Resilient Behavior of Coal Pond Ash

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Abstract. The mechanical response of pavement materials, known as resilient characteristics such as resilient modulus (M_R), permanent deformation (ϵ_p), is a significant input in the design of pavements. As a result, the current work is focused to investigate the above-mentioned characteristics of coal pond ash, as well as other geo-mechanical properties for its application in pavement sub-base layer. The influence of different stress levels (confining stress σ_c, & deviatoric stress, σ_d) on the resilient behaviour of pond ash was studied using repeated load triaxial (RLT) experiments. The test findings show that increasing stress levels resulted in a minor improvement in the resilient behaviour of pond ash. In addition, the obtained M_R and ϵ_p values are validated using existing mechanistic-empirical prediction models.

Keywords: Pavement · Subbase · Coal Pond ash · Stiffness (M_R) · Deformation (ϵp)

1 Introduction

In the process of generating electricity, thermal power plants (TPPs) produce a considerable quantity of coal ash (pond ash) as a waste by-product, reaching approximately 200 million metric tons per year. However, only a small portion of this large quantity is utilized in various ways, while the remaining is discarded on valuable land. This leads to contamination of soil and water bodies, thereby adversely affecting public health and the ecosystem [1]. Nonetheless, pond ash exhibits favorable properties, such as low insensitive to water (for compaction), high bearing resistance, less compressible with good shear resistance, and low specific gravity. Therefore, it can potentially serve as a valuable construction material, promoting high-volume utilization for sustainable infrastructure development. Numerous prior investigations on the partial substitution of soil with coal ash (with or without admixtures) have reported improved mechanical properties (strength, failure behaviour) [2]; and such approaches not only facilitate the large-scale applications of coal ash but also provide a cost-effective solution for road construction.

The design and analysis of pavements typically rely on material strength properties such as UCS and CBR [3]. However, evaluating strength properties in a laboratory

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setting under a static load state does not replicate real traffic mechanistic behavior. Moreover, these design parameters are usually limited to traditional construction materials. However, studies have stated that strength parameters such as UCS and CBR can be useful for material selection guidance [4, 5]. Therefore, AASHTO and NCHRP recommended using resilient modulus (M_R), a fundamental stiffness property for characterizing pavements, particularly those that utilize coal ash as a base material, representing the mechanical response of the material (stress, strain, and deflection) as a result of wheel loads [6, 7].

Similarly, the permanent deformation (ϵ_p), which is also an important consideration to investigate the long-term behavior and failure mechanism of pavement structure to its allowable limits [8, 9]. Numerous studies have reported the resilient and deformation behavior of conventional and recycled materials (such as sand, unstabilized/stabilized soils, recycled aggregate materials, and unbound aggregates) under repeated dynamic loading and also developed mathematical models for validating its resilient characteristics [1, 4, 5]. Though the earlier studies have focused on the use of coal pond ash in road structures, there is inadequate literature reported on their resilient behavior under repeated loading. Therefore, this study aims to examine the resilient characteristics of pond ash and its potential for sub-base layer application in pavement construction.

2 Materials and Test Method

2.1 Materials

Pond ash, from Bhupalapalle-Kakatiya Thermal Power Plant (KTPP), India, is used in the study (Fig. 1a), and its grain size distribution is shown in Fig. 1b. The collected ash sample is stored in bulk storage drums to maintain its uniform characteristics throughout the experimental work, using procedures similar to those for handling portland cement. The properties of pond ash are: specific gravity = 1.92, gravel = 64%, sand = 36%, fines = 36%, MDD = 11.2 kN/m^3, OMC = 34.02%, frictional angle = 31°, CBR = 21 (unsoaked), 4.2 (soaked). The chemical composition of pond ash is $SiO_2 = 62.1$; $Al_2O_3 = 13.6$; $Fe_2O_3 = 2.51$; $SO_3 = 0.25$; LOI = 11.02; Others = 8.86; and the lime content in pond ash is 2.6% (< 15%), and hence, based on ASTM C 618-19 standards, it is categorized as Class F type ashes.

2.2 Repeated Load Triaxial (RLT) Test

For the purpose of computing M_R, the RLT test is one of the most important experiments (Fig. 2). To this, pond ash (75 X 150 mm, diameter and length) specimens are prepared by compacting it in eight layers (25 blows/layer); and the testing was carried out following the AASTHO T-307 codal procedure [6]. During the test progress, a cyclic loading of total of 15 stress levels of each 100 load repetitions were applied in sequences with a load time (0.1 sec) at a frequency of 1.0 Hz (Fig. 3a). Finally, M_R for each stress level is calculated by averaging the moduli of the last 5 cycles of each stress level combination [1, 6].

Permanent deformation is an important consideration in determining the enduring behaviour of road structures. Hence, to know the deformation behaviour of pond ash as

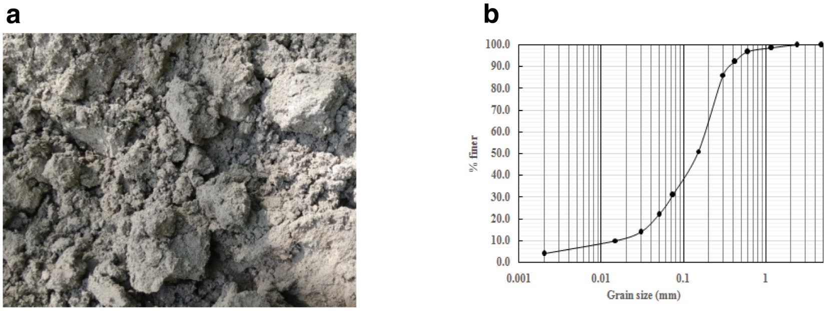


Fig. 1 (a) Pond ash sample, (b) Grain size curve for pond ash

Fig. 2. Cyclic Triaxial Equipment

a pavement material, RLT tests were conducted at load stress combinations which are considered based on previous literature i.e., at a constant confining stress (σ_c) of 34.5 kPa with 3- different deviatoric stress, σ_d of 100 kPa, 200 kPa, and 300 kPa for load cycles of 3000 N, 3000 N, and 4000 N to a total of 10000 N load replications in 3-different stress stages, respectively. For this, the specimens are prepared in the same manner as an M_R test [1].

3 Results

3.1 Resilient Modulus

In accordance with the AASHTO T-307 standard, resilient modulus (M_R) tests are conducted on pond ash under various combinations of σ_c and σ_d, as illustrated in Fig. 3b. Typically, the base/subbase layers of a flexible pavement experience σ_c and σ_d of 34.5 kPa &

Table 1. Regression analysis model constants of M_R

Model	$M_R = k_1 * \left(\frac{\sigma_c}{P_a}\right)^{k_2} * \left(\frac{\sigma_d}{P_a}\right)^{k_3}$ [**M1**]			$M_R = k_1 * \left(\frac{\theta}{P_a}\right)^{k_2} * \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3}$ [**M2**]		
Model constants	K_1	K_2	K_3	K_1	K_2	K_3
	0.528	0.371	-0.231	0.488	0.448	-0.721
R^2	0.928			0.769		

P_a = Atm. Pres. (101.3 kPa); τ_{oct} = shear stress (octahedral); bulk stress; θ; and k_1–k_3 = model constants

103.4 kPa [1]. Thus, these stresses were taken as reference values for the comparison of MR. The results indicate that the M_R values of compacted pond ash increased from 13 MPa to 25 MPa as the stress levels increased. For instance, at a σd of 103.4 kPa, an increase of σc from 34.4 kPa to 137.9 kPa led to a 66% increase in M_R values due to increased confinement, which resulted in a decrease of lateral strain deformation under the given σ_d stress level. On the other hand, at σ_c of 34.4 kPa, with an increased σ_d from 34.4 kPa to 103.4 kPa resulted in 28% decrease in M_R values due to development of strain softening in the specimen during loading.

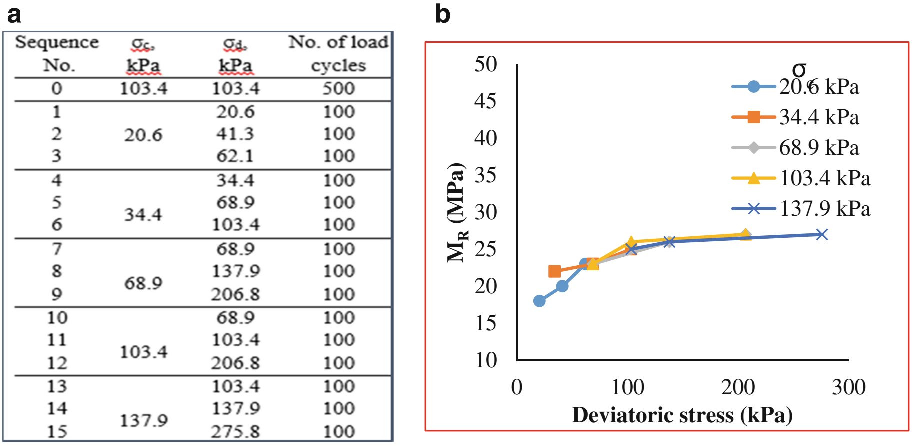
Similar findings have been reported in previous studies for ash-based fills and fine-grained silty soils compacted to their MDD at OMC. However, the increased M_R of pond ash does not meet the minimum M_R requirement of 100 MPa for sub-base application.

3.2 Modelling Studies for M_R

By using two stress-dependent 3-parameter models constitutive models (M1 and M2), the obtained experimental results of M_R values are carried out for validation to determine the respective regression model constants with correlation coefficients [1]. And, the correlation coefficients (R^2) of the corresponding M_R models are presented in Table 1. These 3-parameter models consider the influence of all applied stress conditions on the sample, including confining, deviatoric, bulk, and shear stresses. The constants represented by k_1, k_2, and k_3 in the equations are directly related to the material's elastic behavior; and the R-square values vary based on the impact of applied stresses on the specimen. It is noted that the R^2 for Model 1 and Model 2 are both greater than 0.75, indicating that the M_R behavior of pond ash was effectively predicted. Model 2 demonstrates a lower impact of shear stress conditions (with a high negative exponent) compared to Model 1. Consequently, Model 1 exhibits a higher regression coefficient in this case.

3.3 Permanent Deformation

The effect of σd & load reiterations (N) on deformation (ϵ_p) is depicted in Fig. 4. It is observed that ϵp increases with increasing load cycles (N) (from 2.313% to 3.562% for 100 N to 10,000 N), as each load cycle application contributes to a small rise in strain buildup and deformation in the testing specimen. For instance, at σ_c of 34.5 kPa,



Sequence No.	σc, kPa	σd, kPa	No. of load cycles
0	103.4	103.4	500
1	20.6	20.6	100
2		41.3	100
3		62.1	100
4	34.4	34.4	100
5		68.9	100
6		103.4	100
7	68.9	68.9	100
8		137.9	100
9		206.8	100
10	103.4	68.9	100
11		103.4	100
12		206.8	100
13	137.9	103.4	100
14		137.9	100
15		275.8	100

Fig. 3. a. Load sequence for M_R. b. Variation in M_R of pondash w.r.t. σ_c & σ_d

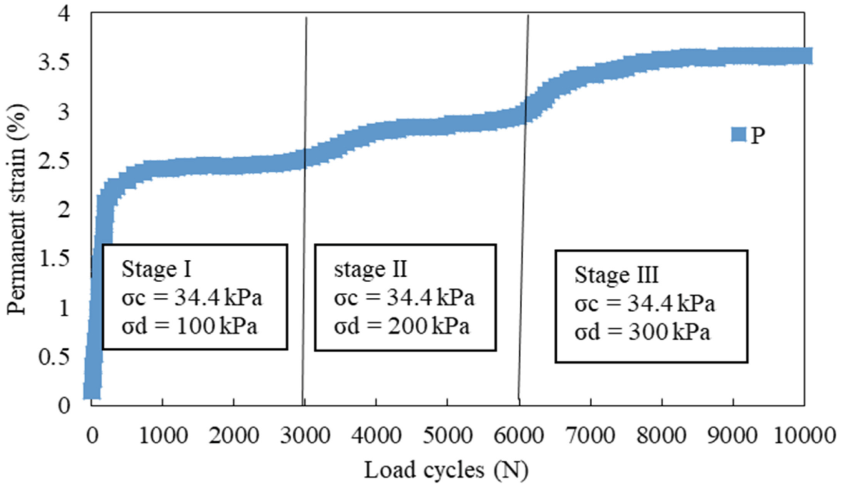


Fig. 4. Permanent strain (ϵ_p) of pond ash

ϵ_p values increase with an increase in σ_d (Fig. 4). However, at the beginning of loading process, the responses are plastic for few load cycles and then the ϵ_p values increased rapidly with increased load repetitions. After the post-compaction phase is completed, the ϵ_p curve remains constant, indicating that the response becomes resilient; and, this behavior of pond ash is consistent with previous literature [1].

3.4 Modelling Studies for Ep

Similar to M_R model studies, several studies have also anticipated the deformation characteristic models. Through those studies, two relevant ϵ_p models are selected for validation of experimental ϵ_p characteristics. Table 2 summarizes the correlation coefficients

Table 2. Regression analysis model constants of ϵ_p

Model	$\epsilon_p = \alpha_1 * \left(\frac{\sigma_d}{P_a}\right)^{\alpha_2} * N^{\alpha_3}$ [M1]			$\epsilon_p = \alpha_1 * \left(\frac{\sigma_{oct}}{P_a}\right)^{\alpha_2} * N^{\alpha_3}$ [M2]		
Model constants	α1	α2	α3	α1	α2	α3
	1.404	0.293	0.014	1.383	0.314	0.014
R^2	0.965			0.967		

Here, $\alpha_1 - \alpha_3$ = model constants

(R^2) of the corresponding ϵ_p models after performing a statistical multi-regression analysis; and, it is observed that the R^2 values for both models are greater than 0.9, indicating that the deformation behavior of pond ash is effectively predicted.

4 Conclusions

In civil engineering practice, coal ash has potential for various applications due to its intrinsic self-hardening properties. In India, most power plants produce low-lime fly ashes, classified as "class F ashes," which may not be suitable for pavement construction due to their inadequate strength (i.e., CBR = 4.2) and low resilient characteristics (M_R < 100MPa). Therefore, the addition of suitable admixtures or inclusions to modify or stabilize these ashes is necessary to enhance their properties for sub-base layer applications. Regression analysis was performed to study the M_R and ϵ_p of pond ash samples, and the results indicated that the selected stress-based models were effective in fitting the experimental data.

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