Study on Stabilization of Soil Using Crumb Rubber Powder and Lime

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Abstract: **This paper presents a study on the stabilization of soil using two different stabilizers: the use of Crumb Rubber Powder (CRP) and the combination of CRP and lime. Various laboratory tests were conducted to evaluate the properties of the untreated soil and the effectiveness of the stabilization methods. The results of the study showed that the addition of CRP and lime improved the properties of the soil. The Unconfined Compression Strength (UCS) tests revealed that the optimal percentage of lime for soil stabilization was 3%, while the optimal percentage of CRP was 10%. The addition of CRP and lime also improved the California Bearing Ratio (CBR) values of the soil. Furthermore, the study compared the strength-carrying capacity of soil treated with varying percentages of CRP and lime. It was observed that there was a slight increase in strength for samples cured for 7 days compared to immediate test values. Overall, the findings of this study demonstrate the potential of using CRP and lime for soil stabilization, leading to improved soil properties. These findings can contribute to the development of sustainable and cost-effective solutions in the field of geotechnical engineering.**

Keywords* — *California Bearing Ratio, Compaction, Crumb Rubber Powder, Lime, Soil Stabilization, Unconfined Compressive Strength

I. INTRODUCTION

The paper provides information on a comparative study conducted to investigate the stabilization of soil using crumb rubber powder (CRP) and lime. The study focuses on evaluating various properties of the soil and determining the effectiveness of the stabilization methods.

The soil in its loose condition is unfavourable for any civil engineering constructions, be it foundations of any structures or subgrade/ embankment of roads. Such soils possess low bearing capacity. If a weak soil base is used for construction with time, it compacts and consolidates which results in differential settlement of structure. To avoid such failures stabilization is needed. There are several techniques to improve the bearing capacity of soil, one such method is stabilization. Stabilization enhances the physical properties of soil thereby increasing its load-bearing capacity. Stabilization can be done by adding any additives of natural, synthetic, chemical or solid substances.

Expansive soil, clayey soil, or any soil with low bearing capacity can be stabilized using various techniques and methods of stabilization. The adjustments in the soil properties are brought about either by the incorporation of additives or by mechanical mixing of different soil types. This just alludes to the process of changing soil properties to improve or increase strength and durability.

In developing countries like India waste management is a huge issue. The effective utilization of waste produced and its proper management would boost economic growth and as well as help in keeping the environment clean. The demand for automobiles is extensively increasing globally. The demand for automobiles also leads to demand to produce rubber tyres. The problem arises in the disposal of these scrap tyres, which are nonbiodegradable and it's aiding in disturbing the balance of the ecosystem.

 DOI : 10.35291/2454-9150.2024.0002

Stabilizing the soil by using these wastes conserves various natural resources and further, it brings environment-friendly circumstances. One of the ways of utilizing these waste scrap tyres is by using crumb rubber powder or tyre powder in stabilization.

Infusion of crumb rubber powder with soil is observed to enhance the soil properties. This study deals with soil stabilization using crumb rubber and lime. Lime stabilization upgrades designing properties in soils, including improved quality; improved protection from crack, weariness, and perpetual twisting; improved engineering properties, and protection from the harmful impacts of dampness.

In the study [1], two problematic clayey soils were examined, and varying percentages of crumb rubber powder (CRP) were used as a stabilizer. The percentages of CRP used were 5%, 10%, 15%, and 20%. The study observed that the strength properties of the stabilized soils increased with 10% CRP, as determined through California Bearing Ratio (CBR) tests. Additionally, the effect of different quantities of stabilizer on drainage characteristics was studied. It was found that the addition of 10% CRP resulted in increased strength and permeability characteristics in both soils. In another work [2] focused on enhancing the properties of clay for Mangalore tiles manufacturing, CRP was used as a stabilizer, with a concentration of 5%. The study conducted unconfined compressive strength (UCS) tests on both problematic clay and stabilized clay. The results showed an increase in strength in the problematic clay after stabilization with 5% CRP, making the clay suitable for tile manufacturing.

In the study [3], black cotton soil and red soil were investigated, with CRP used as a stabilizing agent. Different percentages of CRP (5%, 10%, 15%, and 20%) were added to the soils. The properties of the soil, compaction, CBR, and direct shear tests were conducted to assess the behaviour and performance of the stabilized soil. The study found that the CBR value increased for 10% CRP, beyond which the CBR value decreased. The results indicated that the addition of CRP had a greater impact on the bearing capacity of black cotton soil compared to the red soil. A study [4], investigated the effective utilization of waste tyres as a stabilizer. They used tyre powder in varying percentages of 5%, 10%, 15%, and 20%. The study aimed to determine the effect of tyre powder on the shear strength of soil through direct shear tests and its influence on the bearing capacity of soil through California Bearing Ratio (CBR) tests. The results showed that the shear strength of black cotton soil increased with the addition of 10% tyre powder. Additionally, the CBR value of the soil increased for 10% tyre powder. However, beyond this percentage, the soil strength gradually decreased. The findings suggest that the addition of tyre powder can enhance the shear strength and bearing capacity of the soil up to a certain percentage. Beyond that, the effectiveness of the stabilizer diminishes. These results highlight the importance of optimizing the percentage of tyre powder for soil stabilization to achieve the desired improvements in soil properties. In the study [5], the researchers aimed to utilize locally available materials and enhance the strength and stiffness of soft soil. They achieved this by stabilizing the soil using varying percentages of waste tyre powder. The properties of the stabilized soil, including permeability, compaction, and unconfined compression strength, were evaluated. The samples underwent tests such as California Bearing Ratio (CBR), unconfined compression strength (UCS), and falling head permeability. The results demonstrated significant improvements in the bearing capacity, shear strength, and permeability characteristics of the reinforced soil compared to the unreinforced soil.

In an investigation [6], focused on stabilizing black cotton soil using grounded rubber powder, the researchers added rubber powder in proportions of 5%, 10%, 15%, and 20% to the soil samples. Through UCS and CBR tests, they observed an improvement in the strength of the black cotton soil with the addition of 5% grounded rubber powder. An experimental test was conducted on clay soil using crumb rubber and lime as stabilizers [7]. Crumb rubber was used in varying percentages of 5%, 10%, and 15%, while lime was used in varying percentages of 2%, 4%, and 6%. The addition of crumb rubber and lime resulted in improvements in load-bearing capacity and permeability. CBR and UCS tests showed that the CBR value was significantly higher in the stabilized soil with 15% crumb rubber and 6% lime.

In the experimental investigation [8], black cotton soil was stabilized using crumb rubber with varying percentages of 5%, 10%, and 15%, along with a constant percentage of 3% lime. CBR tests were conducted on unreinforced and reinforced soil samples. The results indicated an increase in the CBR value with higher percentages of crumb rubber. This increase in CBR value led to decreased pavement thickness and increased stability. In the experimental study [9], the effect of tyre chips and lime on expansive soil was investigated. Varying percentages of tyre chips (4%, 8%, 12%, and 16%) were used along with a constant 10% of lime. The study conducted California Bearing Ratio (CBR) tests and found that the strength values of the expansive soil increased with higher percentages of tyre chips and constant lime quantity. The maximum CBR value was obtained at 12% of tyre chips and 10% of lime for the tested expansive soil. In the study [10], the focus was on stabilizing black cotton soil using shredded tyre chips and lime. Varying percentages of tyre chips (1%, 2%, 3%, and 4%) and lime (1%, 2%, 3%, and 4%) were used. UCS and CBR tests were conducted, and it was observed that the strength of the soil improved with higher percentages of

 DOI : 10.35291/2454-9150.2024.0002

stabilizers. The reinforced soil sample with 3% of crumb rubber and 3% of lime exhibited the maximum CBR value.

The modified proctor test is carried out to calculate the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of the soil. In this study, the California Bearing Ratio (CBR) test and Unconfined Compression Strength (UCS) test are carried out to find out the changes in the bearing capacity and strength characteristics of the soil for varying percentages of additives used. UCS is conducted to find the optimum lime and crumb rubber powder to be used in the study.

In conclusion, the paper presents a comprehensive overview of the study on soil stabilization using crumb rubber powder and lime. The study evaluates various properties of the soil and demonstrates the effectiveness of these stabilization methods. The findings provide valuable insights for the construction industry in terms of improving soil stability and reducing construction costs.

II. Materials And Methods

The methodology section outlines the experimental setup and testing protocols, providing insights into the compaction behavior, strength characteristics, and load-bearing capacity of the soil under different stabilization conditions. Additionally, the section discusses the significance of the modified Proctor test for determining the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of the soil, as well as the implications of the California Bearing Ratio (CBR) test for assessing the soil's suitability for supporting pavement and road structures. The methodology section also highlights the importance of conducting Unconfined Compressive Strength (UCS) tests to evaluate the strength behavior of the soil samples treated with different combinations of CRP and lime.

A. Red Soil

The red soil used in this study was procured from Hunsur near Mysore district, Karnataka, India. The grain size analysis was performed to determine the particle size distribution of the soil and crumb rubber powder samples. The results are plotted in Figure 1, which provides insights into the soil's particle size distribution. The Properties of the soil are tabulated in Table 1. The soil selected for this study is classified under Highway Research Board (HRB) soil classification and Bureau of Indian Standards (BIS) classification. The soil is categorized as A-3 soil as per HRB classification and well-graded sandy soil as per BIS classification.

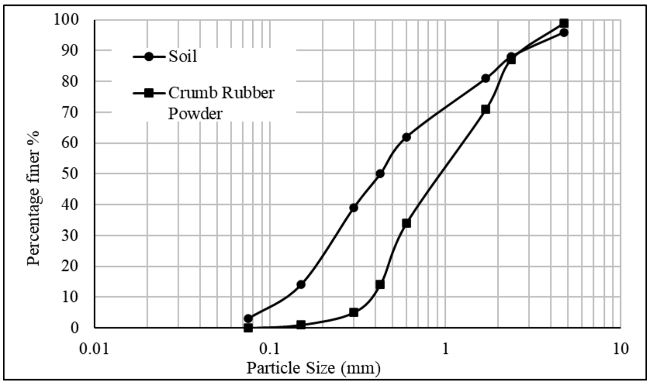

Figure 1 - Gradation curve of soil and crumb rubber powder

Table 1 – Properties of Red Soil

Properties	**Values**
Colour	Red
Specific gravity	2.48
Grain size analysis	
Gravel (%)	4.00
Sand (%)	91.00
Fines (%)	5.00
Compaction characteristics	
Maximum dry density (kN/m^3)	21.57
Optimum moisture content (%)	16.20
Atterberg's Limits	
Liquid limit (%)	35.20
Plastic limit (%)	26.40
Shrinkage limit (%)	17.40
Plasticity index (%)	8.80

B. Crumb Rubber Powder (CRP)

Crumb rubber powder is made from used and scraped tyres. The crumb rubber powder used in this experimentation work is procured locally from Bengaluru, Karnataka, India. Table 2 provides the details of CRP including its appearance, specific gravity, density, moisture content and fineness modulus. The chosen crumb rubber powder's size is in the range of 425 microns to 600 microns. It is carbon black and has a specific gravity of 1.36. For stabilization varying percentages of crumb rubber powder are used that is of 5%, 10%, 15% and 20%. Figure 2 shows the CRP that has been procured for this research.

Figure 2 - Crumb Rubber Powder

 DOI : 10.35291/2454-9150.2024.0002

Table 2 – Properties of CRP

Physical Properties	Values
Appearance	Black and Rough
Specific Gravity	1.72
Density (kg/m^3)	650
Moisture Content (%)	2
Fineness Modulus	4.48

C. Lime

The lime used in this experiment is obtained from Channarayapatna, Karnataka, India. The optimum percentage of lime to be added is found by carrying an unconfined compression strength test for varying percentages of lime of 1%, 2%, 3%, and 4%. Table 3 provides the physical properties of lime, including its appearance, specific gravity, density, and pH. These properties are essential for understanding the characteristics and behavior of lime as a stabilizing agent in soil.

Table 3 – Properties of Lime

Physical Properties	Values
Appearance	Dry White Powder
Specific Gravity	2.23
Density (kg/m^3)	500
pH	12.4

D. Unconfined Compressive Strength Test

The unconfined compressive strength (UCS) test was conducted as per IS 2720 to evaluate the strength of the soil samples treated with different combinations of CRP and lime. The UCS test was conducted by applying a normal strain rate of 1.25 mm/min and the failure point was determined by measuring corresponding its strength value. The test samples were prepared to their OMC and MDD. The samples that were intended for immediate testing were tested immediately after casting, while the samples planned for a 7-day curing period were stored in desiccators. Before conducting the tests, these samples were taken out from the desiccators.

E. California Bearing Ratio Test

CBR is an important parameter of soil for the design of runway and flexible pavements. The test is conducted according to IS 2720 Part 16. The basic principle in a CBR test is to cause a cylindrical plunger of 50 mm diameter to penetrate to soil specimen at a rate of 1.25mm/min. The load required for 2.5 mm and 5mm penetration of a plunger into the soil specimen is recorded. During the test, the soil specimen is confined in a 150 mm diameter mould with a base plate and a loading frame. The cylindrical plunger is attached to the loading frame and is gradually inserted into the soil specimen. The load values corresponding to different penetrations, such as 0.5 mm, 1.0 mm, 1.5 mm, and so on, are noted. These load values are plotted against the corresponding penetrations to create a load-penetration curve.

The CBR value is determined by calculating the ratio of the load required for the specified penetrations to the load required for a standard material. The CBR test provides valuable information about the strength and load-bearing capacity of the soil. It helps in assessing the suitability of the soil for supporting pavement and road structures. Higher CBR values indicate better soil strength and load-bearing capacity, while lower values suggest weaker soil that may require stabilization or additional measures for construction purposes.

F. Mix Proportions

The mix proportions play a crucial role in determining the effectiveness of the stabilization process. The optimal blend of materials can enhance the strength, stiffness, and other desired properties of the soil. The researchers suggest that the mix proportions were varied to assess the impact of different percentages of CRP and lime on the soil's behaviour and performance.

The study uses varying percentages of CRP and lime in the soil stabilization process. Four different percentages of CRP (5%, 10%, 15%, and 20%) were added to the soil samples. Lime was used in varying percentages of 1%, 2%, 3%, and 4% in combination with CRP was added to the soil. The mix proportions are mentioned in Table 4, including varying percentages of CRP and lime added to the soil samples. The mix proportions are crucial for assessing the impact of different percentages of CRP and lime on the soil's behavior and performance.

Table 4 – Mix Proportions of Soil with Lime and Crumb Rubber Powder

Mix Name	CRP (%)	Lime (%)
S	-	-
SL1	-	1
SL2	-	2
SL3	-	3
SL4	-	4
SC1	5	-
SC2	10	-
SC3	15	-
SC4	20	-
SLC1	5	Optimum Quantity obtained after UCS test
SLC2	10	
SLC3	15	
SLC4	20	
SLC5	Optimum	Optimum

III. Results And Discussions

A. Compaction Characteristics

The compaction characteristics of the soil samples were evaluated in the study. The compaction analysis involved determining the maximum dry density (MDD) and the

 DOI : 10.35291/2454-9150.2024.0002

optimum moisture content (OMC) for different combinations of soil with lime and soil with crumb rubber powder (CRP). The compaction tests were conducted using the modified Proctor method. The results in Table 5 provide insights into the compaction behaviour and the optimal combinations of stabilizers for achieving the desired compaction properties.

Table 5 – Compaction characteristics of soil with varying CRP and Lime Contents

Mix	MDD (kN/m^3)	OMC (%)
S	2.21	16.2
SL1	2.19	16.03
SL2	2.15	15.94
SL3	2.11	15.74
SL4	2.08	15.58
SC1	2.16	16.16
SC2	2.09	15.91
SC3	2.04	13.82
SC4	2.00	13.71

According to the data presented in Table 5, the maximum dry density (MDD) of the soil is recorded as 22.10 kN/m³, with an optimum moisture content (OMC) of 16.2%. It is observed that the addition of crumb rubber powder (CRP) to the soil leads to a reduction in MDD for all combinations with higher percentages of CRP. This reduction in MDD can be attributed to the replacement of higher-density soil particles by lower-density CRP particles. The lightweight nature of CRP also contributes to this decrease in MDD.

Furthermore, the increase in CRP content results in a decrease in OMC. This is due to the negligible water absorption capacity of CRP. The findings align with previous studies [11], which also reported a decrease in MDD due to the entrapment of air caused by the non-polar nature of rubber. Additionally, the data reveals that the soil treated with lime exhibits a decrease in MDD compared to the soil alone. The addition of lime pulverizes the soil and shifts the MDD curve to the left of the optimum, indicating a decrease in MDD. This shift is attributed to the replacement of higher specific gravity soil particles by lower specific gravity powdered lime.

In summary, the data suggests that the addition of CRP and lime influences the MDD and OMC of the soil. The presence of CRP and lime alter the soil's characteristics, resulting in changes in its compaction behavior. These findings are consistent with previous research and highlight the potential of CRP and lime as stabilizers for soil improvement.

B. UCS

The UCS test is conducted for various combinations of soil with lime, soil with crumb rubber powder (CRP), and soil with a combination of lime and CRP. The test results provide insights into the strength behaviour and carrying capacity of the soil under different stabilization conditions.

UCS with varying percentages of lime

From Figure 3, it is observed that (both for immediate testing as well as with curing) as the soil treated with varying percentages of lime increases the shear strength carrying capacity also increases up to soil with 3% lime (by weight of the soil) beyond 3% lime (optimum percentage) strength reduces. Hence soil treated with 3% lime is considered a lime fixation point. An increase of the strength in Soil treated with 3% lime due to the formation of calcium silicate hydrates and aluminates by the reaction of lime and available silica and alumina with calcium in the soil. The excess addition of lime beyond 3% in soil reduces the strength since the reaction between the lime and soil in the presence of water will produce silicate hydrates of varying calcium-silicate ratios.

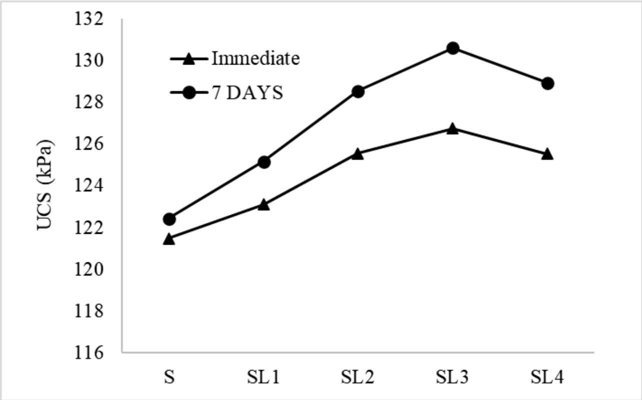

Figure 3 – UCS of soil with varying percentages of lime

UCS with varying percentages of CRP

From Figure 4, it has been observed that there is a slight decrease in strength from 7 day cured sample as compared to the immediate tested value because there are no chemical reactions taking place in between the soil and CRP due to rubber being an inert material which does not react with soil and also the addition of CRP does not alter the mechanical properties of soil, additionally, when sampling in desiccators for 7 days, it may lead to the destructions of surface tension, absorption of moist, finally, it fulfils all voids leads to decrease in load carrying capacity of the mix. According to Wang and Song, 2015, decreases in shear strength value are due to the negligible load-carrying capacity of CRP.

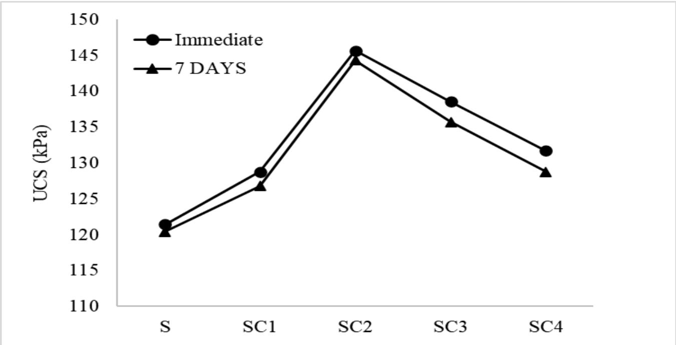

Figure 4 - UCS of soil with varying percentages of CRP

DOI : 10.35291/2454-9150.2024.0002

C. Optimization of Lime and CRP

UCS with varying percentages of CRP and lime

Figure 5 illustrates that there is an increase in strength for the 7-day cured sample compared to the immediate tested value. This increase can be attributed to the chemical reactions that occur between the soil and crumb rubber powder (CRP) over the curing period. The optimum lime-treated soil mixed with varying percentages of CRP exhibits a higher strength carrying capacity, with the incorporation of CRP content up to 10%. The rate of strength loss is higher at higher CRP contents, which can be attributed to two possible factors. Firstly, the difficulty in packing lightweight CRP particles at higher CRP content leads to the creation of more voids within the soil matrix [12]. Secondly, the sliding of rubber particles at higher CRP content results in a loss of bonding and friction within the blend [13]. These observations highlight the importance of finding the optimal balance between CRP content and soil properties to achieve the desired strength characteristics. The findings suggest that a careful selection of CRP content is necessary to ensure effective soil stabilization and maximize the strength-carrying capacity of the blend.

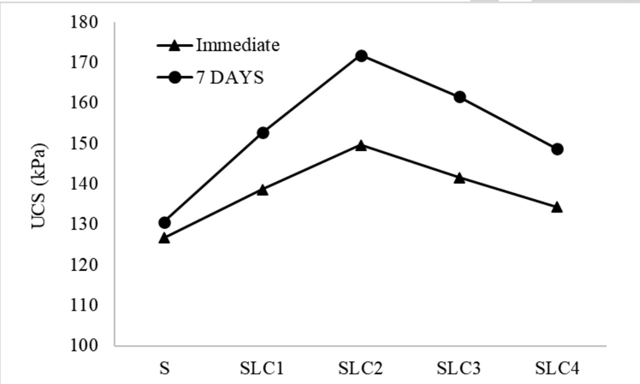

Figure 5 - UCS of soil with optimum quantity of lime and varying percentages of CRP

UCS with optimum quantity of lime and CRP

Figure 6 illustrates the Unconfined Compressive Strength (UCS) of the soil with the optimal quantity of lime and crumb rubber powder (CRP). Unconfined compressive strength tests were conducted on soil alone, soil with 10% CRP, and 3% Lime-treated soil with 10% CRP (Figure 6). It is found that compared to all combinations, soil, treated with optimum lime and optimum CRP increases in strength in terms of percentage by 40.32 compared with soil alone. This increase in strength is due to the formation of clusters and the distribution of clusters with age leads to higher strength with curing compared to the immediate tested sample also increases in strength value are due to the compressibility nature of CRP takes some extent of load.

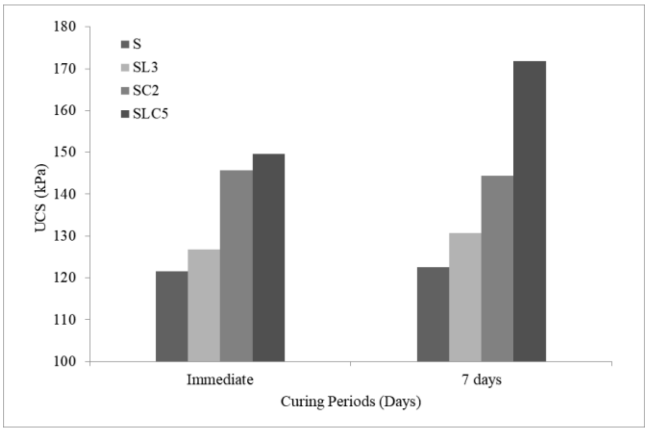

Figure 6 - UCS of soil with the optimum quantity of lime and optimum CRP

D. Stress-Strain Behaviour

Based on the information provided in Figure 7, it can be concluded that there is a noticeable change in the load-taking pattern of the blend from a brittle to ductile behaviour. This change is attributed to several factors. Firstly, the addition of lime to the soil results in the exhibition of its cementitious properties, which contribute to the observed change in behaviour. Secondly, the lower Young's modulus of elasticity of the crumb rubber powder (CRP) compared to lime-treated soil specimens plays a role in this transformation [11]. Furthermore, the elastic nature of CRP in a soil composite helps prevent the generation and growth of cracks during compression, contributing to ductile behaviour. Additionally, the elastic compression of CRP leads to strain softening after reaching the peak axial strain, further influencing the load-taking pattern [13]. Lastly, CRP acts as a reinforcement material in the soil, enhancing its ability to resist cracking [12]. These factors collectively contribute to the observed change in load-taking pattern, transforming the behaviour of the blend from brittle to ductile. The incorporation of lime and CRP in the soil stabilization process brings about these changes, ultimately improving the overall performance and strength characteristics of the soil.

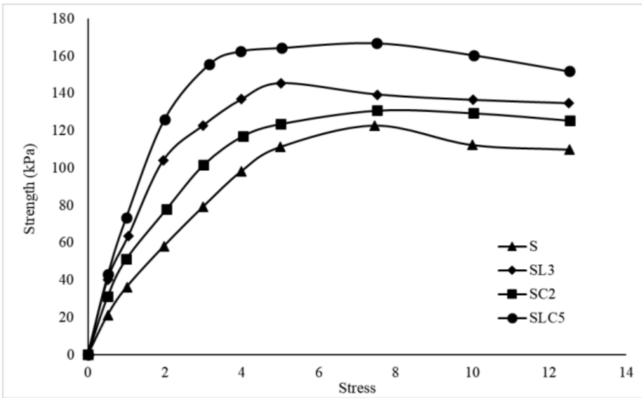

Figure 7 – Stress-Strain Curve of optimum mixes

E. CBR

The CBR tests were conducted on different combinations

 DOI : 10.35291/2454-9150.2024.0002

of soil with lime, crumb rubber powder (CRP), and their optimal blends. The results showed that the addition of lime and CRP to the soil improved its CBR values, indicating an enhancement in the bearing capacity of the soil. The CBR values increased with an increase in the percentage of CRP and lime in the soil. The optimal combination of lime and CRP resulted in the highest CBR values, indicating the effectiveness of this blend in soil stabilization. The rate of strength loss was observed to be higher at higher CRP contents, possibly due to difficulties in packing lightweight CRP particles and the loss of bonding and friction within the blend. Table 6 shows the values of soaked CBR for optimum mixes. The load versus penetration curve of optimum mixes is shown in Figure 8.

Table 6 - Soaked CBR for optimal combination of soil with Lime and CRP

Penetration (mm)	CBR Value			
	S	SL3	SC2	SLC5
2.5 mm	4.10	12.30	9.02	20.22
5.0 mm	3.28	10.20	8.38	18.58

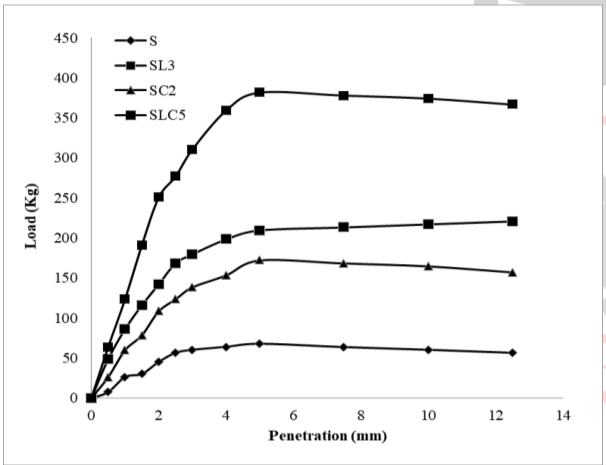

Figure 8 - Variation of Load versus Penetration for various optimum matrixes (Soaking conditions)

The CBR values of the soil treated with lime and CRP were found to be higher than those of the untreated soil, indicating the positive impact of these stabilizers on the soil's bearing capacity. Lime-treated soil with optimum CRP improves the California bearing ratio by 71.72% and 393.20% respectively for unsoaked and soaked conditions compared with soil (Table 7). The CBR values were also influenced by the curing periods, with the 7-day cured samples generally exhibiting higher CBR values compared to the immediately tested samples [14]. This indicates that the improvement in the California bearing ratio is due to the formation of the cluster in the presence of C-S-H gel and the densification of the cluster with soaking. Hence subgrade strength improves, so sub base and base course thickness greatly reduces, so it substantially reduces the overall cost of the project. The optimum lime stabilized with CRP in soil has a considerably higher CBR value than all other combinations due to the compressible properties of CRP resisting the load up to a certain extent along with clusters formed by the additions of lime, both can make the sample matrixes to take load to the maximum extent.

Table 7 - California bearing ratio for optimal combination of soil with Lime and CRP.

Mix	CBR Value	
	Unsoaked Sample	Soaked Sample
S	7.25	4.10
SC2	10.11	9.02
SL3	8.88	12.30
SLC5	12.45	20.22

IV. Conclusions

Based on the comprehensive investigation and analysis conducted in this study, the following key findings and conclusions can be drawn:

1. The addition of crumb rubber powder (CRP) and lime significantly improved the properties and performance of the soil, as evidenced by the Unconfined Compression Strength (UCS) and California Bearing Ratio (CBR) tests.
2. The optimal percentage of lime for soil stabilization was determined to be 3%, while the optimal percentage of CRP was found to be 10%, based on the strength-carrying capacity and compaction characteristics of the soil.
3. The UCS of the soil treated with lime increased by 40.32% compared to untreated soil. This increase in strength is attributed to the formation of calcium silicate hydrates and aluminates by the reaction of lime and available silica and alumina in the soil. The addition of lime resulted in the improvement of the CBR by 71.72% and 393.20% for unsoaked and soaked conditions, respectively, compared to untreated soil.
4. The addition of CRP to the soil resulted in an increase in the CBR values, with the soil treated with 10% CRP exhibiting the highest strength-carrying capacity compared to other combinations tested in UCS tests. The soil treated with 10% CRP improved the gradation curve, transforming it from poorly graded to well-graded soil. The CBR values of the soil treated with CRP and lime were found to be higher than those of the untreated soil, indicating the positive impact of these stabilizers on the soil's bearing capacity.
5. The optimal combination of lime and CRP resulted in the highest CBR values, indicating the effectiveness of this blend in soil stabilization. The soil stabilized with CRP and lime showed improved California Bearing Ratio (CBR) values compared to untreated soil, indicating enhanced strength and load-bearing

 DOI : 10.35291/2454-9150.2024.0002

capacity. The addition of lime and CRP to the soil improved its CBR values, indicating an enhancement in the bearing capacity of the soil.

In conclusion, the findings of this study highlight the potential of using CRP and lime for soil stabilization, leading to improved soil properties. The incorporation of lime and CRP in the soil stabilization process resulted in a noticeable change in the load-taking pattern of the soil from brittle to ductile behavior, ultimately improving the overall strength characteristics of the soil and exhibited improved California Bearing Ratio (CBR) values compared to untreated soil, indicating enhanced strength and load-bearing capacity. These findings have significant implications for the development of sustainable and cost-effective solutions in the field of geotechnical engineering.

Acknowledgment

The authors like to express their gratitude to Ms. Soundarya B N for their contribution towards experimental work and acknowledge Government SKSJ Technological Institute, Bengaluru for providing their laboratory facilities to complete the study.

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 DOI : 10.35291/2454-9150.2024.0002