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An Analytical study on flexible pavement and rigid pavement design of a Road

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Abstract: *The Analytical design of flexible and rigid pavement for a given stretch 200 km have been worked out various values of effective California Bearing Ratio (CBR) of subgrade soil varying from 5% to 15% and the initial traffic i.e. 150 msa is high. The designs have been evolved using the latest relevant guidelines of Indian Road Congress (IRC). IRC: 37-2012 and 2018 have been used for the design of flexible pavements and drafted the pavement thicknesses of designed catalogue. IRC: 58-2015 has been used for the design of rigid pavements. The design of flexible pavement is based upon the fatigue and rutting failure of the pavement. For rigid pavement the design is based upon the fatigue analysis of bottom up cracking and top down cracking of the pavement. The rate analysis for various items of the work is given as per designs obtained and the cost estimation for the designed pavements have been done as per IRC guidelines. The present study is on various trail pavement sections using IITPAVE software, the individual layer thicknesses are assumed for design of flexible pavement. On the other hand the designs of rigid pavements are done on the effective CBR of subgrade and traffic on the designed thickness and findout the cost of construction of these pavements.*

Keywords: *Analysis, Flexible pavement, Rigid pavement, Thickness of pavement, construction cost*

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I.INTRODUCTION

Transportation is vital for the overall development of any country growth. The transportation by road is the only which could give maximum flexibility of service from origin to destination to everyone. It is best for transporting products and people to and from rural places where other modes of transportation are not available. The road network in India is over 57 lakh km which is second largest network in the world. The United State has more roadways, with 66.2 lakh kilometres. In India, there are more than 1.69 kilometres of road per square kilometre of area. This is higher than the Japan (0.89 km) and United States (0.66 km). The road density of India is also higher than China (0.45 km) and Russia (0.07 km)[1]. R-56 Research schemes (1999) of Roads wing Design CBR of subgrade for flexible pavements work done by Sudhakar Reddy et al[2]. (2001) Guidelines for the design of flexible pavements in India as IRC:37-2012[3] and IRC: 37-2018[4]. IRC: 37 guidelines are based upon fatigue cracking in bituminous layer, rutting due to permanent deformation in subgrade and bituminous layer[5]. It provides the mathematical models for calculating the allowable horizontal tensile strain at the bottom of the bituminous layer for fatigue failure and allowable vertical compressive strain over the subgrade for rutting failure of the pavement[6]. IITPAVE software provided with IRC: 37 is used to find the actual strains at these critical locations. The design of the pavement should be selected in such away that the computed strains will be less than the limiting strain values corresponding to be design traffic selected, in order that the assumed design is safe[7].

IRC: 58-2015[8]. guidelines are based upon fatigue analysis of bottom up cracking (tensile stresses are generated at bottom of the slab in day time) and top down cracking (tensile stresses are generated at top of the slab in night time) of rigid pavement. The cumulative fatigue damage (CFD) for both bottom up cracking (BUC) and top down cracking (TDC) is found out. If it is less than one then the assumed thickness of the pavement is safe[9].

The design of both flexible and rigid pavements have been worked out for a three lane carriageway road, each 10.5 m wide, 200 km length, for various values of CBR of subgrade varying from 5% to 15% and initial traffic 150 msa on the road[10]. The design life of flexible pavement is considered as 20 years whereas for rigid pavement is taken as 30 years. The annual growth rate of commercial vehicles is taken as 6.0%. The shoulders for both the flexible and rigid pavements are assumed as earthen shoulders[11].

MORTH Standard Data Book has been used to do the rate analysis of various items of design. The rates obtained for a 200 km Road. [12].

II. ANALYTICAL DESIGN OF FLEXIBLE PAVEMENTS

In the design of flexible pavement, fatigue and rutting criteria have been considered for 90% reliability for traffic greater than 30 msa. The allowable strains have been worked out with the help of equations provided in IRC: 37 and the actual strains are obtained from IITPAVE software.
As per IRC: 37, the design traffic is calculated by using the equation 1.

$$N = (365*A*D*F*((1+r)^{n}-1))/r \qquad (1)$$

Where,
N = Cumulative standard axle repetitions during design period
A = Initial traffic intensity (CVPD) in the year of construction
D = Lane distribution factor
F = Vehicle damage factor (VDF)
r = Annual rate of growth of commercial vehicles (for 6% rate of growth)
n = Design life in years (20 years)
The traffic in the year of completion of construction

$$A = P\ (1+r)^{X}$$

Where,
P = traffic intensity (cvpd) at last count
x = no. of years between last count & year of completion of the construction
Allowable horizontal tensile strain at the bottom of the bituminous layer (ε_t) is calculated by using the equation 3.

$$N_f = 0.5161*C*10^{-4}\ [1/\varepsilon_t\ ]]^{3.89}*[1/M_R]^{0.854} (2)$$

Where
N_f = fatigue life in number of standard axles
$C = 10^{M}$
$M = 4.84$ ($[V_b/V_a + V_b]$ -0.69)
V_a = percent of effect of air voids in mix
V_b = percent volume of bitumen in the mix
M_R = Resilient modulus of the bituminous layer
Allowable vertical strain in the subgrade (ε_v) is calculated by using the equation 4.

$$N = 1.41*10^{-8}*\{1/\varepsilon_v\}^{4.5337} \quad (3)$$

Where,
N = No of cumulative standard axles
ε_v = vertical strain in the subgrade

Table 1. Standard Conditions for Pavement Analysis using IITPAVE

Analysis Conditions	
Material response model	Linear elastic model
Layer interface condition	Fully bonded (all layers)
No. Of wheels	Dual-loaded wheel
Contact stress for critical parameter analysis	0.56 Mpa for tensile strain for bituminous layer and vertical compressive strain on subgrade; 0.80 Mpa for cement treated base

Using design guidelines of IRC: 37, Design a new pavement with various layer material selection, i.e Pavement is layered by bituminous layer, granular base (WMM) and cementitious subbase. The thickness of various layers are assumed, for these assumed values of design thicknesses, IITPAVE is to find out actual tensile strain at the bottom of bituminous layer caused by fatigue and vertical strain above the subgrade caused by rutting, the critical locations of strains are showing in figure 1 and table 1 showing the standard conditions for pavement analysis using IITPAVE. If these actual strains are less than the allowable stains calculated by the equations 2 and 3 the assumed thicknesses of various layers are found to be safe and adopted as design thicknesses for the pavement. On the guidelines of the given flexible pavement has been designed for varying values of CBR of subgrade from 5% to 15% and initial traffic is 150 msa. The design results have been shown in table 2, pavement thicknesses are shown in table .

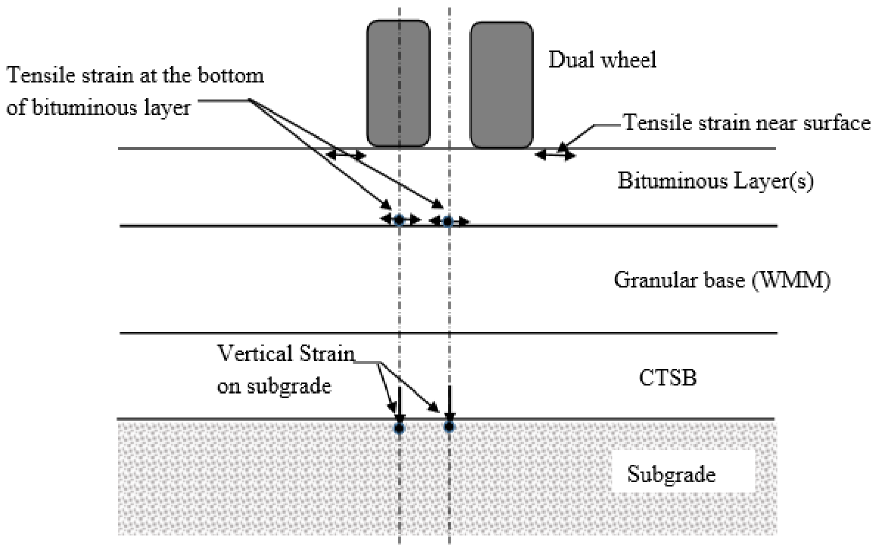

Figure 1:Showing the locations of critical strains.

Table 2. Design Results of Flexible Pavement

CBR (%)	Thickness (mm)	Allowable strains (€ z , € t)	Actual strains (€ z , € t)	Pavement composition is safe/ not safe
5	670	€ $_z$= 0.000290	€ z = 0.000225	safe
			€t = 0.000141	
10	640		€ z = 0.000205	safe
			€t = 0.000141	
12	500	€ t = 0.000142	€ z = 0.000288	safe
			€t = 0.000128	
15	470		€ z = 0.000280	safe
			€t = 0.000120	

```
No. of layers               4
E values (MPa)         3000.00  800.00  600.00   86.00
Mu values                 0.350.350.250.35
thicknesses (mm)        100.00  140.00  250.00
single wheel load (N) 20000.00
tyre pressure (MPa)       0.56
Dual  Wheel
  Z        R       SigmaZ       SigmaT       SigmaR       TaoRZ        DispZ        epZ          epT          epR
100.00     0.00-0.2721E+00 0.3090E+00 0.2395E+00-0.2376E-01 0.2833E+00-0.1547E-03 0.1068E-03 0.7555E-04
100.00L    0.00-0.2721E+00-0.2505E-01-0.4356E-01-0.2376E-01 0.2833E+00-0.3101E-03 0.1068E-03 0.7555E-04
100.00   155.00-0.1516E+00 0.1640E+00-0.1651E+00-0.1396E+00 0.2823E+00-0.5041E-04 0.9162E-04-0.5647E-04
100.00L  155.00-0.1516E+00-0.1613E-01-0.1039E+00-0.1396E+00 0.2823E+00-0.1370E-03 0.9162E-04-0.5647E-04
490.00     0.00-0.2010E-01 0.7161E-01 0.6016E-01-0.3397E-02 0.2269E+00-0.8841E-04 0.1027E-03 0.7880E-04
490.00L    0.00-0.2011E-01 0.1938E-02 0.4183E-03-0.3397E-02 0.2269E+00-0.2434E-03 0.1027E-03 0.7881E-04
490.00   155.00-0.2162E-01 0.7688E-01 0.6805E-01-0.5072E-02 0.2329E+00-0.9642E-04 0.1088E-03 0.9040E-04
490.00L  155.00-0.2162E-01 0.2121E-02 0.9507E-03-0.5075E-02 0.2329E+00-0.2639E-03 0.1088E-03 0.9040E-04
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Table 3. Design Thickness Values of Flexible Pavement

CBR of Subgrade (%)	Initial traffic (msa)	Thickness of layer (mm)				Total Thickness (mm)
		Surface course (BC)	Binder (DBM)	Base (WMM)	Subbase (CTSB)	
5	150	50	90	250	280	670
10		50	90	220	280	640
12		50	70	180	200	500
15		50	90	140	190	470

BC: Bituminous concrete, DBM: Dense bituminous macadam, WMM: Wet mix macadam, CTSB: Cement treated subbase

Using design guidelines of IRC: 37, Design a new pavement with various layer material selection, i.e. Pavement with bituminous layer, foam bitumen stabilised RAP and cementitious subbase. The thickness of various layers are assumed, for these assumed values of design thicknesses, IITPAVE is used to find out actual tensile strain at the bottom of bituminous layer caused by fatigue and vertical strain above the subgrade caused by rutting, the critical locations of strains are showing in figure 2 and Table 1 showing the standard conditions for pavement analysis using IITPAVE. If these actual strains are less than the allowable stains calculated by the equations 2 and 3 the assumed thicknesses of various layers are found to be safe and adopted as design thicknesses for the pavement. On the guidelines of the given flexible pavement has been designed for varying values of CBR of subgrade from 5% to 15% and initial traffic is 150 msa. The design results have been shown in table 4, pavement thicknesses are shown in table 5.

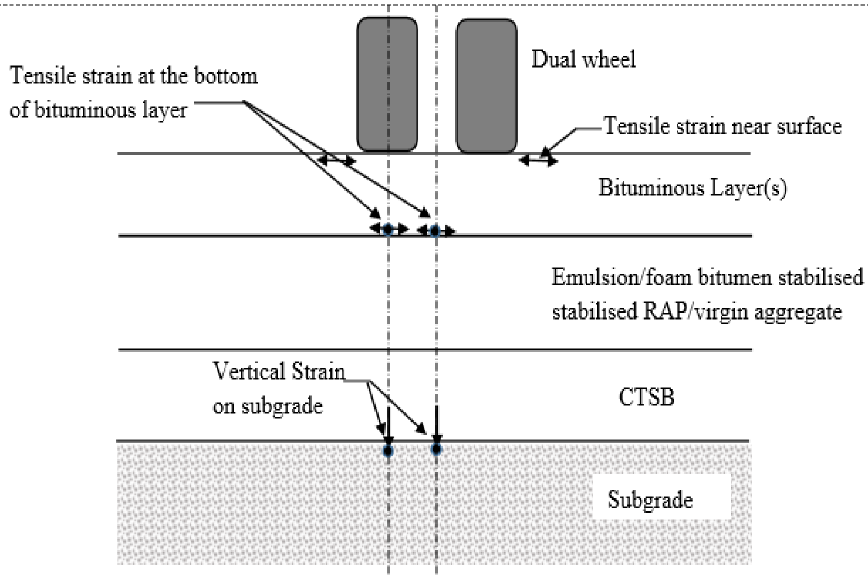

Figure 2. Showing the locations of critical strains.

Table 4. Design Results of Flexible Pavement

CBR (%)	Thickness (mm)	Allowable strains ($€_z$, $€_t$)	Actual strains ($€_z$, $€_t$)	Pavement composition is safe/ not safe
5	520	$€_z$= 0.000291	$€_z$ = 0.000290	safe
			$€_t$ = 0.000105	
10	480	$€_t$ = 0.000140	$€_z$ =0.000285	safe
			$€_t$ = 0.000104	

12	460		€ z = 0.000290	safe
			€t = 0.000109	
15	440		€ z = 0.000290	safe
			€t = 0.000110	

Table 5. Design Thickness Values of Flexible Pavement

CBR of Subgrade (%)	Initial traffic (msa)	Thickness of layer (mm)				Total Thickness (mm)
		Surface course (BC)	Binder (DBM)	Base (RAP)	Subbase (CTSB)	
5	150	50	50	180	250	520
10		50	50	140	230	480
12		50	50	120	240	460
15		50	50	100	240	440

BC: Bituminous concrete, DBM: Dense bituminous macadam, RAP: Reclaimed asphalt pavement, CTSB: Cement treated subbase

III. ANALYTICAL DESIGN OF RIGID PAVEMENT

Rigid pavement design has been done for the dual carriageway pavement provided with dowel and tie bars and concrete shoulders. The IRC: 58-2015 guidelines cover the plain jointed cement concrete pavements with and without tied concrete shoulders. These criteria is applicable for roads having average daily commercial vehicles more than 450 with laden weight exceeding 3 tonnes. Percentage of traffic in predominant direction is taken as 50%. Cumulative fatigue damage (CFD) analysis for bottom up cracking (BUC) and top down cracking (TDC) is done as per the guidelines given in IRC: 58. Equations 4 to 9 are used to calculate maximum tensile stress at the bottom of the slab and equation 10 is used to calculate maximum tensile stress at the top of the slab.

3.1Maximum tensile stress at the bottom of the slab (for Bottom-up cracking)

3.1.1 Single axle – Pavement with tied concrete shoulders

- $k \le 80$ Mpa/m

$$S = 0.008 - 6.12\,(\gamma h^2/kl^2) + 2.36\,Ph/(kl^4) + 0.0266\,\Delta T \qquad (4)$$

- $k > 80$ Mpa/m, $k \le 150$ Mpa/m

$$S = 0.08 - 9.69(\gamma h^2/kl^2) + 2.09\,Ph/(kl^4) + 0.0409\,\Delta T \qquad (5)$$

- $k > 150$ Mpa/m

$$S = 0.042 + 3.26\,(\gamma h^2/kl^2) + 1.62\,Ph/(kl^4) + 0.0522\,\Delta T \qquad (6)$$

3.1.2 Tandem axle – Pavement with tied concrete shoulders

- $k \le 80$ Mpa/m

$$S = -0.188 + 0.93(\gamma h^2/kl^2) + 1.025\,Ph/(kl^4) + 0.0207\,\Delta T \qquad (7)$$

- $k > 80$ Mpa/m, $k \le 150$ Mpa/m

$$S = -0.174 + 1.21\,(\gamma h^2/kl^2) + 0.87\,Ph/(kl^4) + 0.0364\,\Delta T \qquad (8)$$

- $k > 150$ Mpa/m

$$S = -0.210 + 3.88\,(\gamma h^2/kl^2) + 0.73\,Ph/(kl^4) + 0.0506\,\Delta T \qquad (9)$$

3.2 Maximum tensile stress at the top of the slab (for Top – down cracking)

$$S = -0.219 + 1.686BPh/kl^4 + 168.48h^2/kl^2 + 0.1089\ \Delta T \qquad (10)$$

Where,
S = flexural stress in slab, MPa
ΔT = maximum temperature differential in °C during day time for bottom-up cracking
= sum of the maximum night time negative temperature differential and built-in negative temperature differential in °C for top-down cracking
h = thickness of the slab, m
k = effective modulus of subgrade reaction of foundation, MPa/m

l = radius of the relative stiffness = $\{Eh^3/\ (12k\ (1-\mu^2)\}^{0.25}$
E = young ‘s modulus of concrete, MPa
μ = Poisson’s ratio of concrete
γ = unit weight of concrete (24 kN/m^3, density = 2400kg/m^2)
P = For bottom- up cracking analysis: single/tandem rear axle load (kN). No fatigue damages computed for front (steering) axles for bottom-up cracking case
= For top-down cracking analysis: 100% rare single axle, 50% of rear tandem axle and 33% of rear tridem axle. Front axle weight is not required to be given as input for top – down cracking case in the equation 10. 50% of rear single axle, 25% of rear tandem axle and 16.5% of rear tridem axle, has been considered in the finite element analysis as the front axle weights for single, tandem and tridem rear axles respectively
B = 0.66 for transverse joints with dowel bars (load transfer efficiency was taken as 50%)
= 0.90 for transverse joints without dowel bars (load transfer efficiency was taken as 10%)

The fatigue analysis for various classes of load as per the commercial vehicles on the road is done for both bottom-up cracking and top-down cracking. The assumed thickness of the pavement is considered safe if the cumulative fatigue damage of both the analysis is less than 1.

On the basis of the design, the result obtained for the thickness of Pavement Quality Concrete (PQC, Grade M-40) slabs are shown in the table 6. The Pavement Quality Concrete slab is provided over a layer of 150 mm thick Dry Lean Concrete (DLC) which in turns rests on a drainage layer of 150 mm granular subbase (GSB). The interface layer (125 micron PVC sheet) between the concrete slab and the DLC layer can be smooth that reduce the inter layer friction thereby allows relative movement between the slab and DLC layer which can prevent reflection cracking in the pavement slab.

Table 6. Thickness of pqc slab Values of Rigid Pavement

CBR (%)	Initial traffic (CVPD)	Thickness of PQC slab (mm)	Bottom-up cracking (BUC)	Top-down cracking (TDC)	Cumulative fatigue damage (CFD) = (BUC+TDC)
5	6000	330	0.057	0.466	0.523
8		320	0.182	0.697	0.879
15		320	0.178	0.668	0.846

IV. CONSTRUCTION COST OF FLEXIBLE & RIGID PAVEMENTS

MORTH Standard Data book has been used to do the rate analysis of various items of design. The rates drafted for a road located at Amaravati, Guntur district, India for these items per cubic meter in Rupees are GSB = 1715, WMM = 6799, BC = 8106, DLC = 2730, PQC = 6530, CTSB = 4200. Using these rates the cost per square meter of rigid pavement and flexible pavement has been worked out and shown in table 7,8 and 9.

Table 7. Cost of flexible pavement

Flexible pavement with bituminous layer with wet mix macadam (Base) and cementitious subbase				
CBR	**5**	**10**	**12**	**15**
Pavement thickness (mm)	670	640	500	470
Cost of road construction (Cr)	1722	1636	1319	1256

Table 8. Cost of flexible pavement

Flexible pavement with bituminous layer with Foam bitumen stabilized RAP (Base) and Cementitious subbase				
CBR	**5**	**10**	**12**	**15**
Pavement thickness (mm)	520	480	460	440
Cost of road construction (Cr)	828	793	809	808

Table 9. Cost of rigid pavement

Plain jointed rigid pavement having quality concrete with 125 µ pvc sheet, dry lean concrete and granular subbase			
CBR	**5**	**8**	**15**
Pavement thickness (mm)	630	620	620
Cost of road construction (Cr)	1180	1156.3	1156.6

V. CONCLUSIONS

1. IRC: 37-2018 by using IITPAVE software. It is observed that the newly designed flexible pavement combinations are pavement having bituminous layer with granular base (WMM), CTSB (Case-1) and pavement having bituminous layer with foam bitumen stabilised RAP, CTSB (Case-2) depending upon the soil subgrade CBR value at 5%, 10%, 12% and 15% which is designed as high traffic 150 msa by selected pavement thickness is safe for design.
2. The plain jointed rigid pavement from IRC:58-2015 by using kgpslab software was designed the effective CBR of compacted subgrade 5%, 8% and 15% at 100% frequency of single, tandem and tridem axle load spectrum provided slab thickness 330mm, 320mm and 320mm respectively and the design is safe.
3. For high value of initial traffic of 150 msa, the cost of construction of flexible pavement Case-1 is 2 times and 1.5 times the cost of flexible pavement Case-2 with CBR of soil subgrade 5% to 10% and 12% to 15%.
4. For high value of initial traffic of 6000 CVPD, the cost of construction of rigid pavement is 1.28 to 1.39 times the cost of flexible pavement Case-2 with CBR of soil subgrade varying from 5% to 15%.

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