Fly Ash and Geogrid Reinforced Clay: A Sustainable Approach for Road and Embankment Construction

S. Harish Ragav[1], P. Pongokul[1], G. Sanjaykumar[1], Jeevanantham Venkatesh[1], Jayashree Jayakumar[2,*] and Hema Sudhakar[2]

[1]Department of Civil Engineering, Ramco Institute of Technology, Virudhunagar District, Tamil Nadu, India

[2]Department of Civil Engineering, Sri Ramakrishna Engineering College, Coimbatore, Tamil Nadu, India

Abstract: Clayey soils are often regarded as problematic soil in civil engineering due to their low shear strength, high compressibility and poor drainage capacity. These characteristics limit their suitability for use in roadways, embankments and foundation subgrades unless appropriate stabilization techniques are adopted. In recent years, the use of industrial by-products and geosynthetic materials has gained attention as a sustainable and cost-effective solution. This study presents an experimental investigation into the combined effects of Class C fly ash and Geogrid reinforcement on the geotechnical performance of clayey soil.

A systematic testing program was conducted on untreated clay, clay mixed with varying percentages of fly ash (10% – 30%), and clay–fly ash composites reinforced with Geogrid layers (single and double layers). Standard laboratory experiments, including Atterberg limits, compaction characteristics and California Bearing Ratio (CBR) tests, were conducted to evaluate the strength improvement. The results revealed that untreated clay exhibited a CBR of 5.79%, confirming its weakness in its natural state. The inclusion of fly ash significantly enhanced strength, with the CBR progressively increasing to 15.16% at 30% replacement. Further improvement was obtained when Geogrid was incorporated. The optimum performance was achieved with 20% fly ash combined with two Geogrid layers placed at 0.5 and 0.66 depths from the top, resulting in a maximum CBR value of 16.35%, which is nearly three times higher than that of untreated soil.

The findings highlight that the modification made by flyash and geogrid causes favourable improvements in CBR through enhanced strength and load distribution. In addition, the reuse of fly ash addresses disposal concerns while reducing construction costs. This study confirms that fly ash–Geogrid stabilization is a practical, eco-friendly and technically viable method for improving weak subgrades, making it highly suitable for sustainable road and embankment construction. The study also establishes a predictive model correlating CBR with fly ash content and geogrid configuration, enabling intelligent, data-driven approaches to subgrade design.

Keywords: Clay soil, Class C Flyash, Geogrid, CBR, Predictive model, Sustainable Infrastructure.

1. INTRODUCTION

Clayey soils are commonly encountered in subgrade layers of roadways and foundations, yet their poor engineering characteristics such as high plasticity, low shear strength, excessive swelling, and high compressibility make them unsuitable for supporting heavy structural loads. These limitations often lead to excessive settlement, cracking, and instability in civil engineering projects. Consequently, stabilization becomes a necessity when clayey soils are to be used in infrastructure development.

Conventional stabilization techniques typically involve chemical additives such as lime and cement. However, with growing emphasis on sustainable and cost-effective practices, attention has shifted towards utilizing industrial by-products and geosynthetic materials. Fly ash, an industrial residue produced from coal combustion, has shown promise in soil stabilization due to its pozzolanic and cementitious properties. In particular, Class C fly ash, with its high calcium oxide content, exhibits self-cementing behavior that contributes to strength gain and reduced plasticity when mixed with clayey soils.

Geogrids, a class of geosynthetic reinforcement materials, provide mechanical stabilization by interlocking with soil particles, thereby enhancing tensile resistance, improving load transfer, and reducing deformation. The combination of fly ash and Geogrid offers a synergistic stabilization mechanism, with the former modifying soil chemistry and the latter improving stress distribution. While individual applications of fly ash and Geogrid are well-documented, comprehensive studies on their combined effect remain limited.

Although fly ash and geogrid have been individually studied for soil stabilization, limited research exists on their combined influence on clayey subgrades. This study aims to experimentally investigate the synergistic effect of Class C fly ash and geogrid reinforcement on CBR improvement and to develop a predictive correlation model for intelligent subgrade design.

2. LITERATURE REVIEW

Past research has established the beneficial role of fly ash and geosynthetics in soil improvement. (Noaman *et al*., 2022) reviewed the effect of fly ash on

*Address correspondence to this author at the Department of Civil Engineering, Sri Ramakrishna Engineering College, Coimbatore, Tamil Nadu, India;
E-mail: jjayashree16@gmail.com

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clayey soils and highlighted significant improvements in stability, permeability, and CBR values. (Jahandari *et al*., 2022) examined lime–Geogrid stabilized subgrades and found considerable enhancement in ductility and geotechnical behavior under varying moisture conditions, though excessive moisture reduced bonding efficiency.

Similarly, (Biswas *et al*., 2015) conducted experiments on Geogrid-reinforced foundations and reported up to a 5.6-fold increase in bearing capacity depending on subgrade strength and reinforcement configuration. (Deepak *et al*., 2021) emphasized that Class C fly ash, due to its self-cementing properties, was more effective than Class F fly ash in reducing plasticity and enhancing soil workability.

Recent research has consistently highlighted the effectiveness of fly ash in improving the geotechnical properties and stability of soils, with experimental results showing notable percentage gains in strength and stability parameters. The addition of fly ash alters soil structure through pozzolanic activity and filler effects, leading to increased shear strength, improved compaction, and reduced plasticity under different moisture and loading conditions (Jahandari *et al*., 2022; Noaman *et al*., 2022). Comparative studies on clayey subgrades reveal that untreated soils exhibit poor bearing capacity, whereas the inclusion of fly ash with geogrid reinforcement enhances load resistance by more than 40–60%, while also reducing settlement significantly (Biswas *et al*., 2015; Singh *et al*., 2012). Similarly, stabilized clay soils treated with optimum fly ash content recorded an improvement in California Bearing Ratio (CBR) values by 50–70%, which was markedly higher than those achieved using traditional stabilizers alone (Deepak *et al*., 2021). Furthermore, the combined application of geosynthetics with fly ash has been reported to produce an additional 20–30% strength gain over the individual use of either material, making it a highly eco-friendly and cost-efficient ground improvement approach (Chatrabhuj & Meshram, 2024)

Several review and experimental studies have also compared the performance of fly ash-stabilized soils under different loading and environmental conditions. For example, fine-grained soils blended with fly ash demonstrated up to 80% higher strength under cyclic loading compared to untreated soils, ensuring greater resilience in repeated load scenarios (Karim *et al*., 2020; Turan *et al*., 2022). When compared with lime or cement stabilization, fly ash showed comparable strength improvement, often recording 60–70% increase in unconfined compressive strength (UCS), while offering lower costs and reduced carbon footprint (Alterary & Marei, 2021). Jayashree and Jeevanantham (2022) demonstrated that blending fly ash and rice husk ash significantly enhanced CBR and UCS of clayey soils due to pozzolanic activity. Similarly, Jeevanantham *et al*. (2016) highlighted that fly ash improves bonding and reduces plasticity in cohesive soils, supporting its suitability for subgrade stabilization. Reviews further highlight that lime stabilization performs effectively in expansive soils, but fly ash provides superior improvement in soft clays and silty soils due to its better reduction in compressibility and permeability (Jazi *et al*., 2023). In pavement applications, fly ash-treated subgrades have exhibited up to 55% improvement in resilient modulus and longer service life compared to untreated sections (Wagale *et al*., 2024). Reinforcement of fly ash layers with geogrids has also resulted in significant gains, with CBR values increasing by nearly 100% in some cases compared to fly ash-only stabilization (Sinha *et al*., 2022). (Jayakumar *et al*., 2020) investigated the use of non-woven geotextile and geogrid layers in expansive clay and observed a significant improvement in CBR values, with the control sample showing about 3.54%. The findings emphasize that both the type of reinforcement material and the depth at which it is placed play a crucial role in enhancing performance. These findings collectively demonstrate that fly ash, especially when used synergistically with geogrids or geosynthetics, provides not only measurable improvements in soil strength and durability but also contributes to sustainability in modern geotechnical engineering.

Although these studies demonstrate the individual advantages of fly ash and Geogrid, limited research has been carried out on their combined application for clayey soils. This study aims to fill that gap by providing experimental evidence of the synergistic benefits of Class C fly ash and Geogrid in improving subgrade performance.

Recent advancements in intelligent geotechnics emphasize data-driven modeling, performance monitoring, and numerical simulations for reinforced soil systems. Studies have incorporated finite element models and embedded sensor networks to evaluate the real-time behavior of geogrid-reinforced subgrades. Such approaches align with the present study, which contributes empirical data that can serve as input for predictive and intelligent geotechnical design frameworks.

3. MATERIAL COLLECTION

3.1. Soil Sample

For this experimental study, the soil sample is collected from a construction site located at 11°07'52.6"N 76°57'35.1"E Coimbatore, Tamil Nadu shown in Figure **1** & **2**. Representative bulk soil

Figure 1: Soil Sampling Site.

Figure 2: Clay sample.

samples are collected and used for laboratory investigation to determine various indices and strength properties of soil. All the index and engineering properties tests were conducted in accordance with IS standard (IS 2720) and are listed in the Table **1**. Based on the index property test results the soil is classified as clay of high plasticity (CH).

Table 1: Properties of Soil

Properies		Value
Grain size distribution	Gravel (%)	1.97
	Sand (%)	3.333
	Clay + Silt (%)	95
Specific gravity		2.715
Water content (%)		7.7
Liquid limit (%)		49
Plastic limit (%)		10.28
Plasticity Index (%)		38.72
Optimum moisture content (OMC)		18
IS classification		CH
Compressive strength (N/mm^2)		0.048

The California Bearing Ratio (CBR) test was conducted on clay soil to assess its load-bearing capacity under simulated pavement conditions. The test involved applying a standard penetration load to compacted soil specimens and recording the resistance at various depths. Figure **3** results indicated that the natural clay exhibited a relatively low CBR value, reflecting its limited strength for use in subgrade applications.

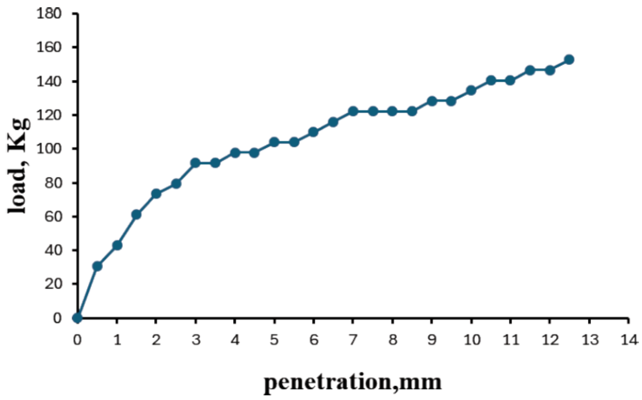

Figure 3: Load – Penetration curve of clay soil under CBR test.

The California Bearing Ratio (CBR) test results for clay soil showed a penetration value of 5.79% at 2.5 mm and 5.05% at 5.0 mm. Since the higher value between the two is considered for evaluation, the final CBR value of the soil was determined to be 5.79%, indicating the relatively low strength of the untreated clay subgrade.

Figure 4: Class C Fly ash.

3.2. Fly Ash

The flyash is purchased from GSR Flyash Bricks in Coimbatore shown in Figure **4**. Class C fly ash typically contains high levels of aluminium oxide, silica, and calcium oxide. The chemical constituents of flyash is illustrated in Table **2**.

Table 2: Properties of Fly Ash

Properties	Weight in %
Silica	63.85
Alumina	27.62
Iron oxide	3.70
Calcium oxide	1.36
Magnesium oxide	0.35
Sodium oxide	0.29
Sulphur trioxide	0.08
Titanium dioxide	1.92
Potassium oxide	0.83

3.3. Geogrids

Geogrids are high-strength geosynthetic materials used to reinforce soil in civil engineering applications such as retaining walls, embankments, road bases, and landfills. Made from polymers like high-density polyethylene (HDPE), polypropylene (PP), or polyester (PET), they feature a grid-like structure that allows soil or aggregate to interlock, improving stability and load distribution as illustrated in Figure **5**. Geogrids offer excellent tensile strength (typically 20 to 200 kN/m), low elongation, and strong resistance to creep, chemicals, UV exposure, and biological degradation. They are available in uniaxial, biaxial, and triaxial forms, depending on directional strength requirements, and come in various sizes to suit specific engineering needs. The physical properties of geogrids are listed in the Table **3**.

Table 3: Properties of Geogrid

Property	Typical Value
Tensile Strength	100 kN/m (can be uniaxial or biaxial)
Aperture Size	25 mm × 25 mm to 40 mm × 40 mm
Roll Width	4.0 m – 5.0 m
Roll Length	50 m – 100 m
Thickness	2 mm – 5 mm
Material	Polyester (PET), HDPE, or PP (with bitumen or PVC coating)
Mass per Unit Area	400 – 800 g/m² (varies with coating and weave)
Elongation at Break	Typically, <10%

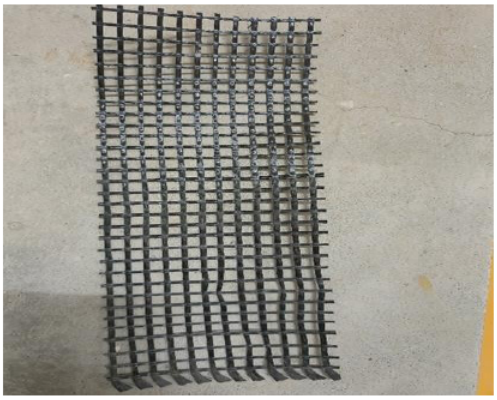

Figure 5: Geogrid.

3.3.1. Tensile Strength Test on Geogrid

The tensile strength characteristics of the geogrid were evaluated in accordance with IS 16474:2015 – Method of Test for Tensile Properties of Geogrids by the Single or Multi-Rib Tensile Method is shown in the Table **4**. The tests were performed at the geotechnical laboratory of P.A.C.R. Polytechnic College, Rajapalayam shown in Figure **6**. In this procedure, geogrid specimens were subjected to uniaxial tensile loading under controlled conditions to determine their load–elongation response. The results obtained provide essential data on the tensile behavior of the geogrid, which is critical for assessing its suitability and performance in soil reinforcement applications.

Table 4: Tensile Strength Values

Test no	Elongation (inch)	Break load (Kg)
1	2.5	120
2	0.4	110
3	0.4	115
4	0.4	102
5	0.4	104

Figure 6: Tensile strength for Geogrid.

The obtained tensile strength values are essential input parameters for finite element modelling (FEM) of reinforced soil systems, enabling simulation of stress–strain behaviour and prediction of performance under different load conditions. This linkage between laboratory data and computational modelling aligns with the concept of intelligent geotechnical design

4. EXPERIMENTAL INVESTIGATION

4.1. Effect of Fly Ash on CBR

The experimental program was designed to evaluate the improvement of clayey soil through stabilization with fly ash at varying proportions of 10%, 15%, 20%, 25%, and 30% by weight of dry soil. For each mix, soil samples were prepared and compacted at their optimum moisture content to ensure uniformity and accuracy in testing. The California Bearing Ratio (CBR) test was then conducted to determine the penetration resistance and assess the load-bearing capacity of the treated soil.

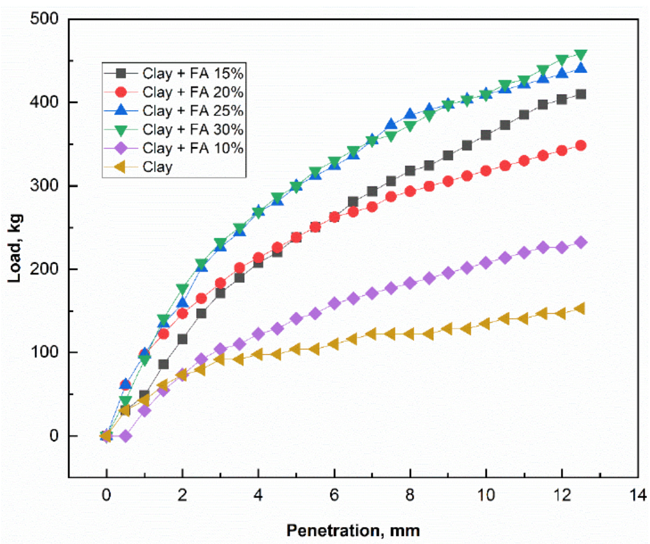

Figure 7: Load – Penetration curve of clay soil treated with different percentage of fly ash under CBR test.

The California Bearing Ratio (CBR) test results clearly demonstrate the progressive improvement in the load-bearing capacity of clay soil with the addition of fly ash at varying proportions shown in Figure **7**. The untreated clay exhibited a low CBR value of 5.79%, confirming its poor strength for subgrade applications. With the inclusion of 10% fly ash, the CBR value increased to 7.58%**,** showing an improvement of nearly 31% over untreated clay. Further addition of fly ash yielded even greater enhancements, with values of 11.67% at 15% fly ash and 12.04% at 20% fly ash, corresponding to increases of about 101% and 108%, respectively. At 25% fly ash, the CBR reached 14.71%, representing a 154% improvement, and a maximum value was observed at 30% fly ash, recording 15.16%, which is nearly a 162% increase compared to untreated soil. This steady rise in CBR can be attributed to the self-cementing and pozzolanic reactions of Class C fly ash, which reduce plasticity, fill soil voids, and form a denser, stronger matrix. Hence, the results justify that fly ash stabilization not only enhances the strength characteristics of clay but also promotes sustainable use of industrial by-products in subgrade and pavement construction.

4.2. Combined Effect of Fly Ash and Geogrid

In the next phase of the experimental program, the effect of geogrid reinforcement in combination with 20% fly ash–stabilized clay was investigated through CBR testing. Soil samples were prepared by mixing clay with 20% fly ash by weight of dry soil, followed by compaction at optimum moisture content. Geogrid layers were then incorporated within the compacted samples at different depths to study their influence on load-bearing performance. Figure **8** shows the single-layer reinforcement, whereas the geogrid was placed at a depth of 0.5H (where *H* is the specimen height). For double-layer reinforcement, two different configurations were adopted: one with geogrids positioned at 0.33H and 0.66H, and another with layers at 0.33H and 0.5H as shown in Figure **9**. The prepared specimens were subjected to CBR testing under standard loading conditions, and the penetration resistance was recorded at incremental depths. This experimental procedure enabled the evaluation of both the individual and combined effects of fly ash stabilization and geogrid reinforcement, as well as the influence of layer positioning on improving the subgrade strength.

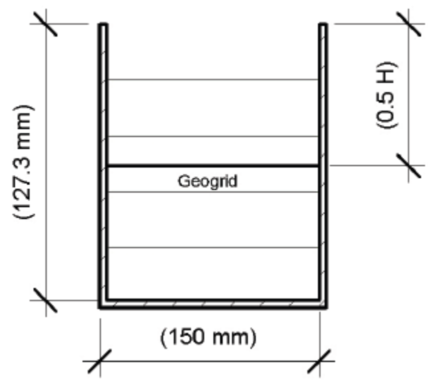

Figure 8: Schematic diagram of Single Layer Geogrid in CBR.

The incorporation of geogrid reinforcement along with 20% fly ash stabilization further enhanced the CBR values of clay soil compared to fly ash treatment alone. With a single geogrid layer at 0.5H**,** the CBR value increased to 13.82%, which represents an improvement of approximately 132% over untreated clay (5.79%) and about 15% higher than clay with only 20% fly ash (12.04%). When double geogrid layers

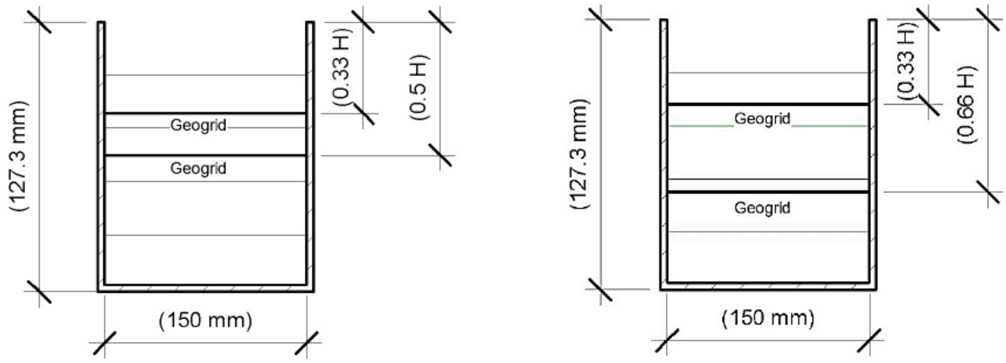

Figure 9: Schematic diagram of Double Layer Geogrids in CBR.

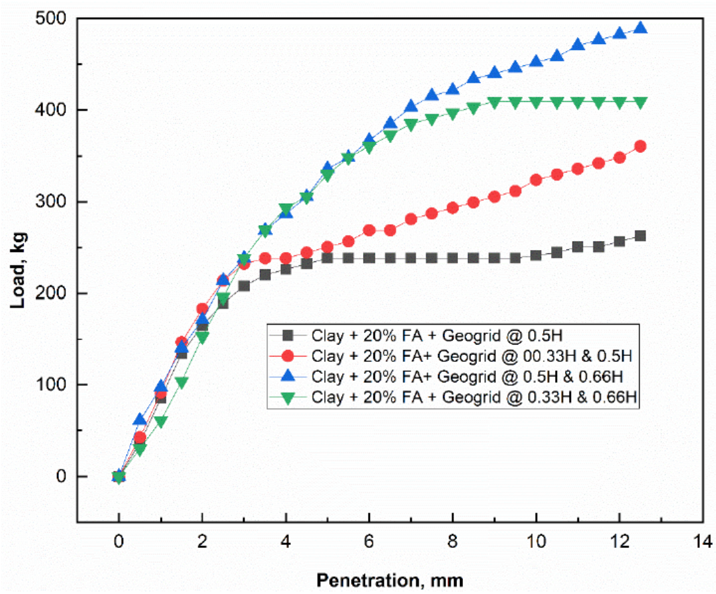

Figure 10: Load – Penetration curve of clay soil treated with 20% fly ash and Geogrids under CBR test.

were introduced, the performance improved significantly. The configuration with geogrids placed at 0.33H and 0.5H achieved a CBR value of 15.60%, marking a 169% increase over untreated clay and a 30% increase over 20% fly ash alone. Similarly, the arrangement at 0.33H and 0.66H yielded a CBR of 16.05%, showing an improvement of about 177% compared to untreated clay and 33% compared to fly ash alone. The highest strength was observed with geogrid layers positioned at 0.5H and 0.66H, where the CBR reached 16.35%, nearly 182% higher than untreated clay and about 36% higher than the fly ash–only sample. These results justify that the synergistic effect of fly ash stabilization and geogrid reinforcement not only improves the strength of clay subgrades but also highlights the importance of optimal geogrid placement, with double-layer configurations providing superior performance compared to single-layer reinforcement.

5. RESULTS AND DISCUSSION

The results of the CBR tests shown in Figure **11** clearly indicate that untreated clay possesses the lowest strength, with a CBR value of 5.79%, reaffirming its inadequacy as a subgrade material in its natural state. The addition of fly ash resulted in a gradual and consistent improvement in strength, with 10% fly ash increasing the CBR to 8.3%, reflecting a moderate enhancement. Further increments in fly ash content yielded higher values, with 11.92% at 15%, 12.04% at 20%, 14.71% at 25%, and a maximum of 15.16% at 30%, demonstrating the effectiveness of fly ash in stabilizing clay through its self-cementing and pozzolanic properties. When geogrid reinforcement was incorporated along with 20% fly ash, the strength improved significantly, with the highest value of 16.35% observed at a double-layer configuration placed at 0.5H and 0.66H, which is nearly 182% higher than untreated clay. Other geogrid arrangements also showed notable improvements, including 16.05% at 0.33H and 0.66H, 15.6% at 0.33H and 0.5H, and 13.82% for a single layer at 0.5H. These results justify that while fly ash alone enhances the strength of clay soils, the combined effect of fly ash and geogrid reinforcement provides superior performance. The improved load-bearing capacity can be attributed to the

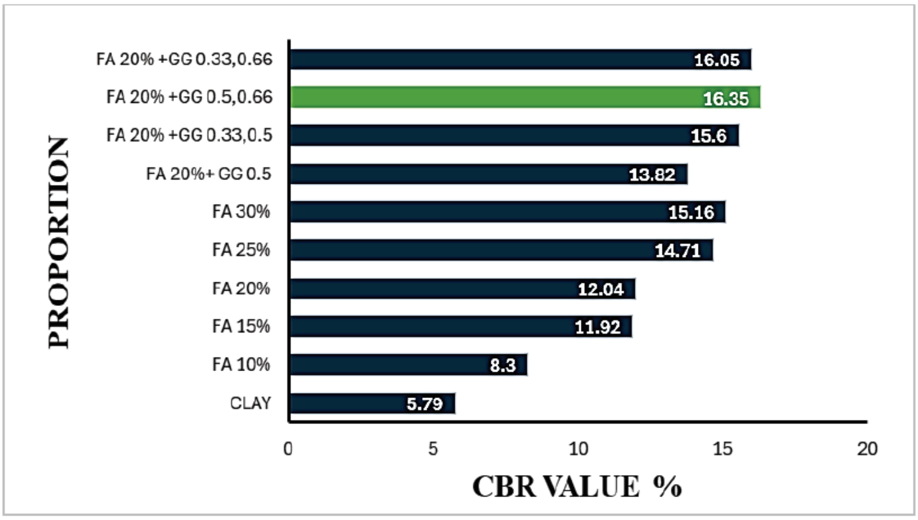

Figure 11: Material Proportions VS CBR value%.

synergistic action of fly ash reducing plasticity and densifying the soil matrix, while the geogrid interlocks with soil particles, offering mechanical reinforcement and restricting deformation. This combined stabilization technique thus emerges as a technically effective and sustainable solution for subgrade and pavement construction.

The experimental findings highlight the combined benefits of chemical and mechanical stabilization. The addition of Class C fly ash reduced the plasticity of clay, improved its workability, and increased density, all of which contributed to strength gain. The self-cementing property of Class C fly ash further enhanced bonding between soil particles, reducing compressibility and improving load resistance.

Geogrid reinforcement complemented these improvements by providing tensile strength and distributing applied stresses more effectively across the soil mass. The interlocking mechanism between soil particles and the Geogrid apertures contributed to greater confinement and reduced deformation. The optimum results achieved with two Geogrid layers at 0.5H and 0.66H suggest that reinforcement placed closer to the load-bearing region is more effective in improving soil performance.

These results align with previous studies in the literature, confirming that while fly ash alone improves soil significantly, the addition of Geogrid leads to further enhancement through a synergistic mechanism. The near-tripling of CBR values compared to untreated clay demonstrates the potential of this technique for practical implementation in subgrade and embankment construction.

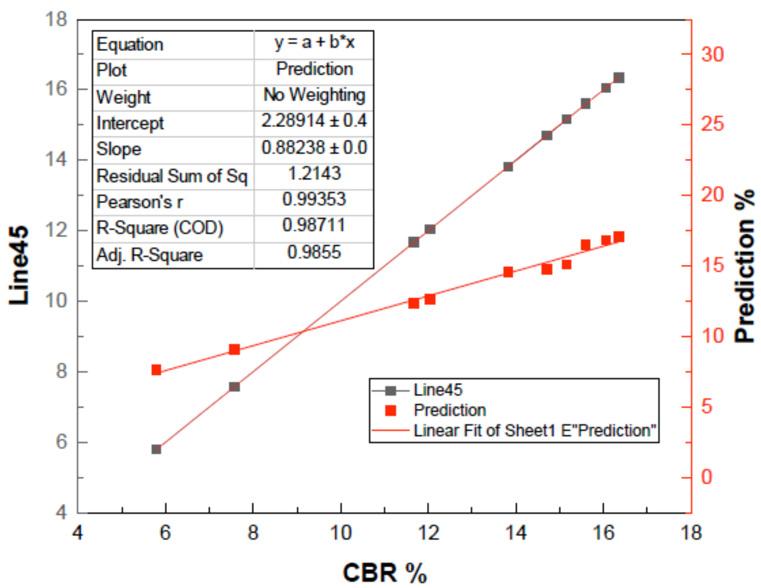

Figure 12: Predicted Vs Observed CBR Comparison.

5.1. Predictive Modelling of CBR

To evaluate the predictive performance and reliability of the proposed model, both simple linear regression and multiple linear regression analyses were performed using the experimental CBR dataset. The simple linear regression model considered only the influence of fly ash content on the CBR, while the multiple linear regression (MLR) model incorporated both fly ash percentage and the number of geogrid layers as independent variables.

The simple linear regression analysis yielded the equation (1),

$$\boldsymbol{CBR = 2.29 + 0.88(FA\%)} \quad (1)$$

with a correlation coefficient of R^2=0.987R^2 and an adjusted R^2=0.985R^2, as shown in Figure **12**. The high correlation demonstrates that the CBR increases linearly with fly ash content, confirming the beneficial effect of pozzolanic stabilization on soil strength. However, this single-variable model does not account for the reinforcement effects of geogrid inclusion, which also significantly influences load distribution and confinement.

To capture the combined influence of both stabilizing agents, a multiple linear regression model was developed, expressed in equation (2).

$$\boldsymbol{CBR = 5.48 + 0.34(FA\%) + 1.84(Geogrid\ Layers)} \quad (2)$$

The model exhibits a high degree of correlation, with a coefficient of determination R^2=0.9647R^2 and an adjusted R^2=0.9546R^2, indicating that approximately 96% of the variability in CBR can be explained by the combined influence of fly ash percentage and geogrid reinforcement. The residual sum of squares as 4.213 is relatively low, confirming the adequacy of the fitted model. The positive regression coefficients signify that both fly ash and geogrid layers contribute positively to the improvement of subgrade strength. The proposed equation thus provides a reliable empirical tool for predicting the CBR of stabilized clay based on material composition and reinforcement configuration, facilitating intelligent and performance-based design of pavement subgrades. The regression model offers valuable input parameters for FEM analysis of reinforced subgrades and supports the development of intelligent pavement management systems through predictive performance estimation.

Future studies can expand this framework using advanced machine learning techniques such as decision trees or artificial neural networks to further enhance the prediction accuracy of CBR for varied soil–stabilizer combinations.

6. COST ANALYSIS

A cost analysis was performed for a 1 km stretch of embankment with a width of 7.5 m and thickness of 0.35 m. The total volume of stabilized soil was estimated at 2,625 m³, with a corresponding soil mass of 4,635.4 tons. At 20% fly ash replacement, the required fly ash quantity was approximately 927.1 tons. Geogrid coverage for the section was calculated as 7,500 m². Considering a unit cost of ₹1,000 per ton for fly ash and ₹100 per square meter for Geogrid, the total cost of stabilization was estimated at ₹16.77 lakhs. This analysis indicates that the proposed stabilization method is cost-effective, particularly when considering the long-term performance benefits and the reuse of industrial waste materials.

Although the initial cost appears moderate, the inclusion of fly ash and geogrid substantially reduces long-term maintenance requirements. Considering durability and extended service life, a preliminary life-cycle cost assessment (LCCA) indicates that the proposed stabilization could reduce maintenance costs by 25–35% compared to conventional lime-treated sections. This supports sustainable and intelligent decision-making in geotechnical design.

CONCLUSIONS

The experimental study confirmed that clayey soils in their natural state are unsuitable for subgrade applications due to their very low CBR value. Stabilization with Class C fly ash significantly improved soil strength, with optimum results observed at 30% replacement. The addition of Geogrid reinforcement further enhanced load-bearing capacity, with the best performance achieved at 20% fly ash combined with two Geogrid layers at 0.5H and 0.66H depths, resulting in a maximum CBR of 16.35%.

The combined use of fly ash and Geogrid offers a sustainable, technically sound, and economically feasible solution for stabilizing weak clayey subgrades. This approach not only improves soil performance but also addresses environmental concerns by promoting the beneficial reuse of industrial by-products. The technique holds considerable promise for road, embankment, and pavement construction in regions with problematic soils.

The increased and more predictable CBR of the stabilized subgrade provides a reliable foundation for integrating sensor-based pavement health monitoring and intelligent design tools. The uniform performance supports digital twin models and adaptive maintenance strategies in smart infrastructure systems.

The developed empirical model and the experimental results provide a foundation for integrating data-driven tools into geotechnical design. The predictive relationship established between material composition and strength behavior can support intelligent design frameworks, numerical simulations, and real-time performance monitoring systems for next-generation sustainable infrastructure.

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