CHAPTER 8

RANKING OF WARM MIX ASPHALT ADDITIVES

8.1 Preface

Warm mix asphalt (WMA) technologies offered similar or even better performance despite being produced at lower production temperatures, as demonstrated in the preceding chapters. The appreciation of WMA technologies, based on different performance tests, was attained at both the asphalt binder and asphalt mixture levels. These tests include the evaluation of performance against different distresses such as rutting, fatigue, and moisture failures. The reduction in energy consumption and corresponding GHG emissions was also assessed. It was identified that the influence of WMA technologies is a function of base asphalt binder, aggregate source, and type of WMA additive, irrespective of the testing scheme. Therefore, choosing the best WMA technology for a given project is not straightforward. The most desirable technology will be the one whose overall performance (considering all critical parameters) is optimum.

This chapter presents a simple ranking framework to select the most suitable (or 'best') WMA additive, relative to other WMA, in terms of different testing aspects. Needless to say, any WMA additive, with any combination of asphalt binder and aggregate, may indicate a different ranking depending on the testing method. For example: if a WMA additive indicates higher performance against moisture damage, it does not necessarily offer similar performance against other mode of distresses (such as rutting or fatigue). In addition, the performance of WMA binders and mixtures, as indicated in previous chapters, was influenced by the change in aggregate source and/or base asphalt binder.

Therefore, the ranking was evaluated for each group (GVG, DVG, GP, and DP), considering the effect of base asphalt binder, aggregate source and optimum dosage of the WMA additive. Following the development of relative rating at each phase (denoted as average rank value (*ARV*)) and for each corresponding combination, all the ranks were summed up to find the global average ranking (*GAR*) [656]. The same approach was applied to rank the WMA additive for each group defined in this study. The methodology followed for assigning rank is explained in subsequent sections.

8.2 Ranking Approach

The ranking approach, as explained below, was followed for each testing phase, and for each group, considering the effect of aggregate source and base asphalt binder. For 'n' number of sample combinations, subjected to 't' number of tests, different results are obtained. These test results are reported in the same format as shown in Table 8.1. C_1, C_2, ..., C_n represents the sample combination (for example, GVG, GS, GSR, GC, and GR for GVG group) and T_1, T_2, ..., T_t indicate the test conducted on the sample (for example, rutting, fatigue, moisture, etc.). Since the sample was ranked based on the performance results, it is essential to normalize the values to a standard scale because all the test results will yield values with different units. Equation 8.1 was used to normalize the obtained results.

$$N = \frac{V - \min(V's)}{\max(V's) - \min(V's)} \qquad (8.1)$$

N denotes the normalized value for the selected test parameter of each test method (rutting, fatigue, moisture, and energy and environment). V in Equation 8.1 indicates the true value of the corresponding parameter obtained from the respective test. min (V's) and max (V's) designates the minima and maxima values among different combinations for a particular test method, respectively. The normalized values were determined for all the parameters obtained from the test methods conducted at each testing phase. This normalization technique yields values from 0 to 1.

Further, a unique rank was assigned corresponding to each combination, based on the magnitude of the normalized value calculated for each test result. The rank for each test and the respective combination is denoted by rank value (RV_{Tt}). The value of rank ranges from 1 to n as there are 'n' different combinations. In general, rank 1 indicates the highest-ranking, whereas rank n implies the lowest rank value. All the ranks are given depending upon the highest and lowest N value. It should be noted that a higher value of result is considered to offer better performance and thereby exhibit the highest rank. For cases where a lower value is desirable, the inverse of the obtained result is reported for that particular test. For example, a lower amount of heat energy is desirable for pavement construction; thus, its inverse value was considered in the ranking analysis. After successful ranking at each test method, all the assigned ranks are summed up corresponding to each combination and are designated by $\Sigma\ RV$. It is expected that the combination with a lower summation value will indicate better performance in comparison to other combinations. Thereafter, the final ranking is allocated from 1 to n depending upon the magnitude of $\Sigma\ RV$, and is signified as 'ARV'. Similarly, ARV was evaluated for each phase and corresponding to each group (GVG, DVG, GP, and DP) considered in the present study.

Table 8.1. Format of the ranking methodology

Combinations		C_1	C_2	C_n
Test Method	$\boldsymbol{T_1}$	V_{11}	V_{21}	V_{n1}
	$\boldsymbol{T_2}$	V_{12}	V_{22}	V_{n2}
	$\boldsymbol{T_t}$	V_{1t}	V_{2t}	V_{nt}

Normalized Values	$\boldsymbol{N_{T1}}$	N_{11}	N_{21}	N_{n1}
	$\boldsymbol{N_{T2}}$	N_{12}	N_{22}	N_{n2}
	$\boldsymbol{N_{Tt}}$	N_{1t}	N_{2t}	N_{nt}
$\boldsymbol{RV_{T1}}$		-	-	-
$\boldsymbol{RV_{T2}}$		-	-	-
$\boldsymbol{RV_{Tt}}$		-	-	-
$\boldsymbol{\Sigma RV}$		-	-	-
ARV		-	-	-

Note: "V_{nt}" represents the value of n^{th} combination for t^{th} test and "N_{nt}" refers to the normalized value of n^{th} combination for t^{th} test.

Since Aspha-Min (Am) was directly added during the production of asphalt mixtures, the rank of Aspha-Min was not included in the ranking of the binder phase. However, the rank of Aspha-Min was included while selecting the optimal or relatively better solution among different asphalt mixtures.

An attempt was made to find the global average ranking (*GAR*) of different WMA combinations for each group. *GAR* is defined as the rank value irrespective of the testing phase and corresponding test methods. The *GAR* ranges from 1 to n as there are n different combinations in a particular group. The combination with *GAR* 1 indicates superior performance/highest ranking than the combination with *GAR* n. Since the rank of Aspha-Min was not established at the binder phase, the analysis of *GAR* was done after neglecting the assigned rank of Aspha-Min in the mixture phase. Therefore, a new table (Table 8.2) was generated showing the *RV's* of different combinations (without Aspha-Min) at both binder and mixture phases. Again, the *ARV*, for a particular test (rutting, fatigue, and moisture), was calculated for each group. This was done to assess the rank of different combinations with respect to a particular performance, irrespective of the results obtained at the binders and mixture phase.

It should be noted that *Σ RV* and *ARV* corresponding to energy requirement and environmental burdens (E&E) were not calculated separately, because the value of E&E was equal for both binders and mixture phase. Thus, for calculating *Σ ARV*, the value of *RV* was taken into consideration. This is applicable only while accounting E&E into the ranking analysis. The calculated *ARV* for rutting, fatigue, and moisture, along with the *ARV* of energy and environmental aspects were further summed up corresponding to each combination (*Σ ARV*). Thus, depending on the magnitude of *Σ ARV*, the global average ranking (*GAR*) of different combinations was established. It should be noted that the ranking of the selected combinations, irrespective of the aggregate source and base asphalt binder, was not established because the optimum dosage of WMA additives is different for each group. Hence, it will not be appropriate/logical to rank the asphalt binders and mixtures, prepared with different optimum dosages, at the same scale.

Table 8.2. Format for global average ranking

Combinations		C_1	C_2	C_n
Binder Phase	**Rutting**	RV_{b1R}	RV_{b2R}	RV_{bnR}
	Fatigue	RV_{b1F}	RV_{b2F}	RV_{bnF}
	Moisture	RV_{b1M}	RV_{b2M}	RV_{bnM}
Mixture Phase	**Rutting**	RV_{m1R}	RV_{m2R}	RV_{mnR}
	Fatigue	RV_{m1F}	RV_{m2F}	RV_{mnF}
	Moisture	RV_{m1M}	RV_{m2M}	RV_{mnM}
$\Sigma RV_{Rutting}$		-	-	-
$\Sigma RV_{Fatigue}$		-	-	-
$\Sigma RV_{Moisture}$		-	-	-

$ARV_{Rutting}$	-	-	-
$ARV_{Fatigue}$	-	-	-
$ARV_{Moisture}$	-	-	-
Energy and Environment	$RV_{1E\&E}$	$RV_{2E\&E}$	$RV_{nE\&E}$
Σ ARV	-	-	-
Global Average Ranking (GAR)	-	-	-

Note: RV_{bnR}, RV_{bnF}, and RV_{bnM} denote the ranking value of n^{th} combination for rutting, fatigue, and moisture test, respectively, at the binder phase. RV_{mnR}, RV_{mnF}, and RV_{mnM} refer to the ranking value of n^{th} combination for rutting, fatigue, and moisture test, respectively, at the mixture phase. $RV_{nE\&E}$ indicates the ranking value of n^{th} combination based on energy and environmental aspects.

8.3 Results and Discussion

Different test parameters at each testing phase (asphalt binders and mixtures), as illustrated in Table 8.3, were selected to rank WMA additives. Initially, the original results were reported for all the tests conducted to check the effectiveness of WMA additives. It was found that the higher values of all the test parameters, for any asphalt binder or mixture, indicate better performance, except the heat energy requirement. In general, a lower amount of heat energy is desirable for relating the importance/function of WMA additives in pavement construction. Thus, the inverse value of required heat energy was reported in-place of original results.

Table 8.3. Selected test parameters for ranking

Testing phase	**Test Parameter**			
	Rutting	**Fatigue**	**Moisture**	**Energy and Environment**

Asphalt Binder	Rutting Parameter	Fatigue life (N_F) at 10% Strain	Bond Strength Ratio	Heat Energy
Asphalt Mixture	Creep Modulus	Fatigue Index	Tensile Strength Ratio	

Note: Rutting parameter and creep modulus are in kPa.kJ/mol and MPa, respectively. The unit of fatigue life and fatigue index are number of cycles and J/m^2/kN, respectively. BSR and TSR are in percentage, whereas heat energy is in Joules.

Table 8.4 to Table 8.7 presents the test results obtained at the binder testing phase for different groups (GVG, DVG, GP, DP) defined in this study. The respective normalized and rank values for different combinations are also reported in Table 8.4 to Table 8.7. While comparing different WMA additives, it was found that the use of Rediset with both VG30 and PMB40 exhibited highest-ranking, except in GVG group where Sasobit Redux (1st place) outperformed. The combination of Sasobit showed the lowest rank in all the groups, except in DVG group where the addition of Cecabase indicated the worst performance, among other WMA additives. The ranking protocol indicated that the performance of organic-based additives (4th place) in GP and DP group was lower than PMB40 (3rd place). On the other hand, it was found that the rank of all the WMA binders (prepared with VG30) is superior than VG30 (5th place). This indicated that the influence of WMA additives on the performance of asphalt binder is highly dependent on the type of base asphalt binder.

Table 8.4. Asphalt binder testing results and corresponding normalized and rank values for GVG group

Combinations		**GVG**	**GS**	**GSR**	**GC**	**GR**
Test Method	**Rutting**	236.68	896.16	237.24	227.18	246.48
	Fatigue	11.59	10.47	28.81	45.12	27.99
	Moisture	90.47	89.41	95.15	97.54	99.87

	Energy and Environment	5.64E-09	6.20E-09	6.28E-09	6.17E-09	5.97E-09
Normalized Values	$N_{Rutting}$	0.01	1.00	0.02	0.00	0.03
	$N_{Fatigue}$	0.03	0.00	0.53	1.00	0.51
	$N_{Moisture}$	0.10	0.00	0.55	0.78	1.00
	$N_{Energy\ and\ Environment}$	0.00	0.88	1.00	0.83	0.51
$RV_{Rutting}$		4	1	3	5	2
$RV_{Fatigue}$		4	5	2	1	3
$RV_{Moisture}$		4	5	3	2	1
$RV_{Energy\ and\ Environment}$		5	2	1	3	4
$\Sigma\ RV$		17	13	9	11	10
ARV		**5**	**4**	**1**	**3**	**2**

Table 8.5. Asphalt binder testing results and corresponding normalized and rank values for DVG group

Combinations		**DVG**	**DS**	**DSR**	**DC**	**DR**
Test Method	**Rutting**	236.68	1787.16	237.24	225.74	277.37
	Fatigue	11.59	38.51	28.81	39.80	97.26
	Moisture	92.12	93.87	98.19	97.33	111.15
	Energy and Environment	5.45E-09	5.93E-09	6.08E-09	5.93E-09	6.10E-09
Normalized Values	$N_{Rutting}$	0.01	1.00	0.01	0.00	0.03
	$N_{Fatigue}$	0.00	0.31	0.20	0.33	1.00
	$N_{Moisture}$	0.00	0.09	0.32	0.27	1.00
	$N_{Energy\ and\ Environment}$	0.00	0.74	0.97	0.73	1.00
$RV_{Rutting}$		4	1	3	5	2
$RV_{Fatigue}$		5	3	4	2	1
$RV_{Moisture}$		5	4	2	3	1
$RV_{Energy\ and\ Environment}$		5	3	2	4	1
$\Sigma\ RV$		19	11	11	14	5

ARV	**5**	**2**	**2**	**4**	**1**

Table 8.6. Asphalt binder testing results and corresponding normalized and rank values for GP group

Combinations		**GP**	**GPS**	**GPSR**	**GPC**	**GPR**
Test Method	**Rutting**	3657.40	2619.21	1174.60	2049.67	2182.79
	Fatigue	167.91	61.88	69.75	683.09	118.78
	Moisture	92.79	94.81	96.45	97.74	105.72
	Energy and Environment	5.28E-09	5.65E-09	5.78E-09	5.97E-09	6.04E-09
Normalized Values	$N_{Rutting}$	1.00	0.58	0.00	0.35	0.41
	$N_{Fatigue}$	0.17	0.00	0.01	1.00	0.09
	$N_{Moisture}$	0.00	0.16	0.28	0.38	1.00
	$N_{Energy\ and\ Environment}$	0.00	0.48	0.66	0.91	1.00
$RV_{Rutting}$		1	2	5	4	3
$RV_{Fatigue}$		2	5	4	1	3
$RV_{Moisture}$		5	4	3	2	1
$RV_{Energy\ and\ Environment}$		5	4	3	2	1
$\Sigma\ RV$		13	15	15	9	8
ARV		**3**	**4**	**4**	**2**	**1**

Table 8.7. Asphalt binder testing results and corresponding normalized and rank values for DP group

Combinations		**DP**	**DPS**	**DPSR**	**DPC**	**DPR**
Test Method	**Rutting**	3657.40	2619.21	1174.60	2049.67	2182.79
	Fatigue	167.91	61.88	69.75	683.09	118.78
	Moisture	92.79	94.81	96.45	97.74	105.72
	Energy and Environment	5.11E-09	5.42E-09	5.47E-09	5.47E-09	5.53E-09

Normalized Values	$N_{Rutting}$	1.00	0.58	0.00	0.35	0.41
	$N_{Fatigue}$	0.17	0.00	0.01	1.00	0.09
	$N_{Moisture}$	0.00	0.16	0.28	0.38	1.00
	$N_{Energy\ and\ Environment}$	0.00	0.74	0.85	0.86	1.00
$RV_{Rutting}$		1	2	5	4	3
$RV_{Fatigue}$		2	5	4	1	3
$RV_{Moisture}$		5	4	3	2	1
$RV_{Energy\ and\ Environment}$		5	4	3	2	1
$\Sigma\ RV$		13	15	15	9	8
ARV		**3**	**4**	**4**	**2**	**1**

Table 8.8 to Table 8.11 presents the obtained results, normalized values and corresponding ranking of WMA additives based on the performance of asphalt mixtures prepared with different combinations of base asphalt binder, aggregate type, and WMA technologies. Irrespective of any base asphalt binder, WMA mixtures produced by incorporating Aspha-Min, in combination with granite aggregates, showed the worst performance (6th place). On the other hand, the *ARV* of Aspha-Min with dolomite-based asphalt mixtures (3rd place) was found to be better than the corresponding asphalt mixtures prepared with VG30 or PMB40 without any WMA additives (DVG and DP). The variation in ranking with change in the aggregate source is attributed to the difference in the compatibility of Aspha-Min with different aggregate types. A similar kind of variation was observed with the change in base asphalt binder for other WMA additives. GSR, DR, GPR, DPC displayed the highest ranking in their groups i.e., GVG, DVG, GP, and DP respectively. On an average, organic-based WMA additives indicated superior ranking in asphalt mixtures prepared with VG30, whereas the

chemical-based agents outperformed in polymer-modified asphalt mixtures. This is attributed to the change in the interaction between the WMA additives and base asphalt binders. This variation in ranking is independent of the aggregate source. The addition of any WMA additive in VG30 or PMB40 with dolomite aggregates showed an improved ranking, in comparison to the corresponding asphalt mixtures prepared without any WMA additive (6^{th} place). The average ranking analysis signified that the change in the ranking of WMA additives is a function of base asphalt binder as well as aggregate source.

Table 8.8. Asphalt mixture testing results and corresponding normalized and rank values for GVG group

Combinations		**GVG**	**GS**	**GSR**	**GC**	**GR**	**GAm**
Test Method	**Rutting**	6.31	14.23	4.20	3.25	2.91	2.90
	Fatigue	396.00	318.00	480.00	446.00	481.00	462.00
	Moisture	91.92	92.70	92.18	98.82	98.19	88.55
	Energy and Environment	5.64E-09	6.20E-09	6.28E-09	6.17E-09	5.97E-09	6.17E-09
Normalized Values	$N_{Rutting}$	0.30	1.00	0.12	0.03	0.00	0.00
	$N_{Fatigue}$	0.48	0.00	0.99	0.79	1.00	0.88
	$N_{Moisture}$	0.33	0.40	0.35	1.00	0.94	0.00
	$N_{Energy\ and\ Environment}$	0.00	0.88	1.00	0.83	0.51	0.83
$RV_{Rutting}$		2	1	3	4	5	6
$RV_{Fatigue}$		5	6	2	4	1	3
$RV_{Moisture}$		5	3	4	1	2	6
$RV_{Energy\ and\ Environment}$		6	2	1	3	5	4

Σ RV	18	12	10	12	13	19
ARV	**5**	**2**	**1**	**2**	**4**	**6**

Table 8.9. Asphalt mixture testing results and corresponding normalized and rank values for DVG group

Combinations		**DVG**	**DS**	**DSR**	**DC**	**DR**	**DAm**
Test Method	**Rutting**	8.41	12.11	9.89	4.46	5.35	6.33
	Fatigue	395.00	405.00	419.00	507.00	600.00	420.00
	Moisture	92.35	92.85	95.17	99.02	98.26	92.42
	Energy and Environment	5.45E-09	5.93E-09	6.08E-09	5.93E-09	6.10E-09	6.26E-09
Normalized Values	$N_{Rutting}$	0.52	1.00	0.71	0.00	0.12	0.24
	$N_{Fatigue}$	0.00	0.05	0.12	0.55	1.00	0.12
	$N_{Moisture}$	0.00	0.07	0.42	1.00	0.89	0.01
	$N_{Energy\ and\ Environment}$	0.00	0.60	0.78	0.59	0.80	1.00
$RV_{Rutting}$		3	1	2	6	5	4
$RV_{Fatigue}$		6	5	4	2	1	3
$RV_{Moisture}$		6	4	3	1	2	5
$RV_{Energy\ and\ Environment}$		6	4	3	5	2	1
Σ RV		21	14	12	14	10	13
ARV		**6**	**4**	**2**	**4**	**1**	**3**

Table 8.10. Asphalt mixture testing results and corresponding normalized and rank values for GP group

Combinations		GP	GPS	GPSR	GPC	GPR	GPAm
Test Method	**Rutting**	11.62	12.70	11.11	10.56	12.14	11.51
	Fatigue	575.00	524.00	523.00	611.00	558.00	499.00
	Moisture	92.68	96.32	96.71	99.59	99.45	91.12
	Energy and Environment	5.28E-09	5.65E-09	5.78E-09	5.97E-09	6.04E-09	5.83E-09
Normalized Values	$N_{Rutting}$	0.50	1.00	0.26	0.00	0.74	0.45
	$N_{Fatigue}$	0.68	0.22	0.21	1.00	0.53	0.00
	$N_{Moisture}$	0.18	0.61	0.66	1.00	0.98	0.00
	$N_{Energy\ and\ Environment}$	0.00	0.48	0.66	0.91	1.00	0.73
$RV_{Rutting}$		3	1	5	6	2	4
$RV_{Fatigue}$		2	4	5	1	3	6
$RV_{Moisture}$		5	4	3	1	2	6
$RV_{Energy\ and\ Environment}$		6	5	4	2	1	3
$\Sigma\ RV$		16	14	17	10	8	19
ARV		**4**	**3**	**5**	**2**	**1**	**6**

Table 8.11. Asphalt mixture testing results and corresponding normalized and rank values for DP group

Combinations		DP	DPS	DPSR	DPC	DPR	DPAm
Test Method	**Rutting**	15.64	14.30	9.02	12.50	10.61	14.42
	Fatigue	502.00	564.00	615.00	676.00	587.00	500.00
	Moisture	94.31	95.61	96.82	99.78	100.33	95.25

	Energy and Environment	5.11E-09	5.42E-09	5.47E-09	5.47E-09	5.53E-09	5.53E-09
Normalized Values	$N_{Rutting}$	1.00	0.80	0.00	0.53	0.24	0.82
	$N_{Fatigue}$	0.01	0.36	0.65	1.00	0.49	0.00
	$N_{Moisture}$	0.00	0.22	0.42	0.91	1.00	0.16
	$N_{Energy\ and\ Environment}$	0.00	0.74	0.85	0.85	1.00	1.00
$RV_{Rutting}$		1	3	6	4	5	2
$RV_{Fatigue}$		5	4	2	1	3	6
$RV_{Moisture}$		6	4	3	2	1	5
$RV_{Energy\ and\ Environment}$		6	5	4	3	2	1
$\Sigma\ RV$		18	16	15	10	11	14
ARV		**6**	**5**	**4**	**1**	**2**	**3**

The rank value for different combinations of WMA additives, asphalt binders, and aggregate sources corresponding to different aspects such as rutting, fatigue, moisture, and energy and environmental burdens are shown in Table 8.12 to Table 8.15. As expected, the rank value of organic-based WMA additive, such as Sasobit, exhibited the highest rank against rutting distress, as compared to other WMA additives. This is attributed to the crystallization effect of Sasobit at temperatures lower than their melting point. This behavior was found to be consistent in all the defined groups (GVG, DVG, GP, and DP). Considering fatigue and moisture damage, chemical-based WMA agents (Cecabase and Rediset), in comparison to other WMA additives, reflect superior performance and so the top ranking in the ranking analysis, irrespective of base asphalt binder and aggregate source. The reason behind the increased moisture resistance is the antistripping characteristics of chemical-based WMA agents. Based on the energy and environmental aspects, it was identified that all the WMA additives necessitate lower energy for the production of asphalt mixtures and thus emit lower GHG emissions, indicating lower environmental burdens. This is the main purpose of adding/adopting WMA technologies for the construction of asphalt pavements. The variation in the rank of WMA additives for E&E category is attributed to two major reasons: (1) difference in the extent of reduction in production temperatures of asphalt mixtures with the addition of WMA additives (2) The interaction/compatibility between asphalt binder, aggregate source, and WMA additives. For example: The highest rank (1^{st} place) in GVG group was imparted by the inclusion of Sasobit Redux, whereas its rank shifted to a lower place in the case of DVG, GP and DP groups. In line with the same context, Rediset was found to be the top-ranked WMA additive for DVG, GP and DP groups, as per the ranking analysis demonstrated in Table 8.12 to Table 8.15.

Although the above discussion on ranking level gives an indication of relatively best WMA additive based on a particular performance or a particular testing phase, it is more logical to identify the overall rank considering all the test parameters. This was done by calculating *GAR* for different combinations of aggregates, asphalt binder, and WMA additives, as reported in the last row of Table 8.12 to Table 8.15. *GAR* analysis revealed that the ranking of WMA additives alters with the change in aggregate source or base asphalt binder, for example: Sasobit Redux resulted in highest global average ranking *(GAR = 1)* in GVG group, whereas the highest ranking in DVG, GP, and DP group was attained by Rediset. Notably, the *GAR* of organic-based WMA additives was found either the same or superior in the case of groups where the base asphalt binder is PMB40 (GP and DP). Different WMA additives perform differently based on their working mechanism, thus there is a variation in their rank values. However, none of the WMA combinations, within any group, indicated lower ranking (as shown by *GAR)* in comparison to the combinations prepared without any WMA additive. Based on the overall analysis, it can be stated that the application of WMA technologies will certainly facilitate sustainable and resilient infrastructure development by imparting technical, social and environmental benefits.

Table 8.12. Global average ranking for GVG group

Combinations		GVG	GS	GSR	GC	GR
Binder Phase	**Rutting**	4	1	3	5	2
	Fatigue	4	5	2	1	3
	Moisture	4	5	3	2	1
Mixture Phase	**Rutting**	2	1	3	4	5
	Fatigue	4	5	2	3	1
	Moisture	5	3	4	1	2
$\Sigma\, RV_{Rutting}$		6	2	6	9	7
$\Sigma\, RV_{Fatigue}$		8	10	4	4	4
$\Sigma\, RV_{Moisture}$		9	8	7	3	3
$ARV_{Rutting}$		2	1	2	5	4
$ARV_{Fatigue}$		4	5	1	1	1
$ARV_{Moisture}$		5	4	3	1	1
Energy and Environment (RV/ ARV)		5	2	1	3	4
$\Sigma\, ARV$		16	12	7	10	10
Global Average Ranking (GAR)		**5**	**4**	**1**	**2**	**2**

Table 8.13. Global average ranking for DVG group

Combinations		DVG	DS	DSR	DC	DR
Binder Phase	**Rutting**	4	1	3	5	2
	Fatigue	5	3	4	2	1
	Moisture	5	4	2	3	1
Mixture Phase	**Rutting**	3	1	2	5	4
	Fatigue	5	4	3	2	1
	Moisture	5	4	3	1	2
$\Sigma\, RV_{Rutting}$		7	2	5	10	6
$\Sigma\, RV_{Fatigue}$		10	7	7	4	2
$\Sigma\, RV_{Moisture}$		10	8	5	4	3
$ARV_{Rutting}$		4	1	2	5	3
$ARV_{Fatigue}$		5	3	3	2	1
$ARV_{Moisture}$		5	4	3	2	1
Energy and Environment (RV/ ARV)		5	3	2	4	1
$\Sigma\, ARV$		19	11	10	13	6
Global Average Ranking (GAR)		**5**	**3**	**2**	**4**	**1**

Table 8.14. Global average ranking for GP group

Combinations		GP	GPS	GPSR	GPC	GPR
Binder Phase	**Rutting**	1	2	5	4	3
	Fatigue	2	5	4	1	3
	Moisture	5	4	3	2	1
	Rutting	3	1	4	5	2

Mixture Phase	**Fatigue**	2	4	5	1	3
	Moisture	5	4	3	1	2
$\Sigma\, RV_{Rutting}$		4	3	9	9	5
$\Sigma\, RV_{Fatigue}$		4	9	9	2	6
$\Sigma\, RV_{Moisture}$		10	8	6	3	3
$ARV_{Rutting}$		2	1	4	4	3
$ARV_{Fatigue}$		2	4	4	1	3
$ARV_{Moisture}$		5	4	3	1	1
Energy and Environment (RV/ ARV)		5	4	3	2	1
$\Sigma\, ARV$		14	13	14	8	8
Global Average Ranking (GAR)		**4**	**3**	**4**	**1**	**1**

Table 8.15. Global average ranking for DP group

Combinations		**DP**	**DPS**	**DPSR**	**DPC**	**DPR**
Binder Phase	**Rutting**	1	2	5	4	3
	Fatigue	2	5	4	1	3
	Moisture	5	4	3	2	1
Mixture Phase	**Rutting**	1	2	5	3	4
	Fatigue	5	4	2	1	3
	Moisture	5	4	3	2	1
$\Sigma\, RV_{Rutting}$		2	4	10	7	7
$\Sigma\, RV_{Fatigue}$		7	9	6	2	6
$\Sigma\, RV_{Moisture}$		10	8	6	4	2
$ARV_{Rutting}$		1	2	5	3	3

$ARV_{Fatigue}$	4	5	2	1	2
$ARV_{Moisture}$	5	4	3	2	1
Energy and Environment (RV/ ARV)	5	4	3	2	1
Σ ***ARV***	15	15	13	8	7
Global Average Ranking (GAR)	**4**	**4**	**3**	**2**	**1**

8.4 Summary

This chapter deals with the ranking of WMA additives based on a simple ranking approach. Overall, using the mentioned procedure, the best WMA additives for a particular type of base asphalt binder and aggregate source can be assessed. It should be noted that this is a specific ranking procedure applied to the results obtained in this study. It is possible to develop alternate ranking procedures for finding the optimal combinations of WMA additives, base asphalt binder and aggregate source.

The following are the key conclusions from this chapter:

- Based on the ranking at asphalt binder phase, the use of Rediset with both VG30 and PMB40 showed highest-ranking, except in GVG group. The combination of Sasobit exhibited the inferior rank in all the groups, except in DVG group where the addition of Cecabase indicated the worst performance, among other WMA additives. The relative rank of organic-based additives in PMB40 was lower than the rank assigned for PMB40 without any WMA additive.
- The ranking analysis at mixtures phase indicated that organic-based WMA additives exhibited superior rank in asphalt mixtures prepared with VG30, whereas the chemical-based agents outperformed in polymer-modified asphalt mixtures. The addition of any WMA additive in VG30 or PMB40 with dolomite aggregates

showed improved performance. On the other hand, no specific trend was observed between the rank of WMA mixtures prepared with granite aggregates. Aspha-Min, which is a foaming-based WMA additive, attained the lowest ranking in combination with granite aggregates, irrespective of base asphalt binder.

- Comparing WMA additives, Sasobit, an organic-base WMA additive, exhibited highest-ranking against rutting distress, whereas chemical agents, such as Cecabase and Rediset, indicate superior performance against fatigue and moisture damage, irrespective of any group. The addition of WMA additives with any combination of asphalt binder and aggregate resulted in lower energy consumption and corresponding GHG emissions than the base asphalt mixtures (GVG, DVG, GP, and DP).
- *GAR* revealed that all the WMA combinations, within any group, showed either similar/improved performance and so the same/highest ranking than the combinations prepared without any WMA additive. The change in *GAR* is highly dependent on the type of base asphalt binder and aggregate source. Considering different aspects at binders and mixtures phase, higher global average ranking (*GAR)* for WMA gives an eminent support for the application of WMA technologies in pavement construction.