Proceedings of the 7th International Conference on Civil Structural and Transportation Engineering (ICCSTE'22)
Niagara Falls, Canada – June 05-07, 2022
Paper No. 216
DOI: 10.11159/iccste22.216

Bulk Utilisation of Industrial Byproducts in Granular Layers of Flexible Pavements

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Abstract **-** To sustainably counter the problems of depleting natural aggregate resources and environmentally injurious metal slag and flyash open dumps, establishing the technical and economic feasibility of using industrial wastes to replace the natural aggregate is the need of the hour. The focal point of this research is to substantiate the bulk utilization of fly ash with different metal slags, namely, copper slag & granulated blast furnace slag (GBFS) base and subbase materials in flexible pavement. Based on detailed laboratory study and finite element analyses, three optimal combinations of waste materials were chosen, i.e., 40% copper slag + 60% fly ash (CCF) as base layers and fly ash + 5% lime (FL), 80% fly ash + 20% GBFS (FG) as subbase layers. To compare the field performance and service life of flexible pavement constructed with these three waste mixes in base and subbase layers with that of conventional pavement section, structural evaluation is carried out by means of falling weight deflectometer (FWD) on 9 test sections (each 3.5 m wide and 50 m long) with different thicknesses of base (150 mm & 250 mm) and subbase (200, 300 & 400 mm) layers with waste mixes. The results showed that upto 4200 tons of natural aggregates could be saved per lane per km of highway construction, with an overall cost saving of 4% to 15% by using this technology.

Keywords**:** Flyash, Metal Slags, Falling Weight Deflectometer, backcalculated moduli, service life ratio

1 Introduction

India has the second-largest road network in the world, spanning a total of 5.6 million kilometers. Since independence in 1947, expeditious infrastructure development impetus rapid growth in the transport and highway sector. The Ministry of Road Transport and Highways (MoRTH), Government of India, has set a target to construct 10,000 km National Highways in 2018-2019. In Dec 2020, MoRTH proposed to develop an additional 60,000 km of national highways by the year 2025. For construction, maintenance, and widening of roads, up to 15,000 tons of natural aggregates are required per lane per km of road, most of which is consumed by the granular base and subbase layers. Consequently, there is and would be a scarcity of suitable conventional materials for the construction of subbase and base layers of flexible pavements. Besides, the cost of extracting good quality natural material required is also increasing.

On the other hand, due to rapid economic growth and industrialization, many industrial waste materials are being generated, creating a tremendous threat to public health and ecology. The annual generation of fly ash in India was reported to be 196 million tons in 2017-18, with a utilization rate of 67% (CEA 2018). The total accumulation of copper slag in India was about 10 million tons in 2007 and had been increasing with 2.2 to 3 tons per ton of copper produced since then ([1], [2]). Bulk utilization of industrial wastes in road construction can solve the following two problems with one effort: (a) Solid waste disposal problem, preserving valuable land from huge dumps of waste; and (b) Provision of much-needed construction materials, thus protecting fast-depleting natural resources of aggregates.

From the previous studies, Havanagi et al. ([1] and [3]) substantiated that copper slag-fly ash mixture can be used as an embankment and subbase material for road construction. Consoli et al. ([4] and [5]), Ghosh and Subbarao [6] reported enhanced geotechnical properties of soil-fly ash-lime and fly ash-lime mixtures. In recent years, extensive investigations have been carried out on other industrial wastes such as steel slag [7], dolime fines, flyash and copper slag ([7]–[9]).

However, most of the previous studies are limited to just laboratory investigations. The use of industrial slags, namely, copper slag, GBFS, etc., stabilized with fly ash on Indian highways, has not been reported yet. Waste materials have never been used on Indian roads due to the absence of data about the field performance of flexible pavements.

2 Objectives

This study encompasses the early field performance of test sections constructed with industrial waste mixtures CCF, in the base layers and FL and FG in the subbase layers of flexible pavement. The major objectives of this study are as follows:

- To design and construct nine different test sections of flexible pavements as part of a state highway using three optimal combinations of different waste materials in the base and subbase layers.
- To perform structural evaluation of the nine test sections using Falling Weight Deflectometer (FWD).
- To compare the field performance, service life and cost-efficacy of flexible pavement constructed with these three optimal combinations of waste materials in base and subbase layers with conventional pavement section (control).
- To calculate the savings in the natural aggregates for waste mix in base and subbase layers.

3 Experimental program

3.1 Materials

The industrial wastes used for construction are Electric arc furnace (EAF) steel slag, Copper slag, Class F fly ash and Class C Fly ash. EAF Steel slag was procured from Essar Steel, Hazira, Gujarat. Copper slag was procured from Birla Copper, Dahej, Gujarat. Class F fly ash was procured from Reliance Industries Ltd., Hazira and Lignite (Class C) fly ash from Lignite Power Plant, Nani Naroli, Surat. Hydrated lime with available lime content not less than 70%, when tested according to IS: 1514 [10], was procured from Super Lime Traders, Surat, Gujarat. According to the toxicity characteristic leaching procedure (TCLP) – Method 1311 [11] specified by the United States Environmental Protection Agency, all the chosen industrial wastes were confirmed as non-hazardous.

3.2 Design of test tracks

The conventional control test tracks were designed based on the strength of the subgrade soil and the traffic data provided by the Road and Building Department, Surat, Gujarat. The thicknesses of pavement test tracks with industrial waste mix base and subbase layers were determined as per design methodology given by Patel [12] in his doctoral work, IRC 37 [13] guidelines for conventional flexible pavements and guidelines for cemented base and subbase.

Table 1: Design thickness of different layers of the nine test tracks.

Test Section	Layer thickness in mm								Total thickness (mm)
	BC	DBM	CRL	WMM	CCF	GSB	FL	FG	
Control	40	140	-	250	-	330	-	-	760
CCF 150	40	140	100		150	300	-	-	730
CCF 250	40	140	100		250	300	-	-	830
FL 200	40	140	-	250	-	-	200	-	630
FL 300	40	140	-	250	-	-	300	-	730
FL 400	40	140	-	250	-	-	400	-	830
FG 200	40	140	-	250	-	-	-	200	630
FG 300	40	140	-	250	-	-	-	300	730
FG 400	40	140	-	250	-	-	-	400	830

A total of 9 different test tracks, 50m long, 3.5m wide, resting on a subgrade of 4% CBR and traffic intensity of 75 million standard axles were designed. The thickness adopted for bituminous concrete (BC), dense bituminous mix (DBM), crack relief layer (CRL), wet mix macadam (WMM) & granular subbase (GSB) for conventional control sections and stabilized base and subbase sections are mentioned in Table 1.

Initially, a control section was designed as per the IRC 37 [13]. For CCF base, two different thicknesses, one thickness lower than conventional WMM (150 mm) and another equal to WMM (250 mm), were adopted to evaluate the pavement performance. Similarly, in the case of subbase waste mixes, FL and FG, three different thicknesses 200 mm, 300mm and 400 mm; one lower, one equal and one higher thickness than that determined for GSB for each of the optimal waste mixes were adopted.

3.3 Structural performance using FWD

FWD tests were performed in a zigzag manner at nine different locations, such that all points were equidistant from each other. Deflections corresponding to four different target loads at each test location, 40, 55, 70 and 80 kN, were measured. These values correspond to the equivalent standard axle load (ESAL) and the possible range of vehicular overloading, respectively. Seven geophones were spaced at 0, 300, 600, 900, 1200, 1500, and 1800 mm to record pavement's structural response in terms of peak deflection in microns, which is typically termed as a deflection basin. Individual layer moduli were determined using a back-calculation procedure based on a FE method available in ELMOD 6. In this procedure, a forward calculation using assumed values of layer moduli is carried out to generate a deflection basin. In an axisymmetric FE model, pavement layers are modelled as linear elastic materials with known thicknesses and Poisson's ratios. The generated deflection basin is thus compared with the observed basin to compute deviation in terms of percentage differences and root-mean-square (RMS) values. The algorithm is trained to iterate and arrive at the "most possible set" of layer moduli for which the percentage difference and RMS values are the least (1% to 3%). Seed moduli selected by the user initiate and guide the iteration process. The seed moduli are the most expected values of the layer moduli from the engineer's perspective.

4 Results and Discussion

4.1 FWD Backcalculated Moduli

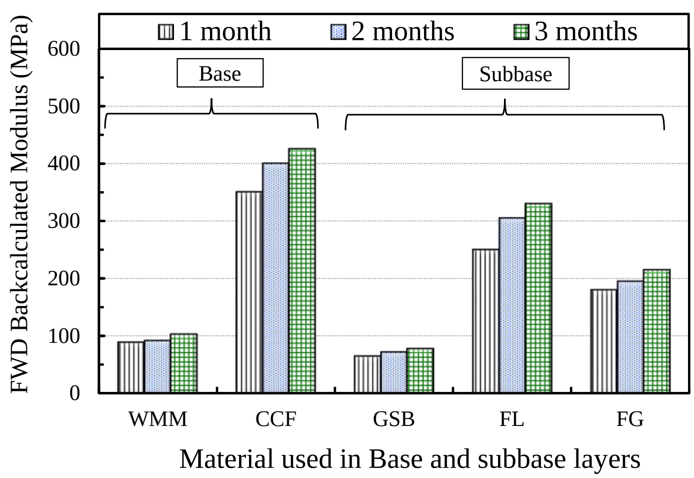

Fig. 1: Change in Backcalculated moduli values of all the base and subbase layers with curing period

Figure 1 presents the change in average backcalculated moduli (27 observations per mix per month) of different base subbase layers with curing period. For granular base and subbase, the moduli values increased slightly from 90 MPa to 100 MPa for WMM and from 68 MPa to 80 MPa for GSB. The slight increase in the granular moduli could be attributed to traffic compaction, which sets the freshly constructed pavements into a denser matrix, increasing the granular moduli. On the other hand, the waste mix base and subbase layers showed a 15% to 30% increase in the layer moduli owing to the pozzolanic reaction taking place in the flyash. In the presence of lime and waster, Silica, Alumina and Ferrous oxide in the flyash dissolves and dissociates into cations and anions. The cations then form cementitious gels, Calcium-Silicate-Hydrates (C-S-H) and Calcium-Alumino-Silicate-Hydrates (C-A-S-H). The amount of C-H-S and C-A-S-H gels formed is directly proportional to the fineness of flyash, lime content, ambient temperature etc. Three months after construction, CCF moduli values increased by 25% from 350 MPa to 425 MPa, while FL moduli increased by 32% from 250 MPa to 330 MPa. FG moduli increased by 15.6% from 186 MPa to 215 MPa. In the case of CCF and FL, class C flyash constitutes 15% free lime content and class F flyash, with externally added 5% lime work as cementitious materials, respectively. FG moduli increased by a lower extent due to lower free lime content available in the class F flyash (8.88%).

4.2 Service Life Ratio and Cost comparison

The service life ratio (SLR) of pavements with waste mixtures in base and sub-base layers compared to the conventional control section based on fatigue criteria is given by the following equation as per IRC 37 [13].

$$SLR = \left(\frac{\varepsilon_{t_1}}{\varepsilon_{t_2}}\right)^{3.89} \tag{1}$$

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 SLR and the construction costs of all nine different test sections are given in Table 2. For the different waste mix test sections, the SLR is consistently more than one due to the superior modulus of CCF base and FL, FG subbase compared to WMM and GSB, respectively. Compared to FL and FG, CCF test sections exhibit higher SLR owing to closeness to the asphalt base. The tensile strain at the bottom of the HMA layer is higher when the modulus of the base layer is low. In the FL and FG test sections, the HMA layer lies on the WMM layer, which is weaker than CCF. Compared to FL and FG layers, CCF improves the fatigue life of the HMA layer with the least overall pavement thickness. Therefore, the cost saving is maximum in CCF layer. The cost saving in the FL is lower than FG because of the additional lime required to make FL, which is very costly.

Table 2: Summary of service life ratio, waste utilization and savings in the aggregates for all the waste mix test sections.

Material	Thickness (mm)	SLR	Overall Construction cost (INR)			Waste Utilization, in tons/km of road length			Granular layer thickness in Equivalent design			Total aggregates used (tons/km)	Aggregate saved compared to control (%)
			Rate (m^3)	Rate/km (lakhs)	Savings (%)	Flyash	Metal Slag	Total	HMA	Base	Subbase		
Control section	WMM 250	1.00	1,399	86.6	--	--	--	--	180	250	330	7435.55	--
	GSB 330		1,328			--	--	--					
Test sections with waste mixtures in base layer													
CCF	150	1.34	850	76.34	11.85	567	378	945	140	100 (CRL)	300	4661.5	37
	250	1.59		73.03	15.70	945	630	1575	120		250	3668.2	50
Test sections with waste mixtures in subbase layer													
FL	200	1.29	683	78.43	9.43	840	--	840	160	120	-	3329.1	55
	300	1.44		80.70	6.81	1260	--	1260	150	110	-	3051.7	58
	400	1.54		83.04	4.11	1680	--	1680	140	100	-	2774.3	62
FG	200	1.12	632	77.92	10.02	672	168	840	160	150	-	3557.1	52
	300	1.23		79.89	7.74	1008	252	1260	150	140	-	3279.7	55
	400	1.31		81.96	5.35	1344	336	1680	150	120	-	3127.7	58

4.3 Waste utilization and savings in the aggregates

From Table 2, compared to CCF, FL and FG consume more flyash in weight and volume. However, it must be noted that CCF utilizes class C flyash, which has golden brown color and is not used in cement blends and brick making. In any case, the results show that by adopting the waste mix layers, at least 1000 kg (ton) of waste materials will utilised per km of a 3.5 m lane of the highway. Using the backcalculated moduli of different pavement layers, the optimum thickness of different pavement layers for CCF, FL and FG are calculated to achieve SLR equal to one, i.e., for a target design life of 75 million standard axle loads. Based on the revised thicknesses of different layers, the amount of aggregates saved is calculated. In the waste mix test sections, sections with CCF base consume the maximum amount of aggregates, while sections with FL subbase consume the least. The CCF base only replaces 250 mm of the WMM layer and requires 100 mm thick CRL. However, the use of the FL and FG subbase replaces the thicker GSB layer and reduce the thickness of WMM.

5 Conclusions

Following conclusions were drawn from the study:

- At the outset, the feasibility of constructing pavement sections with industrial waste mixtures in base and subbase layers was substantiated.
- Backcalculated moduli for both CCF base and FL, FG subbase layers were higher than conventional control section. It increased with the curing period due to the pozzolanic reaction in the flyash.
- SLR of 1.12 to 1.6 can be achieved when the equal thickness of the CCF base, FL, and FG subbase are used with a cost-efficacy of 4% to 15.5% compared to the conventional control section.
- At least a ton of waste materials can be consumed with maximum savings in the aggregate consumption of 62% compared to the conventional section.

These results allow a design of pavement that could serve different purposes such as the least crust thickness (FL 200 section), maximum waste utilization as per the available waste source or Maximum saving in natural aggregate consumption.

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