MECHANICAL STRENGTH AND STIFFNESS BEHAVIOUR OF CLASS F-POND ASH

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https://doi.org/10.26782/jmcms.2019.12.00019

Abstract

The pond ash (class F) as an individual material is unsuitable for utilization in pavement constructions due to few undesirable physico-mechanical properties. Treatment of pond ash by suitable additives like cement and lime would improve its usability. The present study is intended to determine the strength and stiffness properties such as Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR) and Resilient modulus ($M_R$) of both untreated and lime-treated pond ash for its pavement subbase application. The experimental investigation illustrates the enhancement in UCS, CBR, and $M_R$ properties of lime-treated pond ash compared to untreated/virgin pond ash specimens. Further, a significant improvement was observed at lime content about 8%, which can be considered as optimum addition to pond ash for pavement constructions.

Keywords: Pond ash; Lime; UCS; CBR; Resilient Modulus

I. Introduction

Pavements are the essential engineering infrastructures for the development of any country, and its long term performance mainly depends on the soundness of pavement layers. Presently, in India, due to rapid growth in transportation infrastructure development, the demand for traditional road materials has been increased, which is driving pressure on natural resources. However, due to government regulations, the supply of such natural road materials like crushed rock and gravel has diminished. Therefore, the availability of natural materials has become both scarce and expensive.

On the other hand, many manufacturing and processing units/industries facing a challenging problem such as disposal of their waste generation. One of such waste materials is pond ash, produced from thermal power plants (TPPs). Generally, in the process of electricity generation, TPPs generate a huge volume of coal ash as a waste by-product in the form of bottom ash and fly ash. These ashes are combined with
water and carried out of the plant into an ash pond in the form of a slurry, which is called pond ash (Kumar et al., 2007; Suthar and Aggarwal, 2018). In India, the quantity of coal ash is about 196M metric tons covered over 200 million m² of vast land (CEA, 2017). Out of this large quantity, only a small portion is being utilized in distinct ways, and the remaining is unused, causing contamination problems in soil as well as water bodies due to the presence of toxic components, which further affects public health and ecology (Gupta and Kumar, 2017; Patel and Shahu, 2018). Apart from that, these pond ash materials have suitable engineering properties such as low specific gravity, high shear resistance, high CBR, insensitivity to water while compacting, and low compressible nature (Pullaiah et al., 2000; Ghosh, 2009). Because of these characteristics, pond ash is being used successfully in various applications.

In previous years, researchers have studied the use of fly ash as a partial substitute material (with or without addition of admixtures) to the soil and observed an improved mechanical behaviour in terms of strength and stiffness characteristics. This improvement indicates the enhanced resisting support to the higher surcharge loads and leads to less deformation (Nicholson and Kashyap, 1993; Viswanath et al., 1996; Consoli et al., 2001; Puppala et al., 2003; Arora and Aydilek, 2005; Titli et al., 2012; Saghafi et al., 2012; kang et al., 2015; Patel and Shahu, 2016). A field study was conducted with 100% fly ash (without addition of admixture/aggregates) as base material at Fulsher, Texas, USA with a trial track construction and reported an average UCS of about 255 kPa with 28 days of curing. Further, after four months of construction, the corrugation of top asphaltic layer was also reported in some locations. Hence, the trial was considered as failure, and no further attempt was made to do this type of practice (Wong and Ho, 1989). Therefore, fly ash itself cannot be considered as a component material for the road base/subbase construction when it has to be placed in upper layers of pavement. Hence, fly ash should be treated with suitable additives like cement or/and lime to achieve significant strength improvement and adequate structural performance as pavement layer (Sarkar and Dawson, 2015). In this way, many studies have been conducted with coal fly ash treated with various cementitious additives (cement, lime, gypsum, GGBS, silica fume etc.), shown the enhanced strength and durability characteristics, and confirmed its suitability for pavement layers (Lav et al., 2006; Singh and Ramaswamy, 2006; Chand and Subbarao, 2007; Ghosh and Subbarao, 2007; Sivapullaiah and Moghal, 2011; Samanta, 2018).

Generally, in the design of coal ash-based pavements, mechanistic-empirical pavement design guideline (M-EPDG) methods are preferable to classical empirical methods as these are restricted to traditional pavement materials only. In these methods, the stresses caused by wheel load are determined to understand the mechanical response of pavement materials. Therefore, it is felt necessary to study the fundamental characteristics of pond ash such as strength and stiffness to perform a pavement analysis.

Therefore, in the present experimental work, lime was chosen as a stabilizing agent for pond ash, as it is more commonly used for stabilization in geotechnical applications. The mechanical strength and stiffness characteristics of pond ash with
and without lime addition are investigated for its effective use in pavements as subbase layer. The properties investigated in this study are Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR) and Resilient Modulus (M_r).

II. Materials

II.i. Pond ash

The source of pond ash used in this study is Kakatiya thermal power plant (KTPP) in Telangana, India. The physical properties and chemical constituents of pond ash are shown in Table 1 and Table 2. The percentage of lime in pond ash is <15%. Therefore, according to ASTM C 618-89 specifications, it can be categorized into Class F, and its particle size distribution is shown in Fig: 1.

Table 1. Physical properties of Pond ash

| S. No | Property                          | Value     |
|-------|-----------------------------------|-----------|
| 1     | Colour                            | Light grey|
| 2     | Specific Gravity                  | 1.93      |
| 3     | Plasticity Index                  | Non-Plastic|
| 4     | Grain Size Distribution           |           |
|       | i) % Gravel                       | 0         |
|       | ii) % of Sand                     | 65        |
|       | iii) % of Fines                   | 35        |
|       | Group Symbol                      | SM        |
| 5     | Maximum Dry Density, MDD (kN/m³)  | 11.21     |
|       | Optimum Moisture Content, OMC (%) | 34.02     |
| 6     | Angle of Internal Friction(φ)     | 32.1°     |
| 7     | CBR (%)                           |           |
|       | i) Unsoaked                       | 21.3      |
|       | ii) Soaked                        | 4.2       |
| 8     | Permeability, k (cm/s)            | 6.7 x 10⁻⁴|
| 9     | Compression Index, (C_c)          | 0.08746   |

Table 2. Chemical constituents of Pond ash

| Major Compounds as Oxides | % by mass |
|--------------------------|-----------|
| SiO₂                     | 62.1      |
| Al₂O₃                    | 13.6      |
| Fe₂O₃                    | 2.56      |
| SiO₂, Al₂O₃, Fe₂O₃       | 78.26     |
| CaO                      | 1.2       |
| SO₃                      | 0.25      |
| LOI (Loss on Ignition)   | 11.43     |
| others                   | 8.86      |

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II.ii. Lime

The lime used in this study is commercially available quicklime (CaO) and its chemical composition on dry weight basis is: SiO₂ = 4.5%; Al₂O₃ = 4.63%; Fe₂O₃ = 2.3%; MgO = 9.2%; CaO = 72.13% and others = 7.2%.

III. Experimental Plan and Test Procedures

In order to study the strength and stiffness properties of lime treated pond ash, the experimental work was scheduled as follows: (a) Compaction test on lime treated pond ash (b) UCS test on lime treated pond ash at 7, 28, 56, and 90 days of curing period, and its micro-level investigation through SEM analysis (c) CBR test on lime treated pond ash under both soaking conditions after curing of 7, 28 and 56 days (d) Repeated load triaxial (RLT) test on pond ash and modified pond ash (with optimum lime content) at 3, 7 and 28 days.

III.i. Compaction test

The MDD and OMC of pond ash and lime treated pond ash with different proportions were determined by conducting proctor compaction as per IS 2720-7 (1980).

III.ii. Unconfined compressive strength (UCS) test

UCS test is a standard method of testing to determine the relative response of treated material to increase the strength over a period of time. For this purpose, all the specimens of size 50 mm diameter and 100 mm height were prepared at corresponding MDD and OMC. The prepared specimens were then wrapped in a plastic cover to minimize the loss of moisture under controlled temperature and humidity in desiccators for respective curing periods (7, 28, 56 and 90 days). All the tests were conducted by following IS 4332-5 (1970) at a strain rate of 0.6 mm/min. The failure load was considered when the loading dial gauge shows three or more consecutive readings in decreasing or constant load manner, or until it reaches to a strain rate of 20%.
III.iii. California bearing ratio (CBR) test

CBR is a key parameter used in pavement design analysis. In order to evaluate the suitability of lime treated pond ash as pavement layer, specimens were prepared in standard CBR mould with respective compaction efforts (MDD and OMC). These specimens were sealed in plastic bags at room temperature of 27 ± 1°C for 7, 28, and 56 days of curing period. Consequently, the specimens were immersed in water for four days to study the soaking effect prior to testing. All the experiments were performed as per IS 2720-16 (1987) at a strain rate of 1.2 mm/min under both unsoaked and soaked conditions.

III.iv. Repeated load triaxial (RLT) test

For the design of pavements, $M_R$ plays a vital role in determining how the pavement system responds to traffic loading. Hence, the knowledge of $M_R$ of pavement layers is necessary. For this purpose, AASTHO 1993 [XXV] and NCHRP 2004 [XXVI] have developed guidelines and suggested to use of $M_R$ in pavement design and analysis. Accordingly, specimens of size 75 mm diameter with 150 mm height were prepared by compacting in 8 layers with 25 blows per each layer and kept in a desiccator for corresponding curing duration. For testing purpose, a triaxial pressure chamber was used to accommodate the sample, and water was used as a confining fluid to apply confining stress ($\sigma_c$) around the sample. The cyclic loads were implemented as a haversine function with 0.1 sec loading time and 0.5 Hz loading frequency. The test was conducted as per AASTHO T-307 protocol [XXVII]. During the test, the sample was subjected to repeated cyclic deviatoric ($\sigma_d$) and static confining stresses ($\sigma_c$). At first, the experiment begins with a conditioning phase by implementing 500 load repetitions at maximum $\sigma_d$ and $\sigma_c$ of 103.4 kPa each, to minimize the imperfect contact between sample cap and test specimen. Subsequently, 15 sequences of 100 deviatoric load repetitions at corresponding $\sigma_c$ levels were applied to the specimen. Table 3 represents the load application sequence to the specimen. Finally, the modulus at each stress level was calculated by taking an average value of moduli of the last five cycles for each sequence using Equation (1).

$$M_R = \frac{\sigma_d}{\varepsilon_r}$$

Equation (1)

Where, $M_R$ = Resilient modulus; $\sigma_d$ and $\varepsilon_r$ = Deviatoric stress and Resilient deformation at a given load pulse.

Table: 3 loading sequence used in the present study (AASTHO T-307)

| Sequence No | Confining stress (kPa) | Deviatoric stress (kPa) | No of load cycles |
|------------|------------------------|------------------------|-------------------|
| 0          | 103.4                  | 103.4                  | 500               |
| 1          | 20.6                   | 20.6                   | 100               |
| 2          | 41.3                   | 41.3                   | 100               |
| 3          | 62.1                   | 62.1                   | 100               |
| 4          | 34.4                   | 34.4                   | 100               |
| 5          | 68.9                   | 68.9                   | 100               |
| 6          | 103.4                  | 103.4                  | 100               |
IV. Results and Discussions

IV.i. Compaction Characteristics

The compaction test results of lime treated pond ash samples with various proportions are shown in figure 2. The MDD and OMC of pond ash are 1.121 g/cc and 34.02% respectively. When pond ash is mixed with lime from 2% to 12% (with 2% increment each), MDD value has increased from 1.121 g/cc to 1.274 g/cc. This increment can be attributed to lime with better plasticity at OMC, which facilitates the rearrangement of pond ash particles in a better way. Also, lime is finer material than pond ash, which fills the voids between pond ash particles, resulting in an increase in MDD value. Whereas, OMC value has decreased from 34.02% to 30.29%, due to sealing of cavities present in the pond ash particles, which reduces the water ingress into cavities. Similar kind of behaviour was observed in previous studies (Bera et al., 2007; Ghosh, 2009).

| Lime Content (%) | MDD (g/cc) | OMC (%) |
|------------------|------------|---------|
| 2                | 1.121      | 34.02   |
| 4                | 1.217      | 32.91   |
| 6                | 1.222      | 31.72   |
| 8                | 1.225      | 30.53   |
| 10               | 1.228      | 29.34   |
| 12               | 1.231      | 28.15   |
| 14               | 1.234      | 26.96   |
| 16               | 1.237      | 25.77   |
| 18               | 1.240      | 24.58   |
| 20               | 1.243      | 23.39   |
| 22               | 1.246      | 22.20   |
| 24               | 1.249      | 20.91   |
| 26               | 1.252      | 19.72   |
| 28               | 1.255      | 18.53   |

Fig: 2 Compaction results of lime treated pond ash mixes

IV.ii. Unconfined Compression Strength

The effect of lime contents and curing period on UCS of lime treated pond ash specimens are shown in Figure 3 (a ) and (b) and discussed below.
IV.ii.a. Effect of lime:

With the addition of lime to pond ash, the UCS value increases at all curing periods. The cause of increase in UCS value would be attributed to mainly two factors: i) Formation of pozzolanic products such as calcium silicate hydrates (C-S-H), and calcium aluminosilicate hydrate (C-A-S-H) gels, due to the reaction between added free lime with silica and aluminium present in pond ash, ii) The increase of unit weight of pond ash-lime mix and consequent reduction in void ratio in its compacted state (Sivapullaiah et al., 2000; Ghosh and Subbarao, 2007). When Pond ash is mixed with lime content of 2% to 12%, the UCS values increased from 86 kPa to 1136 kPa when cured for 28 days. However, the strength improvement is much less at lower lime contents, i.e., 86 kPa, 236 kPa and, 450 kPa for 2%, 4% and 6%. Though these samples were cured for longer periods, the UCS gain is less when compared to higher lime content. This is due to the amount of lime added to the pond ash gets mostly utilized in initial colloidal reactions, and sufficient lime is not left for pozzolanic reaction development. When the lime content is increased from 6% to 8%, significant strength improvement is observed at all curing periods. With further increase of lime contents to 10% and 12%, the rate of gain in strength is marginal. From these observations, it can be understood that about 6% of lime is consumed for colloidal type reactions, and the remaining is consumed for pozzolanic responses (Pani and Singh, 2017).

![Fig: 3 (a) Variation of UCS for different lime contents at different curing days](image)

IV.ii.b. Effect of Curing Period:

The UCS increases with respect to the curing period in all lime treated mixes. At lower curing periods, UCS gain is less, which gradually increases at longer curing periods. A substantial improvement in UCS can be observed at a curing period of 56 days (Fig 3 (b)), which is due to the slow rate of pozzolanic reaction between pond ash and lime during the initial days, which accelerates along with curing period. The equilibrium state of ultimate strength can be reached at longer curing periods (Chand and Subbarao, 2007). At 8% lime, the attainment in strength w.r.t 7-day curing period is 154%, 528% and 908% at 28, 56 and 90 days respectively.
IV.ii.c. SEM observations:

The test results were analysed through a micro-level study using scanning electron microscope (SEM), as it is necessary to identify the morphological changes taking place in the mixes. The lime treated pond ash samples were extracted from the middle portion of the sample, by breaking it into small fragments for microstructural investigation. Fig: 3(c) shows the SEM images of both untreated and treated pond ash mixes with various lime contents at 28 days curing period. The SEM image of untreated pond ash is shown here for the comparative purpose only. The SEM images of 2%, 4% and 6% lime contents show disjointed particles on the surface of pond ash, indicate a lower amount of hydration/pozzolanic products formation. Whereas, the samples with lime contents of more than 6% show a higher amount of hydration products formation such as C-S-H, C-A-S-H gels as a dense continuous material on the surface of pond ash, which causes more bonding nature between pond ash particles and leads to significant strength improvement in UCS.

Fig: 3(c) SEM images of pond ash with different lime contents at 28 days curing
Similarly, Fig. 3(d) shows the SEM images of 8% lime treated pond ash at various curing periods. At longer curing periods, the lime treated pond ash shows better bonding nature between pond ash particles and developed pozzolanic products. Furthermore, the formation of needle-shaped crystals (ettringites) was observed at longer curing periods, which fills the void space between the ash particles. The filled void space by ettringites make the mix denser and causes strength and stiffness improvement in mixes. However, the increase in bonding and ettringites formations were more effective when curing period increases of 28 days to 56 days, which results in higher UCS gain rate. Moghal and Sivapulliah (2011) also reported a similar kind of observations for fly ash-lime-gypsum samples.

As per the Indian Road Congress (IRC: 72-2015), the minimum UCS value required for stabilized materials to use in subbase layer construction is 750 kPa @ 28 days curing period. From the test results, it is observed that pond ash with a minimum of 8% lime content satisfying the above criteria, and hence it is considered as optimum content for the pond ash.

IV.iii. California Bearing Ratio

The CBR test results of both pond ash and lime treated pond ash at curing periods of 7, 28 and 56 days under both soaking conditions are illustrated in Figs. 4(a) and (b). The influence of lime content, curing period and soaking on CBR of pond ash were discussed below.

IV.iii.a. Effect of lime content

Addition of lime to the pond ash causes an increase in CBR value at all curing periods irrespective of its soaking condition [Fig. 4(a) and (b)]. The reason for this increase can be attributed to the pozzolanic reaction in presence of lime (Suthar and Aggarwal 2018). Higher the lime content, higher is the generation of cementing agents, which binds the pond ash particles effectively, causing higher CBR values at all curing periods.
The Bearing ratio gain factor (BR\textsubscript{gain}) is a non-dimensional parameter expressed as the ratio of BR of treated pond ash to untreated pond ash as shown in Equation (2) (Suthar and Aggarwal, 2018; Ghosh, 2009). Fig: 4 shows the BR\textsubscript{gain} of lime treated pond ash under both soaking conditions with respect to untreated pond ash. From this figure, it can be observed that the effect of lime on BR\textsubscript{gain} of treated pond ash is more significant in soaked condition than in unsoaked condition at all curing periods. The ranges of BR\textsubscript{gain} at 7, 28 and 56 days are 2.12 to 7.05, 2.0 to 7.47 and 2.41 to 8.90 respectively for the soaked condition, and 1.23 to 3.01, 1.34 to 3.08 and 1.45 to 2.98 respectively for the unsoaked condition. However, the increase in BR\textsubscript{gain} is significantly high up to 8% lime, and beyond that, it is minimal.

\[
\text{BR}_{\text{gain}} = \left[ \frac{\text{BR}_{\text{treated}}}{\text{BR}_{\text{untreated}}} \right] \quad \text{Equation (2)}
\]
The lime treated pond ash specimens were cured for 7, 28 and 56 days to investigate the effect of curing on CBR. With an increase of curing period, bearing ratio values increased continuously at all lime contents under both soaking conditions [Fig. 4 (a) and (b)]. The reason for increase in CBR is pozzolanic reaction pond ash and lime. Initially, the pozzolanic reaction takes place at a slow rate, which increases at later stages. Due to this, the rate of gels formation also increases with curing period, which results in CBR improvement (Pani and Singh, 2017). For all mixes, the improvement in CBR under soaked condition is approximately 30% to 56% from 7 to 28 days, and 9% to 31% from 28 to 56 days.

**IV.iii.c. Effect of soaking**

The CBR of untreated pond ash under soaked condition is lower than that of unsoaked condition. This can be attributed to the softening nature of pond ash during soaking, caused due to the absence of pseudo-cohesion, which is generally observed in unsoaked condition due to capillary action (Puppala, 2003). In general, the soaked condition is the worst possible condition in the field which occurs when layers of pavement are completely inundated. Upon soaking, ingress of water takes place, which significantly reduces the CBR value to a considerable extent (Sivapullaiah and Moghal, 2011). From Fig. 3(a) and (b), it is observed that at shorter curing period and lower lime content, the resistance to the penetration is less when compared to longer curing period and higher lime content. The CBRs of pond ash under soaked condition is about 50% to 70% of that of unsoaked condition for all cases, except the samples of 2% and 4% lime which lies in the range of 34% to 60% due to lack of lime and sufficient time for curing. However, even after soaking, the CBR values are relatively higher for mixes with about 6% lime.

According to the Indian Road Congress (IRC: 37-2012), the minimum bearing ratio required for subbase material is 30% for cumulative traffic loads of 3msa (million
standard axles). The results of the present study show that ≥ 6% lime content is good enough for pavement subbase applications.

**IV.iv Resilient Modulus (M<sub>R</sub>)**

As per AASTHO T-307, 15 steps of repeated loading with various levels of confining and deviatory stresses were applied to the specimen in sequence, as shown in Table 3. The primary reason for applying these loads is to simulate the wide range of traffic loading. Therefore, M<sub>R</sub> values of corresponding stress levels should be used in the design of pavement base/subbase layer.

**IV.iv.a M<sub>R</sub> of untreated Pond ash**

The M<sub>R</sub> of untreated pond ash under different confining (σ<sub>c</sub>) and deviatory stress (σ<sub>d</sub>) conditions are shown in Fig: 5(a). It is observed that the variation in M<sub>R</sub> of pond ash does not show much difference at all bulk stress conditions (16-22 MPa). This type of behaviour is mostly observed in fine grained soils of low plasticity compacted to MDD at OMC conditions. With an increase of σ<sub>d</sub>, the Mr value is slightly varying due to lower stiffness of pond ash, which weakens the specimen (Patel and Shahu, 2016; Rout et al., 2012). However, its rate of decrement in M<sub>R</sub> is lower at higher σ<sub>c</sub> conditions. Similarly, M<sub>R</sub> values increase with increased σ<sub>c</sub> due to added confinement, which causes a reduction in lateral strain deformation and improves the load-carrying capacity. The similar type trends were observed in previous studies also (Puppala et al., 2003 and Saghafi et al., 2012).

**IV.iv.b. M<sub>R</sub> of lime treated Pond ash**

The combined effect of σ<sub>c</sub> and σ<sub>d</sub> stress levels on M<sub>r</sub> of lime treated pond ash after 28 days curing period is shown in Fig: 5 (b to f). With an increase of either σ<sub>c</sub> or σ<sub>d</sub>, M<sub>R</sub> values increased at all lime contents and varying from 26-159 MPa for all stress conditions. Generally, in most of the field conditions, base and subbase layers of typical flexible pavement experience a confining and deviatory stresses of 34.5 kPa and 103.4 kPa, respectively (NCHRP 2004). Hence, this stress level is chosen as a reference while comparing M<sub>r</sub> at different lime contents.
When the $\sigma_c$ increased from 34.5 kPa through 137.9 kPa at $\sigma_d$ of 103.4 kPa, $M_R$ increased by 4.25%, 23%, 28%, 33% and 37% for lime contents of 2% to 10% respectively. Likewise, when $\sigma_d$ increased from 34.4 kPa through 103.4 kPa at $\sigma_c$ of 34.4 kPa, $M_R$ increased by 25%, 27%, 41%, 52% and 36% for lime contents of 2% to 10% respectively. The reason for increase in $M_R$ with an increase of lime content is attributed to i) higher lime content leading to increased production of cementitious compounds (Patel and Shahu, 2016) ii) exhibition of strain hardening nature due to lime stabilization. This type of behaviour is mostly observed in granular materials (Rout, 2012). The similar increasing trend was observed for both UCS and CBR values with the addition of lime. However, in all cases, the increasing rate of $M_R$ is lower with an increase of $\sigma_d$ as higher $\sigma_c$ stress levels [Fig: 5(b) to 5(f)].

From the Mr values of treated samples for subbase application, it can be observed that the Mr values of 2%, 4% and 6% lime are varying from 26-52 MPa, 31-68 MPa and 43-100 MPa different stress conditions respectively. Whereas for lime contents of 8% and 10%, these values vary from 52-138 MPa and 60-160 MPa, and which are well within the range specified by NCHRP 1-37 A, for various soils (i.e. clayey soils to well graded gravel) used in pavement applications ranging from 55-282 MPa. Thus, pond ash with 8% lime can be used in the design and construction of pavement subbase layer.

**Fig: 5(b)** variation in $M_R$ of 2% lime treated pond ash w.r.t. $\sigma_d$ at different $\sigma_c$ stress levels

**Fig: 5(c)** variation in $M_R$ of 4% lime treated pond ash w.r.t. $\sigma_d$ at different $\sigma_c$ stress levels

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The effect of curing period (3, 7, and 28 days) on $M_R$ of 8% lime treated pond ash, at various $\sigma_c$ and $\sigma_d$ are illustrated in Fig: 5(c) and 5(d). As the duration of curing increases, $M_R$ of lime treated specimen increases irrespective of stress levels. For an
increase in curing period from 3 days to 28 days, at $\sigma_d$ of 34.4 kPa, $M_R$ increased by 45%, 55%, and 75% for $\sigma_d$ of 34.4 kPa, 68.9 kPa, and 103.4 kPa respectively. In the same way, for an increase in curing period from 3 days to 28 days, at a constant $\sigma_d$ of 103.4 kPa, $M_R$ increased by 75%, 89%, and 87% at $\sigma_d$ of 34.4 kPa, 103.4 kPa, and 137.9 kPa respectively. Due to the slow reaction of pozzolanic activity, the amount of gel formation increases with the passage of time and hence, stiffness of the material increases. This similar variation was observed in previous studies (Saghafi, 2012; Patel and Shahu, 2016).

![Graph: Variation in $M_R$ for different curing periods and stress levels](image1)

**Fig: 5(c)** variation in $M_R$ of 8% lime treated mix at $\sigma_d$ of 34.4 kPa with various $\sigma_c$ stress levels for different curing period

![Graph: Variation in $M_R$ for different curing periods and stress levels](image2)

**Fig: 5(d)** variation in $M_R$ of 8% lime treated mix at $\sigma_d$ of 103.4 kPa with various $\sigma_c$ stress levels for different curing periods

IV.v. Environmental Concern

The objective of this study is to investigate the strength and stiffness characteristics of lime treated pond ash as a pavement material. But, its utilization may arise environmental concern due to its toxic nature and leaching behaviour. However, this concern is beyond the scope of the current study, thorough research on leaching characteristics is necessary.

V. Conclusions

The strength (UCC and CBR) and stiffness ($M_R$) characteristics of lime treated pond ash were investigated for its potential use in pavement subbase layers of...
flexible pavements. For this investigation, the UCS, CBR and RLT tests were performed, and the following conclusions are drawn:

- With the addition of lime to the pond ash, the voids in the mix are filled, leading to a reduction in void space, which further results in increased MDD and decreased OMC.

- UCS of pond ash increased considerably with the increase of lime content due to the increased availability of lime for the pozzolanic reaction. But this increment is significant only at 6% to 8% lime content, and marginal beyond that.

- The microstructural study through SEM and XRD test can help to understand the modifications that are responsible for improving engineering behaviour of lime treated pond ash mixes.

- The formation of hydration products increases with an increase in lime content, leading to the enhanced strength and stiffness of pond ash.

- Compared to untreated pond ash, the effect of lime content and curing period on CBR are more predominant on soaked pond ash. The CBRs of soaked pond ash is in the range of 50% to 70% of that of unsoaked pond ash, except for low lime contents (2% and 4%). Further, BR\text{gain} of lime treated pond ash under soaked condition is highest at 8% lime content, beyond which its gain is insignificant.

- The M\text{R} of lime treated pond ash are varies from 26 to 160 MPa when compared with untreated pond ash of 15-22 MPa at variation confining and deviatoric stress conditions. However, pond ash at higher lime contents (i.e. above 6%) shows the considerable Mr values for subbase application.

- As the duration of curing increases, the UCS, CBR and M\text{R} of lime treated pond ash increases due to the enhanced rate of pozzolanic activity.

- Based on this experimental study, pond ash with 8% lime has shown better strength and stiffness characteristics. For its qualities, it can be concluded that the pond ash with 8% lime is a potential material having applications in road subbase construction.

VI. Acknowledgement:

The author wish to express his gratitude to National Institute of Technology, Warangal for providing laboratory facilities to conduct experiment work and Ministry of Human Resources Development (MHRD), India for project fellowship to the corresponding author.
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