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OPEN ACCESS

SUSTAINABLE SOIL STABILIZATION USING INDUSTRIAL BY-PRODUCTS: FLY ASH, LIME, AND QUARRY DUST

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ABSTRACT

Soil stabilization is necessary to improve the strength of weak soils used in construction works. Clayey soils usually have low bearing capacity, high shrink swell behavior, and are sensitive to moisture. In this study, we used industrial waste materials fly ash, lime, and quarry dust are to improve soil properties. The soil samples were replaced and mixed with soil in different percentages of fly ash, lime, and quarry dust and tested and examined as per IS standards. These results have the comparisons of compaction test, Optimum Moisture Content (OMC), and California Bearing Ratio (CBR) tests with respect to original soil. The results showed that the treated soil samples have better strength and load-bearing capacity compare to original one. This mix proportion of mix (fly ash 20%, lime 4% and quarry dust 12%) helps in improving soil performance while stabilizing soil for foundations, and pavement construction and reducing environmental pollution by using these industrial waste materials.

Keywords: Soil Stabilization, Fly Ash, Lime, Quarry Dust, CBR, Optimum Moisture Content, Sustainable Construction

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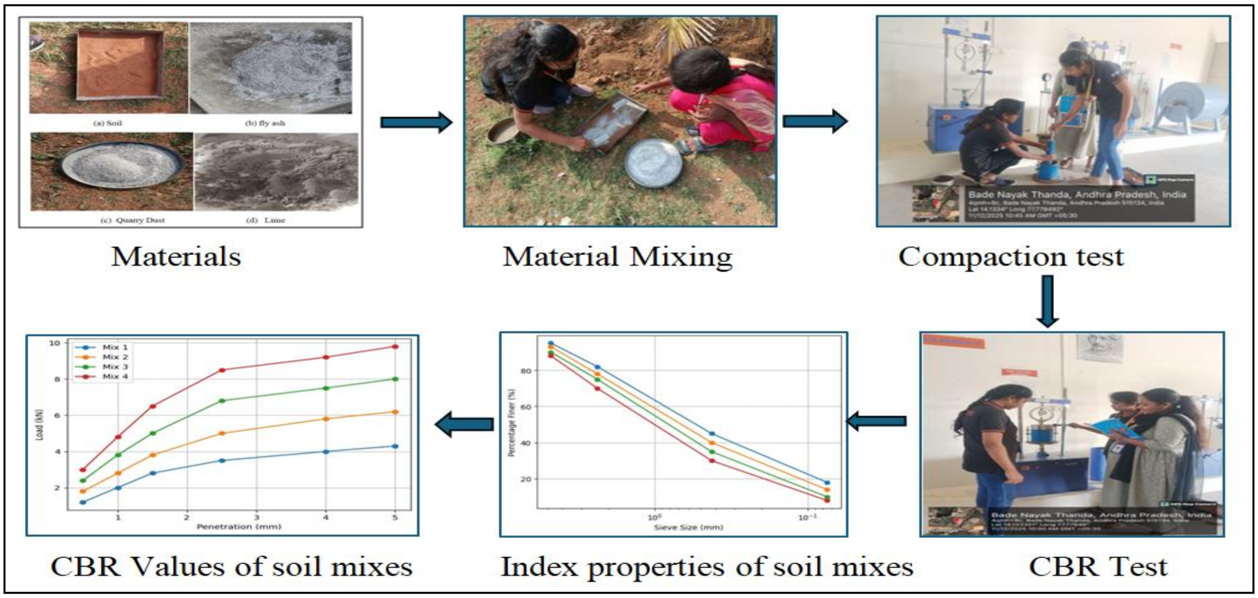
Graphical Abstract:



1. Introduction

Soil stabilization is an important geotechnical technique used to improve the engineering properties of weak soils for construction purposes. Many natural soils, especially clayey soils, show poor strength, low bearing capacity, and high-volume change with moisture variation. To overcome these problems, industrial waste materials such as fly ash, lime, and quarry dust can be effectively used. These materials not only enhance soil strength but also help in waste utilization and environmental protection, making construction more economical and sustainable. Rapid infrastructure development requires strong and durable subgrade soils. However, many construction sites contain weak soils that cannot safely support loads. Conventional stabilization methods are costly and increase environmental pollution. Industrial wastes like fly ash and quarry dust are generated in large quantities and create disposal problems. Hence, there is a strong need to study soil stabilization using fly ash, lime, and quarry dust to improve soil properties while reducing construction cost and environmental impact.

Soil stabilization has been practiced since ancient times using materials like lime and natural additives. With industrial growth, researchers started exploring industrial by-products such as fly ash for soil improvement. Lime stabilization became popular for clay soils due to its chemical reaction with soil minerals. In recent decades, quarry dust has gained attention as a replacement material because of its availability and strength-enhancing properties. These developments led to modern eco-friendly soil stabilization techniques.

1.1 Scope of Work

The scope of this study includes laboratory evaluation of soil stabilized with varying percentages of fly ash, lime, and quarry dust. The work involves testing untreated and treated soil samples to determine changes in compaction characteristics, strength, and bearing capacity. The study focuses on identifying the optimum mix proportion for maximum performance. The findings can be applied to road subgrades, embankments, and foundation soils in low-cost and sustainable construction projects.

1.2 Objective of the Study

The main objective of this project is to improve the engineering properties of weak soil using industrial waste materials. Specific objectives include evaluating the effect of fly ash, lime, and quarry dust on soil strength, compaction behavior, and bearing capacity. The study also aims to identify the optimum percentage of stabilizers and promote sustainable construction practices by reducing waste disposal problems and minimizing the use of conventional materials.

1.3 Previous Researchers' Study

Previous studies have shown that fly ash improves soil workability and reduces plasticity, while lime increases strength through pozzolanic reactions. Researchers have reported significant improvement in CBR and shear strength values of clay soils stabilized with fly ash and lime. Quarry dust has been found effective in increasing density and reducing compressibility...

In recent years, soil stabilization using industrial waste materials has received significant attention due to sustainability concerns and the need for cost-effective ground improvement techniques.

M. Di Sante, M. Khizar Khan, L. Calò, E. Fratalocchi & F. Mazzieri (2025). The Combined Use of Fly Ash and Lime to Stabilize a Clayey Soil: A Sustainable and Promising Approach, Geosciences, 15(9), 346.Summary: This study investigated the use of Class F fly ash combined with quicklime for stabilizing clayey soils. The mixture enhanced mechanical characteristics such as reduced compressibility and improved shear strength, attributed to pozzolanic reactions and lime activation. Microstructural analysis supported the formation of cementitious products.

S. Ahmad (2024). Utilization of fly ash with and without secondary additives for stabilizing expansive soils: A review, Journal/Publisher, (Review Paper). Summary: This paper critically reviewed how fly ash affects geotechnical properties (Atterberg limits, UCS, CBR, swell) of expansive soils. FA content between ~25–40% showed significant improvements in plasticity, strength, and volumetric stability, highlighting its value as an industrial by-product stabilizer.

More recently, Singh et al. (2023) reported that soil stabilized with fly ash, lime, and quarry dust showed significant improvement in strength, durability, and CBR values. The authors emphasized that this approach supports sustainable construction by utilizing industrial wastes and reducing environmental pollution.

T. Sambre et al. (2022-2024). Sustainable soil stabilization of expansive soil subgrades using lime-fly ash mixtures, Journal of Sustainable Construction Materials (approx.). Summary: Though published early 2024, this study tested lime and fly ash mixtures on high-plasticity soils, showing reduced swell potential, increased UCS/CBR, and enhanced pavement performance. Significant engineering improvements were noted with a 1:4 lime-to-fly ash ratio.

Patel et al. (2021) examined combined stabilization using fly ash and quarry dust and observed improved compaction characteristics and bearing capacity compared to untreated soil. The combined use of materials resulted in better particle packing and reduced void ratio.

Prabakar et al. (2020) evaluated the use of quarry dust as a stabilizing agent and found an increase in maximum dry density and shear strength. The study highlighted quarry dust as an economical alternative material for improving subgrade soils.

Ramesh and Siva pullaiah (2019) studied lime-treated expansive soils and reported a reduction in plasticity index, swelling potential, and moisture sensitivity. The authors concluded that lime stabilization is highly effective for clay soils subjected to seasonal moisture variations.

Kumar et al. (2018) investigated the stabilization of clayey soil using fly ash and lime and observed considerable improvement in California Bearing Ratio (CBR) and unconfined compressive strength. Their study confirmed that fly ash improves soil workability, while lime contributes to strength development through pozzolanic reactions.

2.MATERIALS AND METHODOLOGY

2.1 METHODOLOGY

The methodology adopted in this project involves laboratory testing of untreated and treated soil samples with different proportions of fly ash, lime, and quarry dust. Initially, the natural soil was tested to determine its basic engineering properties. Then, soil samples were prepared by adding varying percentages of fly ash, lime, and quarry dust. Standard laboratory tests such as Proctor compaction test, Optimum Moisture Content (OMC), and California Bearing Ratio (CBR) test were conducted. The results of treated soil were compared with untreated soil to evaluate improvement and to determine the Optimum mix proportion.

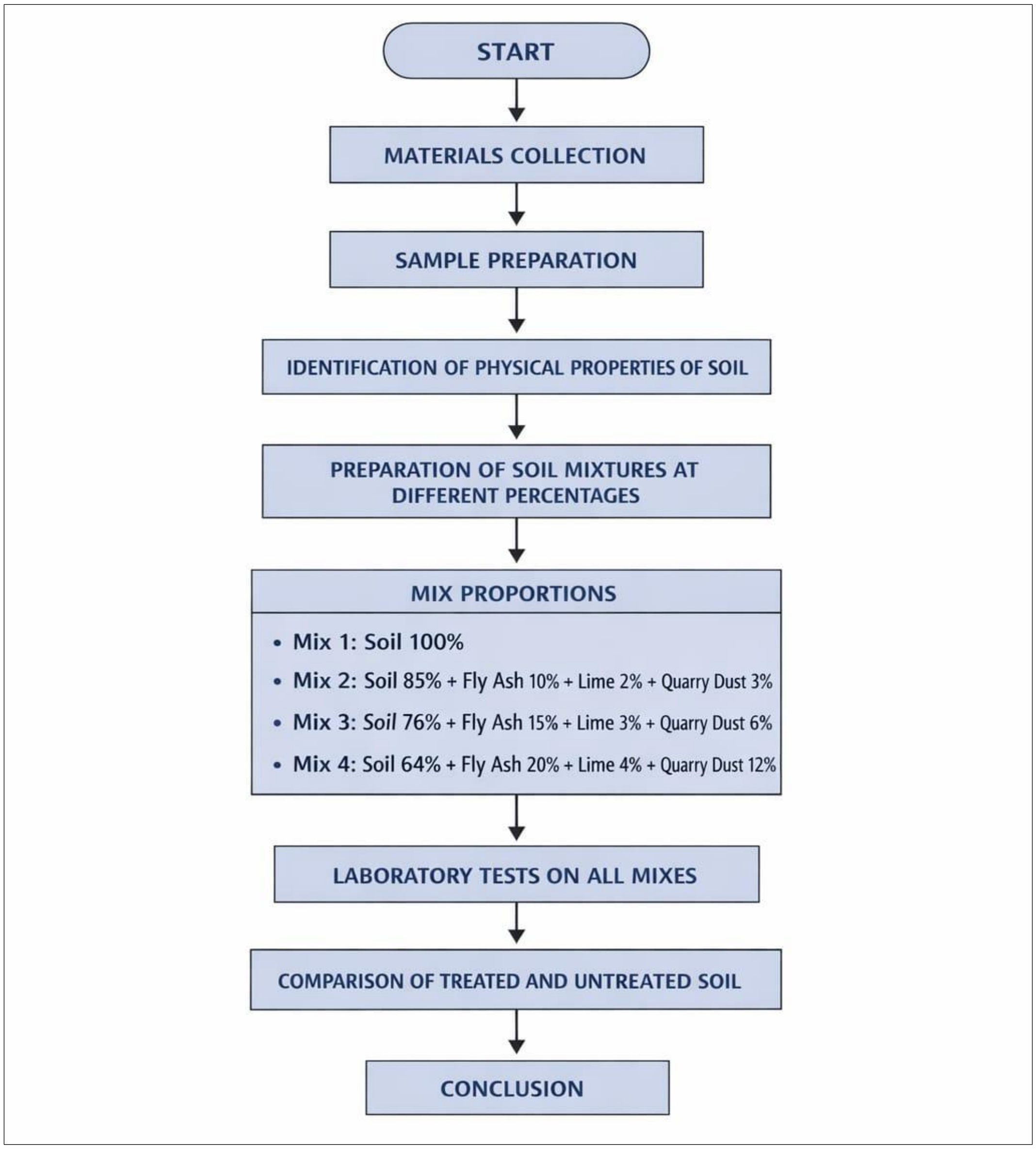


Fig.1: Proposed Methodology

2.2 Materials Used

2.2.1 Soil

Locally available clayey soil was collected from the site. The soil was air-dried, pulverized, and sieved before testing. Basic properties such as grain size distribution, Atterberg limits, and moisture content were determined as per IS standards

2.2.2 Fly Ash

Fly ash collected from a nearby thermal power plant was used as an industrial waste material. It is a fine, pozzolanic material that improves workability and reduces plasticity of soil.

Fig.2: Soil Stabilization Materials

2.2.3 Lime

Commercially available hydrated lime was used. Lime reacts chemically with clay minerals and improves strength and durability of soil.

2.2.4 Quarry Dust

Quarry dust obtained from a stone crushing unit was used. It acts as a granular material that increases density and improves load-bearing capacity.

2.2.5 Water: Clean potable water was used for mixing and testing purposes

2.3 Soil Mix Proportions

2.3.1 Mix Proportions for Soil Stabilization

In the present study, soil stabilization was carried out using industrial waste materials such as fly ash and quarry dust, along with lime as a chemical stabilizing agent. The primary objective of developing different soil mix proportions was to improve the engineering properties of the soil while promoting sustainable and eco-friendly construction practices. A total of four soil mixes (Mix 1 to Mix 4) were prepared for experimental investigation. Mix 1, consisting of 100% natural soil, was used as the control mix to evaluate the baseline properties of untreated soil. In the subsequent mixes, the percentage of natural soil was gradually reduced, while the proportions of fly ash, lime, and quarry dust were increased systematically. The step-by-step replacement of soil with fly ash, lime, and quarry dust was adopted to study their combined effect on compaction and strength characteristics. Fly ash contributes to pozzolanic reactions, lime enhances soil strength through chemical stabilization, and quarry dust improves gradation and density. This combination not only improves mechanical performance but also reduces the consumption of natural soil and provides a productive use for industrial waste materials. The selected mix proportions were designed to achieve improved strength, durability, and load-bearing capacity of the soil, making it suitable for pavement subgrade and foundation applications while addressing environmental concerns related to waste disposal.

Table 1: Proposed Mix Proportions of Materials for Soil Stabilization Materials

Materials	Mix 1 (%)	Mix 2 (%)	Mix 3 (%)	Mix 4 (%)
Soil	100	85	76	64
Fly Ash	0	10	15	20
Lime	0	2	3	4
Quarry Dust	0	3	6	12

Soil mix sample preparation is a critical stage in soil stabilization, as it directly influences the accuracy and reliability of laboratory test results. In this study, representative soil samples were collected from the selected site and air-dried to remove excess moisture. The dried soil was then pulverized and sieved to eliminate oversized particles and ensure uniformity. After preparation of the natural soil, required quantities of fly ash, lime, and quarry dust were measured accurately based on the specified mix proportions. The soil and stabilizing materials were thoroughly mixed in dry condition to achieve a uniform blend. This step ensured even distribution of fly ash, lime, and quarry dust throughout the soil matrix.

Following dry mixing, water was added gradually to each mix to attain the optimum moisture content required for effective compaction and chemical reactions. Adequate moisture was maintained to activate the lime, which reacts with soil particles and fly ash to form cementitious compounds, thereby improving strength and stiffness. The prepared soil mixtures were then compacted using standard laboratory procedures and tested for engineering properties such as compaction characteristics and strength parameters. Proper mixing and preparation ensured consistency in test results and reliable evaluation of the effectiveness of soil stabilization using industrial wastes.

3. RESULTS AND DISCUSSION

3.1 Material Properties

The performance of stabilized soil depends largely on the physical and engineering properties of the materials used. In the present study, soil was stabilized using fly ash, lime, and quarry dust, each contributing uniquely to the improvement of soil characteristics. Natural soil possesses properties such as texture, plasticity, moisture content, and shear strength, which directly influence its load-bearing capacity. Fly ash is a fine-grained pozzolanic material with low plasticity and good workability, which enhances long-term strength through pozzolanic reactions. Lime acts as a chemical stabilizer that reacts with clay minerals, reducing plasticity and increasing stiffness and strength. Quarry dust, being a well-graded granular material, improves particle interlocking and increases density. The combined use of fly ash, lime, and quarry dust improves compaction characteristics, reduces plasticity, and significantly enhances the strength of stabilized soil.

Laboratory investigations were carried out to evaluate the effectiveness of soil stabilization using fly ash, lime, and quarry dust. Both untreated and treated soil samples were tested to study the variation in their engineering properties. The tests conducted include Atterberg limits, specific gravity, moisture content, Standard Proctor compaction test, and California Bearing Ratio (CBR) test. The results obtained from these tests are discussed in detail in the following sections.

3.1.1 Specific Gravity

Specific gravity is an important index property that reflects the density and mineral composition of soil. It is affected by the addition of lighter materials such as fly ash and quarry dust.

Table 2: Specific Gravity for Different Mix Proportions

SI. No	Description	Symbol	Mix -1	Mix -2	Mix -3	Mix-4
1	Mass of empty density bottle (kg)	M1	0.211	0.214	0.213	0.212
2	Mass of bottle + dry soil (kg)	M2	0.576	0.554	0.548	0.542
3	Mass of bottle + soil + liquid (kg)	M3	0.675	0.642	0.635	0.628
4	Mass of bottle + liquid only (kg)	M4	0.561	0.561	0.561	0.561
5	Specific Gravity	G	2.65	2.58	2.52	2.46

A decreasing trend in specific gravity was observed with increasing percentages of fly ash and quarry dust. This is attributed to the lower specific gravity of these materials compared to natural soil.

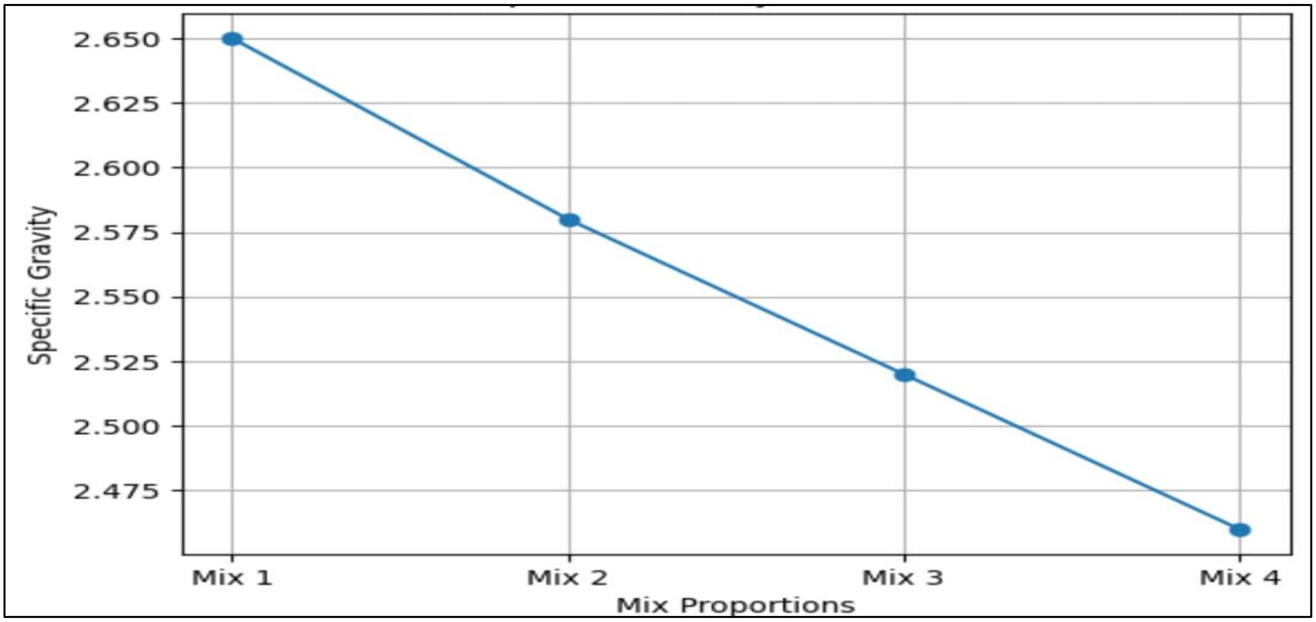


Fig.3: specific gravity values for mixes

The specific gravity of soil decreases from 2.65 to 2.46 with the increase in fly ash, lime, and quarry dust content.

3.2.3 Moisture Content

Moisture content plays a crucial role in soil compaction and strength development. The moisture requirement of soil changes when stabilizing agents are added**.**

Table 3: Moisture Content for Different Mix Proportions

Mix	Moisture Content (%)	Observation
Mix 1	18.5	Natural soil
Mix 2	16.8	Reduced moisture demand
Mix 3	15.2	Improved condition
Mix 4	14.0	Minimum moisture requirement

The moisture content decreases with stabilization due to reduced clay activity and improved gradation. Fly ash and quarry dust reduce water absorption, while lime enhances soil structure.

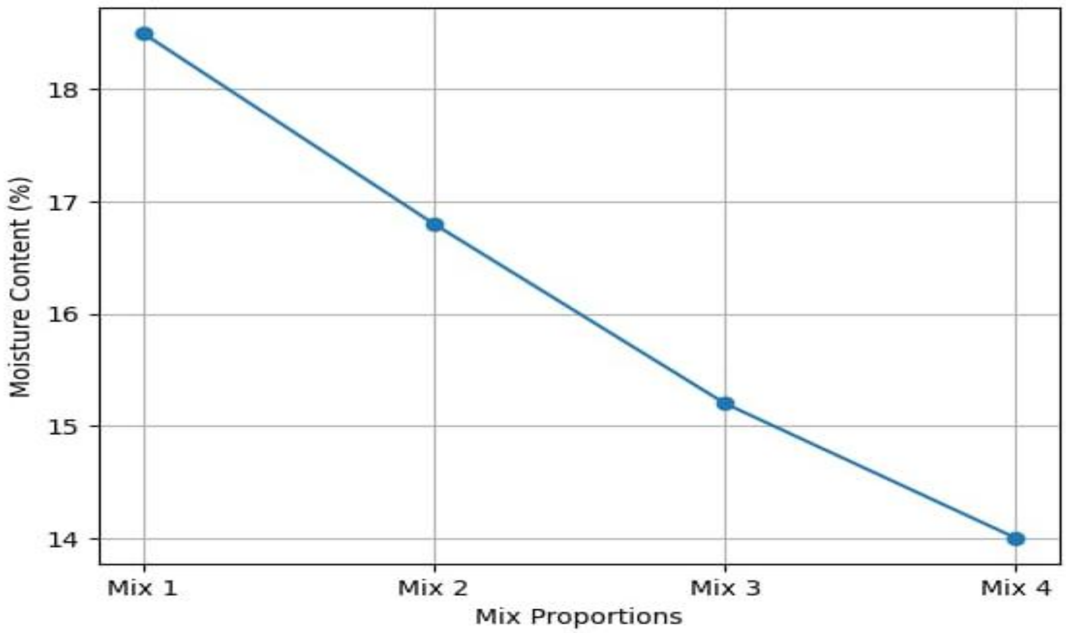


Fig.4: Moisture content values for mixes

The graph shows a continuous decrease in moisture content with the addition of fly ash, lime, and quarry dust.

3.2.1 Sieve Analysis

Sieve analysis determines particle size distribution and soil gradation. Addition of quarry dust improves gradation, while fly ash fills voids between particles.

Table 4: Percentage Finer Values

Sieve Size (mm)	S1 (%)	S2 (%)	S3 (%)	S4 (%)
4.75	95	93	90	88
2.36	82	78	75	70
0.425	45	40	35	30
0.075	18	14	10	8

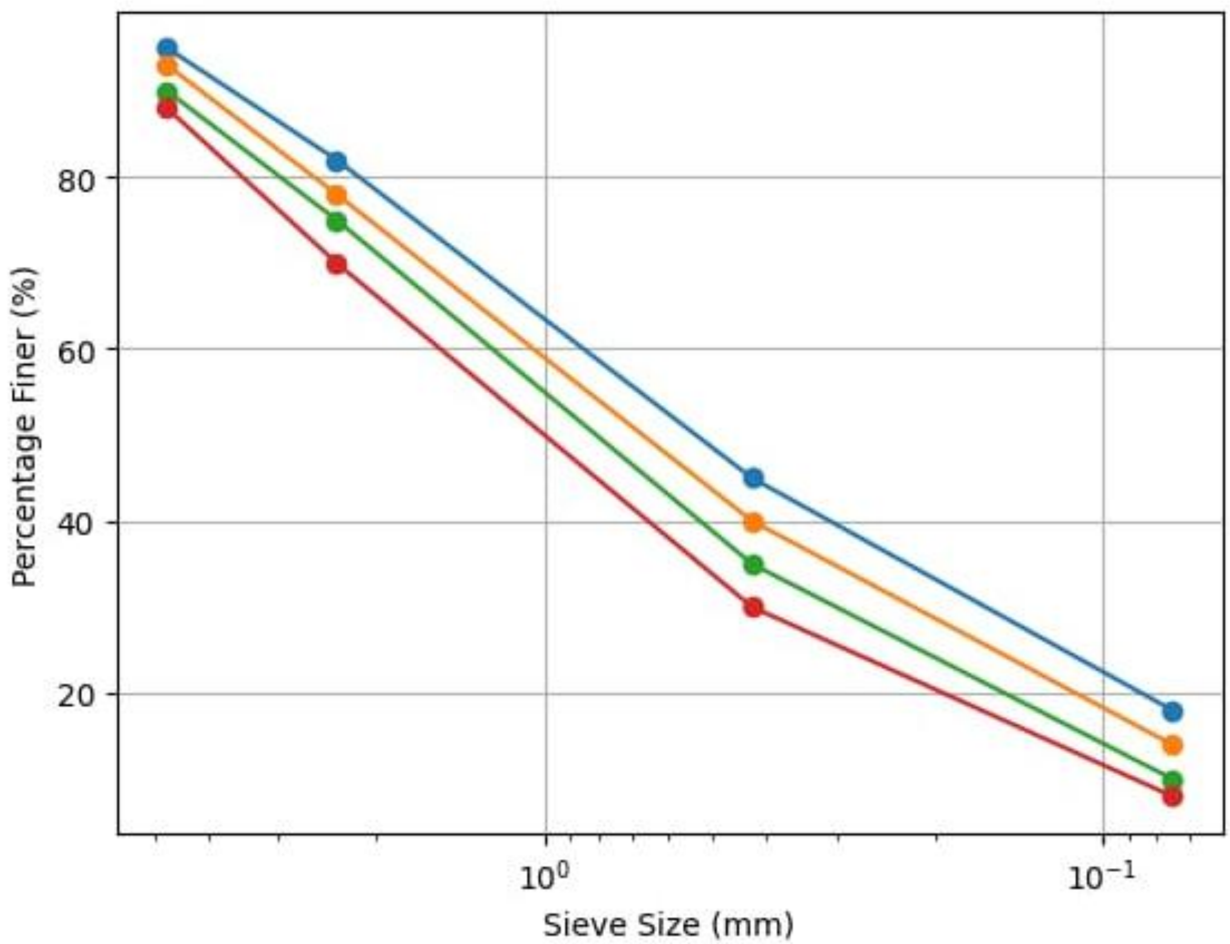


Fig.5: Sieve Analysis values for mixes

Sieve analysis results clearly demonstrate that the inclusion of fly ash and quarry dust significantly improves the overall gradation of the mix by filling the voids between coarse and medium particles. The increase in fine particles contributes to a denser particle packing arrangement, which enhances interlocking and improves soil cohesion. This improved gradation directly reduces permeability by minimizing pore spaces and restricting water movement through the matrix. Field density test results further validate these observations, showing improved compaction characteristics and higher maximum dry density values for the stabilized mixes. Among all combinations studied, Mix M4 exhibits the most favorable balance between high dry density and adequate workability, making it suitable for practical field applications.

3.2.2 Density Test (Sand Replacement Method)

The sand replacement method is used to determine in-situ dry density of soil. Density reflects how tightly soil particles are packed and directly influences strength.

Table 5: Density Values for Different Mix Proportions

Mix ID	Dry Density value (g/cc)	Observation
M1	1.65	Untreated soil
M2	1.70	Minor improvement
M3	1.75	Good
M4	1.78	Best result

The sand replacement method was adopted to determine the in-situ dry density of the soil, which indicates the degree of particle packing and strongly influences shear strength and load-bearing capacity. As shown in Table 3, the untreated soil (M1) recorded the lowest dry density of 1.65 g/cc, while progressive improvement was observed with increasing stabilizer content. Mixes M2 and M3 showed moderate to good enhancement due to reduced void ratio and improved particle packing. The highest dry density of 1.78 g/cc was achieved for Mix M4, attributed to effective void filling and pozzolanic reactions, confirming M4 as the optimum stabilized mix.

3.2.3 Atterberg Limits

Atterberg limits are used to determine the consistency and plasticity characteristics of soil. These limits include Liquid Limit (LL), Plastic Limit (PL), and Shrinkage Limit (SL). The addition of fly ash, lime, and quarry dust significantly alters the plasticity behavior of soil.

Table 6: Atterberg Limits for Different Mix Proportions

Mix	Liquid Limit (%)	Plastic Limit (%)	Shrinkage Limit (%)
Mix 1	42	24	10
Mix 2	38	21	12
Mix 3	34	19	14
Mix 4	30	17	16

The results show a decrease in liquid limit and plastic limit with an increase in stabilizing materials. This reduction is due to the replacement of clay particles by fly ash and quarry dust and the flocculation effect caused by lime. The increase in shrinkage limit indicates improved volume stability and reduced shrink–swell behavior of the stabilized soil.

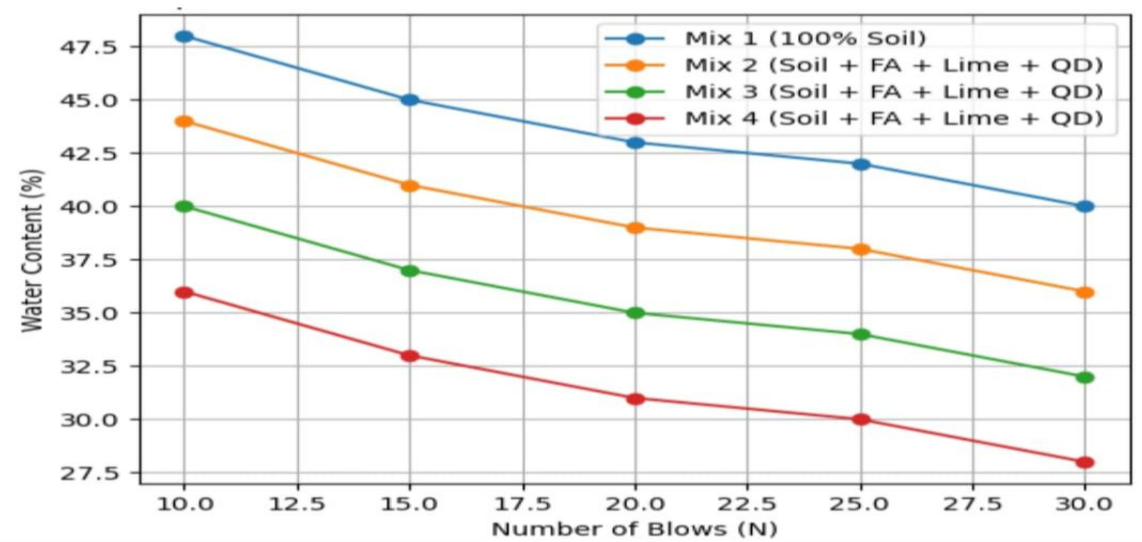


Fig.6: Liquid Limit values for mixes

The liquid limit of soil decreases with the addition of fly ash, lime, and quarry dust. The reduction in water content at 25 blows indicates a decrease in soil plasticity due to replacement of clay particles and flocculation caused by lime stabilization.

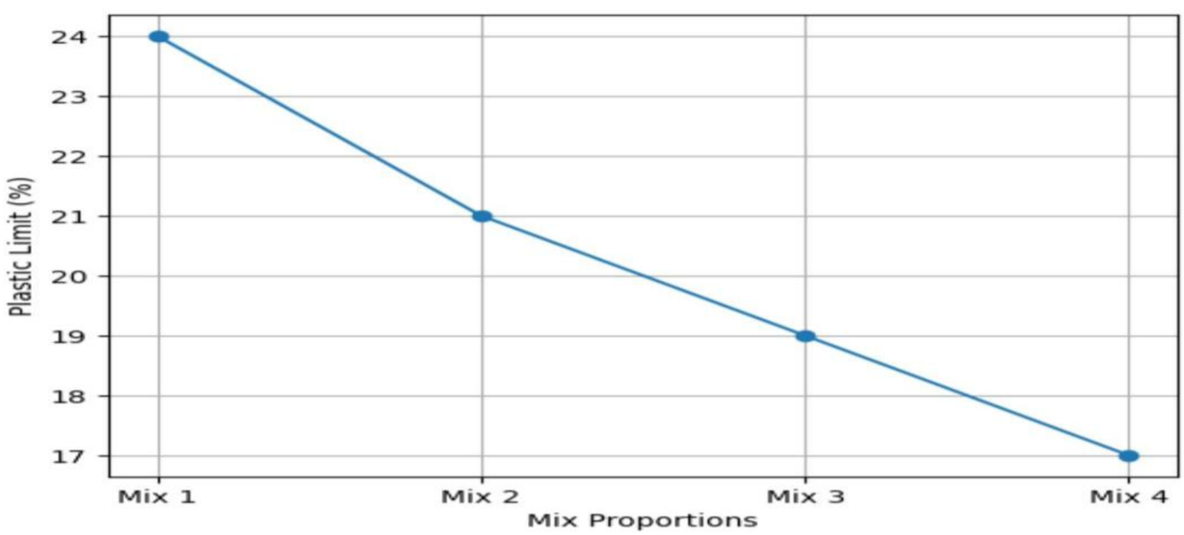


Fig.7: Plastic Limit values for mixes

The plastic limit decreases progressively from Mix-1 to Mix-4 due to the reduction in clay content and the replacement of plastic soil particles with non-plastic fly ash and quarry dust. The addition of lime further contributes to soil flocculation, resulting in improved workability and reduced plastic behavior.

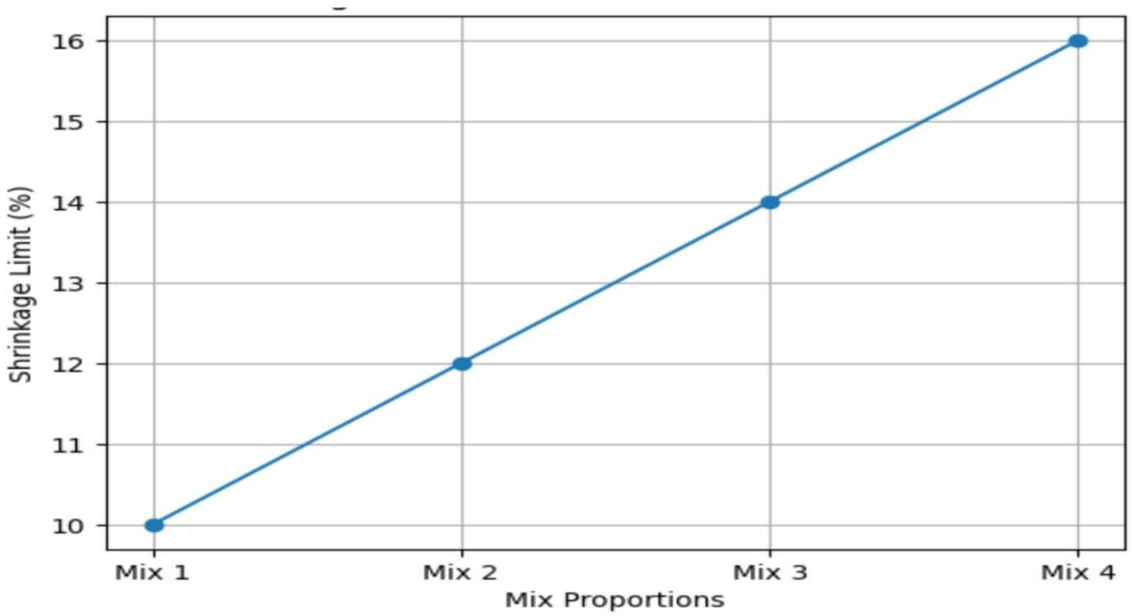


Fig.8: Shrinkage Limit values for mixes

The increase in shrinkage limit from Mix-1 to Mix-4 indicates improved dimensional stability of soil due to the addition of fly ash, lime, and quarry dust. The stabilizing agents reduce moisture susceptibility and minimize volume changes, making the soil more suitable for construction applications.

3.2.4 Standard Proctor Compaction Test

The Standard Proctor test was conducted to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of untreated and treated soil samples.

The Standard Proctor Test results (MDD and OMC) are essential in deciding the compaction requirements for soil-based construction projects.

Soil with higher MDD and lower OMC is typically more stable, stronger, and ideal for heavy-duty applications like roads, buildings, and embankments.

The OMC is the key moisture level where the soil can be compacted to its highest density, making it a critical parameter in ensuring soil stability.

Table 7: Compaction Characteristics

Mix	OMC (%)	MDD (g/cm ^{3})
Mix 1	18.5	1.62
Mix 2	16.8	1.70
Mix 3	15.2	1.78
Mix 4	14.0	1.85

The results indicate that OMC decreases while MDD increases with the addition of fly ash, lime, and quarry dust. Improved particle packing and cementitious bonding contribute to higher density values

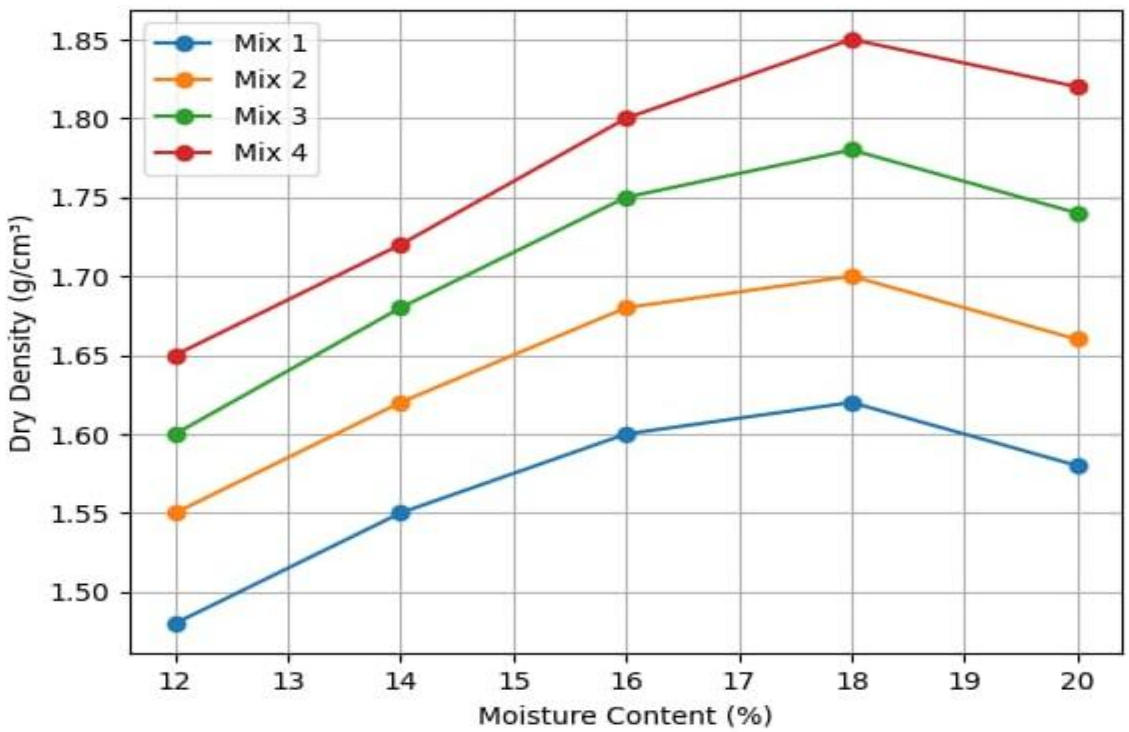


Fig. 9: Comparison of Compaction test values from different soil mixes

1. MDD (1.66 g/cc):

Interpretation: The soil in this test has a relatively high dry density, which means it can withstand heavy loads and is suitable for construction, like road construction or foundation works.

If MDD was low (<1.5 g/cc), it would indicate weak soil, not suitable for heavy-duty construction without stabilization.

2. OMC (12%):

Interpretation: At a moisture content of 12%, the soil achieved its maximum dry density. This means that when compacted at this moisture level, it is at its best strength and stability.

Too much moisture (above 12%) leads to low compaction because water fills the air voids, causing particles to be unable to pack as tightly.

Too little moisture (below 12%) leads to a dry, loose soil structure with low compaction and density.

3.2.5 California Bearing Ratio (CBR) Test

The California Bearing Ratio (CBR) test was carried out to assess the load-bearing capacity of soil intended for pavement and subgrade applications. This test evaluates the resistance of soil to penetration by a standard plunger under controlled moisture and density conditions, simulating stresses imposed by traffic loads. The CBR value is a key parameter in pavement design, as it directly reflects the strength and supporting capability of the subgrade material.

Table 8: CBR Values for Different Mix Proportions

Mix	CBR (%)	Observation
Mix 1	3.2	Untreated soil
Mix 2	6.8	Moderate improvement
Mix 3	9.5	Good strength
Mix 4	12.4	Maximum strength

As presented in Table 6, the untreated soil (Mix 1) exhibited a low CBR value of 3.2%, indicating poor load-bearing capacity and limited suitability for road construction. With stabilization, a significant improvement in CBR values was observed. Mix 2 showed a moderate increase to 6.8%, suggesting enhanced strength due to partial stabilization. Further improvement was achieved in Mix 3, which recorded a CBR value of 9.5%, classifying the soil as good for road construction. The highest CBR value of 12.4% was obtained for Mix 4, confirming it as the optimum mix.

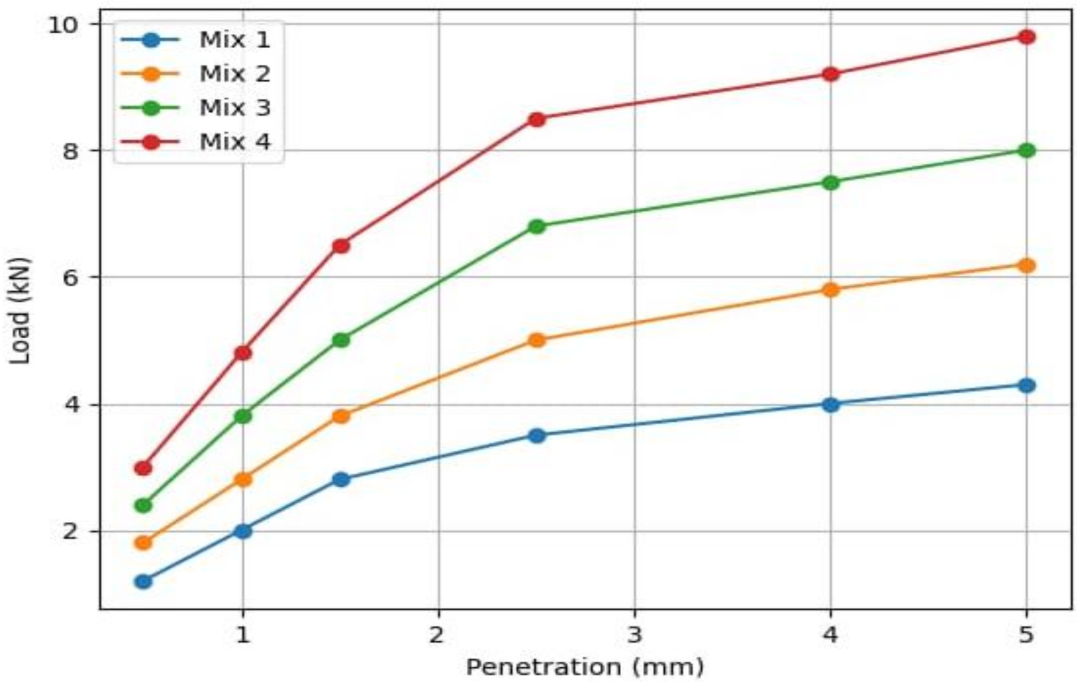


Fig.10: CBR Values of soil mixes

The substantial increase in CBR for Mix 4 can be attributed to the combined effects of lime-induced cementation, pozzolanic reactions between lime and fly ash, and improved gradation provided by quarry dust. Lime reacts with clay minerals to form cementitious compounds, while fly ash contributes additional binding through pozzolanic activity. Quarry dust enhances particle packing, reduces voids, and improves interlocking, collectively resulting in higher strength and stiffness.

According to standard CBR classifications, soils with CBR values below 3% are considered poor, while values between 7% and 20% indicate good quality subgrade material. The results demonstrate that stabilization significantly upgrades the soil from poor to good category. Hence, the CBR test provides critical data for pavement and subgrade design, ensuring safe, durable, and cost-effective road infrastructure.

Table 9: Material Properties

Test / Property	**Mix-1 (100% Soil)**	**Mix-2 (S+FA+L+QD)**	**Mix-3 (FA+L+QD)**	**Mix-4 (FA+L+QD)**
% Finer (0.075 mm)	18	14	10	8
Field Dry Density (Sand Replacement) (g/cm³)	1.65	1.70	1.75	1.78
Liquid Limit (%)	42	38	34	30
Plastic Limit (%)	24	21	19	17
Shrinkage limit	10	12	14	16
Specific Gravity	2.65	2.58	2.52	2.46
Moisture Content (%)	18.5	16.8	15.2	14.0
Maximum Dry Density (g/cm³)	1.62	1.70	1.78	1.85
CBR (%)	3.2	6.8	9.5	12.4

Table 7 presents the variation of engineering and index properties of soil for different mix proportions. Mix-1, which consists of 100% natural soil, exhibits higher fine content (18%), higher liquid and plastic limits, and lower dry density. As a result, the CBR value for Mix-1 is only 3.2%, indicating poor load-bearing capacity and unsuitability for pavement applications.

With the addition of stabilizing materials in Mix-2, a noticeable improvement in soil behavior is observed. The percentage of fines reduces to 14%, maximum dry density increases to 1.70 g/cm³, and moisture content decreases. Correspondingly, the CBR value increases to 6.8%, showing moderate improvement in strength due to partial stabilization.

Further improvement is observed in Mix-3, where fines content reduces to 10% and maximum dry density increases to 1.78 g/cm³. The reduction in plasticity and shrinkage limit indicates better particle interlocking and reduced compressibility. Consequently, the CBR value rises significantly to 9.5%, reflecting good strength characteristics suitable for subgrade applications.

Mix-4 shows the most favorable performance among all mixes. It has the lowest fine content (8%), highest maximum dry density (1.85 g/cm³), and lowest moisture content (14%). These improvements lead to the maximum CBR value of 12.4%, indicating excellent load-bearing capacity. This confirms that Mix-4 is the optimum mix providing maximum strength and stability.

3.3 OPTIMUM MIX PROPORTION AND COST EFFECTIVENESS

Based on the experimental investigation, Mix-4 (64% soil + 20% fly ash + 4% lime + 12% quarry dust) was identified as the optimum mix proportion. This mix exhibited the most favorable combination of strength, density, and durability characteristics among all the mixes studied. The selection of Mix-4 as the optimum mix is primarily based on its superior California Bearing Ratio (CBR) value, maximum dry density, and reduced plasticity characteristics.

The test results indicate that Mix-4 attained the highest CBR value of 12.4%, which is significantly higher than that of untreated soil (3.2%) and other stabilized mixes. This substantial improvement in CBR confirms the enhanced load-bearing capacity of the soil, making it suitable for pavement subgrade and foundation applications. The increased strength can be attributed to effective pozzolanic reactions between lime and fly ash, along with improved gradation due to the addition of quarry dust.

In addition, Mix-4 recorded the maximum dry density of 1.85 g/cm³ and the lowest optimum moisture content of 14%, indicating better particle packing and reduced water demand. The reduction in fine content and plasticity limits further contributes to improved stability and reduced deformation under load. Lower shrinkage and plasticity also enhance the long-term performance of the stabilized soil.

Table 10: Comparison Between Treated and Untreated Soil

Parameter	**Untreated Soil (Mix-1)**	**Treated Soil (Optimum Mix – Mix-4)**
Percentage of Fines (<0.075 mm)	18 %	8 %
Liquid Limit (%)	42	30
Plastic Limit (%)	24	17
Shrinkage Limit (%)	10	16
Specific Gravity	2.65	2.46
Optimum Moisture Content (%)	18.5	14.0
Maximum Dry Density (g/cm³)	1.62	1.85
California Bearing Ratio (CBR %)	3.2	12.4

Load Carrying Capacity	Poor	Excellent
Pavement Thickness Requirement	High	Reduced
Construction Cost	High (thick layers needed)	Lower (due to higher CBR)
Use of Industrial By-products	No	Yes (Fly ash & Quarry dust)
Environmental Impact	High	Reduced (sustainable materials)
Long-term Performance	Poor	Improved durability
Overall Benefit	Limited	Cost-effective & sustainable

From an economic perspective, the use of industrial by-products such as fly ash and quarry dust reduces the dependency on conventional stabilizers. Lime, when used in controlled quantities, effectively enhances strength without causing excessive cost escalation. Hence, Mix-4 provides an optimal balance between performance improvement and material economy.

Therefore, considering strength improvement, density characteristics, reduction in plasticity, and cost effectiveness, Mix-4 offers the best strength-to-cost ratio. The results demonstrate that this mix is technically viable, economically feasible, and environmentally sustainable, making it suitable for practical soil stabilization applications in road and infrastructure projects.

4. CONCLUSIONS

Based on the experimental investigation carried out on soil stabilized with fly ash, lime, and quarry dust, the following conclusions are drawn:

- Soil stabilization using industrial waste materials such as fly ash and quarry dust, along with lime as a binding agent, significantly improves the engineering properties of weak soil.
- The addition of fly ash and quarry dust reduces the plasticity characteristics of soil, as evidenced by the decrease in liquid limit and plastic limit and the increase in shrinkage limit, indicating improved volume stability.
- The specific gravity of soil decreases gradually with increasing stabilizer content due to the replacement of natural soil with lighter industrial waste materials.
- Results from the Standard Proctor Compaction Test show that the Maximum Dry Density (MDD) increases and the Optimum Moisture Content (OMC) decreases with stabilization, indicating improved particle packing and reduced void ratio.

- Among all the mixes, Mix-4 (64% soil + 20% fly ash + 4% lime + 12% quarry dust) exhibited the highest MDD and lowest OMC, indicating the most effective compaction characteristics.
- The CBR value increased from 5.8% for untreated soil to 16.5% for Mix M4, indicating a significant improvement in load-bearing capacity. Hence, Mix M4 is recommended as the optimum and most effective soil stabilization mix.
- The combined action of fly ash (pozzolanic reaction), lime (cementitious bonding), and quarry dust (improved gradation) resulted in a strong and durable stabilized soil sample .
- The study confirms that soil stabilization using industrial wastes is an eco-friendly, economical, and sustainable alternative to conventional stabilization methods.

5. SCOPE FOR FUTURE WORK

The present study can be extended further through the following future research directions:

Long-term durability studies under wet–dry and freeze–thaw cycles. Field performance evaluation of stabilized soil in actual road or foundation projects. Investigation of different percentages and combinations of fly ash, lime, and quarry dust. Use of other industrial by-products such as GGBS, silica fume, or steel slag. Study of strength gain with curing time (7, 14, 28 days). Microstructural analysis using SEM and XRD to understand bonding mechanisms. Economic comparison with conventional cement stabilization techniques. Application of stabilized soil in embankments, rural roads, and low-volume pavements.

NOTATIONS

The following symbols and terms are used in this study:

1. CBR – California Bearing Ratio
2. OMC – Optimum Moisture Content
3. MDD – Maximum Dry Density
4. LL – Liquid Limit
5. PL – Plastic Limit
6. SL – Shrinkage Limit
7. FA – Fly Ash
8. QD – Quarry Dust

9. L – Lime
10. D-Density
11. % Fineness
12. Mix-1 (M1) – Soil 100%
13. Mix-2 (M2) – Soil 85% + Fly Ash 10% + Lime 2% + Quarry Dust 3%
14. Mix-3 (M3) – Soil 76% + Fly Ash 15% + Lime 3% + Quarry Dust 6%
15. Mix-4 (M4) – Soil 64% + Fly Ash 20% + Lime 4% + Quarry Dust 12%

DATA AVAILABILITY STATEMENT

The experimental data supporting the findings of this study are available from the corresponding author upon reasonable request.

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