# Performance Evaluation of Hybrid Natural Fiber Stabilization in Subgrade Soil

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***Abstract*—Weak subgrade soil reduces pavement stability and load-bearing capacity. This study evaluates hybrid stabilization using NaOH-treated bamboo fibers and quarry dust to improve soil properties. The treated fibers enhance bonding with soil, while quarry dust increases density and strength. Test results show improved CBR value, reduced plasticity, and better durability, promoting a sustainable and eco-friendly stabilization method.**

***Index Terms*—Hybrid Stabilization; Subgrade Soil; Bamboo Fiber; NaOH Treatment; Quarry Dust; CBR Improvement; Soil Strength; Sustainable Pavement; Eco-friendly Stabilization.**

## I. INTRODUCTION

Weak clayey subgrade soil is a major cause of distress and premature failure in rural roads due to its high plasticity, low bearing capacity, and significant swelling and shrinkage behaviour under moisture variations. Improving such soils using conventional stabilizers like cement or lime increases cost and carbon emissions, making sustainable alternatives essential for low-volume rural road construction. This study investigates the performance of clay soil stabilized with bamboo fibre and quarry dust as an eco-friendly and economical solution. Bamboo fibre acts as a natural reinforcement material that enhances tensile strength, controls crack propagation, and improves ductility, while quarry dust, an industrial by-product, improves soil gradation, reduces plasticity, and enhances compaction by filling voids between soil particles. The combined effect is expected to improve strength characteristics, compaction properties, and California Bearing Ratio (CBR) values, thereby enhancing subgrade performance. Through laboratory evaluation of engineering properties, this project aims to demonstrate that bamboo fiber and quarry dust stabilization is a sustainable, cost-effective, and locally available technique for long-lasting rural road infrastructure development.

## II. LITERATURE REVIEW

A study published in the IOSR Journal of Mechanical and Civil Engineering by H. Venkateswarlu, D. S. V. Prasad, and G. V. R. Prasada Raju (2018) investigated the stabilization of expansive soil using quarry dust. Different percentages of quarry dust were mixed with clay soil to study its effect on engineering properties. Laboratory tests such as compaction, CBR, and shear strength were conducted. The results showed that the addition of quarry dust improved soil strength and reduced swelling characteristics. The study concluded that quarry dust is an effective and economical stabilizing material for weak subgrade soil.

A research study by Adwiyah Asyifa and Syafi'ul Umam (2020) examined the effect of quarry dust on subgrade soil stabilization. Quarry dust was added in varying proportions such as 5%, 10%, 15%, and 20%. Laboratory tests including compaction and California Bearing Ratio (CBR) were carried out to evaluate soil performance. The results indicated that the addition of quarry dust increased soil density and improved CBR values. The study concluded that quarry dust enhances the load-bearing capacity of pavement subgrade soil.

A study by A. K. Mishra and R. K. Yadav (2021) investigated the use of bamboo fibre for subgrade soil stabilization. Different percentages of bamboo fibres were mixed with clayey soil to evaluate improvements in engineering properties. Laboratory tests such as compaction and California Bearing Ratio (CBR) were conducted. The results showed that bamboo fibre addition increased soil strength and reduced deformation. The study concluded that bamboo fibre is an effective and sustainable reinforcement material for weak subgrade soil.

A study by Sahil Patil, Zaid Shaikh, Duhit Patil, and Karan Pujari (2023) examined the stabilization of subgrade soil using bamboo fibre as a natural reinforcement material. The research focused on improving the strength and durability of weak subgrade soil used in pavement construction. Laboratory tests such as Atterberg limits, compaction test, and California Bearing Ratio (CBR) were conducted. Results showed that the inclusion of bamboo fibre significantly increased the CBR value and shear strength of the soil. The study concluded that bamboo fibre is an eco-friendly and cost-effective material for subgrade soil stabilization.

This project focuses on the stabilization of weak subgrade soil using quarry dust and bamboo fibre as reinforcing materials. The objective is to improve the engineering properties of subgrade soil, such as strength, compaction, and load-bearing capacity. Bamboo fibre is used as a natural reinforcement material, while quarry dust acts as a granular stabilizer to enhance soil density and shear strength. Laboratory tests such as compaction and CBR tests are conducted to evaluate the performance of the stabilized soil. The study aims to develop an eco-friendly, economical, and sustainable method for improving pavement subgrade using natural fibres and industrial by-products.

## III. MATERIALS USED IN THE STUDY

### 3.1. Geotechnical Properties of Subgrade Soil.

Evaluation of subgrade soil properties is necessary to ensure proper pavement performance. These properties include parameters such as grain size distribution, Atterberg limits, moisture content, and compaction characteristics. They influence the load-bearing capacity and stability of the pavement foundation. Weak subgrade soil often leads to excessive settlement and reduced pavement life. Therefore, evaluating these properties is essential before applying any stabilization technique.

### 3.2. Bamboo Fiber as Natural Reinforcement.

Bamboo fiber is a natural and biodegradable material widely used as reinforcement in soil stabilization. It possesses good tensile strength and flexibility, which helps improve the mechanical behavior of soil. When mixed with soil, bamboo fiber enhances shear strength and reduce the chances of cracking and deformation. They also help in distributing applied loads more effectively within the soil matrix. Due to its eco-friendly and sustainable nature, bamboo fiber is considered a suitable reinforcement material in geotechnical applications.

### 3.3. Alkali Treatment of Bamboo Fiber

Alkali treatment of bamboo fiber is performed using sodium hydroxide (NaOH) solution to enhance its surface characteristics. The treatment removes impurities such as lignin, hemicellulose, and oils from the fiber surface. This process increases surface roughness and improves the bonding between bamboo fibers and soil particles. As a result, the interaction between fiber and soil becomes stronger. This leads to improved strength and durability of the stabilized soil.

### 3.4. Quarry Dust as a Stabilizing Material.

Quarry dust is a by-product obtained during the crushing of rocks in quarries. It is widely used as a stabilizing material in soil improvement due to its granular nature. When mixed with soil, quarry dust improves density, compaction, and shear strength. It also reduces plasticity and enhances the load-bearing capacity of the subgrade. Therefore, quarry dust is considered an economical and effective material for soil stabilization.

## IV. MIX DESIGN

The mix design ratio for the stabilization of subgrade soil using quarry dust and bamboo fibre was prepared by adding suitable proportions of quarry dust and treated bamboo fibres to the natural soil. Quarry dust was used as a partial replacement material to improve the strength and gradation of the soil, while bamboo fibres were added as reinforcement to enhance the tensile strength and reduce cracking. The bamboo fibres used in the mix were generally of length 20–30 mm and uniformly distributed within the soil–quarry dust mixture. Based on experimental trials, the optimum water content for the mix was maintained at 16% to achieve proper compaction and workability during sample preparation. The materials were thoroughly mixed in dry condition first, followed by the gradual addition of water to reach the required moisture content. This mix design helps improve the load-bearing capacity, durability.

4.1. Materials.
1. Clay soil (rural area)
2. Quarry dust
3. NaOH treated bamboo fiber (L = 30mm)
4. 16% of water content (standard)

4.2. Tabulation for mix ratio (S: Q: B).

Table 1

| Sample.no | Clay soil (S) | Quarry dust (Q) | Bamboo fiber (B) |
|---|---|---|---|
| Soil | 5000 kg | - | - |
| S1 | 4500 kg | 10% | 0.25% |
| S2 | 4750 kg | 15% | 0.5% |
| S3 | 4000 kg | 20% | 0.75% |
| S4 | 3750 kg | 25% | 1% |

## V. ANALYSIS AND APPROACH

5.1. CBR – Test.
The California Bearing Ratio (CBR) test is conducted to evaluate the strength and load-bearing capacity of the stabilized soil mixture containing quarry dust and bamboo fiber. In this study, the prepared soil mix with the selected proportions of quarry dust and bamboo fiber was compacted at an optimum moisture content of 16% in a standard CBR mould. The specimen was then soaked or unsoaked depending on the testing requirement and tested in a CBR testing machine by allowing a plunger to penetrate the sample at a constant rate. The resistance offered by the soil mixture against penetration was recorded and compared with the standard value to determine the CBR value. The addition of quarry dust improves the density and strength of the soil, while bamboo fibers enhance reinforcement and resistance to deformation, resulting in an increased CBR value compared to natural soil. This indicates improved load-carrying capacity of the stabilized subgrade soil for pavement applications.

5.2. Procedure.
1. Material Preparation
Clay soil was first collected, air-dried, and pulverized to remove lumps and impurities. Quarry dust was then added to the soil in the required proportion to improve the strength and gradation of the soil. Alkali-treated bamboo fibres of 30 mm length were prepared and checked for uniform size before mixing. All the materials were kept in dry condition before the mixing process.

2. Mixing of Materials
The clay soil and quarry dust were first mixed thoroughly in dry condition to obtain a uniform blend. After that, the alkaline treated bamboo fibres (30 mm) were gradually added and mixed evenly to avoid fibre clustering. Water was then slowly added to the mixture until the optimum moisture content of 16% was achieved. The entire mixture was properly blended to ensure uniform distribution of soil.

Fig.1

3. Compaction of Sample in CBR Mould
The prepared mixture was placed in a standard CBR mould in three equal layers. Each layer was compacted using a standard rammer to achieve the required density. After compaction, the top surface was levelled carefully. A filter paper and perforated plate were placed on the top surface of the specimen.

Fig.2

4. Soaking of Specimen
The mould containing the compacted specimen was placed in water for 96 hours (4 days) for soaking. This soaking process simulates field conditions where

subgrade soil may be exposed to water. During this period, the specimen absorbs water and reaches a saturated condition.

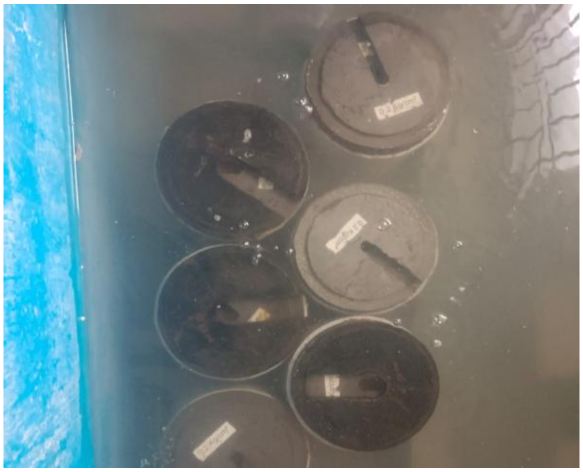


Fig.3

5. CBR Testing

After the soaking period, the mould was removed from the water and allowed to drain. The specimen was then placed in the CBR testing machine. A standard plunger was made to penetrate the soil at a constant rate of 1.25 mm per minute, and the load values corresponding to different penetration depths were recorded.

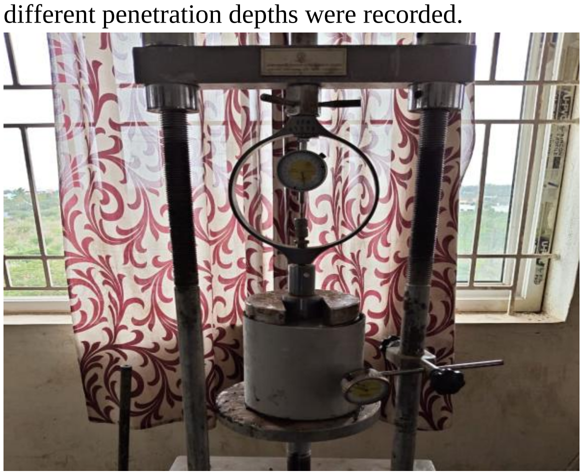


Fig.4

6. Determination of CBR Value

Finally, the recorded load values were compared with standard load values to calculate the CBR value. The obtained CBR value indicates the load-bearing capacity of the stabilized soil mixture containing clay soil, quarry dust, and alkaline treated bamboo fibres.

Table: 2 Tabulation for Soil & S1.

| Penetration(mm) | Soil (Load=KN) | S1 (Load=KN) |
|---|---|---|
| 0 | 0 | 0 |
| 0.5 | 0.15 | 0.17 |
| 1 | 0.21 | 0.26 |
| 1.5 | 0.23 | 0.34 |
| 2 | 0.25 | 0.36 |
| 2.5 | 0.26 | 0.42 |
| 3 | 0.27 | 0.54 |
| 4 | 0.315 | 0.68 |
| 5 | 0.33 | 1.05 |
| 7.5 | 0.36 | 1.17 |
| 10 | 0.362 | 1.29 |
| 12.5 | 0.37 | 1.32 |

Table: 3 Tabulation for S2 & S3.

| Penetration(mm) | S2(Load=KN) | S3 (Load=KN) |
|---|---|---|
| 0 | 0 | 0 |
| 0.5 | 0.18 | 0.15 |
| 1 | 0.28 | 0.23 |
| 1.5 | 0.36 | 0.30 |
| 2 | 0.45 | 0.37 |
| 2.5 | 0.53 | 0.44 |
| 3 | 0.63 | 0.52 |
| 4 | 0.785 | 0.65 |
| 5 | 1.20 | 0.78 |
| 7.5 | 1.28 | 0.98 |
| 10 | 1.43 | 1.00 |
| 12.5 | 1.61 | 1.30 |

Table: 4 Tabulation for S4.

| Penetration(mm) | S4(Load=KN) |
|---|---|
| 0 | 0 |
| 0.5 | 0.13 |
| 1 | 0.20 |
| 1.5 | 0.26 |
| 2 | 0.32 |
| 2.5 | 0.38 |
| 3 | 0.45 |
| 4 | 0.57 |
| 5 | 0.69 |
| 7.5 | 0.87 |
| 10 | 1.03 |
| 12.5 | 1.15 |

5.3. Calculation.

- ✓ 1370 kg at 2.5 mm penetration
- ✓ 2055 kg at 5 mm penetration
- ✓

CBR (%) $= \frac{Test\ Load}{Standard\ Load} \times 100$

Sample (Soil)

For 2.5mm

$0.26 = 26\text{kg}$

$\frac{26}{1370} \times 100 = 1.90\%$

For 5mm

$0.33 = 33\text{kg}$

$\frac{33}{2055} \times 100 = 1.60\%$

Sample 2, (S2

For 2.5mm

$0.53 = 53\text{kg}$

$\frac{53}{1370} \times 100 = 3.87\%$

For 5mm

$1.20 = 120\text{kg}$

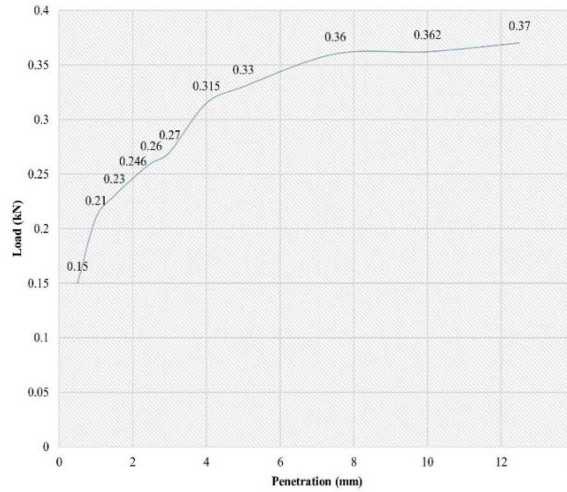
$\frac{120}{2055} \times 100 = 5.8\%$

The results of the California Bearing Ratio (CBR) Test indicate that soil stabilized with bamboo fibre and quarry dust (4250:15%:0.5%) Sample-3 performs better than normal untreated soil. The addition of bamboo fibre improves the reinforcing capacity of the soil, while quarry dust enhances particle interlocking and reduces voids. As a result, the stabilized soil shows a higher CBR value, greater strength, and better load-bearing capacity compared to natural soil.

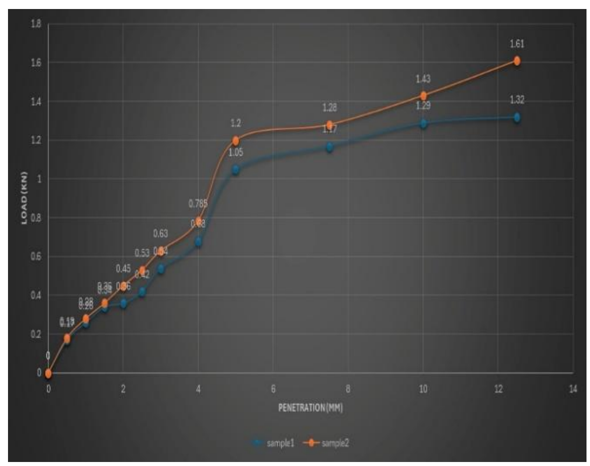
## VI. RESULT AND DISCUSSION

### 6.1. CBR – Load Vs Penetration

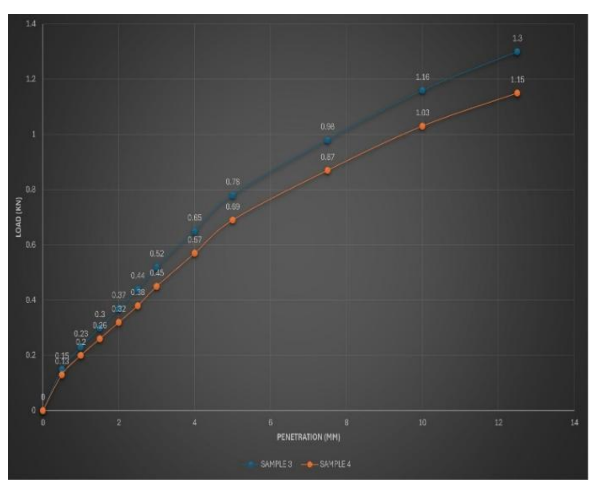
The California Bearing Ratio (CBR) test results clearly distinguish the structural performance between the two analyzed materials. Sample 3 (Green) exhibits a high-strength profile, characterized by a steep load-penetration curve. At the critical 2.5 mm mark, it sustains a load of 54.01 kg, which more than doubles to 122.37 kg at 5.0 mm. This aggressive increase in resistance suggests a well-graded, granular material with excellent interlocking properties, making it an ideal candidate for base or sub-base layers in heavy-duty pavement construction.



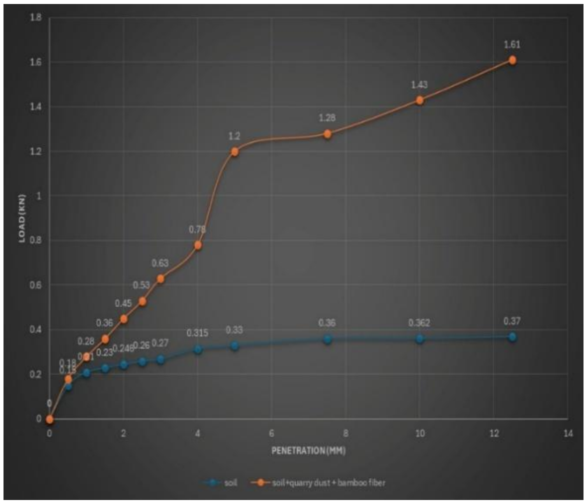

Graph: 1 Soil sample




Graph: 2 Sample S1 & S2




Graph: 3 Sample S3 & S4




Graph: 4 Soil sample & S2

In contrast, Sample 1 (Red) displays a significantly weaker load-bearing capacity and a flatter deformation curve. Its resistance at 2.5 mm is only 26.51 kg, and it fails to gain substantial strength as penetration increases, reaching only 33.65 kg at 5.0 mm. This behavior is typical of fine-grained plastic soils, such as silts or clays, which offer low stability under traffic loads. From an engineering standpoint, using Sample 1 as a subgrade would necessitate a much thicker pavement crust or chemical stabilization to prevent premature road failure.
Ultimately, these results dictate the economic and structural design of the project. Sample 3 is the superior engineering choice, as its high CBR value allows for a reduction in the total thickness of the upper pavement layers, directly lowering material costs. Sample 1, while potentially usable, represents a "weak link" that would require more expensive design interventions. For long-term durability and resistance to rutting and shearing, Sample 3 provides the necessary structural integrity required for sustainable infrastructure.

## VII. CONCLUSION

The performance evaluation of hybrid natural fiber stabilization demonstrates that the synergistic combination of different organic fibers, such as coir and jute, creates a superior reinforcement matrix within subgrade soil compared to single-fiber applications. By intertwining within the soil voids, these fibers act as a secondary tensile network that effectively bridges potential shear planes and restricts lateral particle displacement, leading to a marked increase in California Bearing Ratio (CBR) values and overall shear strength. This hybridization not only enhances the load-bearing capacity and ductility of weak subgrades—thereby reducing the required thickness of overlying pavement layers—but also provides an eco-friendly, cost-effective alternative to traditional chemical stabilizers, successfully transforming marginal soils into stable, sustainable foundations for infrastructure.

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CONFLICTS OF INTEREST
The authors declare that there is no conflict of interest.

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