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Experimental Studies on Fiber Reinforced Soil Stabilized with Lime and Fly Ash

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Abstract

This study investigates the enhancement in strength of fiber-reinforced soil stabilized with lime and fly ash, focusing on key parameters essential for highway design and construction i.e., California Bearing Ratio (CBR) and compaction characteristics. Laboratory tests were conducted to determine the CBR values, Maximum Dry Density (MDD), and Optimum Moisture Content (OMC) of soil stabilized with varying percentages of fly ash (FA) and lime, and reinforced with different types and percentages of fibers, specifically coir fibers (CF) and polypropylene fibers (PF). The addition of stabilizing agents (fly ash and lime) to the fiber-reinforced soil was found to increase the OMC and decrease the MDD. Notably, a significant increase in the CBR value was observed up to an optimum content of these admixtures. However, adding fibers beyond a certain percentage resulted in the sample breaking. This study is novel in its comprehensive evaluation of both natural (coir) and synthetic (polypropylene) fibers in combination with traditional stabilizers (fly ash and lime), offering insights into the optimal mix for enhancing soil strength. The findings contribute to more efficient and durable highway construction practices by identifying the balance between fiber reinforcement and chemical stabilization.

1. Introduction

The soil is the cheapest available materials utilized for various construction-related purposes. It has negligible tensile strength, and its characteristics may depend strongly on variability in composition and environmental conditions. Despite the widespread availability of local soils near a construction site, its effective use is often limited for critical applications like the construction of embankments and pavements. Various challenges arise in its application, including instability, insufficient bearing capacity, and excessive permeability, which pose obstacles to its successful incorporation as a construction material. Therefore, enhancement of soil properties through the incorporation of additives has been a subject of considerable research interest in the field of geotechnical engineering.

Fly ash, a by-product of thermal power plants, is utilized only in small percentage, with the remainder is piled up, posing major environmental risks. Considering its inexpensive cost and abandoned availability, more research is required to determine whether it can be used in a resilient and sustainable way. In this context, this study aims to explore the improvement of engineering properties of fiber reinforced soil by stabilizing it with fly ash and lime. Through this exploration, we can contribute to sustainable and resilient solutions for using locally available soils for pavement construction, ultimately helping to increase the strength and durability of pavement subgrade soil.

Numerous researchers have investigated the factors contributing to the failure of pavement subgrade layers, including moisture levels and subgrade soil compositions. Armstrong and Zornber [1] focused on moisture fluctuations in expansive clay subgrades of roadways, revealing that water infiltration can lead to significant issues such as pavement settlement and longitudinal cracking in flexible pavements and expansive subgrades. Trzebiatowski et al. [2] reported that subgrades rich in fine particles can aggravate problems, necessitating costly replacement with higher-strength soils for improved road performance. Consequently, enhancing ground conditions to ensure economical pavement performance involves effectively altering subgrade soil properties [3], [4]. One such approach to improving ground conditions is through the stabilization of in-situ soil using waste materials that contain pozzolanic substances. One example of such waste material used as a base additive is fly ash [5], which is usually mixed with other stabilizing agents like lime and cement. Phummiphan et al. [6] utilized high calcium FA-based geopolymers for the stabilization of marginal lateritic soils and investigated the influence of different alkali activators and varying curing times on the unconfined compressive strength (UCS) and the microstructural characteristics of the treated soil. Arora and Aydilek [7] investigated the suitability of Class F fly ash in combination with soil–cement or soil–lime for highway base layers. They utilized the results from UCS, CBR, and resilient modulus tests to determine the necessary base layer thickness for different traffic loads and conditions. Kumar et al. [8] explored the combined effects of polyester fiber inclusions and lime stabilization to enhance the mechanical properties of expansive soils.

Majumder et al. [9] conducted a study on cement-treated aggregates that are abundantly available in Eastern India. The study reported that use of cement as a stabilizing material can transform the locally available pit run and laterite aggregates into cost-efficient construction materials for roads with low traffic volume. Trzebiatowski et al. [2] described a case history on use of fly ash for the stabilization of a sandy clay highway subgrade. Both laboratory and field tests were performed to assess the strength and stiffness of the stabilized soil, and the method was reported to be effective. Patil and Patil [10] also studied the various geotechnical properties of clayey soil and grade III materials stabilized with pond ash and RBI Grade 81. The study reported a significant improvement in the CBR values of the treated soil. Wahhab and Asi [11] reported an improvement in shear strength and decrease in the damage due to water permeability after treating marl and dune sand with lime and cement. Babu et al. [12] investigated the effect of randomly including coir fibers on the strength, swelling and compressibility characteristics of black cotton soil. Swami and Arun [13] observed that second-class locally available materials can enhance the strength of lower pavement layers through appropriate stabilization techniques. ash et al. [14] reported that Class F fly ash can be used in the stabilization process, when combined with another activator, such as lime or cement. They investigated the effect of fly ash on the compaction of fine sand and its suitability as a material for embankments, using cement as the activator. Peethamparan and Olek [15], Salahudeen et al. [16], and Amadi and Osu [17] studied and observed that the strength characteristics of stabilized soils are time-dependent, with potential for strength to increase over time due to saturation or pozzolanic reactions. Mishra and Gupta [18] studied the effect of recycled polyethylene terephthalate (PET) fibers in combination with the fly ash on the engineering properties of clayey subgrade soil. The study reported improvement in shear strength, CBR value, and a decrease in the plasticity index of the stabilized soil. Li et al. [19] investigated the potential of greywacke marginal aggregates as road construction material by treating them with lime and cement. The study reported that cement stabilization was more effective than lime stabilization in improving the permanent strain behavior of the marginal aggregate.

The literature study reveals that utilization of soil stabilization techniques plays a significant role in improving subgrade soil. These techniques involve modifying subgrade soil properties through various methods, such as adding chemicals and mechanical reinforcement, to achieve desired engineering properties. Therefore, this study is focuses on using fly ash as a primary additive, supplemented with lime and fiber as secondary additives to stabilize subgrade soils. The objective is to enhance the strength, durability, and stability of subgrade soils, thereby reducing maintenance costs and extending the life of pavements.

2. Materials Used

2.1 Soil

The present study is conducted on two types of soil: clayey soil and red soil (laterite soil). Red soil, or laterite soil, appears in various colors across India, depending on the landscape of the region. It derives its name from its distinctive red color, which is due to the high iron oxide content present in the soil. Red soil contains very little lime, magnesium, and humus, and its pH varies from acidic to neutral. Red soil originates from the weathering of metamorphic and crystalline rocks over several decades. It can also form from quartz rocks and acid granite. Red soil is somewhat rich in aluminum and silica and can be found with various compositions of clay, silt, and sand, with many of these soils being loamy in nature. Additionally, red soil has varying specific gravities. The red soil used in this study was collected from the foothill of Kharsingsa in the Papum Pare district of Arunachal Pradesh, an area that has experienced many landslides in the past.

Clayey soils are widespread in many parts of India. These soils can cause damage to foundations, buildings, roads, and other geotechnical infrastructure due to their low strength, high compressibility, and significant volumetric changes. Clayey soil has a vast range of geochemical compositions. In addition to clay particles, it contains varying proportions of silt, sand, and organic matter. The clay minerals present in clayey soil include kaolinite, montmorillonite, and illite, among others. These minerals contribute to the cohesive and plastic properties of clayey soil. Clayey soil exhibits significant shrink-swell behavior in response to changes in moisture content. When wet, it expands and swells, exerting pressure on surrounding structures. Conversely, when dry, it contracts and shrinks, potentially causing soil cracking and settlement. Clayey soil has relatively low bearing capacity and shear strength, particularly when saturated with water. It is prone to deformation and instability under heavy loads, making it unsuitable for supporting large structures without proper stabilization. The clayey soil for the present study was collected from the foothill of Banderdewa, located at the border of Arunachal Pradesh and Assam, two neighbouring states of North-East India.

The basic properties of these two types of soils used in the study are presented in Table 1. The clayey soil (S1) used in the study is classified as inorganic clays of low to medium plasticity (CL) and the red soil (S2) is classified as inorganic silts and clayey silts (ML).

Table 1 *Physical properties of soil*

Properties	Clayey soil (S1)	Red soil (S2)
Specific Gravity	2.65	2.42
Plastic limit (%)	48	18.15
Liquid limit (%)	26	22.5
MDD (gm/cc)	15.81	1.8
OMC (%)	19.7	15.47
Soil classification	CL	ML
Unsoaked CBR (%)	10.62	13.06
Soaked CBR (%)	4.53	5.68

2.2 Fly Ash

In this study, class F fly ash (FA) is used as the base additive. The fly ash used in the study was collected from the National Thermal Power Corporation (NTPC) Limited, located in Assam, India. According to the Unified Soil Classification System (USCS), fly ash is classified as non-plastic fine silt, which can be used as a primary binder material. Kumar et al. [8] conducted experiments to investigate the physical properties of fly ash, which are shown in Table 2.

Table 2 *Physical properties of fly ash [8]*

Property	Value
Class	Class F or low lime fly ash
Specific Gravity	2.14
Liquid Limit (%)	43
Plastic Limit (%)	Non-plastic
OMC (%)	34
MDD (gr/cm^3)	1.1

Karami et al. [20] conducted a study to investigate the chemical composition of Class F fly ash using X-ray fluorescence spectroscopy, with the results described in Table 3. It is observed from Table 3 that the primary constituents of fly ash are aluminum dioxide (alumina), silicon dioxide (silica), and iron oxide. Various investigators have reported that fly ash is very effective for soil stabilization due to its pozzolanic characteristics. It can help stabilize soil in two different ways: (i) by filling up the voids between soil particles, and (ii) by acting like fine aggregates when mixed with cementitious materials such as lime and cement. In particular, fly ash reacts with soil particles and moisture, causing the mixture to act as a cementitious material.

Table 3 *Chemical composition of fly ash [20]*

Ingredient/ Parameter	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	CaO	MgO	P_2O_5	SO_3	K_2O	Na_2O	Loss due to ignition
Content by Weight (%)	41.53	27.51	10.38	1.9	0.16	14.52	0.99	0.5	0.57	0.71	0.96	0.27

2.3 Lime

Hydrated lime or slaked lime used in this study is a concentrated form of lime, which can be used as a secondary additive. Slaked lime (Calcium Hydroxide) is an inorganic compound that can be expressed by the chemical formula Ca $(OH)_2$. It is a white powder or colorless crystal and is produced when quicklime (CaO) is allowed to react with water described in Equation (1). Slaked lime has many common names like hydrated lime, caustic lime, builder's lime etc. Slaked lime was manufactured and supplied by a local supplier located in Assam, India. The physical and chemical properties of slaked lime from Kumar et al. [8] are described in Table 4 and Table 5.

$$\underset{\text{(Quick Lime)}}{CaO} + H_2O \rightarrow \underset{\text{(Slaked Lime)}}{Ca(OH)_2} \tag{1}$$

Table 4 *Physical properties of hydrated lime [8]*

Properties	Value
Specific gravity	2.05
Density (kg/m^3)	510
Normal consistency (%)	43.5
Initial setting time (min)	165
Final setting time (h)	46.25
Fineness (percentage by weight on 300 µm sieve)	2.65
Soundness (Le Chatelier's expansion ((mm))	1.8
Compressive strength (14 days) (N/mm^2)	1.45
Compressive strength (28 days) (N/mm^2)	2.18

Table 5 *Chemical composition of hydrated lime [8]*

Properties	Ca $(OH)_2$	Cl^-	SiO_2	Al_2O_3 / FeO	Water	As	Pb	SO_3	MgO
Value (%)	82	0.01	2.5	3.5	0.6	0.0004	0.0001	0.9	3.5

2.4 Fly Ash and Lime Mixture

When fly ash and lime are mixed with soil, the plastic limit (PL) increases and the liquid limit (LL) decreases, thereby decreasing the plasticity index (PI) of the mixture. This also improves the workability of the soil mixture. Moreover, the pozzolanic reaction between fly ash and lime materials in the soil results in the formation of cementitious compounds, which strengthen the soil matrix. This leads to improved load-bearing capacity and resistance to deformation under traffic load. In the present study, fly ash is used as the primary stabilizer, and slaked lime is used as the secondary stabilizer. The mixed proportions of fly ash and slaked lime used in the study are 20%, 35%, and 50%, and 2%, 3.5%, and 5%, respectively, by weight of the soil sample.

2.5 Fibers

The third set of secondary additives or stabilizers used in this study are fibers. Two types of fibers are used, namely: Natural (coir fibers) and Synthetic or Artificial fibers (polypropylene fibers). The length of fibers used in this study is kept as 2 cm. The fiber contents used in this study are 0.3%, 0.6% and 0.9% for all the fibers.

2.5.1 Natural Fibers

There are many natural fibers used for soil stabilization, and in this study, coir fibers (CF) are used. Natural fibers are environmentally friendly and biodegradable. However, cementitious materials such as lime are used as a secondary additive, which helps the natural fibers resist contact with water, thereby preventing them from decomposing easily.

Since coconut belongs to the palm family, it grows widely in India, which encounters both subtropical and tropical climates. Coconut or coir fibers have a low specific gravity of about 0.87 g/cm^3 [21]. Coir fibers are very strong, possessing the highest tear strength among all natural fibers. Moreover, they maintain high tear strength even in wet conditions. Hence, in this study, coir fibers are chosen as a stabilizing material. Other important physical properties are provided in Table 6.

Table 6 *Physical properties of coir fibers [21]*

Parameter	Value
Diameter (mm)	0.1-0.5
Density (g/cm^3)	1.3-1.4
Breaking tensile strength (MPa)	500-700
Young's modulus (GPa)	2-8
Tensile strength (MPa/g.cm^{-3})	55-125

2.5.2 Synthetic or Artificial fibers

There are many synthetic or artificial fibers used for soil stabilization, and in this study, polypropylene fibers (PF) are used. The specific gravity of polypropylene fibers is 0.9-0.91 g/cm^3, giving them the largest volume for a given weight. The high yield indicates that polypropylene fibers provide good volume and are widespread due to their light weight. The size of the polypropylene fibers used in this study is 2 cm. The melting point of polypropylene fiber is 165°C. Other important physical properties of polypropylene fibers are listed in Table 7.

Table 7 *Physical properties of polypropylene fiber [22]*

Parameter	Value
Diameter (mm)	0.01-0.015
Density (g/cm3)	0.9-0.91
Breaking tensile strength (MPa)	525
Young's modulus (GPa)	36-40
Tensile strength (MPa/g.cm^{-3})	50-600

3. Research Methodology

This paper aims to conduct an experimental study on the behavior of fly ash-stabilized clayey soil and red soil when mixed with traditional (lime) and non-traditional (fibers) stabilizers. Fly ash is used to stabilize expansive soils on unsealed pavements by combining traditional additives, like lime, with novel additives, such as coir fibers and polypropylene fibers. The experiments conducted to investigate the behavior of the soil treated with different additives include the California Bearing Ratio tests and IS light compaction tests (equivalent to the standard Proctor test). The compaction tests help investigate the compaction behavior of the soil, whereas the CBR tests are used to determine the soil's strength as a subgrade. The CBR tests are conducted in accordance with IS code 2720 (Part 16):1987, while the compaction tests are conducted in accordance with IS code 2720 (Part 7):1974. Table 8 provides a description of the experimental program, where a '✓' sign indicates the test performed corresponding to a combination shown against it.

3.1 Sample Preparation and Testing Program

The clayey soil and red soil collected from the sites were oven-dried at a temperature of 110°C for 24 hours. IS light compaction tests were conducted on the oven-dried samples passing through a 4.75 mm sieve to obtain Maximum Dry Density (MDD), Optimum Moisture Content (OMC), and CBR (Sl No. 1 of the experimental program in Table 8). The CBR tests were performed in a compact CBR load frame (three-speed), which has a penetration speed of 1 mm per minute with a static tensile load of 50 kN.

In the first stage of the test program, oven-dried soil was mixed with a certain percentage of fly ash, lime, or fibers (coir fibers or polypropylene fibers) in accordance with the test program (Sl No. 2 to 5 of Table 8), and the OMC and MDD were determined for each combination. For each combination of soil, fibers, and lime, a pair of CBR specimens was prepared at MDD and OMC. One set of specimens was used for the unsoaked CBR test and another set for the soaked CBR test.

In the second stage of the test program, soil was mixed with different percentages of fly ash and lime together to investigate improvements in compaction characteristics and CBR (Sl No. 6 of Table 8). In the last stage of the test program, the mixture of soil, fly ash, and lime was reinforced by mixing it with either coir fibers (Sl No. 7 of Table 8) or polypropylene fibers (Sl No. 8 of Table 8) to investigate the effect of fiber reinforcement on the compaction characteristics and CBR of soil stabilized with fly ash and lime together. The total number of test combinations used in the study with different stabilizers and soils is 46. The percentage combinations of stabilizers with both soil types are given in Table 8. These combinations are also explained briefly in the following sections for ease of reference.

Table 8 *The experimental program of the study*

SL. No.	Sample Combinations	Stabilizing agents (%)				IS Light Compaction Test	CBR Test
		Fly Ash (FA) (F-Class)	Lime	Natural Fibre (CF)	Synthetic Fiber (PF)		
01	Soil	-	-	-	-	✓	✓
02	Soil+Fly Ash	20 35 50	-		-	✓	✓
03	Soil+Lime	-	2 3.5 5		-	✓	✓
04	Soil+ CF	-	-	0.3 0.6 0.9	-	✓	✓
05	Soil+ PF	-	-	-	0.3 0.6 0.9	✓	✓
06	Soil+Fly Ash+Lime	20 35 50	2 3.5 5	-	-	✓	✓
07	Soil+Fly Ash +Lime+ CF	20 35 50	2 3.5 5	0.3 0.6 0.9	-	✓	✓
08	Soil+Fly Ash +Lime+ PF	20 35 50	2 3.5 5	-	0.3 0.6 0.9	✓	✓

3.2 Soil–fly Ash Mixtures

To investigate the influence of fly ash on clay soil, various combinations were prepared. Fly ash was added to oven-dried soil at proportions of 20%, 35%, and 50%. Water was then mixed according to the OMC determined from the compaction test. Subsequently, CBR tests (both soaked and unsoaked) were conducted to assess the strength of soil.

3.3 Soil-lime Mixtures

To study the effect of lime on clay soil, numerous combinations were prepared. Lime was added to oven-dried soil at proportions of 2%, 3.5% and 5%. Water was then mixed according to the OMC determined from the compaction test. Then, CBR (soaked and unsoaked) were conducted on all combinations to examine the strength.

3.4 Soil-fiber Mixtures

To study the effect of fibers on clay soil, samples were prepared using two different types of fibers: coir fibers and polypropylene fibers. The fibers, each with an average length of 2 cm, were added individually at proportions of 0.3%, 0.6%, and 0.9%. The samples were prepared at the OMC obtained from the compaction test carried out for each corresponding combination. Then, CBR tests (soaked and unsoaked) were performed on each combination to examine the strength.

3.5 Soil-fly Ash-lime Mixtures

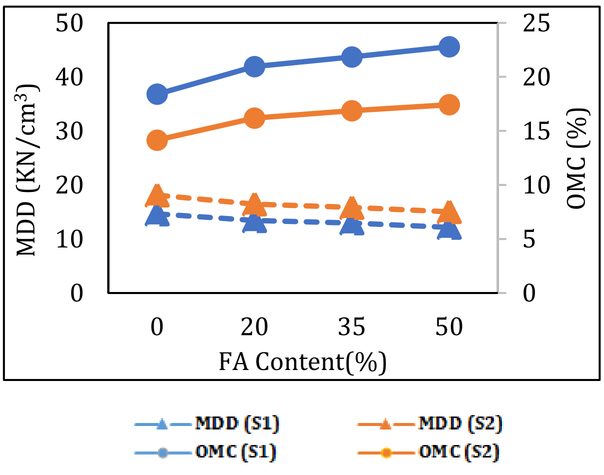
In this part of the study, lime (at proportions of 2%, 3.5%, and 5% by weight) was added to all previously prepared combinations of oven-dried soils mixed with fly ash at room temperature. The samples were then prepared at the OMC determined from the compaction test for each corresponding combination. Both soaked and unsoaked CBR tests were conducted to assess the strength.

3.6 Soil-fly Ash-lime-fiber Mixtures

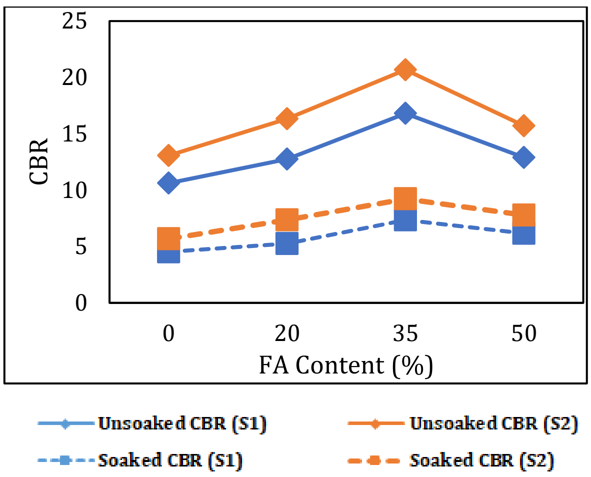
To study the effects of fibers on the strength of the soil-fly ash-lime mixture, fibers in varying percentages were gradually added at room temperature. These soil-fly ash-lime-fiber combinations were thoroughly mixed with water corresponding to the OMC for each combination. Subsequently, both soaked and unsoaked CBR tests were conducted to assess the strength.

4. Results and Discussion

The results obtained from numerous tests on all 46 combinations of both the soils with different stabilizers were compiled. A comparative study was conducted to observe the influence of these stabilizers on the compaction and strength characteristics of the soils. Consequently, conclusions were drawn regarding the optimum combination of these stabilizing materials to enhance their efficiency and efficacy as construction materials. Curves were plotted from the recorded observations for comparison, as shown in Fig. 1–14.

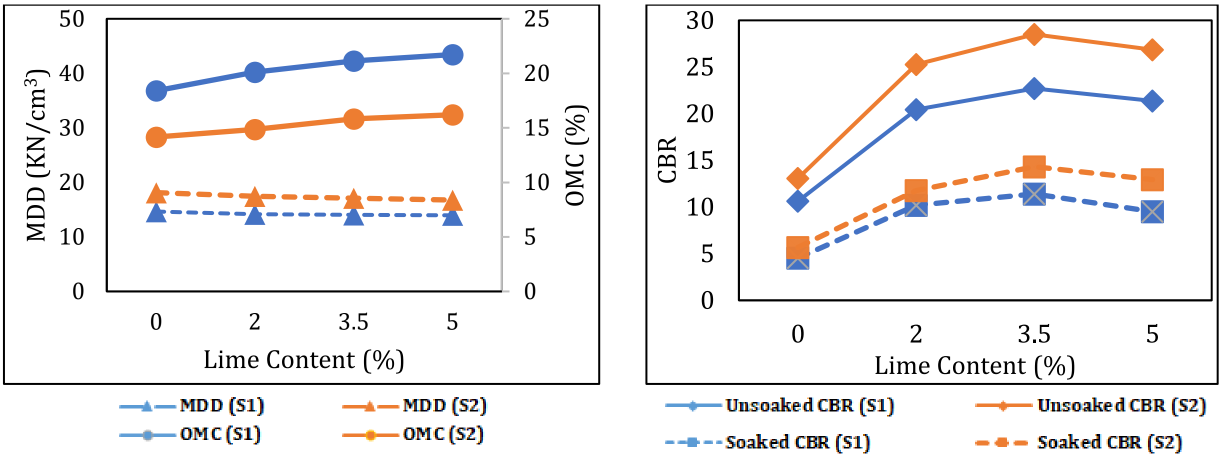


(a)



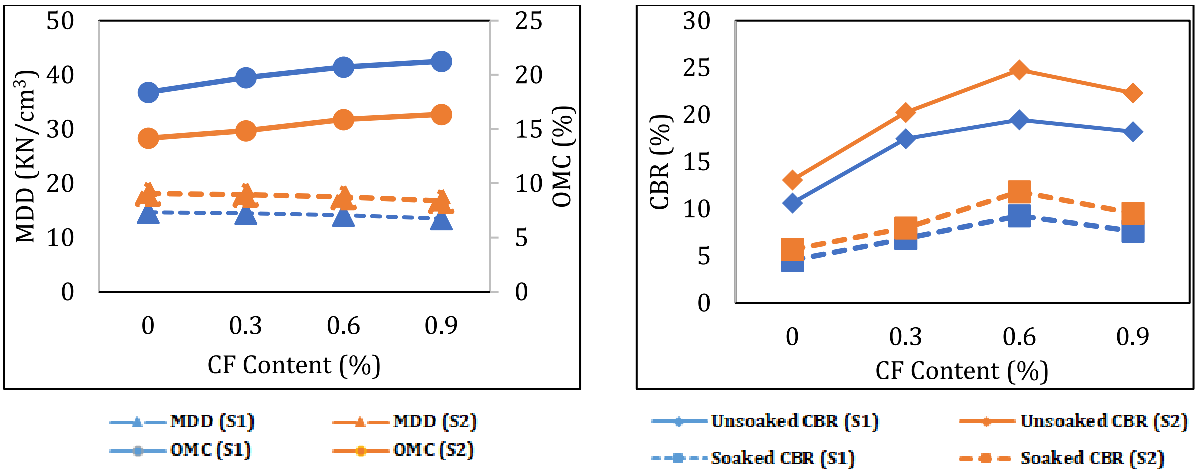
(b)

Fig. 1 *(a) MDD and OMC vs FA content; (b) Unsoaked and soaked CBR vs FA content*



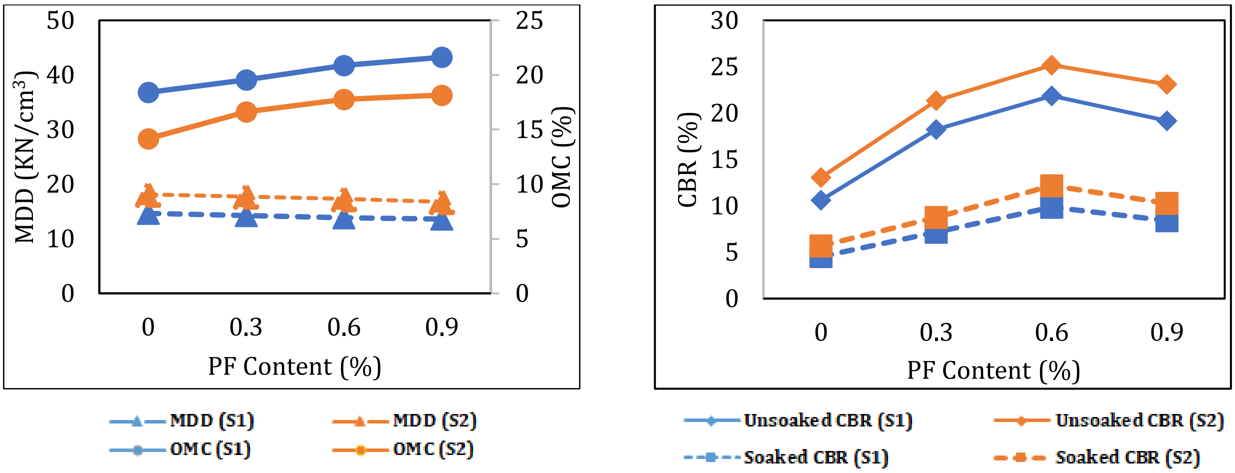
(a) **(b)**

Fig. 2 *(a) MDD and OMC vs Lime content; (b) Unsoaked and soaked CBR vs Lime content*



(a) **(b)**

Fig. 3 *(a) MDD and OMC vs CF content; (b) Unsoaked and soaked CBR vs CF content*

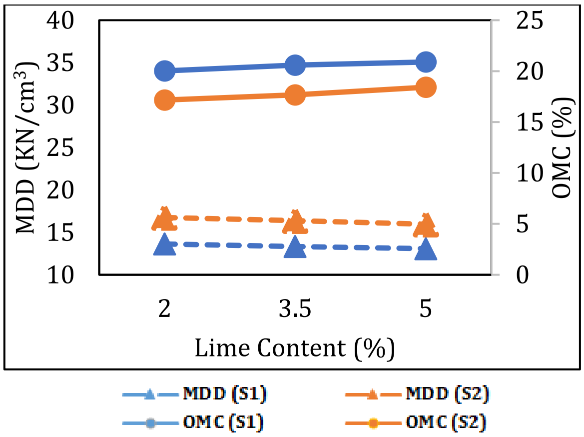


(a) **(b)**

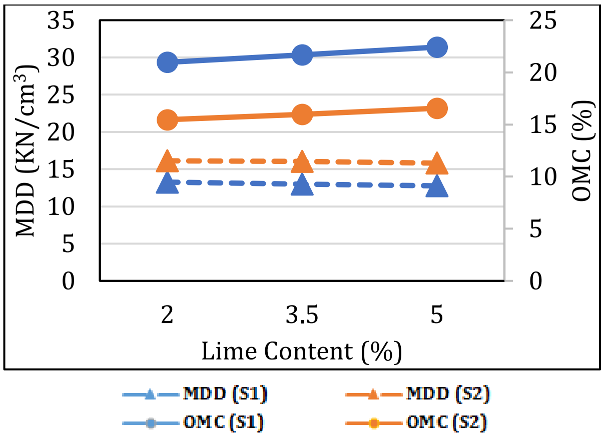
Fig. 4 *(a) MDD and OMC vs PF content; (b) Unsoaked and soaked CBR vs PF content*

From the evaluations of compaction tests performed on the soil stabilized with additives individually shown in Fig. 1(a), 1(b), 2(a), 2(b), 3(a), 3(b), 4(a), and 4(b), it can be observed that the MDD of clayey and red soil decreases gradually with the addition of additives, while the OMC of both soils increases with the gradual addition of additives. The decrease in MDD occurs because the bulk density of FA, lime, and fibers (CF and PF) is lower than that of both soils, thereby reducing the overall density of the mixture. Moreover, fibers tend to expand themselves by entrapping air bubbles between soil and fiber particles after water is added, thus increasing the volume of the mixture. The OMC of both soils combined with fly ash (FA) and lime individually increases due to the presence of cementitious materials in FA and lime, which react with water in an exothermic reaction, causing the water in the mixture to be absorbed or evaporated. Similarly, in the case of soils mixed with fibers, the OMC increases due to the fibers' tendency to absorb water.

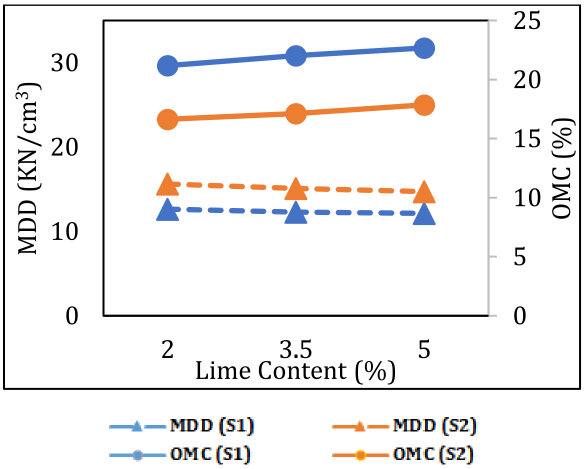
Among all the combinations, the maximum MDD is observed when 0.3% CF is added. This occurs because CF has a higher tendency compared to other additives to absorb water, making the combination heavier compared to the others. The least MDD is observed when 50% FA is added. This is due to FA having a lower density and adding 50% FA by weight to the soil significantly reduces the overall density of the combination. The highest OMC is observed when 5% lime is added to both soils. This happens because lime tends to react with water in an exothermic reaction, which causes water to either be absorbed or evaporate.



(a)



(b)



(c)

Fig. 5 *MDD and OMC vs Lime content for (a) Soil+20% FA + lime; (b) Soil+35% FA + lime; (c) Soil+50% FA + lime*

From the evaluations of CBR tests (unsoaked and soaked) on soil stabilized with additives individually shown in Fig. 1(c), 1(d), 2(c), 2(d), 3(c), 3(d), 4(c), and 4(d), it can be observed that the CBR value of clayey and red soil increases in both soaked and unsoaked conditions until it reaches an optimum point. Further addition of additives beyond this point causes the CBR value to decrease. This behavior is consistent across all combinations of soil with additives. The initial reason for the increase in unsoaked CBR value with the addition of FA or lime to soil individually is that the cementitious materials present in the additives react with water and increase the strength of the soil considerably. Similarly, in a soaked condition, the cementitious materials present in lime and FA undergo curing for four days, increasing the strength of the soil considerably. While the decrease in CBR value for both soaked and unsoaked conditions is observed after further addition of additives as the combination of soil and FA or lime becomes heterogeneous in nature, which reduces the attraction between soil particles.

The reason for the increase in unsoaked and soaked CBR values with the addition of fibers (CF and PF) to soil individually is due to the elastic nature of the combination. The elastic nature increases the compressive strength of the soil and fiber mixture, which contributes to the increase in CBR value. While the decrease in CBR value for both soaked and unsoaked conditions is observed after further addition of fibers as the combination of soil and fibers becomes heterogeneous in nature, which reduces the attraction between soil particles.

Among all the combinations, the maximum unsoaked CBR value is observed when 0.6% PF is added. This occurs because the PF imparts high elasticity to the mixture when combined with soil. The lowest CBR value in both unsoaked and soaked conditions is observed when 20% FA is added. This is because FA contains a low amount of cementitious material, and hence the mixture is unable to provide sufficient compressive strength to the soil.

The highest CBR value in soaked condition is observed when 3.5% lime is added to both soils. This occurs because lime reacts with water to form slaked lime, which provides high strength. From the evaluations of the compaction tests on the soil and FA mixtures stabilized with lime shown in Fig. 5, it can be observed that the MDD of the mixture of FA and soil decreases gradually with the addition of lime, while the OMC of the mixture increases. The decrease in MDD is observed because the bulk density of lime is lower than that of the mixtures, thus reducing the overall density of the combination. Meanwhile, the OMC of the mixture of FA with clayey and red soil increases because lime reacts with water in an exothermic reaction, causing the water present in the combination to be either absorbed or evaporated.

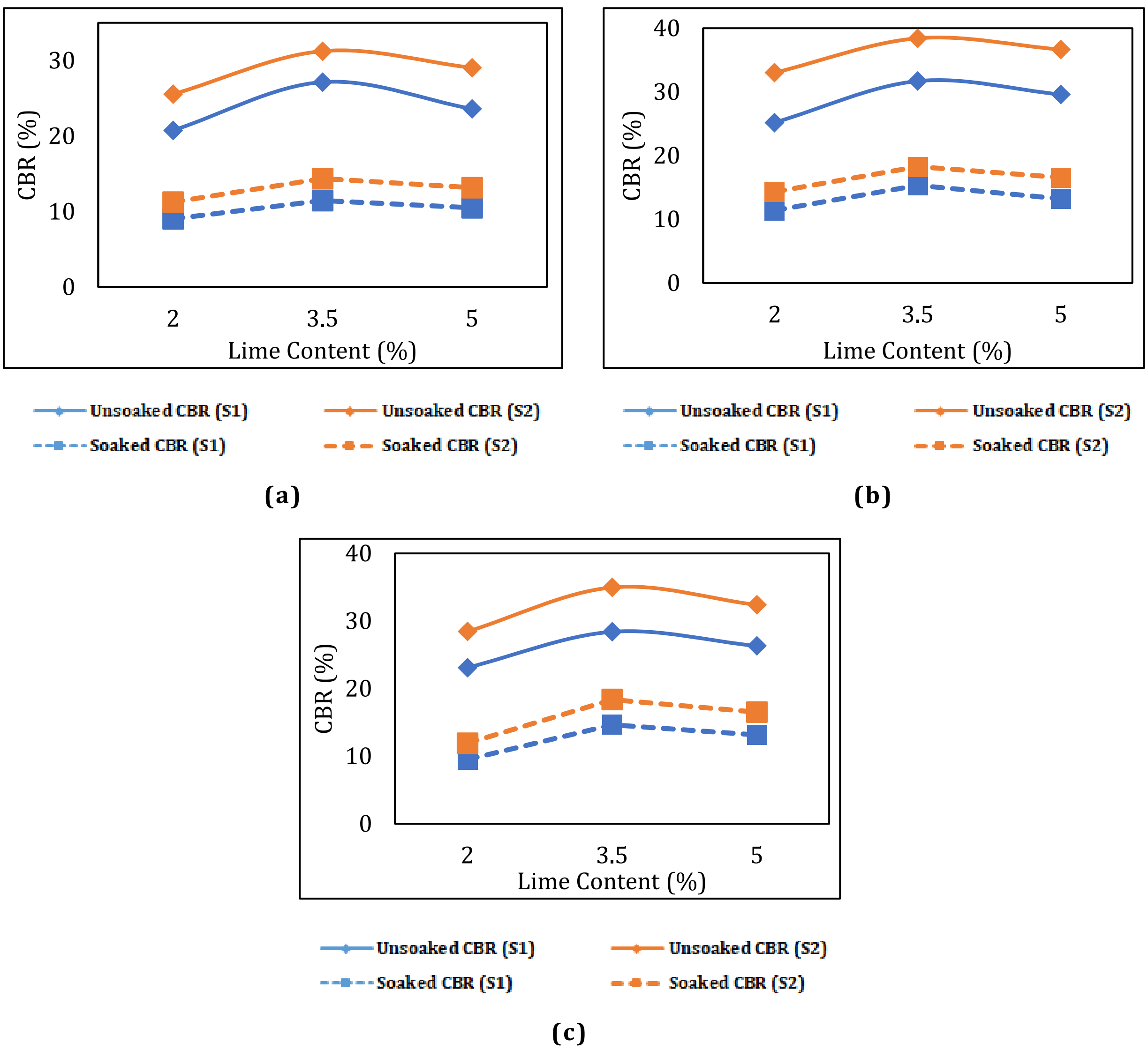


Fig. 6 *CBR vs lime content of (a) Soil+20% FA + lime; (b) Soil+35% FA + lime; (c) Soil+50% FA + lime*

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Among all the combinations, the maximum MDD is observed when 2% lime is added to the mixture of 20% FA with soil. This occurs because the total amount of additives is low. The least MDD is observed when 5% lime is added to the mixture of 50% FA with soil in both types of soil. This happens because the bulk density of lime is lower than that of the mixture of 50% FA and soil, reducing the overall density of the combination. Additionally, FA has a comparatively low density, and after adding 50% FA by weight to the soil, the overall density of the combination is significantly reduced. The maximum OMC is observed when 5% lime is added to the mixture of 50% FA. This occurs because both lime and FA tend to react with water in an exothermic reaction, causing the water to be either absorbed or evaporated.

From the evaluations of CBR tests (unsoaked and soaked) on soil and FA mixtures stabilized with lime shown in Fig. 6, it can be observed that the CBR value in soaked and unsoaked conditions increases gradually, reaches an optimum point with the addition of lime, and then decreases with further addition of lime. This occurs because the cementitious materials in FA and lime react with water in an exothermic reaction, which provides strength to the mixtures and causes the CBR value to increase. However, further increases in lime and FA make the mixture more heterogeneous, leading to a decrease in strength with additional lime and FA content.

Among all the combinations, the maximum unsoaked and soaked CBR value is observed when 3.5% lime is added to the mixture of 35% FA with soil. This occurs because FA and lime in the mixture bind with other particles without disturbing the homogeneous nature of the mixture. The least CBR value in both soaked and unsoaked conditions is observed when 2% lime is added to the mixture of 20% FA and soil (both clayey and red soils). This happens because the amount of cementitious materials (lime and FA) in the mixture is lower than in other mixtures, resulting in the lowest CBR value for this combination.

From the results of compaction tests on the soil, FA, and CF mixture stabilized with lime shown in Fig. 7 and 8, it can be observed that the MDD of the mixture decreases gradually with the addition of lime, while the OMC of the mixture increases with the gradual addition of lime. The decrease in MDD is observed because the bulk density of lime, FA, and CF is lower than that of the soil in the mixtures, and hence, with the further increase in these additives, the overall density of the combination is reduced. The OMC of the mixture increases as lime and FA tend to react with water in an exothermic reaction, causing the water present in the combination to be either absorbed or evaporated. Moreover, CF also tends to absorb water, further increasing the OMC of the overall combination.

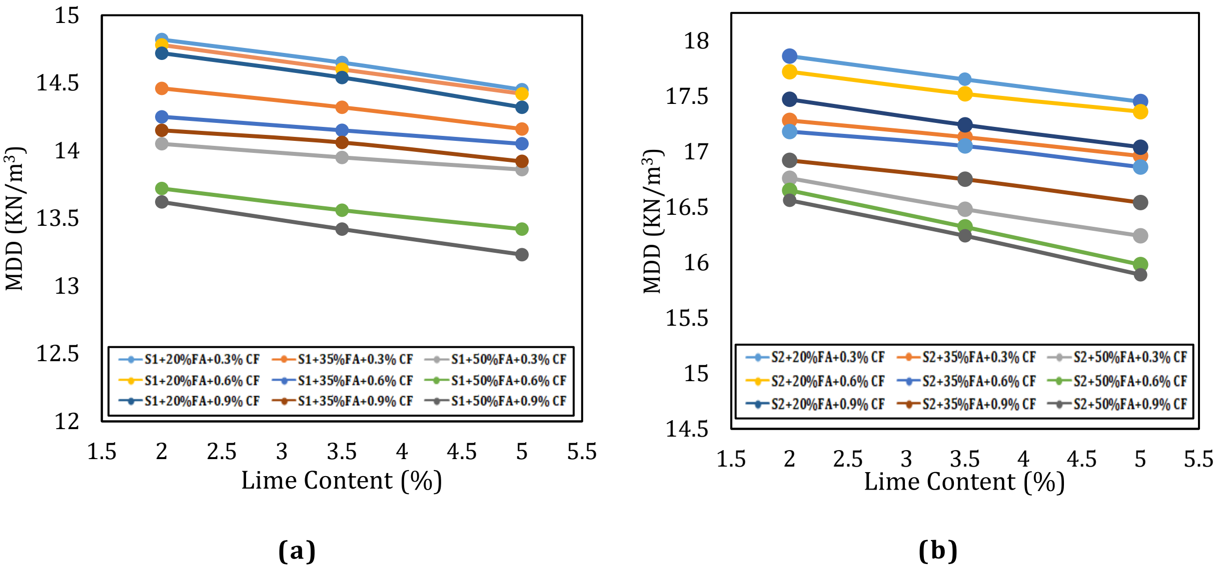
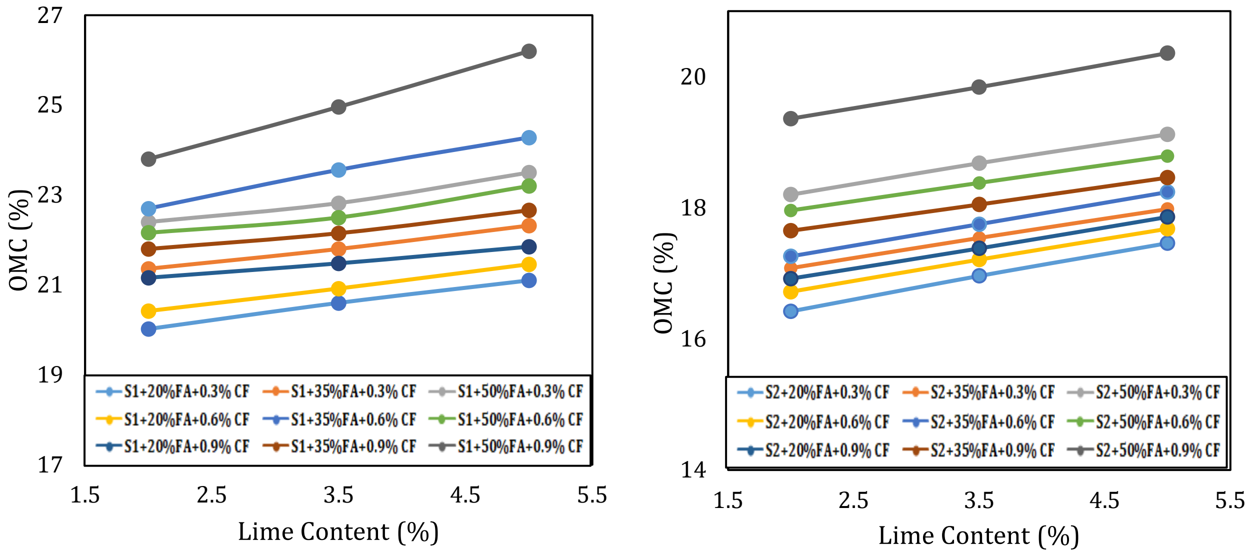


Fig. 7 *MDD vs lime content of (a) S1+FA + lime+CF; (b) S2+FA + lime+CF*

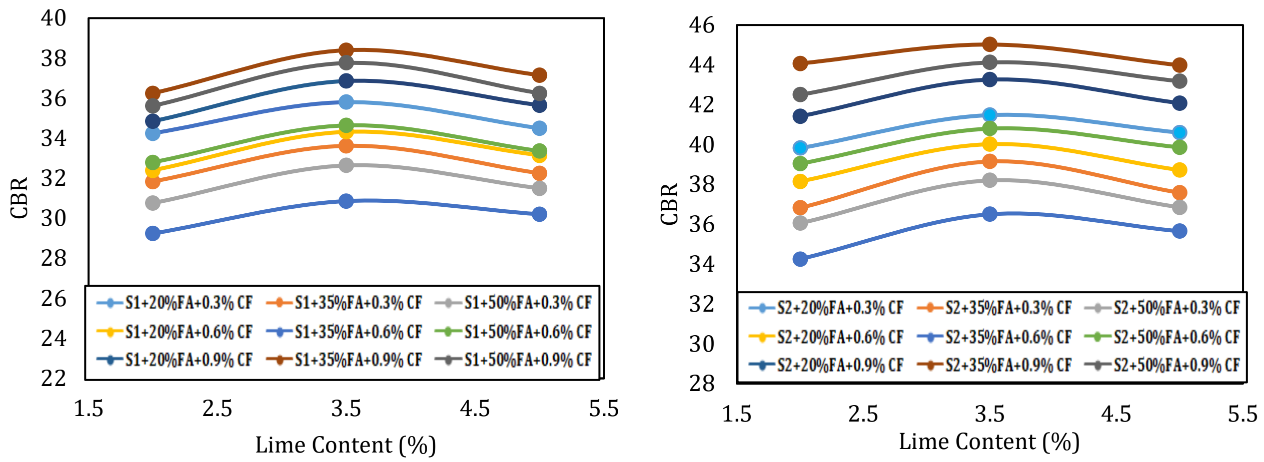
Penerbit UTHM



(a) **(b)**

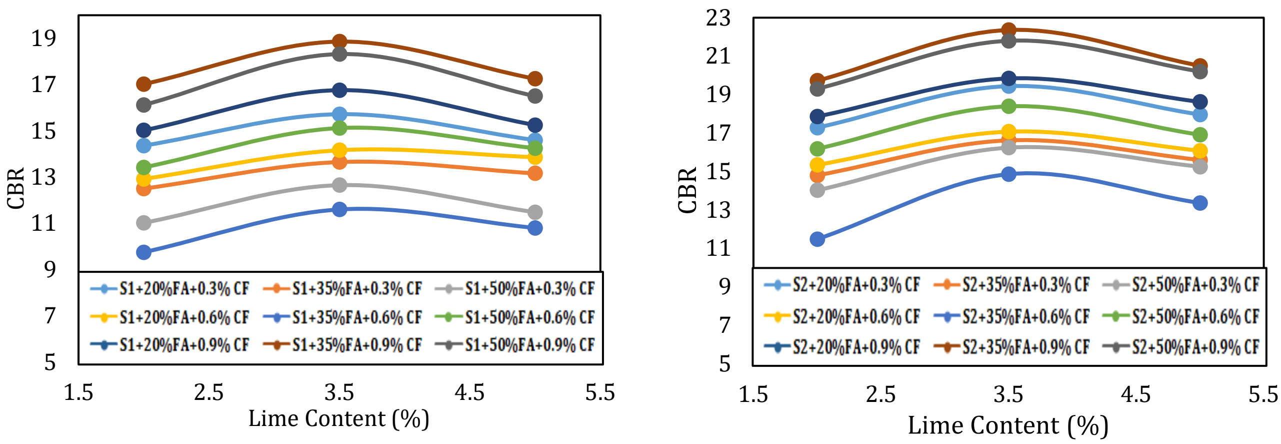
Fig. 8 *OMC vs lime content of (a) S1+FA+ lime+CF; (b) S2+FA+ lime+CF*

Among all the combinations, the maximum MDD is observed when 20% FA, 0.3% CF and 2% lime are added to both the soil. This occurs because the total amount of additives is low. The least MDD is observed when 50% FA, 0.9% CF and 5% lime are added to red and clayey soil. This is because the bulk density of the additives (lime, FA, and CF) is lower than that of the soil alone. Hence, the overall density of the combination is reduced since the maximum amounts of additives are present in the combination. The highest OMC is observed when 50% FA, 0.9% CF and 5% lime are added to red and clayey soil. This occurs because both lime and FA tend to react with water in an exothermic reaction, causing the water to be either absorbed or evaporated. Additionally, this combination contains the maximum amount of CF among all the combinations, which further contributes to the high OMC.



(a) **(b)**

Fig. 9 *Unsoaked CBR vs lime content of (a) S1+lime+ FA+CF; (b) S2+lime+ FA+CF*

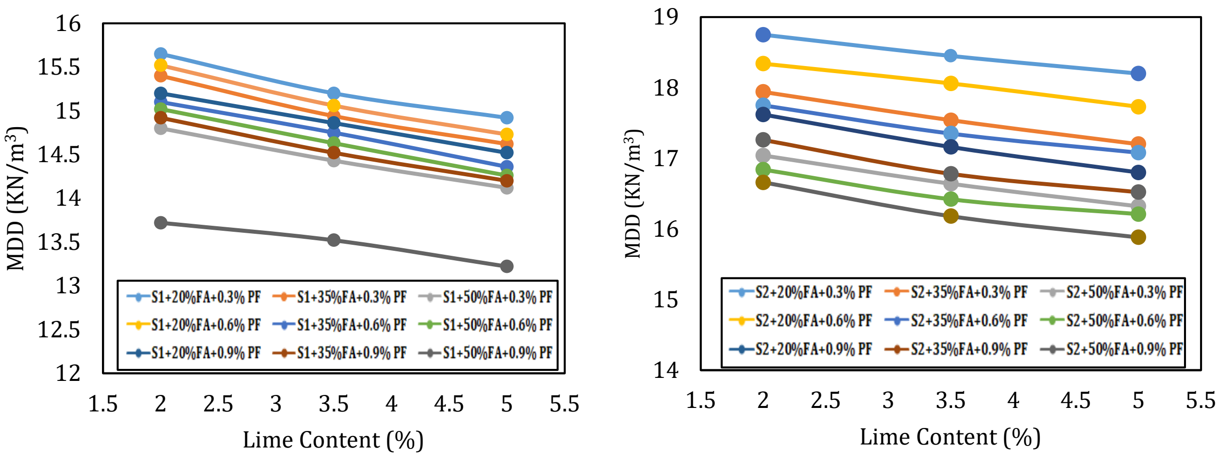


(a) **(b)**

Fig. 10 *Soaked CBR vs lime content of (a) S1 S2+lime +% FA+CF+lime; (b) S2+lime +% FA+CF*

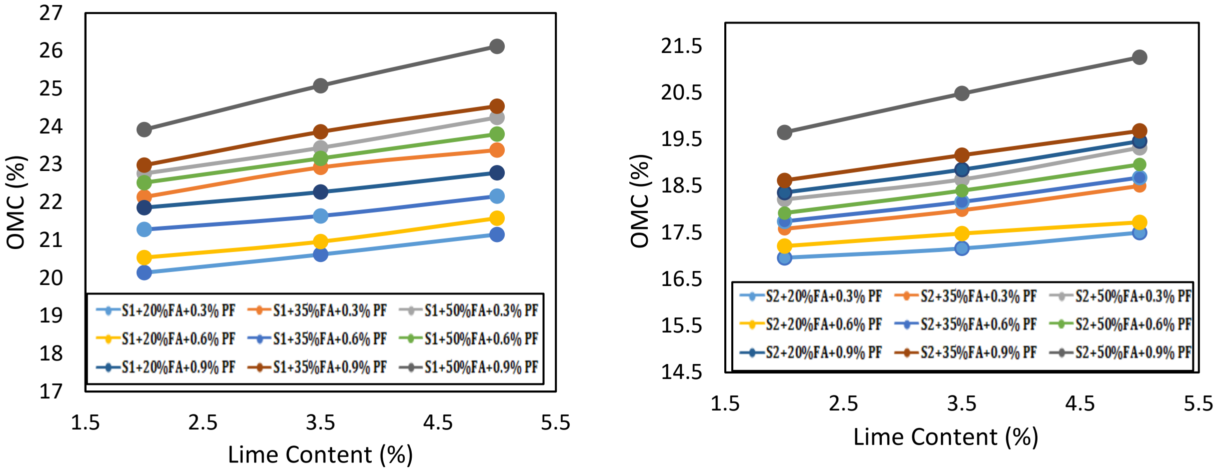
From the evaluations of soaked and unsoaked CBR tests on soil, FA, and CF mixtures stabilized with lime shown in Fig. 9 and 10, it can be observed that the soaked and unsoaked CBR values of the mixture of FA, CF, and soil increase and reach an optimum point with the addition of lime content, then gradually decrease with further addition of lime. The further addition of additives makes the mixture heterogeneous, which makes the sample unstable. Among all the combinations, the maximum soaked and unsoaked CBR values are observed when 35% FA, 0.9% CF and 3.5% lime are added to red and clayey soil. This occurs because FA and lime in the mixture bind with the other particles without disturbing the homogeneous nature of the mixture. Additionally, the high amount of CF makes the mixture elastic, which again increases the compressive strength of the mixture. The least soaked and unsoaked CBR values are observed when 20% FA, 0.3% CF and 2% lime are added to red and clayey soil. This occurs because the amounts of additives, i.e., FA, CF, and lime, are comparatively low in this combination. Hence, the additives do not contribute enough to the overall strength of the combination.

From the evaluations of compaction tests on soil, FA, and PF mixtures stabilized with lime shown in Fig. 11 and 12, it can be observed that the MDD of the mixture of FA and PF with clayey and red soil decreases gradually with the addition of lime, while the OMC of the mixture increases with the gradual addition of lime. Among all the combinations, the maximum MDD is observed for both soils when 20% FA, 0.3% PF and 2% lime are added, and the least MDD is observed when 50% FA, 0.9% PF and 5% lime are added to red and clayey soil. This happens because the bulk densities of all the additives are lower than that of the soil. The maximum OMC is observed when 50% FA, 0.9% PF and 5% lime are added to red and clayey soil. This occurs because both lime and FA tend to react with water in an exothermic reaction, which again causes water to be either absorbed or evaporated. Besides, PF tends to absorb water, and being the combination with the maximum PF, the OMC of the mixture is increased.



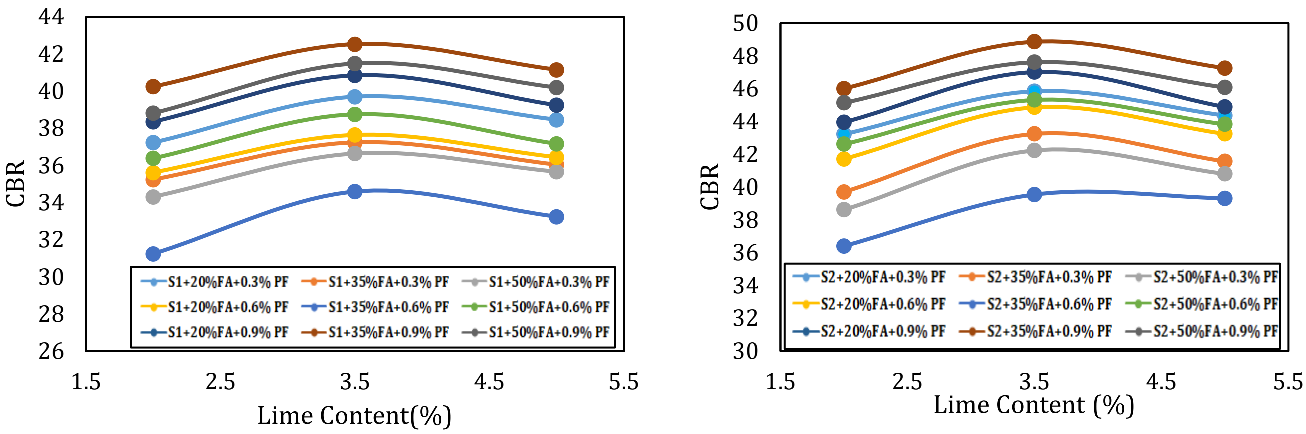
(a) **(b)**

Fig. 11 *MDD vs lime content of (a) S1+lime +FA+PF; (b) S2+lime +FA+PF*



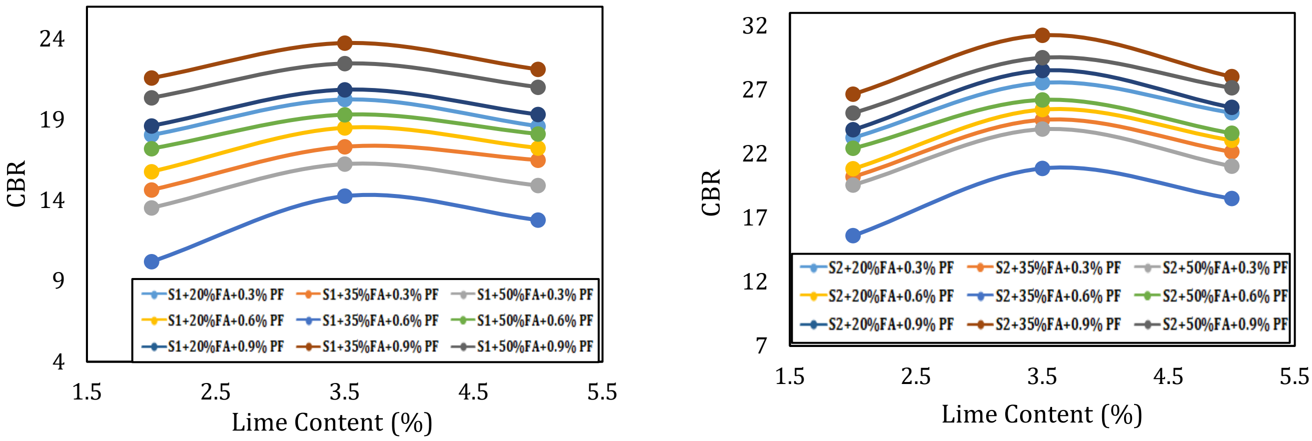
(a) **(b)**

Fig. 12 *OMC vs lime content of (a) S1+lime +FA+PF; (b) S2+lime +FA+PF*



(a) **(b)**

Fig. 13 *Unsoaked CBR vs lime content of (a) S1+% FA+PF+ lime; (b)S2+% FA+PF+ lime*



(a) **(b)**

Fig. 14 *Soaked CBR vs lime content of (a) S1+% FA+PF+lime ; (b) S2+% FA+PF+lime*

From the evaluations of soaked and unsoaked CBR tests on soil, FA, and PF mixtures stabilized with lime shown in Fig. 13 and 14, it can be observed that the soaked and unsoaked CBR values of the mixture of FA and PF with clayey and red soil increase and reach an optimum point with the addition of lime content, then gradually decrease with further addition of lime. Among all the combinations, the maximum soaked and unsoaked CBR values are observed when 35% FA, 0.9% PF and 3.5% lime are added to red and clayey soil. This occurs because FA and lime present in the mixture bind with the other particles without disturbing the homogeneous nature of the mixture. Additionally, the high amount of PF makes the mixture elastic, which again increases the compressive strength of the mixture. The least soaked and unsoaked CBR values are observed when 20% FA, 0.3% PF and 2% lime are added to red and clayey soil.

5. Conclusion

This study has provided valuable insights into the effectiveness of stabilizing two indigenous soils from landslide-prone areas of Arunachal Pradesh using fiber reinforcement and fly ash as a primary additive. Lime was used to enhance the stabilization effect of fly ash by acting as an alkaline activator for pozzolanic reactions. Through a series of laboratory tests and analyses, it was observed that the optimal combination of fly ash, lime, and fiber significantly improved the CBR values of the soils studied. Key findings from the investigation include:

1. The maximum unsoaked and soaked CBR values when lime alone was used as admixture increased by 22.70% & 11.40% for clay soil and 28.50% & 14.32% for red soil respectively.
2. The maximum unsoaked and soaked CBR values when fly ash was added along with lime as admixture was increased by 31.70% & 15.32% for clay soil and 38.42% & 8.26% for red soil respectively, with the combination of soil + 35% FA + 3.5% lime.
3. The optimum combination of soil, fly ash, lime, and polypropylene fiber was found to be soil+35% FA+3.5% lime+0.9% PF. This led to an increase in the unsoaked and soaked CBR values by 46.08% and 29.50% for the red soil, and 40.20% and 21.02% for clay soil respectively.

These results demonstrate that strategic use of admixtures can significantly enhance the strength and suitability of clay and red soils for construction purposes. The combination of fly ash, fibers, and lime can be recommended as an effective stabilization technique for clayey soils, also providing an environmentally friendly method for utilizing an industrial by-product. Future research should focus on investigating the long-term durability and performance of soil stabilized with fly ash, fibers, and lime under various environmental conditions. This will provide further insights into the practical applications and sustainability of these stabilization techniques.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Raja Sarkar, Dipika Devi;* ***data collection:*** *Raja Sarkar;* ***analysis and interpretation of results:*** *Raja Sarkar, Dipika Devi, S. K. Tamang;* ***draft manuscript preparation:*** *Dipika Devi, Raja Sarkar, S. K. Tamang. All authors reviewed the results and approved the final version of the manuscript.*

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