An Investigation on the Influence of Palm Oil Fuel Ash (POFA) and Magnesium Chloride ($MgCl_2$) on Improving The Strength Characteristics Of Expansive Soil as Sub-Grade For Flexible Pavements

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Abstract: Expansive soils create serious trouble in construction works, especially in pavements, because the soil subgrade beneath the pavement is prone to moisture which causes swelling when they are wet and shrink during dry periods. This swell and shrink phenomenon leads to cracks, settlement and early damage in pavements. The Expansive soils are spread widely across many regions of the world especially in Indian sub-continental areas like Indo-Gangetic plains, Coastal areas of the Indian peninsula and across the Deltas of the Indian rivers. The Expansive soils remain a major issue in developing countries such as India, where constructions are frequent and the scarcity of spaces in the densely packed cities create a situation where there would be a necessity to reclaim the spaces that sits on expansive soils for which the soil stabilization is essential. POFA is a pozzolanic industrial byproduct generated from the edible oil industry, and its utilization in construction activities provides an efficient and environmentally friendly solution. In this research, an attempt was made to amend the strength of ES, by incorporating POFA as an admixture along with Magnesium Chloride as a chemical additive. Various laboratory tests were conducted to evaluate the changes in the geomechanical properties of the ES. The results showed a vivid increment in the strength and load-carrying capacity. The findings proved that POFA and $MgCl_2$ are economical and eco-friendly materials for stabilizing expansive soils as sub-grade to improve the performance of flexible pavements.

Key Words: Expansive Soil, Palm Oil Fuel Ash (POFA), Magnesium Chloride ($MgCl_2$), Soil Stabilization, CBR, OMC, MDD.

1. Introduction

The shrink and swell tendency of ES is mainly due to the presence of soil mineralogical components such as montmorillonite, Illite etc, which poses serious challenges in the infrastructure, because it leads to the development of cracks, differential settlements, and structural instability [18][22]. Such changes adversely affect structures constructed over these soils, often resulting in premature failures and increased maintenance requirements [1][2]. Consequently, the economic burden associated with repair and rehabilitation becomes substantial.

As a part of this exploration, the soil was sampled from the site was identified as ES due to its expansive nature. The main criteria to distinguish between the expansive soil and the marine clay is that the Natural Moisture Content (NMC) in the marine clay is more than the liquid limit whereas in the ES, the NMC will be less than the LL [21]. The presence of such expansive soils in sub-grade layer is of main concern in flexible pavements, as the performance and longevity are closely tied to the strength characteristics and stableness of the underlying soil [2][19]. Weak expansive soils exhibit low load-bearing capacity and poor resistance to deformation, which ultimately leads to the deterioration of pavements under repeated traffic loading.

Given these circumstances, this research examines the potential use of POFA, which is a new generation by-product generated from palm oil industries, as a soil stabilizing admixture [7][8][9][11][13]. The POFA possesses pozzolanic properties, which contributes to improve the soil strength, reduced plasticity, and enhanced overall engineering behavior of expansive soils because of its cementicious properties overtime [6][8][9][13]. Subsequently, the addition of POFA, positively influences the compaction characteristics and increases the bearing capacity of the soil [8][10][11][12]. Along with POFA, the addition of chemical additive like Magnesium Chloride (MgCl2) at 8M was explored in the present study [14][15]. This combination contributes in increasing the Geomechanical behaviour of expansive soil by filling the soil voids and acts as fillers through pozzolanic reactions.[10][11]. The magnesium chloride chemically stabilizes the soil through the flocculating effect of Mg^{2+} ions aggregation and moisture sensitivity reduction [14][15]. The subgrade performance of flexible pavements can be effectively improved through the stabilization of expansive soils with POFA and $MgCl_2$, resulting in enhanced durability and allowable bearing pressure. Hence the treated soil becomes more reliable for use in pavement layers, ultimately contributing to more sustainable and resilient infrastructure development.

2. Objectives of the Study

1. To characterize the geotechnical properties of the untreated ES sample obtained from the site.
2. To evaluate the outcome of incorporating POFA at different proportions on the geotechnical behaviour of the expansive soil and to identify the optimum proportion required for its stabilization.
3. To find out the optimum dosage of Magnesium Chloride ($MgCl_2$) and its influence on the mechanical parameters of ES treated with the optimum proportions of POFA.
4. To compare and analyze the mineralogical structure of the soil prior to its stabilization and to compare the soil mineralogical changes post stabilization by conducting X-Ray Diffraction (XRD).
5. To assess the suitability of the stabilized soil for its application as a subgrade in flexible pavement construction as per IRC recommendations and to check its viability through Laboratory Cyclic Plate Load Test on model pavement.
6. To examine the potential for the sustainable utilization of POFA being an industrial by-product in the treatment of swelling soils as subgrade for the pavement construction.

3. Materials Utilized

3.1 Expansive Soil

Expansive soil is sampled from Anatavaram panchayat division in Dr. B.R.A.K District, Andhra Pradesh at a depth of 1-foot from the site GL to eliminate vegetation and other non-synthetic materials. The soil was dark in colour with very fine consistency. Hence it is also called as BCS and it is very expansive in nature. It significantly swells in wet conditions and it shrinks and cracks in dry conditions.

TABLE-1 - GEOMECHANICAL PARAMETERS OF UNTREATED ES

S.No	Test	Symbol	Results
1	Differential Free Swell (%)	DFS	100
2	Specific Gravity	*G*	2.56
3	Particle Size Distribution	PSD	-

	Gravel (%)	-	0
	Sand (%)	-	6.3
	Silt (%)	-	25.5
	Clay (%)	-	68.2
4	Atterberg limits	-	-
	Liquid limit (%)	W_L	63.12
	Plastic limit(%)	W_P	36.79
5	Plasticity Index (%)	I_P	36.33
6	Shrinkage Limit (%)	W_S	12
7	Modified Proctor Compaction Test	-	-
	Optimum moisture content (%)	OMC	27.22
	Maximum dry density (g/cc)	MDD	1.62
8	CBR, 4 days Soaked (%)	-	1.15
9	Cohesion (kN/m²)	C	121.41
10	Angle of Internal Friction (^{0})	ϕ	2.55

3.2 Palm Oil Fuel Ash (POFA):

The POFA is an by-product from edible oil Industry and it was sampled from Patanjali Foods Limited near Samalkot, Kakinada District, Andhra Pradesh.

TABLE-2 - CHEMICAL CONSTITUENTS OF POFA

S.no.	Chemical Composition	Formula	Percentage (%)
1	Silicon Dioxide	SiO_2	53.8
2	Aluminium oxide	Al_2O_3	5.67
3	Ferric Oxide	Fe_2O_3	4.55
4	Calcium Oxide	CaO	4.25
5	Potassium Oxide	K_2O	4.48
6	Loss of Ignition	LOI	10.5

(Courtesy: Patanjali Foods Limited, Samalkot, Kakinada (Dt), A.P, India)

3.3 Magnesium Chloride ($MgCl_2$):

Magnesium Chloride ($MgCl_2$) is procured from e-commerce for the purpose of experiment. The Magnesium chloride is an important laboratory chemical which is a white crystalline and odourless compound. It is not explosive but it is highly reactive in nature and dissolves easily in water. Magnesium chloride absorbs moisture from the air at room temperature and forms a hydrated compound. It is widely used in medicines, agriculture, and industrial processes because of its useful chemical properties.

Table 3 - CHEMICAL COMPOSITION OF MAGNESIUM CHLORIDE

S.No.	Specifications	Percentage (%)
1	Acidity	0.001
2	Calcium Sulphate	0.005
3	Barium	0.002
4	Potassium Chloride (KCl)	0.002

(Courtesy: FIZMERK INDIA CHEMICALS)

4. Experimental Methodology

4.1 Sample Preparation and Stabilization:

The soil obtained from the site was air-dried, thoroughly pulverized, and sieved through a 425 μm IS sieve before being used to determine its index parameters in accordance with the relevant standards. The laboratory investigations were carried out on the samples of untreated Expansive Soil, Expansive Soil treated with with varying percentages of the POFA and $MgCl_2$. The POFA with proportions 6%, 12%, 18%, 24% and $MgCl_2$ with proportions 0.5%, 1%, 1.5%, 2% were established in present study. The tests were conducted as per Indian Standards (IS) code of practice and ASTM Standards.

4.2 Index and Swell Characteristics:

The specific gravity of the soil was determined using a density bottle in accordance with **IS 2720 (Part 3):1980**. The Atterberg limits, comprising LL, PL, and PI, were established as per IS 2720 (Part 4):1970. Diffrential Free Swell (DFS) was evaluated for untreated ES, POFA-treated ES, and POFA–$MgCl_2$-treated ES following the relevant [21]

4.3 Compaction and CBR:

Modified Proctor compaction tests were conducted for determining the relationship between water content and dry density and to determine the OMC in accordance with **IS 2720 (Part 8):1983**. The California Bearing Ratio tests (CBR) were subsequently conducted on the untreated and stabilized ES specimens using different POFA and $MgCl_2$ dosages, following **IS 2720 (Part 7)**. [21].

4.4 Shear Strength Characteristics:

Triaxial compression tests were conducted to evaluate the shear strength characteristics of untreated ES and stabilized soil mixtures. The tests were conducted in accordance with **IS 2720 (Part 11)**. The experimental programme considered untreated ES, POFA-treated ES, and POFA–$MgCl_2$-treated ES specimens to assess the influence of stabilization on the shear strength parameters, particularly cohesion and the angle of internal friction [21].

4.5 Soil Mineralogical Analysis:

The oven-dried soil was air-dried, pulverized, and passed through a 75 μm IS sieve. Untreated ES, ES blended with optimum POFA, and ES blended with optimum POFA and $MgCl_2$ were prepared at OMC, homogenized, and cured for 7 days in airtight packs before conducting XRD, to identify the mineralogical characteristics based on the diffraction intensity with respect to the 2θ angle.

4.6 Laboratory Cyclic Plate Load Test;

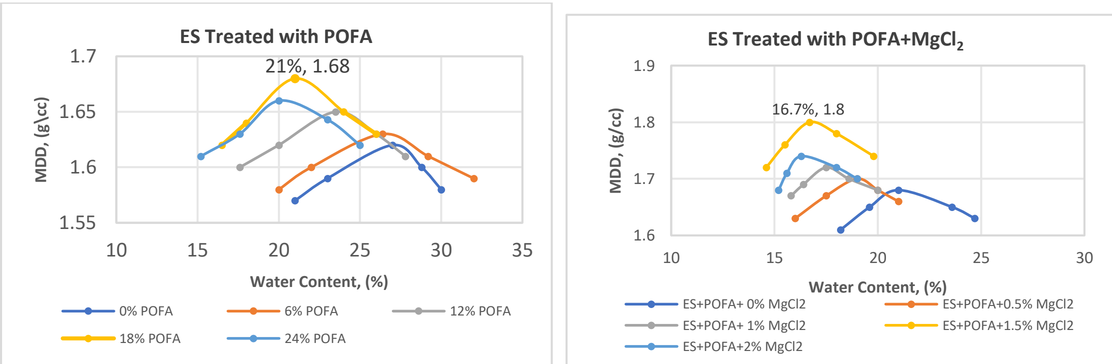
The laboratory cyclic plate load test (CPLT) of model pavement has been conducted in a steel test tank by preparing the soil sub-grade of 30cm, sub-base of 5cm and a base course of 5cm in sequential layers and it was compacted at OMC to achieve the specified target of denseness. A leveled surface was provided for installing a stiff round mild-steel plate of 100 mm diameter, and the application of load to the plate was given through a hydraulic jack supported by a loaded reaction frame on an unstabilized and stabilized ES to evaluate the cyclic pressure–settlement response under repeated loading.

Fig. 4.1 Author Conducting Laboratory CPLT

5. Results & Discussions

The outcomes of this research work indicated that the addition of POFA at 6%, 12%, 18%, and 24% influenced the engineering properties of ES, with the optimum performance being observed at **18% POFA**. Further stabilization of the optimum POFA-treated ES was carried out using $MgCl_2$ at dosages of 0.5%, 1.0%, 1.5%, and 2.0%, among which **1.5% $MgCl_2$** exhibited the optimum stabilization performance. The DFS showed a progressive reduction with increasing stabilizer content, indicating a decrease in the swelling phenomenon and an overall improvement in the engineering behaviour of the treated ES.

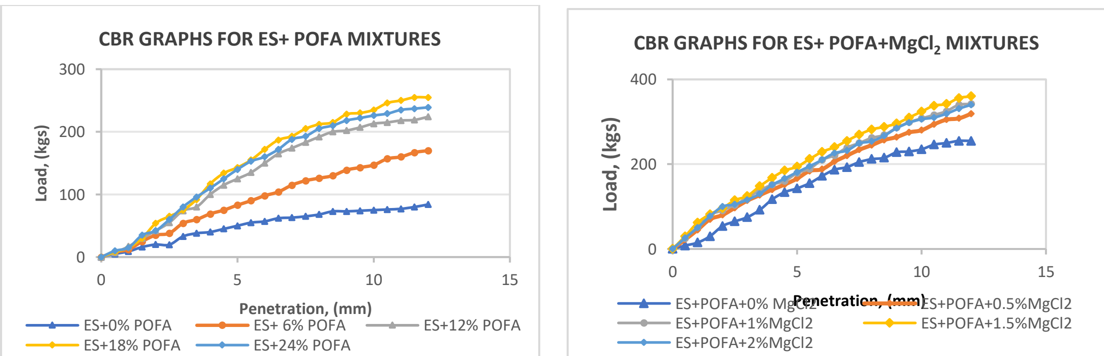
5.1 Moisture and Density variation of ES treated with varying percentages of POFA & various percentages of $MgCl_2$:



(i) (ii)

Fig. 5.1: (i) Moisture and Density variation of ES treated with varying percentages of POFA & (ii) ES treated with optimum POFA & various percentages of Magnesium Chloride

5.2 CBR of Expansive soil treated with varying percentages of POFA & various percentages of $MgCl_2$:



(i) (ii)

Fig. 5.2: (i) CBR variation of ES treated with varying percentages of POFA & (ii) ES treated with optimum POFA & treated with various percentages of Magnesium Chloride

Table 4 - Geotechnical Properties of Untreated and Treated Expansive soil

S.No	Property	Untreated Expansive Soil	Expansive Soil treated with 18% of POFA	Expansive Soil + 18% POFA and 1.5% $MgCl_2$
1	Differential Free Swell (%)	100	26	18
2	Liquid Limit (%)	63.12	50.72	45.97
3	Plastic Limit (%)	36.79	35.19	27.38
4	Plasticity Index (%)	32.83	14.93	9.03
5	Specific Gravity	2.56	2.6	2.65
6	Shrinkage Limit (%)	12	16	21
7	Soil Classification	CH	CH	CI
8	Optimum Mosture Content (%)	27.22	21	16.7
9	Maximum Dry Density	1.62	1.68	1.8
10	Soaked CBR	2.28	4.74	8.39
11	Cohesion (kN/m^2)	124.41	50.12	30
12	Angle of Internal Friction	2.55	7	8.8

5.3 Soil Mineralogical Analysis (XRD):

The XRD presents a clear change in the mineral structure of the expansive soil after treatment. The untreated ES displays high intensity peaks representing Quartz and swelling Montmorillonite, a clay mineral. Introducing POFA lowered these peak heights, which indicates the initial breakdown of the crystalline minerals. The combination of POFA and $MgCl_2$ reduces the Montmorillonite peak to near baseline levels. This systematic drop in intensity proves that the crystalline minerals are successfully transforming into stable amorphous phases. Therefore, this chemical treatment effectively controlled the minerals responsible for the soil expansion.

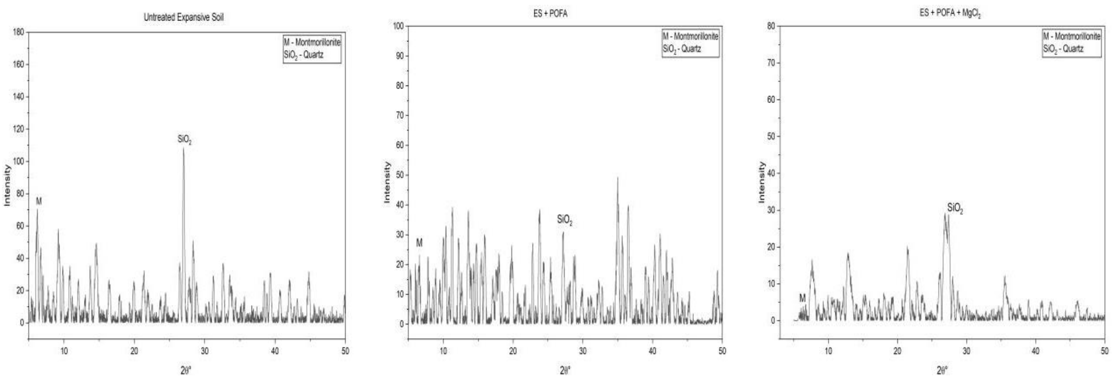


Fig. 5.3 XRD Analysis of Untreated ES, POFA Treated ES, ES+POFA+$MgCl_2$

5.4 Laboratory Cyclic Plate Load Test (CPLT) on Model Flexible Pavement:

The cyclic plate load was carried out and it is observed that the load bearing capability and stiffness of the expansive soil were significantly improved after stabilization. The untreated soil failed at 600 kPa with a settlement of 3.2 mm. Stabilization increased the failure load to 1000 kPa with a settlement of 2.47 mm. The optimum combination of 18% POFA + 1.5% $MgCl_2$ with soil significantly performed well and failed at 2400 kPa pressure with the settlement of 1.525 mm, confirming its good subgrade structural competence and deformation resistance for pavement applications under cyclic pressures.

Table 9 - Laboratory Cyclic Plate Load Test of Model Pavement

Treatment	Failure Load (kPa)	Settlement at Failure (mm)	Load Improvement	Settlement Reduction
Untreated ES	600	3.385	-	-
ES+ 18% POFA	1,500	2.25	+150%	33.53%
ES+ 18% POFA+ 1.5% $MgCl_2$	2400	1.525	+300%	54.95%

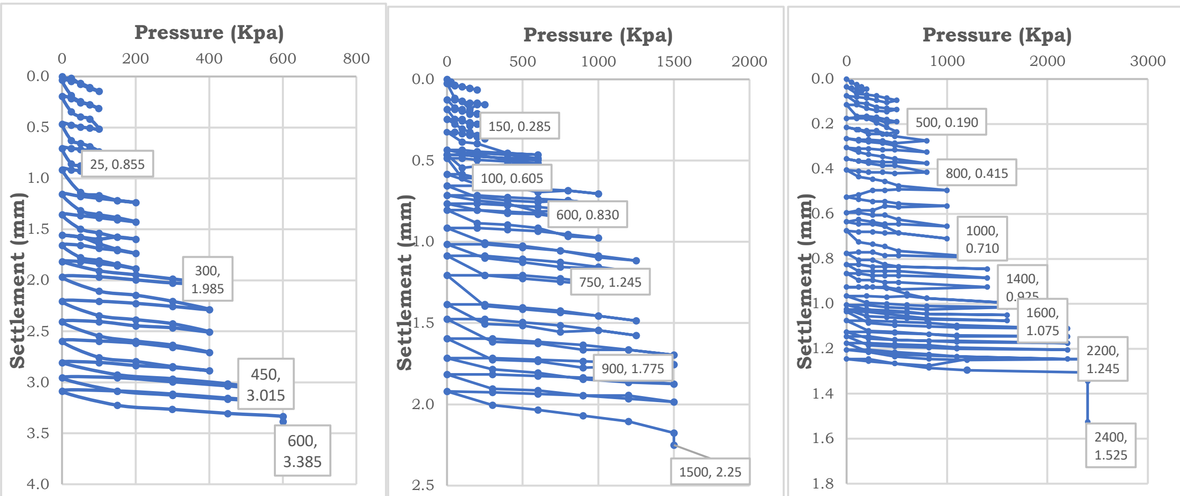


Fig. 5.4 XRD Analysis of Untreated ES, POFA treated ES, Combination of POFA Treated ES+$MgCl_2$

6. Conclusions

1. The untreated ES soil was identified as highly compressible clay (CH) and it exhibited a DFS value of 100%, which indicates a high degree of expansiveness and poor suitability as a pavement subgrade.
2. The addition of 18% POFA significantly lowered the swell of the soil, proving its effectiveness in improving the behavior of expansive soils.
3. The combination of 18% POFA and 1.5% $MgCl_2$ further reduced the DFS value to 18%, showing better control of soil expansion compared to POFA alone.
4. The Atterberg limits decreased considerably after stabilization, which indicates a reduction in plasticity and moisture susceptibility of the soil. The soil classification changed from CH to CI due to reduction in Atterberg's limits after stabilization.

5. The specific gravity increased slightly after treatment, suggesting the development of a denser and more stable soil structure.

6. The soil stabilized with POFA, POFA+ $MgCl_2$ exhibited improved compaction characteristics as witnessed by a reduced OMC and an elevated MDD.

7. The "ϕ" value increased significantly from 2.55° to 8.8°, at optimum dosage of POFA+$MgCl_2$ while cohesion reduced significantly from 124.41 kN/m² to 30 kN/m² which proves the effectiveness of stabilization.

8. As per IRC recommendations, the treated soil should possess a minimum of 8% CBR to be used as sub-grade. Since the CBR obtained in soil treated with optimum proportions of POFA+$MgCl_2$ was 8.5%, it clearly proves that the stabilization process enhanced the strength resistance parameters of the ES and enhanced its potential to use in pavement applications.

9. It is evident from the laboratory CPLT that the combination of POFA and $MgCl_2$ has significantly contributed to the stabilization of soil and it reaffirms the suitability of this combination as sub-grade for the flexible pavements by improving the maximum contact pressure of soil and significantly reducing the permanent axial strain under cyclic loads.

10. The soil mineralogical analysis through XRD has confirmed the presence of predominant Montmorillonite mineral along with Quartz in the untreated expansive soil, which contributed to the significant swelling of untreated soil and it is evident from the POFA treated soil that the Montmorillonite peaks were significantly reduced and modified due to mineralogical changes through interactions with the reactive silica-rich constituents of POFA. The addition of $MgCl_2$ further modified the montmorillonite reflections, potentially due to Mg^{2+} cation exchange and changes in the clay inter layer structure. Hence the stabilization promoted the mineralogical modification and stabilization of the expansive soil .

11. Overall, the enhanced performance was observed in combination of 18% POFA and 1.5% $MgCl_2$ when compared to POFA alone in enhancing the strength and firmness of ES, thereby fashioning it as a sustainable and economical substitute for subgrade improvement in flexible pavement construction.

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