Proceedings of the 8th World Congress on Civil, Structural, and Environmental Engineering (CSEE'23)
Lisbon, Portugal – March 29 – 31, 2023
Paper No. ICGRE 150
DOI: 10.11159/icgre23.150

Field Investigation on Complete Replacement of Granular Subbase with Flyash and Blast Furnace Slag in Flexible Pavement

M. D. Bakare[1], J. T. Shahu[2], S. Patel [3]
[1, 2]Indian Institute of Technology, Delhi
Hauz Khas, New Delhi, India
cez178530@civil.iitd.ac.in , shahu@civil.iitd.ac.in
[3] Sardar Vallabhbhai Patel National Institute of Technology, Surat
Ichhanath, Surat, India
spatel@amd.svnit.ac.in

Abstract **-** With rapid industrial and transportation-related infrastructural growth in India, the problems of environmentally injurious metal slags, flyash open dumps and depleting natural aggregate resources are ever-increasing. The focal point of this research is to substantiate the bulk utilization of fly ash and granulated blast furnace slag (GBFS) as a replacement for a granular subbase (GSB) in flexible pavement. Based on detailed laboratory study and finite element analyses, optimal combinations of two waste mixes, i.e., fly ash + 5% lime (FL) and 80% fly ash + 20% GBFS (FG) were chosen. 7 test sections (each 3.5 m wide and 50 m long) with different thicknesses of waste mix subbase (200, 300 & 400 mm) layers were constructed. To compare the field performance and service life of waste mix test sections with conventional control section with GSB, structural and functional evaluation is carried out employing a falling weight deflectometer (FWD) and Bump Integrator for two years. The results showed that this technology could save up to 4200 tons of natural aggregates per lane per km of highway construction, with an overall cost saving of 4% to 10%.

Keywords**:** Flyash, blast furnace slag, 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 kilometres. Since independence in 1947, expeditious infrastructure development has impeded rapid growth in the transport and highway sectors. The Ministry of Road Transport and Highways (MoRTH), Government of India, has set a target to construct 10,000 km of National Highways in 2018-2019. In Dec 2020, MoRTH proposed to develop an additional 60,000 km of national highways by 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 constructing subbase and base layers of flexible pavements. Besides, the cost of extracting good quality natural material 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. Blast Furnace Slag (BFS) and Fly Ash (FA) are being generated at an alarming rate and openly dumped out, creating a tremendous menace to human health and ecology. In FY 2020-21, India produced 232 million tons of FA with a utilization rate of 92% [1]. According to Rastogi and Paul, approximately 1400 million tons of legacy FA lay unutilized in India [2]. India, the third-largest steel producer worldwide, generated about 40 million tons of BFS between 2017 and 2018 [3]. Complete replacement of GSBindustrial wastes in road construction can solve the following two problems with one effort: (a) Solid waste disposal problem, preserving valuable land from vast 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. ([4] and [5]) substantiated that copper slag-fly ash mixture can be used as an embankment and subbase material for road construction. Consoli et al. ([6] and [7]), Ghosh and Subbarao [8] 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 [9], dolime fines, flyash and copper slag ([9]–[11]).

However, most of the previous studies are limited to just laboratory investigations. The use of industrial slags, 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 FL and FG in the subbase layers of flexible pavement. The primary objectives of this study are as follows:

- Design and construct seven test sections of flexible pavements as part of a state highway using three thicknesses of FL and FG subbase layers.
- To perform a structural and functional evaluation of the seven test sections using a Falling Weight Deflectometer (FWD) and Bump Integrator (BI).
- To compare the field performance, service life and cost-efficacy of flexible pavement constructed with FL and FG subbase layers with conventional pavement section (control).
- Calculate the savings in the natural aggregates for waste mix in subbase layers.

3 Experimental program

3.1 Materials

The industrial wastes used for construction are Granulated Blast furnace slag and Class F fly ash. GBFS was procured from Essar Steel, Hazira, Gujarat and Class F fly ash was procured from Reliance Industries Ltd., Hazira. Hydrated lime with available lime content not less than 70%, when tested according to IS: 1514 [12], was procured from Super Lime Traders, Surat, Gujarat. According to the toxicity characteristic leaching procedure (TCLP) – Method 1311 [13] specified by the United States Environmental Protection Agency, all the chosen industrial wastes were confirmed as non-hazardous.

3.2 Design of test sections

The conventional control test sections 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 sections with industrial waste mix subbase layers were determined as per design methodology given by Patel [14] in his doctoral work, IRC 37 [15] guidelines for conventional flexible pavements and guidelines for cemented subbase.

Table 1: Design thickness of different layers of the test section.

Test Section	Layer thickness in mm						Total thickness (mm)
	BC	DBM	WMM	GSB	FL	FG	
Control	40	140	250	330	-	-	760
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 7 different test sections, 50m long, 3.5m wide, resting on a subgrade of 4% CBR and traffic intensity of 75 million standard axles were designed. The design thickness of bituminous concrete (BC), dense bituminous mix (DBM), wet mix macadam (WMM) and granular subbase (GSB) are given in Table 1.

Initially, a control section was designed as per IRC 37 [15]. For 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 Construction of the test sections

For FG and FL, GBFS, FA and lime were weighed and mixed using a weigh-batcher and a batching plant. In general, to avoid breaking up of binding gels in chemically stabilized materials, compaction must be carried out immediately after after mixing with water [16]. Furthermore, binding gels after complete addition of water corresponding to OMC would reduce the workability of the waste mix, subsequently making the waste mix laborious to unload, lay and spread [17]. Therefore, after dry mixing of FG and FL, only half of the water corresponding to OMC was added using a water tanker of 12,000-litre capacity. The remaining 50% of the water to reach the target OMC was spread and mixed uniformly while laying and spreading. The layers were then rolled by an 80 kN smooth wheel vibratory roller till a field density as per IS 2720 part 28 [18] was up to 95% of MDD. To compensate for the moisture loss due to evaporation, all the waste mix test sections were cured for seven days by sprinkling water three times a day. In-situ stiffness of all the subbase layers after seven days was determined using a Light Weight Deflectometer (LWD) (Dynatest 3031, Denmark) as a part of stiffness-based quality control according to ASTM E2583 [19].

3.4 Structural and Functional performance using FWD and BI

FWD tests were performed zigzag 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, typically termed a deflection basin. Individual layer moduli were determined using a back-calculation procedure based on a FE method available in ELMOD 6. This procedure uses a forward calculation using assumed values of layer moduli 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 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. From the engineer's perspective, the seed moduli are the most expected values of the layer moduli.

Pavement surface roughness is quantitatively measured using a fifth-wheel BI developed by Central Road Research Institute (CRRI), India. It is a single-wheeled trailer with a pneumatic tire mounted on a chassis towed by a vehicle during testing. It measures pavement roughness on a single longitudinal profile using a quarter-car simulation. The operating speed of BI is 32 ± 1 km/hr. International Roughness Index (IRI) can be calculated using Eq. 1 [20].

$$IRI = \sqrt[1.12]{\frac{UI}{630}} \tag{1}$$

During post-monsoon harvesting season, the Indian highways often experience overloading when single and tandem axle trucks loaded to maximum capacity carry the harvest from farms to factories. Therefore, a truck overloading program was planned to simulate the same after two years post-construction. Two single axle dual, wheel trucks filled with construction and demolition waste were passed over the test sections. Gross weight of the trucks were 24 tons which corresponded to rear axle load of 16 tons (160 kN). Each truck made a total of 940 rounds. Vehicle Damage Factor was calculated using the fourth power rule given in IRC 37 [15] was equal to 16. Hence, the total number of equivalent standard axle load (80 kN) passes corresponding to (940×2) 1880 truck passes was equal to about 30,000.

4 Results and Discussion

4.1 Quality of construction and modulus of subbase using LWD

Figure 1 presents 7-day LWD moduli values in the test sections with different subbase layers. According to Mooney and Miller, the depth of influence for a standard LWD is 0.9 times its diameter for sandy layers compacted over soft clay [21]. Therefore, the LWD moduli represent individual subbase layer modulus (and not the composite modulus). FL exhibited 86% higher modulus (213 MPa) than FG. The waste mix subbase had 40% to 250% higher modulus than GSB (80 MPa). The modulus of GSB is consistent with the modulus values reported by Umashankar et al. [22]. The COV is higher for FL, followed by FG and GSB. The Higher LWD moduli substantiate the superior strength of the waste mix subbase layers attained within 7 days of curing. The variation in the moduli results from nonuniformity in large-scale mixing in the field. However, as the COV values were less than 20%, the quality of the construction is deemed satisfactory [23]. Therefore, the results of LWD tests underline the feasibility of adopting the construction procedure followed in the study for satisfactory quality of construction.

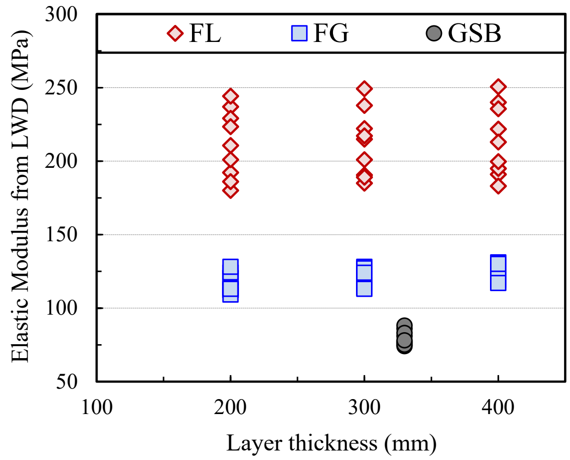

Figure 1. LWD modulus of FL, FG and GSB layers recorded 7-day post-construction.

4.2 FWD Backcalculated moduli

Figure 2 presents the change in average backcalculated moduli (27 observations per mix per month) of different subbase layers with curing period. FL and FG FWD moduli increased by 30% and 26% in the 270-day curing period post-construction owing to the pozzolanic reaction in the flyash. In the presence of lime and water, Silica, Alumina and Ferrous oxide in the flyash dissolve and dissociate into cations and anions. The cations 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 and ambient curing temperature. The peak average FWD moduli after 270 days of curing exhibited by FL (518 MPa) and FG (319 MPa) were 5 to 3 times that of the GSB (109 MPa). Peak performance was followed by change due to seasonal variation.

Average pre- to post-monsoon reduction in FWD moduli in the first cycle (July-Nov 2019) was about 9%, 13%, 15% and 19% for FL, FG, CFA and GSB subbase layers while in the second cycle (Feb-Sept 2020) it was 10%, 17% and 20% for FL, FG and GSB subbase layers. These values are comparable to different guidelines, which compare peak modulus (summer/dry condition) to the least modulus (post-monsoon or thawing) to establish correction factors for seasonal variation [24]. For example, In Idaho and Washington, a correction factor of 0.65 to 0.85 is used to convert the summer modulus to the thawing modulus [25], [26]. All the test sections showed statistically significant reduction (pre- to post-monsoon) in modulus values in both cycles. However, during the recuperation period, the modulus recovery was insignificant for FL layers (6%) and significant for FG and GSB subbase layers (11% and 23%, respectively). The preceding observations indicate that FL resists seasonal change in the modulus better than FG and GSB layers due to the low permeability (10^{-5} to 10^{-6} m/s) of the FL matrix [27], which restricts saturation of the layer by limiting the capillary rise of moisture from the subgrade. Consequently, FL exhibited a statistically insignificant recovery in the modulus value during recuperation, which was half to a third compared to that exhibited by FG and GSB layers.

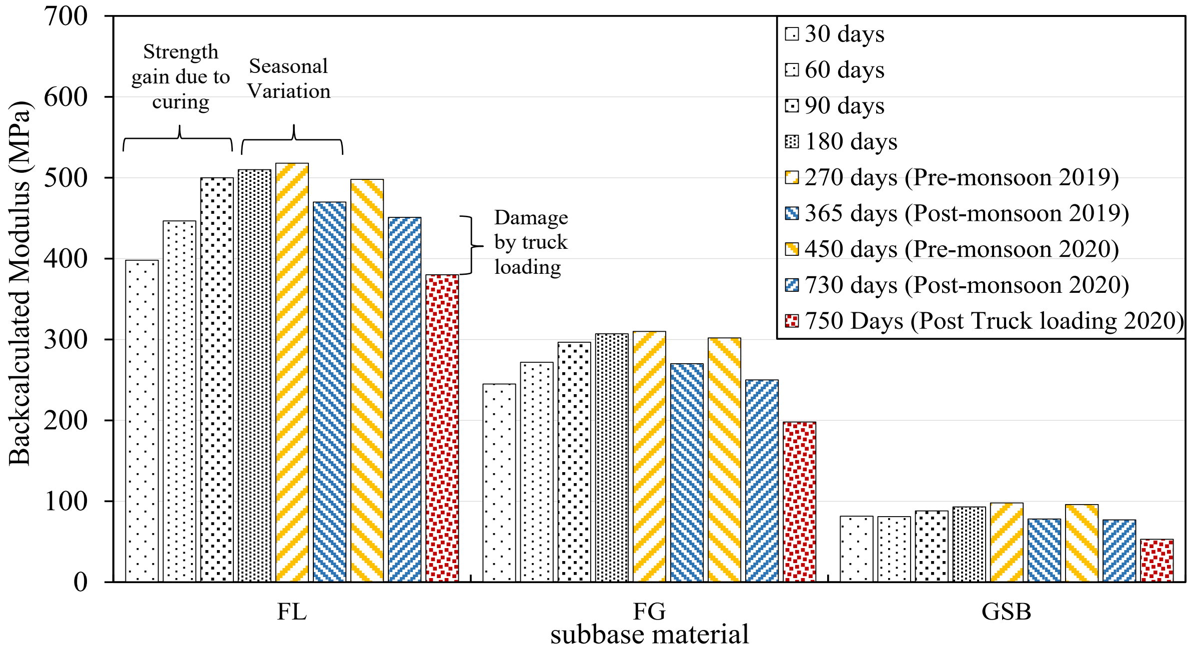

Fig. 2: Change in Backcalculated moduli values of FL, FG and GSB layers with curing period

4.3 Functional Performance of test sections

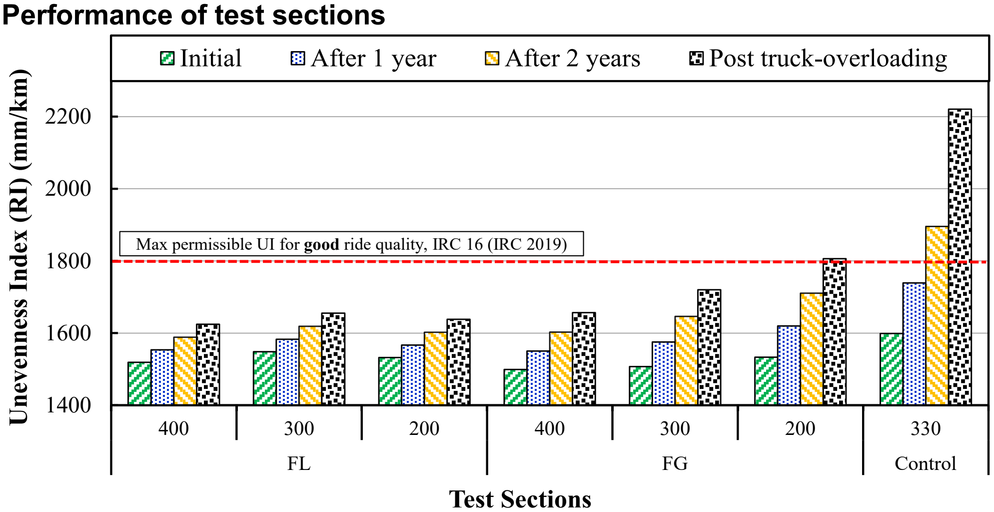

Figure 3. Summary of Unevenness Index using fifth wheel Bump Integrator.

Figure 3 presents the summary of UI of all seven test sections. All the test sections satisfied the IRC SP 16 criteria of good ride quality with initial UI less than 1800 mm/km. The FL test sections and FG 400 exhibited a mere 7% increase in the UI values after two years compared to 14% to 16% of FG 200 section and 18% of the control section. However, all the values after two years were either just below or above the threshold. UI from initial bump integrator tests indicate that appreciable differences in the functional performance would be realized only after the test sections are subjected to traffic loading for extended service periods without maintenance (4 to 8 years). However, it can be said that, with no intervention, i.e., maintenance, the test sections with FL with a slower rate of increase in UI indicate toward superior riding quality for a longer duration compared to the control section.

4.4 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 control section based on fatigue criteria is given by equation 2 as per IRC 37 [15].

$$SLR = \left(\frac{\varepsilon_{t_1}}{\varepsilon_{t_2}}\right)^{3.89} \tag{2}$$

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 seven different test sections are given in Table 2. The SLR is consistently more than one for the different waste mix test sections due to the superior modulus FL and FG subbase compared to GSB. The cost saving in the FL is lower than FG because the externally added lime 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 After 2 years	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 (WMM)	Subbase		
Control section	WMM 250	1.00	1,399	86.6	--	--	--	--	180	250	330	7435.55	--
	GSB 330		1,328			--	--	--					
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

4.5 Waste utilization and savings in the aggregates

From Table 2, the results show that by adopting the waste mix layers, at least 1000 kg (ton) of waste materials can be utilized 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 FL and FG are calculated to achieve SLR equal to one, i.e., for a target design life of 75 million standard axle loads. The amount of aggregates saved is calculated based on the revised thicknesses of different layers. In the waste mix test sections, sections with FL subbase consume the least amount of aggregates as the use of the FL and FG subbase replaces the thicker GSB layer and reduces the WMM thickness.

5 Conclusions

Following conclusions were drawn from the study:

- At the outset, the feasibility of constructing pavement sections with industrial waste mixtures in subbase layers was substantiated.
- Backcalculated moduli for both FL and 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 FL and FG subbase are used with a cost-efficacy of 4% to 10% 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 minimum crust thickness (FL 200 section), maximum waste utilization as per the available waste source or maximum saving in natural aggregate consumption.

References

[1] I. R. Mocharla, R. Selvam, V. Govindaraj, and M. Muthu, "Performance and life-cycle assessment of high-volume fly ash concrete mixes containing steel slag sand," *Constr Build Mater*, vol. 341, p. 127814, Jul. 2022, doi: 10.1016/J.CONBUILDMAT.2022.127814.

[2] A. Rastogi and V. K. Paul, "A critical review of the potential for fly ash utilisation in construction-specific applications in India," *Environmental Research, Engineering and Management*, vol. 76, no. 2, pp. 65–75, Jul. 2020, doi: 10.5755/J01.EREM.76.2.25166.

[3] NITI Aayog, "Strategy Paper On Resource Efficiency in Steel Sector Through Recycling of Scrap & Slag," *Ministry of Steel, Government of India*, 2018, doi: https://www.srtmi.com/uploads/pdf/RE_Steel_Scrap_Slag-NITIayog-28092018.pdf.

[4] V. G. Havanagi, A. K. Sinha, S. Mathur, and P. Prasad, "Experimental Study on the Use of Copper Slag Wastes in Embankment and Pavement Construction," *Symposium on ENGINEERING OF GROUND & ENVIRONMENTAL GEOTECHNICS*, no. 1982, pp. 259–264, 2008.

[5] V. G. Havanagi, S. Mathur, P. S. Prasad, and C. Kamaraj, "Feasibility of Copper Slag–Fly Ash–Soil Mix as a Road Construction Material:," *https://doi.org/10.3141/1989-43*, vol. 2, no. 1989, pp. 13–20, Jan. 2007, doi: 10.3141/1989-43.

[6] N. C. Consoli, P. D. M. Prietto, J. A. H. Carraro, and K. S. Heineck, "Behavior of Compacted Soil-Fly Ash-Carbide Lime Mixtures," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 127, no. 9, pp. 774–782, Sep. 2001, doi: 10.1061/(ASCE)1090-0241(2001)127:9(774).

[7] N. C. Consoli, A. D. Rosa, and R. B. Saldanha, "Variables Governing Strength of Compacted Soil–Fly Ash–Lime Mixtures," *Journal of Materials in Civil Engineering*, vol. 23, no. 4, pp. 432–440, Apr. 2011, doi: 10.1061/(ASCE)MT.1943-5533.0000186.

[8] A. Ghosh and C. Subbarao, "Strength Characteristics of Class F Fly Ash Modified with Lime and Gypsum," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 133, no. 7, pp. 757–766, Jul. 2007, doi: 10.1061/(ASCE)1090-0241(2007)133:7(757).

[9] S. Patel and J. T. Shahu, "Resilient Response and Permanent Strain of Steel Slag-Fly Ash-Dolime Mix," *Journal of Materials in Civil Engineering*, vol. 28, no. 10, p. 04016106, May 2016, doi: 10.1061/(asce)mt.1943-5533.0001619.

[10] S. Patel and J. T. Shahu, "Comparison of Industrial Waste Mixtures for Use in Subbase Course of Flexible Pavements," *Journal of Materials in Civil Engineering*, vol. 30, no. 7, p. 04018124, Jul. 2018, doi: 10.1061/(ASCE)MT.1943-5533.0002320.

[11] J. T. Shahu, ; S Patel, and A. Senapati, "Engineering Properties of Copper Slag-Fly Ash-Dolime Mix and Its Utilization in the Base Course of Flexible Pavements," 2013, doi: 10.1061/(ASCE)MT.1943-5533.0000756.

[12] BIS (Bureau of Indian Standard), "Methods of sampling and test for quick lime and hydrated lime," 1990.

[13] US EPA, "Method 1311: Toxicity Characteristic Leaching Procedure," *SW-846. United States Environmental Protection Agency. Washington D. C.*, pp. 1–35, 1992, Accessed: Oct. 08, 2021. [Online]. Available: https://www.epa.gov/hw-sw846/sw-846-test-method-1311-toxicity-characteristic-leaching-procedure

[14] Satyajit. Patel, "Experimental and Numerical Studies on Utilization of Some Industrial Wastes in Flexible Road Pavements," Indian Institute of Technology, Delhi, 2016.

[15] IRC, "Guidelines for the Design of Flexible Pavements," *IRC 37. New Delhi, India.*, 2012.

[16] D. Little and S. Nair, *Recommended Practice for Stabilization of Subgrade Soils and Base Materials*. Washington, D.C.: Transportation Research Board, 2009. doi: 10.17226/22999.

[17] K. J. Osinubi and C. M. Nwaiwu, "Compaction Delay Effects on Properties of Lime-Treated Soil," *Journal of Materials in Civil Engineering*, vol. 18, no. 2, pp. 250–258, Apr. 2006, doi: 10.1061/(asce)0899-1561(2006)18:2(250).

[18] BIS, "Methods for Test for Soils: Part 28 - Determination of dry density of soil in place by the sand replacement method," *IS 2720 Part 28. New Delhi, India.*, 2005.

[19] ASTM, “Standard Test Method for Measuring Deflections with a Light Weight Deflectometer (LWD),” *ASTM E2583-07. American Society for Testing and Materials. West Conshohocken, PA.*, 2007, doi: 10.1520/E2583-07R20.2.
[20] IRC, “Guidelines on Measuring Road Roughness and Norms,” *IRC SP 16. New Delhi, India.*, 2019.
[21] M. A. Mooney and P. K. Miller, “Analysis of Lightweight Deflectometer Test Based on In Situ Stress and Strain Response,” *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 135, no. 2, pp. 199–208, Feb. 2009, doi: 10.1061/(asce)1090-0241(2009)135:2(199).
[22] B. Umashankar, C. Hariprasad, and G. T. Kumar, “Compaction Quality Control of Pavement Layers Using LWD,” *Journal of Materials in Civil Engineering*, vol. 28, no. 2, p. 04015111, Feb. 2016, doi: 10.1061/(asce)mt.1943-5533.0001379.
[23] W. F. Barstis and J. Metcalf, “Practical approach to criteria for the use of lime-fly ash stabilization in base courses,” in *Transportation Research Record*, 2005, vol. 1936, no. 1936, pp. 20–27. doi: 10.3141/1936-03.
[24] J. M. Ovik, B. Birgisson, D. E. Newcomb, and D. of C. Engineering, “Characterizing Seasonal Variations in Pavement Material Properties for Use in a Mechanistic-Empirical Design Procedure.” p. 221, 2000. [Online]. Available: https://conservancy.umn.edu/handle/11299/701
[25] D. van Deusen, “Improved spring load restriction guidelines using mechanistic analysis,” in *Proceedings of the International Conference on Cold Regions Engineering*, 1998, pp. 188–199. Accessed: Jun. 06, 2022. [Online]. Available: https://trid.trb.org/view/672621
[26] F. Bayomy, F. Al-Kandari, and R. Smith, “Mechanistically Based Flexible Overlay Design System for Idaho,” *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1543, pp. 10–19, Jan. 1996, doi: 10.3141/1543-02.
[27] A. Ghosh and C. Subbarao, “Hydraulic Conductivity and Leachate Characteristics of Stabilized Fly Ash,” *Journal of Environmental Engineering*, vol. 124, no. 9, pp. 812–820, Sep. 1998, doi: 10.1061/(asce)0733-9372(1998)124:9(812).