Partial Replacement of Conventional Material with Stabilized Soil in Flexible Pavement Design

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ABSTRACT

Due to rapid urbanization and industrialization, the construction of roads increases rapidly for easy and fast transportation. Adequate land is not available everywhere to construct good roads; hence, roads are forcefully built on locally available soil such as loose soil or expansive soil. In this paper, an experimental investigation was carried out on low plastic soil (LPS) to enhance engineering properties by using chemical soil stabilization (fly ash-based geopolymer). The design of flexible pavement thickness was carried out for conventional and stabilized soil material using IITPAVE software as per IRC 37 guidelines. The results show the feasibility of fly ash-based geopolymer significant enhancement of strength were observed in terms of unconfined compressive strength (UCS) for various curing days (0 to 128 days), California bearing ratio (CBR), and Resilient modulus (Mr). The microstructural analysis via Scanning Electronic Microscope (SEM) and X-Ray Diffraction Analysis (XRD) was also revealing the formation of geopolymeric gel which leads to the dense matrix to soil mass. The flexible pavement thickness significantly reduces with the application of stabilized low plastic soil.

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1. INTRODUCTION

The road is the lifeline of any developing country; the economic growth is majorly dependent on the development of the road network. India has the second-largest road network in the world, spanning a total of 5.89 million kilometers. This road network transports 64.5% of all goods in the country and 90% of India’s total passenger traffic uses the road network to commute as per Indian Road Industry Report [1]. Road transportation has gradually increased over the years with an improvement in connectivity between cities, towns, and villages in the country. With this increasing road transport, a huge amount of natural resources get consumed which is not healthy from an environmental perspective. Also, the stability of the road is a major issue caused due to the underlying subgrade or sub-base layer material. Therefore, to reduce the use of natural resources and construct sustainable roads by means of maximizing the use of locally available material or industrial byproducts. Generally, the majority of roads are constructed on locally available soil which may not have adequate properties to bear the upcoming loads.

The local soil has low shearing strength, high swelling-shrinkage behaviour, large deformation [2]. Therefore, it is necessary to treat the existing land through ground improvement techniques to fulfill the increasingly demanding situations. Many techniques are widely in practice to treat the existing soil as subgrade and sub-base material, out of that chemical treatment is the most common, cost-effective, and widely used. Traditionally, cement and/or lime are the most common stabilizers (binders), which form the cementitious material and hold the soil particles closely by internal chemical reactions in the presence of water. However, the production of this stabilizer causes more emissions of a greenhouse gas like carbon dioxide (CO₂) which is hazardous to the environment. Therefore, researchers or engineers always search for new, sustainable, cost-effective stabilizer alternatives to ordinary portland cement and lime [3].

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In this context, the use of local soil and an industrial byproduct such as cement kiln dust, calcium carbide residue, granulated blast furnace slag, fly ash, and geopolymeric binder in soil stabilization has been studied by several researchers [4–7] in recent years. Davydovits [8] proposed the geopolymer as an inorganic aluminosilicate material formed from the polycondensation of silica and alumina. The silica and alumina-rich precursors are majorly found in the coal ashes (fly ash), which are available in a tremendous amount. In India, coal ash production is nearly 226.13 million metric tons and utilization is about 187.87 million metric tons, i.e. 83.05% [9]. Therefore, a fly ash-based geopolymer could also be a better option for soil stabilization already proposed by Zhang et al. [10] and has become a green area for research in soil stabilization. Although, numbers of literature are available on fly ash-based geopolymer in building material applications [11−13]. All this literature explains the significant applicability of fly ash-based geopolymer as building materials, especially as concrete or mortar that shows the high mechanical strength, more durable, and sustainable material. However, selected studies are available on fly ash-based geopolymer in expansive soil stabilization [7, 12, 14−19]. The stabilization of clay soil by means of geopolymerization would improve the mechanical strength (UCS, CBR, etc.). For the alkaline activation of fly ash, sodium hydroxide and sodium silicate are the best combinations [20–22]. The modular ratio (sodium silicate /sodium hydroxide) is greater than 1.5 strength of stabilized soil decreases [16]. Therefore, looking at the rare application of fly ash-based geopolymer in soil stabilization, this paper deals with the feasibility of the fly ash-based geopolymer for locally available soil stabilization, that can be suitable as a road pavement material.

The contribution of various authors shows the importance of fly ash-based geopolymer for soil stabilization and its potential to provide eco-friendly solutions for various geotechnical projects. However, the application of these stabilized materials for actual road pavement design is very selected [23]. Thus, this paper aimed to design the flexible pavement with low plastic soil and fly ash-based geopolymer as a stabilizer. It also aimed to provide the application of fly ash in pavement construction, in an eco-friendly manner and to develop a sustainable methodology. The paper consists of the material used for the study followed by the sample preparation and testing methodology adopted. The mechanical performance in terms of UCS, CBR, and resilient modulus along with microstructural analysis was carried out to understand the micro-level changes that occurred in soil samples. Furthermore, the application of stabilized soil is demonstrated in the flexible road pavement with a comparison of conventional soil.

## 2. MATERIALS

Experimental investigations are performed on low plastic soil (LL < 50), collected from Raipur city, Chhattisgarh, India. The engineering properties of LPS and fly ash, such as specific gravity (G), liquid limit (LL), plastic limit (PL), plasticity index (PI) and maximum dry density (MDD), optimum moisture content (OMC) are determined according to IS:2720 (Part 3)-1980, IS:2720 (Part 5)-1985, and the values are tabulated in Table 1. Fly ash (FA) used for the experiments were obtained from the National Thermal Power Corporation and Steel Authority of India Limited (NSPCL), Bhilai, Chhattisgarh, India. The chemical composition of low plastic soil and fly ash is determined by Energy-dispersive X-ray spectroscopy (EDX) analysis and presented in Table 2. The results show that the major components in fly ash are SiO₂, Al₂O₃, and Fe₂O₃, suitable precursors for forming a good geopolymer [24, 25]. Also, fly ash is non-plastic, non-swelling material which acts as a filler in the soil mass also helps to the reduction of plastic characteristics of the soil. According to ASTM C 618 – 05, 2005 [26], it is categorized as F-type fly ash. Figure 1 presents the particle size distribution curve for LPS and FA, respectively. The percentage variation of various sizes of particles is presented in Table 1.

For the geopolymerization of fly ash, a proportionate mixture of sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃) solutions were used. The liquid sodium silicate consists of Na₂O= 14.35% and SiO₂= 33.10%, while sodium hydroxide solution of 6 molars (M). The researchers suggested a suitable concentration for NaOH between 4.5 to 18 molars [27–29]. Hence, from an economic and safety point of view, low concentrated

### Table 1. Engineering Properties

| Sr. No. | Properties     | Low Plastic Soil | Fly Ash |
|---------|---------------|------------------|--------|
| 1       | G             | 2.59             | 2.44   |
| 2       | LL (%)        | 42.3             | 34.56  |
| 3       | PL (%)        | 20.16            | NA     |
| 4       | PI (%)        | 22.14            |        |
| 5       | Sand (%)      | 30.21            |        |
| 6       | Silt & Clay (%) | 69.8             | 100    |
| 7       | Classification| CL               | F Class [26] |
| 8       | MDD (kN/m³)   | 18.42            | 11.56  |
| 9       | OMC (%)       | 15.8             | 18.18  |
| 10      | UCS (kPa)     | 238              |        |
| 11      | CBR (%)       | 4.8              |        |
NaOH, i.e., 6 molar, were adopted for the experimental investigation.

The chemical composition of LPS and fly ash is summarized in Table 2.

### 3. SAMPLE PREPARATION AND TESTING

Many researchers studied on stabilization of soil [6, 30–34]. They found the optimized percentage of various binders, such as fly ash content, lime content, rice husk ash, etc., lies between 15 to 25%. Therefore, LPS blended with various proportions of fly ash (10, 15, 20, 25, and 30%) with an alkaline activator to form a geopolymer. The NaOH of 6M solution was prepared just one day before casting of samples for the test by mixing 240 g (NaOH molecular weight 40 g/mole* 6M) of NaOH flakes to make a 1-liter solution in water. The Na$_2$SiO$_3$/NaOH ratio was selected as 1:5 to see the effect of activator on LPS-FA composite as per the recommendation [16].

A predetermined (calculated based on MDD) proportion of LPS and FA was mixed homogeneously, and then an activator (calculated based on OMC) was added. The sample was filled into UCS mould and compacted for making a cylindrical sample of 50 mm diameter and 100 mm height. For the result consistency average of 3 samples, were prepared. The total number of samples with respect to curing days cast was 93 as mentioned in TABLE 2. After compaction, the samples were extracted and placed in an airtight plastic bag for curing according to the standard method suggested [35]. Under ambient temperature or room temperature (25–28 °C), all samples were cured for 0, 7, 14, 28, 56, and 128 days and, after curing, tested as per IS 4332 Part V (1970). The specimen prepared at their respective MDD and OMC for the CBR test and tested for unsoaked and soaked conditions. The resilient modulus of all samples was estimated according to AASHTO: T 307-99 [36]. Scanning Electronic Microscope (SEM), and X-ray Diffraction (XRD) were also carried out to understand the microstructural characteristics of stabilized LPS after 28 days curing period, and also to check the formation of geopolymer.

### 4. RESULT AND DISCUSSION

#### 4.1. Unconfined Compression Test

The LPS stabilized with fly ash-based geopolymer for various fly ash content and curing periods of 0, 7, 14, 28, 56, and 128 days to understand the effect of fly ash content and time effect on strength enhancement. The UCS results were reported using the average UCS value of three samples to assure the test result consistency. It can be observed that from Figure 2 with the increase in fly ash content up to 25% UCS value increases further replacement it decreases. This UCS increment is may due to a higher amount of alumina and silica leached from the available fly ash content, which may lead to geopolymer gel/matrix formation. That indicates up to 25% of fly ash as it gets consumed to form geopolymer gel. However, further reduction may occur due to some particles remaining unreacted with further fly ash replacement, and that act as filler material.

Curing of sample promotes the polymeric reaction at the ambient temperature samples become hardened.

![Figure 1. Particle Size Distribution](image)

### TABLE 1. Chemical Composition

| Constituents (%) | LPS (%) | FA (%) |
|------------------|--------|-------|
| Silica (SiO$_2$) | 66.99  | 62.39 |
| Alumina (Al$_2$O$_3$) | 12.89  | 24.47 |
| Iron Oxide (Fe$_2$O$_3$) | 12.09  | 5.74  |
| Calcium Oxide (CaO) | 2.22   | 1.79  |
| Magnesium Oxide (MgO) | 1.32   | 0.62  |
| Potassium (K) | 3.4    | 2.75  |
| Titanium (Ti) | 0.93   | 2.25  |

![Table 2. Sample Details](image)

| Samples | LPS (%) | FA (%) | No. of Samples | Curing Periods |
|---------|---------|--------|----------------|---------------|
| FA      | 100     | 0      | 3              | 0 days        |
| FA10    | 90      | 10     | 18             | 0, 7, 14, 28, 56 and 128 days |
| FA15    | 85      | 15     | 18             |               |
| FA20    | 80      | 20     | 18             |               |
| FA25    | 75      | 25     | 18             |               |
| FA30    | 70      | 30     | 18             |               |
slowly. As shown in Figure 2, with an increasing curing period, strength increases, indicating that at ambient temperature the polymeric reaction takes place, which binds the soil particles closely. The continuous increment in the UCS value was observed with curing days. However, UCS value for 7 and 14 days curing periods of FA10 % to FA30 % containing soil specimen satisfy the minimum required strength (750 kPa) for stabilized sub-base layer at the end of 28 days curing period. Further, increasing in curing periods 28 to 128 days the stabilized LPS satisfies the minimum strength requirement for the granular base/sub-base. A similar trend of results was observed by the various researchers [14–17, 37]. These strength enhancements show the continuous formation of polymeric reaction and binding of soil particles due to more silicate and aluminate availability for geopolymer formation [17, 38].

4.2. California Bearing Ratio (CBR) and Resilient Modulus (Mr) CBR test performed on soil specimen for unsoaked and 28 days (4 days soaking + 24 days curing) cured samples. Figure 3 shows the variation of CBR value to fly ash content. It has been observed that the CBR value for LPS is 18.5 % for unsoaked conditions and 4.8% for soaked conditions. The CBR value for unsoaked conditions increases due to mixes offering more resistance due to better packing of different sized fractions. Further, for curing samples rapid improvement in the CBR value has been observed this can be attributed to the less attraction of water during the curing process as a result of the dense microstructure of soil particles due to gel formation [17, 19, 39, 40].

Resilient Modulus (Mr) is a fundamental material property used to characterize unbound pavement materials [36]. The variation of resilient modulus (Mr) to the fly ash content is shown in Figure 4. The result showed a similar type of trend as observed in CBR tests. The Mr value of fly ash-based geopolymer treated soil is in the range of 148 to 179 MPa which is much higher than the untreated LPS (55.62 MPa).

4.3. Microstructural Analysis The microstructural and morphologic study on the fly ash-based geopolymer specimens was elaborated via XRD and SEM an advanced tool for monitoring the microstructural changes.

4.3.1. X-Ray Diffraction Analysis (XRD) The X-ray diffraction technique is the most widely used method to identify soil minerals and study their crystal structure. Figure 5 shows the XRD pattern for the various fly ash content for stabilized LPS after 28 days of curing. The LPS shows the presence of clay minerals such as montmorillonite (M), illite (I) along with quartz (Q), and a small amount of muscovite (Ms) & feldspar (F). Thus, LPS with fly ash-based geopolymer altered the diffraction pattern significantly; new reflection patterns were also seen, namely sillerminate (S), phillipsite (P),
mullite (Mu), and cristobalite (C) approximately at 2Ө = 21.22°, 27.07°, 35.49°, 39.87°, 42.75°, 50.50°, 60.30°, 68.53°, 75.97°, 81.70°, and 82°. These minerals roughly belong to crystalline phases detected in the formed gel by the active dissolution of sodium aluminosilicate compounds with pozzolanic particles [21, 22]. Furthermore, it was also observed that low-intensity peaks of LPS show participation in the process of geopolymerization [41]. Also, some of the peaks were absent compared to the virgin LPS, indicating the disturbance of the layered structure of clay mineralogy [22]. It could be said that the binding effect of geopolymer gel renders the improvement in the mechanical strength of the soil. Moreover, due to the formation of new crystalline minerals which disturbed the original layered structure that controls the swelling behaviour of soil. As stabilized LPS becomes less prone to swelling and shrinkage behaviour. Hence, it can be concluded that the binding effect of geopolymeric gel due to the presence of aluminosilicate and zeolite group (Sillimanite & Phillipsite) would improve the mechanical strength of LPS.

4. 3. 2. Scanning Electronic Microscope (SEM)

The microstructural changes of LPS are understood by SEM images analysis after 28 days of curing. Figure 6 (b to f) shows SEM images for fly ash content of 10, 15, 20, 25 and 30%. The images reveal that the fly ash was consumed for the formation of geopolymeric gel or reaction product. This product form mainly due to the dissolution of silica and alumina ions leading to leaching of sodium aluminate hydrate gel (NASH) and further with polymerization reaction in the presence of calcium at ambient temperature, it produces the calcium aluminosilicate hydrate (CASH). However, a few quantities of unreacted or partially reacted fly ash particles were also observed especially in the FA30 sample.
5. DESIGN OF FLEXIBLE PAVEMENT THICKNESS USING STABILIZED SOIL

The application of stabilized soil is demonstrated in terms of the design of flexible pavement thickness for high-volume roads as per IRC:37-2018 [42]. The pavement thickness using low plastic soil is tabulated in Table 4. The CBR value of the LPS subgrade is 4.8%; therefore, the stabilized soil having a CBR more or equal to 10% should be laid. As per IRC:37-2012, from Figure 7, the effective CBR is found to be 8%. The resilient modulus of LPS from the experiment is 55 MPa.

The elasticity modulus for the binder course and surface course is considered to be 3000 MPa, whereas the elastic modulus of Wet Mix Macadam (WMM) and Granular Sub-Base (GSB) is estimated together using Equation (1). The horizontal tensile strain ($\varepsilon_t$) and vertical compressive strain ($\varepsilon_v$) of the conventional material are analyzed from IITPAVE (pavement analysis software), and the results are tabulated in Table 4.

$$M_{R_{gain}} = 0.2 \times (h)^{0.45} \times M_{R_{Support}}$$  \hspace{1cm} (1)

As from the above experimental analysis, fly ash-based geopolymer could find a good soil stabilizer of fly ash 25% and 6M NaOH (FA25+6M). the proposed pavement thickness with stabilized LPS is calculated and tabulated as per IRC 37 in Table 5. The stabilized LPS CBR value was found to be 38% so, from Figure 7, the effective CBR is 22%, and the resilient modulus for the modified subgrade is 179 MPa should be limited to 100 MPa.

The elastic modulus of the WMM course is considered as 350 MPa and for the binder course and surface course together is 3000 MPa. As per IRC SP 89-2018, the cement-treated sub-base (CTSB) should have a minimum elastic modulus of 2000 MPa, and using Eq. (2) the resilient modulus ($M_R$) of stabilized LPS is calculated. The UCS value for stabilized soil (FA25+6M) after 28 days of curing is 2,050 MPa, and the resilient modulus is found to be 2050 MPa. Hence, the conventional subbase material can be replaced with CTSB of LPS+FA25+6M. The calculated resilient modulus of stabilized soil is too high, thus 600 MPa is considered for the analysis as per IRC 37. The cross-section of the proposed high-volume road pavement is as shown in Figure 8. The estimated horizontal tensile ($\varepsilon_t$) and vertical compressive ($\varepsilon_v$) strain calculated through IITPAVE software were found to be less than the conventional material pavement material.

$$M_R = 1000 \times U_{CS_{28\text{ days}}}}$$  \hspace{1cm} (2)

Table 6 compares pavement thickness using conventional pavement material and fly ash-based geopolymer LPS used as a sub-base material.

| Design Traffic (MSA) | Pavement Thickness (mm) | Total Thickness (mm) | $M_R$ (MPa) | $\varepsilon_t (10^{-4})$ | $\varepsilon_v (10^{-4})$ |
|----------------------|-------------------------|---------------------|-------------|--------------------------|--------------------------|
| 5                    | GSB 150 WMM 250 BC 50 SC 30 | 480 | 163 | 6.17 | 3.22 |
| 10                   | GSB 200 WMM 250 BC 60 SC 30 | 540 | 172 | 4.98 | 2.93 |
| 20                   | GSB 200 WMM 250 BC 90 SC 40 | 580 | 172 | 3.94 | 2.27 |
| 30                   | GSB 200 WMM 250 BC 95 SC 40 | 585 | 172 | 3.83 | 2.2 |
| 40                   | GSB 200 WMM 250 BC 105 SC 40 | 595 | 172 | 3.62 | 2.06 |
| 50                   | GSB 200 WMM 250 BC 115 SC 40 | 605 | 172 | 3.42 | 1.93 |
significant reduction of pavement thickness was observed that indicates the reduction in the use of natural resources such as aggregates, moorum, etc. Also, for soil stabilization, the traditional stabilizer such as cement and lime can be replaced with sustainable soil stabilizers (fly ash geopolymer). Furthermore, the industrial by-product can be effectively utilized in an eco-friendly manner for construction activity. Based on the above observations, applying fly ash-based geopolymer to stabilizing LPS in subgrade and subbase layers becomes economical; partially replacing inert material and saving natural recourse leads to a more sustainable solution.

### Table 3. Pavement Thickness Using Stabilized LPS

| Design Traffic (MSA) | Pavement Thickness (mm) | Total Thickness (mm) | εf (10^-4) | εt (10^-4) |
|----------------------|-------------------------|----------------------|------------|------------|
|                      | CTSB | WMM | BC | S C |                      |            |            |
| 5                    | 200  | 150 | 0  | 40 | 390               | 4.30  | 1.03 |
| 10                   | 200  | 150 | 0  | 40 | 390               | 4.30  | 1.03 |
| 20                   | 200  | 150 | 50 | 30 | 430               | 3.55  | 0.82 |
| 30                   | 200  | 150 | 50 | 40 | 440               | 3.37  | 0.77 |
| 40                   | 200  | 150 | 55 | 40 | 445               | 3.28  | 0.75 |
| 50                   | 200  | 150 | 65 | 40 | 455               | 3.12  | 0.71 |

### Table 4. Comparison of Pavement Thickness

| Design Traffic (MSA) | Pavement Thickness (mm) | Total Thickness Reduction (mm) | % Reduction Thickness |
|----------------------|-------------------------|--------------------------------|-----------------------|
|                      | Conventional Material   | Stabilized LPS                 |                       |
| 5                    | 480                      | 390                            | 90                    | 18.75 |
| 10                   | 540                      | 390                            | 150                   | 27.78 |
| 20                   | 580                      | 430                            | 150                   | 25.86 |
| 30                   | 585                      | 440                            | 145                   | 24.79 |
| 40                   | 595                      | 445                            | 150                   | 25.21 |
| 50                   | 605                      | 455                            | 150                   | 24.79 |

### 6. CONCLUSIONS

Following conclusions were drawn based on the laboratory experimental results, and application of fly ash-based geopolymer stabilized LPS for the design of pavement thickness for high volume roads.

- Low plastic soil treated with fly ash-based geopolymer significantly increases strength characteristics (UCS and CBR). The fly ash content of 25% with 6M NaOH concentration shows the highest strength.
- The strength improvement with fly ash-based geopolymer stabilized LPS after 7 days of curing is greater than the minimum strength requirement for sub-base course of road pavement as per IRC: 37-2012.
- The microstructure of stabilized LPS shows the formation of geopolymer gel; as a result, particles are closely packed with each other and form a dense matrix.
- The granular sub-base material can be replaced with cement-treated sub-base material.
- A significant reduction of pavement thickness was observed with the application of fly ash-based geopolymer.

Fly ash-based geopolymer can be the found effective chemical stabilizer for stabilizing low plastic soil, but the
challenge lies in its effective application. Also, the exact dosage of fly ash and activator needs to be checked before a particular field application. This research could also contribute to waste mitigation as well as the development of sustainable soil stabilizers in the road construction industry.

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