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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 (M_R). The microstructural analysis via Scanning Electronic Microscope (SEM) and X-Ray Diffraction Analysis (XRD) was also reveling 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 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 (CO_2) 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. Davidovits [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 SiO_2, Al_2O_3, and Fe_2O_3, 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 (Na_2SiO_3) solutions were used. The liquid sodium silicate consists of Na_2O= 14.35% and SiO_2= 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/m^3)	18.42	11.56
9	OMC (%)	15.8	18.18
10	UCS (kPa)	238	-
11	CBR (%)	4.8	-

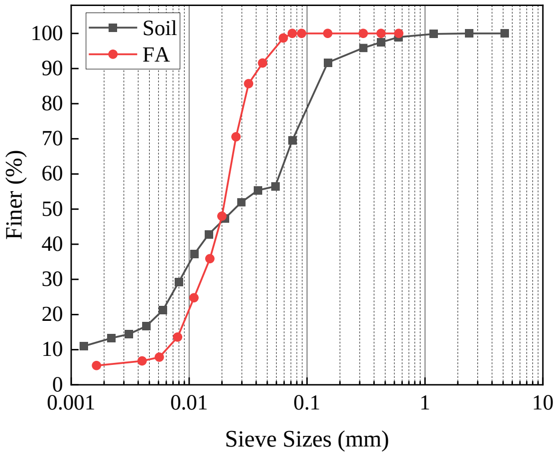


Figure 1. Particle Size Distribution

NaOH, i.e., 6 molars, were adopted for the experimental investigation.

The chemical composition of 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_2SiO_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.

TABLE 1. Chemical Composition

Constituents (%)	LPS	FA
Silica (SiO_2)	66.99	62.39
Alumina (Al_2O_3)	12.89	24.47
Iron Oxide (Fe_2O_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

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	

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

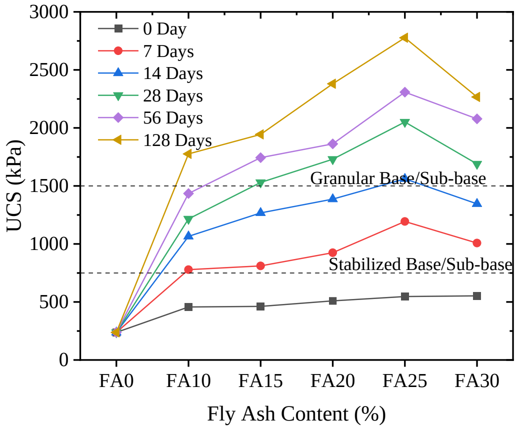


Figure 2. UCS Result

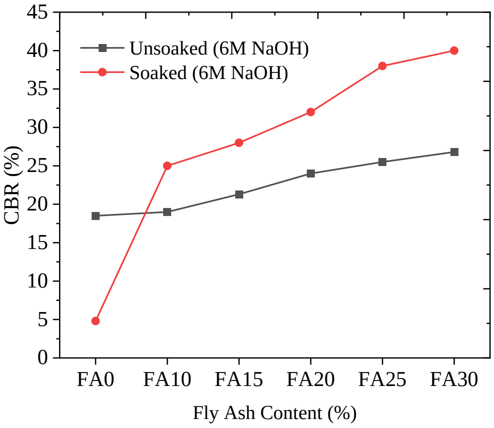


Figure 3. CBR Strength Result

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 (M_R)

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 (M_R) is a fundamental material property used to characterize unbound pavement materials [36]. The variation of resilient modulus (M_R) to the fly ash content is shown in Figure 4. The result showed a similar type of trend as observed in CBR tests. The M_R 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).

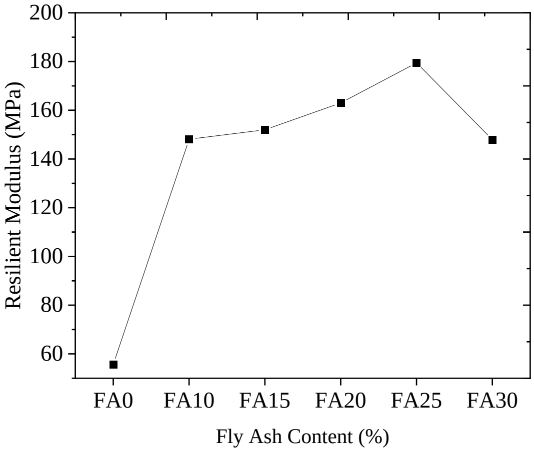


Figure 4. Resilient Modulus for untreated and treated LPS

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 sillimanite (S), phillipsite (P),

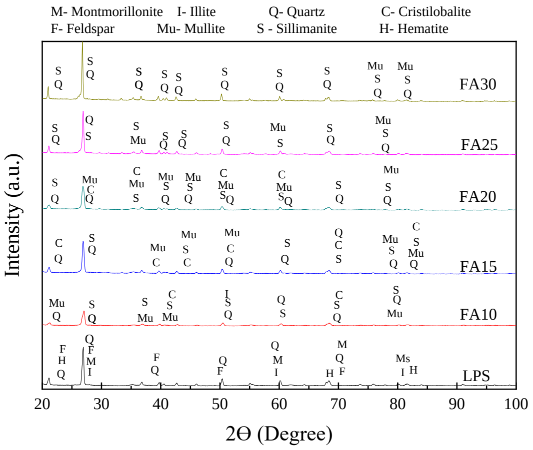


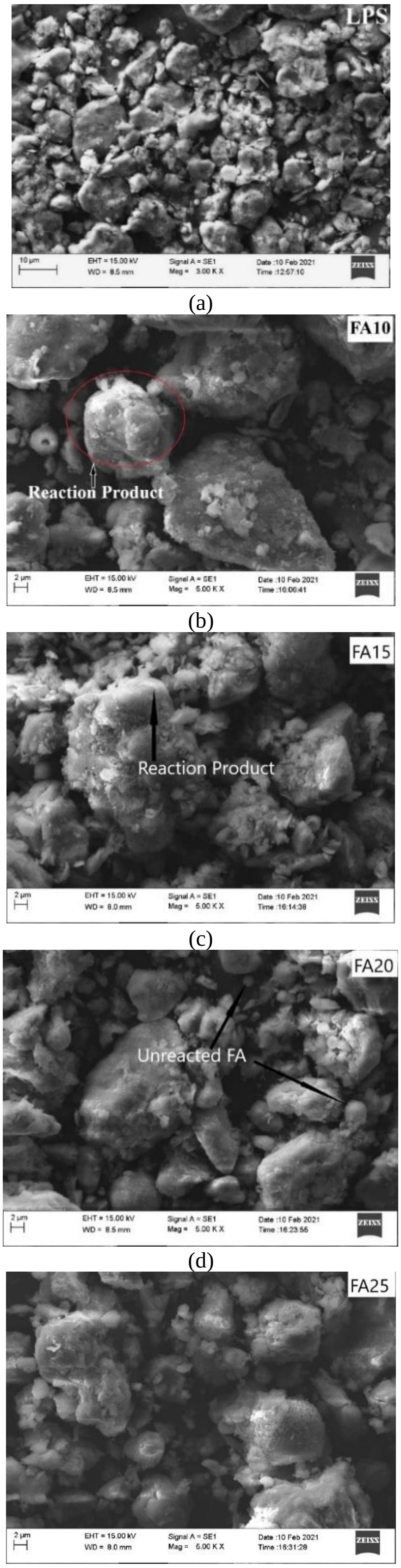
Figure 5. XRD

mullite (Mu), and cristobalite (C) approximately at 2Θ = 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.



(a)

(b)

(c)

(d)

(e)

(f)

Figure 6. SEM for (a) LPS (b) FA10 (c) FA15 (d) FA20 (e) FA25 and (f) FA30

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.

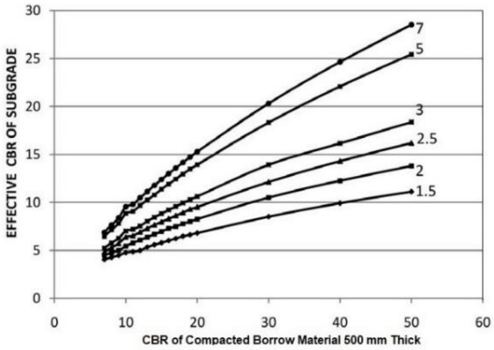


Figure 7. Effective CBR for Subgrade as per IRC: 37-2012 [43]

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 (εt) and vertical compressive strain (εv) of the conventional material are analyzed from IITPAVE (pavement analysis software), and the results are tabulated in Table 4.

$$MR_{gain} = 0.2 * (h)^{0.45} * MR_{Support} \tag{1}$$

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 (εt) and vertical compressive (εv) strain calculated through IITPAVE software were found to be less than the conventional material pavement material.

$$M_R = 1000 * UCS_{28\ Days} \tag{2}$$

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

TABLE 4. Pavement Thickness Using Conventional Material

Design Traffic (MSA)	Pavement Thickness (mm)				Total Thickness (mm)	M_R (MPa)	ε_v (10^{-4})	ε_t (10^{-4})
	GSB	WMM	BC	SC				
5	150	250	50	30	480	163	6.17	3.22
10	200	250	60	30	540	172	4.98	2.93
20	200	250	90	40	580	172	3.94	2.27
30	200	250	95	40	585	172	3.83	2.2
40	200	250	105	40	595	172	3.62	2.06
50	200	250	115	40	605	172	3.42	1.93

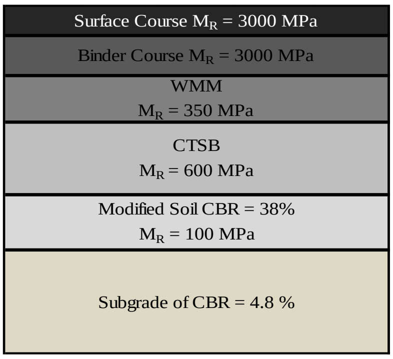


Figure 8. Proposed Cross Section of High-Volume Road Pavement

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)	ε_v (10^{-4})	ε_t (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.

7. REFERENCES

1. IBEF, R. India Brand Equity Foundation 2019.
2. Mitchell J.K., and Soga K.Fundamentals of Soil Behavior. John Wiley & Sons, Inc. (2005).
3. Turkane S.D., and Chouksey S.K. "Application of Response Surface Method for Optimization of Stabilizer Dosages in Soil Stabilization". ***Innovative Infrastructure Solutions***, (2022), 1-12. https://doi.org/10.1007/s41062-021-00704-9
4. Ghosh P., Kumar H., and Biswas K. "Fly Ash and Kaolinite-Based Geopolymers: Processing and Assessment of Some Geotechnical Properties". ***International Journal of Geotechnical Engineering***, Vol. 10, No. 4, (2016), 377-386. https://doi.org/10.1080/19386362.2016.1151621
5. Leong H.Y., Ong D.E.L., Sanjayan J.G., and Nazari A. "Strength Development of Soil-Fly Ash Geopolymer: Assessment of Soil, Fly Ash, Alkali Activators, and Water". ***Journal of Materials in Civil Engineering***, Vol. 30, No. 8, (2018), https://doi.org/10.1061/(ASCE)MT.1943-5533.0002363
6. Kanthe V., Deo S., and Murmu M. "Combine Use of Fly Ash and Rice Husk Ash in Concrete to Improve Its Properties". ***International Journal of Engineering, Transactions A: Basics***, Vol. 31, No. 7, (2018), 1012-1019. https://doi.org/10.5829/ije.2018.31.07a.02
7. Phummiphan I., Horpibulsuk S., Sukmak P., Chinkulkijniwat A., Arulrajah A., and Shen S.L. "Stabilisation of Marginal Lateritic Soil Using High Calcium Fly Ash-Based Geopolymer". ***Road Materials and Pavement Design***, Vol. 17, No. 4, (2016), 877-891. https://doi.org/10.1080/14680629.2015.1132632
8. Davidovits J. "Geopolymers". ***Journal of Thermal Analysis***, Vol. 37, No. 8, (1991), 1633-1656. https://doi.org/10.1007/bf01912193
9. Central Electricity Authority "Report on Fly Ash Generation at Coal/Lignite Based Thermal Power Stations and Its Utilization in the Country for the Year 2019-20" (2020), 1-32
10. Zhang M., Guo H., El-Korchi T., Zhang G., and Tao M. "Experimental Feasibility Study of Geopolymer as the Next-Generation Soil Stabilizer". ***Construction and Building Materials***, Vol. 47, (2013), 1468-1478. https://doi.org/10.1016/j.conbuildmat.2013.06.017
11. Amran M., Debbarma S., and Ozbakkaloglu T. "Fly Ash-Based Eco-Friendly Geopolymer Concrete : A Critical Review of the Long-Term Durability Properties". ***Construction and Building Materials***, Vol. 270, (2021), 121857. https://doi.org/10.1016/j.conbuildmat.2020.121857
12. Toniolo N., and Boccaccini A.R. "Fly Ash-Based Geopolymers Containing Added Silicate Waste. A Review". ***Ceramics International***, Vol. 43, No. 17, (2017), 14545-14551. https://doi.org/10.1016/j.ceramint.2017.07.221
13. Rashad A.M. "A Brief on High-Volume Class F Fly Ash as Cement Replacement - A Guide for Civil Engineer". ***International Journal of Sustainable Built Environment***, Vol. 4, No. 2, (2015), 278-306. https://doi.org/10.1016/j.ijsbe.2015.10.002
14. Abdullah H.H., Shahin M.A., Walske M.L., and Karrech A. "Systematic Approach to Assessing the Applicability of Fly-Ash-Based Geopolymer for Clay Stabilization". ***Canadian Geotechnical Journal***, Vol. 57, No. 9, (2020), 1356-1368. https://doi.org/10.1139/cgj-2019-0215
15. Corrêa-Silva M., Araújo N., Cristelo N., Miranda T., Gomes A.T., and Coelho J. "Improvement of a Clayey Soil with Alkali Activated Low-Calcium Fly Ash for Transport Infrastructures Applications". ***Road Materials and Pavement Design***, Vol. 20, No. 8, (2019), 1912-1926. https://doi.org/10.1080/14680629.2018.1473286
16. Murmu A.L., Jain A., and Patel A. "Mechanical Properties of Alkali Activated Fly Ash Geopolymer Stabilized Expansive Clay". ***KSCE Journal of Civil Engineering***, Vol. 23, No. 9, (2019), 3875-3888. https://doi.org/10.1007/s12205-019-2251-z
17. Murmu A.L., Dhole N., and Patel A. "Stabilisation of Black Cotton Soil for Subgrade Application Using Fly Ash Geopolymer". ***Road Materials and Pavement Design***, (2018), 1-19. https://doi.org/10.1080/14680629.2018.1530131
18. Parhi P.S., Garanayak L., Mahamaya M., and Das S.K. "Stabilization of an Expansive Soil Using Alkali Activated Fly Ash Based Geopolymer". In: Hoyos LR, McCartney J (eds) Advances in Characterization and Analysis of Expansive Soils and Rocks, GeoMEast 2017, Sustainable Civil Infrastructures. Springer International Publishing, Cham, https://doi.org/10.1007/978-3-319-61931-6_4
19. Varma N., Kumar T., and Nagaraju V. "Compressive Strength of High Plastic Clay Stabilized with Fly Ash-Based Geopolymer and Its Synthesis Parameters". In: Transportation, Water and Environmental Geotechnics Proceedings of Indian Geotechnical Conference 2020. 25-37, https://doi.org/10.1007/978-981-16-2260-1_3
20. Hardjito D., Wallah S.E., Sumajouw D.M.J., and Rangan B.V. "On the Development of Fly Ash-Based Geopolymer Concrete". ***ACI Materials Journal***, Vol. 101, No. 6, (2004), 467-472. https://doi.org/10.14359/13485
21. Syed M., GuhaRay A., and Kar A. "Stabilization of Expansive Clayey Soil with Alkali Activated Binders". ***Geotechnical and Geological Engineering***, Vol. 38, No. 6, (2020), 6657-6677. https://doi.org/10.1007/s10706-020-01461-9
22. Miao S., Shen Z., Wang X., Luo F., Huang X., and Wei C. "Stabilization of Highly Expansive Black Cotton Soils by Means of Geopolymerization". ***Journal of Materials in Civil Engineering***, Vol. 29, No. 10, (2017), 1-9. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002023
23. Amulya S., and Ravi Shankar A.U. "Replacement of Conventional Base Course with Stabilized Lateritic Soil Using Ground Granulated Blast Furnace Slag and Alkali Solution in the Flexible Pavement Construction". ***Indian Geotechnical Journal***, Vol. 50, No. 2, (2020), 276-288. https://doi.org/10.1007/s40098-020-00426-2
24. Khale D., and Chaudhary R. "Mechanism of Geopolymerization and Factors Influencing Its Development: A Review". ***Journal of Materials Science***, Vol. 42, No. 3, (2007), 729-746. https://doi.org/10.1007/s10853-006-0401-4
25. Zhuang X.Y., Chen L., Komarneni S., Zhou C.H., Tong D.S., Yang H.M., Yu W.H., and Wang H. "Fly Ash-Based Geopolymer: Clean Production, Properties and Applications". ***Journal of Cleaner Production***, Vol. 125, (2016), 253-267. https://doi.org/10.1016/j.jclepro.2016.03.019
26. ASTM C 618 - 05 "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete"
27. Mustafa Al Bakri A.M., Kamarudin H., Bnhussain M., Rafiza A.R., and Zarina Y. "Effect of Na_2SiO_3/NaOH Ratios and NaOH Molarities on Compressive Strength of Fly-Ash-Based

Geopolymer". ***ACI Materials Journal***, Vol. 109, No. 5, (2012), 503-508. https://doi.org/10.14359/51684080

28. Nematollahi B., and Sanjayan J. "Effect of Different Superplasticizers and Activator Combinations on Workability and Strength of Fly Ash Based Geopolymer". ***Materials and Design***, Vol. 57, (2014), 667-672. https://doi.org/10.1016/j.matdes.2014.01.064
29. Yaghoubi M., Arulrajah A., Disfani M.M., Horpibulsuk S., Bo M.W., and Darmawan S. "Effects of Industrial By-Product Based Geopolymers on the Strength Development of a Soft Soil". ***Soils and Foundations***, Vol. 58, No. 3, (2018), 716-728. https://doi.org/10.1016/j.sandf.2018.03.005
30. Çokça E. "Use of Class C Fly Ashes for the Stabilizationof an Expansive Soil". ***Journal of Geotechnical and Geoenvironmental Engineering***, Vol. 127, No. 7, (2001), 568-573. https://doi.org/10.1061/(ASCE)1090-0241(2001)127:7(568)
31. Kate J.M. "Strength and Volume Change Behavior of Expansive Soils Treated with Fly Ash". In: Innovations in Grouting and Soil Improvement. American Society of Civil Engineers, Austin, Texas, 1-15, https://doi.org/10.1061/40783(162)19
32. Mahajan S.M., and Parbat D.K. "Effects of Fly Ash on Engineering Properties of BC Soil". ***International Journal of Research in Engineering, Science and Technologies***, Vol. 1, No. 5, (2015),
33. Trivedi J.S., Nair S., and Iyyunni C. "Optimum Utilization of Fly Ash for Stabilization of Sub-Grade Soil Using Genetic Algorithm". ***Procedia Engineering***, Vol. 51, (2013), 250-258. https://doi.org/10.1016/j.proeng.2013.01.034
34. Turkane S.D., and Chouksey S.K. "Partial Replacement of Moorum with Fly Ash in Embankment". ***Lecture Notes in Civil Engineering***, Vol. 77, (2021), 381-391. https://doi.org/10.1007/978-981-15-5195-6_30
35. Kaniraj S.R., and Gayathri V. "Factors Influencing the Strength of Cement Fly Ash Base Courses". ***Journal of Transportation Engineering***, Vol. 129, No. 5, (2003), 538-548. https://doi.org/10.1061/(ASCE)0733-947X(2003)129:5(538)
36. AASHTO T 307-99 "Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials of Soils and Aggregate Materials" (2012).
37. Syed M., GuhaRay A., Agarwal S., and Kar A. "Stabilization of Expansive Clays by Combined Effects of Geopolymerization and Fiber Reinforcement". ***Journal of The Institution of Engineers (India): Series A***, Vol. 101, No. 1, (2020), 163-178. https://doi.org/10.1007/s40030-019-00418-3
38. Zuhua Z., Xiao Y., Huajun Z., and Yue C. "Role of Water in the Synthesis of Calcined Kaolin-Based Geopolymer". ***Applied Clay Science***, Vol. 43, No. 2, (2009), 218-223. https://doi.org/10.1016/j.clay.2008.09.003
39. Teerawattanasuk C., and Voottipruex P. "Comparison between Cement and Fly Ash Geopolymer for Stabilized Marginal Lateritic Soil as Road Material". ***International Journal of Pavement Engineering***, Vol. 20, No. 11, (2019), 1264-1274. https://doi.org/10.1080/10298436.2017.1402593
40. Phetchuay C., Horpibulsuk S., Arulrajah A., Suksiripattanapong C., and Udomchai A. "Strength Development in Soft Marine Clay Stabilized by Fly Ash and Calcium Carbide Residue Based Geopolymer". ***Applied Clay Science***, Vol. 127-128, (2016), 134-142. https://doi.org/10.1016/j.clay.2016.04.005
41. Murmu A.L., and Patel A. "Studies on the Properties of Fly Ash-Rice Husk Ash-Based Geopolymer for Use in Black Cotton Soils". ***International Journal of Geosynthetics and Ground Engineering***, Vol. 6, No. 3, (2020), 1-14. https://doi.org/10.1007/s40891-020-00224-z
42. Indian Road Congress. "Guidelines for the design of flexible pavements (Fourth Revision). IRC 37-2018. New Delhi, India." (2018).
43. Congress, Indian Roads. "IRC: 37-2012, Guidelines for the Design of Flexible Pavements." In *Indian Roads Congress, New Delhi, India*. (2012).

Persian Abstract

چکیده

به دلیل شهرنشینی و صنعتی شدن سریع، ساخت جاده ها برای حمل و نقل آسان و سریع به سرعت افزایش می یابد. خاک مناسب در همه جا برای ساخت جاده های خوب در دسترس نیست. از این رو، جاده ها به اجبار بر روی خاک در دسترس محلی مانند خاک سست یا خاک گسترده ساخته می شوند. در این مقاله، یک بررسی تجربی بر روی خاک کم پلاستیک (LPS) برای افزایش خواص مهندسی با استفاده از تثبیت شیمیایی خاک (ژئوپلیمر مبتنی بر خاکستر بادی) انجام شد. طراحی ضخامت روسازی انعطاف پذیر برای مصالح خاک معمولی و تثبیت شده با استفاده از نرم افزار IITPAVE طبق دستورالعمل IRC 37 انجام شد. نتایج نشان می‌دهد که امکان‌پذیری ژئوپلیمر مبتنی بر خاکستر بادی، افزایش قابل‌توجهی استحکام از نظر مقاومت فشاری محدود (UCS) برای روزهای مختلف پخت (۰ تا ۱۲۸ روز)، نسبت باربری کالیفرنیا (CBR)و مدول ارتجاعی (MR) مشاهده شد. تجزیه و تحلیل ریزساختاری از طریق میکروسکوپ الکترونیکی روبشی (SEM) و تجزیه و تحلیل پراش پرتو ایکس (XRD) همچنین تشکیل ژل ژئوپلیمری را که منجر به ماتریکس متراکم به توده خاک می‌شود، آشکار کرد. ضخامت روسازی منعطف به طور قابل توجهی با استفاده از خاک کم پلاستیک تثبیت شده کاهش می یابد.