# CHAPTER 7. DOSAGE OPTIMISATION AND SELECTION OF WMA ADDITIVES

## 7.1 Preamble

WMA technology is one of sustainable technology used for construction of greener roads [2]. The primary aim of this technology is to lower the production temperature of asphalt mixtures without compromising their performance. The amount of reduction achieved in production temperatures depends on the type (mechanism) and dosages of WMA technology. From the previous chapter, it has been found that 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 performance of asphalt binder, such as rutting, fatigue cracking, and moisture sensitivity of asphalt binder [54,99,440]. 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 industry. Multiple studies [34,207,441] have indicated the importance of WMA additive dosage and its effect on the quality of the asphalt binder. It is desirable to select the dosage that not only reduces the production temperature, but also provides similar/better performance compared to conventional HMA (like base asphalt binders). Therefore, the dosage should be optimized by satisfying/ keeping in view the basic characteristics of asphalt binder, which are highly dependent on the production temperatures. In this study, the dosages of WMA additives have been optimised based on their temperature reduction and performance characteristics.

The selection of WMA additive depends on the performance requirement of the project or location [369]. It is expected that WMA technology performs same or even better than HMA. If this objective is not achieved, then all of its above-mentioned benefits will be worthless

[10,270]. The performance requirement of location or project depends on the environmental and traffic conditions [10,369]. For example, better performance of WMA additives against rutting is required at project where service temperature is higher and traffic is of slow moving nature. Therefore, the selection of WMA additives can be ranked based on desirable performance. At present, there are no established guidelines or standards to support pavement engineers in selecting the appropriate WMA additive type according to the project requirement. Generally, the selection of WMA additive is very subjective in which choice of WMA additive is based on availability of construction technique, construction materials, and expertise of engineer. This subjective selection does not guarantee that the selected binder is best for particular project requirement. Therefore, there is a need to select the WMA additives based on the performance parameters. In this study, performance against rutting, fatigue cracking, low temperature cracking and moisture damage has been considered for the selection of WMA additives. This chapter will provide the selection of WMA additives at binder level according to their performance and requirement of the projects.

## 7.2 Scope and Objectives

This study is focused on optimisation and selection of WMA additives according to the performance requirements of location or project. The performance of various WMA additives has been evaluated using various performance tests such as MSCR test, LAS test, and BBS test and results of these tests has been discussed in previous chapter. From the study, it has been found that the WMA additives and their dosages significantly affect the performance of base asphalt binders. In order to check the effect of WMA additives and their dosages on the performance of asphalt binder, the statistical analysis in the form of analysis of variance (ANOVA) has been performed in this Chapter. To do this, the statistical (Three-way ANOVA) analysis has been performed initially to check effect of WMA additives and their dosages on the performance parameters of base asphalt binders. Following statistical analysis, the ranking methodology has been adopted to decide the optimum dosage of each additive. Finally, the chapter involves a simple ranking framework to select the most suitable (or 'best') WMA additive, relative to other WMA based on performance requirement project or location.

The primary objectives of the present chapter are:

- Assessing the effect of WMA additives and their dosages on performance parameters of asphalt binder using three-way ANOVA test.
- To optimise the dosages of WMA additives based on their workability (temperature reduction) and performance characteristics.
- To select most suitable (or 'best') WMA additive based on ranking methodology according to the performance requirement of project or location.

## 7.3 Statistical Analysis

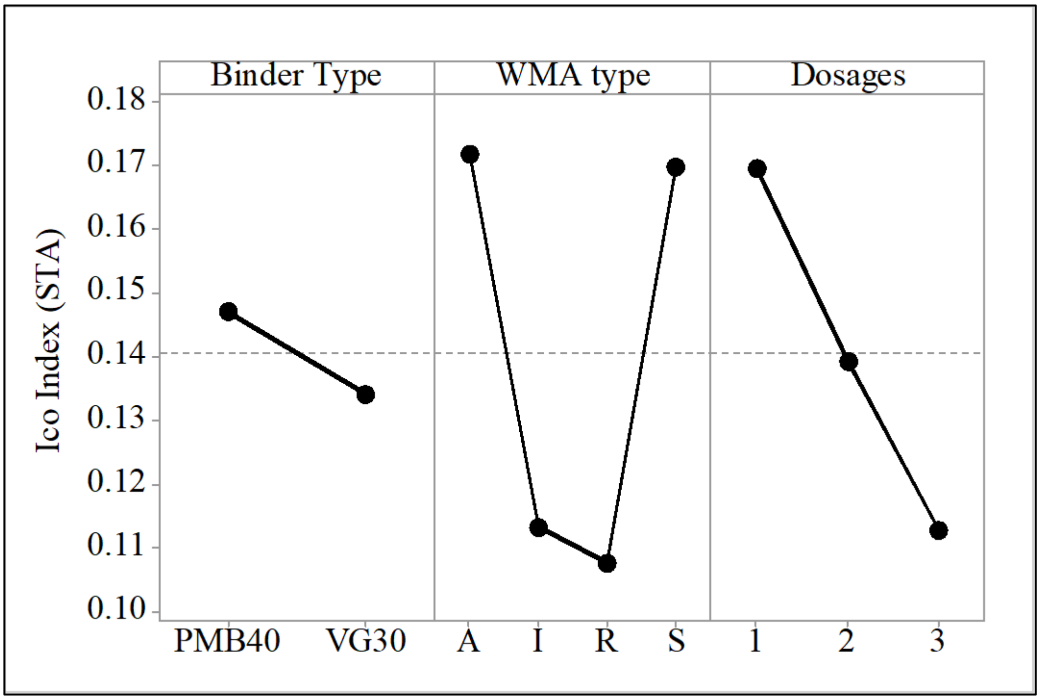
There are several design of experiment (DOE) methods such as Analysis of Variance (ANOVA) and factorial analysis generally used in the field of material engineering for statistical analysis [442–444]. In this study 3-way ANOVA was performed to identify the influence of independent variables on dependent variables due to its simplicity and easiness. Binder type, WMA type and their dosages, temperature, aggregate type was considered as the independent variables whereas carbonyl index ($I_{CO}$), non-recoverable creep compliance ($J_{nr}$), percent recovery (%R), fatigue life, dry POTS, wet POTS, and BSR were taken as dependent variables. The effect of dependent variable on independent variable is significant when p-value is less than 5% at 95% confidence level. The primary purpose of this section is to study the effect of binder type, WMA dosages, and testing temperature on the various performance parameters.

### *7.3.1 Aging*

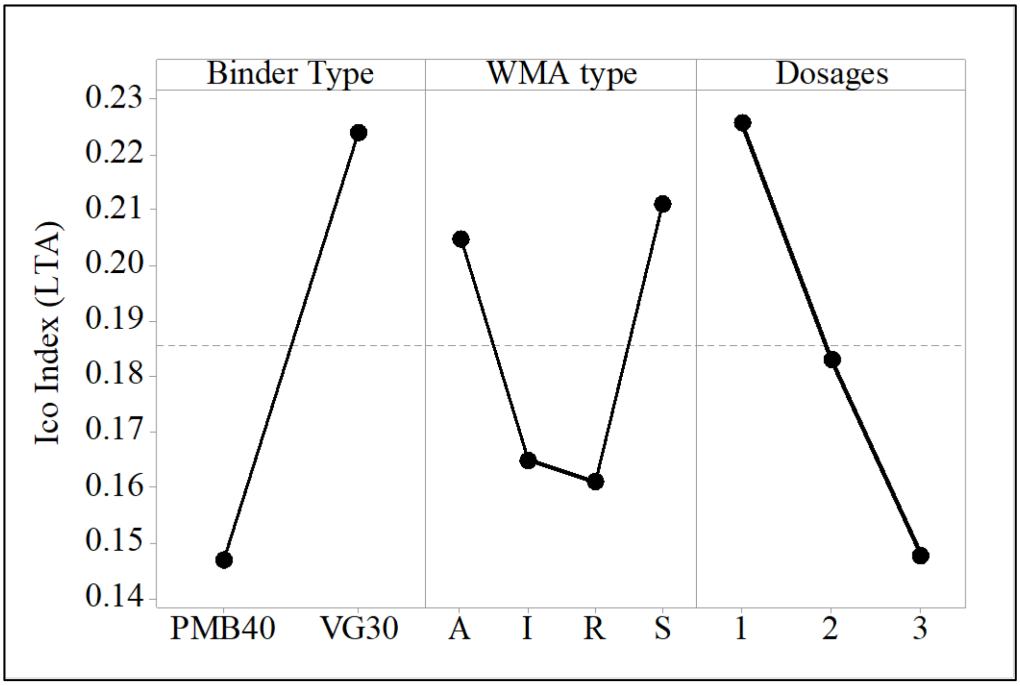
The 3-way ANOVA was performed to study the effect of binder type, WMA type, and their dosages on aging index of the binder. In this analysis, only carbonyl index is considered as independent variable. This can be due to the fact that the carbonyl index is well correlated with field as well laboratory aging [445,446]. Table 7-1 shows the results of the 3-way ANOVA at a confidence level of 95% ($\alpha = 0.05$) for carbonyl index after short term and long-term aging. The effect of the variables will be considered significant when the p-value is less than 0.05. Based on the results, it can be stated that WMA type and their dosages significantly influence the carbonyl index values after short term aging as p-value<0.05. This shows the importance of these parameters in governing the potential of WMA asphalt binders against aging. This variation may result from the different aging temperatures provided by the various WMA additives and their dosages. This different aging temperatures can be attributed to different mechanism associated with WMA type. The dosages also showed significant impact on aging of asphalt binder. Production temperatures decreased with increasing the dosage of WMA additives and as a result aging reduced. Although the carbonyl index values changed with binder type after short term aging, effect of binder type was not very significant in the case of carbonyl index values (after short term aging). Addition of WMA resulted in similar MT and CT ranges for both the binders and hence no significant effect on carbonyl index values after shot term aging. On the other hand, the binder type was found to be significant parameter in case of long-term aging as p-value <0.05. Thus, in addition to WMA, binder type is also important to ensure sufficient aging resistance. In literatures, it has been found that the polymer modified binder showed better resistance against aging as compared to viscosity grade binders [257,447]. To better understand the significance of binder type, WMA types and their respective dosages on aging index, the main effect plots were plotted, as shown in Figure 7-1. The main effect plot was interpreted by examining the changes in the carbonyl index after short-term ($I_{CO}$) and long-term aging ($I_{SO}$) with varying binder types, WMA additives, and their dosages. Steeper slopes in the plot indicate a greater influence on aging behavior. PMB40 exhibited better resistance to aging compared to VG30. Among the WMA additives, Sasobit and Asphaltan A demonstrated superior aging performance, while Rediset and Iterlow were associated with higher aging susceptibility. Additionally, increasing the dosage of WMA additives generally resulted in a decrease in $I_{CO}$ and $I_{SO}$ values suggesting higher aging sensitivity. These observations underscore the critical role of selecting appropriate binder type, additive, and dosage to enhance the aging resistance of asphalt binders.

Table 7-1. Summary of three-way ANOVA at 95% confidence level for Carbonyl index.

| Parameter | Source | df | Mean Square | F-calculated | P- value |
|---|---|---|---|---|---|
| $I_{CO}$ Index (STA) | Binder Type | 1 | 1.8625 | 1.49 | 0.239 |
| | WMA Type | 3 | 13.625 | 10.90 | 0.0001 |
| | Dosage | 2 | 12.075 | 9.66 | 0.002 |
| | Error | 17 | 1.25 | | |
| | Total | 23 | | | |
| $I_{CO}$ Index (LTA) | Binder Type | 1 | 59.696 | 42.64 | 0.00001 |
| | WMA Type | 3 | 5.6088 | 4.92 | 0.012 |
| | Dosage | 2 | 16.5756 | 14.54 | 0.0001 |
| | Error | 17 | 1.14 | | |
| | Total | 23 | | | |




(a)




(b)

Figure 7-1. Main effect plot for Ico Index a) After STA b) After LTA

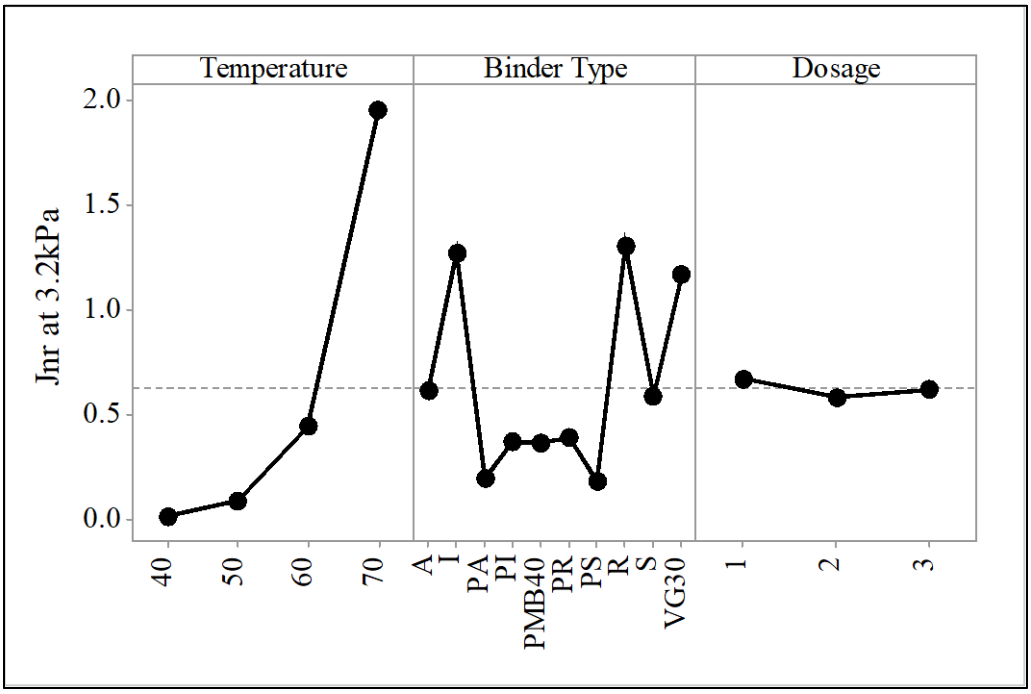
*Note: 1,2, and 3 indicates the 1%,2% and 3% dosages of Sasobit and Asphaltan A. In case of chemical additives 1,2, and 3 indicates 0.4%,0.5% and 0.6% dosages of Rediset and 0.3%,0.4% and 0.5% dosages of Iterlow in base binder, respectively.*

### *7.3.2 Non-Recoverable Creep Compliance and % Recovery*

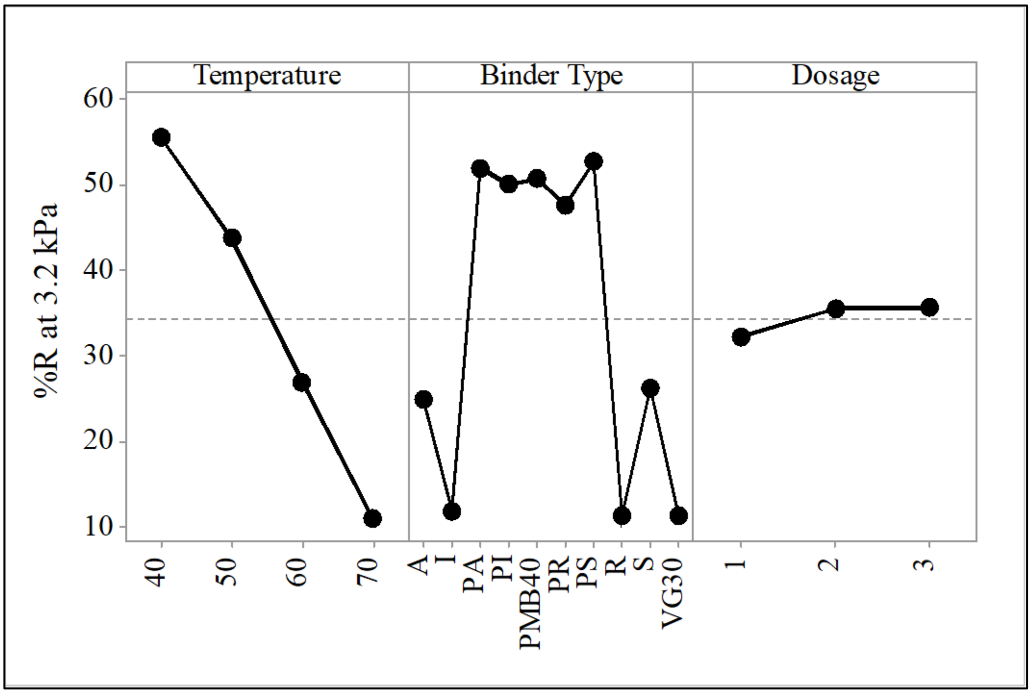
The effect of binder type, WMA type, and their dosages, and temperature on non-recoverable creep compliance and % recovery of the binder has been studied using 3-way ANOVA test. Table 7-2 shows the results of the 3-way ANOVA at a confidence level of 95% ($\alpha = 0.05$) for non-recoverable creep compliance and % recovery. It can be seen that temperature and binder type (WMA modified binders) significantly influence the non-recoverable creep compliance and % recovery as p-value<0.05. This indicates that the type of WMA additives and temperatures are key factors which play important role in rutting resistance of binders. It is obvious that the rutting resistance of binder reduces with increase in temperature of asphalt binder. In case of WMA additives, the behaviour of WMA additives at these temperatures plays important role. The organic additives performed well against rutting due to its crystallization effect which increase the stiffness of asphalt binder [49]. On the other hand, as chemical additives do not influence the rheology of base binder, similar rutting performance (as that of base binder) was observed. Due to this different interaction of WMA additives with base binders, they showed significant impact on rutting parameters. The effect of WMA dosages on rutting parameters was found to be insignificant (as p-value>0.05). Although production temperatures reduced with the increase in dosages of additives, performance was found to be relatively same. This analysis showed that the type of WMA additives is important rather than its dosages. This might be due to the fact that the effect of dosages was not pronounced due to the lower production temperatures. The effect of these parameters can be better understood using main effect plot shown in Figure 7-2. The main effect plot showed that the selection of the type of WMA additive for particular temperature is of great importance for achieving satisfactory performance against rutting.

Table 7-2. Summary of three-way ANOVA at 95% confidence level for non-recoverable creep compliance and % recovery.

| Parameter | Source | df | Mean Square | F-calculated | P- value |
|---|---|---|---|---|---|
| $J_{nr}$ at 3.2 kPa | Temperature | 3 | 83.556 | 69.63 | 0.000009 |
| | Binder Type | 9 | 7.824 | 6.52 | 0.00089 |
| | Dosage | 2 | 0.12 | 0.1 | 0.902 |
| | Error | 89 | 1.2 | | |
| | Total | 103 | | | |
| %R at 3.2 kPa | Binder Type | 3 | 384.916 | 274.94 | 0.00004 |
| | WMA Type | 9 | 131.544 | 93.96 | 0.0002 |
| | Dosage | 2 | 3.808 | 2.72 | 0.071 |
| | Error | 89 | 1.4 | | |
| | Total | 103 | | | |




(a)




(b)

Figure 7-2. Main effect plot a) Jnr at 3.2 kPa b) %Recovery at 3.2 kPa

*Note: 1,2, and 3 indicates the 1%,2% and 3% dosages of Sasobit and Asphaltan A. In case of chemical additives 1,2, and 3 indicates 0.4%,0.5% and 0.6% dosages of Rediset and 0.3%,0.4% and 0.5% dosages of Iterlow in base binder, respectively. In this case A, I, R, S indicates WMA modified binders prepared by addition of Asphaltan A, Iterlow, Rediset, and Sasobit in VG30 binder with their respective dosages, respectively. While, PA, PI, PR, PS indicates the WMA modified binders prepared by addition of Asphaltan A, Iterlow, Rediset, and Sasobit in PMB40 binder with their respective dosages, respectively.*

### *7.3.3 Fatigue Life*

Table 7-3 illustrated the combined results of ANOVA at different test conditions. It can be seen that temperature and binder type (WMA modified binders) significantly affects the dependent variable i.e. fatigue life at 2.5% strain level. This can be attributed to the importance of temperature and WMA type in governing the better life of the asphalt binder. Also, dosage has no effect on the fatigue life of the asphalt binder (P value greater than 0.05). As already discussed, this parameter is dependent on the stiffness (elasticity) of binder which is predominantly imparted by binder type and temperatures. For fatigue life, the effect of temperature is more than the binder type owing to the less brittleness of binder with increase in temperature. The 3-way ANOVA showed that the type of WMA additives played important role in enhancing the fatigue life of binder rather than their dosages. This can be attributed to the different stiffness imparted by different WMA additives to base asphalt binders. As discussed earlier, the chemical WMA additives showed higher fatigue life of binder as compared to organic additives, irrespective of type of base binder. This can be due to better flexibility offered by chemical additives to base binders as compared to organic additives. Although production temperatures decreased as additive dosages increased, performance remained pretty consistent. This investigation revealed that the type of WMA additions is more essential than their dosage. This could be because the effect of dosages was less pronounced due to the lower production temperatures. Same observation has also been seen during analysis of rutting parameters. The effect of these parameters can be better understood using main effect plot shown in Figure 7-3. It can be adjudged that the primary factors influencing fatigue life are the temperature and WMA type rather than their dosages.

Table 7-3. Summary of three-way ANOVA at 95% confidence level for fatigue life at 2.5% strain level.

| Parameter | Source | df | Mean Square | F-calculated | P- value |
|---|---|---|---|---|---|
| $N_f$ at 2.5% strain | Temperature | 2 | 63.574 | 45.41 | 0.000008 |
| | Binder Type | 9 | 9.38 | 6.70 | 0.0007 |
| | Dosage | 2 | 1.358 | 0.97 | 0.384 |
| | Error | 64 | 1.4 | | |
| | Total | 77 | | | |

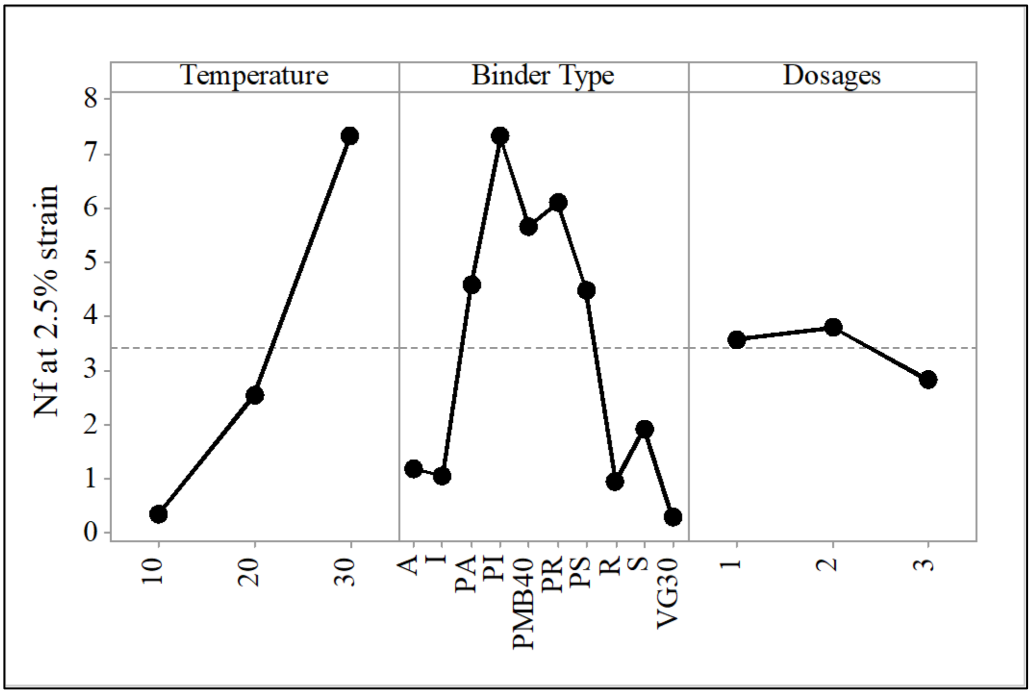



Figure 7-3. Main effect plot for $N_F$ at 2.5% strain level.

*Note: 1,2, and 3 indicates the 1%,2% and 3% dosages of Sasobit and Asphaltan A. In case of chemical additives 1,2, and 3 indicates 0.4%,0.5% and 0.6% dosages of Rediset and 0.3%,0.4% and 0.5% dosages of Iterlow in base binder, respectively. In this case A, I, R, S indicates WMA modified binders prepared by addition of Asphaltan A, Iterlow, Rediset, and Sasobit in VG30 binder with their respective dosages, respectively. While, PA, PI, PR, PS indicates the WMA modified binders prepared by addition of Asphaltan A, Iterlow, Rediset, and Sasobit in PMB40 binder with their respective dosages, respectively.*

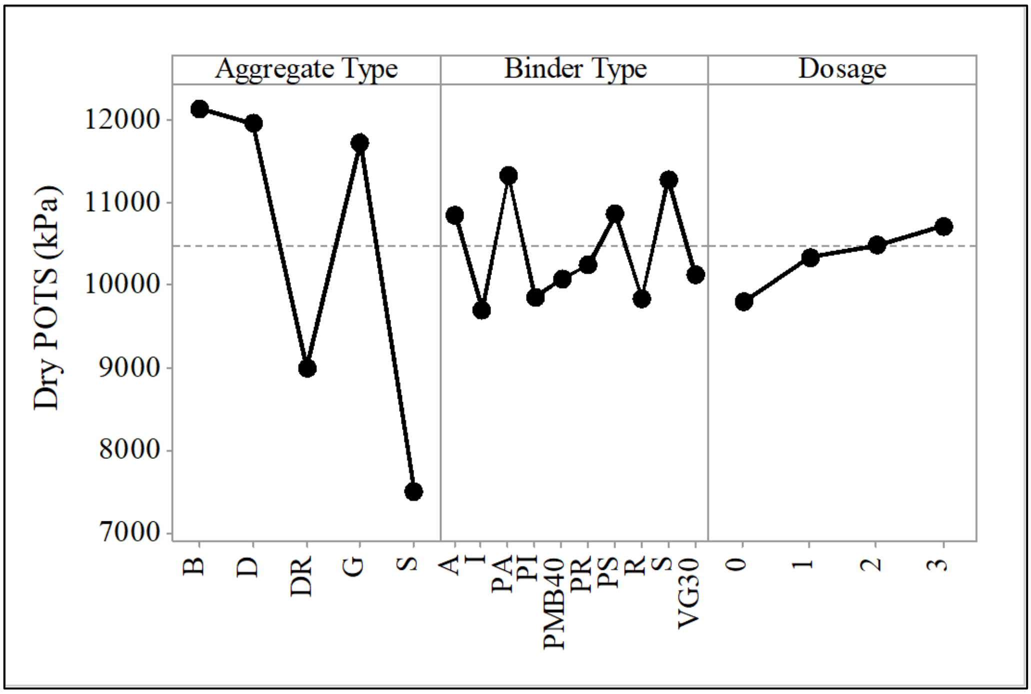
### *7.3.4 Bond Strength Test Parameters (Dry POTS, wet POTS, and BSR)*

Table 7-4 shows the results of the 3-way ANOVA at a confidence level of 95% ($\alpha = 0.05$). The effect of the variables will be considered significant when the p-value is less than 0.05. Based on the results, it can be stated that aggregate type and WMA types significantly influence the POTS and BSR values as p-value<0.05. This shows the importance of these parameters in governing the potential of asphalt mixtures against moisture-induced damage. Attributable to the different mineralogy of the aggregates, aggregate type has the most significant effect compared to other variables. Although WMA additive dosage significantly affects the POTS values, its effect was not very significant in the case of BSR (p-value>0.05) and so the moisture resistance. This agrees with the study conducted by Goh et al. [111], which revealed that WMA additive dosage does not significantly affect the moisture resistance of the asphalt mixtures. To better understand the significance of aggregate type, WM types and their respective dosages on dry POTS, wet POTS, and BSR, the main effect plots were plotted, as shown in Figure 7-4. In dosages, 0 indicates the base binder, whereas 1, 2, and 3 indicate the three different level of WMA additive dosages. The main effect plot showed that the selection of the type of aggregate, base binder, WMA additive and their dosages is of great importance for achieving satisfactory performance against moisture damage.

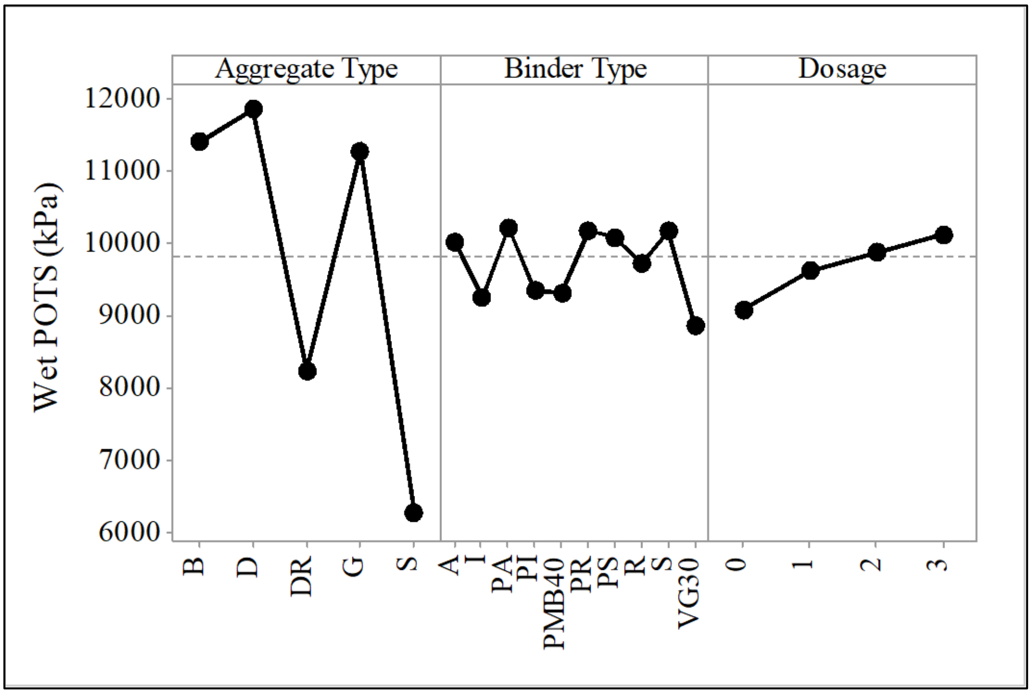
Table 7-4. Summary of three-way ANOVA at 95% confidence level for bond strength parameters.

| **Parameter** | **Source** | **df** | **Mean Square** | **F-calculated** | **P- value** |
|---|---|---|---|---|---|
| Dry POTS | Aggregate Type | 4 | 211323762.830 | 340.876 | 0.0001 |
| | Binder Type | 9 | 10338257.790 | 16.676 | 0.006 |
| | Dosage | 2 | 3637535.796 | 5.868 | 0.004 |
| | Error | 130 | 619943.565 | | |
| | Total | 260 | | | |
| Wet POTS | Aggregate Type | 4 | 287010234.329 | 667.425 | 0.0005 |
| | Binder Type | 9 | 4117751.515 | 9.576 | 0.004 |
| | Dosage | 2 | 5042602.944 | 11.726 | 0.000 |
| | Error | 130 | 430025.917 | | |
| | Total | 260 | | | |
| BSR | Aggregate Type | 4 | 0.180 | 26.115 | 0.0006 |
| | Binder Type | 9 | 0.035 | 5.106 | 0.00044 |

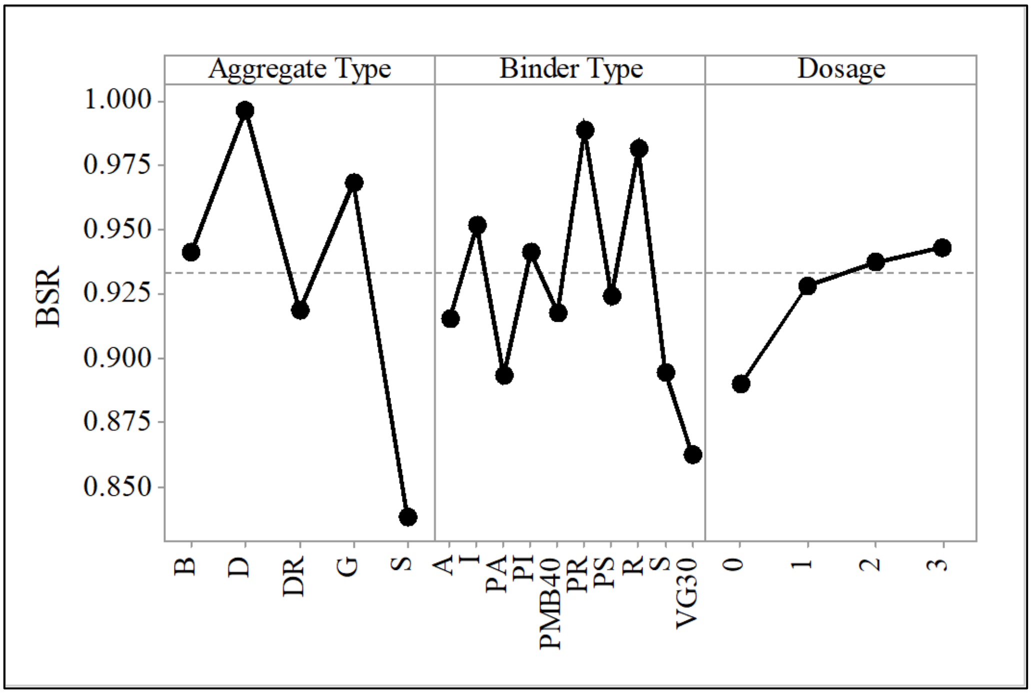
| | | | | | |
|---|---|---|---|---|---|
| | Dosage | 2 | 0.005 | 0.655 | 0.521 |
| | Error | 130 | 0.007 | | |
| | Total | 260 | | | |




(a)




(b)




(c)

Figure 7-4. Main effect plot a) Dry POTS b) Wet POTS c) BSR

*Note: 0,1,2, and 3 indicates the 0%,1%,2% and 3% dosages of Sasobit and Asphaltan A. In case of chemical additives 0,1,2, and 3 indicates 0%,0.4%,0.5% and 0.6% dosages of Rediset and 0%,0.3%,0.4% and 0.5% dosages of Iterlow in base binder, respectively. In this case A, I, R, S indicates WMA modified binders prepared by addition of Asphaltan A, Iterlow, Rediset, and Sasobit in VG30 binder with their respective dosages, respectively. While, PA, PI, PR, PS indicates the WMA modified binders prepared by addition of Asphaltan A, Iterlow, Rediset, and Sasobit in PMB40 binder with their respective dosages, respectively.*

## 7.4 Selection of Optimum Dosage of WMA additives

In this study, ranking methodology has been used to determine the optimum dosages of WMA additives based on their performance parameters. Various performance parameters for each type of distresses have been considered for optimisation the dosages of WMA additives. For rutting, the non-recoverable creep compliance ($J_{nr}$) and % recovery at stress level of 3.2 kPa determined from MSCR test has been considered for ranking analysis. Fatigue life of WMA modified binder at strain level of 2.5% determined from LAS test has been considered for fatigue cracking. The BBS test parameters such as dry POTS and wet POTs values were considered in this study for moisture damage. Along with the performance parameters, the importance is also given to the reduction in MT and CT of WMA modified binders obtained from tribological approach while determining the optimum dosages of WMA additives. While ranking the dosages of additives, performance of WMA and the primary function of WMA additive i.e. reduction in production temperature was considered. It is desirable that the dosage of WMA additive retains superior performance against distresses with maximum temperature reduction. The dosage with these responses can be considered as the best or optimum dosage.

### *7.4.1 Ranking for Optimum Dosage of WMA Additives*

Ranking has been adopted in the study to determine the optimum dosages of WMA additives according to their performance and workability (tribological) characteristics. Ranking was carried out separately for both the base binders. This can be due to their different interaction of WMA additives with viscosity grade binder and polymer modified binder as discussed in previous chapters. This ranking indicates the efficacy of dosages of WMA modified binder based on the average results of all the test conducted in the present study. For 'N' number of dosages of WMA additives subjected to 'T number of tests, obtained values were reported as shown in Table 7-5. The values of the test results are normalized to eradicate the effect of their units. Subsequently, a summation of normalised values for each dosage of WMA additives were taken. The dosage which exhibits higher Σ normalised value is ranked as one. The value of rank ranges from 1 to N as there are 'N' number of combinations where a lower value of rank indicates better results in comparison to other combinations. While ranking the dosages of WMA additives, the equal weightage was given to each performance parameter and reduction in MT and CT. Notably, the dosage with lower rank value indicates better performance relative to other dosages.

Table 7-6 shows the results of performance parameters and reduction in MT and CT for different dosages of Sasobit modified binders. All the performance parameter values were taken as it is as their higher indicate better performace. However, the higher value of $J_{nr}$ showed poor rutting performance. Thus, the inverse of $J_{nr}$ was taken for ranking analysis. The results of these parameters were normalized corresponding to their maximum values to eliminate the effect of their units. Table 7-7 shows the normalised results for various dosages of Sasobit modified binders. After normalisation of results, the summation of normalised values was taken for each dosage of Sasobit. The dosage of Sasobit which showed Σ Normalised value was ranked as one. The summation of normalised value of 4.9 was obtained for 1% of Sasobit where as it increased to 6.1 for 2% of Sasobit. The 3% of Sasobit exhibited higher summation of normalised value i.e., 6.5. Therefore, dose of 3% of Sasobit (S3) was ranked as one as exhibited higher Σ normalised value indicating better performance against all distresses with higher reduction in MT and CT. Similar kind of ranking analysis was performed for different WMA additives for VG30 and PMB40 binder, not shown here for brevity. Table 7-8 shows the optimum dosages of different WMA additives for VG30 and PMB40 binder. It can be observed that the dosages of S3 (of Sasobit), A2 (of Asphaltan A), R0.6 (of Rediset), and I0.4 (of Iterlow) were found to be optimum dosages for VG30 binder. On the other hand, PS2 (of Sasobit), PA2 (of Asphaltan A), PR0.6 (of Rediset), and PI0.5 (of Iterlow) are found to be optimum dosages for PMB40 binder. It can also be observed that the optimum dosage determined from ranking analysis was found to be different for both the base binders. This can be attributed to the different interaction of WMA additives with the viscosity grade binder and polymer modified binder. This implied that the change in type of base binder may change the optimum dosages of WMA additives. Therefore, type of base binder is important while selecting the optimum dosage of WMA additives.

From Table 7-8, it can be observed that the higher dosage of Sasobit i.e., S3 was found to be optimum dosages for VG30 whereas higher dosage of Rediset (R0.6 and PR0.6) and Iterlow (PI0.5) were found to be optimum dosages for PMB40 binder. For different combinations of

WMA additives and base binders, the mid dosages were found to be optimum. As discussed earlier, the S3 was found to be optimum dosage of Sasobit for VG30 binder. There might be chance that the 4% of Sasobit also perform well and will show better rank. To prove this, VG30 binder was modified using 4% of Sasobit. The various performance tests have been performed on this Sasobit modified binder. It was found that the addition of 4% of Sasobit improved the rutting performance of VG30 binder. However, the improvement was found to insignificant when compared with 3% of Sasobit. In this study, it was found that the addition of 4% of Sasobit showed poor performance against fatigue cracking. Figure 7-5 showed that the fatigue life of 4% of Sasobit at 30$^{o}$C determined at 2.5% strain level using LAS test. It can be found that the addition of 4% of Sasobit reduced the fatigue life of the VG30 binder by 47% indicating deterioration of fatigue performance of base binder with this higher content of Sasobit. Also, dry and wet POTS value for 4% of Sasobit were found to be lower than VG30 binder. This can be due to brittle nature of Sasobit modified binder due to higher crystallization effect and higher content of Sasobit. The past studies also showed that the addition of higher content of Sasobit beyond 3% deteriorates the fatigue performance and low temperature cracking performance of binders [49,349,425,448]. The results of the present study were in agreement with past studies. Therefore, the S3 was taken as optimum dosage of Sasobit for VG30. On the other hand, the higher dosage (0.6%) of Rediset was found to be optimum dosages for both the base binder. There might be possibility that the 0.7% of Rediet will perform well and show higher rank. To prove this, VG30 and PMB40 binder was modified using 0.7% of Rediset. The various performance tests have been performed on this Rediset modified binder. It was found that the addition of 0.7% of Rediset improved the fatigue life of both the base binder but rutting performance was found to be very poor. In this study, it was found that the addition of 0.7% of Rediset showed poor performance against rutting for both the base binders. Also, the addition of higher amounts of Rediset to PMB40 will not satisfy the purpose of using a polymer modified binder for improved rutting resistance, as it leads to an increase in $J_{nr}$ values, indicating reduced resistance to rutting. Figure 7-6 showed that the $J_{nr}$ and %R value of 0.7% of Rediset at 60$^{o}$C determined at 3.2kPa using MSCR test. It can be found that the addition of 0.7% of Rediset increased the $J_{nr}$ (reduced rutting performance) of the VG30 binder by 330% whereas it was increased (rutting performance by reduced) approximately by 800% with addition of 0.7% of Rediset to PMB40 as shown in Figure 7-6 (a). The same observations were also made from % recovery parameter as shown Figure 7-6 (b). This indicates the deterioration of rutting performance of base binder with this higher content of Rediset. Although Rediset exhibit anti-stripping properties but the dry and wet POTS values were found to much lower than base binders due to addition of higher dosage of Rediset. This can be attributed to the lowering stiffness of binder due to addition of higher dosages of Rediset. The past studies showed that the addition of higher dosage of Rediset or other chemical WMA additive soften the base binder and deteriorates the rutting performance of base binder [58,449,450]. The results of present study have been agreement with previous studies. The similar kind of observations were obtained for Iterlow WMA additives and results are shown in Figure 7-6. To avoid poor performance against rutting due to higher content (more than manufacturer recommendation) of chemical additives, dosage of Rediset (R0.6 and PR0.6) and Iterlow (PI0.5) were taken as optimum dosages.

Finally, optimum dosages for the VG30 binder were identified as S3 for Sasobit, A2 for Asphaltan A, R0.6 for Rediset, and I0.4 for Iterlow. Similarly, for the PMB40 binder, the optimal dosages were found to be PS2 for Sasobit, PA2 for Asphaltan A, PR0.6 for Rediset, and PI0.5 for Iterlow.

Table 7-5. Ranking methodology

| Adopted Dosages | Tests | | | Normalized Values | | | Σ Normalised Value | Average Ranking |
|---|---|---|---|---|---|---|---|---|
| | $T_1$ | $T_2$ | $T_t$ | $N_{T1}$ | $N_{T2}$ | $N_{Tt}$ | | |
| $D_1$ | $R_{11}$ | $R_{12}$ | $R_{1t}$ | $N_{11}$ | $N_{12}$ | $N_{1t}$ | - | - |
| $D_2$ | $R_{21}$ | $R_{22}$ | $R_{2t}$ | $N_{21}$ | $N_{22}$ | $N_{2t}$ | Max | 1 |
| $D_n$ | $R_{n1}$ | $R_{n2}$ | $R_{nt}$ | $N_{n1}$ | $N_{n2}$ | $N_{nt}$ | - | - |

*Note: T indicates number of tests, N indicates normalised values, R indicates results of the tests, D indicate dosage of WMA additives.*

Table 7-6. Results for different dosages of Sasobit for ranking analysis

| Binder Type | Results | | | | | | |
|---|---|---|---|---|---|---|---|
| | Reduction in MT | Reduction in CT | $1/J_{nr}$ | %R | $NF_{2.5}$ $(\times10^5)$ | Dry POTS | Wet POTS |
| S1 | 11 | 10 | 1.96 | 8.9 | 0.47 | 12.21 | 12.51 |
| S2 | 13 | 14 | 3.05 | 16.1 | 0.517 | 12.82 | 13.03 |
| S3 | 18 | 17 | 3.51 | 19.1 | 0.270 | 14.80 | 13.60 |
| Max | 18 | 17 | 3.515 | 19.120 | 0.518 | 14.80 | 13.60 |

Table 7-7. Normalised values and ranking allocation for different dosages of Sasobit

| Binder Type | Normalised Value | | | | | | | Σ Normalised value | Average ranking |
|---|---|---|---|---|---|---|---|---|---|
| | Reduction in MT | Reduction in CT | $1/J_{nr}$ | %R | $NF_{2.5}$ $(\times10^5)$ | Dry POTS | Wet POTS | | |
| S1 | 0.6 | 0.60 | 0.56 | 0.47 | 0.92 | 0.83 | 0.92 | 4.9 | 3 |
| S2 | 0.74 | 0.81 | 0.87 | 0.84 | 1.00 | 0.87 | 0.96 | 6.1 | 2 |
| S3 | 1 | 1 | 1.00 | 1.00 | 0.52 | 1.00 | 1.00 | 6.5 | 1 |

Table 7-8. Optimum dosage of various WMA additives for VG30 and PMB40 binder.

| Binder Type | WMA Additive | Dosages | Optimum Dose |
|---|---|---|---|
| VG30 | Sasobit | S1, S2, and S3 | S3 |
| | Asphaltan A | A1, A2, and A3 | A2 |
| | Rediset | R0.4, R0.5, and R0.6 | R0.6 |
| | Iterlow | I0.3, I0.4, and I0.5 | I0.4 |
| PMB40 | Sasobit | PS1, PS2, and PS2 | PS2 |
| | Asphaltan A | PA1, PA2, and PA3 | PA2 |
| | Rediset | PR0.4, PR0.5, and PR0.6 | PR0.6 |
| | Iterlow | PI0.3, PI0.4, and PI0.5 | PI0.5 |

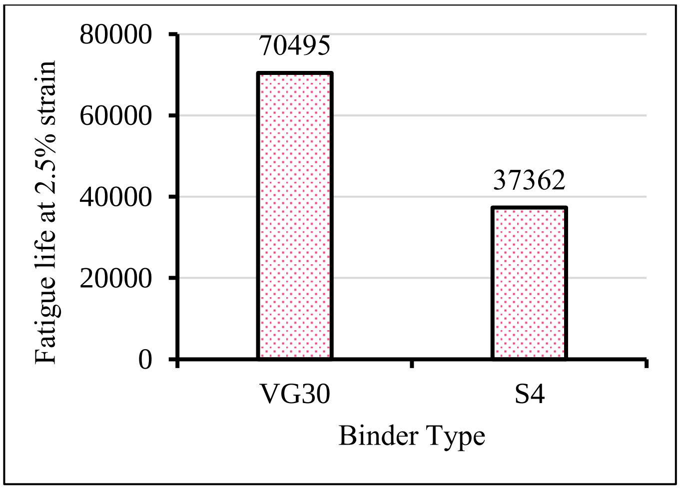
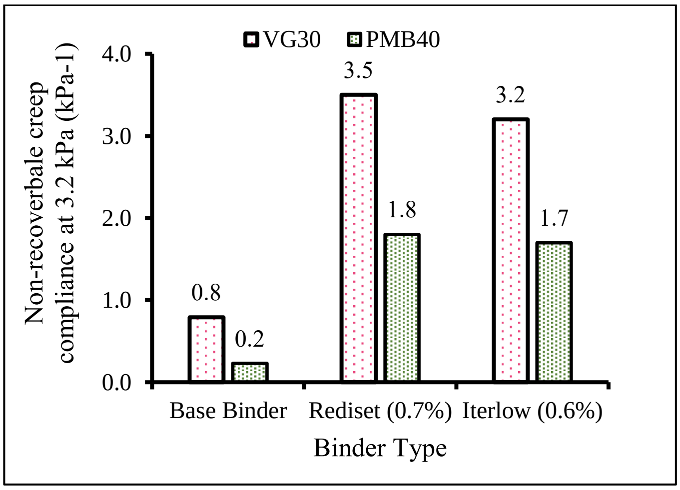
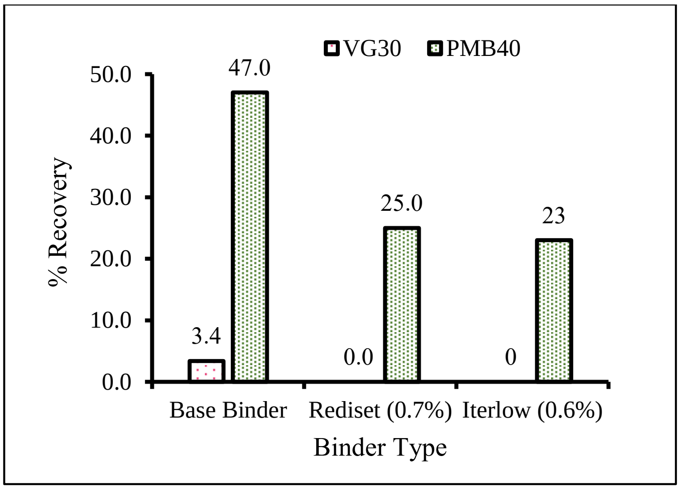



Figure 7-5. Fatigue life comparison for 4% of Sasobit with VG30 binder




(a)




(b)

Figure 7-6. Rutting parameters comparison for 0.7% of Rediset a) $J_{nr}$ b) % R

## 7.5 Selection of WMA Additives

It is imperative that a WMA additive should improve the performance of the binder and mixture against rutting, fatigue cracking, low temperature cracking, and moisture damage compared to a mixture without additive. The selection of a specific WMA additive for a particular location or project should be dictated by conditions such as traffic loading and ambient temperatures [369]. The location is prone to rutting when it has higher traffic loading and ambient temperature exceeds 40$^{o}$C. On the other hand, fatigue cracking is more likely to occur at intermediate temperatures where the binder exhibits a higher stiffness. Moisture damage can be a serious concern at locations where rainfall is high, improper surface drainage, and aggregates used for the construction are highly siliceous in nature. In this study, the warm mix additives were selected based on the performance requirement of the location. From the performance test discussed earlier, it has been found that the performance of the WMA additives is a function of base binders. It can be seen that the effect of WMA modification found to be more prominent with VG30 than PMB40. Therefore, the selection of WMA additive is also greatly influenced by the type of base binder. The different locations according to the predominant distress for selection of WMA additive based on their performance requirement has been discussed in this section. The WMA additive selection framework adopted in this study is based on the assumption that the construction practices followed for the different locations are identical.

### *7.5.1 Location 1 (Prone to Rutting)*

If the location has a higher in-service temperature and is subjected to heavy traffic loading and volume, then rutting is of significant concern. For such locations, organic WMA additives have been suggested as they improved the grade of the base binder (based on high PG) and are suitable for extremely heavy traffic conditions (based on $J_{nr}$ at 3.2 kPa) as discussed in the above-mentioned sections. The use of chemical WMA additives has been recommended for locations when they are combined with polymer modified binders.

### *7.5.2 Location 2 (Prone to Fatigue Cracking)*

If the location has relatively lower in-service temperatures and is subjected to heavy traffic loading and volume, then fatigue cracking should be considered a major distress. In this case, the priority should be given to chemical WMA additives as they showed enough flexibility against cracking at this temperature (based on results of LAS test) discussed in previous sections. Although the Asphaltan A showed enough flexibility (as better or similar failure strain) against cracking, but there is a risk associated with it. Organic additives with higher carbon atoms and melting points should be avoided for fatigue cracking prone areas.

### *7.5.3 Location 3 (Prone to Moisture Damage)*

If the location exhibits higher rainfall, traffic conditions, and use of highly siliceous aggregates, then moisture damage is the severe distress that needs to be addressed. For such locations, both the WMA additives has been suggested based on the bond strength ratio discussed in previous section. The results of BSR also showed that the resistance to moisture damage is a function of aggregate type. Taking aggregate type into consideration, the use of wax type organic additives should be avoided for aggregate containing high silica in their composition. These observations were consistent with the previous literature [416,451,452]. Anti-stripping agents are recommended for wax type organic additives in case of highly siliceous aggregate. Therefore, priority should be given to the chemical WMA additives and amine based organic WMA additives due to their anti-stripping properties resulting from Amine and Silane groups in their structure.

### *7.5.4 Location 4 (Environment Friendly)*

If the location demands lower energy consumption and greenhouse gas (GHG) emission to preserve the environmental aspects, then environmentally friendly candidate can be best suitable choice. Previous literature [113,453] showed that the reduction in production temperature can be used as a tool for environmental assessment. In this study, the reduction in MT and CT determined from workability test was used for the selection of best suitable WMA additive. The results showed that all WMA additives included in this study (as average reduction is around 20$^{o}$C) were appropriate for the such locations having requirement of lower energy consumption and greenhouse gas (GHG) emission.

### *7.5.5 Ranking for Optimum Dosage of WMA Additives*

Ranking has been adopted in the study to rank the WMA additives for their selection corresponding to the types of distress. Ranking was carried out separately for both the base binders. This can be due to their different interaction of WMA additives with viscosity grade binder and polymer modified binder as discussed in previous section. While ranking the additives, performance of WMA and the primary function of WMA additive i.e. reduction in production temperature was considered. It is desirable that the additives retain superior performance against distresses with maximum temperature reduction. The additive with this behavior can be considered as the best additive. Similar ranking framework was adopted in this section as discussed in previous section of this Chapter. The value of rank ranges from 1 to 'n' as there is 'n' different combinations. In general, rank '1' indicates the highest-ranking, whereas rank 'n' implies the lowest rank value.

Better performance of WMA additives against rutting can be ensured by imparting higher stiffness to base binders. To ensure better performance against rutting, the lower value of $J_{nr}$ and higher value of %R is desirable. The performance parameters related with rutting such as $J_{nr}$ at 3.2 kPa and % recovery along with temperature reduction has been considered to rank the binder for rutting. The WMA additives with their optimum dosages have been considered for the ranking analysis. Equal weightage was given to rutting parameters and temperature reduction while ranking the WMA additives for rutting. Table 7-9 shows the results of MSCR test and reduction in MT and CT for different WMA additives added in VG30 binder. In the ranking, all the results of different WMA additives were normalized corresponding to their maximum value. The WMA additives which exhibit higher summation of normalized value was ranked as one. For VG30 binder, the Sasobit of 3% was found to be best suitable additive to perform against rutting by ensuring maximum reduction in MT and CT. Similarly, ranking was performed for WMA additives added in polymer modified binder. The results of ranking are shown in Table 7-10.

Table 7-9. Results of MSCR test and reduction in MT and CT for ranking analysis.

| **Binder Type (VG30)** | **Results** | | | |
|---|---|---|---|---|
| | **Reduction in MT** | **Reduction in CT** | **$J_{nr}$** | **%R** |
| S3 | 17.50 | 16.50 | 3.51 | 19.12 |
| A2 | 15.00 | 14.50 | 2.91 | 15.20 |
| R0.6 | 20.00 | 18.50 | 0.89 | 2.27 |
| I0.4 | 19.50 | 17.50 | 0.96 | 2.59 |
| Max | 20.00 | 18.50 | 3.51 | 19.12 |

Table 7-10. Normalised values and ranking allocation for different WMA additives in VG30

| **Binder Type (VG30)** | **Normalised Value** | | | | **Σ Normalised value** | **Rank** |
|---|---|---|---|---|---|---|
| | **Reduction in MT** | **Reduction in CT** | **$J_{nr}$** | **%R** | | |
| S3 | 0.88 | 0.89 | 1.00 | 1.00 | 3.77 | 1 |
| A2 | 0.75 | 0.78 | 0.83 | 0.79 | 3.16 | 2 |
| R0.6 | 1.00 | 1.00 | 0.25 | 0.12 | 2.33 | 4 |
| I0.4 | 0.98 | 0.95 | 0.27 | 0.14 | 2.37 | 3 |

Similarly, the WMA additives were ranked separately for fatigue cracking, and moisture damage by considering their performance parameters and amount of temperature reduction. Table 7-11 shows the ranking of WMA additives according to the types of distress. It can be seen that for rutting, S3 ranked as 1 when added in VG30 whereas PS2 showed rank 1 when added in PMB40. This can be due to the different interaction of dosages with VG30 and PMB40 which results into different reduction in temperature and improvement in rutting performance due to addition of Sasobit in the base binders. In addition, the dominance of polymeric network of polymer modified binder over the effect of WMA on base binder might be responsible for different ranking. This showed the different interaction of WMA additives with the base binders. It can be seen that the organic additives showed higher ranking when added to VG30. This is attributed to the crystallization effect of these additives. The trend was found to be same when added to PMB40. The chemical additives showed lower ranking likely due to softening point of base binder due to chemical additives. Considering fatigue cracking, chemical WMA additives in comparison to organic WMA additives exhibit superior performance and so showed highest ranking in the ranking analysis, irrespective of base asphalt binder. The superior fatigue performance at intermediate temperature can be due to better flexibility of asphalt binder due to addition of chemical WMA additives. With reference to moisture damage, the additives with Amine and Silane (antistripping properties) in their structure exhibit highest ranking indicating better performance against moisture damage. From the ranking analysis, it can be found that the variation in the rank of WMA additives for both the base binder is attributed to two major reasons: (1) difference in the extent of reduction in production temperatures of asphalt binder with the addition of WMA additives (2) The interaction between asphalt binder and WMA additives. In this study, the purpose of the ranking framework was to prioritize the WMA additives according to requirement of the location or project. The additive with lower ranking does not mean that the additive is poor. It means that the additive should not be prioritize when other better options are available for selection according to the requirement of performance and amount of temperature reduction.

The above suggestions for selecting organic and chemical WMA additives are based on the binder test results. These results will serve as primary guidelines for WMA additives selection. However, it is recommended to perform mixture performance tests for rutting, fatigue cracking and moisture damage to conclude in a more comprehensive way. The WMA additives selection summary is shown in Table 7-11. With above discussion, it can be concluded that the selection of WMA additive is found to be a function of aggregate type and type of base binder used for its modification.

Table 7-11. Selection summary of WMA additives.

| Warm mix additives | | | Selection based on Performance characteristics | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Rutting | | Fatigue | | Moisture damage | |
| | | | Selection | Rank | Selection | Rank | Selection | Rank |
| VG30 | | | | | | | | |
| WMA Additives | Organic | S3 | Yes | 1 | Yes (marginal) | 4 | Yes | 1 |
| | | A2 | Yes | 2 | Yes | 3 | Yes | 2 |
| | Chemical | R0.6 | Yes | 4 | Yes | 1 | Yes | 3 |
| | | I0.4 | Yes | 3 | Yes | 2 | Yes | 4 |
| PMB40 | | | | | | | | |
| WMA Additives | Organic | PS2 | Yes | 1 | Yes | 3 | Yes (for CA)<br>No (for SA)<br>Yes (for SA with AS agent) | 4 |
| | | PA2 | Yes | 2 | Yes (marginal) | 4 | Yes | 1 |
| | Chemical | PR0.6 | Yes | 4 | Yes | 2 | Yes | 2 |
| | | PI0.5 | Yes | 3 | Yes | 1 | Yes | 3 |

*Note: CA and SA are the abbreviations for Calcareous aggregate and Siliceous aggregates. AS is short form of Anti-Stripping.*

## 7.6 Summary

This study aims to optimize and select WMA additives based on the performance requirement of specific locations or projects. It was determined that both the type and dosage of WMA additives significantly influence the performance of base asphalt binders. To evaluate this impact, statistical analysis, specifically analysis of variance (ANOVA), was performed in this chapter. Initially, a three-way ANOVA was conducted to investigate the effects of WMA additives and their dosages on the performance parameters of base asphalt binders. Following this, a ranking methodology was applied to identify the optimal dosage for each additive. The chapter concludes with a straightforward ranking framework to select the most appropriate WMA additive based on the performance requirements of the project or location. This study employs a particular ranking method for evaluating its results. Alternative ranking approaches could be explored to determine the most effective WMA additive according to the performance requirement of a specific location. Key conclusions from this chapter include:

- Results of three-way ANOVA showed that the temperature and WMA type has significant impact on the performance parameters determined from MSCR test and LAS test. However, the effect of dosages on these parameters were found to be insignificant. The analysis indicated that the type of WMA additives is more critical than their dosages. This observation may be attributed to the less pronounced effect of dosages at lower production temperatures.
- Ranking analysis showed that the optimum dosage determined was found to be different for both the base binders. For VG30 as base binder S3, A2, R0.6, and I0.4 are found to be optimum dosages. On the other hand, PS2, PA2, PR0.6, and PI0.5 are found to be optimum dosages for PMB40.
- The selection of WMA additives showed that the organic additives should be prioritize when rutting is primary distress while chemical additives should be prioritized when fatigue cracking is primary distress. For moisture damage, the priority should be given to WMA additive with antistripping properties.