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APPLICATION OF WMA TECHNOLOGY TO BITUMINOUS BASE COURSE MIXES

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Abstract. Warm Mix Asphalt, due to lower mixing and compaction temperatures, provides some engineering benefits over conventional Hot Mix Asphalt. In this study, an attempt is made to assess the viability of using Warm Mix Asphalt technology in bituminous base courses. An organic wax-based Warm Mix Asphalt additive was used in this study to produce Dense Bituminous Macadam, a commonly used bituminous base course mix in India. Experimental variables included three additive contents and four mixing temperatures. Rheological properties of binder modified with different doses of additive were examined. In all, twelve Warm Mix Asphalt Dense Bituminous Macadam mix types were prepared, evaluated and compared with Hot Mix Asphalt Dense Bituminous Macadam (control) mix. Rheological test results showed the addition of wax-based additive improved stiffness and resistance against permanent deformation of the base binder. Tensile Strength Ratio and retained Marshall Stability results indicated that Warm Mix Asphalt Dense Bituminous Macadam mixes were resistant to moisture-induced damage.

Keywords: base course, Hot Mix Asphalt, moisture damage, rheology, Warm Mix Asphalt.

Introduction

Warm Mix Asphalt (WMA) technologies refer to technological advances in highway construction industry that allow significant lowering of mixing and compaction temperatures of conventional hot bituminous mixes. Rising energy prices, global warming, and stringent environmental regulations have resulted in a rapidly growing interest in WMA technologies as means to decrease the energy consumption and emissions without compromising the mechanical properties of bituminous mixes. When compared to mixing temperatures of 150–190 °C for typical Hot Mix Asphalt (HMA), the mixing temperatures for WMA range from 100–140 °C (Capitão, Picado-Santos, & Martinho, 2012; Leng, Gamez, & Al-Qadi, 2014; Rubio, Martínez, Baena, & Moreno, 2012). Decreased production temperatures offer added benefits like reduced carbon footprint of the highway industry, quicker turnover to traffic, longer hauling distances, and reduction of odours and fumes generated at both plant and paving site; thus providing a safer environment for working staff (Choudhary & Julaganti, 2014; You & Goh, 2008). The temperature reduction of 20–40 °C accomplished by WMA is attributed to the use of various technologies that are categorized into three broad groups: organic additives, chemical additives, and water-based or water-containing foaming processes (Rubio, Martínez, Baena, & Moreno, 2012).

Many studies (Hurley & Prowell 2005; Kim, Lee, & Amirkhanian, 2012; Su, Maekawa, & Hachiya, 2009) have been reported on use of WMA technologies in dense-graded surface/wearing courses; however, their use in bituminous base courses is mainly unexplored. A commonly used dense-graded asphalt mix for bituminous base/binder course in India is Dense Bituminous Macadam (DBM). Since base course mixes are generally identified by a coarser gradation and lower bitumen content than that required for a conventional wearing course mix, it is highly imperative to evaluate WMA base course mixes in terms of mix characteristics including mix volumetrics, Marshall parameters, and moisture susceptibility. It is also important to understand how the characteristics of base courses vary with reduced production temperatures and at different contents of WMA additive. Compared to lift thicknesses of surface courses of a bituminous pavement, thickness of base/binder courses is more, which therefore will require larger quantity of asphalt mix. WMA technology is primarily aimed at reduction of energy consumption and emissions associated with asphalt paving by lowering the

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mix production temperatures. If WMA technology could be successfully applied to produce base course mixes, this would open new avenues for its wider applications, allowing realization of its benefits at a much larger scale owing to larger quantity of asphalt mix being involved.

As bituminous binder plays an essential role in the performance of bituminous mixes, it is imperative to evaluate rheological properties of neat and WMA modified binders for essential insights in the properties of bituminous base course mixes produced with WMA additive. In the present study, an attempt is made to assess WMA technology to produce base course (DBM) mixes. The research focuses on evaluation of the effect of WMA additive content and reduction in mixing and compaction temperature on volumetric properties, Marshall parameters, indirect tensile strength and moisture susceptibility of base course (DBM) mix. Rheological properties of the bituminous binder with different content of WMA additive are also evaluated in this study.

1. Material selection and characterization

1.1. Aggregates and gradation

Aggregates used in the study were obtained from a nearby aggregate crusher plant. Physical properties of aggregates were evaluated to meet the requirements for DBM recommended by *MoRTH: 2013 Specifications for Roads and Bridges* and the results are presented in Table 1. The selected aggregate gradation along with upper and lower limits is shown in Figure 1.

1.2. Binder

Viscosity grade bituminous binder (VG-30) was selected based on the guidelines stipulated in *IRC 111:2009 Specifications for Dense Graded Bituminous Mixes*, based on climatic conditions prevalent in most regions of India. Tiki Tar Industries (Gujarat) provided a VG-30 bituminous binder. Table 2 summarizes the physical test results of the VG-30 bituminous binder as per requirements of *IS 73:2013 Paving Bitumen – Specification* (2013). The VG-30 binder was classified as a PG 64-16 binder as per Superpave performance grading (PG) system.

1.3. Warm Mix Asphalt additive

The Warm Mix Asphalt additive used in the present study is an organic wax-based WMA additive. Chemically, it has a long chain of aliphatic hydrocarbons and is produced by coal gasification process through Fischer-Tropsch synthesis. The main chain length of the hydrocarbons in the additive is in the range of 40–115 carbon atoms, while the wax present in the bitumen has a chain length of 22–45 carbon atoms (Jamshidi, Hamzah, &You, 2013). The additive has a melting point range of about 85 °C to 115 °C and is completely soluble in the binder at temperatures above 115 °C (Kanitpong, Sonthong, Nam, Martono, & Bahia, 2007). It forms a homogenous blend with bitumen above its melting point and reduces its viscosity. As it cools down, it completely recrystallises and forms a crystalline network structure that provides added stability to the binder (Hurley & Prowell, 2005; Rubio, Martínez, Baena, & Moreno, 2012). This wax-based additive, known by the trade name "Sasobit", was obtained from KPL International Ltd. (New Delhi) in pellet form. The acronym WBA has been used in this paper to refer the wax-based additive. Three percentages (1%, 2%, and 3%) of the additive by weight of binder were used in the study.

Table 1. Physical properties of aggregates

Test	Requirement*	Result
Cleanliness test, %	≤5	1.60
Combined elongation & flakiness index, %	≤35	29.60
Los Angeles abrasion value, %	≤30	27.00
Impact test value, %	≤24	21.20
Water absorption, %	≤2	1.30
Stripping value of aggregate, %	Retained coating ≥95	100

Note: * requirements are based on *MoRTH: 2013 Specifications for Roads and Bridges*

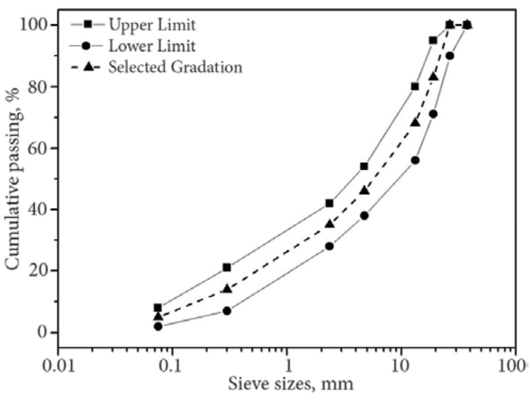

Figure 1. Aggregate gradation for DBM

Table 2. Test results of VG-30 bituminous binder

Test	Requirement*	Result
Absolute viscosity at 60 °C, cP**	2400–3600	2755
Kinematic viscosity at 135 °C, cSt***	≥350	490
Penetration at 25 °C, 0.1mm	50–70	63
Softening point (Ring and Ball), °C	≥47	52
Solubility in trichloroethylene, %	≥99	99.8
Flashpoint (Cleveland open cup), °C	≥220	280
Tests on RTFO residue		
Viscosity ratio at 60 °C	≤4	2.7
Ductility at 25 °C, cm	≥40	62
Equivalent Superpave classification	PG 64-16	

Notes: * requirements are based on *IS 73:2013 Paving Bitumen – Specification*; ** 1 cP = 0.001 Pa.s, *** 1 cSt = 1 mm^2/s

2. Experimental plan

To make a uniform blend of WMA additive and binder, the bituminous binder (VG-30) was first heated to 120–130 °C and required dosage of additive was added. The mixture was then continuously stirred using a mechanical stirrer for 10–15 min at 1000 rpm to get a homogenous blend. These binders at this moment are referred as WMA binders or warm bituminous binders in the paper. These binders were also subjected to short-term and long-term aging using rolling thin-film oven (RTFO) at 163 °C and pressure aging vessel (PAV) at 100 °C, for evaluating rutting ($G^*/\sin\delta$) and fatigue factors ($G^*\sin\delta$). Rheology of warm bituminous binders vis-à-vis control (unmodified) binder was further studied using viscosity, temperature sweep, and repeated creep-recovery test methods All tests were carried out using Anton Paar MCR 102 Dynamic Shear Rheometer (DSR) and Brookfield rotational viscometer RVDV-II+ Pro.

Indian specifications *MoRTH: 2013* recommend Marshall method for designing DBM mixes. Mixing and compaction temperatures were determined for VG-30 binder by equiviscous method as stated in Asphalt Institute (1997) and were found to be 160 °C and 150 °C respectively. Optimum Binder Content (OBC) was determined for HMA DBM mix with VG-30 binder and selected base course gradation in accordance to *ASTM D6926:2010 Standard Practice for Preparation of Bituminous Specimens Using Marshall Apparatus*. Optimum Binder Content evaluated at air void content at the mid-range as stated by Asphalt Institute (1997) and verified for other criteria specified in *MoRTH: 2013* specifications is found to be 5.8%. Marshall parameters and volumetric properties of control DBM mix at OBC, and their requirements are presented in Table 3.

Table 3. Mix design parameters of control DBM mix at OBC

Properties	Requirement	Result
Marshall stability at 60 °C, kN	≥9	12.560
Marshall flow, mm	2–4	3.500
Marshall quotient, kN/mm	2–5	3.590
Air voids, %	3–5	4.000
Voids in mineral aggregates, %	≥12	14.900
Voids filled with bitumen, %	65–75	73.200
Bulk density, g/cm^3	–	2.356

WMA mixes were prepared at four mixing temperatures: at standard mixing temperature of 160 °C (for one-to-one comparison with control mix), and at three reduced temperatures of 140 °C (20 °C reduction), 130 °C (30 °C reduction), and 120 °C (40 °C reduction). Compaction temperatures were kept 10 °C below mixing temperatures. Table 4 shows the various mixing and compaction temperatures used for both control and WMA mixes. These mixes were subjected to a test regime to test mix volumetric and Marshall parameters (stability, flow, and quotient) using Matest 50 kN UTM II digitalized Marshall stability machine. Further, Indirect Tensile Strength (ITS) of the mixes was determined at 25 °C using Cooper servo pneumatic UTM-14 kN and calculated as per Eq. (1):

$$ITS = \frac{2000P}{\pi t D}, \tag{1}$$

where ITS – Indirect Tensile Strength, kPa; P – maximum load, N; t – sample height, mm; D – sample diameter, mm.

Moisture susceptibility characteristics of WMA DBM mixes were determined in this study through Tensile Strength Ratio (TSR) and Retained Marshall Stability (RMS) test methods. Tensile Strength Ratio test also called modified Lottman test, measures reduction in ITS from the effect of moisture conditioning, which includes vacuum saturation and a freeze-thaw cycle. The test was conducted on the Marshall specimens prepared at 7±0.5% air voids as per the guidelines stated in *AASHTO T283:2007 Standard Method of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage*. Tensile Strength Ratio is determined as the ratio of ITS of moisture conditioned specimens to that of unconditioned specimens. Retained Marshall Stability test used in the study compares Marshall stability of a conventionally tested specimen (unconditioned specimen) to that of specimen immersed in water bath at 60 °C for 24 hours before testing (conditioned specimen). Retained Marshall Stability is expressed as the ratio of the stability of conditioned specimens to that of unconditioned specimens. Based on *MoRTH: 2013* specifications, a minimum of 80% TSR and 75% RMS were used in the present study as the acceptance criteria.

Statistical analysis was performed on the test results of bulk density, Marshall stability, Marshall Quotient (MQ), TSR, and RMS of WMA DBM mixes. Randomized Complete Block Design (RCBD) approach was followed to

Table 4. Different mixing and compaction temperatures used in the study

Mix type	Mixing temperature, °C	Compaction temperature, °C	Reduction in mixing and compaction temperature, °C
Control (Hot Mix Asphalt) Dense Bituminous Macadam	160	150	0
Warm Mix Asphalt Dense Bituminous Macadam	160	150	0
	140	130	20
	130	120	30
	120	110	40

perform analysis of variance (ANOVA) at a significance level of 5% to analyse the experimental results of base course mixes with different additive contents and production temperatures (Ott & Longnecker, 2015). Under the RCBD approach, various dosage rates of the wax-based additive were considered as a primary variable (treatments) and mixing temperatures as a secondary variable (blocks).

3. Results and discussion

3.1. Rheological properties

3.1.1. Viscosity

Viscosity is a measure of consistency of bituminous binder and reflects the internal resistance of the binder when it flows. Viscosity was measured using DSR at 60 °C and Brookfield rotational viscometer at 135 °C as a function of shear rate. Results of viscosity at 60 °C and 135 °C are depicted in Figures 2–3. In Figure 2, the tag "VG" refers to the control VG-30 binder (without additive), while the tag "VG + 1%WBA" refers to the VG-30 binder containing 1% dosage of the wax-based additive, and so on. At 60 °C, WMA binders show higher viscosity compared to the control binder, indicating addition of the additive improves rutting resistance at high pavement service temperatures. Higher viscosity is attributed to the formation of crystalline network structure by additive particles in the binder that helps in improving the binder stiffness. From Figure 2, it is also observed that control binder shows Newtonian behaviour, as viscosity remains nearly constant with change in shear rate. On the other hand, the addition of the additive changes the behaviour from Newtonian to shear thinning as viscosity reduces with increase in shear rate. Biro, Gandhi, and Amirkhanian (2009) also reported similar observations. Figure 3 shows addition of additive reduces the viscosity of binder at 135 °C, thereby improving workability, and helps in achieving a reduction in production temperatures. It is also seen that control, as well as WMA binders, show Newtonian behaviour. The results at 135 °C are in good agreement with those reported by Wasiuddin, Saha, King and Mohammad (2012).

3.1.2. Rutting parameter ($G^*/\sin\delta$)

Rutting parameter ($G^*/\sin\delta$) values of both control and WMA binders were determined at 64 °C under both unaged and RTFO aging states using DSR at 10 rad/s frequency with 25 mm parallel plate geometry and 1 mm gap. The selected test temperature of 64 °C is the high-temperature performance grade (PG) of the control VG-30 bituminous binder and is a typical high pavement service temperature at which the pavement becomes susceptible to permanent deformation. Complex modulus (G^*) indicates the total resistance of the binder to deformation, where phase angle (δ) is the time lag between applied stress and the resulting strain. Results of $G^*/\sin\delta$ are shown in Figure 4. Rutting resistance of warm asphalt binders is found to increase with an increase in the additive content irrespective of the aging state. The increase in $G^*/\sin\delta$ values are attributed to added stiffness imparted to the binder by crystalline network structure, and it can also help to increase the high-temperature performance grade of the binder. A higher improvement is observed on addition of 2% and 3% additive when compared to the control binder. Addition of 3% additive increases $G^*/\sin\delta$ by 1.46 and 1.63 times in unaged and RTFO aged conditions respectively, compared to corresponding control binders.

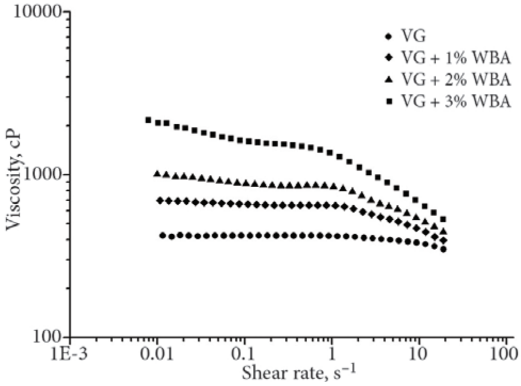

Figure 2. Viscosity results at 60 °C

Note: the acronym WBA refers to wax-based additive used in study

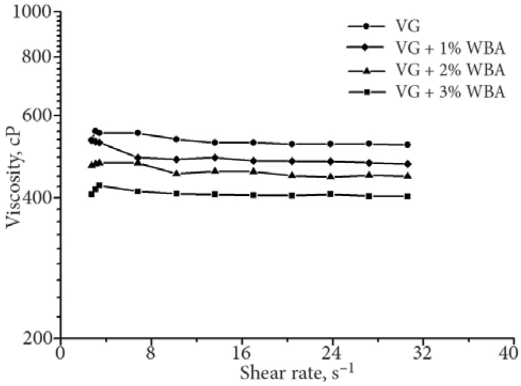

Figure 3. Viscosity results at 135 °C

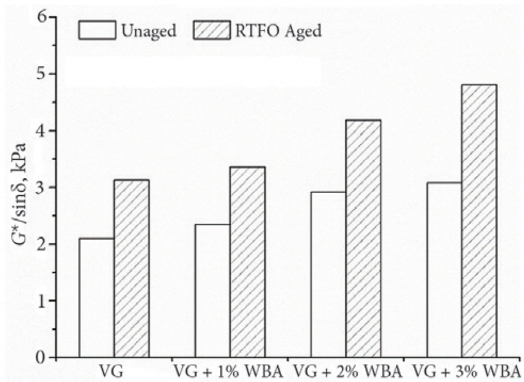

Figure 4. $G^*/\sin\delta$ results at 64 °C

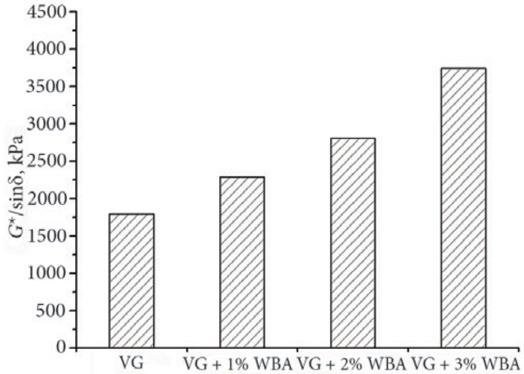

Figure 5. $G^*\sin\delta$ results at 28 °C

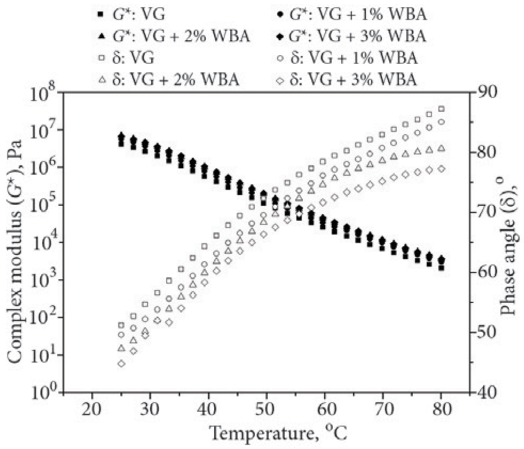

Figure 6. Temperature sweep results

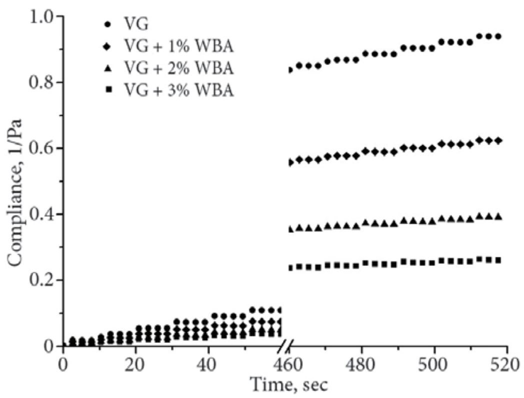

Figure 7. Results of repeated creep-recovery test performed at 64 °C

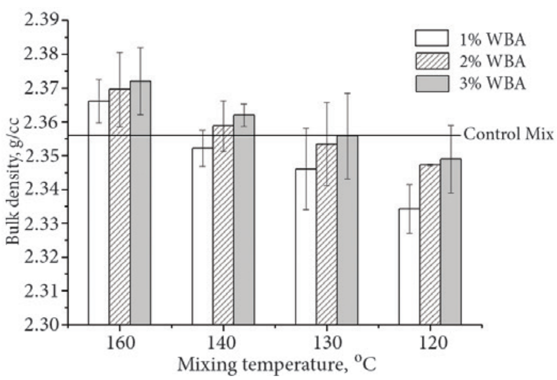

Figure 8. The bulk density of WMA mixes

3.1.3. Fatigue parameter ($G^*\sin\delta$)

$G^*\sin\delta$ values of long-term aged control and warm asphalt binders, evaluated at an intermediate temperature of 28 °C, are presented in Figure 5. The selected test temperature of 28 °C is the grade-specific intermediate temperature of the control VG-30 bituminous binder (classified as a PG 64–16 binders as per Superpave PG system). An increase in additive dosage increases $G^*\sin\delta$ values, indicating reduced fatigue resistance of warm asphalt binders. However, $G^*\sin\delta$ values are much below the maximum permissible limit of 5000 kPa even at 3% additive content. Note that the short-term aging (that preludes PAV aging) of all warm asphalt binders was performed at 163 °C temperature used for control binders. This high temperature is likely to have resulted in excess stiffness, and reduced fatigue performance at an intermediate temperature.

3.1.4. Temperature sweep

Temperature sweep test offers an idea about the temperature dependency of the complex modulus (G^*) and phase angle (δ) of binder. Temperature dependency of both control and WMA binders after RTFO aging were determined in the temperature range of 25–80 °C at 10 Hz frequency and the results are shown in Figure 6. Addition of the wax-based additive increases G^* and decreases δ in the test temperature range, therefore helps to enhance the resistance of binder towards permanent deformation. A significant decrease in δ is observed at test temperatures greater than about 50 °C with the increase in additive content showing that the additive enhances the elastic nature of the VG-30 binder.

3.1.5. Repeated creep-recovery test

The repeated creep-recovery test was performed on short-term aged binders using DSR at 64 °C by applying shear stress of 10 Pa for 1 s in a total cycle length of 10 s and monitoring the strain for 52 cycles. The selected test temperature is the same as used in $G^*/\sin\delta$ test. Results of the test are expressed as compliance, the ratio of strain to the applied stress. Compliance values of WMA binders are shown in Figure 7. Addition of the additive decreases the compliance values appreciably suggesting an increase in stiffness of binder achieved through the crystalline network structure formed with the additive. Lower compliance indicates higher resistance to permanent deformation. There is a reduction of 47%, 61% and 87% in last compliance values (at the end of 52$^{\text{nd}}$ test cycle) with additions of 1%, 2%, and 3% additive contents, indicating its addition provides better resistance towards permanent deformation. These results agree with results of $G^*/\sin\delta$, temperature sweep, and viscosity at 60 °C.

3.2. Volumetric properties of DBM mixes with WMA additive

3.2.1. Bulk density and air voids

Figure 8 presents a variation of bulk density with additive dosages and mixing temperatures. It is seen that bulk density increases with increase in additive dosage and decreases with a decrease in mixing temperature. Bulk densities of WMA DBM mixes are higher than the control HMA at a standard temperature of 160 °C, indicating increase in workability of the mix as the additive decreases the viscosity of binder at temperatures above its melting point. As mixing temperature decreases, the workability of WMA mixes decreases resulting in lower bulk densities. The bulk density of WMA mixes with 2% and 3% additive dosage even up to 30 °C reduction in production temperatures are found to be like that of the control mix. Hence, WMA DBM mixes achieve bulk density comparable to control mix even at lower temperatures (up to 30 °C lower). Moreover, increase in additive content from 1% to 2% shows greater improvement in bulk density as compared to 2% to 3%. This effect is more pronounced at higher reductions in the mixing temperatures.

Results of statistical analysis performed on bulk density values are presented in Tables 5–6. Table 5 indicates reduction in mixing temperature from 160 °C to 140 °C caused an insignificant reduction in bulk density of WMA mixes in comparison to control mix. At remaining reductions (30 °C and 40 °C) in the mixing temperatures, however, the reduction is found to be is significant. Improvement in bulk density on the addition of the additive is found to be statistically insignificant at all dosages (Table 6) likely due to high variability in the bulk density values of WMA DBM mixes. However, from Figure 8, it is seen that increase in additive dosage improves the average density of mixes at all mixing temperatures. Therefore, it appears that the additive enhances compactability of WMA DBM mixes.

From Figure 9, which presents air void results of WMA DBM mixes at different production temperatures, it is found WMA mixes with 2% and 3% additive content have air voids similar to the control mix (4%) even after 30 °C reduction in production temperatures. This implies about 30 °C reduction in mixing and compaction temperature is achieved for WMA DBM mixes with an air void content similar to control mix. Also, air void content of WMA mixes increases with a decrease in mixing temperature. It is expected as compactability reduces at lower mixing temperatures. All WMA DBM mixes satisfy the air voids criteria of 3–5% required by the *MoRTH: 2013* specifications.

3.3. Marshall parameters of WMA DBM mixes

Marshall stability values of WMA DBM mixes are shown in Figure 10. Addition of additive results in significant increase in stability at 160 °C (0 °C reduction), with a value of 15.70 kN for WMA mix (3% additive dosage) against 12.56 kN for control HMA, an increase of about 25%. Warm Mix Asphalt mixes with 3% dosage show higher stability of 13.20 kN even at 130 °C (30 °C reduction) than 12.56 kN of the control HMA at 160 °C. However, stability values of WMA mix at 120 °C (40 °C reduction) are lower than the control HMA. In general, it is observed that stability values of WMA DBM mixes decrease with a decrease in the mixing temperatures and increase with an increase in the additive percentage. Increase in air void content and a decrease in bulk density at lower mixing temperatures explain the decrease in stability with a reduction in production temperatures. The increase in stability at any temperature with increase in additive content is due to the formation of crystalline lattice structure increasing the stiffness of binder, as also observed in the viscosity results at 60 °C (Figure 2). Marshall stability values of WMA and the control HMA DBM mixes meet the minimum requirement of 9 kN according to *MoRTH:2013* specifications at all mixing temperatures except in case for 1% additive at 120 °C.

Results of MQ, defined as the ratio of stability to flow, are shown in Figure 11. Marshall Quotient values of WMA mix with 2% and 3% additive contents are comparable to the control mix even up to 30 °C reduction in production temperatures. Marshall Quotient value decreases with a decrease in mixing temperature and increases with increase in additive dosage. Higher MQ value of mix represents higher resistance towards permanent deformation (Hınıslıoğlu & Ağar, 2004).

Statistical analysis was performed on Marshall Stability, and MQ values of WMA DBM and the results are

Table 5. Statistical analysis results on bulk density (irrespective of additive content)

	160 °C	140 °C	130 °C	120 °C
160 °C	–			
140 °C	NS	–		
130 °C	S	NS	–	
120 °C	S	S	NS	–

Note: NS: not significant; S: significant

Table 6. Statistical analysis results on bulk density (irrespective of mixing temperature)

	Control	1% WBA	2% WBA	3% WBA
Control	–			
1% WBA	NS	–		
2% WBA	NS	NS	–	
3% WBA	NS	S	NS	–

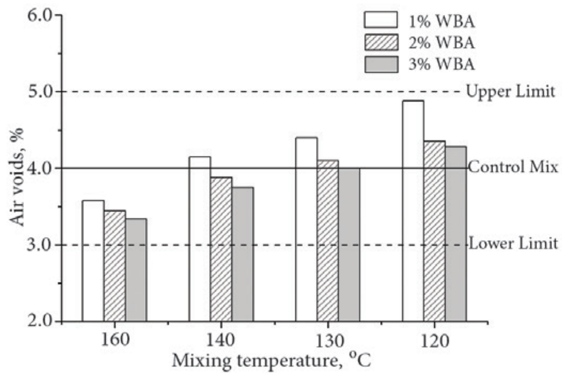

Figure 9. Air voids of WMA mixes

Table 7. Statistical analysis results of Marshall Stability and Marshall Quotient (irrespective of additive content)

	Marshall stability				Marshall Quotient			
	160 °C	140 °C	130 °C	120 °C	160 °C	140 °C	130 °C	120 °C
160 °C	–				–			
140 °C	NS	–			NS	–		
130 °C	S	NS	–		S	NS	–	
120 °C	S	S	NS	–	S	S	NS	–

Table 8. Statistical analysis results of Marshall Stability and Marshall Quotient (irrespective of mixing temperature)

	Marshall Stability				Marshall Quotient			
	Control	1% WBA	2% WBA	3% WBA	Control	1% WBA	2% WBA	3% WBA
Control	–				–			
1% WBA	NS	–			NS	–		
2% WBA	NS	NS	–		NS	NS	–	
3% WBA	NS	S	NS	–	NS	S	NS	–

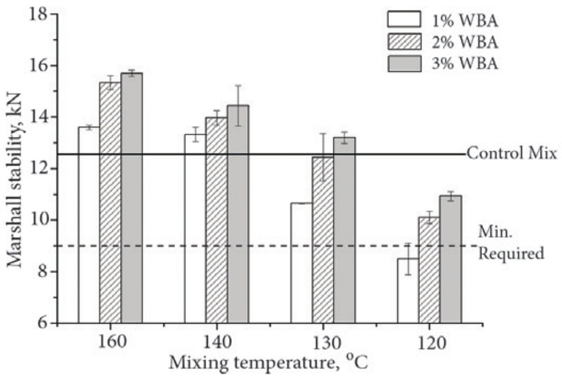

Figure 10. Marshall Stability of WMA mixes

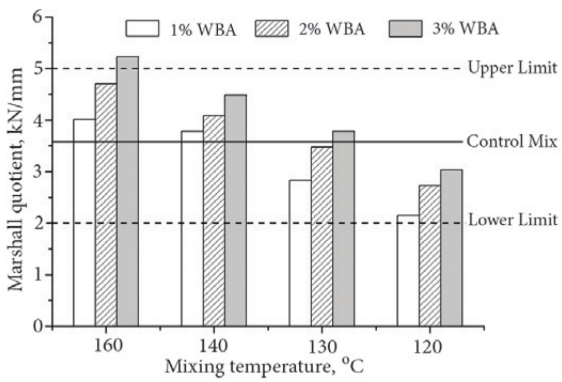

Figure 11. Marshall Quotient of WMA mixes

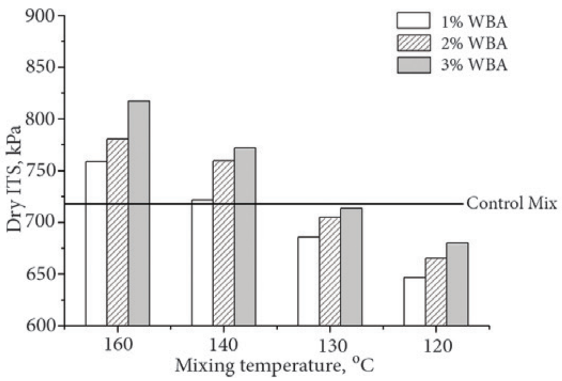

Figure 12. Dry ITS of WMA mixes

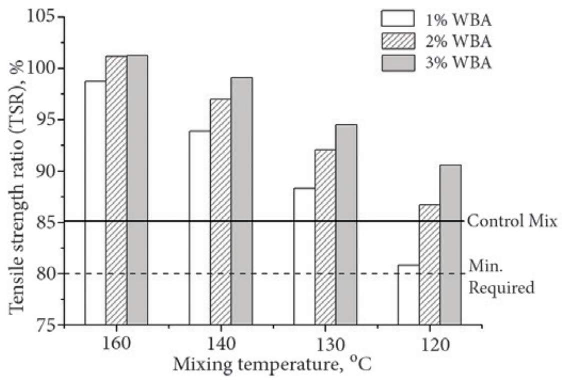

Figure 13. Tensile Strength Ratio of WMA mixes

shown in Tables 7–8. Table 7 shows reduction in mixing temperature from 160 °C to 140 °C had no significant effect on Marshall Stability and MQ values of WMA DBM mix when compared to control mix. The reduction was, however, significant at other lower mixing temperatures. Irrespective of mixing temperatures, Marshall Stability and MQ values of WMA DBM mix on the addition of WMA additive are found to be statistically insignificant at all additive percentages as per Table 8. However, from Figures 10–11, it is seen that increase in WMA additive dosage increased Marshall stability and MQ values of DBM mixes at all mixing temperatures. Therefore, it is clear the addition of WMA additive enhances Marshall stability and MQ values of WMA DBM mixes.

3.4. Indirect Tensile Strength and moisture susceptibility of WMA DBM mixes

Indirect tensile strength (ITS) test is used to describe the tensile properties of bituminous mixes which is further associated with their cracking resistance. The dry (unconditioned) ITS results of WMA DBM mixes with different additive contents, and at different temperatures of production are presented in Figure 12. It is clear WMA DBM mixes show higher or comparable tensile strength than the control mix up to 30 °C reductions. Further, the results show that tensile strength increases as additive content increases, irrespective of the production temperature. A higher tensile strength generally corresponds to a better cracking resistance.

Figure 13 shows the moisture susceptibility resistance in terms of TSR values of WMA DBM mixes with different additive dosages and mixing temperatures. It is seen that moisture susceptibility resistance of WMA mixes increases with increase in additive dosage. Tensile Strength Ratio values of WMA mix with 2% and 3% dosage, even at 120 °C (i.e., 40 °C reduction), are found to be higher than control mix produced at 160 °C. From Figure 14, it is also observed that increase in the additive dosage reduces the difference between dry and wet ITS values at all mixing temperatures resulting in higher TSR values for warm mixes when compared with the control mix. However, TSR values decrease with a reduction in mixing temperatures, which is likely due to reduced stiffness of binder at lower production temperatures as also observed in the results of dry and wet ITS values shown in Figure 14. Contrary to the low moisture damage performance of the wax-based additive modified mix reported in some studies (Hurley & Prowell, 2005; Kanitpong et al., 2007), the addition of the additive in bituminous base course mix shows acceptable performance even at 40 °C reduction in production temperature. All WMA DBM mixes satisfy the least smallest TSR requirement of 80% set forth by *MoRTH: 2013* specifications.

Retained Marshall stability values of WMA DBM mixes are depicted in Figure 15. It is observed that increase in the additive content increases the RMS values implying a higher resistance towards moisture susceptibility. It is also observed that RMS values decrease with a decrease in mixing temperature and increase with an increase in additive dosage. Although the RMS values of WMA mixes at lower temperatures are smaller than the value for control HMA, all WMA mixes with different additive percentages and mixing temperatures meet the minimum RMS need of 75% by *MoRTH: 2013*. Tables 9–10 show the results

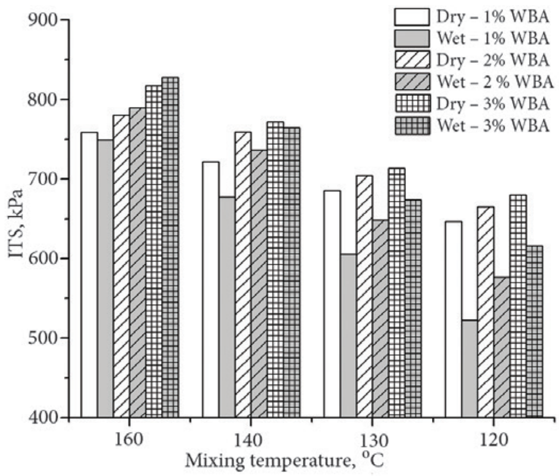

Figure 14. Dry and wet ITS values of WMA mixes

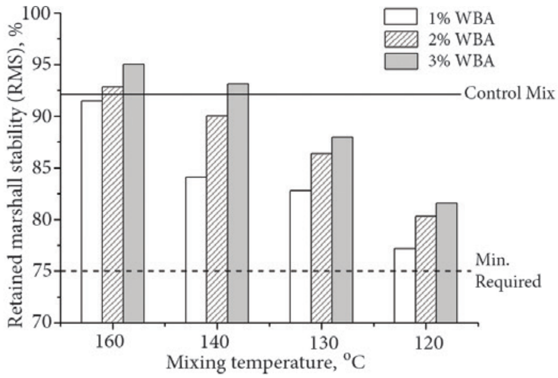

Figure 15. Retained Marshall Stability of WMA mixes

Table 9. Statistical analysis results of Tensile Strength Ratio and retained Marshall stability (irrespective of additive content)

	Tensile Strength Ratio				Retained Marshall Stability			
	160 °C	140 °C	130 °C	120 °C	160 °C	140 °C	130 °C	120 °C
160 °C	–				–			
140 °C	NS	–			NS	–		
130 °C	S	NS	–		S	NS	–	
120 °C	S	S	NS	–	S	S	NS	–

Table 10. Statistical analysis results of Tensile Strength Ratio and retained Marshall Stability (irrespective of mixing temperature)

	Tensile Strength Ratio				Retained Marshall Stability			
	Control	1% WBA	2% WBA	3% WBA	Control	1% WBA	2% WBA	3% WBA
Control	–				–			
1% WBA	NS	–			S	–		
2% WBA	S	NS	–		S	NS	–	
3% WBA	S	S	NS	–	S	S	NS	–

of statistical analysis (ANOVA) performed on TSR and RMS values of WMA DBM mixes. From Table 9, it is observed there is a significant difference in both TSR and RMS values with a reduction in mixing temperature from 160 °C to 130 °C and 120 °C, irrespective of additive content. Table 10 shows that 2% and 3% additive dosage has a significant effect on TSR and RMS values of WMA mixes in comparison to control mix.

Conclusions

The present study was conducted to evaluate the feasibility of using Warm Mix Asphalt technology in the design of bituminous base course (Dense Bituminous Macadam) mixes. The study was designed using VG-30 binder, three percentages of a wax-based Warm Mix Asphalt additive, and four production temperatures. Rheological properties of a control (without Warm Mix Asphalt additive) and Warm Mix Asphalt binders along with properties of control Hot Mix Asphalt and Warm Mix Asphalt Dense Bituminous Macadam mix in terms of volumetric, Marshall parameters, indirect tensile strength, and moisture susceptibility were investigated. The main conclusions drawn from the study are:

1. Addition of the wax-based additive increased the viscosity of binder at 60 °C and decreased the viscosity at 135 °C signifying the additive improves the stiffness of binder at high pavement service temperatures and workability at mixing temperatures.
2. Results of rutting parameter ($G^*/\sin\delta$), temperature sweep, and repeated creep-recovery tests revealed addition of the additive increased the stiffness of binder as well as reduced the phase angle, thus making the binders more resistant to permanent deformation.
3. Bulk density and air void content of Warm Mix Asphalt Dense Bituminous Macadam mix with 2% and 3% additive dosages at 130 °C (30 °C reduction in production temperature) were found to be similar to control Hot Mix Asphalt Dense Bituminous Macadam mix.
4. Addition of the additive also increased the Marshall Quotient values, implying enhanced stiffness of Warm Mix Asphalt Dense Bituminous Macadam mixes, which is expected to offer better resistance against permanent deformation.
5. Tensile Strength Ratio and Retained Marshall Stability results showed the additive increased the moisture susceptibility resistance of base course mixes even at reduced production temperatures.
6. Warm Mix Asphalt Dense Bituminous Macadam mixes with 2% additive dosage were able to meet all Marshall mix design and moisture susceptibility requirements up to 40 °C reduction in production temperatures and showed comparable performance to control Hot Mix Asphalt up to 30 °C reductions. Therefore, the selected Warm Mix Asphalt additive helps to design and construct Dense Bituminous Macadam mixes at lower temperatures than typical production temperatures, thus extending the applications of Warm Mix Asphalt technologies to bituminous base course mixes.

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