Research Article

Effect of Curing Conditions and Freeze-Thaw Cycles on the Strength of an Expansive Soil Stabilized with a Combination of Lime, Jaggery, and Gallnut Powder

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This investigation involved the utilization of the combination of lime, jaggery, and gallnut powder, adopted in South India traditionally. This combination of materials, used for the manufacture of lime-based mortars, was adopted in stabilization of an expansive soil. Three combinations of lime, jaggery, and gallnut powder (LJG) in the ratios of 8:2:2, 8:2:1, and 8:1:2 were put into use. The effect of subjecting the combinations to alternate cycles of freeze-thaw (up to 3 cycles) and three different curing conditions of air, moisture, and heat was also investigated. In addition, a mineralogical investigation for studying the reaction products was also carried out. The investigation proceeded with the determination of the unconfined compression strength (UCS) of stabilized specimens of dimensions 38 mm × 76 mm, cured for periods of 3, 7, 14, and 28 days. The results of the investigation revealed that the addition of LJG resulted in an increase in the strength of the stabilized soil. Freeze-thaw cycles resulted in a reduction in strength with LJG821 proving to be the most optimal combination developing the maximum strength and least strength loss due to freeze-thaw cycles. Thermal curing proved to be the most optimal curing condition out of all curing conditions evaluated.

1. Introduction

Lime stabilization is one of the most preferred methods for the stabilization of problematic soils such as expansive soils. It offers a very cost-effective method for improving the properties of poor soils. However, in recent times, a lot of auxiliary amendments, especially, solid wastes have been attempted in lime stabilization to achieve two objectives primarily: (i) sustainable reuse of wastes and their valorisation [1, 2] and (ii) enhancement of the performance of lime under varying soil conditions [3]. Several investigations have also concentrated on the use of natural materials and polymers in the stabilization of soil. Chang et al. [4] investigated the effect of xanthan gum on the strengthening of soil. Moghadam et al. [5] investigated the performance of sugarcane mulch in the stabilization of dune sand. Achenza and Fenu [6] investigated the potential of natural polymers and fibres in earth stabilization for masonry construction. Blanck et al. [7] delved into the use of organic nontraditional

additives including lignosulphonates from wood pulp industries in soil treatment. Shirsavkar and Koranne [8] and Ravi et al. [9] investigated the potential of a natural polymer, molasses in road construction, and soil stabilization, respectively. In India, however, the use of natural materials in construction activities has been an age-old practice. Several natural materials including egg-shell lime, jaggery, gallnut, and egg white have been used in construction activities. Excavations at the imperial capital city of Rajendra Chola, an ancient Tamil king of the Chola Dynasty revealed the use of lime mortar mixed with jaggery and clay as binder for construction of palace walls in the kingdom [10]. According to Varghese [11], a mixture of egg-shell lime, powdered marble, river sand with fermented gallnut, and jaggery water was used to formulate the Madras plaster. Shell, jaggery, and egg white are known to enhance the binding capability of lime plaster [12]. Thus, use of natural materials is not new in the field of Civil Engineering. It is in recent times that there is a renewed interest to explore the potential of such

traditionally adopted natural materials in Civil Engineering. The use of a combination of lime, jaggery, and gallnut has been recorded in several instances in traditional South Indian construction activities [13, 14]. Radhakrishnan and Priya [15] reported that traditional lime-based plasters included jaggery for friction and gallnut powder as a bonding agent. In this investigation, an attempt has been made to evaluate the effect of this traditional combination, jaggery, gallnut powder, and lime, in the stabilization of an expansive soil. Though earlier attempts have been made [13, 14], they were only limited to investigating the feasibility of adopting this traditional combination in soil stabilization. This investigation, however, tried to evaluate the effects of curing period, curing conditions, and freeze-thaw cycles on the performance of the combination supported with mineralogical investigation.

2. Materials and Methods

The various materials adopted in the investigation include expansive soil, which needs to be improved, industrial grade lime, jaggery, and gallnut powder as additives.

2.1. Materials. The expansive soil was subjected to geotechnical characterization in accordance with various codes of Bureau of Indian Standards (BIS) and the evaluated properties of the soil have been tabulated in Table 1. The lime used in the investigation was high-quality industrial-grade hydrated lime. It was sourced from M/s. Shashun Chemicals, Chennai, India.

Jaggery, a mixture of sugar and molasses, is a traditional Indian sweetener produced from sugarcane. Jaggery is formed as a remnant when clarified sugarcane juice is boiled. It is usually available in the market in three forms, solid, liquid, and granulated jaggery [23]. Jaggery was bought from a local store in packages of 1.5 kg. It was then grated, pulverized, dried and sieved before use in sample preparation. A detailed description of its preparation is described under the subsection: preparation of materials.

Gallnut is an evergreen tree, native to southern Asia including India. The nut of the tree has been used in construction since ancient days in Southern India, especially Tamil Nadu. Gallnut was directly bought in powdered form from a local supplier. It was then stored in a closed air-tight container for later use in the investigation.

All the materials adopted in the study were subjected to X-ray fluorescence (XRF) for determination of their chemical composition. The results of the test are given in Table 2.

2.2. Methods. The experimental investigation involved the following stages: preparation of materials, characterization of materials, determination of initial consumption of lime (ICL), selection of mix ratios, and sample preparation and testing.

2.2.1. Preparation of Materials. The soil sample was prepared in the laboratory in accordance with the BIS code [24].

TABLE 1: Geotechnical properties of the soil.

Property	Value
Liquid limit [16]	65.4%
Plastic limit [16]	29%
Plasticity index	36.4%
Shrinkage limit [17]	10.1%
Specific gravity [18]	2.79
Maximum dry density (MDD) [19]	19.25 kN/m ³
Optimum moisture content (OMC) [19]	27.1%
Unconfined compression strength (UCS) [20]	244.3 kPa
Free swell index [21]	100%
% gravel [22]	0
% sand [22]	2.5
% silt and clay [22]	97.5
Soil classification [22]	CH

TABLE 2: Chemical composition of materials.

Component (%)	Soil	Lime	Jaggery	Gallnut powder
Na ₂ O	1.415	7.296	20.062	11.042
MgO	1.737	4.514	4.178	8.887
Al ₂ O ₃	18.818	0.212	4.996	3.867
SiO ₂	63.615	4.451	34.945	18.140
P ₂ O ₅	0.043	0.07	1.468	2.828
SO ₃	0.207	1.645	12.803	13.571
K ₂ O	2.288	0.000	6.754	13.311
CaO	2.297	81.752	11.743	21.199
TiO ₂	0.873	0.032	0.667	1.614
MnO	0.035	0.000	0.103	0.407
Fe ₂ O ₃	7.484	0.028	2.280	5.133

The lime used in the investigation was used in its processed form as available from the package supplied by the manufacturer. Powdered jaggery was used in the investigation. Jaggery being a natural sweetener, it had natural moisture content in it and care was taken to remove moisture as much as possible. Grated thin films of jaggery were well crushed and then placed in an oven at 50°C, until it dried. The temperature was kept low to prevent them from burning up. It was again crushed well and then sieved through 600 μ sieve to achieve uniform grain-sized particles. Any remnant sticky particles were eliminated, and the fine powder was taken for preparing the sample. The gallnut powder sourced from a local store was sieved through 75 μ sieve to eliminate coarse particles. Potable tap water available in the lab was used for mixing of the materials and sample preparations. Figure 1 shows the materials used in this investigation after preparation.

2.2.2. Characterization of Materials. The experimental investigation began with the characterization of materials adopted in the investigation. The soil was investigated for its geotechnical properties in the laboratory in accordance with

FIGURE 1: (a) Soil, (b) lime, (c) jaggery, and (d) gallnut powder.

codes of BIS. The other materials were subjected to XRF to determine their chemical composition. The materials after preparation were sieved through $75\ \mu$ sieve and were sealed in an air-tight polythene bag for XRF testing. The test was performed under an X-ray tube with a voltage of 50 kV and a current of 1 mA guided through a guide tube of diameter $100\ \mu$ for a period (live time) of 60 seconds. The XRF samples were sent to the Central Electrochemical Research Institute, Karaikudi, Tamil Nadu, for testing, and results were reported.

2.2.3. Determination of Initial Consumption of Lime. There is a minimum lime content that must be added to the soil for achieving modification of soil properties. This content is determined using the Eades and Grim pH [25] test in accordance with ASTM code [26]. Several researchers have adopted this established method for fixing the lime content required for the modification of soil properties in order to improve its performance.

2.2.4. Selection of Mix Ratios. The mix ratios of jaggery, gallnut powder, and lime were fixed randomly such a way that the proportions of jaggery and gallnut powder were varied with respect to the minimum lime content fixed from the Eades and Grim pH test. The mix ratios adopted in this investigation for lime:jaggery:gallnut powder (LJG) were 8:2:2, 8:1:2, and 8:2:1. In earlier work done, James and Pandian [13] had adopted 1:1:1 and 2:3:1, whereas James et al. [14] had adopted a ratio of 1:4:2. Based on the selected mix ratios, the dosages of lime, jaggery and gallnut powder adopted in the study have been given in later section.

2.2.5. Sample Preparation and Testing. The effect of the stabilization was evaluated by preparing statically compacted UCS specimens of dimensions $38\text{ mm} \times 76\text{ mm}$. The samples were prepared at maximum dry density and optimum moisture content. For the evaluation of each combination, three samples were prepared. The samples were then air cured by sealing them inside polythene bags for periods of 3, 7, 14, and 28 days after which they were subjected to UCS test by straining the samples at a rate of 0.625 mm/minute . The UCS test was performed in an electrically operated 50 kN capacity machine with three strain rates. The average strength of three samples was reported. In order to reduce errors in results, eccentric deviations in the test results were neglected from averaging. In the case of outliers in results, tests were repeated to get confirmation. In order to study the effect of cycles of freeze and thaw, 28-day cured samples were placed inside a deep freezer for a period of 24 hours to simulate freezing and were placed at room temperature for a period of 24 hours to simulate thawing. This represented one cycle of freeze-thaw. All samples were subjected to 1, 2, and 3 cycles of freeze-thaw followed by evaluation of UCS. Güllü and Khudir [27] subjected their lime-stabilized fibre-reinforced soil samples up to 3 cycles of freeze-thaw. In order to study the effect of curing conditions, UCS tests were performed on 7-day cured samples. Three different curing conditions were evaluated: air curing, moisture curing, and thermal curing. Moisture curing was performed by sandwiching the samples in beds of cotton that were kept moist throughout the duration of the curing period. Thermal curing was performed by placing the samples in a hot air oven at a temperature of 50°C for the curing period. The 14-day cured sample of the optimal combination was subjected to the X-ray diffraction (XRD) test to determine the mineralogy of the stabilized specimen. X-rays of a wavelength of $1.54\ \text{\AA}$ were used with a goniometer radius of 240 mm. The goni scan started at a 2-theta position of 10.0114° and ended at 89.9794° with a scan step time of 18.0899 seconds. Continuous scanning was adopted with a fixed divergence slit width (0.9570°). The generator settings adopted were a current of 30 mA and a voltage of 40 kV.

3. Results and Discussion

The ICL of the soil sample determined from the Eades and Grim pH test came out to be 4%. According to ASTM [26], it is the lowest lime content required to raise the pH of the soil to 12.4. With this lime content as primary binder, jaggery and gallnut powder were considered as auxiliary additives to soil to study the effect of the combination in soil stabilization subjected to freeze-thaw cycles as well as curing conditions. Figure 2 shows the determination of ICL from the pH test. From the pH test results, the pH reached 12.43, when the lime content was 4%, and hence was taken as the ICL for the soil under investigation. When the lime content reaches ICL, soil pH becomes sufficiently high to make the soil silica and alumina soluble. When the lime content is increased beyond ICL, the residual calcium from lime will react with the soluble silica and alumina in the soil initiating pozzolanic reactions. Such pozzolanic reactions will continue as long as

FIGURE 2: ICL from Eades and Grim pH.

high-pH environment and residual calcium are available, leading to the formation of reaction products that enhance the stabilization of soil [28]. The chemical reactions are as follows [3]:

3.1. UCS of Lime-Jaggery-Gallnut Powder Stabilized Soil. The strength of the stabilized soil using the traditional combination of lime, jaggery, and gallnut powder was evaluated by conducting the UCS test. Three different combinations of LJG were adopted for stabilizing the soil: 8 : 2 : 2, 8 : 2 : 1, and 8 : 1 : 2. The minimum lime content was fixed as 4% based on the Eades and Grim pH test.

Figure 3 shows the results of the UCS test of the LJG combinations for various curing periods. It can be seen that addition of the traditional combination results in an increase in the strength of the virgin soil. The strength of the soil at 28 days of curing has been used for representing the strength curve for soil. It is clearly evident that all LJG combinations lie above the strength curve of virgin soil. However, with increase in curing period, LJG821 produced the best increase in strength compared to virgin soil. The strength of the virgin soil increased from 244.3 kPa to 377.02 kPa for the combination LJG821. LJG822 increased in strength till 7 days of curing beyond which the gain in strength was marginal. However, this marginal increase is higher than that of virgin soil at 309.69 kPa. LJG812 produces a slightly anomalous strength gain pattern wherein there is a slight dip in the strength at 7 days of curing. Further gain in strength was noticed which is higher than that in LJG822, achieving a strength of 349.8 kPa at 28 days of curing. A similar gain in strength due to addition of LJG combinations was also reported by James and Pandian [13]. James et al. [14], in another work, had reported a loss in strength due to addition of an LJG combination but had concluded that provision of curing

FIGURE 3: UCS of LJG combinations with curing.

period could possibly result in strength gain. In both the aforementioned works, samples were tested immediately after preparation and effect of curing was not taken into account. The present study clearly shows that provision of curing can result in an increase in strength of the soil stabilized with the traditional combination of lime, jaggery, and gallnut powder.

Analysing the 28-day strengths of the various combinations of LJG, the percentage strength gains calculated are shown in Figure 4. LJG821 developed a strength gain of 54.33%, the maximum of all three combinations. LJG812 gained 43.18%, whereas LJG822 developed the least strength gain of 26.76%. James and Pandian [13] reported an increase in the strength of the soil from 215 kPa to 340 kPa and 403 kPa for LJG ratios of 1 : 1 : 1 and 2 : 3 : 1, which translates to a strength gain of 58.14% and 87.44%, respectively. However, it must be noted that the strength gain values in their work correspond to immediate strength.

Figure 5 shows the comparison of the strength of LJG-stabilized soil from the present work and earlier work done by James and Pandian [13] and James et al. [14]. Before the comparison, a few important differences between the earlier studies and the present one need to be understood. The earlier investigations adopted the same combination of lime, jaggery, and gallnut powder, albeit with different soils. In addition, they did not consider the effect of curing on the stabilization process. The strength and index properties reported in the earlier work were performed immediately after mixing and sample preparation. Secondly, earlier studies adopted very high doses of jaggery and gallnut powder, whereas the present work kept their dosages to low levels. Finally, the earlier studies varied the percentage of dosage of the whole combination. Within the particular dosage, a particular proportion of the three additives were maintained. Several such percentages were adopted for each ratio of additives. Thus, they essentially tried identifying an optimal percentage providing the maximum benefits by trial and error. In the present work, however, lime content was fixed by an established method, and with reference to the minimum lime content, the proportions of jaggery and gallnut powder were varied. Thus, the minimum lime

FIGURE 4: Percentage strength gain of L/JG combinations.

FIGURE 5: Comparison of present work with previous studies.

content in each case was the same, while only jaggery and gallnut powder contents were varied to alter the ratios. In order to understand the composition of the present study and earlier studies, a comparison of the dosages of lime, jaggery, and gallnut powder in all three studies is shown in Table 3. It can be seen that the maximum lime content was adopted in the present study when compared to the previous studies. On the other hand, the dosages of jaggery and gallnut powder in the earlier studies were higher when compared to the present study. The total additive content in all the three studies varied from 5 to 8%. In the studies that produced positive results, it can be seen that the total additive content used was around 5%. However, too many investigations have not been performed in using this combination for soil stabilization, and hence, more research can provide a realistic scenario in its utilization in soil stabilization.

The results from previous studies were from uncured specimens. A 3-day cured specimen result from the present study gives a more realistic comparison. It can be seen that with the exception of the results from James et al. [14], the other two achieved positive increase in strength of the stabilized soil. The work done by James and Pandian [13]

shows the maximum benefits in the strength of the stabilized soil compared to the present work. It can be seen that when the ratio of jaggery and gallnut powder became very high with reference to lime as in James et al. [14], the strength of the stabilized soil reduced when compared to the virgin soil. In the present study, the proportions of jaggery and gallnut powder were lesser in relation to lime. Though, they produced improvement in strength of the soil, it could not achieve the levels of those investigated by James and Pandian [13] wherein the proportions of the three were comparable. Thus, too high or too low proportions of jaggery and gallnut powder do not produce optimal results. Another observation that could be noticed was that in both the studies that produced positive outcomes, combinations wherein gallnut powder was lesser than jaggery proportion produced higher strength. In the work done by James et al. [14], only one combination was investigated because of which a comparative statement either in support or against the aforementioned postulation could not be arrived at. Moreover, the lime content in that investigation was the lowest which may also have been a contributing factor. Thus, it can be stated that, in future investigations, wherein different combinations of lime, jaggery, and gallnut powder may further be investigated, it is best to keep the proportions of the three at comparable levels with jaggery always higher than gallnut powder. Moreover, in all three investigations, the strength of the stabilized soil was compared with that of virgin soil. It needs to be seen whether this traditional combination can outshine the performance of pure lime in stabilizing the soil, which can be done by comparing the performance of the combination against that of lime-stabilized soil rather than virgin soil in future investigations.

3.2. Effect of Freeze-Thaw on UCS of Stabilized Soil. The stabilized specimens were subjected to freeze-thaw conditions in order to determine the durability of the stabilized soil specimens subjected to extreme conditions. The samples were subjected to freezing for 24 hours followed by thawing for another 24 hours comprising one cycle. The specimens were subjected to one, two, and three cycles of freeze and thaw. Figure 6 shows the effect of freeze-thaw cycles on the various combinations of L/JG. It can be clearly seen that the increase in number of freeze-thaw cycles resulted in a reduction in the strength of the stabilized soil across all three combinations. Aldaood et al. [29] reported a reduction in UCS of lime-treated gypseous soil with increase in number of freeze-thaw cycles. Similar reduction in UCS of stabilized soils with increase in freeze-thaw cycles have been reported by others as well [27, 30, 31]. However, it can be seen that the loss in strength was the lowest for LJG821 when compared to the other combinations. All three combinations result in a steep reduction in strength after the first cycle of freeze-thaw. However, after the second cycle, there is difference in the strength loss pattern for all three combinations. LJG822 results in a steady loss in strength for cycles 1 and 2; thereafter, there is stabilization of strength loss indicated by the flattening of the curve. In the case of LJG812, an undulating pattern of strength loss is seen between the three

TABLE 3: Doses of lime and additives.

Study	Designation	Ratio of LJG	Lime (%)	Jaggery (%)	Gallnut powder (%)	Total additive (%)
Present study	LJG822	8:2:2	4	1	1	6
	LJG821	8:2:1	4	1	0.5	5.5
	LJG812	8:1:2	4	0.5	1	5.5
James and Pandian [13]	LJG111	1:1:1	1.67	1.67	1.67	5
	LJG231	2:3:1	1.67	2.5	0.83	5
James et al. [14]	LJG142	1:4:2	1.14	4.57	2.29	8

cycles of freeze-thaw. LJG821 results in lesser strength loss after cycle 1, and there is a marginal difference in strength loss between cycle 2 and cycle 3. However, comparing all three combinations, LJG821 seems to be the one which is comparatively more resistant to freeze-thaw cycles.

Figure 7 shows the percentage change in the strength of the stabilized soil subjected to increasing number of freeze-thaw cycles. The percentage strength change was calculated based on two criteria: first, cumulative percentage change in strength with reference to zero cycles of freeze-thaw, and second, percentage strength change with each subsequent cycle of freeze-thaw. In the former, the samples that were not subjected to freeze-thaw were the control specimens based on which the percentage strength change was worked out for all three cycles of freeze-thaw. In the latter, the strength of the specimen of the preceding cycle was the control specimen for calculating the percentage strength change of the subsequent cycle. The solid bars represent cumulative percentage strength change, whereas the striped bars represent subsequent percentage strength change. It can be seen that LJG821 resulted in the least cumulative percentage loss in strength after three cycles of freeze-thaw at 12.3%, while the other two combinations of LJG822 and LJG812 lost 24.2% and 28.7% strength, respectively. Thus, LJG821 loses around 1/8th of its strength, whereas the other two lose close to 1/4th of their strength after three cycles of freeze-thaw. Comparing the subsequent percentage strength change, LJG822 sheds 12% of its cycle 1 strength after 2 cycles of freeze-thaw, while LJG812 loses 13.8% of its cycle 2 strength after 3 cycles of freeze-thaw. It is only the combination of LJG821 which shows more or less similar loss in strength after cycles 2 and 3 at 2% and 3.3%, respectively. Thus, it can be stated that LJG821 is more durable compared to the other two combinations.

3.3. Effect of Curing Conditions on the UCS of Stabilized Soil. In order to study the effect of different curing conditions, the stabilized soil samples were cured for 7 days under thermal, moisture, and air curing conditions. The results of the investigation are shown in Figure 8. It can be clearly seen that thermal curing produced the best result in terms of strength of the stabilized soil. The strength gained by the stabilized soil was above 1 MPa, whereas the other two methods of curing paled in comparison. Air curing resulted in a nominal increase in strength of the stabilized soil, in the range of 0.3 MPa, while moisture curing resulted in strength loss. Thus, thermal curing developed more than three times the strength of air curing. Nasrizar et al. [32] reported that curing of lime-stabilized soil at elevated temperatures

FIGURE 6: Effect of freeze-thaw cycles on UCS of stabilized soil.

FIGURE 7: Percentage strength change with freeze-thaw cycles.

accelerates the rate of strength gain leading to higher strength. The moisture cured samples produced strengths lower than the virgin soil. In fact, the strengths of the moisture cured samples were in the order of one-fifth of the strength of the virgin soil. This needs to be probed in future investigations with regards to the water resistance and durability of the traditional combination in soil applications.

FIGURE 8: UCS of stabilized soil subjected to different curing conditions.

An unexpected observation that can be seen in thermal curing is that LJG812 produced the highest strength of all three combinations against the expected combination of LJG821. However, the variation in strength between the two is just 60 kPa. Hence, it can be concluded that LJG821 also produces high strength upon thermal curing. In the case of moisture curing, the results of the three combinations are very close to each other. Moreover, moisture curing led to very poor results because of which the variations have not been delved into much detail.

3.4. Mineralogy of Stabilized Soil. In order to understand the chemical changes taking place at microlevel, an investigation of the mineralogy of the stabilized sample was carried out to study the reaction products responsible for the strength gain of the stabilized soil. A sample of stabilized soil of the combination LJG821 was sent for mineralogical analysis as it produced the maximum strength of all three combinations. Figure 9 shows the mineralogy of LJG821. In general, it is possible to understand the presence of crystalline and amorphous phases from the diffractogram. Presence of crystalline phases results in sharper and clearer peaks in the scatter pattern, whereas amorphous phases do not contribute much to diffraction peaks and, hence, result in the formation of a broad hump (sometimes referred to as halo) rather than sharp peaks. It is an indirect indicator of the presence of amorphous phases in the material. However, the extent of presence of amorphous materials plays a vital role in the pattern developed. Identifying amorphous content can be difficult because at low concentrations their contribution to intensity peaks is not clear, and a broad diffraction hump can result in overlap of peak intensities. In most of the cases, the presence of amorphous phases is either not detected or ignored. In the present case from Figure 9, it can be seen that development of such a broad hump is marginal or not noticeable. However, in such cases other methods can be adopted to quantify crystalline and amorphous phases like

FIGURE 9: Mineralogy of stabilized soil with lime, jaggery, and gallnut powder.

single peak method and whole pattern methods like traditional Rietveld method, internal standard method, external standard method, linear calibration model, degree of crystallinity, and PONKCS method [33]. Since the objective of performing the analysis was identifying the reaction products, along with near absence of hump formation, Rietveld analysis for quantification of the phases was not performed.

Analysis of the raw data from mineralogical experiments was carried out using Crystal Impact Match v3.0.3. The analysis shows the formation of minerals like tilleyite, xonotlite, $\alpha\text{-C}_2\text{SH}$, yeelimite, and calcite. Tilleyite, xonotlite, and $\alpha\text{-C}_2\text{SH}$ are all CSH minerals [34]. Some of the major peaks of the diffraction pattern were observed at 2-theta values of 20.85° , 26.65° , 27.45° , 27.9° , 50.13° , and 59.98° with corresponding d-spacings of $4.26045\text{ \AA}$, $3.34538\text{ \AA}$, $3.24911\text{ \AA}$, $3.19805\text{ \AA}$, $1.81984\text{ \AA}$, and $1.54232\text{ \AA}$, respectively. The formation of calcite also contributes to strength gain, however, not to the same level as that of CSH minerals [35]. Yeelimite, on the other hand, is formed because of the presence of sulphate group in both jaggery and gallnut powder. Thus, it can be seen that the formation of CSH minerals is responsible for the gain in strength of the stabilized soil. This may be due to the supply of calcium from lime and gallnut powder with good proportions which reacts with the silica from soil and jaggery in the presence of water to form CSH gel responsible for the strength gain.

4. Conclusion

Based on the experimental investigation carried out on the stabilization of soil using the traditional combination of lime, jaggery, and gallnut powder, the following can be concluded:

- (i) A minimum of 4% lime is essential for modifying the soil properties in accordance with the Eades and Grim pH test. Addition of a combination of lime, jaggery, and gallnut powder resulted in an increase in the UCS of the stabilized soil with curing for all three combinations investigated. Thus, the right proportions of lime, jaggery, and gallnut powder and sufficient curing period are two important parameters that affect the strength of the stabilized soil. The strength gain was in the range of 26% to 54% over a curing period of 28 days.
- (ii) Based on the present and earlier similar work, it can be concluded that strength development was better when jaggery outweighed gallnut powder, provided there was enough lime to drive the stabilization reactions.
- (iii) Alternate cycles of freeze-thaw resulted in a reduction in strength of the stabilized soil with increase in number of cycles indicating that the freeze-thaw condition is capable of partly reversing the strength gained by stabilization. The loss in strength varied from 1/8th to 1/4th of the initial strength after three cycles of freeze-thaw.
- (iv) Thermal curing resulted in the maximum gain in strength, whereas moisture curing resulted in detrimental effects. Thermal curing was capable of producing more than three times the strength developed by air curing. Thus, curing condition is the third important parameter that influences stabilization by this combination.
- (v) Mineralogical investigation of the stabilized sample indicated the formation of CSH minerals, similar to conventional lime stabilization, resulting in strength gain over time.
- (vi) In short, the proportion of lime, jaggery, and gallnut powder, curing period, curing condition, and durability condition (cycles of freeze-thaw) will influence the strength gained by the stabilized soil, based on which LJG821 seems to be the optimal combination for stabilizing this soil out of all combinations evaluated.
- (vii) Traditionally, gallnut powder was fermented before it was used/mixed with lime in mortars. Thus, activation of ingredients is another important parameter that can be studied in future investigations. Though, freeze-thaw durability was studied in this investigation, other durability conditions like cycles of wetting-drying, extreme pH environments, and stabilization of sulphate rich soils can also be evaluated in future investigations to open the potential of this traditional combination in soil stabilization.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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