CHAPTER 8:
STRUCTURAL DESIGN AND COST COMPARISON OF RIGID PAVEMENT

8.1 GENERAL

In this study, the emphasis was laid on producing dense concrete of better mechanical and durability properties. The main goal of the present work was to study the utility of RSA and MS as a cementitious material and was an attempt to address the strength and durability aspect of M40 grade PQC using low cost and abundantly available mineral admixture like rice straw ash. Although, works related to admixing of mineral admixtures in concrete have been conducted for a long time, the present work dealt with the formulation of new cementitious materials containing a composite of rice straw ash and microsilica.

Based on the test results in the preceding chapters, concrete of five mixes, namely R0, R10, M7.5, R5M7.5 and R10M7.5, were chosen for further analysis. R0 was selected because it was the control mix and was considered as a baseline for comparing the improvement in the properties of concrete due to admixing of RSA and MS in various proportions. R10 was chosen because it was the only concrete mix containing RSA as a mineral admixture. M7.5 was selected because it had the maximum strength amongst all the concrete mixes. R5M7.5 was chosen because it had the maximum strength amongst the concrete mixes containing composite of RSA and MS while R10M7.5 was chosen because of maximum replacement level of OPC and also because the improvement in the durability properties of concrete of mix R10M7.5 (w.r.t R0) was found to be maximum. The structural design of rigid pavement containing concrete of these 5 mixes was done based on the IRC 58 (2015) [250]. Based on the results of structural design, the cost of these concrete mixes for constructing 1 km of national highway (divided, 2 lanes, one way) was compared.

8.2 STRUCTURAL DESIGN

As per IRC 58 [250], following parameters were assumed:

1. Lane width = 3.5 m, Transverse joint spacing = 4.5 m
2. Tied concrete shoulders and transverse joints with dowel bars
3. Design life = n = 35 years
4. Total two-way commercial vehicles per day (cvpd) in the year of completion of construction = A = 6000
5. Average annual growth rate of traffic = r = 0.075 (7.5%)
6. Average number of axles per commercial vehicle = N = 2.5
7. Lateral placement factor = L = 0.125

Based on above assumptions, following forecasting was done to reckon design traffic:

- Total number of commercial vehicles during design period (two-way) = V = $\frac{365 \times A \times ((1+r)^n - 1)}{r}$ = 337,811,016
- Total two-way axle load repetitions during the design period = A_t = $N \times V$ = 844,527,540
- Design traffic after adjusting for lateral placement of axles = A_d = $L \times A_t$= 105,565,943
- Night time (12 hours) design axle repetitions (with the assumption that 60% of total traffic in terms of number of axles is during night time) = A_{ni} = $0.6 \times A_d$ = 63,339,566
- Day time (12 hours) design axle repetitions (with the assumption that 40% of total traffic in terms of number of axles is during day time) = A_{da} = $0.4 \times A_d$ = 42,226,377

- Design number of axle load repetitions for Top-Down Cracking (TDC) analysis = Night time (6 hours) axle load repetitions (with the assumption that 55% of total commercial vehicles have wheel base < 4.5 m) = $A_{TDC} = A_{ni} * 0.5 \times 0.55$ = 17,418,380
- Design number of axle load repetitions for Bottom-Up Cracking (BUC) analysis = Day time (6 hours) axle load repetitions = A_{BUC} = $A_{da} \times 0.5$ = 21,113,188

Table 8.1 Category-wise design axle load repetitions for fatigue analysis

Axle Category	**Proportion (assumed)**	**Design Axle Load Repetitions for**	
		BUC analysis (A_{BUC}×proportion)	**TDC analysis (A_{TDC}×proportion)**
Front Single (steering)	0.45	9,500,935	7,838,271
Rear Single	0.15	3,166,978	2,612,757
Tandem	0.25	5,278,297	4,354,595
Tridem	0.15	3,166,978	2,612,757
Total	**1.00**	**A_{BUC} = 21,113,188**	**A_{TDC} = 17,418,380**

Table 8.2 shows the proportion of cementitious materials and HRWR dosage of concrete of mix R0, R10, M7.5, R5M7.5 and R10M7.5. It also gives the elastic modulus (E), Poisson's ratio (μ), unit weight (w), radius of relative stiffness (l) and 28 days flexural strength of these concrete mixes. The elastic modulus was calculated by the static uniaxial compressive test.

Table 8.2 Pavement structural details for different concrete mix

Concrete Mix		**R0**	**R10**	**M7.5**	**R5M7.5**	**R10M7.5**
Mix Proportion (% by wt.)	OPC	100	90	92.5	87.5	82.5
	RSA	-	10	-	5	10
	MS	-	-	7.5	7.5	7.5
HRWR Dosage (% by wt of total binder content)		0.4	1.5	1.2	2	2.5
28 days Design Flexural Strength ('f_r', in MPa)		5.62	5.65	6.5	6.07	5.7
Modulus of Elasticity ('E', in MPa)		31100	37923	40527	39715	38055
Poisson's Ratio ('μ')		0.1834	.1798	.1677	.1679	.1688
Unit Weight ('w', in KN/m^3)		24.31	24.35	24.34	24.37	24.39
Radius of Relative Stiffness ('l', in m)	k_e = 208 MPa/m	1.95h^3	1.95h^3	1.98h^3	1.97h^3	1.95h^3
	k_e = 278 MPa/m	1.81h^3	1.82h^3	1.84h^3	1.84h^3	1.81h^3
	k_e = 300 MPa/m	1.78h^3	1.78h^3	1.81h^3	1.8h^3	1.78h^3

As per IRC 58 [250], three values of modulus of subgrade reaction of subgrade (k) were assumed as 48, 55 and 62 MPa/m. The effective k-values (k_e) of combined foundation (subgrade + granular sub-base + DLC sub-base) were 208, 278 and 300 MPa/m respectively. The thickness of DLC sub-base and granular sub-base was assumed to be 100 mm each and the maximum temperature differential for the concrete slab during day-time was 16.5 ^{0}C and during night-time, it was 13.2 ^{0}C. Table 8.2 shows the pavement structural details for different concrete mix. The percentages of axle load class (assumed) of rear single, tandem and tridem axle are given in Table 8.3.

Table 8.3 Percentage of Axle Load Class (assumed)

Rear Single Axle		**Rear Tandem Axle**		**Rear Tridem Axle**	
Load Group (kN)	Frequency (%)	Load Group (kN)	Frequency (%)	Load Group (kN)	Frequency (%)
185-195	18.15	380 - 400	14.5	530-560	5.23
175-185	17.43	360 - 380	10.5	500-530	4.85
165-175	18.27	340 - 360	3.63	470-500	3.44
155-165	12.98	320 - 340	2.5	440-470	7.12
145-155	2.98	300 - 320	2.69	410-440	10.11
135-145	1.62	280 - 300	1.26	380-410	12.01
125-135	2.62	260 - 280	3.9	350-380	15.57
115-125	2.65	240 - 260	5.19	320-350	13.28
105-115	2.65	220 - 240	6.3	290-320	4.55
95-105	3.25	200 - 220	6.4	260-290	3.16
85-95	3.25	180 - 200	8.9	230-260	3.1
< 85	14.15	< 180	34.23	< 230	17.58
Total	100		100		100

The analysis of cumulative fatigue damage caused due to BUC and TDC was done for three different 'k_e'. For each concrete mix, the optimal thickness of slab ('h') was finalized at each 'k_e'. The analysis to determine the optimal thickness of slab of different concrete mix (k = 48 MPa/m, k_e = 208 MPa/m only) is shown in Table 8.4 to Table 8.8. By adopting a similar procedure, the results for optimal thickness of slab were calculated at k_e = 278 MPa/m and k_e = 300 MPa/m and are given in Table 8.9.

Case I, when k_e = 208 MPa/m

Table 8.4 (a) BUC* fatigue damage analysis (for day-time (6 hour)) of concrete mix ***R0 at h = 0.26 m***

Rear Single Axles					Rear Tandem Axles				
Expected Repetitions[a] (n_i)	Stress[b], in MPa	Stress Ratio (SR)[c]	Allowable Repetitions[d] (N_i)	Fatigue Damage[e] (n_i/N_i)	Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)
574807	2.655	0.472	4240880	0.136	765353	2.2597	0.402	infinite	0.000
552004	2.566	0.457	22114482	0.025	554221	2.1791	0.388	infinite	0.000
578607	2.476	0.441	infinite	0.000	191602	2.0986	0.373	infinite	0.000
411074	2.387	0.425	infinite	0.000	131957	2.0181	0.359	infinite	0.000
94376	2.298	0.409	infinite	0.000	141986	1.9375	0.345	infinite	0.000
51305	2.208	0.393	infinite	0.000	66507	1.857	0.330	infinite	0.000
82975	2.119	0.377	infinite	0.000	205854	1.7765	0.316	infinite	0.000
83925	2.030	0.361	infinite	0.000	273944	1.6959	0.302	infinite	0.000
83925	1.940	0.345	infinite	0.000	332533	1.6154	0.287	infinite	0.000
102927	1.851	0.329	infinite	0.000	337811	1.5349	0.273	infinite	0.000
102927	1.762	0.313	infinite	0.000	469768	1.4543	0.259	infinite	0.000
448127	1.672	0.298	infinite	0.000	1806761	1.3738	0.244	infinite	0.000
3166978	**Cumulative Fatigue Damage (CFD) from Single Axles**			**= 0.161**	**5278297**	**CFD from Tandem Axles**			**= 0.000**

a. It represents expected repetitions at each axle load group. Also, n_i was calculated with the help of values given in Table 8.1 and 8.3. For eg: n_i = 18.15% of 3166978 = 574807
b. It represents a combination of stresses (stresses due to load, warping and friction). It was calculated from equations given in IRC 58 [250].
c. It is ratio between total stresses and 28 days flexural strength of the concrete mix. Also, SR was calculated with the help of values given in Table 8.2. For eg: SR = 2.655/5.62 = 0.472
d. It represents allowable repetitions at each axle group and was calculated from the formula given in IRC 58 (2015).
- If SR < 0.45, N_i= Infinite. For eg: SR = 0.441 < 0.45 → N_i= Infinite
- If 0.55 ≥ SR ≥ 0.45, N_i= [4.2577/(SR – 0.4325)]^3.268. For eg: SR = 0.457 > 0.45 → N_i = 22114482
- If SR > 0.55, N_i= (0.9718 - SR)/0.0828

e. It is the fatigue damage caused by the particular axle load group. Fatigue damage = n_i/N_i. For eg: Fatigue damage = n_i/N_i = 552004/22114482 = 0.025
* The stresses due to tridem axles are minimal in comparison with stresses due to rear single and tandem axles. Therefore they were not considered for BUC fatigue damage analysis.

Table 8.4 (b) TDC fatigue damage analysis (for night-time (6 hour)) of concrete mix ***R0 at h = 0.26 m***

Rear Single Axles					Rear Tandem Axles					Rear Tridem Axles				
Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)	Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)	Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)
474215	2.505	0.446	infinite	0.000	631416	2.5358	0.451	50467251	0.013	136647	2.454	0.437	infinite	0.000
455404	2.444	0.435	infinite	0.000	457232	2.4745	0.440	infinite	0.000	126719	2.393	0.426	infinite	0.000
477351	2.382	0.424	infinite	0.000	158072	2.4131	0.429	infinite	0.000	89879	2.331	0.415	infinite	0.000
339136	2.321	0.413	infinite	0.000	108865	2.3517	0.418	infinite	0.000	186028	2.27	0.404	infinite	0.000
77860	2.260	0.402	infinite	0.000	117139	2.2903	0.408	infinite	0.000	264150	2.208	0.393	infinite	0.000
42327	2.198	0.391	infinite	0.000	54868	2.2289	0.397	infinite	0.000	313792	2.147	0.382	infinite	0.000
68454	2.137	0.380	infinite	0.000	169829	2.1676	0.386	infinite	0.000	406806	2.086	0.371	infinite	0.000
69238	2.075	0.369	infinite	0.000	226003	2.1062	0.375	infinite	0.000	346974	2.024	0.360	infinite	0.000
69238	2.014	0.358	infinite	0.000	274339	2.0448	0.364	infinite	0.000	118880	1.963	0.349	infinite	0.000
84915	1.953	0.347	infinite	0.000	278694	1.9834	0.353	infinite	0.000	82563	1.902	0.338	infinite	0.000
84915	1.891	0.336	infinite	0.000	387559	1.922	0.342	infinite	0.000	80995	1.84	0.327	infinite	0.000
369705	1.830	0.326	infinite	0.000	1490578	1.8607	0.331	infinite	0.000	459323	1.779	0.317	infinite	0.000
2612757	**CFD from Single Axles**			**= 0**	**4354595**	**CFD from Tandem Axles**			**= 0.013**	**2,612,757**	**CFD from Tridem Axles**			**= 0.00**

- The CFD from single, tandem and tridem axles for BUC as well as TDC was 0.174 (0.161+0+0+0.013+0) which is less than 1. *Hence, the trial thickness of 26 cm was acceptable.*
- By adopting a similar procedure for trial thickness of 25 cm, the CFD from single, tandem and tridem axles for BUC as well as TDC was 1.097 (0.922+0+0.05+0.122+0.003) which is more than 1. *Hence, the trial thickness of 25 cm was not acceptable for mix R0 at k_e = 208 MPa/m.*

Table 8.5 (a) BUC fatigue damage analysis (for day-time (6 hour)) of concrete mix ***R10 at h = 0.23 m***

Rear Single Axles					Rear Tandem Axles				
Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)	Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)
574807	2.731	0.483	1921441	0.299	765353	2.3361	0.413	infinite	0.000
552004	2.637	0.467	7012650	0.079	554221	2.2516	0.399	infinite	0.000
578607	2.544	0.450	59775896	0.010	191602	2.167	0.384	infinite	0.000
411074	2.450	0.434	infinite	0.000	131957	2.0824	0.369	infinite	0.000
94376	2.356	0.417	infinite	0.000	141986	1.9979	0.354	infinite	0.000
51305	2.262	0.400	infinite	0.000	66507	1.9133	0.339	infinite	0.000
82975	2.169	0.384	infinite	0.000	205854	1.8288	0.324	infinite	0.000
83925	2.075	0.367	infinite	0.000	273944	1.7442	0.309	infinite	0.000
83925	1.981	0.351	infinite	0.000	332533	1.6596	0.294	infinite	0.000
102927	1.887	0.334	infinite	0.000	337811	1.5751	0.279	infinite	0.000
102927	1.793	0.317	infinite	0.000	469768	1.4905	0.264	infinite	0.000
448127	1.700	0.301	infinite	0.000	1806761	1.406	0.249	infinite	0.000
3166978	**CFD from Single Axles**			**= 0.388**	**5278297**	**CFD from Tandem Axles**			**= 0.000**

Table 8.5 (b) TDC fatigue damage analysis (for night-time (6 hour)) of concrete mix ***R10 at h = 0.23 m***

Rear Single Axles					Rear Tandem Axles					Rear Tridem Axles				
Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)	Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)	Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)
474215	2.546	0.451	52363284	0.009	631416	2.578	0.456	23960414	0.026	136647	2.492	0.441	infinite	0.000
455404	2.481	0.439	infinite	0.000	457232	2.5135	0.445	infinite	0.000	126719	2.428	0.43	infinite	0.000
477351	2.417	0.428	infinite	0.000	158072	2.4491	0.433	infinite	0.000	89879	2.363	0.418	infinite	0.000
339136	2.353	0.416	infinite	0.000	108865	2.3847	0.422	infinite	0.000	186028	2.299	0.407	infinite	0.000
77860	2.288	0.405	infinite	0.000	117139	2.3203	0.41	infinite	0.000	264150	2.234	0.395	infinite	0.000
42327	2.224	0.394	infinite	0.000	54868	2.2559	0.399	infinite	0.000	313792	2.17	0.384	infinite	0.000
68454	2.159	0.382	infinite	0.000	169829	2.1915	0.388	infinite	0.000	406806	2.106	0.373	infinite	0.000
69238	2.095	0.371	infinite	0.000	226003	2.1271	0.376	infinite	0.000	346974	2.041	0.361	infinite	0.000
69238	2.030	0.359	infinite	0.000	274339	2.0627	0.365	infinite	0.000	118880	1.977	0.35	infinite	0.000
84915	1.966	0.348	infinite	0.000	278694	1.9983	0.353	infinite	0.000	82563	1.912	0.338	infinite	0.000
84915	1.902	0.337	infinite	0.000	387559	1.9339	0.342	infinite	0.000	80995	1.848	0.327	infinite	0.000
369705	1.837	0.325	infinite	0.000	1490578	1.8694	0.331	infinite	0.000	459323	1.784	0.316	infinite	0.000
2612757	**CFD from Single Axles**			**= 0.009**	**4354595**	**CFD from Tandem Axles**			**= 0.026**	**2,612,757**	**CFD from Tridem Axles**			**= 0.00**

- The CFD from single, tandem and tridem axles for BUC as well as TDC was 0.423 (0.388+0+0.009+0.026+0) which is less than 1. *Hence, the trial thickness of 23 cm was acceptable.*
- By adopting a similar procedure for the trial thickness of 22 cm, the CFD from single, tandem and tridem axles for BUC as well as TDC was 2.409 (2.033+0+0.115+0.252+0.009) which is more than 1.

  Hence, the trial thickness of 22 cm was not acceptable for mix R10 at k_e = 208 MPa/m

Table 8.6 (a) BUC fatigue damage analysis (for day-time (6 hour)) of concrete mix ***M7.5 at h = 0.2 m***

Rear Single Axles					Rear Tandem Axles				
Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)	Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)
574807	3.159	0.486	1628861	0.353	765353	2.7228	0.419	infinite	0.000
552004	3.043	0.468	6222972	0.089	554221	2.6178	0.403	infinite	0.000
578607	2.926	0.450	62790761	0.009	191602	2.5127	0.387	infinite	0.000
411074	2.810	0.432	infinite	0.000	131957	2.4077	0.370	infinite	0.000
94376	2.693	0.414	infinite	0.000	141986	2.3026	0.354	infinite	0.000
51305	2.577	0.396	infinite	0.000	66507	2.1976	0.338	infinite	0.000
82975	2.460	0.378	infinite	0.000	205854	2.0926	0.322	infinite	0.000
83925	2.344	0.361	infinite	0.000	273944	1.9875	0.306	infinite	0.000
83925	2.227	0.343	infinite	0.000	332533	1.8825	0.290	infinite	0.000
102927	2.111	0.325	infinite	0.000	337811	1.7775	0.273	infinite	0.000
102927	1.994	0.307	infinite	0.000	469768	1.6724	0.257	infinite	0.000
448127	1.877	0.289	infinite	0.000	1806761	1.5674	0.241	infinite	0.000
3166978	**CFD from Single Axles**			**= 0.451**	**5278297**	**CFD from Tandem Axles**			**= 0.000**

Table 8.6 (b) TDC fatigue damage analysis (for night-time (6 hour)) of concrete mix ***M7.5 at h = 0.2 m***

Rear Single Axles					Rear Tandem Axles					Rear Tridem Axles				
Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)	Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)	Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)
474215	2.834	0.436	infinite	0.000	631416	2.8736	0.442	infinite	0.000	136647	2.767	0.426	infinite	0.000
455404	2.754	0.424	infinite	0.000	457232	2.7936	0.430	infinite	0.000	126719	2.687	0.413	infinite	0.000
477351	2.673	0.411	infinite	0.000	158072	2.7135	0.417	infinite	0.000	89879	2.607	0.401	infinite	0.000
339136	2.593	0.399	infinite	0.000	108865	2.6335	0.405	infinite	0.000	186028	2.527	0.389	infinite	0.000
77860	2.513	0.387	infinite	0.000	117139	2.5534	0.393	infinite	0.000	264150	2.447	0.376	infinite	0.000
42327	2.433	0.374	infinite	0.000	54868	2.4734	0.380	infinite	0.000	313792	2.367	0.364	infinite	0.000
68454	2.353	0.362	infinite	0.000	169829	2.3933	0.368	infinite	0.000	406806	2.287	0.352	infinite	0.000
69238	2.273	0.350	infinite	0.000	226003	2.3132	0.356	infinite	0.000	346974	2.206	0.339	infinite	0.000
69238	2.193	0.337	infinite	0.000	274339	2.2332	0.344	infinite	0.000	118880	2.126	0.327	infinite	0.000
84915	2.113	0.325	infinite	0.000	278694	2.1531	0.331	infinite	0.000	82563	2.046	0.315	infinite	0.000
84915	2.033	0.313	infinite	0.000	387559	2.0731	0.319	infinite	0.000	80995	1.966	0.302	infinite	0.000
369705	1.953	0.300	infinite	0.000	1490578	1.993	0.307	infinite	0.000	459323	1.886	0.290	infinite	0.000
2612757	**CFD from Single Axles**			**= 0.000**	**4354595**	**CFD from Tandem Axles**			**= 0.000**	**2,612,757**	**CFD from Tridem Axles**			**= 0.00**

- The CFD from single, tandem and tridem axles for BUC as well as TDC was 0.451 (0.451+0+0+0+0) which is less than 1. *Hence, the trial thickness of 20 cm was acceptable.*
- By adopting a similar procedure for trial thickness of 19 cm, the CFD from single, tandem and tridem axles for BUC as well as TDC was 3.266 (3.099+0.019+0.036+0.112+0) which is more than 1. *Hence, the trial thickness of 19 cm was not acceptable for mix M7.5 at k_e = 208 MPa/m.*

Table 8.7 (a) BUC fatigue damage analysis (for day-time (6 hour)) of concrete mix ***R5M7.5 at h = 0.21 m***

Rear Single Axles					Rear Tandem Axles				
Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)	Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)
574807	2.996	0.494	1033000	0.556	765353	2.572	0.424	infinite	0.000
552004	2.888	0.476	3203031	0.172	554221	2.4748	0.408	infinite	0.000
578607	2.780	0.458	18347242	0.032	191602	2.3776	0.392	infinite	0.000
411074	2.672	0.44	infinite	0.000	131957	2.2804	0.376	infinite	0.000
94376	2.565	0.423	infinite	0.000	141986	2.1832	0.360	infinite	0.000
51305	2.457	0.405	infinite	0.000	66507	2.086	0.344	infinite	0.000
82975	2.349	0.387	infinite	0.000	205854	1.9888	0.328	infinite	0.000
83925	2.241	0.369	infinite	0.000	273944	1.8915	0.312	infinite	0.000
83925	2.133	0.351	infinite	0.000	332533	1.7943	0.296	infinite	0.000
102927	2.025	0.334	infinite	0.000	337811	1.6971	0.280	infinite	0.000
102927	1.917	0.316	infinite	0.000	469768	1.5999	0.264	infinite	0.000
448127	1.809	0.298	infinite	0.000	1806761	1.5027	0.248	infinite	0.000
3166978	**CFD from Single Axles**			**= 0.76**	**5278297**	**CFD from Tandem Axles**			**= 0.000**

Table 8.7 (b) TDC fatigue damage analysis (for night-time (6 hour)) of concrete mix ***R5M7.5 at h = 0.21 m***

Rear Single Axles					Rear Tandem Axles					Rear Tridem Axles				
Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)	Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)	Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)
474215	2.723	0.449	infinite	0.000	631416	2.7605	0.455	27619233	0.023	136647	2.662	0.439	infinite	0.000
455404	2.649	0.436	infinite	0.000	457232	2.6864	0.443	infinite	0.000	126719	2.588	0.426	infinite	0.000
477351	2.575	0.424	infinite	0.000	158072	2.6123	0.43	infinite	0.000	89879	2.513	0.414	infinite	0.000
339136	2.501	0.412	infinite	0.000	108865	2.5382	0.418	infinite	0.000	186028	2.439	0.402	infinite	0.000
77860	2.427	0.400	infinite	0.000	117139	2.4641	0.406	infinite	0.000	264150	2.365	0.390	infinite	0.000
42327	2.353	0.388	infinite	0.000	54868	2.39	0.394	infinite	0.000	313792	2.291	0.377	infinite	0.000
68454	2.279	0.375	infinite	0.000	169829	2.3159	0.382	infinite	0.000	406806	2.217	0.365	infinite	0.000
69238	2.205	0.363	infinite	0.000	226003	2.2418	0.369	infinite	0.000	346974	2.143	0.353	infinite	0.000
69238	2.131	0.351	infinite	0.000	274339	2.1677	0.357	infinite	0.000	118880	2.069	0.341	infinite	0.000
84915	2.057	0.339	infinite	0.000	278694	2.0936	0.345	infinite	0.000	82563	1.995	0.329	infinite	0.000
84915	1.982	0.327	infinite	0.000	387559	2.0195	0.333	infinite	0.000	80995	1.921	0.316	infinite	0.000
369705	1.908	0.314	infinite	0.000	1490578	1.9454	0.32	infinite	0.000	459323	1.847	0.304	infinite	0.000
2612757	**CFD from Single Axles**			**= 0.000**	**4354595**	**CFD from Tandem Axles**			**= 0.023**	**2,612,757**	**CFD from Tridem Axles**			**= 0.00**

- The CFD from single, tandem and tridem axles for BUC as well as TDC was 0.783 (0.76+0+0+0.023+0) which is less than 1. *Hence, the trial thickness of 21 cm was acceptable.*
- By adopting a similar procedure for trial thickness of 21 cm, the CFD from single, tandem and tridem axles for BUC as well as TDC was 4.349 (3.877+0.029+0.134+0.299+0.01) which is more than 1. *Hence, the trial thickness of 20 cm was not acceptable for mix R5M7.5 at k_e = 208 MPa/m.*

Table 8.8 (a) BUC fatigue damage analysis (for day-time (6 hour)) of concrete mix ***R10M7.5 at h = 0.23 m***

Rear Single Axles					**Rear Tandem Axles**				
Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)	Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)
574807	2.732	0.479	2575774	0.223	765353	2.3287	0.409	infinite	0.000
552004	2.638	0.463	10220031	0.054	554221	2.2441	0.394	infinite	0.000
578607	2.544	0.446	infinite	0.000	191602	2.1596	0.379	infinite	0.000
411074	2.451	0.430	infinite	0.000	131957	2.075	0.364	infinite	0.000
94376	2.357	0.414	infinite	0.000	141986	1.9905	0.349	infinite	0.000
51305	2.263	0.397	infinite	0.000	66507	1.906	0.334	infinite	0.000
82975	2.169	0.381	infinite	0.000	205854	1.8214	0.320	infinite	0.000
83925	2.075	0.364	infinite	0.000	273944	1.7369	0.305	infinite	0.000
83925	1.982	0.348	infinite	0.000	332533	1.6523	0.290	infinite	0.000
102927	1.888	0.331	infinite	0.000	337811	1.5678	0.275	infinite	0.000
102927	1.794	0.315	infinite	0.000	469768	1.4832	0.260	infinite	0.000
448127	1.700	0.298	infinite	0.000	1806761	1.3987	0.245	infinite	0.000
3166978	**CFD from Single Axles**			**= 0.277**	**5278297**	**CFD from Tandem Axles**			**= 0.000**

Table 8.8 (b) TDC fatigue damage analysis (for night-time (6 hour)) of concrete mix ***R10M7.5 at h = 0.23 m***

Rear Single Axles					**Rear Tandem Axles**					**Rear Tridem Axles**				
Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)	Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)	Expected Repetitions (n_i)	Stress, in MPa	Stress Ratio (SR)	Allowable Repetitions (N_i)	Fatigue Damage (n_i/N_i)
474215	2.546	0.447	infinite	0.000	631416	2.5786	0.452	44087044	0.014	136647	2.493	0.437	infinite	0.000
455404	2.482	0.436	infinite	0.000	457232	2.5141	0.441	infinite	0.000	126719	2.428	0.426	infinite	0.000
477351	2.417	0.424	infinite	0.000	158072	2.4497	0.43	infinite	0.000	89879	2.364	0.415	infinite	0.000
339136	2.353	0.413	infinite	0.000	108865	2.3853	0.418	infinite	0.000	186028	2.299	0.404	infinite	0.000
77860	2.289	0.402	infinite	0.000	117139	2.3208	0.407	infinite	0.000	264150	2.235	0.392	infinite	0.000
42327	2.224	0.390	infinite	0.000	54868	2.2564	0.396	infinite	0.000	313792	2.17	0.381	infinite	0.000
68454	2.160	0.379	infinite	0.000	169829	2.1919	0.385	infinite	0.000	406806	2.106	0.369	infinite	0.000
69238	2.095	0.368	infinite	0.000	226003	2.1275	0.373	infinite	0.000	346974	2.042	0.358	infinite	0.000
69238	2.031	0.356	infinite	0.000	274339	2.0631	0.362	infinite	0.000	118880	1.977	0.347	infinite	0.000
84915	1.966	0.345	infinite	0.000	278694	1.9986	0.351	infinite	0.000	82563	1.913	0.336	infinite	0.000
84915	1.902	0.334	infinite	0.000	387559	1.9342	0.339	infinite	0.000	80995	1.848	0.324	infinite	0.000
369705	1.838	0.322	infinite	0.000	1490578	1.8697	0.328	infinite	0.000	459323	1.784	0.313	infinite	0.000
2612757	**CFD from Single Axles**			**= 0.000**	**4354595**	**CFD from Tandem Axles**			**= 0.014**	**2,612,757**	**CFD from Tridem Axles**			**= 0.00**

- The CFD from single, tandem and tridem axles for BUC as well as TDC was 0.291 (0.277+0+0+0.014+0) which is less than 1. *Hence, the trial thickness of 23 cm was acceptable.*
- By adopting a similar procedure for trial thickness of 22 cm, the CFD from single, tandem and tridem axles for BUC as well as TDC was 1.966 (1.694+0+0.081+0.185+0.006) which is more than 1. *Hence, the trial thickness of 22 cm was not acceptable for mix R10M7.5 at k_e = 208 MPa/m.*

Table 8.9 CFD values for different 'k_e' and different trial thicknesses

'k_e' value, in MPa/m	Mix Designation	Trial thickness ('h'), in m	CFD for BUC due to Rear		CFD for TDC due to Rear			Total CFD	Remarks
			Single Axles	Tandem Axles	Single Axles	Tandem Axles	Tridem Axles		
208	R0	**0.26**	0.161	0	0	0.013	0	0.174	Pass
		0.25	0.922	0	0.05	0.122	0.003	1.097	Fail
	R10	**0.23**	0.388	0	0.009	0.026	0	0.423	Pass
		0.22	2.033	0	0.115	0.252	0.009	2.409	Fail
	M7.5	**0.20**	0.451	0	0	0	0	0.451	Pass
		0.19	3.099	0.019	0.036	0.112	0	3.266	Fail
	R5M7.5	**0.21**	0.76	0	0	0.023	0	0.783	Pass
		0.20	3.877	0.029	0.134	0.299	0.01	4.349	Fail
	R10M7.5	**0.23**	0.277	0	0	0.014	0	0.291	Pass
		0.22	1.694	0	0.081	0.185	0.006	1.966	Fail
278	R0	**0.26**	0.142	0	0	0	0	0.142	Pass
		0.25	0.855	0	0.031	0.093	0	0.979	Pass
		0.24	3.289	0	0.244	0.469	0.025	4.027	Fail
	R10	**0.23**	0.342	0	0	0.019	0	0.361	Pass
		0.22	1.929	0	0.091	0.206	0.007	2.223	Fail
	M7.5	**0.20**	0.417	0	0	0	0	0.417	Pass
		0.19	2.989	0.016	0.029	0.093	0	3.127	Fail
	R5M7.5	**0.21**	0.695	0	0	0.016	0	0.711	Pass
		0.20	3.732	0.025	0.111	0.253	0.008	4.129	Fail
	R10M7.5	**0.23**	0.262	0	0	0.01	0	0.272	Pass
		0.22	1.604	0	0.063	0.151	0.004	1.822	Fail
300	R0	**0.26**	0.138	0	0	0	0	0.138	Pass
		0.25	0.839	0	0.029	0.086	0	0.954	Pass
		0.24	3.247	0	0.231	0.449	0.024	3.951	Fail
	R10	**0.23**	0.335	0	0	0.017	0	0.352	Pass
		0.22	1.905	0	0.086	0.197	0.006	2.194	Fail
	M7.5	**0.20**	0.411	0	0	0	0	0.411	Pass
		0.19	2.963	0.016	0.028	0.089	0	3.096	Fail
	R5M7.5	**0.21**	0.685	0	0	0.015	0	0.7	Pass
		0.20	3.698	0.024	0.106	0.243	0.008	4.079	Fail
	R10M7.5	**0.23**	0.256	0	0	0	0	0.256	Pass
		0.22	1.583	0	0.059	0.143	0.004	1.789	Fail

It can be seen in Table 8.9 that minimum slab thickness which would be able to sustain the traffic loads (assumed) in case of control concrete R0 was 26 cm (at k_e = 208 MPa/m). However, when k_e value was increased to 278 Mpa/m and 300 MPa/m, the optimal slab thickness of mix R0 reduces to 25 cm. In other words, the cumulative fatigue damage (CFD) on the rigid pavement diminishes with an increase in the effective modulus of subgrade reaction of foundation (k_e). It was perceived in the structural design of each concrete mix. This result was expected as a certain level of protection to the deflection of slab is also provided by the subgrade. The more the 'k_e' is, the higher will be the upward reaction of subgrade to the deflection of concrete slab.

When 10% RSA (mix R10) and 10% RSA-7.5% MS (mix R10M7.5) were admixed with OPC, the optimal slab thickness reduces to 23 cm. The increment in the k_e value did not affect the optimal slab thickness in case of mix R10 and mix R10M7.5. However, for higher k_e, the CFD was marginally reduced in both mixes R10 and R10M7.5. In case of optimal slab thickness of mix R10, the CFD at k_e = 208 MPa/m was 0.423 which decreases to 0.352 when k_e was 300 MPa/m. Similarly, in case of optimal slab thickness of mix R10M7.5, the CFD at k_e = 208 MPa/m was 0.291, which decreases to 0.256 when k_e was 300 MPa/m. It signifies the importance of the k_e value of the foundation. The lower CFD in mix R10M7.5 in comparison with mix R10 could be attributed to the higher flexural strength of mix R10M7.5. When 5% RSA-7.5% MS (mix R5M7.5) and 7.5% MS (mix M7.5) were admixed with OPC, the optimal slab thickness reduced further to 21 cm and 20 cm respectively due to their even higher flexural strength.

8.3 COST COMPARISON

In the current study, the rate analysis of rigid pavement was based on varying proportion of cementitious materials (OPC, RSA and MS) in each concrete mix. The cost of HRWR was also considered for the rate analysis because of its varying proportion in the concrete of different mix. The costs of other materials in each concrete mix like aggregates and water were not considered based on the fact that their quantities were identical. Other factors which include but not limited to, are labour cost, machinery cost, overheads, contractor's profit etc. However, these were also not included in the rate analysis for the same reason.

Per kg costs of materials were finalized after taking into consideration the present market rates (year 2019). The costs of OPC, MS and HRWR per kg were finalized at 8 Rs., 30 Rs. and 32 Rs. respectively as shown in Table 8.10. Because of the abundance availability of rice straw in India and without any proper and justified use, it is treated as waste material and therefore, can be obtained easily from rice farms present across the country. However, the cost of RSA was finalized at 2 Rs. per kg because of other governing factors like labour charges, handling charges, transportation charges etc.

It can be seen in Table 8.10 that the cost of 1 m^3 of R10 concrete mix was lower than the cost of 1 m^3 of control concrete R0. The per kg cost of RSA was 25% of that of the OPC however, due to admixing of RSA, only 3% depreciation in the cost of 1 m^3 of concrete was observed. This may be attributed to the high HRWR requirement of the concrete mix R10 as compared to the control concrete R0. Unlike RSA, admixing of 7.5% MS (M7.5) significantly hiked the cost of 1 m^3 of concrete by approximately 23%. Similarly, the hike in per m^3 cost of concrete mixes R5M7.5 and R10M7.5 in comparison with R0 was 22.9% and 21.2% respectively.

For constructing 1 km length of NH (two lane, one way), maximum cost saving was observed in concrete mix R10 (w.r.t. R0 at k_e = 208 MPa/m) followed by concrete mix M7.5 and R5M7.5. As per the analysis of cumulative fatigue damage, the slab thickness in case of concrete mix R10M7.5 was significantly reduced as compared to that in the control mix R0. However, the cost of construction of 1 km of NH was higher in case of concrete mix R10M7.5. It was due to high HRWR dosage as well as high proportion of microsilica in mix R10M7.5 which were the costly ingredients of the concrete mix. If R0 mix with k_e = 278 MPa/m and 300 MPa/m was taken into account, the only mix which incurred a lower cost for constructing 1 km of NH was R10. The percentage cost reduction due to admixing of RSA was 14.23% and 8% as compared to the cost of control concrete R0 with k_e = 278 MPa/m and 300 MPa/m respectively.

8.4 CONCLUSIONS

In this chapter, CFD analysis as per IRC 58: 2015 was applied for predicting the slab thickness of rigid pavement of five different concrete mixes. It was found that admixing of RSA and MS considerably reduces the slab thickness of the rigid pavement. The lowest slab thickness was observed in mix M7.5, followed by R5M7.5. However, as per cost analysis for constructing the NH, it was found that the cheapest concrete mix would be R10 followed by mix M7.5. However, MS is an expensive mineral admixture used only when there is great concern about the durability of a structure.

Table 8.10 Cost comparison[a] of 1 m^3 of concrete and 1 km of NH

Mix Designation	1 m^3 of concrete					1 km length of NH[b]		
	Quantity (kg)				Total Cost (Rs.)			
	OPC (@8 Rs. per kg)	**RSA** (@2 Rs. per kg)	**MS** (@30 Rs. per kg)	**HRWR** (@32 Rs. per kg)		**Optimal Slab Thickness** (m)	**Quantity** (m^3)	**Total Cost** (Rs.)
R0	406	-	-	1.624	3300	0.26[c]	1820	60,06,000
						0.25[d]	1750	56,00,000
R10	365.4	40.6	-	6.09	3200	0.23	1610	51,52,000
M7.5	375.55	-	30.45	4.872	4074	0.2	1400	57,03,600
R5M7.5	355.25	20.3	30.45	8.12	4056	0.21	1470	59,62,320
R10M7.5	334.95	40.6	30.45	10.15	4000	0.23	1610	64,40,000

a. Only OPC, RSA, MS and HRWR were considered
b. For one-way traffic only (7 m width with 3.5 m for each lane)
c. For k_e = 208 MPa/m
d. For k_e = 278 MPa/m and 300 MPa/m