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Evaluation of coal pond ash and quarry dust mix for pavement application

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Abstract

The depletion of high-quality natural resources such as soils and aggregates emphasize the necessity of incorporating alternative sustainable materials in road construction. Utilizing these waste materials not only addresses the challenge of their safe disposal but also contributes to sustainable road infrastructure development. The present work examined the potential of coal pond ash (Class F) modified with cementitious material like lime (L) and quarry dust (Q) in the subbase layer of flexible pavements. Through a series of tests including compaction, unconfined compression strength, durability assessment, and repeated load triaxial testing, it was determined that a mixture containing lime modified pond ash (70% P + 10% L) along with quarry dust of 20% exhibited the desired strength and durability characteristics required for subbase material in flexible pavement construction. Also, the proposed mixture demonstrated higher resilient modulus (M_R) than the traditional subbase layer (GSB). Further, the performance of pavement structure with the proposed mix by using KENLAYER analysis showed service life ratio (SLR) values of 1.175 for fatigue and 1.143 for rutting criteria in compared with GSB. From these findings it is suggested that the proposed mix offers a viable and sustainable solution for the road applications.

Keywords: Pond ash, Quarry dust, Subbase, UCS, Resilient modulus, SLR

1. Introduction

The construction of road networks is a crucial component of infrastructure development, and it relies heavily on the presence of ample quantities of superior natural aggregates [1]. However, the growing challenge of obtaining these aggregates as a result of diminishing natural resources has emerged as an urgent issue. To tackle this challenge, the use of industrial waste materials and by-products in road construction has become an important approach to reduce the dependence on limited natural resources. The construction industry commonly utilizes a diverse range of industrial waste materials, such as coal ash, steel slag, copper slag, silica fume, GGBFS, and rice husk ash [2]. These materials function as additional cementitious additives, either on their own or in conjunction with conventional cementitious components such as cement, lime, and gypsum [3, 4]. Among these industrial by-products, coal ash (which exists in the forms of fly ash, bottom ash, and pond ash) is particularly noteworthy due to its pozzolanic characteristics. The pozzolanic nature of this substance is due to its composition, which is characterized by a significant amount of calcium oxide (CaO), as well as silica and alumina [5, 6]. In general, Coal ashes are classified into two categories, Class 'C' and Class 'F', based on their calcium oxide content. Class-C ashes (CaO > 15%) possess inherent self-cementing properties, and do not necessitate the use of activators, whereas Class-F ashes (CaO < 15%) may require activators to initiate the hydration process. A significant amount of research has been focused on the incorporation of Class-C and F coal ashes, occasionally without and with the addition of other additives to enhance the strength of different layer materials in the construction of flexible pavement [3, 7-9]. An example of this is the combination of coal fly ash and copper slag to form a pavement material. The aptness of this mixture was proven through a comparative analysis that included the construction of full-scale pavement sections using both traditional and the suggested blend materials under real-life circumstances [10]. The study revealed enhancements in strength, resilient modulus, and California Bearing Ratio (CBR) measurements [3]. Furthermore, pond ash modified lime and fiber exhibited improved strength and resilient properties, making it a suitable material for pavement subbase applications [8]. The incorporation of reclaimed asphalt pavement material alongside fly ash as a foundational material was determined to meet established design criteria [11]. Incorporating fly ash into traditional materials for base and subbase layers resulted in notable enhancements in strength, thereby leading to reductions in the thickness of these layers. Therefore, the use of coal fly ash in large amounts for pavement construction is both economically feasible and environmentally sustainable [12, 13]. Concurrently, the dust generated from crushing aggregates which is known as quarry dust boons environmental issues due to its contribution to air pollution when not reused. The effective use of quarry dust in construction projects could result in cost reduction, material conservation, and enhanced utilization of available resources [2, 4]. Recent research has investigated the potential of quarry dust in construction applications. The application of quarry dust to soft subgrade soils led to increased CBR values [10]. Quarry dust has been used effectively to treat expansive clay soils in road construction to prevent its swelling nature by providing a cost-effective solution for the stabilization of natural soils.

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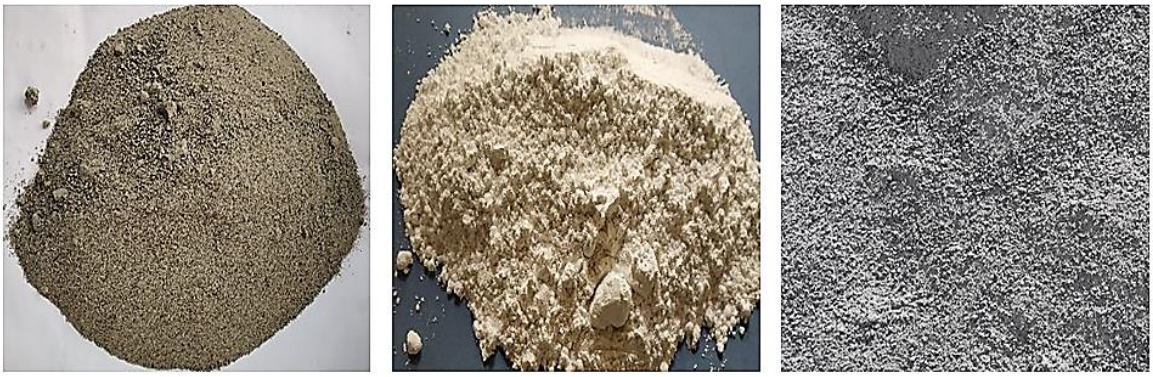
Hence, in this study, the conventional practice of using finite and non-renewable natural aggregates and soil for subbase construction on roads highlights the need to investigate sustainable alternatives. Coal pond ash, a residual substance generated by thermal power plants, and quarry dust, a discarded material resulting from aggregate crushing operations, present easily accessible waste resources that offer a viable solution to decrease dependence on diminishing natural resources. According to IRC 37-2012 [14] specification, it is allowed to include cemented subbase layers in the flexible pavement, in addition to a crack-relief layer. Hence, the present work aims to assess the viability of utilizing coal pond ash (treated with cementitious materials, lime) along with quarry dust as a sustainable alternative material for the construction of subbase layer in flexible pavements.

2. Materials and methods

2.1 Materials

Pond ash, sourced form Bhupalapalle- KTPP power plant, India, is used in the study, and its properties are as follows: specific gravity = 1.925, particle size analysis (gravel = 0%, sand = 64%, fines = 36%), compaction parameters (MDD = 11.26 kN/m^3, OMC = 34%), angle of friction = 31°, CBR = 21%. The lime content present in pond ash (P) is 2.6% (< 15%), and hence, as per ASTM standards, it is Class-F type ash material. The additive lime used in the study is commercially available lime with a purity of 72%. Quarry dust (Q) utilized in this work is obtained from a nearby stone crushing plant in Warangal, Telangana. The quarry dust had the particle of size that pass through 1.18mm sieve (Figure 1).



(a) (b) (c)

Figure 1 Materials for Experimentation (a) Pond ash (P), (b) Lime (L), (c) Quarry dust (D)

2.2 Experimental test program

Pond ash collected in the present study is Class-F type, hence for the development of pozzolanic nature, it is mixed/treated with lime content of 10% (The lime content selected here is based on the purity of lime and pH test). Afterward, the lime-treated pond ash blends are then mixed with various proportions of quarry dust including 10%, 20%, 30%, and 40%. A summary of the mix designations and descriptions is provided in Table 1.

Table 1 Mixes used in the study

Description	Indication
Pond ash (P)+ Lime (L) + 0% Quarry dust(Q)	PLQ0
Pond ash + 10% Lime + 10% Quarry dust	PLQ10
Pond ash + 10% Lime + 20% Quarry dust	PLQ20
Pond ash + 10% Lime + 30% Quarry dust	PLQ30
Pond ash + 10% Lime + 40% Quarry dust	PLQ40

Firstly, Proctor compaction test (IS 2720-Part 8) [15] is conducted on all mixes to establish MDD and OMC values. For this, the pond ash, lime, and quarry dust were measured on a dry weight basis and placed in a small-sized mixer. The materials were thoroughly blended in the mixer, and then water was gradually added to the mix in an incremental way. Then, the UCS test (IS 2720-Part 10 [16]) is carried out on specimens measuring 100 mm in height and 50mm in diameter prepared at respective MDD and OMC of mixes. The prepared UCS specimens are cured in plastic bags at a room temperature of 27 ± 2 °C by keeping them in a desiccator. UCS test was then performed as per IS 4332-V (2006). Before testing, samples were submerged in water for at least one hour saturation to reduce matrix suction.

Further, as per ASTM D559, similar cylindrical specimens are prepared to assess the weight loss when subjected to alternate wetting and drying conditions (Figure 2).

Based on the outcomes of the above two tests, the mix proportions meeting IRC criteria are selected for determining resilient modulus (M_R) values in accordance with AASHTO-T307 [17]. M_R value is a critical parameter in the design of flexible pavements, as it characterizes the pavement material response to the real loads caused by traffic-induced movement. Further, to assess the performance of a pavement structure, service life ratio (SLR) is computed using KENLAYER program from the fatigue and rutting criteria.

(a) (b) (c) (d)

Figure 2 a) PLQ Samples, b) UCS Test, c) CBR Test and d) Durability test

For computing M_R, specimens of size 75 mm X 150 mm, diameter and length are prepared and conducted test on repeated load triaxial equipment (Figure 3) by following AASTHO T-307 [17] specifications. During the test, a cyclic loading of total 15 stress levels each of 100 load repetitions (Table 2) is applied in sequences with a loading and unloading time of 0.1 and 0.9 seconds at a frequency of 1.0 Hz. At the end, M_R for each stress level combination is calculated by averaging the moduli of the last 5 cycles (96^{th} to 100^{th}) using the following equation (1)

$$M_R = \frac{\sigma_d}{\epsilon_r} \tag{1}$$

σ_d and ϵ_r = Deviatoric stress and resilient deformation at a given load cycle combination

Figure 3 Triaxial testing Equipment

Table 2 Loading sequence (AASTHO T-307)

Sequence No.	Confining Stress, σ_c, (kPa)	Deviatoric Stress, σ_d, (kPa)	Load cycles
0	103.4	103.4	500
1		20.6	100
2	20.6	41.3	100
3		62.1	100
4		34.4	100
5	34.4	68.9	100
6		103.4	100
7		68.9	100
8	68.9	137.9	100
9		206.8	100
10		68.9	100
11	103.4	103.4	100
12		206.8	100
13		103.4	100
14	137.9	137.9	100
15		275.8	100

3. Results

3.1 Standard proctor compaction

The compaction properties of various mix proportions (PLQ blends) are illustrated in Table 3. It is observed that the MDD and OMC of pond ash and lime treated pond ash pond ash are 12.25 kN/m^3, 12.56 kN/m^3 and 26.12%, 27.15%, respectively; and these MDD and OMC values are well within the range of Indian coal ashes [18]. Upon incremental addition of quarry dust (PLQ10 to PLQ30), MDD values increased from 13.41 kN/m^3 to 15.82 kN/m^3, and the corresponding OMC values decreased from 25.16% to 22.16%. However, with the addition of 40% quarry dust (PLQ40), both MDD and OMC exhibited minimal changes. This phenomenon can be attributed to the fact that the pozzolanic reaction is initiated as soon as water is introduced into the pond ash-lime mixes, and ash consumes water during this reaction. Quarry dust, being non-cohesive and of finer size, does not absorb water during the strength development process [2]. Additionally, the specific surface area of pond ash surpasses that of quarry dust, necessitating a higher proportion of pond ash in the mixture to achieve the desired MDD due to its enhanced water consumption during compaction.

Table 3 Compaction Properties of PLQ Mixes

Mix	MDD (kN/m^3)	OMC (%)
P	12.25	26.12
PL	12.56	27.15
PLQ10	13.41	25.16
PLQ20	14.91	24.48
PLQ30	15.01	23.16
PLQ40	15.07	22.52

3.2 UCS test

The variation in UCS values for PLQ specimens obtained after 7 and 28 days of curing period are depicted in Figure 4. From this, it is observed that with an increase in curing time, the UCS values increased significantly for PLQ mixes. This enhancement can be attributed to the progressive development of the pozzolanic reaction between the constituent particles, resulting in improved interparticle bonding and overall strength. It is also noted that as the percentage of quarry dust addition increased the strength of the PLQ is increased consistently up to 20% Q and shown beneficial effects. Beyond this, a declining trend is observed in UCS values. This phenomenon can be attributed to the increasing presence of coarser non-cohesive particles by adding quarry dust in the mixes which may impede the formation of binding gels crucial for cementation during the curing process. As per IRC 37, the subbase material should possess UCS of more than 7 MPa after 7-days. From the results, PLQ20 mix marginally met the strength requirements specified by IRC 37 [14].

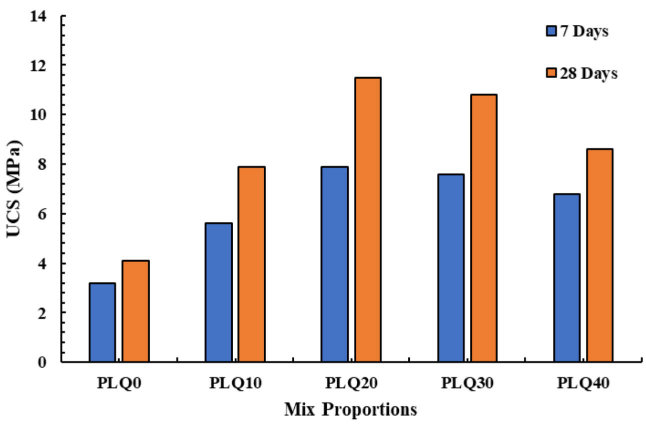


Figure 4 Variation in UCS of PLQ mixes at 7- and 28-days curing periods

3.3 Durability test

For evaluating the durability of materials all PLQ specimen cured for 7 days are subjected to 12 wetting and drying cycles following ASTM D559 guidelines (wet–dry durability test: water bath for 5 h- oven dry at 72°C for 42 h-hand brushing); and the test results are presented in Table 4 with percentage of weight loss. In the context of a durability assessment for materials intended to deploy as a subbase in flexible pavement systems, the weight loss remains less than 14%, as per IRC 37 standards [14]. It is observed that specimens of PLQ10 and PLQ20, satisfactorily met the durability criteria. Conversely, PLQ30 (very near to 14%) and PLQ40 doesn't meet the required standards, which could be due to inadequate inter-particle bonding of the particles leading to increased susceptibility to degradation under cyclic loading and environmental conditions.

Table 4 Percentage weight loss of PLQ mixes

Mix	Weight loss (%)
PLQ10	7.18
PLQ20	10.13
PLQ30	13.14
PLQ40	28.24

3.4 Repeated load triaxial test

From the test results of UCS and durability, PLQ20 mix satisfied the required criteria for subbase application, hence consequently, repeated load triaxial (RLT) test is performed on PLQ20 specimens after 7days of curing as well as on traditional granular subbase (GSB) material, and the same results are compared for their performance.

The GSB material used in this study was sourced from a local stone quarry in Warangal; typically consists of coarse aggregates, sand, and fine particles of silt and clay. The GSB has the following properties: MDD = 2.22 g/cc, OMC = 7.2%, LL = 24%, PI < 6 and soaked CBR = 33.56% meeting the specifications requirements of subbase as per MoRTH specifications. For the preparation of specimens for triaxial test, a steel split mold with dimensions of 75 mm x 150 mm was used, and samples were compacted in a minimum of six layers under MDD and OMC. The particles larger than one-fourth of the specimen diameter were removed prior to compaction. The remaining testing procedure is similar to those used for PLQ mixes.

In adherence to the established standards such as AASHTO T307 and NCHRP 2003, for a typical flexible pavement, confining stress (σ_c) of 34.5 kPa and deviator stress (σ_d) of 103.5 kPa are considered as a critical stress level in the middle of pavement layer. Hence, for subsequent comparison M_R values of PLQ20 and GSB at this stress level combination are considered for respective performance characteristics.

As depicted in Figure 5, it is observed that with increased deviator stress at all confining stress level, M_R values are found to be increased in both PLQ20 and GSB. However, the rate of increment is higher for PLQ20. Attributable to the progressive formation of cementitious bonds among its constituent particles over time. This phenomenon imparts a strain-hardening nature to PLQ20 specimens, enhancing their ability to withstand repeated loading cycles [3, 19].

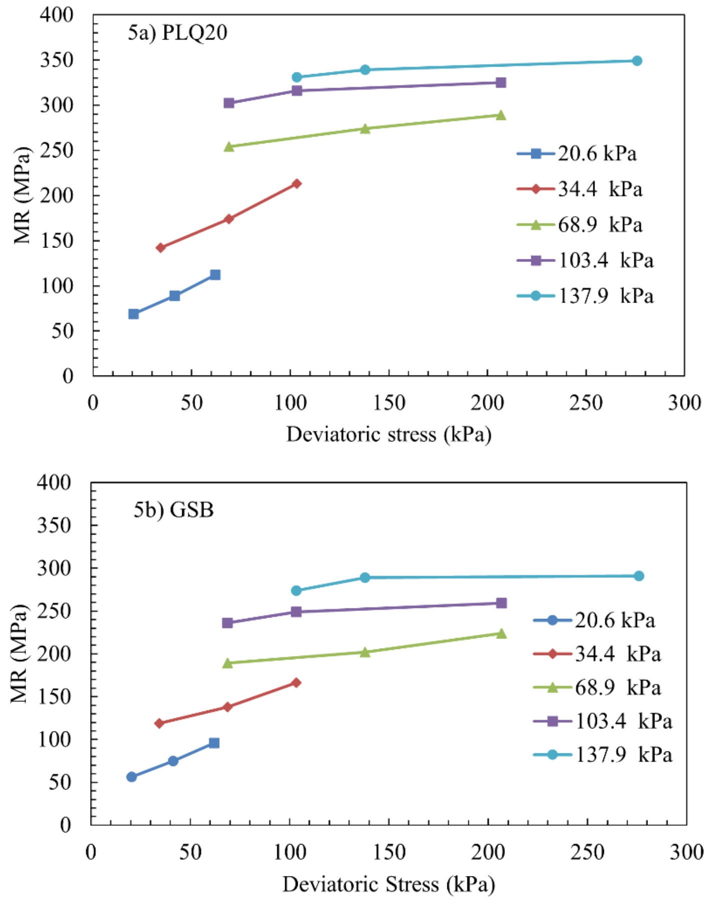


Figure 5 M_R values of a) PLQ20 at 7 days, and b) GSB at various stress levels (σ_c and σ_d)

To facilitate the predicting of the M_R of mixes at different stress levels, present work employed the bulk stress model [20], Power model [21]. as two-parameter based model approaches. Linear statistical regression analysis is subsequently carried out to validate experimental M_R values and ascertain the corresponding regression model constants (K values) and correlation coefficients (R^2 values) enabling robust predictions of M_R under different loading conditions. Where, σ_d, σ_c, σ_1 represents deviatoric stress, confining stress (kPa), axial stress (kPa) respectively, θ indicates bulk stress, k_1 to k_4 are regression constants, R^2 is regression coefficient.

$$M_R = k_1 \times \theta^{\,k_2} \tag{2}$$

$$M_R = k_3 \times \sigma_d^{\,k_4} \tag{3}$$

Figures 6 and 7 show the measured v/s predicted M_R plots generated by both bulk stress and power model. The regression constants K_1 to K_4 and corresponding R_2 values of models are given in Table 5.

From the results it is observed that the bulk stress model is able to predict the resilient modulus behaviour, as indicated by higher R^2 values exceeding 0.75.

This performance can be attributed to the comprehensive consideration of stress effects, encompassing both confining stress (σ_c) and deviator stress (σ_d), inherent in the bulk stress model. In contrast, the Power model neglects the influence of confining stress, resulting in diminished predictive accuracy.

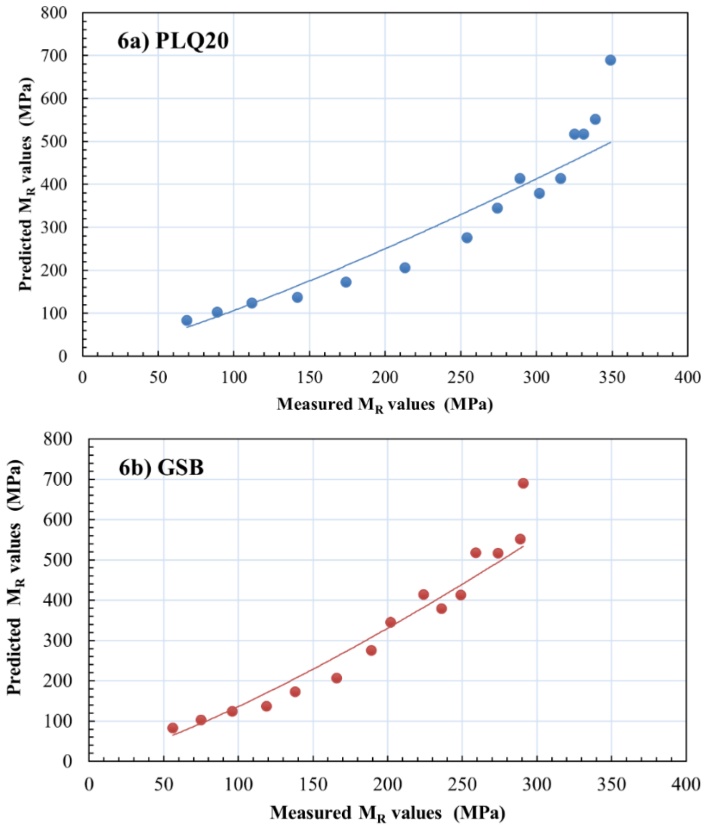


Figure 6 Measured and predicted M_R values comparison using model 1 a) PLQ20 b) GSB

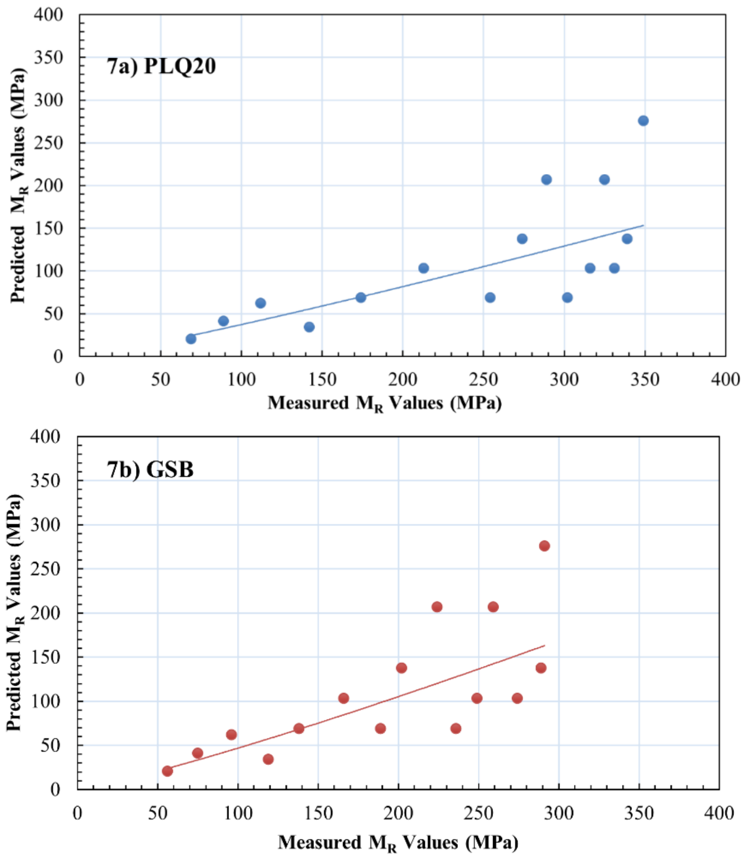


Figure 7 Measured and predicted M_R values Comparison of using model-2 a) PLQ20 b) GSB

Table 5 Regression model constants of M_R

	Regression constants	Mixes	
		PLQ20	GSB
Model 1	K_1	0.358	0.375
	K_2	1.235	1.279
	R^2	0.90	0.94
Model 2	K_3	0.204	0.217
	K_4	1.131	1.167
	R^2	0.54	0.55

4. Pavement analysis

To compare the performance of proposed mix (PLQ20) material and conventional granular subbase, KENLAYER program was used to simulate the analysis. For this, a pavement section for traffic of 15 msa load with 15 years of design period. In accordance with IRC 37, the details of each layer of pavement section considered in the study are as follows: The surface layer (BC+DBM, thickness 110mm), Base layer (wet mix macadam, WMM, thickness 250mm) and subbase layer (GSB for traditional and PLQ20 for proposed mix of thickness 110mm). The properties Mr and Poisson's ratio (μ) of pavement layers for KENLAYER analysis are shown in Table 6.

Table 6 Pavement cross section details used for KENLAYER program

Layer	M_R (MPa)	μ
BC + DBM	3000	0.35
WMM	450	0.35
GSB / PLQ20	166/213	0.4
Subgrade	50	0.4

To assess and quantify the performance of pavement section using conventional and proposed mixes, SLR parameter is calculated based on fatigue (Equation 4) and rutting criteria (Equation 5):

$$SLR_{\,fatigue} = \left(\frac{\epsilon_{t1}}{\epsilon_{t2}}\right)^{3.890} \tag{4}$$

$$SLR_{\,rutting} = \left(\frac{\epsilon_{v1}}{\epsilon_{v2}}\right)^{4.5337} \tag{5}$$

where ϵ_{t1} and ϵ_{t2} represent the maximum horizontal tensile strain at the bottom of GSB and PLQ20 mix, respectively. Likewise, ϵ_{v1} and ϵ_{v2} are the maximum vertical strain at the top of the subgrade for GSB and PLQ20, respectively. The SLR values indicate the relative remaining life of the pavement sections under different conditions.

Table 7 presents the strain values developed at top and bottom of subgrade and bituminous layers for both traditional and proposed road sections obtained from KENLAYER program, along with their corresponding SLR values. It is observed that the pavement section with PLQ20 mix in the subbase layer demonstrated SLR values of 1.175 for fatigue and 1.143 for rutting; and these results indicate that the proposed pavement offers a 17.5% longer service life in fatigue and a 14.3% longer service life in rutting, compared to traditional GSB.

Table 7 Service life ratio results for GSB and PLQ20 mix proportions

Subbase layer material	Strain		SLR	
	Fatigue (ϵ_t)	Rutting (ϵ_v)	Fatigue	Rutting
GSB	-2.226×10^{-4}	3.385×10^{-4}	1	1
PLQ20	-2.135×10^{-4}	3.287×10^{-4}	1.175	1.142

5. Conclusions

The study is focused on the utilization of coal pond ash modified with lime and quarry dust in the subbase layer of flexible pavements; from the experimental findings, the following conclusions are drawn:

- The PLQ20 mixture effectively meets the desirable strength and durability characteristics (UCS of > 7 MPa after 7-day curing, and <14% weight loss) for subbase material in flexible pavement construction specified in standard IRC codal specifications and indicating its ability to withstand environmental conditions and cyclic loading.
- At different stress levels, the PLQ20 mixture shows noticeably higher M_R values than the traditional GSB layer which indicating its ability to withstand repeated loading cycles as it is important parametric aspect for the longevity and stability of flexible pavements.
- The bulk stress model, which comprehensively considers both confining stress and deviator stress, offers a better fit with experimental and predicted M_R values compared to the power model
- The KENLAYER analysis revealed that the pavement with the PLQ20 mix achieved SLR values of 1.175 for fatigue and 1.143 for rutting criteria, compared to the traditional pavement section. These values indicate that the proposed pavement offers a longer service life than the conventional pavement.

From these findings, it is suggested that the PLQ20 mix proportion can be employed in the subbase layer of flexible pavement.

6. Acknowledgments

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