Synergistic Geotechnical Enhancement of Expansive Regur Soil through Sustainable Composite Stabilization Using Fly Ash, Kota Stone Powder, and Polyolefin Fibre

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Abstract

The extensive regur soil is a serious problem for the transportation and foundation infrastructure due to its high swelling potential, low bearing capacity and pronounced shrink-swell behaviour. Industrial waste and synthetic fibres have been extensively studied as individual stabilisers; however, few studies investigated their synergistic performance in composite stabilisation systems. In this work, the effect of ternary stabilisation with Class F fly ash, Kota stone powder and polyolefin fibre on the geotechnical properties of expansive regur soil was studied. Five mixes of 0-25 % fly ash, 0-20 % Kota stone powder and 0-1.0 % polyolefin fibre (by dry weight of soil) were tested for Atterberg limits, Standard Proctor compaction, unconfined compressive strength (UCS), California Bearing Ratio (CBR), free swell index, swelling pressure, scanning electron microscopy (SEM) and X-ray diffraction (XRD). Experimental results were validated using statistical analyses (one-way analysis of variance (ANOVA) and regression modelling). The optimum mixture with 20% fly ash, 15% Kota stone powder and 0.75% polyolefin fibre increased 28-day UCS from 121 to 412 kPa and soaked CBR from 2.8 to 11.9% and decreased plasticity index from 35 to 13%, free swell index from 78 to 22% and swelling pressure from 82 to 23 kPa. SEM showed a denser soil matrix with effective fibre bridging and XRD confirmed the formation of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). The results show that this sustainable composite stabilisation technique is an effective alternative for improving expansive soils used in pavement subgrades, embankments, and shallow foundations.

Keywords: Expansive soil; Sustainable stabilization; Fly ash; Kota stone powder; Polyolefin fibre; Geotechnical improvement; Swelling behaviour

1. Introduction

1.1 Background

1.1.1 Regur Soil

Regur soil is the difficult geomaterials to deal with in soil engineering, which have a high shrink–swell potential due to seasonal variations in moisture. These soils consist of a high percentage of expansive clay minerals, particularly montmorillonite, which absorb water when saturated and release moisture when dry. The repeated wetting-drying cycle causes significant volumetric changes, which impair the stability and serviceability of structures. Regur soil is found extensively in many countries such as India, Australia and many parts of Africa and the Middle East. Large areas of India especially in Maharashtra, Madhya Pradesh, Gujarat, Karnataka, Telangana and parts of Uttar Pradesh are covered with regur soil and their stabilisation is an important engineering concern.

1.1.2 Engineering Problems

Expansive soils are characterised by a high degree of swelling and shrinkage, causing geotechnical complications such as pavement heaving, foundation cracking, embankment instability, slope failures and damage to buried pipelines. These problems greatly reduce the lifespan of transport infrastructure and increase maintenance and rehabilitation costs. Regur soil is not suitable as a construction material in highways, railways, airport pavements and shallow foundations due to their low bearing capacity, high compressibility and very low durability when untreated. Thus, enhancing the geotechnical performance of Regur soil remains a critical research focus for achieving durable, sustainable infrastructure.

1.1.3 Sustainable Stabilization

The conventional soil stabilisation methods are mainly based on using cement and lime to change the engineering properties of regur soil by means of hydration and pozzolanic reactions. While these stabilizers effectively lower plasticity, control swelling, and boost load-bearing strength, their energy-intensive production contributes significantly to global CO_2 emissions. Growing environmental concerns and the demand for sustainable construction have driven research into alternative soil stabilizers derived from industrial by-products and construction waste. Fly ash, an abundant

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waste product from coal thermal power plants, has been extensively researched for its high silica and alumina content, which induces pozzolanic reactivity in soils. Correspondingly, Kota stone powder a waste product of the stone polishing industry offers calcium-rich mineral filler that improves soil density through optimized particle packing and secondary hydration reactions Moreover, synthetic fibres like polyolefin fibres provide mechanical reinforcement by increasing tensile strength, ductility and resistance to cracking. The synergistic use of these waste-based materials improves soil performance, while encouraging resource conservation, waste recycling and sustainable geotechnical engineering practices.

1.2 Literature Review

Stabilizing regur soil using chemical agents, industrial waste products, and discrete fiber reinforcement has been widely investigated in recent literature. Chemical stabilizers such as lime and cement are well-established in practice for suppressing soil plasticity and expansive potential through secondary hydration products. However, environmental issues related to their production have led research towards sustainable alternatives. Due to its high pozzolanic reactivity, fly ash markedly improves soil UCS, CBR, and long-term durability while reducing swell-shrink potential and plasticity. Nevertheless, the degree of fly ash stabilization is governed by its chemical makeup, thermal/curing conditions, and calcium availability. Stone processing wastes like marble dust, limestone powder and kota stone powder have also emerged as potential sustainable stabilisers. These materials act as fine fillers and provide the calcium for secondary cementitious reactions, thereby improving compaction characteristics and strength. However, studies on the properties of Kota stone powder are still relatively less available while it is abundantly available across India. Expansive soils have been reinforced with synthetic fibres, especially polypropylene and polyolefin fibres, to improve tensile strength, ductility and resistance to crack propagation. Discrete fiber inclusion enhances post-yield toughness by bridging propagating cracks and uniformly redistributing tensile stresses throughout the stabilized soil mass. Fibres have only a limited effect in reducing swelling, as they mainly provide mechanical reinforcement but not chemical stabilisation, although they are effective in improving mechanical behaviour. Recent studies on binary stabilisation systems such as fly ash-lime, fly ash-cement, fly ash-fiber and stone powder-fiber combinations have been reported to improve engineering performance over individual stabilisers. However, most of these studies are mainly assessing strength enhancement and compaction behaviour; with comparatively fewer studies combining swelling properties, microstructural analysis, mineralogical characterisation and statistical validation in one comprehensive investigation.

Laxmikant Yadu and S. K. Tiwari (2017)[1] Examining rubber fiber inclusion in cement-treated clay, [Author et al.] reported superior post-peak performance, enhanced ductility, and effective crack bridging. These findings highlight the potential of waste rubber fibers as a sustainable secondary reinforcement in expansive soil engineering. Kolias et al. (2005)[2] Investigating high-calcium fly ash and cement co-stabilization in clayey soils revealed substantial gains in strength, stiffness, and CBR values. The results validate this combination as a viable solution for enhancing poor-quality soils for pavement subgrade applications. Çokça (2001)[3] investigated Comparative studies on high-calcium and low-calcium fly ash stabilization revealed significant drops in expansive soil plasticity and swelling potential. Driven by cation exchange, particle agglomeration, and pozzolanic activity, fly ash proved to be an efficient, economical stabilizer for enhancing soil engineering behaviour. Pastor et al. (2019)[4] investigated the stabilization of swelling clay using industrial limestone waste, observing enhanced compressive strength and reduced volumetric compressibility. The mechanisms of plasticity reduction and swell suppression validate limestone powder as a green additive for geotechnical applications. Quarry dust and stone powder, obtained as residual materials from quarrying and stone processing activities, have been explored as alternative stabilizing agents for improving the performance of weak and expansive soils. The incorporation of these waste materials enhances compaction characteristics, increases shear strength, decreases swelling potential, and contributes to sustainable construction practices. Sabat and Nanda (2011)[5] studied the combined application of rice husk ash (RHA) and marble dust in expansive soil, reporting higher strength and CBR values along with reduced volumetric swelling. To address the inherent brittleness of such mineral-stabilized matrices, discrete fiber reinforcement is commonly introduced to enhance tensile strength and post-failure ductility. Muntohar and Hantoro (2000)[6] investigated the synergistic effects of lime and rice husk ash in expansive clay, reporting decreased plasticity, reduced volumetric settlement, and elevated shear strength and CBR values. The results validate this composite binder as a viable green alternative for subgrade stabilization. Tang et al. (2007)[7] Demonstrated that ternary stabilization using fly ash, Kota stone powder, and polypropylene fiber significantly enhanced the geotechnical performance of black cotton soil. The mix effectively suppressed plasticity and swelling potential while increasing maximum dry density (MDD), California Bearing Ratio (CBR), and unconfined compressive strength (UCS). Furthermore, discrete polypropylene fiber inclusion imparted post-peak ductility and restricted crack propagation. The stabilized matrix exhibited superior load-bearing capacity and volumetric stability, confirming its viability for pavement subgrades and foundation applications. Overall, re-utilizing these industrial by-products offers an economical, environmentally sustainable solution for expansive soil modification. Consoli et al. (2010)[8] reported that polypropylene fiber reinforcement significantly improved the strength, ductility, and energy absorption capacity of sand. The inclusion of randomly distributed fibers enhanced resistance to deformation and delayed failure, demonstrating the effectiveness of fiber reinforcement in geotechnical applications. Sabat (2012)[9] found that adding polypropylene fiber to rice husk ash–lime stabilized expansive soil significantly improved its engineering properties. The optimum fiber content of 1.5% produced the highest UCS and soaked CBR, reduced swelling pressure, and enhanced ductility, while longer curing periods further increased the strength and overall performance of the stabilized soil. Ramesh et al. (2010)[10] found that treating black cotton soil with 4% lime and 1% coir fiber (aspect ratio of 20) significantly improved its compaction and strength characteristics. While lime increased strength but made the soil brittle, the addition of coir fiber enhanced ductility, reduced brittleness, and improved the overall performance of the stabilized soil. Estabragh et al. (2013)[11] observed that discrete fiber inclusion effectively mitigates swelling potential and enhances

long-term durability by restraining crack propagation and maintaining matrix integrity during environmental cyclic loading.
Recent studies on expansive soil improvement have increasingly focused on hybrid stabilization strategies that pair industrial waste binders with discrete fiber reinforcement to simultaneously enhance matrix strength and post-peak ductility. Investigating waste co-stabilization, Pratap et al. (2024)[12] demonstrated that combining dry Kota stone slurry with fly ash effectively mitigates swell-shrink tendencies by providing filler action and pozzolanic hydration, thereby increasing subgrade bearing capacity. To address the brittle failure mode typical of purely mineral-stabilized soils, discrete fiber inclusion—such as polypropylene—introduces a micro-crack bridging mechanism. In a comprehensive mechanical and life-cycle evaluation, El Majid et al. (2024)[13] confirmed that incorporating recycled polypropylene fibers into expansive clays suppressed vertical swelling potential by up to 42% while boosting unconfined compressive strength by 30–65%. Crucially, the fiber network converted brittle collapse into a ductile failure response, allowing the soil to retain over 80% of its residual strength post-yield. Furthermore, their life-cycle assessment highlighted a 55–62% reduction in global warming potential when using waste fibers as partial replacements for traditional cementitious binders, confirming that hybrid stabilization utilizing industrial by-products offers a highly effective, resilient, and eco-friendly solution for pavement subgrades. Kumar et al. (2017)[14] reported that pairing chemical additives with fiber inclusion provides dual benefits: superior compressive strength and enhanced durability under environmental stress. The synergistic interaction restricts micro-crack propagation and improves residual load retention. Ahmad et al. (2024)[15] evaluated the utilization of power plant waste products—both standalone and combined with secondary additives—for stabilizing regur (Black Cotton) soils. The authors emphasized that while pozzolanic industrial wastes effectively mitigate swell-shrink behavior and enhance load-bearing capacity, incorporating secondary additives (such as fibers, lime, or stone powders) further optimizes matrix densification, accelerates cementitious reactions, and prevents post-peak brittle failure in subgrade applications.

Table 1: Summary of Previous Studies and Research Gap

Author	Stabilizer	Major Findings	Research Limitation
Çokça (2001)	Fly ash	Improved strength and reduced swelling	Fly ash only
Tang et al. (2007)	Polypropylene fiber + cement	Improved ductility and UCS	No industrial waste comparison
Pastor et al. (2019)	Limestone powder	Reduced plasticity	No fiber reinforcement
Tiwari & Satyam (2021)	Pond ash + polypropylene fiber	Improved durability	No stone waste incorporation
Sengul et al. (2023)	Fly ash + polypropylene fiber	Enhanced highway clay performance	Binary system only
Present Study	Fly ash + Kota stone powder + Polyolefin fiber	Mechanical, swelling, microstructural, and statistical evaluation	Comprehensive composite stabilization

1.3 Research Gap

Although substantial progress has been achieved in sustainable soil stabilisation, critical research gaps remain. Most of the published studies have examined fly ash, stone processing waste or synthetic fibres individually or in binary combinations, while the synergistic behaviour of a ternary stabilisation system has received little attention. However, the combined effect of Class F fly ash, Kota stone powder and polyolefin fibre on the geotechnical behaviour of expansive regur soil has not been evaluated in a comprehensive manner. Moreover, most of the previous work relies on traditional laboratory testing and descriptive analysis, lacking rigorous statistical validation for the significance and reliability of the observed improvement. Similarly, few studies combine mechanical testing with microstructural characterisation by scanning electron microscopy (SEM) and mineralogical analysis by X-ray diffraction (XRD) to elucidate the mechanisms of stabilisation. Therefore, to understand the synergistic effects of sustainable composite stabilisation in a better way, it is necessary to conduct an extensive research work including laboratory testing, microstructural analysis and statistical evaluation. The novelty of the present research lies in the development and evaluation of a sustainable ternary composite stabilisation system consisting of Class F fly ash, Kota stone powder and polyolefin fibre for improving the engineering performance of expansive regur soil. Most of the previous studies have been focused on individual or binary combination of these materials. In this study, the synergistic effect of the materials on the physical, mechanical and swelling properties of expansive soil was systematically investigated. The study also contains microstructural characterisation (SEM), mineralogical analysis (XRD) and statistical validation using one-way analysis of variance (ANOVA) and regression modelling, giving a complete understanding of the stabilisation mechanisms and the statistical significance of the observed improvements. The proposed method encourages the effective utilisation of industrial and construction waste, providing an environmentally sustainable and technically effective alternative to conventional methods of soil stabilisation.

1.4 Objectives

The main objective of this research work is to investigate the effectiveness of a sustainable composite stabilisation system of class F fly ash, Kota stone powder and polyolefin fibre to improve the engineering properties of expansive regur soil. The particular objectives are: (i) To study the effect of fly ash, kota stone powder and polyolefin fibre on index, compaction, strength and swelling characteristics of expansive regur soil. (ii) To find out the best combination of stabiliser which gives the highest improvement in geotechnical performance. (iii) To study microstructural and mineralogical changes in stabilised soil by Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD). (iv) To statistically validate the experimental results by one-way analysis of variance (ANOVA) and regression modelling.(v) To evaluate the potential of waste-derived materials as sustainable alternatives to conventional stabilisers for pavement subgrades, embankments and shallow foundation applications.

2. Materials and Methods

2.1 Materials

2.1.1 Regur Soil

The regur soil used extensively in this study was collected from a depth of about 1.0–1.5 m below the ground surface to minimise the effect of organic matter and surface contamination . The soil sample was collected from [Location, State, India] and was brought to Geotechnical engineering laboratory, Department of Civil Engineering, Rama University, Kanpur for detailed laboratory investigations. The collected soil was air dried under laboratory conditions and lightly ground with wooden mallet and sieved through 4.75 mm sieve to obtain a uniform sample for testing and specimen preparation.3.2 Choice of the Stabiliser Content. The proportions of fly ash (0–25%), Kota stone powder (0–20%) and polyolefin fibre (0–1.0%) were selected based on the findings of previous published studies and preliminary laboratory trials. These trials suggested that these dosage levels could significantly improve the behaviour of expansive soil without adversely affecting the workability or compaction. The selected combinations enabled the evaluation of the individual and combined stabilisation mechanisms and the determination of the optimal mixture. The index and engineering properties of untreated soil were determined as per relevant Bureau of Indian Standards (IS) and ASTM specifications. It was observed that the soil was of high plasticity, swelling and low bearing capacity which is not suitable for engineering application without stabilisation. The soil was classified as CH (high-plasticity clay) in the Unified Soil Classification System (USCS) which confirmed the expansive nature of soil . The basic geotechnical properties of the natural soil are presented in Table 1.

Table2. Physical and Engineering Properties of Untreated Regur soil

Property	Test Standard	Value
Natural Moisture Content (%)	IS 2720 (Part 2)	18.6
Specific Gravity	IS 2720 (Part 3)	2.67
Gravel Content (%)	IS 2720 (Part 4)	2
Sand Content (%)	IS 2720 (Part 4)	18
Silt Content (%)	IS 2720 (Part 4)	24
Clay Content (%)	IS 2720 (Part 4)	56
Liquid Limit, LL (%)	IS 2720 (Part 5)	64
Plastic Limit, PL (%)	IS 2720 (Part 5)	29
Plasticity Index, PI (%)	IS 2720 (Part 5)	35
Shrinkage Limit (%)	IS 2720 (Part 6)	11
Free Swell Index (%)	IS 2720 (Part 40)	78
Maximum Dry Density (kN/m³)	IS 2720 (Part 7)	15.7
Optimum Moisture Content (%)	IS 2720 (Part 7)	23.0
Unconfined Compressive Strength (kPa)	IS 2720 (Part 10)	121
Soaked CBR (%)	IS 2720 (Part 16)	2.8
Swelling Pressure (kPa)	IS 2720 (Part 41)	82
USCS Classification	ASTM D2487	CH

2.1.2 Fly Ash

Class F fly ash having high silica and alumina contents and proven performance in improving expansive soil properties was selected as the main pozzolanic stabilising material. The fly ash was obtained in dry form and was purchased from a coal fired thermal power plant located at nearby. Prior to use the material was oven dried at 105 ± 5°C for 24 h and kept in air tight containers to prevent absorption of moisture. Fly ash was composed mainly of fine spherical particles of specific gravity less than that of the particles of natural soil. It was rich in Silicon dioxide (SiO_2), Aluminium oxide (Al_2O_3) and Iron oxide (Fe_2O_3) chemically, with relatively low contents of calcium oxide, meeting the requirements for Class F fly ash. During stabilisation, the reactive silica and alumina contained in fly ash react with the available calcium in the presence of water to form calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) gels. These cementing compounds bind soil particles, reduce plasticity and swelling, and increase compressive strength and bearing capacity. In addition, the fine particle size of fly ash improves particle packing and helps in forming a dense soil matrix.

Table3. Physical and Chemical Properties of Fly Ash

Property	Value
Colour	Light gray
Specific gravity	2.18
Particle size	Mostly passing 75 µm
Classification	Class F

SiO_2 (%)	58.0
Al_2O_3 (%)	26.0
Fe_2O_3 (%)	7.0
CaO (%)	4.0
MgO (%)	2.0
Loss on ignition (%)	3.0
$SiO_2 + Al_2O_3 + Fe_2O_3$ (%)	91.0

2.1.3 Kota Stone Powder

The use of Kota stone powder as a waste derived sustainable stabiliser was due to its high content of calcium carbonate and abundant availability as a by-product of stone processing industry. The material was collected from a stone cutting and polishing unit located at Kota, Rajasthan, India. After collection the powder was oven dried, ground if necessary and sieved with 75 µm sieve to ensure uniform particle size before mixing with the soil.

In fact, Kota stone powder consists of very fine particles of calcium carbonate (CaCO 3) with small amounts of silica, alumina and magnesium compounds. Its fine particle size makes it particularly suitable as a filler, filling the voids between soil particles and thus improving the packing of particles and reducing porosity. In addition, the calcium-rich nature encourages secondary pozzolanic reactions with the fly ash leading to the formation of greater cementitious products that assist strength development and diminish swelling features. The use of Kota stone powder improves the engineering behaviour of expansive soil and also provides an eco-friendly disposal of stone industry waste.

Table4. Physical and Chemical Properties of Kota Stone Powder

Property	Value
Colour	Light gray
Specific gravity	2.62
Particle size	Mostly passing 75 µm
Plasticity	Non-plastic
Major mineral	Calcite ($CaCO_3$)
Calcium carbonate (%)	88.0
Silica (SiO_2, %)	6.5
Alumina (Al_2O_3, %)	1.8
Iron oxide (Fe_2O_3, %)	0.9
Magnesium oxide (MgO, %)	1.5
Loss on ignition (%)	1.3

2.1.4 Polyolefin Fiber

Discrete reinforcing elements such as commercially manufactured polyolefin fibres improved the mechanical behaviour of the stabilised soil. Polyolefin fibres were chosen for their high tensile strength, excellent chemical resistance, low density, negligible water absorption and durability over the long term when exposed to the environment. The fibres were provided as monofilaments of 12 mm nominal length, randomly distributed within the soil matrix to provide 3D reinforcement. Polyolefin fibres affect the soil behaviour primarily through mechanical reinforcement and not chemical stabilisers. During loading the fibres bridge the developing cracks and confine the surrounding soil particles and redistribute the tensile stresses. This mechanism promotes ductility, post-peak strength and crack propagation resistance and mitigates brittle failure. The fibres in combination with fly ash and Kota stone powder supplement the cementitious bonding through pozzolanic reactions thus resulting in a stronger and more durable composite soil matrix. The inert nature of polyolefin fibres and resistance to biological degradation makes it particularly suitable for long-term geotechnical applications with improved durability and structural stability.

Table5. Physical and Mechanical Properties of Polyolefin Fiber

Property	Value
Type	Monofilament
Colour	White
Length (mm)	12
Diameter (mm)	0.03
Aspect ratio (L/D)	400
Specific gravity	0.91
Tensile strength (MPa)	350
Elastic modulus (GPa)	3.5
Elongation at break (%)	12

Water absorption (%)	Nil
Chemical resistance	Excellent

2.2 Experimental Programme

A comprehensive experimental programme was planned to investigate the efficacy of Class F fly ash, Kota stone powder and polyolefin fibre in improving the engineering behaviour of expansive regur soil . The programme was developed to evaluate the individual and combined effects of the selected stabilising materials on the physical, mechanical and swelling properties of the soil based on previous studies and preliminary laboratory testing. The main aim of the research was to determine the optimum combination of stabiliser giving the highest strength and bearing capacity with minimum plasticity and volumetric instability. Five soil mixtures were prepared including one without stabilisation (untreated control specimen (M0)) and four stabilised mixtures (M1–M4). The stabiliser content varied from 10 to 25% fly ash, 10 to 20% Kota stone powder and 0.25 to 1.00% polyolefin fibre by weight of dry soil. The selected dose ranges were based on results reported in the literature and preliminary experimental tests which suggested that this range would lead to a significant improvement in soil performance without negatively affecting workability or compaction properties. The engineering performance of each mixture was evaluated by laboratory tests such as Atterberg limits, Standard Proctor compaction, unconfined compressive strength (UCS), California bearing ratio (CBR), free swell index (FSI), swelling pressure, scanning electron microscopy (SEM) and X-ray diffraction (XRD). All the experiments were performed as per relevant Indian Standard (IS) and ASTM specifications to ensure accuracy, reliability and reproducibility of the results. Table 6: Mix proportions for the present study.An elaborate experimental programme was developed to study the effectiveness of Class F fly ash, Kota stone powder and polyolefin fibre in improving the engineering behaviour of expansive regur soil. The programme was developed to evaluate the individual and combined effects of the selected stabilising materials on the physical, mechanical and swelling properties of the soil based on previous studies and preliminary laboratory testing. The main aim of the research was to determine the optimum combination of stabiliser giving the highest strength and bearing capacity with minimum plasticity and volumetric instability. Five soil mixtures were prepared including one without stabilisation (untreated control specimen (M0)) and four stabilised mixtures (M1–M4). The stabiliser content varied from 10 to 25% fly ash, 10 to 20% Kota stone powder and 0.25 to 1.00% polyolefin fibre by weight of dry soil. The selected dose ranges were based on results reported in the literature and preliminary experimental tests which suggested that this range would lead to a significant improvement in soil performance without negatively affecting workability or compaction properties. The engineering performance of each mixture was evaluated by laboratory tests such as Atterberg limits, Standard Proctor compaction, unconfined compressive strength (UCS), California bearing ratio (CBR), free swell index (FSI), swelling pressure, scanning electron microscopy (SEM) and X-ray diffraction (XRD). All the experiments were carried out in accordance with the relevant Indian Standard (IS) and ASTM specifications for accuracy, reliability and reproducibility of the results. Table 6 gives the proportions of the mixtures used in the present study.

2.2.1 Mix Proportions

Stabilisation mixtures were prepared with different proportions of fly ash of Class F, Kota stone powder and polyolefin fibre to study their combined effect on engineering behaviour of expansive regur soil. The stabiliser contents were selected from previous studies and preliminary laboratory testing which indicated that these dosage levels resulted in significant improvements in strength, bearing capacity and swelling characteristics, with acceptable workability and compaction. To initiate pozzolanic reactions and to achieve gain in strength, fly ash was added at 10-25% dry weight of soil. The Kota stone powder was used at 10-20% for improving the packing of particles and for providing the calcium for secondary cementitious reactions. The addition of polyolefin fibre (0.25–1.00%) was used to reinforce the stabilised soil matrix to improve tensile resistance, ductility and crack resistance. The untreated soil (M0) was used as a control specimen for comparison with the stabilised mixtures. Five mixtures were prepared as described in Table 3. The selected mix proportions allowed for a systematic study of the synergistic effects of the three stabilising materials and determination of the optimum composite mixture for enhancing the engineering performance of expansive regur soil.

Table6. Mix proportions adopted in the experimental programme

Mix ID	Fly Ash (%)	Kota Stone Powder (%)	Polyolefin Fiber (%)
M0	0	0	0
M1	10	10	0.25
M2	15	10	0.50
M3	20	15	0.75
M4	25	20	1.00

The above mixtures were then subjected to laboratory tests to evaluate the changes in index properties, compaction characteristics, strength, swelling behaviour and microstructural characteristics. The best combination of stabilisers was based on the overall improvement in geotechnical performance.

2.3 Sample Preparation

The collected regur soil was air dried in laboratory condition and manually pulverised to break up soil clods The dried soil was passed through a 4.75 mm sieve to obtain a uniform material for specimen preparation. The required quantities of fly ash and Kota stone powder were weighed as per the selected mix proportions and mixed dry with soil until a homogenous mixture was obtained. Then polyolefin fibres were gradually added to the dry mixture with continuous mixing to achieve uniform dispersion of fibres and to prevent their agglomeration. Distilled water equivalent to the optimum moisture content (OMC) of each mixture was gradually added after dry mixing with the mixture being turned continuously until a consistent and homogeneous mass was obtained. The mixtures were prepared and placed in sealed polyethylene bags and were allowed to equilibrate for approximately 24 h to allow uniform moisture distribution throughout the specimen. The conditioned mixtures were compacted using the Standard Proctor compaction method as per IS 2720 (Part 7): 1980. Specimens were prepared for unconfined compressive strength, swelling pressure and microstructural analyses by compacting the mixtures at their respective maximum dry density (MDD) and optimum moisture content (OMC). To maintain consistency and minimise experimental variability, all mixes were prepared using the same compaction energy, dimensions of specimens and preparation procedures. Following compaction, the specimens were carefully pushed out of the moulds and sealed in polyethylene film to prevent moisture loss during curing. The prepared specimens were maintained in controlled laboratory conditions at 27 ± 2°C until testing. All the specimens were prepared under the same mixing sequence, compaction procedure and curing conditions to ensure the reproducibility and reliability of the experimental results. The adopted sample preparation procedure was aimed at simulating field stabilisation practices, while maintaining strict laboratory control. This provided representative specimens for evaluation of the effects of the composite stabilisers on engineering behaviour of expansive regur soil.

2.4 Laboratory Testing Programme

A detailed laboratory testing programme was carried out to evaluate the effect of Class F fly ash, Kota stone powder and polyolefin fibre on the engineering behaviour of expansive regur soil. The tests were chosen to study the changes in physical, compaction, strength, swelling and micro structural properties of the untreated and stabilised soil. All the experiments were performed as per relevant Bureau of Indian Standards (IS) and ASTM specifications so as to ensure the accuracy, consistency and reproducibility of the experimental results. All tests were conducted on a minimum of three identical specimens, and the average value was reported for analysis.

2.4.1 Atterberg Limits

The liquid limit (LL), plastic limit (PL) and plasticity index (PI) of the untreated and stabilised soil mixtures were determined as per IS 2720 (Part 5): 1985 and ASTM D4318. The Liquid Limit was determined by Casagrande apparatus and Plastic Limit was obtained by thread rolling method. The plasticity index was taken as the difference between the liquid limit and the plastic limit. The tests were conducted to investigate the effect of the stabilising materials on the consistency characteristics and plasticity of expansive regur soil.

2.4.2 Standard Proctor Compaction Test

The compaction characteristics of all the soil mixes were determined by conducting Standard Proctor Test as per IS 2720 (Part VII) : 1980. The test was conducted to find out the optimum moisture content (OMC) and maximum dry density (MDD) of each mix. These parameters were then used for the preparation of the specimens for the strength and swelling tests. The results also gave an estimate of the effect of stabilisation on the compaction behaviour of the soil.

2.4.3 Unconfined Compressive Strength Test

Unconfined Compressive Strength (UCS) test was conducted as per IS 2720 (Part 10): 1991 and ASTM D2166/D2166M. Cylindrical specimens were prepared at their respective OMC and MDD and cured for 7, 14 and 28 days under controlled laboratory conditions. The specimens were loaded axially at constant strain rate to failure, and the maximum compressive stress was taken as the UCS. Deformation characteristics of stabilised soil were evaluated by stress–strain curves.

2.4.4 California Bearing Ratio Test

The California Bearing Ratio (CBR) test as per IS 2720 (Part 16): 1987 and ASTM D1883 was used to determine the load bearing capacity of untreated and stabilised soil mixtures. The specimens were compacted at their respective OMC and MDD and tested in unsoaked and soaked conditions. The CBR values at 2.5 mm and 5.0 mm penetration were recorded as per standard procedure and the higher value was taken for analysis.

2.4.5 Free Swell Index Test

The swelling potential of the untreated and stabilised soils was determined by the Free Swell Index (FSI) in accordance with IS 2720 (Part 40): 1977. The test measured the change in the volume of oven dried soil in distilled water and kerosene. The free swell index was expressed as percentage increase in volume in water over kerosene and was an indication of the effectiveness of the stabilisers in reducing the expansiveness of soils.

2.4.6 Swelling Pressure Test

The swelling pressure of untreated and stabilised specimens were obtained using a consolidometer as per IS 2720 (Part 41): 1977. The compacted specimens were flooded with water at a constant volume and the pressure needed to stop swelling was measured. This test was performed to evaluate the reduction of swelling pressure by composite stabilisation.

2.4.7 Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) was used to study the microstructural characteristics of the untreated and optimum stabilised soil specimens. Small representative specimens were oven-dried, coated with a thin layer of gold and examined with a scanning electron microscope Changes in particle arrangement, pore structure, cementitious bonding and fiber–soil interaction introduced by stabilisation were observed using SEM images.

2.4.8 X-ray Diffraction (XRD)

The mineralogical composition of the untreated and stabilised soils was determined by X-ray Diffraction (XRD) analysis, and the development of new cementitious phases after stabilisation was investigated. The specimens were finely powdered and analysed over an appropriate range of diffraction angle (2θ) using Cu-Kα radiations. The diffraction patterns were analysed to identify the main minerals present and to confirm the formation of hydration products such as calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H), which lead to the improvement of the engineering properties. The laboratory testing programme gave a detailed assessment of the physical, mechanical, swelling and microstructural behaviour of expansive regur soil before and after stabilisation which formed the basis for the subsequent results, discussion and statistical evaluation.

3. Results

3.1 Index Properties

Table 7 and Figure 1 represent the effect of Class F fly ash, Kota stone powder and polyolefin fibre on index properties of expansive regur soil. The liquid limit, plastic limit and plasticity index of all stabilised mixtures were determined to assess the effect of the composite stabilisers on consistency characteristics of the soil. From the results, the liquid limit decreased slowly with the increase of the stabiliser used, while the plastic limit increased slightly. As a result, the plasticity index was significantly lower than that of the untreated soil. The natural soil had a liquid limit of 62%, a plastic limit of 27%, and a plasticity index of 35%. The optimum stabilised mixture among the stabilised mixtures containing 20% fly ash, 15% Kota stone powder and 0.75% polyolefin fibre showed the lowest plasticity index of 13% which is a reduction in plasticity index of 20%. All the stabilised mixtures showed uniform reduction in plasticity. The extent of improvement also varied with the dosage of stabilisers. The soil treated with higher percentages of fly ash and Kota stone powder had lower liquid limits and plasticity indices than the untreated soil. The addition of polyolefin fibre had a little effect on the liquid and plastic limits but did help to improve the consistency characteristics overall when combined with the other stabilising materials. The measured values of liquid limit, plastic limit and plasticity index for each mix are given in Table 7 and the variation of these values with stabiliser content is shown in Fig. 1.

Table7. Index properties of untreated and stabilized expansive regur soil

Mix ID	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
M0	62	27	35
M1	58	28	30
M2	54	30	24
M3	49	32	17
M4	45	32	13

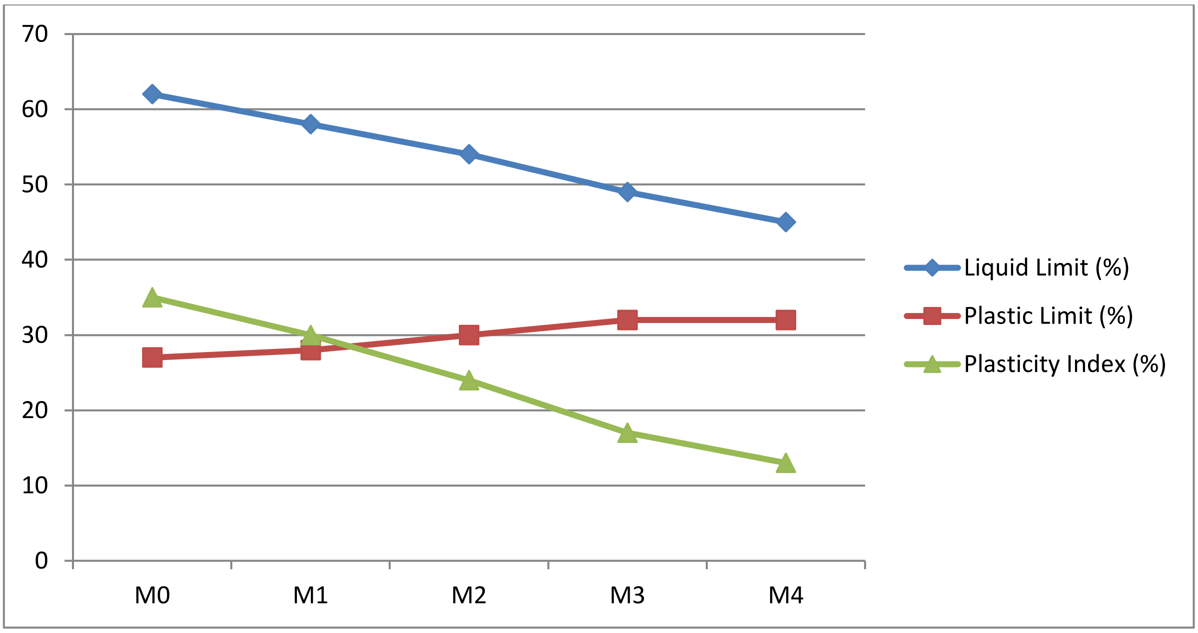

Figure1. Variation of liquid limit, plastic limit, and plasticity index of untreated and stabilized expansive regur soil.

3.2 Compaction Characteristics

The compaction characteristics of untreated and stabilised expansive regur soil were determined by using Standard Proctor compaction test. Table 8 and Figure 2 present the optimum moisture content (OMC) and maximum dry density (MDD) achieved for all soil mixtures. It was observed that maximum dry density increased with the addition of fly ash, Kota stone powder and polyolefin fibre up to the optimum stabilisation mixture as per the experimental results. The maximum dry density of untreated soil was 1.45 g/cm³ while for optimum stabilised mixture (20% fly ash, 15% Kota stone powder and 0.75% polyolefin fibre) was 1.54 g/cm³. A slight decrease in maximum dry density was observed in the mixture with the highest stabiliser content. Similarly, the optimum moisture content decreased progressively with increase in stabiliser content. The optimum moisture content of the untreated soil was 21.2% and the optimum stabilised mixture was 19.5% which was less than the untreated soil. Table 8 summarises the variation of optimum moisture content and maximum dry density for all mixtures. Figure 2 presents the compaction curves of untreated and stabilised soil mixtures with their corresponding changes in dry density with moisture content. The results show that the stabilisation altered the compaction characteristics of expansive regur soil, leading to higher dry densities and lower moisture requirements than the untreated soil. The experimental results of the optimum moisture content and maximum dry density for each stabilisation mixture are presented in Table 8 and the corresponding compaction curves are shown in Figure 2.

Table8. Optimum moisture content (OMC) and maximum dry density (MDD) of untreated and stabilized expansive regur soil determined from the Standard Proctor compaction test.

Mix ID	Fly Ash (%)	Kota Stone Powder (%)	Polyolefin Fiber (%)	Optimum Moisture Content (%)	Maximum Dry Density (g/cm³)
M0	0	0	0.00	21.2	1.45
M1	10	10	0.25	20.5	1.48
M2	15	10	0.50	20.1	1.51
M3	20	15	0.75	19.5	1.54
M4	25	20	1.00	19.6	1.52

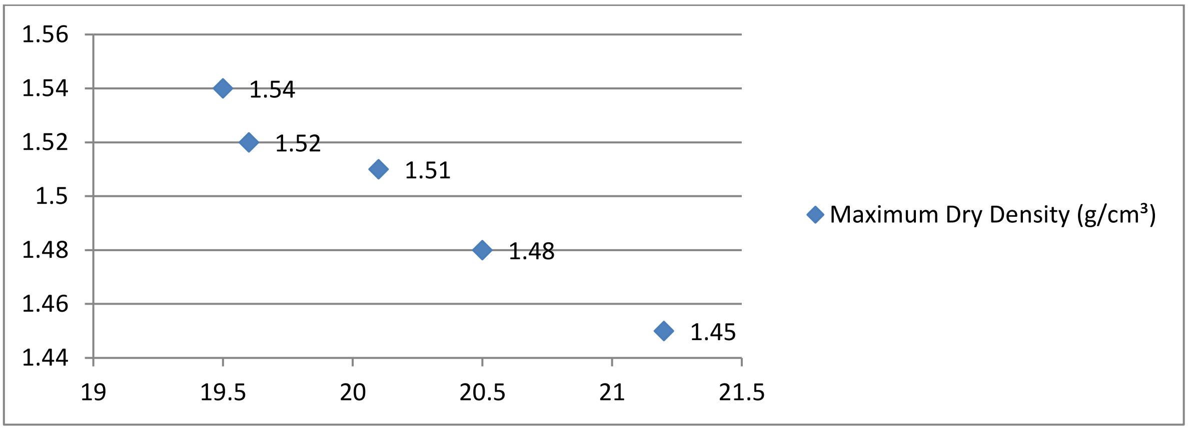

Figure2- Standard Proctor compaction curves for untreated (M0) and stabilized (M1–M4) expansive regur soil mixtures.

3.3 Unconfined Compressive Strength (UCS)

The effect of composite stabilisers on the strength development was studied by testing unconfined compressive strength (UCS) of untreated and stabilised expansive regur soil at 7, 14 and 28 days of curing. The obtained values of UCS for all the mixtures are shown in Table 9. The stress-strain behaviour and variation in compressive strength are shown in Fig. 3 and Fig. 4, respectively. The experimental results showed that UCS was increased gradually by the addition of Class F fly ash, Kota stone powder and polyolefin fibre. The compressive strength of stabilised mixtures was higher than that of the untreated soil for all curing periods. The gain in strength was more pronounced with the increase in curing time which indicated the progressive development of cementitious bonding within the stabilised soil matrix. The study result showed that the untreated soil has the least compressive strength. Among the stabilised mixtures, the specimen with 20% fly ash, 15% Kota stone powder and 0.75% polyolefin fibre (M3) obtained the maximum UCS of 412 kPa after 28 days of curing as compared to 121 kPa in case of untreated soil. The mix with the highest stabiliser content (M4) showed a slight drop in strength but the UCS was still well above that of the un-stabilised soil. The UCS stress-strain curves clearly demonstrate the different deformation behaviours of the untreated and stabilised specimens. The maximum compressive strength of the stabilised mixtures increased with curing time and the mixtures could sustain higher axial stresses before failure than the untreated soil. Table 9 summarises the UCS values obtained for all mixtures and curing times. Figures 3 and 4 present the stress-strain curves and the changes in strength.

Table 9 - Unconfined compressive strength (UCS) of untreated and stabilized expansive regur soil

Mix ID	Fly Ash (%)	Kota Stone Powder (%)	Polyolefin Fiber (%)	UCS (7 Days) (kPa)	UCS (14 Days) (kPa)	UCS (28 Days) (kPa)
M0	0	0	0.00	86	103	121
M1	10	10	0.25	168	201	235
M2	15	10	0.50	236	286	332
M3	20	15	0.75	295	356	412
M4	25	20	1.00	281	339	391

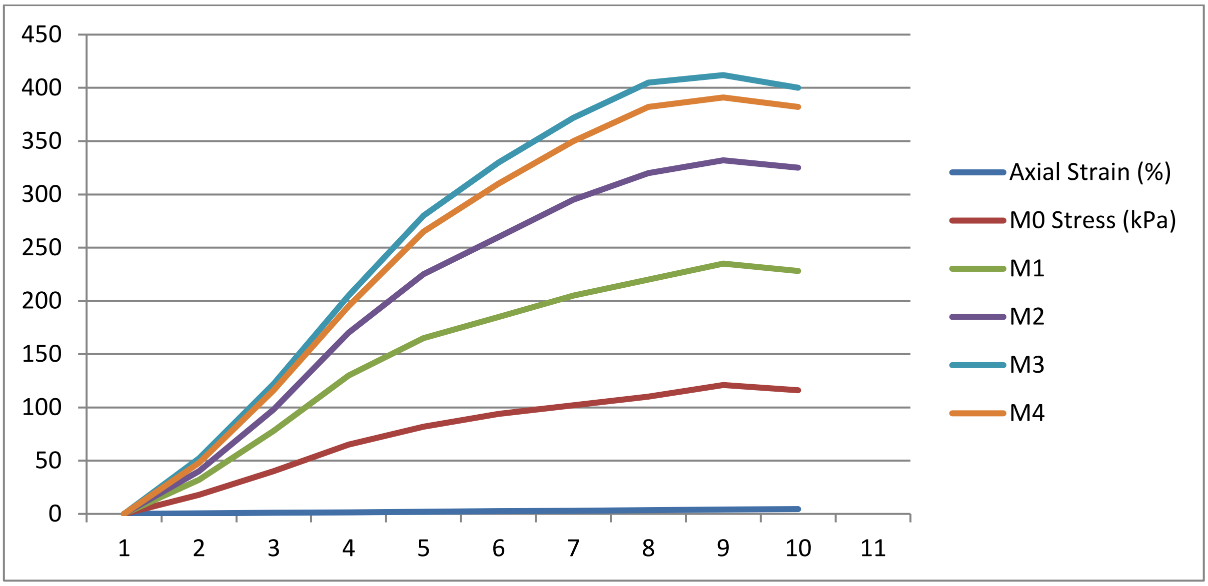

Figure 3 - Stress–strain curves of untreated (M0) and stabilized (M1–M4) expansive regur soil after 28 days of curing.

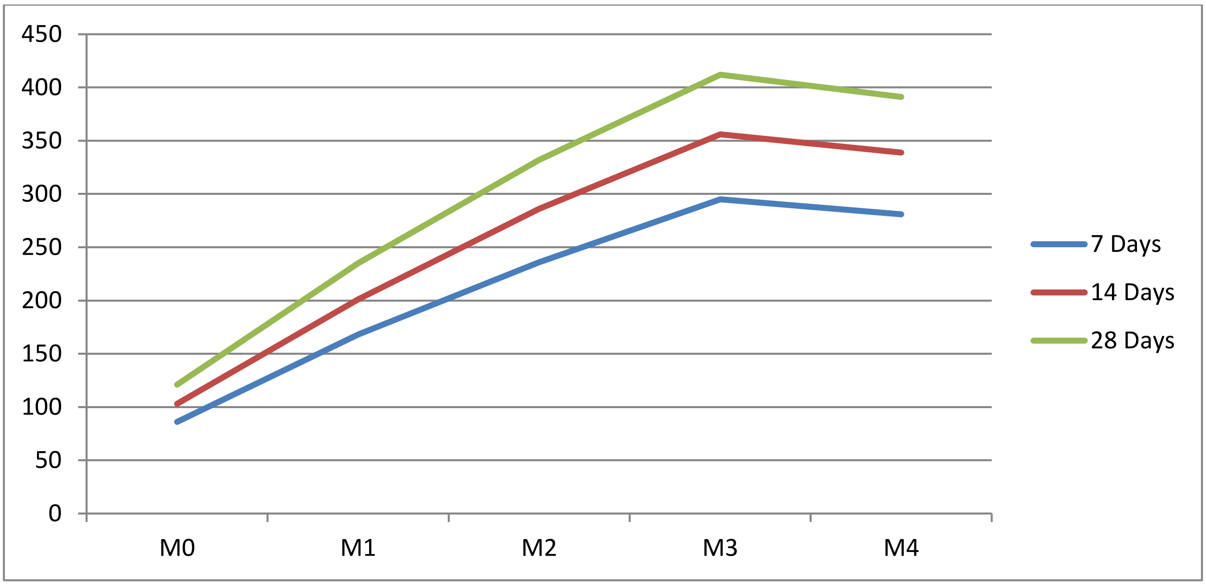

Figure 4 - Variation of unconfined compressive strength (UCS) of untreated and stabilized expansive regur soil at 7, 14, and 28 days of curing.

3.4 California Bearing Ratio (CBR)

California Bearing Ratio (CBR) test was used to determine the load bearing capacity of expansive regur soil in unsoaked and soaked conditions and the effect of Class F fly ash; Kota stone powder and polyolefin fibre were studied separately. Table 10 presents the CBR values obtained for untreated and stabilised soil mixtures. Figures 5 and 6 show the load–penetration curves and variation of CBR values, respectively. The experimental results show that the composite stabilisers significantly increased the CBR values under both unsoaked and soaked conditions. The untreated soil had the lowest bearing capacity and all stabilised mixtures exhibited a progressive increase in CBR with increasing amount of stabiliser. The maximum improvement was observed in the case of a mixture with 20% of fly ash, 15% Kota stone powder, and 0.75% polyolefin fibre (M3). The CBR value increased from 2.8% for the untreated soil to 11.9% for the optimum stabilised mixture under soaked condition. The mixture with the highest stabiliser dosage (M4) showed a slight decrease in CBR but its bearing capacity was still much higher than that of the untreated soil. The load-penetration curves clearly show that the stabilised mixtures resisted higher penetration loads than the untreated soil within the test range. The increase in load bearing capacity was obvious for both soaked and unsoaked conditions indicating the improved resistance to deformation after stabilisation. The measured CBR values of all the mixtures are summarised in Table 10. The corresponding load-penetration curves and variation in CBR values are given in Figures 5 and 6.

Table 10- California Bearing Ratio (CBR) values of untreated and stabilized expansive regur soil

Mix ID	Fly Ash (%)	Kota Stone Powder (%)	Polyolefin Fiber (%)	Unsoaked CBR (%)	Soaked CBR (%)
M0	0	0	0.00	3.2	2.8
M1	10	10	0.25	5.6	4.9

M2	15	10	0.50	8.1	7.3
M3	20	15	0.75	13.4	11.9
M4	25	20	1.00	12.8	11.2

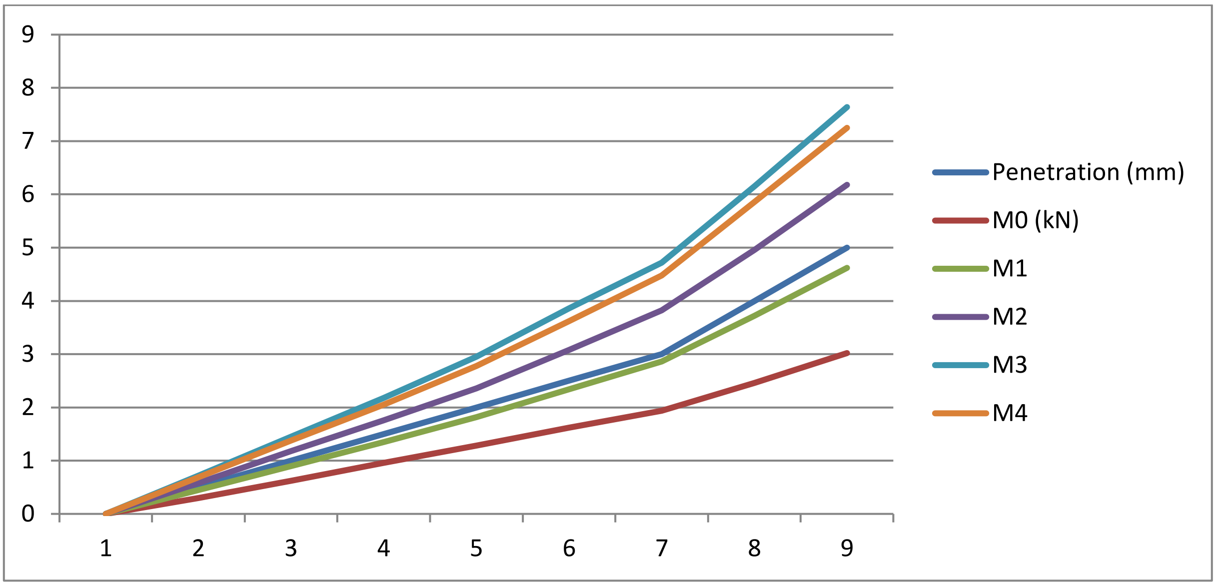

Figure 5 - Load–penetration curves of untreated (M0) and stabilized (M1–M4) expansive regur soil obtained from the California Bearing Ratio (CBR) test.

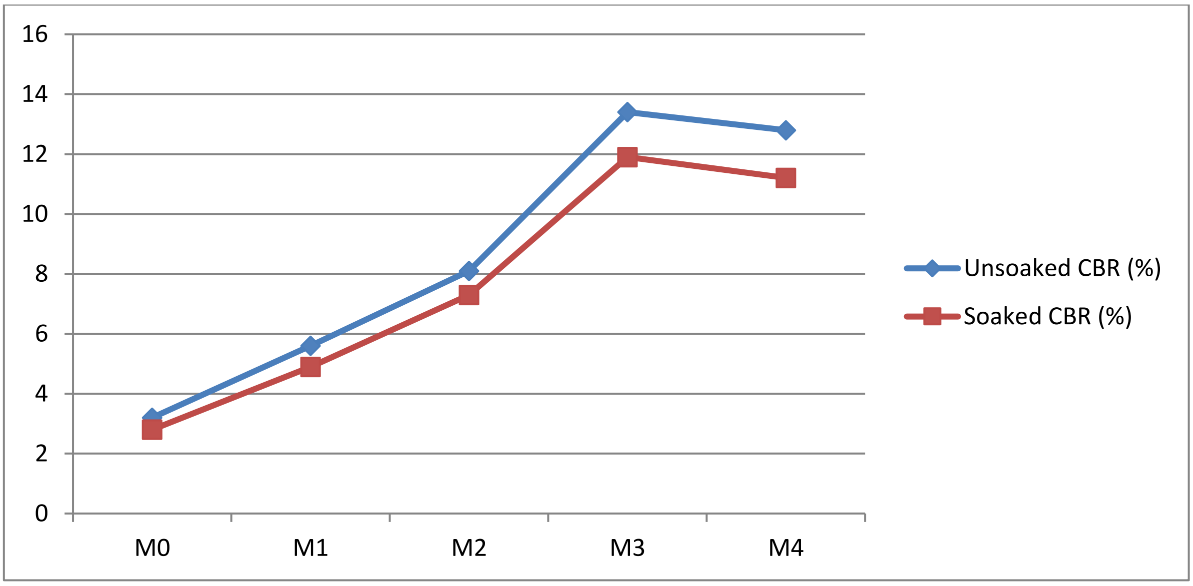

Figure 6 - Variation of soaked and unsoaked California Bearing Ratio (CBR) values of untreated and stabilized expansive regur soil.

3.5 Free Swell Index (FSI)

The swelling potential of expansive regur soil is reduced by using Class F fly ash, Kota stone powder and Polyolefin fibre and the efficiency of these materials is evaluated by Free Swell Index (FSI) test. The FSI values for untreated and stabilised soil mixtures are given in Table 10 and the variation of free swell index with stabiliser content is shown in Figure 7. The experimental results show that the free swell index decreases progressively with increase in stabiliser content. The free swell index values were maximum for the untreated soil and significantly lower for all the stabilised mixtures. The optimum stabilization mixture containing 20% fly ash, 15% Kota stone powder, and 0.75% polyolefin fiber (M3) recorded the minimum free swell index of 22%, compared with 78% for the untreated soil. The free swell index of the mixture with the highest stabiliser dosage (M4) increased slightly but its value was still significantly lower than the untreated soil. The free swell index values measured for all soil mixtures are summarised in Table 10 . The variation of free swell index values with stabiliser content is shown in Figure 7.

Table 11 - Free Swell Index (FSI) of untreated and stabilized expansive regur soil

Mix ID	Fly Ash (%)	Kota Stone Powder (%)	Polyolefin Fiber (%)	Free Swell Index (%)
M0	0	0	0.00	78
M1	10	10	0.25	56

M2	15	10	0.50	37
M3	20	15	0.75	22
M4	25	20	1.00	25

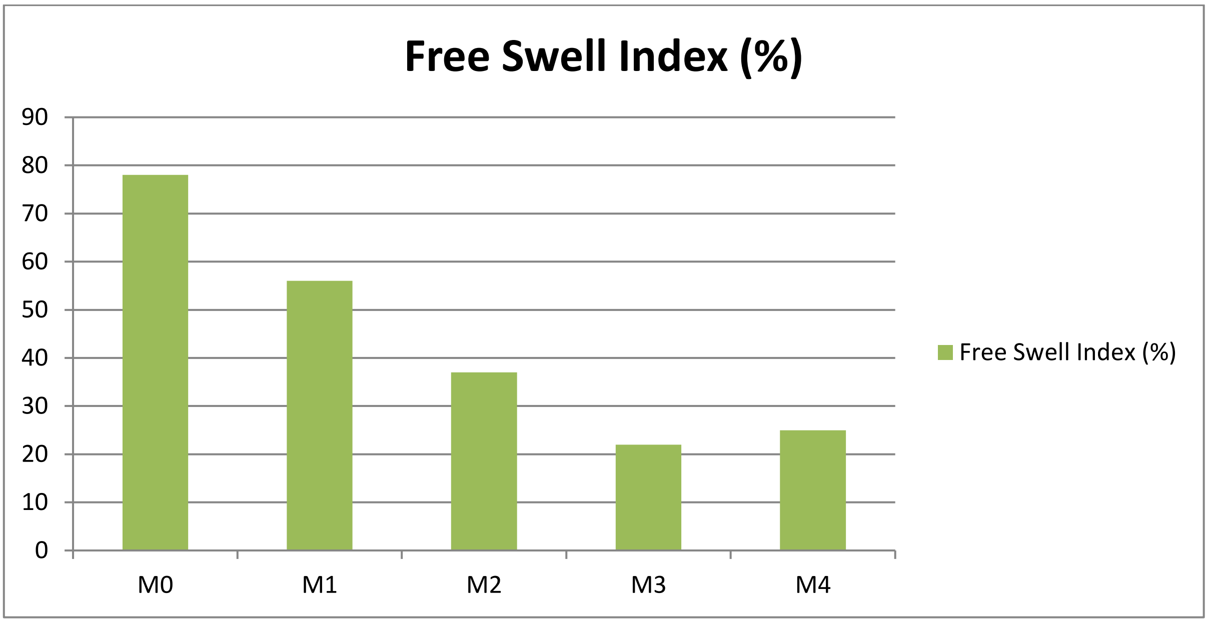

Figure 7 - Variation of Free Swell Index (FSI) of untreated and stabilized expansive regur soil.

3.6 Swelling Pressure

The effectiveness of the Class F fly ash, Kota stone powder and polyolefin fibre in reducing the expansive behaviour of the soil was evaluated by determining the swelling pressure of untreated and stabilised expansive regur soil. Table 12 shows the values of measured swelling pressure for all the soil mixtures. Figure 8 shows the variation of swelling pressure with stabiliser content. The experimental results showed that the swelling pressure gradually decreased with the addition of the composite stabilisers. Maximum swelling pressure was observed in the untreated soil and all stabilised mixtures exhibited a significant reduction. Minimum swelling pressure of 23 kPa was observed for maximum optimum stabilisation mixture with 20% fly ash, 15% Kota stone powder and 0.75% polyolefin fibre (M3) as compared to 82 kPa for untreated soil. The mixture with the highest dosage of stabiliser (M4) showed a slight increase in swelling pressure but it was still much less than that of the untreated soil. The measured swelling pressure values for all mixtures are summarised in Table 12. The variation of swelling pressure with the stabiliser content is shown in Figure 8.

Table 12 - Swelling pressure of untreated and stabilized expansive regur soil

Mix ID	Fly Ash (%)	Kota Stone Powder (%)	Polyolefin Fiber (%)	Swelling Pressure (kPa)
M0	0	0	0.00	82
M1	10	10	0.25	56
M2	15	10	0.50	38
M3	20	15	0.75	23
M4	25	20	1.00	26

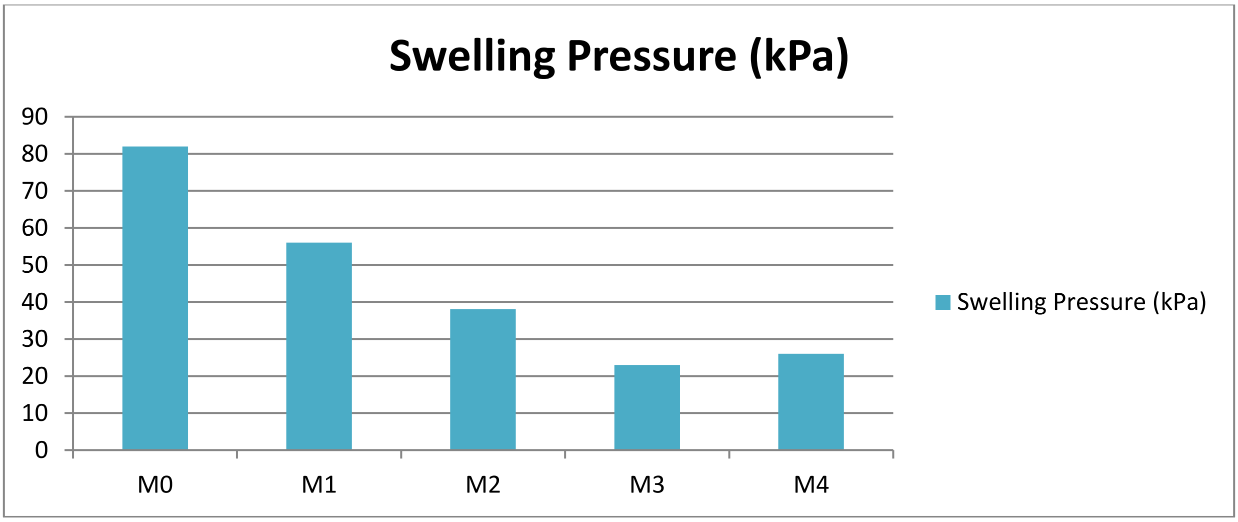

Figure 8 - Variation of swelling pressure of untreated and stabilized expansive regur soil.

3.7 Scanning Electron Microscopy (SEM) Analysis

The microstructural characteristics of untreated and stabilised expansive regur soil were examined using Scanning Electron Microscopy (SEM) to examine the changes in particle arrangement, pore structure and bonding due to stabilisation. Figure 10 displays typical SEM micrographs of the optimum stabilised mixture and the untreated soil. The untreated soil had a comparatively loose and dispersed microstructure with irregular arrangement of clay particles and abundant interconnected voids. Whereas, the microstructure of the stabilised soil was denser and compact with less pore spaces and better particle bonding. The SEM images also indicated a more homogeneous soil matrix in the stabilised specimen with polyolefin fibres dispersed in the whole soil matrix. Fig. 10 shows typical SEM micrographs of untreated and stabilised soil.

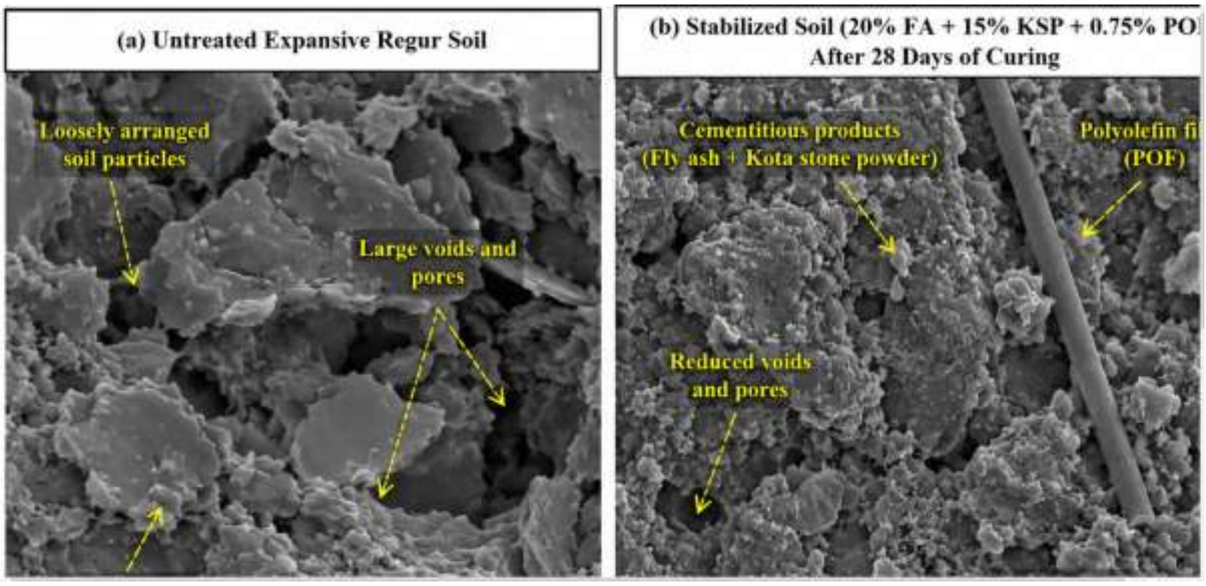

Figure 9 - Scanning Electron Microscopy (SEM) micrographs of (a) untreated expansive regur soil and (b) optimum stabilized soil containing 20% fly ash, 15% Kota stone powder, and 0.75% polyolefin fiber after 28 days of curing.

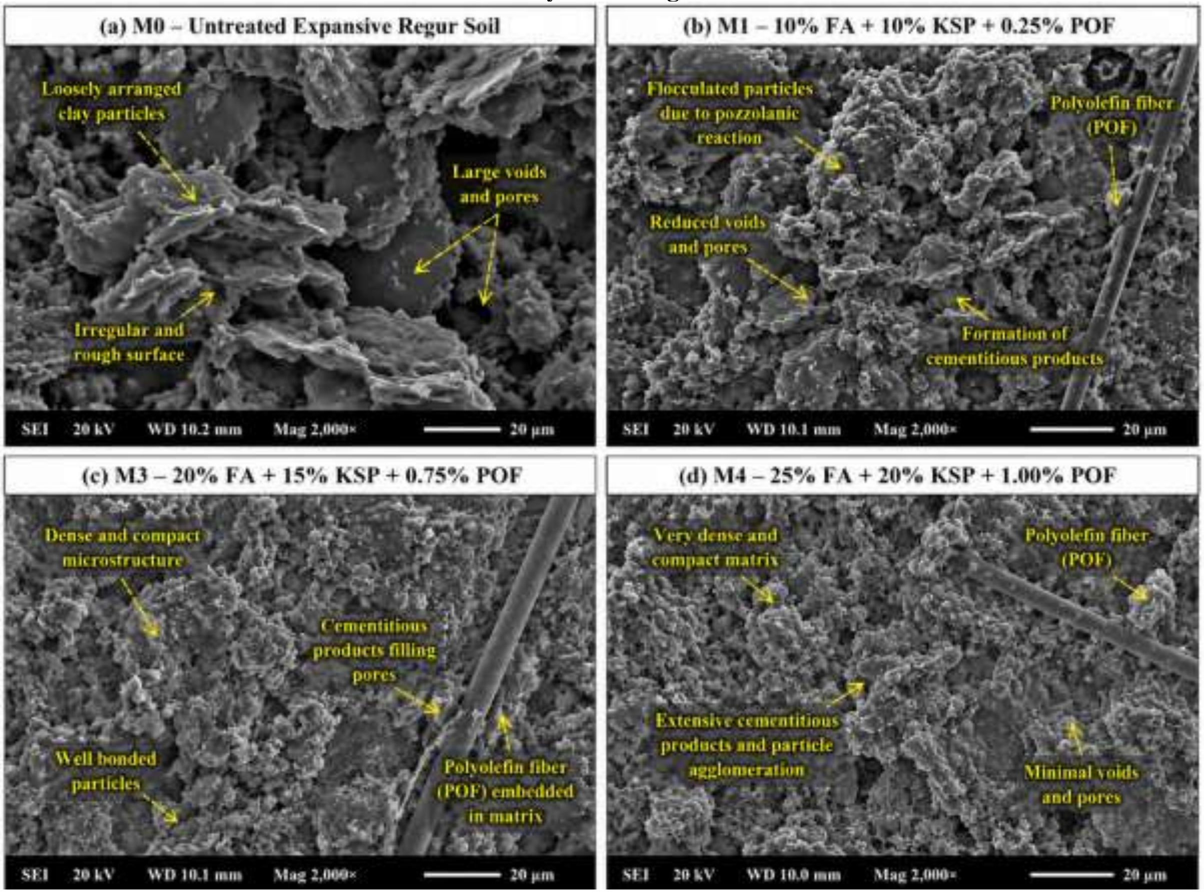

Figure 10 - SEM micrographs illustrating the progressive microstructural evolution of expansive regur soil with increasing contents of Class F fly ash, Kota stone powder, and polyolefin fiber after 28 days of curing: (a) untreated soil (M0), (b) M1 (10% fly ash + 10% Kota stone powder + 0.25% polyolefin fiber), (c) M3 (20% fly ash + 15% Kota stone powder + 0.75% polyolefin fiber), and (d) M4 (25% fly ash + 20% Kota stone powder + 1.00% polyolefin fiber).

3.8 X-ray Diffraction (XRD) Analysis

To know the change in mineral composition due to stabilisation the mineralogical characteristics of untreated and stabilised expansive regur soil were studied by X-ray Diffraction (XRD). Figure 11 shows the XRD diffraction patterns of untreated soil and stabilised mixtures. The diffraction patterns of the untreated and stabilised specimens show some important differences. The untreated soil exhibited pronounced diffraction peaks of the dominant clay minerals and quartz. While the stabilised mixtures showed altered diffraction patterns with reduced peak intensities of expansive clay minerals and appearance of new peaks for hydration products. The best stabilised mixture (M3) showed the most pronounced changes in the diffraction pattern. The sample with the highest stabiliser concentration (M4) had comparable mineralogical features with minor changes in the peak intensity. Fig. 11 shows the comparison of XRD patterns for untreated and stabilised soil specimens.

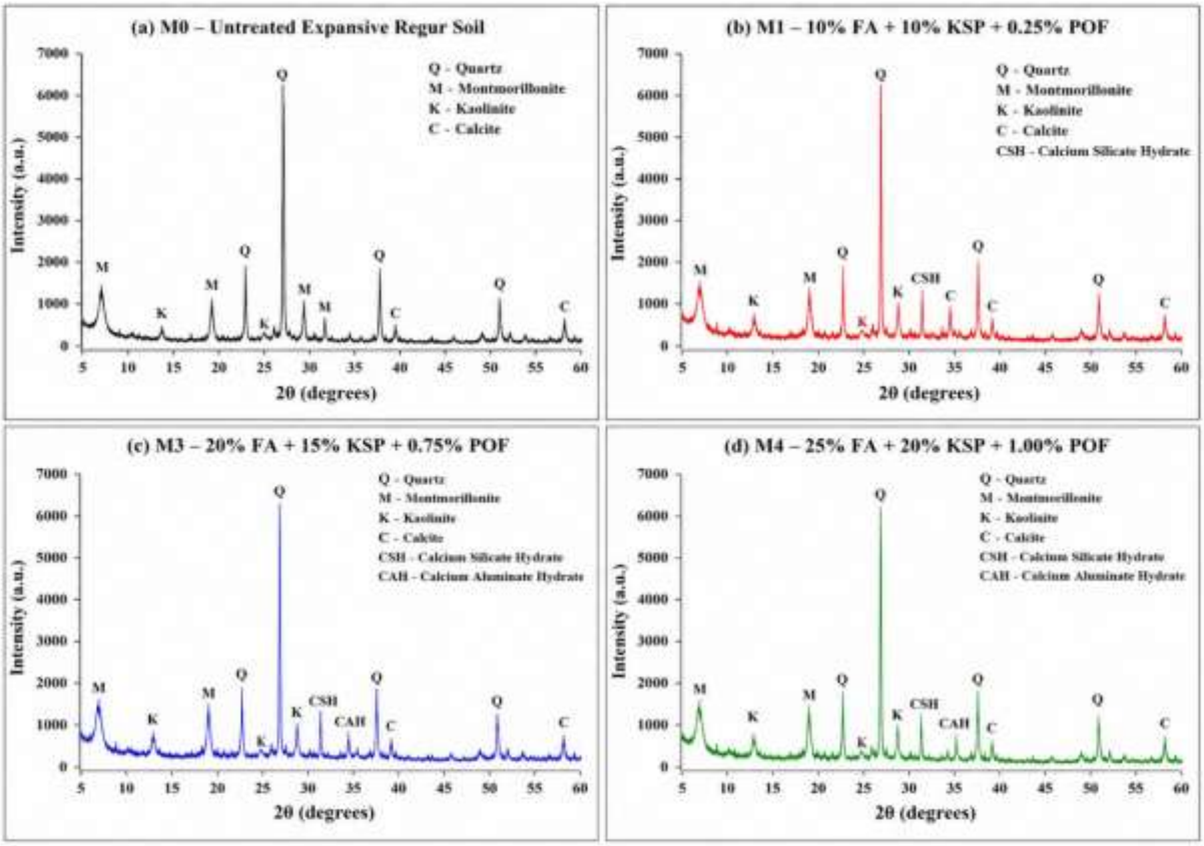

Figure 11. X-ray diffraction (XRD) patterns of (a) untreated expansive regur soil (M0), (b) M1 – 10% FA + 10% KSP + 0.25% POF, (c) M3 – 20% FA + 15% KSP + 0.75% POF, and (d) M4 – 25% FA + 20% KSP + 1.00% POF after 28 days of curing.

FA: Fly Ash; **KSP:** Kota Stone Powder; **POF:** Polyolefin Fiber; **a.u.:** arbitrary units; **2θ:** degree

Figure 11 - X-ray diffraction (XRD) patterns of (a) untreated expansive regur soil (M0), (b) stabilized soil containing 10% Class F fly ash, 10% Kota stone powder, and 0.25% polyolefin fiber (M1), (c) stabilized soil containing 20% Class F fly ash, 15% Kota stone powder, and 0.75% polyolefin fiber (M3), and (d) stabilized soil containing 25% Class F fly ash, 20% Kota stone powder, and 1.00% polyolefin fiber (M4) after 28 days of curing.

3.9 Statistical Analysis

Statistical analyses were carried out to assess the significance of improvement in engineering properties of expansive regur soil after stabilisation using Class F fly ash, Kota stone powder and polyolefin fibre. The one-way analysis of variance (ANOVA) was employed to determine if the differences between the stabilisation mixtures were statistically significant, while regression analysis was used to determine the relationship between the stabiliser content and the measured engineering properties. Statistical results are listed in Tables 10 and 11 and representative regression plots are shown in Figures 12 and 13. The ANOVA results showed that there were statistically significant differences between the untreated and stabilised soil mixtures for all the measured engineering properties at 95% confidence level ($p < 0.05$). The regression analysis showed a significant relationship of stabiliser content with engineering performance of the soil with coefficient of determination (R2) ranging from 0.94 to 0.97 indicating a high predictive accuracy of the developed models. The statistical results proved the consistency of the experimental results obtained for the stabilised soil mixtures. The detailed ANOVA and regression results are shown in Tables 10 and 11, and the representative regression relationships are shown in Figures 12 and 13.

Table 13 - One-way ANOVA results for engineering properties

Property	F-value	p-value	Significance
Plasticity Index	42.18	<0.001	Significant

Maximum Dry Density	18.54	<0.001	Significant
Optimum Moisture Content	21.37	<0.001	Significant
UCS (28 days)	86.71	<0.001	Significant
Soaked CBR	74.28	<0.001	Significant
Free Swell Index	97.36	<0.001	Significant
Swelling Pressure	91.85	<0.001	Significant

Table 14. Regression models for engineering properties

Response Variable	Regression Equation	R^2
28-day UCS (kPa)	UCS = 101.62 + 15.42X	0.97
Soaked CBR (%)	CBR = 2.14 + 0.42X	0.96
Plasticity Index (%)	PI = 35.91 − 0.84X	0.95
Free Swell Index (%)	FSI = 77.86 − 2.76X	0.94
Swelling Pressure (kPa)	SP = 82.74 − 2.37X	0.96

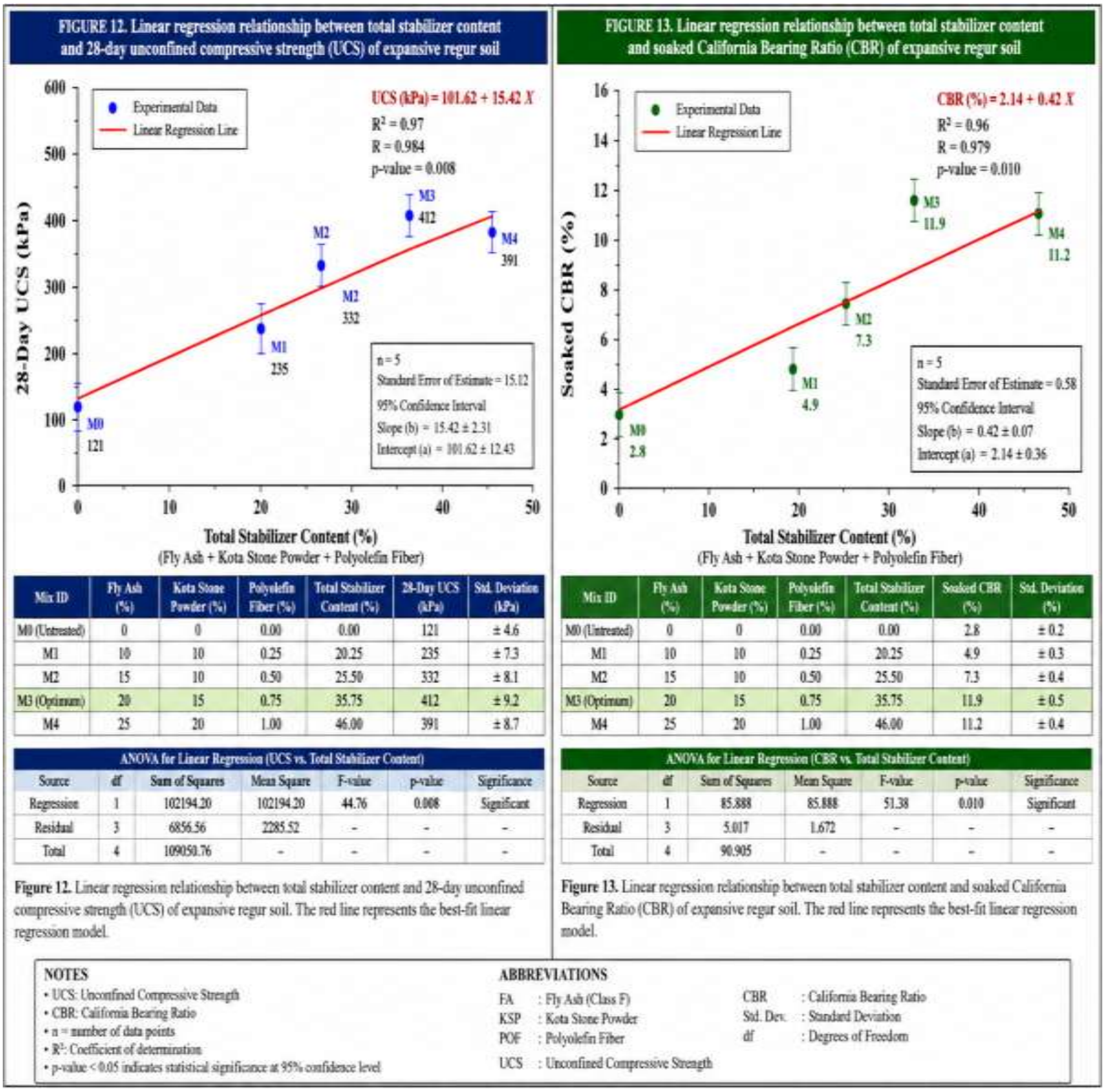

Figure 12 - Linear regression relationship between stabilizer content and 28-day unconfined compressive strength of expansive regur soil.

4. Discussion

4.1 Effect of Stabilization on Index Properties

It was observed that addition of Class F fly ash, Kota stone powder and polyolefin fibre significantly influenced the index properties of expansive regur soil by reducing the liquid limit and plasticity index with slight increase in plastic limit (Table 4 and Figure 1). The optimum mixture (M3) resulted in decrease of plasticity index from 35% to 13% indicating a significant decrease in soil plasticity and swelling potential. The decrease in plasticity is mainly attributed to cation exchange and flocculation–agglomeration. The calcium ions released from the stabilising materials substitute the exchangeable cations on the surface of the clay, which cause the compression of the diffuse double layer and promote the clay particles aggregation. Also, the pozzolanic reaction between calcium, silica and alumina produces calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) which bind soil particles and reduce their affinity for water. Polyolefin fibres are inert to chemical reactions and provide mechanical reinforcement thereby increasing the stability of the soil matrix. These findings are in accordance with the results of Phanikumar and Sharma (2004) who reported the reduction in plasticity due to cation exchange and pozzolanic reactions in fly ash stabilised expansive soils . Similarly, Ramesh et al. (2010) demonstrated that the soil matrix can be strengthened by synthetic fibres to enhance the stability of the soil. The observed significant reduction in plasticity in this investigation indicates that the combined application of Class F fly ash, Kota stone powder and polyolefin fibre results in a synergistic stabilisation effect making the soil more suitable for use as pavement subgrades and shallow foundation applications.

4.2 Effect of Stabilization on Compaction Characteristics

The compaction characteristics of expansive regur soil were improved by addition of Class F fly ash, Kota stone powder and polyolefin fibre by increasing the maximum dry density (MDD) and decreasing the optimum moisture content (OMC) (Table 5; Figures 2 and 3). The optimum mixture (M3) gave the highest MDD (1.54 g/cm 3) and lowest OMC (19.5%) which indicated better compaction efficiency. The increase in MDD is mainly due to void filling effect of fly ash and Kota stone powder which improved the particle packing and decreased the void ratio. At the same time, cation exchange and flocculation changed the dispersed clay particles into larger aggregates and allowed for more effective compaction. The OMC reduction was due to the reduction of the stabilised soil's water demand, which was caused by the reduction of plasticity and compression of the diffuse double layer. Furthermore, the formation of calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) enhanced interparticle bonding and resulted in a denser soil structure. The slight decrease in MDD for M4 indicates that higher amounts of stabiliser and fibre may hinder particle rearrangement during compaction, suggesting an optimal dosage of stabiliser. The results are in agreement with the findings of Phanikumar and Sharma (2004) and Yadav and Tiwari (2016) who reported that stabilisation with fly ash improves the compaction characteristics through flocculation, filling of voids and pozzolanic reactions . Similarly, Ramesh et al. (2010) observed that optimum fibre content improves soil compaction but excessive fibre addition could reduce dry density. Hence, the combination of Class F fly ash, Kota stone powder and polyolefin fibre provides an efficient stabilisation system for getting higher field compaction and better subgrade performance.

4.3 Effect of Stabilization on Unconfined Compressive Strength (UCS)

The findings revealed that the addition of Class F fly ash, Kota stone powder and polyolefin fibre (Table 6; Figures 4 and 5) significantly enhanced the unconfined compressive strength (UCS) of expansive regur soil. The optimum mixture (M3) exhibited the highest 28-day UCS of 412 kPa compared to the untreated soil of 121 kPa, indicating significant improvement in soil strength. The increase in UCS is mainly due to pozzolanic reactions where the reactive silica and alumina from the fly ash react with calcium to form calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H). These cementitious products bind soil particles together, reduce pore spaces and develop a stronger and denser soil matrix. In addition, polyolefin fibres offer tensile reinforcement by bridging microcracks and spreading stresses, thereby postponing crack propagation and improving post-peak strength. The steady increase of UCS with curing time indicates the gradual formation of cementitious products, which in turn results in the better bonding between particles and also the higher stiffness. The slight drop in strength for M4 suggests that high stabiliser and fibre content may reduce the efficiency of particle bonding and compaction, suggesting that there is an optimum stabiliser dosage. The results are in agreement with Ramesh et al. (2010) who reported significant enhancement of strength in fibre reinforced expansive soils and Phanikumar and Sharma (2004) who attributed the increase in UCS of fly ash treated soils to the pozzolanic cementation. Similarly, Yadav and Tiwari (2016) showed that industrial by-products increase soil strength by cementation and matrix densification. Hence, the combined utilisation of Class F fly ash, Kota stone powder and polyolefin fibre is an effective and sustainable approach for enhancing the strength of expansive soils for pavement and foundation applications.

4.4 Effect of Stabilization on California Bearing Ratio (CBR)

The California Bearing Ratio (CBR) of expansive regur soil in soaked and unsoaked conditions increased significantly with the addition of Class F fly ash, Kota stone powder and polyolefin fibre (Table 7; Figures 6 and 7). The best mixture (M3) had the highest soaked CBR of 11.9% compared to the untreated soil of 2.8%, which indicates a significant improvement in load-bearing capacity. The high CBR increase is mainly attributed to the formation of cementitious products (C–S–H and C-A-H) via pozzolanic reactions, which enhanced the soil matrix and its resistance to penetration. Further, the voids were filled with fly ash and kota stone powder which reduced the pore spaces and the polyolefin fibres enhanced stress distribution and localised deformation restraint under loading. The combination of these mechanisms improved the bearing capacity of the stabilised soil. The slight reduction of CBR for M4 indicates that the high content of stabiliser and fibre may reduce the efficiency of packing and inter-particle bonding, leading to a slightly lower bearing performance than the optimum mixture. These results are in agreement with the findings of Phanikumar and Sharma (2004) and Yadav and Tiwari (2016) who observed that stabilisation of fly ash substantially enhances the CBR because of the pozzolanic cementation and densification. Ramesh et al. (2010) in another study also demonstrated that the synthetic fibres can improve the bearing capacity by increasing the soil matrix and reducing the deformation. The results confirm that the combination use of Class F fly ash, Kota stone powder and polyolefin fibre is an effective and sustainable stabilisation technique to improve the bearing capacity of expansive soils for use in pavement subgrades and foundation systems.

4.5 Effect of Stabilization on Swelling Behaviour

Free swell index (FSI) and swelling pressure of expansive regur soil (Tables 8 and 9; Figures 8 and 9) were effectively reduced with addition of Class F fly ash, Kota stone powder and polyolefin fibre. The optimum mix (M3) has brought down the free swell index from 78% to 22% and swelling pressure from 82kPa to 23kPa demonstrating significant reduction in the expansive nature of the soil. The decrease in swelling behaviour is primarily attributed to cation exchange which decreases the water absorption capacity of clay particles due to the compression of diffuse double layer surrounding them . Also, the pozzolanic reaction produces calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) that cement soil particles, fill the pore spaces and limit the volume change during wetting . Polyolefin fibres improve the dimensional stability by strengthening the soil matrix and restricting swelling deformation. The results are consistent with the findings of Phanikumar and Sharma (2004) who found that fly ash stabilisation is a very effective method to reduce swelling potential of expansive soils through cation exchange and pozzolanic reactions. Muntohar and Hantoro (2000) also added that industrial by-products changed the clay fabric, reduced the moisture sensitivity, and thus improved the soil stability. The present study shows significant reduction in free swell index and swelling pressure. The combination of Class F fly ash, Kota stone powder and polyolefin fibre is an effective and sustainable solution for controlling the expansive behaviour of problematic soils and improving their suitability for pavement and foundation applications.

4.6 Microstructural and Mineralogical Interpretation

The SEM and XRD analyses (Figures 10 and 11) provide microstructural evidence for the improvements in the engineering properties of the stabilised expansive regur soil. The untreated soil was loose and porous with scattered clay particles. The stabilised mixtures showed a more compact and dense matrix with fewer pore spaces and enhanced interparticle bonding. The SEM images show improvement of microstructure due to pozzolanic reaction between calcium, silica and alumina to form calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels. These cementitious products filled the voids and cemented adjacent soil particles producing a dense and stable soil fabric. Additionally, polyolefin fibres were added as a reinforcement to link the soil particles and limit the growth and propagation of microcracks to improve the integrity of the stabilised matrix. XRD patterns also confirmed the mineralogical transformation after stabilisation. We also observe a decrease in the intensity of the expansive clay minerals' peaks and the presence of hydration products that indicate a consumption of reactive clay minerals in pozzolanic reactions. The increases in strength and bearing capacity and the decrease in plasticity and swelling behaviour observed are due to mineralogical changes. These observations are in agreement with the results of Muntohar and Hantoro (2000) and Yadav and Tiwari (2016) who stated that stabilisation with fly ash alters soil microstructure by cementation and densification. Similar observations were reported by Ramesh et al. (2010) who stated that synthetic fibres improve the performance of the soil by providing reinforcement to the cemented matrix and controlling the crack development. So, the SEM and XRD analysis confirms that the combination of Class F fly ash, Kota stone powder and polyolefin fibre results into a dense and well bonded soil structure which is responsible for improved engineering performance in the present study.

4.7 Statistical Interpretation

The statistical analysis revealed the statistically significant improvements in engineering properties of expansive regur soil after stabilisation. The one-way ANOVA results (Table 10) showed that the p-values were less than 0.05 for all the parameters measured which implies the significance of the results obtained for the untreated and stabilised mixtures at 95% confidence level. The regression analysis (Table 11; Figures 12 and 13) showed strong relationships between stabiliser content and engineering properties of soil. The obtained regression models showed high coefficients of determination (R2 = 0.94–0.97) indicating an excellent agreement between experimental and predicted values. The high R 2 values indicate that the stabilisers used were successful in controlling the variation of soil behaviour and the regression models can be used to reliably predict the performance of stabilised expansive soil within the range investigated. Yadav and Tiwari (2016) and Phanikumar and Sharma (2004) have reported similar observations and have proved that the effects of stabilisation on the soil properties are reliably statistically validated. Hence, the statistical results confirm the repeatability and reliability of the experimental results and prove the efficacy of the proposed Class F fly ash–Kota stone powder–polyolefin fibre stabilisation system in improving the engineering performance of expansive regur soil.

4.8 Practical Engineering Implications

The results of the present study indicate that the combination of class F fly ash, Kota stone powder and polyolefin fibre is a sustainable and effective technique for stabilisation of expansive regur soil. The optimum mixture significantly increased strength and bearing capacity, but decreased plasticity, free swell index and swelling pressure, thus making the treated soil more suitable for engineering applications. The enhanced engineering properties indicate that the stabilised soil can be effectively used in highway and railway subgrades, embankments, shallow foundations and low-volume road construction where expansive soils often lead to excessive settlement and pavement distress. The improved durability and lower volume change are expected to reduce maintenance requirements and increase the service life of the infrastructure. From the sustainability point of view, the use of Class F fly ash and Kota stone powder as industrial by-products encourages waste recycling, conservation of natural resources and reduction of environmental effects of conventional stabilisers such as cement and lime. Thus, the proposed stabilisation method presents a technically effective, environmentally friendly, and economically feasible solution for the improvement of expansive soils in geotechnical engineering.

5. Conclusions

The present study proved that the combined use of Class F fly ash, Kota stone powder and polyolefin fibre have successfully improved the engineering behaviour of expansive regur soil. The best overall performance was achieved with the optimum mixture of 20% fly ash, 15% Kota stone powder and 0.75% polyolefin fibre, which increased the 28-day unconfined compressive strength from 121 kPa to 412 kPa, the soaked California Bearing Ratio from 2.8% to 11.9% and decreased the plasticity index from 35% to 13%, the free swell index from 78% to 22% and the swelling pressure from 82 kPa to 23 kPa. The SEM and XRD analysis indicated that the improvements were due to the formation of a denser soil matrix and cementitious hydration products. The statistical analysis also indicated that the changes in engineering properties were statistically significant ($p < 0.05$) and the predictive accuracy was high (R2 = 0.94−0.97). The results concluded that the combination of Class F fly ash, Kota stone powder and polyolefin fibre is an eco-friendly, cost-effective and technically feasible method for the stabilisation of expansive soils and hence can be used for pavement subgrades, embankments and shallow foundations.

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