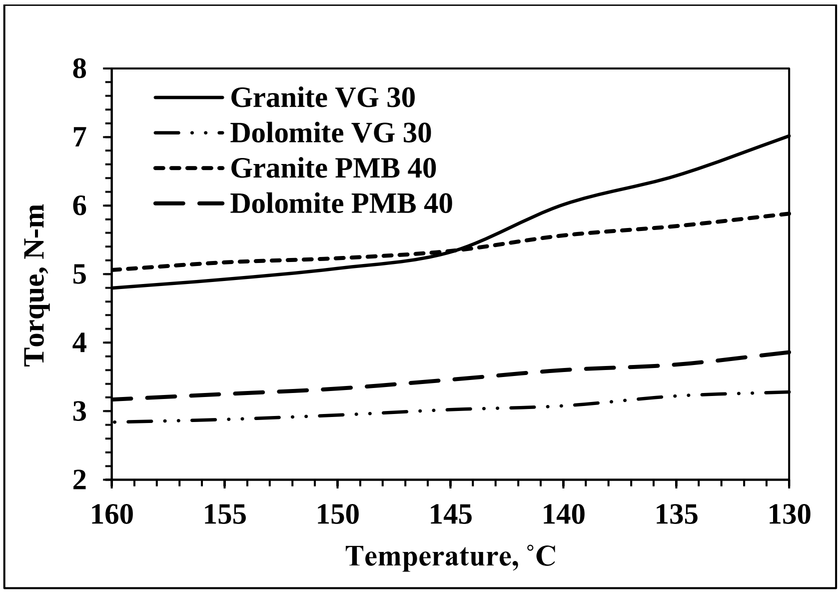
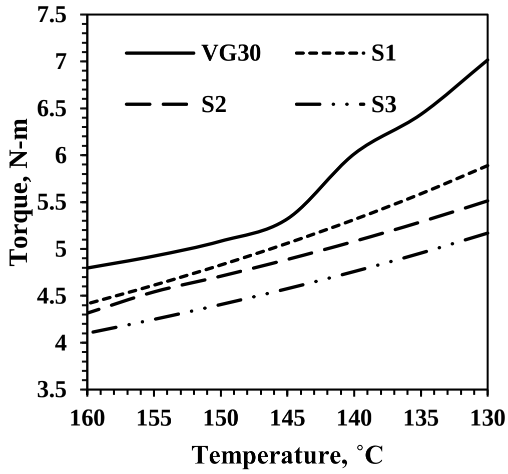


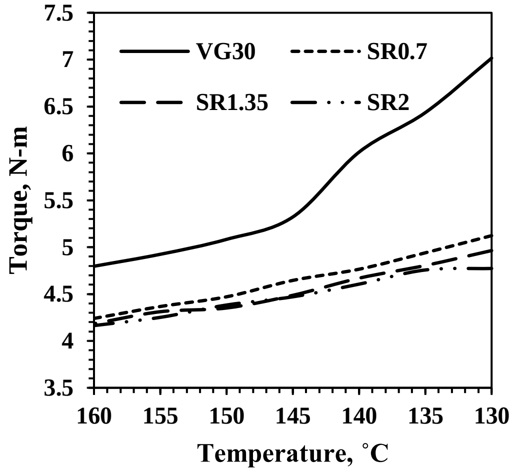
Figure 4.11. Variation of torque with temperature for conventional HMA mixtures

As can be seen in Figure 4.11, PMB40 yielded higher torque values than VG30 binder at temperature ≥ 145°C, whereas the torque value of PMB40 was found to be lower than VG30 at temperatures < 145°C (as indicated by the upward hump in the torque values). The reason behind this unexpected trend may be attributed to the higher rate of cooling with the drop in temperature for HMA prepared with VG30. This trend was seen specifically for granite inclusive asphalt mixtures. Considering dolomite-based asphalt mixtures, the value of PMB40 was relatively higher than VG30 over the selected range of test temperatures. The difference in the cooling behaviour with different aggregate type may be attributed to two specific reasons: (1) difference in aggregate mineralogy, and (2) bonding mechanism between asphalt binder and aggregate. In most of the previous studies [530,531], siliceous aggregate (granite here) was found to be incompatible/less workable with viscosity graded asphalt binders.

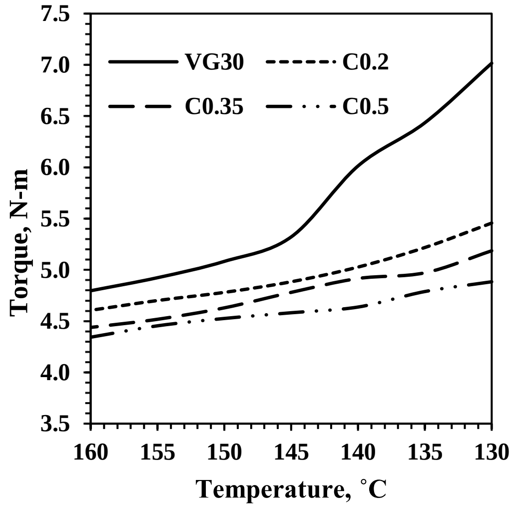
Figure 4.12 and Figure 4.13 shows the variation of torque with temperature, for all the considered asphalt mixtures prepared with VG30 and PMB40, respectively. As is evident, the application of WMA additives, irrespective of aggregate type, exhibited lower torque values (higher level of workability) than HMA mixtures (VG30 and PMB40). In addition, the increment in torque was found to be higher for conventional HMA mixtures in comparison to WMA mixtures. This observation indicates that the HMA mixtures (irrespective of VG30 and PMB40) cools more rapidly with the drop in temperature, which may lead to lower hauling distance in comparison to WMA mixtures. Additionally, reduced cooling rate in WMA mixtures would extend the paving time for the contractors and thereby shorten the overall construction period, in comparison to the conventional HMA mixtures [18,532].


VG30
S1
S2
S3
Torque, N-m
Temperature, ˚C

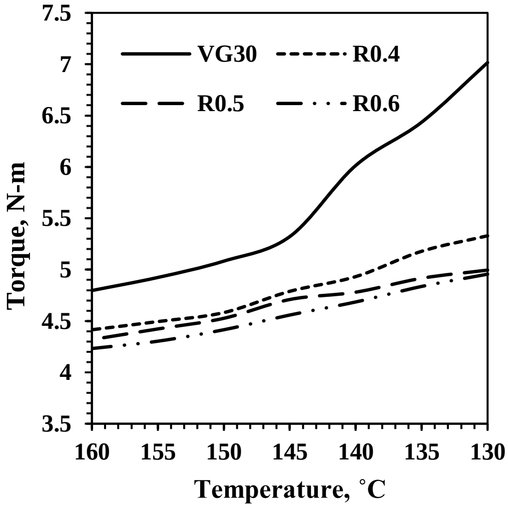
(a)


VG30
SR0.7
SR1.35
SR2
Torque, N-m
Temperature, ˚C

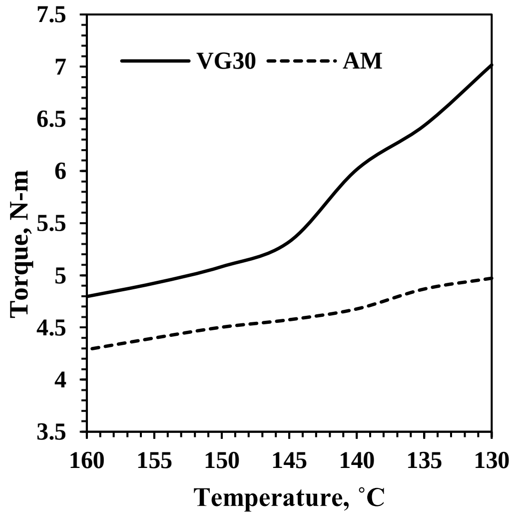
(b)


VG30
C0.2
C0.35
C0.5
Torque, N-m
Temperature, ˚C

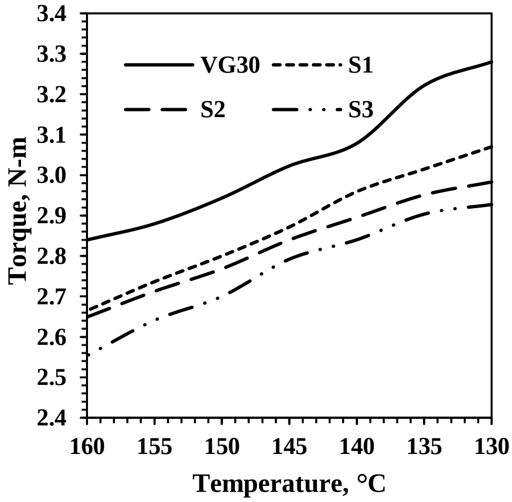
(c)


VG30
R0.4
R0.5
R0.6
Torque, N-m
Temperature, ˚C

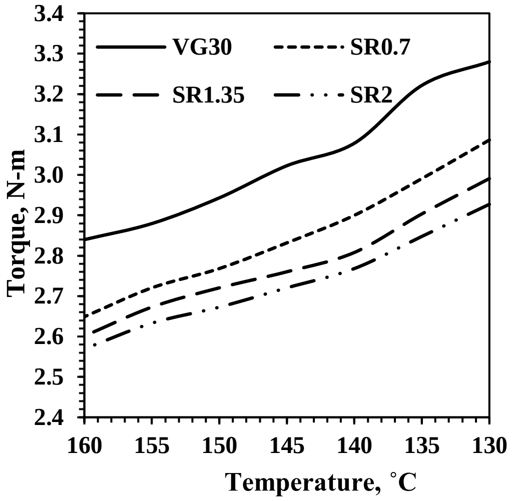
(d)


VG30
AM
Torque, N-m
Temperature, ˚C

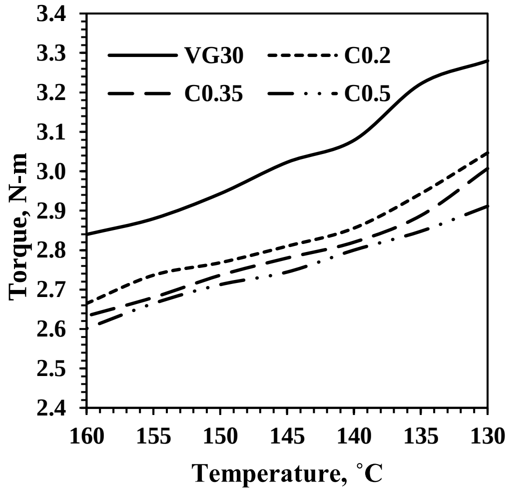
(e)


VG30
S1
S2
S3
Torque, N-m
Temperature, °C

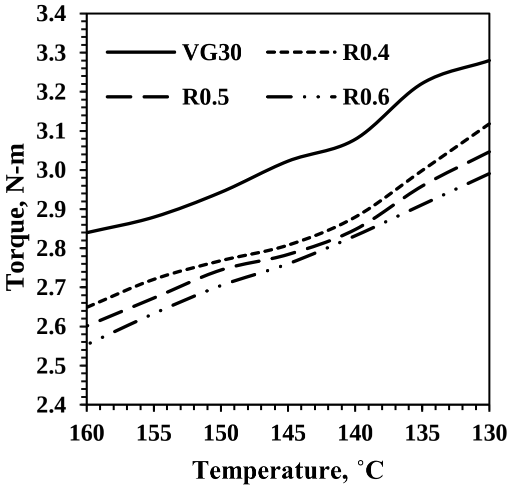
(f)



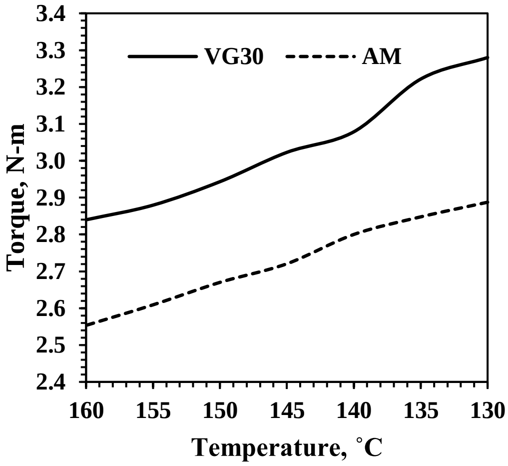
(g)



(h)



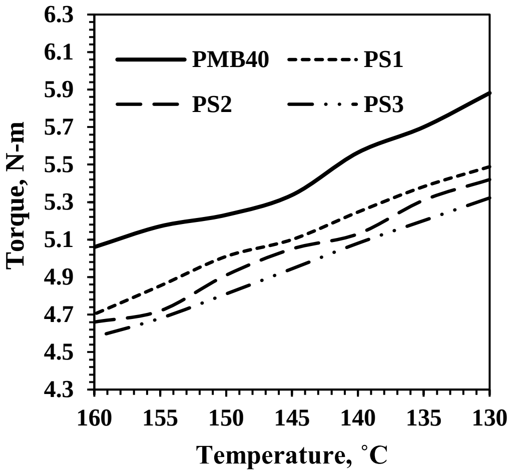
(i)



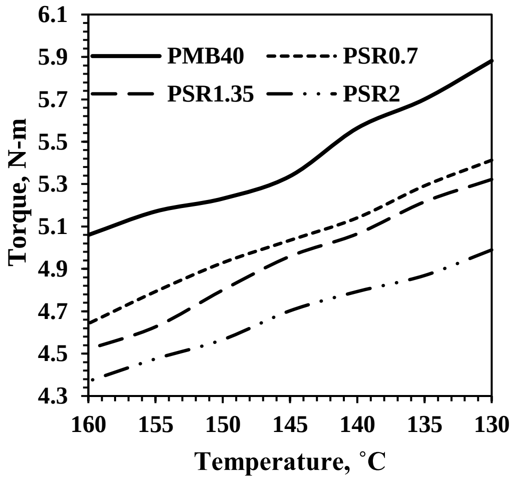
(j)

Figure 4.12. Torque values for different asphalt mixtures prepared with VG30 (a) GS, (b) GSR, (c) GC, (d) GR, (e) GAm, (f) DS, (g) DSR, (h) DC, (i) DR, and (j) DAm

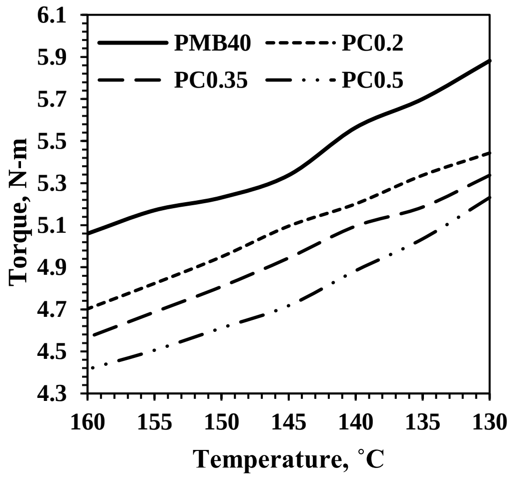
Note: The first alphabet in the mixture combination (with VG30) indicates the aggregate type and the second alphabet denotes the type of WMA additive. For example: GS signifies Sasobit based asphalt mixture prepared with granite aggregates and DAm refers to Aspha-Min based asphalt mixture produced with dolomite aggregates.


PMB40
PS1
PS2
PS3
Torque, N-m
6.3 6.1 5.9 5.7 5.5 5.3 5.1 4.9 4.7 4.5 4.3
160 155 150 145 140 135 130
Temperature, ˚C

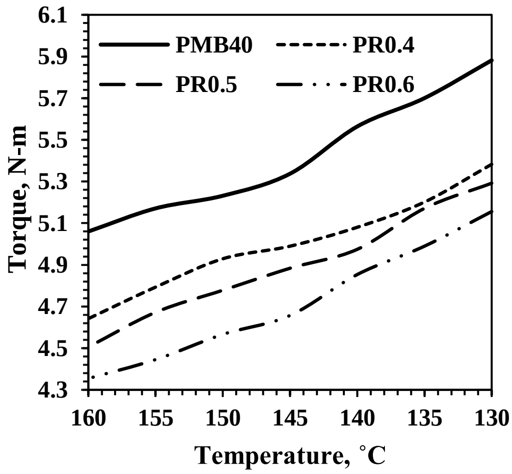
(a)


PMB40
PSR0.7
PSR1.35
PSR2
Torque, N-m
6.1 5.9 5.7 5.5 5.3 5.1 4.9 4.7 4.5 4.3
160 155 150 145 140 135 130
Temperature, ˚C

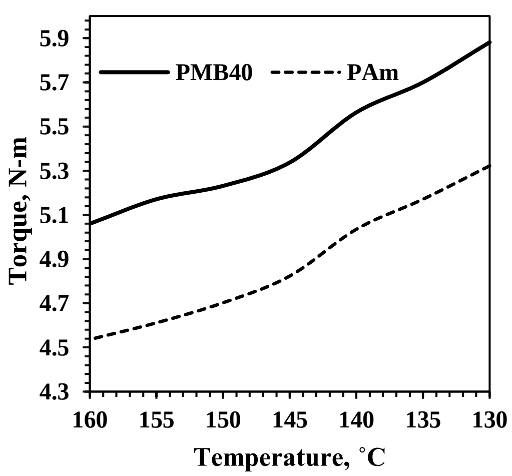
(b)


PMB40
PC0.2
PC0.35
PC0.5
Torque, N-m
6.1 5.9 5.7 5.5 5.3 5.1 4.9 4.7 4.5 4.3
160 155 150 145 140 135 130
Temperature, ˚C

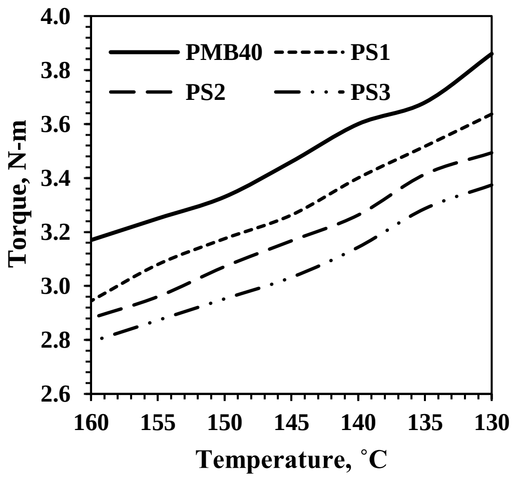
(c)


PMB40
PR0.4
PR0.5
PR0.6
Torque, N-m
6.1 5.9 5.7 5.5 5.3 5.1 4.9 4.7 4.5 4.3
160 155 150 145 140 135 130
Temperature, ˚C

(d)


PMB40
PAm
Torque, N-m
5.9 5.7 5.5 5.3 5.1 4.9 4.7 4.5 4.3
160 155 150 145 140 135 130
Temperature, ˚C

(e)


PMB40
PS1
PS2
PS3
Torque, N-m
4.0 3.8 3.6 3.4 3.2 3.0 2.8 2.6
160 155 150 145 140 135 130
Temperature, ˚C

(f)

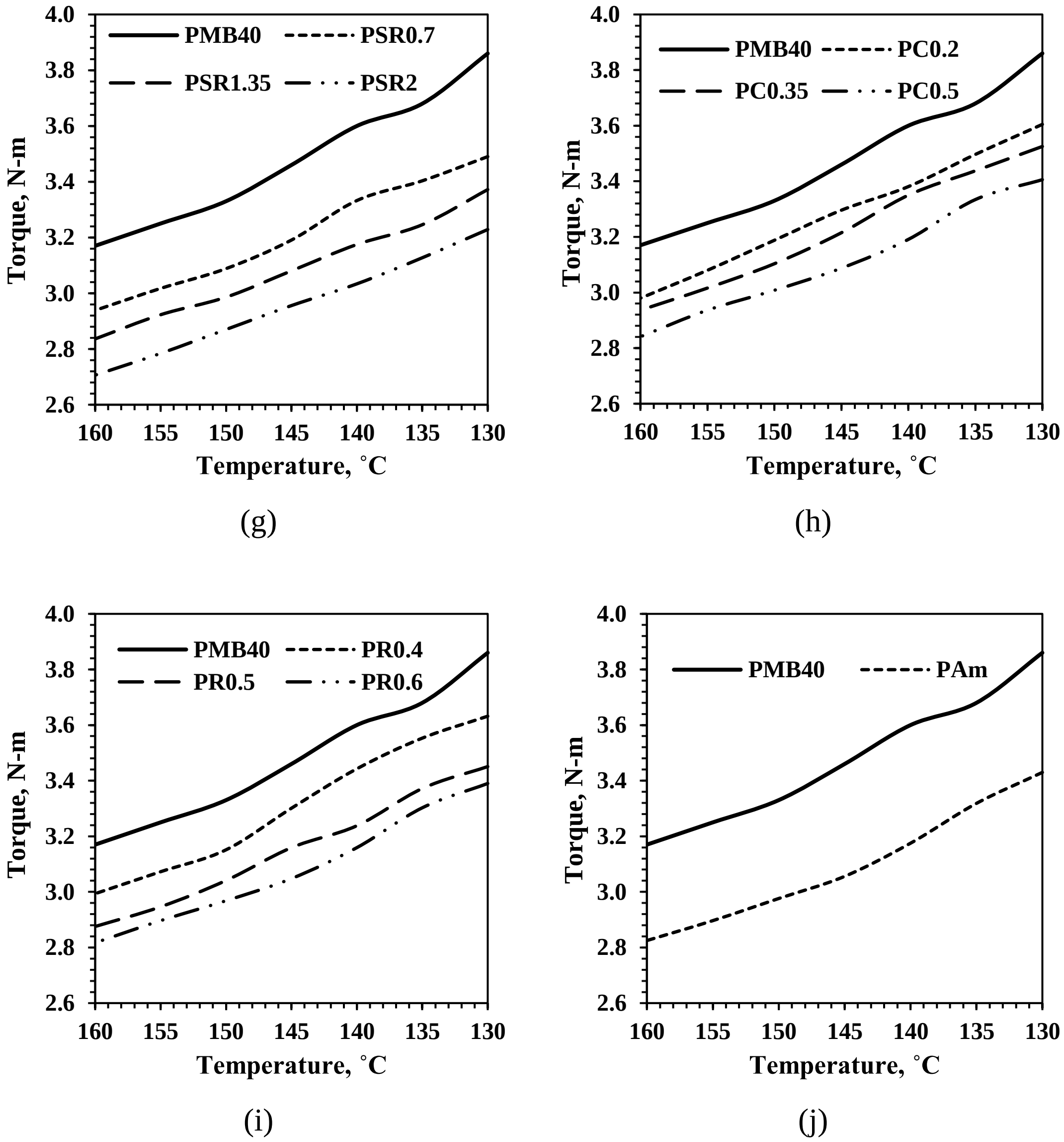
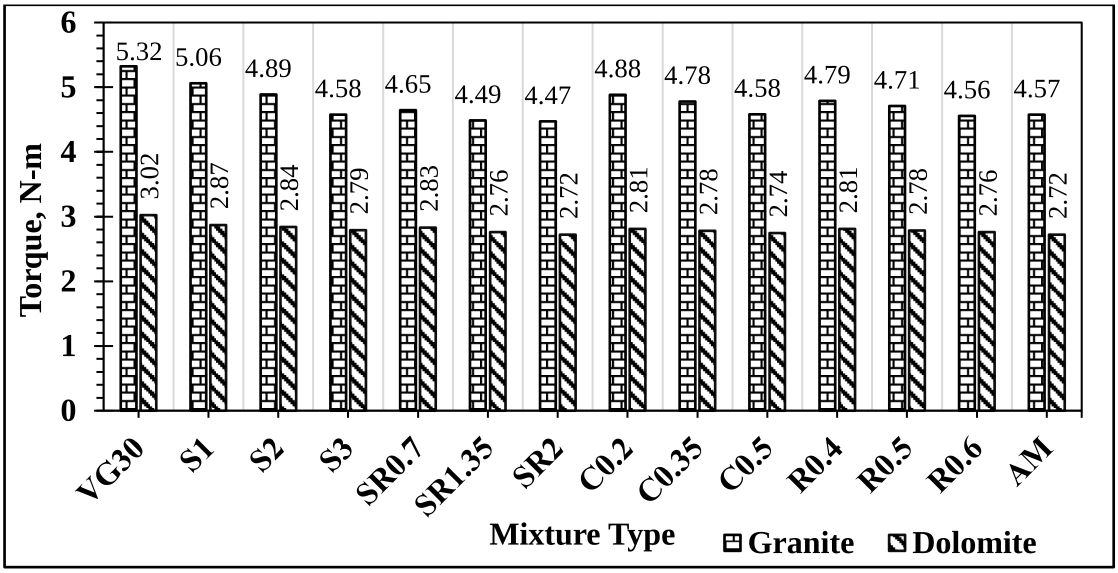


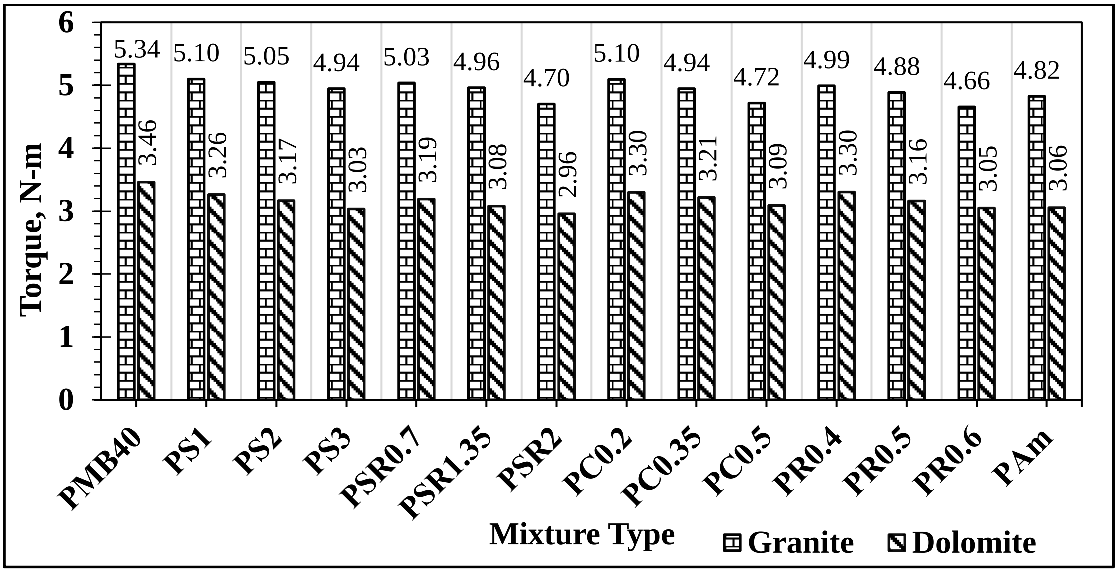
Figure 4.13. Torque values for different asphalt mixtures prepared with PMB40 (a) GPS, (b) GPSR, (c) GPC, (d) GPR, (e) GPAm, (f) DPS, (g) DPSR, (h) DPC, (i) DPR, and (j) DPAm

Note: The first alphabet in the mixture combination (with PMB40) indicates the aggregate type, the second and third alphabet denote binder type and the type of WMA additive, respectively. For example: GPC signifies Cecabase based asphalt mixture prepared with PMB40 and granite aggregates and DPR refers to Rediset based asphalt mixture produced with PMB40 binder and dolomite aggregates.

Needless to say, the reduction in torque value and corresponding improvement in workability was found to be highly dependent on the type of WMA additive and its respective dosage. These effects can be seen from Figure 4.14a and Figure 4.14b for all the tested asphalt mixtures at a representative temperature of 145°C. It was observed that the increase in dosage of WMA additives proportionately lowers the torque, and thereby improves the workability. The extent of improvement in workability may be associated with the working mechanism of different WMA technologies with different aggregate type. It was found that asphalt mixtures with granite aggregate require higher torque to rotate the spindle and thereby resulted in lower workability compared to dolomite inclusive asphalt mixtures. This trend was evident for both the base asphalt binders (VG30 and PMB40). Based on the above discussion, it can be stated that chemical nature/mineralogy of asphalt binder and aggregate can affect the workability characteristics of asphalt mixtures and so the production temperatures. This can also be due to the difference in shape and surface texture of the aggregates, subjected to further investigation.



(a)



(b)

Figure 4.14. Effect of different variables on the torque values of asphalt mixtures (a) VG30 and (b) PMB40

WMA mixtures showed the similar workability (in terms of torque) as that of HMA, at relatively lower production temperatures. This phenomenon was adopted to compare and predict the production temperatures of WMA mixtures corresponding to the same level of workability as obtained for HMA mixtures. It may be expected that the estimated temperatures, at which the torque is higher/similar to the conventional HMA, is appropriate/reasonable for the production of WMA or PMB mixtures. In addition, the workability approach also considers the effect of aggregate type for the evaluation of production temperature, which is missing in IRC SP 101-2019 [27].

4.3.4 Production Temperatures from Workability Approach

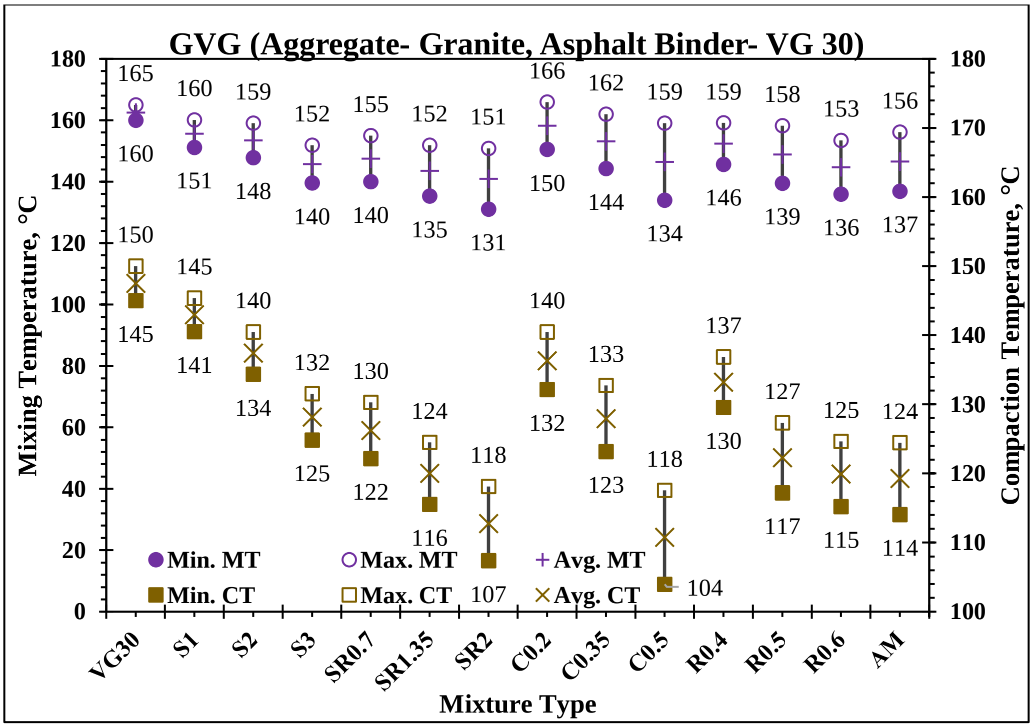
As discussed in the preceding sections, the torque values of HMA prepared with VG30 were used as a reference to estimate the production temperatures of PMB and WMA based mixtures. The reference torque values corresponding to mixing and compaction temperature (as obtained from EQ approach) for different aggregate (granite and dolomite) type are provided in Table 4.6. 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 VG30). Therefore, a simple power model was used to predict the torque value at 165°C and the results are shown in Table 4.6.

Table 4.6. Reference torque values of conventional VG30 asphalt mixtures

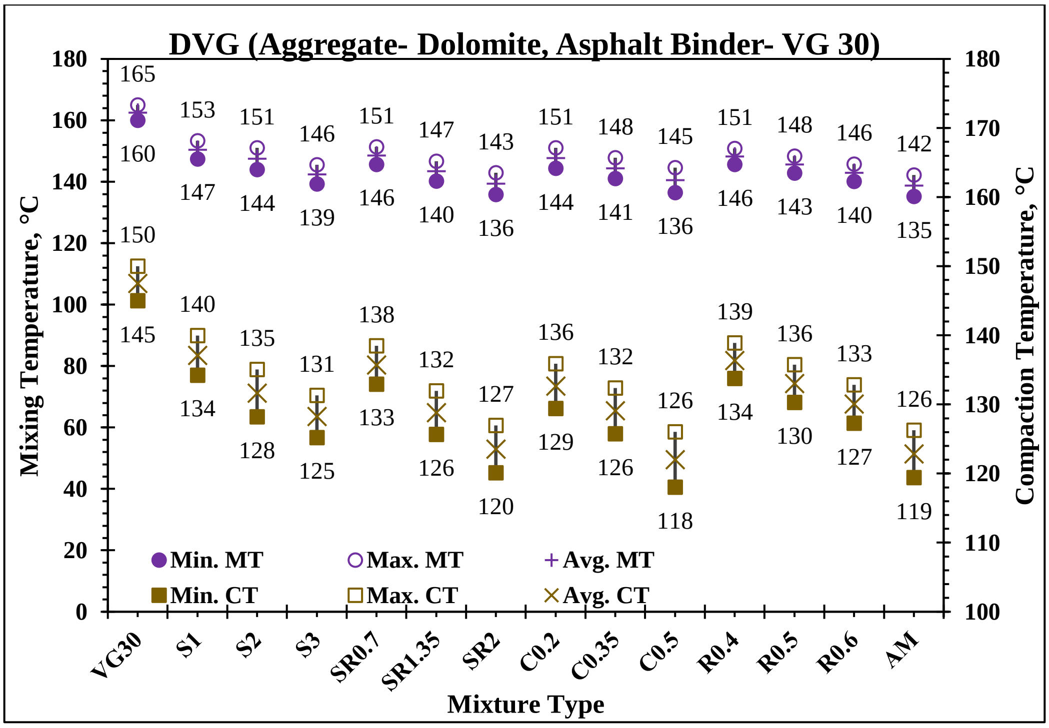
Aggregate	Mixing Temperature, °C	Torque, N-m	Compaction Temperature, °C	Torque, N-m
Granite	160	4.796	145	5.321
	165	4.355	150	5.082
Dolomite	160	2.839	145	3.022
	165	2.758	150	2.943

Figure 4.15 (a-d) shows the ideal range (maximum, minimum and average value) of the mixing and compaction temperatures for different combinations of asphalt mixtures. These combinations are characterized based on the base binder (VG30 and PMB40) and aggregate type (granite and dolomite). It was found that the forecasted mixing and compaction temperature of PMB40 mixtures, irrespective of aggregate type, are higher compared to asphalt mixtures prepared using VG30. This is due to the higher stiffness of PMB40 in comparison to VG30 [533]. However, the mixing and compaction temperatures of all WMA mixtures were found to be lower than conventional HMA mixtures. The change in WMA technology and the dosage greatly influenced the production temperatures. With increase in dosage, the production temperatures

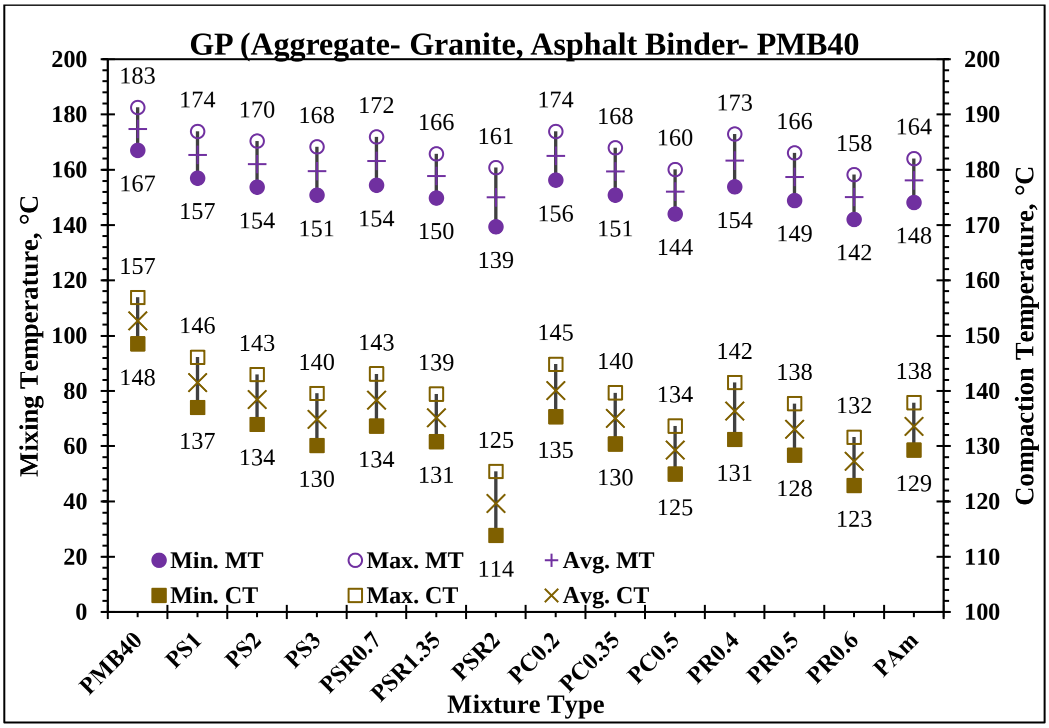
decreased, and vice-versa. These observations were independent of the type of WMA additive. In addition, the extent of reduction is a function of base asphalt binder, and aggregate type, as shown in Table 4.7.



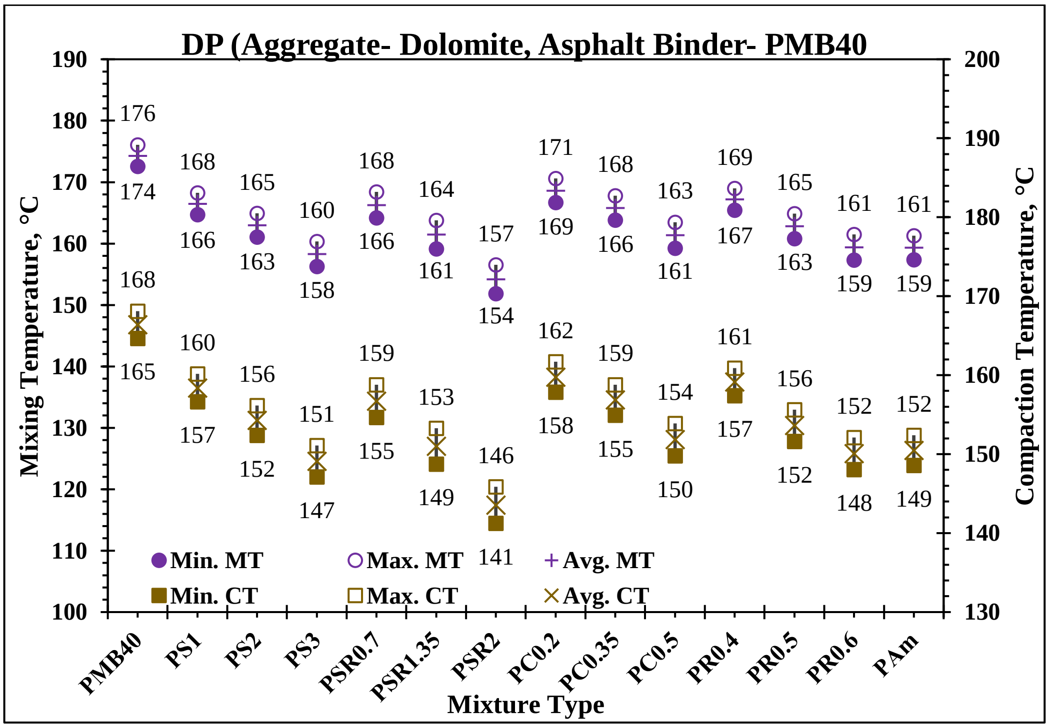
(a)



(b)



(c)



(d)

Figure 4.15. Production temperatures obtained from workability approach (a) GVG, (b) DVG, (c) GP, and (d) DP

Table 4.7. Ranking of different asphalt mixtures based on production temperatures

Binder Type	**Aggregate Type**	**Ranking (Maximum Reduction)**		**Maximum Reduction in MT, °C, [% Reduction]**	**Maximum Reduction in CT, °C, [% Reduction]**
		MT	**CT**		
VG30	**Granite**	SR>R>S>C>Am	C>SR>Am>R>S	21.5 [13.3]	36.7 [24.9]
	Dolomite	Am>SR>C>S>R	C>Am>SR>S>R	23.8 [14.6]	25.5 [17.3]
PMB40	**Granite**	SR>R>C>Am>S	SR>R>C>Am>S	24.7 [14.1]	33 [21.6]
	Dolomite	SR>S>Am>R>C	SR>S>R>Am>C	20.1 [11.6]	22.8 [13.7]

Note 1: MT and CT represent mixing and compaction temperatures, respectively.

Note 2: S, SR, C, R, and Am denote Sasobit, Sasobit Redux, Cecabase, Rediset, and Aspha-Min, respectively.

Average ranking, irrespective of aggregate and binder type, indicated that Sasobit Redux gave maximum reduction in mixing temperature, followed by Rediset, Aspha-Min, Sasobit, and Cecabase. On the other hand, the average ranking of maximum reduction in compaction temperature followed different trend. Sasobit Redux showed highest reduction followed by Cecabase, Aspha-Min, Rediset, and Sasobit. About 5-25°C (approximately 3-15%) and 5-37°C (around 3-25%), reduction in mixing and compaction temperatures, respectively, were obtained for different WMA technologies. 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 asphalt mixtures, were found to be reasonable as compared to the temperatures obtained from conventional EQ approach. After obtaining the production temperatures based on the novel workability approach, it was essential to validate the results. The validation/checks for acceptance/rejection of the proposed workability approach are discussed in the subsequent sections.

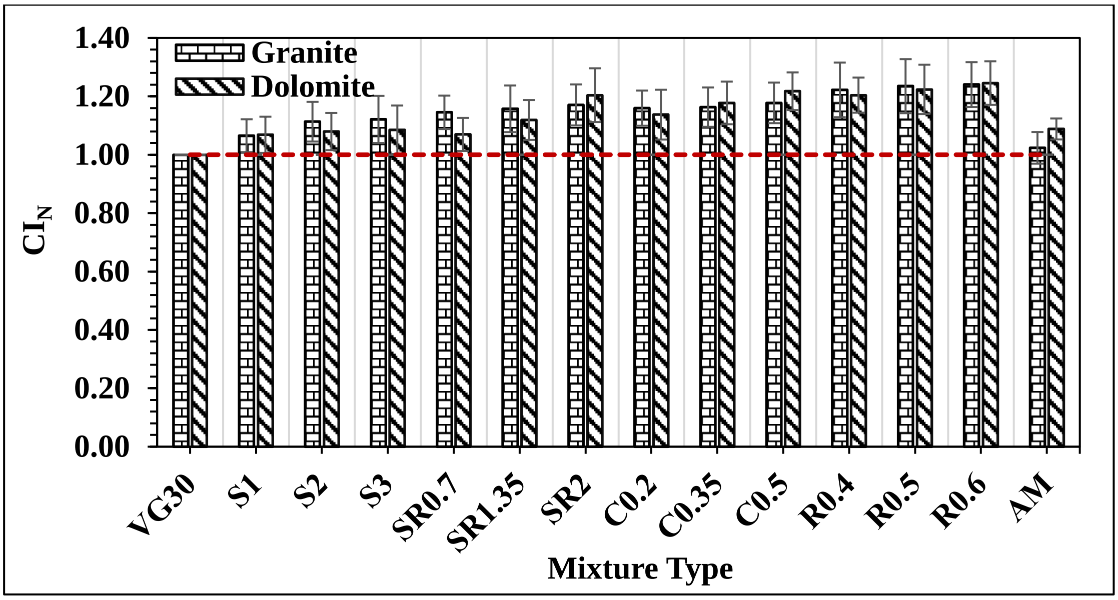
SECTION III

As already stated, the suitability of the workability apparatus for evaluating the production temperatures was addressed through two validation tests, including coating ability and compactability. Three samples for each validation check were used to find the influence of WMA additives. The variation in the results is shown using the error bars. The discussion on these checks are as follows:

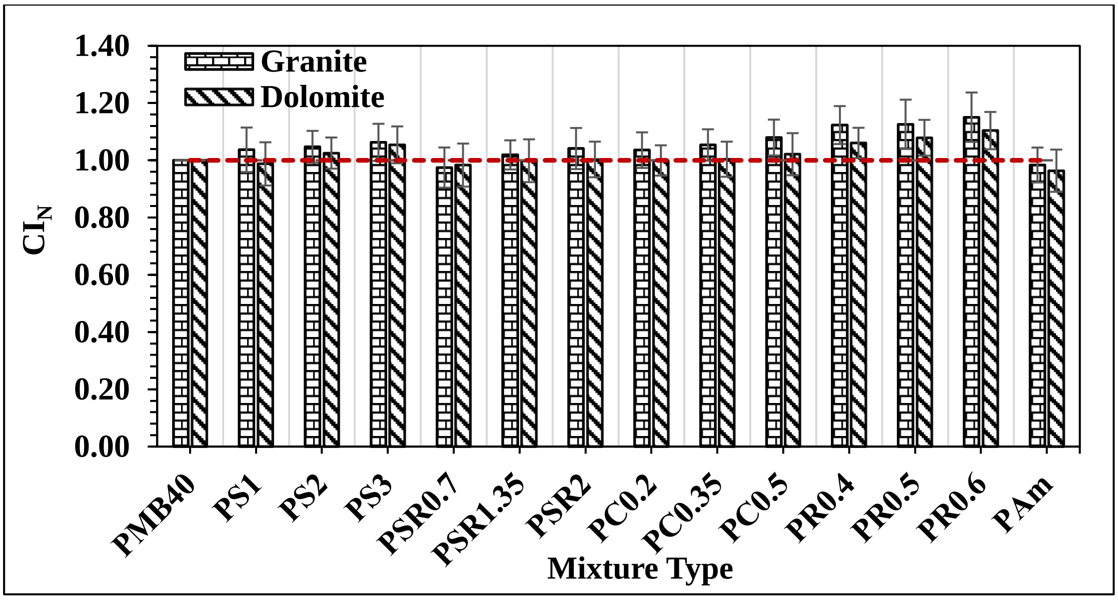
4.3.5 Discussion on Coating Ability

Figure 4.16a and Figure 4.16b shows the value of normalized coating index (CI_N) for all the WMA mixtures prepared using VG30 and PMB40, respectively. Both the figures show the influence of aggregate type in the asphalt mixtures as well. In general, an appropriate mixing temperature should lead to proper coating of asphalt binder over the aggregates [519]. In order to determine CI_N for WMA mixtures, the value of CI_N for HMA mixtures (VG30 and PMB40), with both the aggregate type, were taken as unity. A higher value of CI_N indicates better coating.

Although CI_N increased with the increase in mixing temperature, the addition of WMA additives imparts similar or even better degree of coating than the HMA mixture, even at reduced mixing temperatures. In fact, higher coating of aggregates is fundamental to ensure the workability and durability of asphalt mixtures [524]. It was observed that the influence of WMA additive varies with the type of base asphalt binder and aggregate type. In the present study, the effect of WMA additives was found to be more prominent in VG30 compared to PMB40. On the other hand, no specific trend in CI_N was observed with the change in aggregate type.



(a)



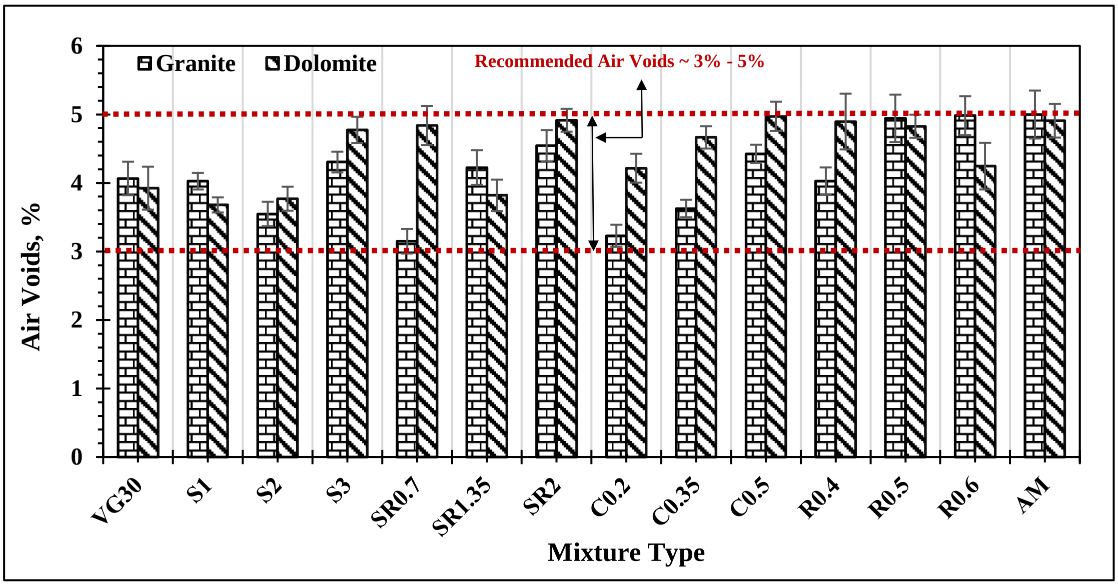
(b)

Figure 4.16. CI_N for all the asphalt mixtures (a) VG30 and (b) PMB40

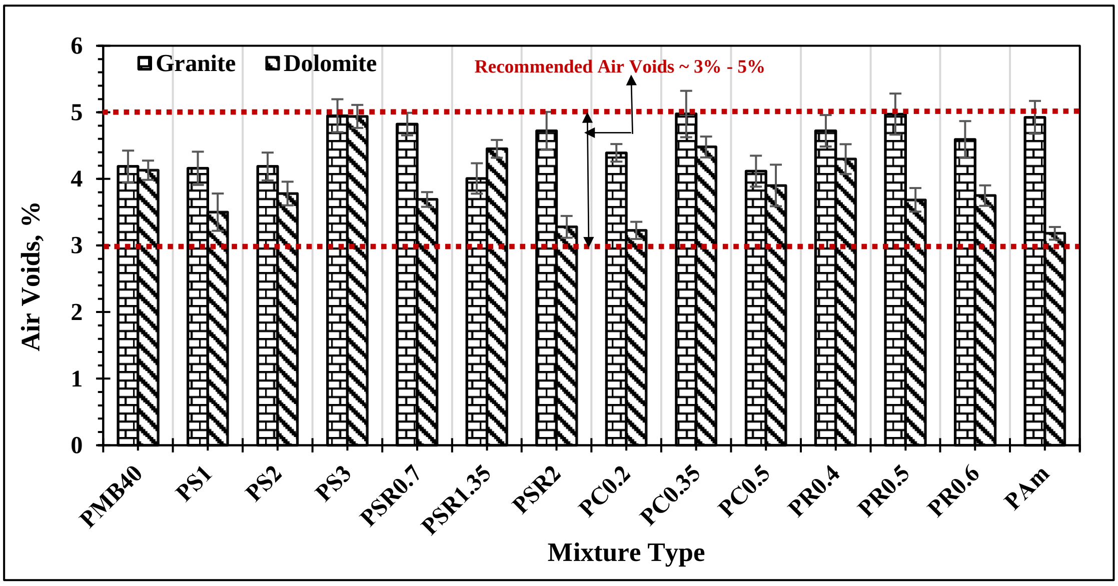
On an average, chemical additives, irrespective of aggregate and binder type, showed higher CI_N, followed by organic and foaming-based technologies. Among different combinations of aggregate and asphalt binder, the CI_N for various WMA binders was ranked as: Rediset > Cecabase > Sasobit Redux > Sasobit > Aspha-Min. Since two different types of aggregate and base binders were used in the present study, the variation/difference in CI_N could be associated with two primary reasons: (a) the difference in the working mechanism of different WMA technologies, (b) difference in interaction/compatibility of WMA additives with the base asphalt binder and aggregate type. Increase in dosage of any WMA additive lead to an improvement in coating ability. Overall, the value of CI_N for all the WMA mixtures was found to pass the criteria of 10% variability, specified as a critical threshold of acceptability, based on the CI_N of conventional HMA mixtures (which ranges from 0.9-1.1), irrespective of the aggregate source.

4.3.6 Discussion on Compactability

The air void in asphalt mixtures is a critical parameter that controls the quality of compacted asphalt mixtures. Therefore, the value of air-voids, for both HMA and WMA mixtures, was determined to validate the compaction temperature. As per the MoRTH guidelines [1], the value of air-voids in a compacted asphalt mixture should range from 3%-5%. Figure 4.17 (a-b) presents the average air voids of WMA mixtures (along with their reference asphalt mixtures) compacted at the temperatures obtained through the workability approach. It was found that HMA and WMA mixtures, irrespective of the aggregate source and base asphalt binder, satisfied the requirement of air-voids specified by MoRTH [1]. The value of air-voids was highly dependent on the base asphalt binder, WMA technology, its dosage and aggregate source. However, no specific trend was observed with the change in any of these variables. Interestingly, the air voids of all the WMA mixtures, even at reduced compaction temperature, were consistent with the results obtained for conventional HMA mixtures. This indicated that the proposed methodology for the evaluation of compaction temperature can be considered more realistic and appropriate in comparison to other methods.



(a)



(b)

Figure 4.17. Air Voids for different asphalt mixtures (a) VG30 and (b) PMB40

4.3.7 Selection of Optimum WMA Additive Dosage

As discussed in the previous sections, the extent of reduction in production temperature increased with the increase in dosage for all the WMA technologies. However, lowering of production temperature beyond a critical limit may adversely affect the engineering characteristics, such as aggregate coating, densification of asphalt mixture, and eventually the mechanical performance. In addition, it was observed that the reduction in production temperatures of WMA mixtures inevitably varies due to the difference in the base asphalt binder and aggregate source. For a particular construction with fixed asphalt binder, aggregate source, and WMA technology, selecting/optimizing the appropriate dosage of WMA additive is critical for asphalt industrialists. Multiple studies [207,317,390] have indicated the importance of WMA additive dosage and its effect on the quality of the asphalt mixtures. It is desirable to select the dosage that not only reduces the production temperature, but also provides similar/better performance compared to conventional HMA. Therefore, the dosage should be optimized by satisfying/ keeping in view the basic characteristics of asphalt mixtures, which are highly dependent on the production temperatures.

The optimum dosage of warm mix additives, pertaining to different technologies, were assessed based on the coating and density checks applied on different asphalt mixtures. These checks were chosen because of two reasons: (a) they account the variability caused by the change in aggregate type and asphalt binder source, and (b) they are directly associated with the production temperatures of asphalt mixtures. Initially, it was proposed to select the optimum dosage based on the coating ability check; however, in the present study, all the WMA mixtures indicated higher CI_N value than conventional HMA mixtures, even at their minimum dosage. Thus, it is quite challenging to select the optimum dosage of WMA additives based on coating check as higher dosage of the additive indicate higher CI_N. In addition, the selection based on the higher value of CI_N (as per the obtained results) is rather questionable or inappropriate. Therefore, it was comprehended that the difference in air void could be an appropriate technique to optimize the dosage of WMA additives. The dosage at which the air voids of the WMA are equal or under 10% variability as that of conventional HMA mixtures was chosen as the optimum dosage. A similar variability value was recommended in IRC SP 101 [27] for the selection of WMA based on the air voids in compacted asphalt mixtures.

Table 4.8 shows the optimum dosage of all the warm mix additives, for different combinations of base asphalt binder, and aggregate. It was found that the optimum dosage varied with the change in aggregate type, base asphalt binder, and WMA technology. The difference in optimum dosage may be attributed to the difference in the interaction between aggregate-asphalt binder-WMA additive. For example: the optimum dosage of Sasobit Redux (1.35% w/b) remains the same, irrespective of the base asphalt binder and aggregate source, whereas 0.5% Cecabase is suitable for granite-based asphalt mixtures, irrespective of the base asphalt binder, 0.2% Cecabase and 0.5% Cecabase are the optimal dosage for dolomite-based asphalt mixtures, prepared with VG30 and PMB40, respectively.

It should be noted that the results or observations reported in the present study were based on the experimental work conducted in the laboratory. In this study, the optimum WMA dosage was determined for four different aggregate and asphalt binder combinations. These WMA combinations differed based on aggregate source and type of base asphalt binder. The combinations are (1) granite aggregate in VG30 mixtures (GVG), (2) dolomite aggregate in VG30 mixtures (DVG), (3) granite aggregate in PMB40 mixtures (GP), and (4) dolomite aggregate in PMB40 mixtures (DP). It is expected that the use of optimum WMA additive dosage would produce a WMA with similar performance as conventional HMA. However, the selection of technology should be based on the requirement of technical prospects, such as mixing and compaction temperatures, rheological and mechanical performance. This requires further investigation, and are presented in the succeeding chapters. These laboratory investigations and analysis are conducted separately for each combination on their optimum WMA dosage. The nomenclature of the respective combinations, as given in Table 4.8, are followed throughout the research work in subsequent chapters.

Table 4.8. Optimum dosage of different WMA additives

Base Asphalt Binder	**WMA Additives**	**Dosage depending on Aggregate Type**	
		Granite [Nomenclature]	**Dolomite [Nomenclature]**
VG30	Sasobit (S)	3% w/b [GS]	2% w/b [DS]
	Sasobit Redux (SR)	1.35% w/b [GSR]	1.35% w/b [DSR]
	Cecabase (C)	0.5% w/b [GC]	0.2% w/b [DC]
	Rediset (R)	0.4% w/b [GR]	0.6% w/b [DR]
	Aspha-Min (Am)*	0.3% w/m [GAm]	0.3% w/m [DAm]
PMB40	Sasobit (S)	2% w/b [GPS]	2% w/b [DPS]
	Sasobit Redux (SR)	1.35% w/b [GPSR]	1.35% w/b [DPSR]
	Cecabase (C)	0.5% w/b [GPC]	0.5% w/b [DPC]
	Rediset (R)	0.6% w/b [GPR]	0.6% w/b [DPR]
	Aspha-Min (Am)*	0.3% w/m [GPAm]	0.3% w/m [DPAm]

Note: w/b and w/m indicate weight by asphalt binder and weight by total mix, respectively.

*Only single dosage was recommended by the manufacturer; therefore, the dosage was taken as optimum value regardless of the coating and compactability check.

4.4 Summary

This chapter demonstrated a workability-based process for evaluation of production temperatures of asphalt mixtures. 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 coating ability and compaction ability checks, respectively. The key conclusions derived from the different sections are as follows:

- Estimation of production temperatures of WMA and PMB mixtures from viscosity measurements is not rational. Workability based procedure is suggested for estimation of the production temperatures. However, the EQ method was found to be suitable only for VG30.
- Value of torque obtained from the fabricated workability setup was successful to quantify the workability characteristics of asphalt mixtures. 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. Sasobit redux and Rediset displayed highest reduction in the production temperatures.
- Aggregate mineralogy and asphalt binder source could affect the workability characteristics of asphalt mixtures and so the production temperatures.

- 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 and foaming-based technologies.
- 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 compactability indicated that the proposed workability method for estimating the production temperatures is reliable and can be used to estimate the production temperatures of WMA mixtures. Thus, it is recommended to use the procedure outlined in this study as a part of IRC SP 101 for evaluation of production temperatures of WMA.
- The optimum dosage of WMA additives varied with the change in base asphalt binder, and aggregate source. The variation was highly dependent on the type of WMA technology.