Early performance of flexible pavement constructed with industrial wastes in base and subbase layers

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Abstract. Implementation of industrial wastes for road construction has become crucial due to fast depleting good quality aggregates on one hand and concerns regarding safe disposal of immensely generating industrial wastes on the other. The focal point of this research is to substantiate the utilization of various industrial wastes such as fly ash, steel slag, copper slag & granulated blast furnace slag (GBFS) in combination with lime as a base and subbase material in flexible pavement. Based on comprehensive laboratory investigations and finite element analyses, six optimal combinations of waste materials were chosen i.e. 40% copper slag + 60% fly ash, 70% copper slag + 23% fly ash + 7% lime & 75% steel slag + 19% fly ash + 6% lime as base layers and fly ash + 5% lime, 80% fly ash + 20% GBFS & 70% copper slag + 30% fly ash as subbase layers. To compare the field performance and service life of flexible pavement constructed with these six optimal combinations in base and subbase layers with that of conventional pavement section, structural evaluation is carried out by means of falling weight deflectometer (FWD) on 16 test sections (each 3.5 m wide and 50 m long) with different thicknesses of base (150mm & 250 mm) and subbase (200, 300 & 400 mm) layers with waste mixes. On the basis of initial structural evaluation by FWD, it was found that pavement sections constructed with the aforementioned waste mixes in the base and subbase exhibited appreciably lower deflections, higher elastic moduli and better service life with 17% cost efficacy when compared to that of conventional pavement section.

Keywords: Slag, Fly ash, Pavement, Falling weight deflectometer, Bump integrator, Service life.

1 Introduction

Enormous amount of natural aggregates is indispensable for the construction, maintenance and widening of roads, subsequently leading to the scarcity of most needed conventional materials for construction of subbase and base layers of flexible pavements. Extraction of natural aggregates from quarries is a major concern as far as ecological balance is concerned. On the other hand, due to hasty industrial development, a large quantity of industrial wastes such as fly ash from thermal power plants and slags from steel and copper industries are being generated creating a tremendous threat to public health and ecology. The befitting solution to the aforementioned issues is bulk utilization of industrial wastes in road construction. In India, power generation from thermal power plants is increasing hastily and the annual generation of fly ash was reported to be 196 million tons in the year 2018 with a 67% utilization rate [1]. In the same year, India's steel production augmented to 106.5 million tons, becoming the second largest steel producer in the world [2]. Steel slag and granulated blast furnace slag (GBFS) are the major byproducts generated by the steel industry. India was the world's fifth largest producer of refined copper in the year 2014 and its capacity stood at 1.07 million tons. For every ton of refined copper produced, about 2.2 tons of slag is generated. Copper slag is a by-product of copper extraction industries and is produced during smelting and converting steps of pyro-metallurgical production of copper.

Lots of researchers have conducted extensive laboratory investigations on various industrial wastes for their effective utilization as a road construction material. Shen et al. [3] studied the feasibility of utilizing steel slag–fly ash–phosphogypsum solidified material as a road base material. Akinwumi et al. [4] investigated the improvement in the geotechnical properties of lateritic soil by the addition of pulverized steel slag. Patel et al. [5] studied the geotechnical properties of copper slag mixed with different percentage of fly ash (20, 25, 30, 35 and 40%) and observed the maximum CBR value of 32% for the mix of 80% slag and 20% fly ash. Havanagi et al. [6, 7] substantiated that, copper slag and fly ash collected from a copper unit and captive thermal power plant in Dahej, Gujarat, India, can be used in embankment, subbase, base layer, and wearing courses of road pavement. Consoli et al. [8, 9] and Ghosh and Subbarao [10] reported on the enhanced geotechnical properties of soil–fly ash–lime and fly ash–lime mixtures. The concept of implementing laboratory-developed waste mixtures as a pavement material will only be practical when field studies are carried out on pavements constructed with these waste mixtures. One such study is the structural evaluation of existing in-service pavement by a falling weight deflectometer (FWD) test, which is a comprehensive nondestructive approach. The following studies exemplify the significance of FWD testing in the structural evaluation of flexible pavements. Barstis and Metcalf [11] initiated the study to evaluate long-term performance of lime–fly ash (LFA) stabilized soil as a base course material. Li et al. [12] presented a case study where asphaltic recycled pavement material (RPM) blended with Class C fly ash was used as base course material in flexible pavement. Ping et al. [13] compared the back-calculated resilient modulus (M_r) obtained from the FWD data with the laboratory M_r for granular subgrade of in-service pavement.

This study encompasses the early field performance of test sections constructed with industrial waste mixtures namely; 40% copper slag + 60% fly ash, 70% copper slag + 23% fly ash + 7% lime & 75% steel slag + 19% fly ash + 6% lime in the base layers and fly ash + 5% lime, 80% fly ash + 20% GBFS & 70% copper slag + 30% fly ash in the subbase layers of flexible pavement. The major objectives of this study are as follows:

- To construct 16 different test sections of flexible pavements as part of a state highway using six optimal combinations of different waste materials in the base and subbase course.
- To perform structural evaluation of 16 different test sections by FWD.
- To compare the field performance, service life and cost efficacy of flexible pavement constructed with these six optimal combinations of waste materials in base and subbase layers with that of conventional pavement section (control).

2 Experimental Program

2.1 Selection of waste mixtures

Based on the extensive laboratory studies, model tests and finite element analyses, six different waste mixtures were adopted in the base course and subbase course of flexible pavement [14]. The industrial wastes used for construction are Electric arc furnace (EAF) steel slag, Copper slag, GBFS, Class F fly ash and Class C Fly ash. EAF Steel slag and GBFS were procured from Essar Steel, Hazira, Gujarat. Copper slag was procured from Birla Copper, Dahej, Gujarat. Class F fly ash (CaO = 8.88%) and Lignite (Class C) fly ash (CaO = 12.9%) were procured from Reliance Industries Ltd., Hazira and Lignite Power Plant, Nani Naroli, Surat. Hydrated lime with purity (available lime content) of not less than 70% when tested according to IS: 1514 – 1990 [15] was procured from Super Lime Traders, Surat, Gujarat. The physical properties of the industrial wastes utilized for construction are presented in Table 1.

Table 1. Physical properties of waste materials

Physical parameters	Copper slag	Steel slag	GBFS	Fly ash
Color	Black	Grey	Grey	Grey
Specific gravity	3.24	3.28	2.45	2.38
Grain size distribution				
Coarse Gravel size (10 mm to 20 mm)	--	29%	--	--
Fine Gravel size (4.75 mm to 10mm)	--	8%	--	--
Coarse sand size (2.0 mm to 4.75 mm)	22%	15%	3%	--
Medium sand size (0.425 mm to 2.0 mm)	71%	37%	79%	--
Fine sand size (0.075 mm to 0.425 mm)	7%	11%	16%	9%
Silt size (0.002 mm to 0.075mm)	--	--	2%	84%
Clay size (<0.002mm)	--	--	--	7%
C_u	2.50	10.26	3.52	6.00
C_c	1.74	1.17	1.42	2.67
IS classification	SP	SW	SP	ML

Based on the leaching test results obtained from the toxicity characteristic leaching procedure (TCLP), it was found that all the industrial wastes were nonhazardous; i.e. the concentrations of heavy metals in the leachate were below TCLP limits. The compaction characteristics and mix designations of the selected waste mixtures determined from Modified proctor test as per IS: 2720 Part 8 – 2006 [16] are shown below in Table 2.

Table 2. Compaction characteristics of desired mix proportions

Mix Proportions	Mix Designation	OMC (%)	MDD (kN/m^3)
Base layer			
70% Copper slag + 23% Fly ash + 7% Lime	CFL	11.5	21.6
75% Steel slag + 19% Fly ash + 6% Lime	SFL	9.5	21.6
40% Copper slag + 60% Lignite fly ash (Class C)	CCF	18.0	17.7
Subbase layer			
Fly ash + 5% lime	FAL	39.5	1.1
80% Fly ash + 20% GBFS	FAG	31.0	1.2
70% Copper slag + 30% Fly ash	CFA	13.0	2.1

The waste mixtures CFL, SFL and CCF intended to be used in the base layers satisfied the minimum UCS of 5 MPa and the FAL mixture intended for subbase layer satisfied the minimum UCS of 1.5 MPa after 28 days curing, as recommended by IRC: SP 20 – 2002 [17]. As CFA and FAG mixtures are not cemented materials, the selection criteria for its use in the subbase layer of flexible pavement was based on a minimum CBR value of 30%, as stipulated in MORTH specifications [18]. The test sections were constructed as a part of a research project funded by the Department of Science and Technology, Government of India (DST). Construction of the 16 different test sections (each 50 m long and 3.5 m wide) was executed by Road & Building Department, Surat as a part of widening of Olpad-Sahol State Highway (GJ SH-6) in Surat District, Gujarat. The location of the test section was finalized in such a way that, the transportation of waste materials from the source to the site shall not affect the pace and cost of construction.

2.2 Design of test sections

Pavement composition of 16 different test sections was designed for a subgrade CBR of 4% and traffic intensity 75 Million Standard Axles (MSA) as per the guidelines given by IRC: 37 – 2012 [19]. Based on the laboratory investigations carried out on various soil samples collected from the field, the subgrade soil was found to be black cotton soil (IS Classification - CH) with soaked CBR less than 2%. As construction of pavement crust on subgrade of 2% CBR is not recommended, it was intended to stabilize the subgrade with 50% fly ash to attain a design CBR of 4%. As it is irrelevant to study the performance of flexible pavement comprising stabilized base/subbase course constructed over stronger subgrade, the stabilization of subgrade soil was limited to a minimal CBR of 4%. In order to affirm the attained subgrade CBR, Dynamic Cone Penetrometer (DCP) Test [20] and Light Weight Deflectometer [21] tests were conducted on finished subgrade. The design thickness adopted for the test sections is presented in Table 3. The holistic performance of different thicknesses for base (150 and 250 mm) and subbase layers (200, 300, and 400 mm) was compared with conventional wet mix macadam (WMM) (250 mm) and granular subbase (GSB) layer (330 mm) of control section. In order to prevent the fatigue cracks developing in the cemented base layers due to long term traffic loading from propagating towards the upper bituminous layers (BC and DBM), crack relief aggregate layer (CRL) was provided for all the sections with CCF, CFL and SFL in base layer.

Table 3. Design thickness adopted for test sections for 4% subgrade CBR and 75 MSA traffic

Type of material	Layers thickness (mm)				
	Bituminous concrete (BC)	Dense bituminous macadam (DBM)	Crack relief aggregate layer (CRL)	Base	Subbase
Test sections with waste mixtures in base layer					
CCF	40	100	100	150	300
				250	
CFL	40	100	100	150	300
				250	
SFL	40	100	100	150	300
				250	
Test sections with waste mixtures in subbase layer					
FAL	40	140	--	250	200
					300
					400
FAG	40	140	--	250	200
					300
					400
CFA	40	140	--	250	200
					300
					400
Control	40	140	--	250	330

2.3 Construction of test sections

The construction methodology stipulated in IRC: SP 20 – 2002 was followed during the construction of all the test sections. In order to periodically test the leachate coming from the test sections during heavy monsoons, leachate collection systems were installed beneath the base layers inside GSB for test sections with waste mixtures in base layers and inside the subbase layers for test sections with waste mixtures in subbase layers during construction. The construction sequence of the test sections are shown below in Fig 1.

(a) Dry mixing of fly ash and slag at mixing plant (b) Addition of lime to fly ash-slag mix (c) Wet mixing of fly ash + slag + lime

(d) Stacking of waste mixture at site (e) Spreading the mixture with grader (f) Installation of leachate collection system

(g) Finished subbase layer (h) Finished base layer (i) bituminous concreting

Fig. 1. Constriction sequence of test sections

Field density tests using sand replacement method as per IS 2720 Part 28 – 2005 [22], LWD tests, field CBR and DCP tests were conducted to assure the quality during the construction of the base and subbase layers with waste mixtures. The photographs of quality control tests are shown in Fig. 2.

2.4 Structural evaluation of test sections

The structural evaluation of all the 16 different test sections was performed by FWD test using a Dynatest 8001 model (Manufacturer: Dynatest, Denmark) [23, 24]. The model has a maximum load capacity of 150 kN and comes with seven detachable geophones (velocity transducers), which can be fixed at different spacing (distance from center of loading plate) based on the given requirements. It uses a quadsegmented loading plate 300 mm in diameter to evenly touch the pavement surface and produce a uniform stress distribution. The photographs of FWD are shown in Fig 3. In FWD, a transient load is applied to the pavement surface and surface deflections are measured by the geophones. The working principle of a typical FWD is illustrated in Fig. 4. D_0, D_1, D_2 etc. in Fig. 4 are the surface deflections measured at different radial distances by the geophones.

Fig. 2. Quality control testing during construction: Field CBR test (left) and LWD test (right)

FWD tests were performed at a test section in a zigzag manner at nine different locations, such that all points were equidistant from each other. The initial test was performed one month after construction and subsequently continued for second and third month. At each test location, deflections corresponding to three different impulse loads, 40, 55 and 70 kN were obtained, which correspond to equivalent standard axle load (ESAL) and probable range of vehicular overloading. As stipulated in IRC: 115 – 2015 seven geophones were spaced at 0, 300, 600, 900, 1,200, 1,500, and 1,800 mm to record the structural response of pavement in terms of peak deflection in microns, which is typically termed a deflection basin.

Fig. 3. Performance of FWD testing on the constructed test sections

Elastic modulus of all the layers of pavement composition were computed from the deflection basin using back-calculation software ELMOD 6 (Manufacturer: Dynatest, Denmark). Here, pavement layers are modeled as linear elastic materials with known thicknesses and Poisson’s ratios in an axisymmetric FE model. Firstly, a forward calculation using assumed values of layer moduli (termed as seed moduli) is carried out to generate a deflection basin. Secondly, the generated deflection basin from forward calculation is compared with the observed basin from the FWD test to compute deviation in terms of percentage differences and root-mean-square (RMS) values. The back-calculation program is trained in such a way that, if the deviation is considerably higher, the entire process is repeated until minimum (1-3%) percentage differences and root-mean-square (RMS) values are obtained; subsequently providing the most probable elastic modulus for the layers. The correctness of the program largely depends on the seed moduli opted by the user and sufficient experience is essential in selecting appropriate seed moduli.

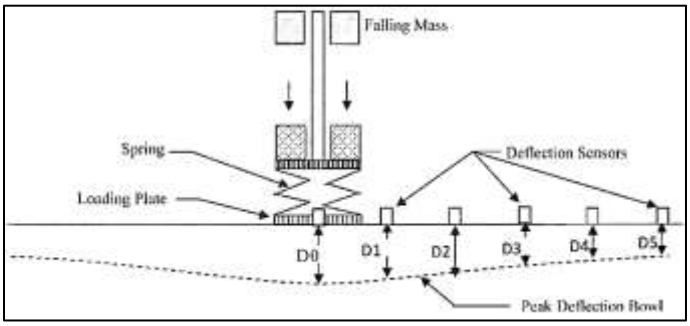

Fig. 4. Working principle of FWD [24]

3 Results and Discussion

3.1 Test sections with waste materials in base layers

Peak deflection (D_0)

The peak deflection (D_0) corresponding to multilevel impulse loads (40 kN, 55 kN and 70 kN) obtained from the initial FWD test carried out on the test sections with CCF, CFL and SFL base layers, one month after construction are presented in Fig 5. All the test sections with waste mixtures in base layers exhibited considerably lower peak deflections when compared to the conventional control section. The higher strength due to the light cementation by pozzolanic reaction between fly ash (CaO = 8.88%) and lime for sections with CFL and SFL base as well as the inherent pozzolanic properties of Class C fly ash (CaO = 12.9%) in the case of CCF are the primary reasons for this lower deflections. For standard impulse load of 40 kN, lowest peak deflection (D_0 = 0.444 mm) was observed for the test section with 250 mm thick SFL base layer; D_0 of conventional control section being 0.780 mm.

Back-calculated elastic modulus (E_{back})

The lower deflections observed for the test sections with waste mixtures in base layers are supported by higher back-calculated elastic modulus (E_{back}). E_{back} of three months after construction for CCF, CFL and SFL base layers were computed and the results gave an indication that curing resulted in slight augmentation in the E_{back}, which is mainly due to gradual pozzolanic reaction occurring even after the construction of the layers.

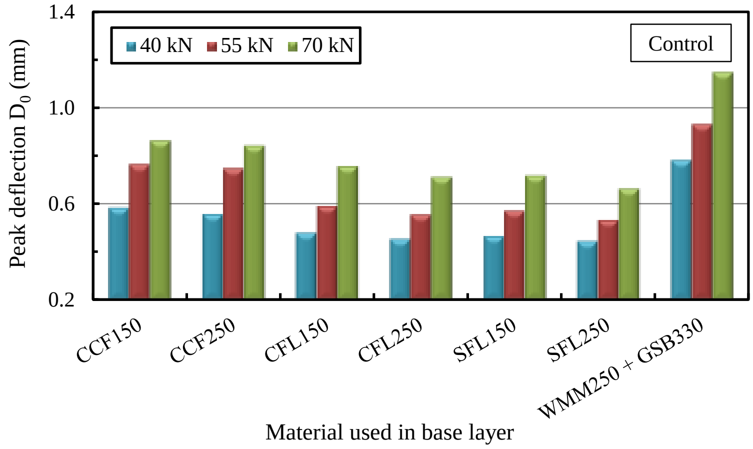

Fig. 5. Peak deflection for test sections with waste mixtures in base layers and control section

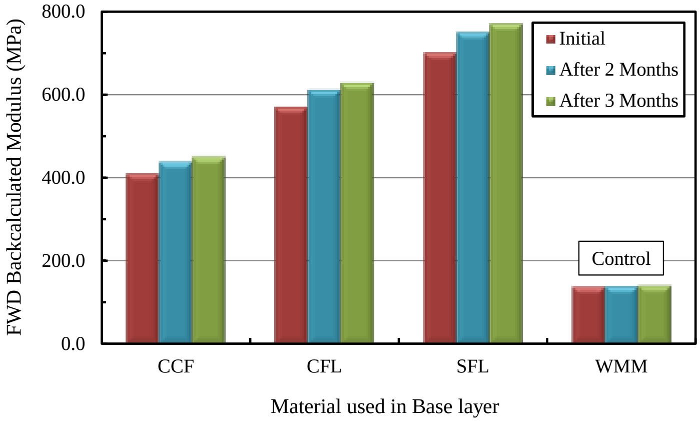

Fig. 6. FWD back-calculated moduli of base layer with waste mixtures and conventional WMM

After 3 months, maximum E_{back} of 771.1 MPa was achieved by SFL base layer, which is 5.5 times higher than the conventional WMM used in the control section. Unlike CCF and CFL, this enhanced modulus is due to the coarser nature of steel slag which forms stronger matrix in the fly ash-lime gel formation. The E_{back} for all the waste mixtures along with WMM are presented in Fig 6.

3.2 Test sections with waste materials in subbase layers

Peak deflection (D_0)

The peak deflection (D_0) which indicates the overall pavement performance, corresponding to multilevel impulse loads (40 kN, 55 kN and 70 kN) obtained from the initial FWD test carried out on the test sections with FAL, FAG and CFA subbase layers, one month after construction are presented in Fig 7. Similar to the test sections with waste mixtures in base layers, sections with FAL, FAG and CFA subbase layers exhibited considerably lower peak deflections when compared to the conventional control section.

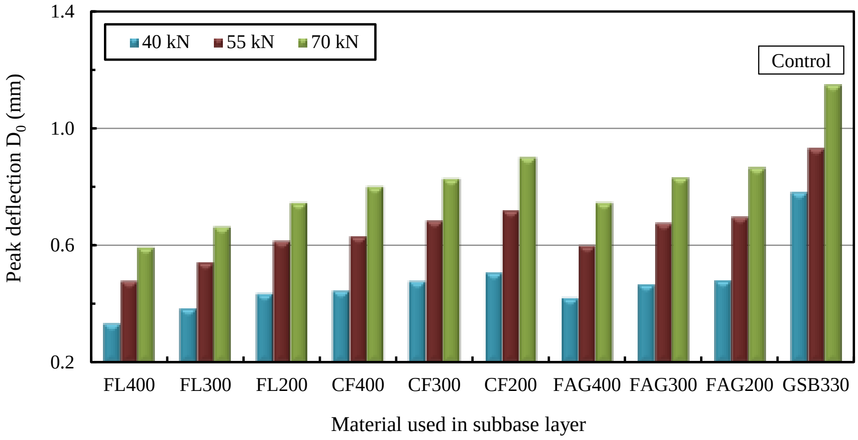

Fig. 7. Peak deflection for test sections with waste mixtures in subbase layers and control section

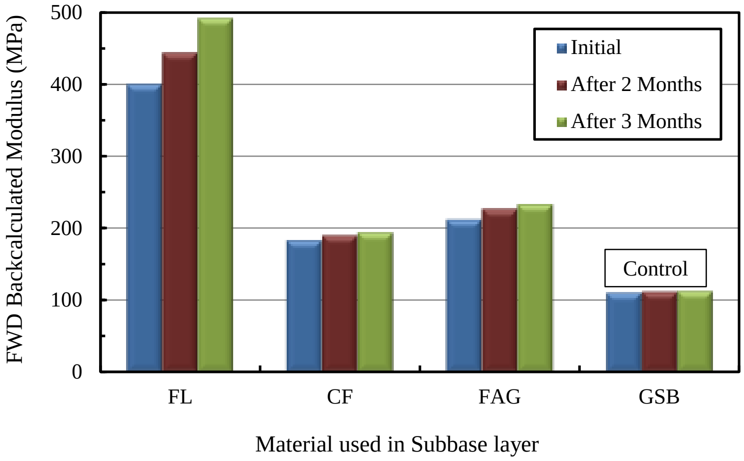

Fig. 8. FWD back-calculated moduli of subbase layer with waste mixtures and conventional GSB

The higher strength due to the light cementation by pozzolanic reaction between fly ash (CaO = 8.88%) and lime is the primary reason for lower deflections in sections with FAL subbase. In the case of sections with FAG and CFA subbase, the slight pozzolanic property of fly ash alongside the coarser nature of GBFS and copper slag justify the lower deflections. For standard impulse load of 40 kN, lowest peak deflection (D_0 = 0.334 mm) was observed for the test section with 400 mm thick FAL subbase layer; D_0 of conventional control section being 0.780 mm.

Table 4. Cost comparison and SLR of waste mixtures and conventional granular materials

Type of material	Thickness (mm)	SLR	Waste Utilization, in tons/km of road length (3.5m wide)				Overall Construction cost (INR)		
			Copper slag	Steel slag	GBFS	Fly ash	Rate (m^3)	Rate/km (lakhs)	Savings (%)
Control section	WMM 250 GSB 330	1.00	--	--	--	--	1399 1328	86.6	--
Test sections with waste mixtures in base layer									
CCF	150	1.34	378	--	--	567	850	71.64	17.3
	250	1.59	630	--	--	945		74.82	13.6
CFL	150	1.47	809	--	--	266	1170	73.62	14.9
	250	1.78	1,348	--	--	443		78.22	9.6
SFL	150	1.53	--	866	--	219	1182	73.68	14.9
	250	1.84	--	1,444	--	366		78.34	9.5
Test sections with waste mixtures in subbase layer									
FAL	200	1.29	--	--	--	840	683	73.96	14.6
	300	1.44	--	--	--	1,260		76.00	12.2
	400	1.54	--	--	--	1,680		78.12	9.8
FAG	200	1.12	--	--	168	672	632	73.50	15.1
	300	1.23	--	--	252	1,008		75.28	13.1
	400	1.31	--	--	336	1,344		77.14	10.9
CFA	200	1.11	1,029	--	--	441	883	75.80	12.5
	300	1.21	1,544	--	--	662		78.80	9.0
	400	1.26	2,058	--	--	882		81.92	5.4

Back-calculated elastic modulus (E_{back})

The lower deflections attained for the test sections with waste mixtures in subbase layers is supported by higher back-calculated elastic modulus (E_{back}). E_{back} of three months after construction, for the FAL, FAG and CFA subbase layers were computed and the results gave an indication that curing resulted to slight augmentation in the E_{back}. This increase in E_{back} indicates gradual pozzolanic reaction between fly ash and lime occurring in the FAL subbase layer. For FAG and CFA layers, the feeble strength gain is due to slight pozzolanic property of fly ash (CaO = 8.88%). After 3 months, maximum E_{back} of 492 MPa was achieved by FAL subbase layer, which is 4.4 times higher than the conventional GSB used in the control section. The E_{back} for all the waste mixtures along with GSB are presented in Fig 8.

3.3 Service life and cost efficacy of test sections

The service life ratio (SLR) of pavements with waste mixtures in base and subbase layers compared to conventional control section based on fatigue criteria is given by the following equation as per IRC: 37 – 2012 [19]:

$$SLR = \left(\frac{\varepsilon_{t1}}{\varepsilon_{t2}}\right)^{3.89} \tag{1}$$

Where ε_{t1} and ε_{t2} = maximum horizontal tensile strains, developed at the bottom of a dense bituminous mix for control section and pavement with waste mixtures as base and subbase layers. The strain values were taken from the FEM plots of ELMOD 6 for ‘most possible sets’ of back-calculated moduli computed for all the layers. The SLR and the construction costs of all 16 different test sections are given in Table 4. It was observed that all pavement sections with waste mixtures in the base and subbase layers performed better than the conventional control section. The construction cost estimate was prepared based on the current schedule of rates of the Public Works Department (PWD) in the state of Gujarat, India. Savings in the range of 9 – 17% can be achieved in overall construction when conventional granular materials are replaced with lightly cemented waste mixtures.

4 Conclusions

Following conclusions were drawn from the study:

- At the outset, the feasibility of constructing pavement sections with industrial waste mixtures in base as well as subbase layers was substantiated. The location of test sections was selected in such a way that, all possible industrial waste materials can be effectively utilized without causing any delay in the construction operations.
- For all the pavement sections with waste mixture in base as well as subbase layers, the peak deflection (D_0) which indicates the overall pavement performance were considerably lower than that of conventional control section.
- The lower D_0 for pavement sections with waste mixtures in base and subbase layers were supported with higher back-calculated moduli. E_{back} for both base and subbase layers were higher than that of conventional control section.
- Cost efficacy up to 17% was achieved with considerably better service life by the replacement of conventional granular materials with lightly cemented waste mixtures. Implementation of such projects on a large scale basis for the construction of highways will lead to effective utilization of industrial wastes subsequently bringing permanent cessation in the exploitation of natural aggregates.

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