Research Article

Plasticity, Swell-Shrink, and Microstructure of Phosphogypsum Admixed Lime Stabilized Expansive Soil

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The study involved utilization of an industrial waste, Phosphogypsum (PG), as an additive to lime stabilization of an expansive soil. Three lime dosages, namely, initial consumption of lime (ICL), optimum lime content (OLC), and less than ICL (LICL), were identified for the soil under study for stabilizing the soil. Along with lime, varying doses of PG were added to the soil for stabilization. The effect of stabilization was studied by performing index tests, namely, liquid limit, plastic limit, shrinkage limit, and free swell test, on pulverized remains of failed unconfined compression test specimens. The samples were also subjected to a microstructural study by means of scanning electron microscope. Addition of PG to lime resulted in improvement in the plasticity and swell-shrink characteristics. The microstructural study revealed the formation of a dense compact mass of stabilized soil.

1. Introduction

Soil is a precious resource that humans depend upon for all activities. With each passing day, the pressure on soil due to human activities is increasing. Acute shortage of land has come to the forefront due to the development activities of modern man. Land becomes more scarce with growth of cities and it often becomes essential to construct buildings and other structures on sites where unfavourable conditions are present [1]. Certain soils like expansive soils are extremely problematic and cause a wide range of problems to a geotechnical engineer. Expansive soils are the soils which swell significantly when they come in contact with water and shrink when the water squeezes out [2]. It has long been known that volume change behavior of expansive soils causes severe distress to the overlying structures. Due to volume change, the soils exert pressure on overlying structures resulting in cracks in sidewalks, basement floors, driveways, pipelines, and foundations [3]. Different soils exhibit different extents of volume change depending upon various factors. The mechanism of swelling is complex and is influenced by a number of factors: the type and amount of clay minerals present in the soil, specific surface area of the clay, structure of the soil, and valency of the exchangeable cation [3]. The greatest problem arises

when montmorillonite mineral content in the soil is high. Thus, such a soil needs to be modified or stabilized in order to make it suitable for construction. Soil stabilization is a common engineering technique used to improve the physical properties of weak soil and make it capable of achieving the desired engineering requirements [4]. Chemical stabilization is the mixing of soil with one or a combination of admixtures of powder, slurry, or liquid [5]. Chemical stabilization results in the modification of the soil through chemical reactions taking place between the stabilizer and the minerals present in the soil. Among the various chemical stabilization techniques adopted for expansive soils, lime stabilization is most widely adopted for controlling the swell-shrink properties of expansive soils [6]. Recently, industrial wastes have also been widely adopted as chemical stabilizers in soil stabilization enabling their reutilization [7]. However, literature suggests that lime along with additives, usually industrial wastes, results in better stabilization of soil [8–14]. One such industrial waste is Phosphogypsum (PG) produced from fertilizer plants. Instances of use of PG in soil stabilization can be found in literature. Degirmenci et al. [15] had adopted combinations of cement and PG for stabilization of soil. Degirmenci [16] had also adopted PG and natural gypsum for manufacture of stabilized adobe soil blocks. James et al. [17] had studied

the effect of PG as a standalone stabilizer in enhancing the strength and index properties of an expansive soil. Ghosh [18] had adopted lime and PG for stabilization of pond ash and investigated its compaction characteristics. Kumar et al. [19] studied the stabilizer combination of lime and PG for stabilizing bentonite. A lot of work has been done with PG as the focus; however, works related to combinations of lime and PG in soil stabilization are limited. The few works that have been done with the said combination involved a trial and error approach of selecting lime contents for stabilization purposes. Moreover, utilization of PG in earlier studies was at high dosage levels in soil stabilization and they concentrated more on the engineering properties rather than index properties. The index properties of soils are as important as their engineering properties. They are indirect indicators of the engineering behavior of any soil. Unfortunately, not many researchers concentrate on the index properties of stabilized soils as more importance is given in directly analyzing the engineering characteristics themselves. In order to address the aforementioned shortcomings, an investigation was designed to evaluate the strength and index properties of a lime stabilized expansive soil admixed with PG, in small doses of less than 2%. However, this paper limits itself to analyzing the combined effect of lime and PG on the index properties of the soil alone with the use of scanning electron microscopy (SEM) to see the changes at the microstructural level.

2. Materials and Methods

The materials that were used in this study include the natural soil, hydrated lime, and PG. The natural soil used in this study was obtained from Thatthamanji Village in Tiruvallur, Tamil Nadu, India. The properties of the soil were tested in the laboratory and are shown in Table 1. Various tests on soil including liquid limit and plastic limit [20], shrinkage limit [21], specific gravity [22], grain size distribution [23], proctor compaction [24], UCC strength [25], and pH [26] were performed in accordance with specifications of Bureau of Indian Standards (BIS).

2.1. Lime. Lime is a broad term that includes quick lime [CaO], slaked or hydrated lime [Ca(OH)₂], and carbonate lime [CaCO₃]. Hydrated lime and quick lime are the most commonly used forms of lime in soil stabilization. Carbonate lime is not preferred for soil stabilization because of its inert nature. However, carbonate lime in the form of egg shell powder adopted in soil stabilization resulted in improvement of soil properties [27]. The lime adopted in the present study was laboratory grade hydrated lime manufactured by Messrs. Nice Chemicals India Private Limited. Laboratory grade lime was adopted in order to have a better control over the results obtained.

2.2. Phosphogypsum (PG). PG is an industrial waste produced during the manufacture of phosphoric acid for fertilizer production by wet acid method [15, 28]. The worldwide annual production of PG is estimated to be in the range

TABLE 1: Properties of soil.

Property	Value
Liquid limit	68%
Plastic limit	27%
Plasticity index	41%
Shrinkage limit	10%
Specific gravity	2.76
% gravel	0
% sand	2.5
% silt	60.5
% clay	37
Maximum dry density	15.3 kN/m ³
Optimum moisture content	25%
UCC strength	115.8 kPa
Soil pH	6.53
Soil classification	CH

of 100–280 million tonnes [28, 29]. India produces about 11 million tonnes of PG every year [30]. PG contains naturally occurring radioactive materials like Ra-226 [15, 16, 28, 31], which may be the reason for its ban in several countries [28]. However, in India, in 2009, the Atomic Energy Regulation Board of India decreed vide its directive (number 01/09) that sale of PG for construction purposes does not require its approval provided the activity concentration of Ra-226 in it is less than 1.0 Bq/g [30]. PG used in this study was sourced from the fertilizer plant of Coromandel International Limited, located in Ennore, north of Chennai, India. The specific gravity of PG determined in the laboratory came out to be 2.48. Figure 1 shows the microstructure of the materials adopted in the study obtained using scanning electron microscopy (SEM). The chemical composition of the materials adopted in the study is shown in Table 2.

2.3. Methods. The sequential methodology adopted in the experimental investigation involved preparation and characterization of materials, determination of lime content and PG content for stabilization, laboratory experimental investigation, and finally concluding with a microstructural examination.

2.3.1. Preparation and Characterization of Materials. The soil obtained from field was prepared for various laboratory tests in accordance with BIS code [32]. The hydrated lime obtained from the manufacturer was used as provided. Industrial waste materials tend to have variations in their characteristics based on their source and contamination during storage. Hence, in order to achieve uniformity of the waste material for use in the stabilization process, PG obtained from the disposal site was crushed, pulverized, and thoroughly mixed manually using a trowel. In order to further reduce variations and improve reactivity of the waste material, it was sieved through BIS 75-micron sieve and only the fine fraction was used in the investigation. Following this, the materials were subjected to characterization to determine their properties. The soil

TABLE 2: Chemical composition of materials.

Compound	Al ₂ O ₃	CaO	Fe ₂ O ₃	K ₂ O	MgO	MnO	Na ₂ O	P ₂ O ₅	SiO ₂	TiO ₂	SO ₃
Soil	18.818	2.297	7.484	2.288	1.737	0.035	1.415	0.043	63.615	0.876	0.207
Lime	0.053	72.767	0.037	0.003	14.604	0.004	0.047	0.005	0.245	0.003	0.048
PG	0.649	35.728	4.88	0.042	0.661	0.001	0.106	10.701	16.957	0.015	4.598

FIGURE 1: Microstructure of soil, lime, and PG.

was subjected to geotechnical characterization to determine its index and engineering properties. All the materials were subjected to X-Ray Fluorescence (XRF) test for determining their chemical composition. PG sent for XRF test to the Sophisticated Analytical Instrument Facility at Indian Institute of Technology Bombay, Mumbai, was from the crushed, mixed, and sieved sample.

2.3.2. Determination of Lime and PG Content. Following the characterization of materials, the next step involved determination of lime content required for stabilization. This investigation adopted a scientific method of determination of lime content for stabilization instead of the usual trial and error method. Three lime doses were identified for chemical stabilization of the soil sample. One was the initial consumption of lime (ICL) determined using Eades and Grim pH test [33]. Soil samples of 25 g each were taken in plastic bottles with cap and were mixed with lime in increments of 0.5% by weight. 100 mL of distilled water was added to each bottle and they were shaken for 30 seconds. The mixture was repeatedly shaken for 30 seconds at intervals of 10 minutes for a period of 1 hour in accordance with ASTM code [34]. A calibrated pH meter was used to determine the pH of the lime-soil solutions. The lowest percentage of lime in soil that gives a pH of 12.4 is the approximate lime percentage for stabilizing the soil. Second was optimum lime content (OLC) determined by performing unconfined compression (UCC) test in accordance with BIS code [25] on soil mixed with increasing lime content and cured for 2 days. Earlier authors have also used a similar procedure for determination of OLC [35–37]. For determination of OLC, UCC samples were prepared at optimum moisture content and maximum dry density obtained from standard proctor compaction test. The lime content in the samples was added by dry weight. The lime content that produced the maximum strength was taken as the OLC. The third lime content was taken as one value less than ICL (LICL) in order to understand the effect of lime below the minimum requirement. The quantities of PG (0.25%, 0.5%, 1%, and 2%)

used were fixed randomly but were restricted to small dosages.

2.3.3. Experimental Investigation. In lieu of studying the index properties by directly mixing the soil sample with lime and PG, UCC samples were cast for various combinations and cured for designated periods. This ensured that the soil was sufficiently modified due to the chemical reactions taking place within the material. The UCC test samples were prepared by mixing soil, lime, and PG in various proportions in dry conditions. It is well known that addition of lime to soil results in a reduction in maximum dry density and increase in the optimum moisture content. Hence, moisture density relationships were obtained for all three lime contents by means of Jodhpur mini compaction test. According to Singh and Punmia [38] the results of the Jodhpur mini compaction test are close to that of standard proctor compaction within the limits of experimental error. One of the density and moisture content values obtained from the compaction tests was fixed for preparation of UCC samples. The samples were moulded in a split mould of 38 mm diameter and 76 mm height using static compaction. They were then demoulded and were cured for chemical reactions to proceed for a period of 28 days in sealed polythene covers. The preparation of UCC test samples is shown in Figure 2. At the end of the curing period, the samples were subjected to continuous axial loading until the samples failed. All the specimens were strained at a strain rate of 0.625 mm/minute. The failed samples were then dried, crushed, and pulverized for carrying out the index properties test. However, the results of the strength tests are discussed in an earlier paper by the authors [39]. This work deals with the effects of addition of PG on the index properties of the soil. The index tests on the stabilized soil samples were all done in accordance with relevant BIS codes.

2.3.4. Microstructural Study. A microstructural study was performed on the failed test specimens for understanding the changes taking place in the soil structure due to stabilization.

FIGURE 2: Preparation and curing of UCC test samples.

3. Results and Discussion

Based on Eades and Grim test, the minimum quantity of lime for modification of soil (ICL) was 5.5%. The OLC determined from UCC tests was 7%. The LICI content was adopted as 3%. The soil samples were stabilized using these three lime contents and admixed with PG in varying doses and the index properties of the stabilized soil were investigated.

3.1. Effect of PG on Plasticity of Lime Stabilized Soil. The addition of PG to lime stabilized soil resulted in a modification in the Atterberg limits of the soil. Figure 3 shows the effect of addition of PG on the plasticity of 3% lime stabilized soil. It can be seen that the effect of addition of PG on the plasticity of 3% lime stabilized soil is through the modification of liquid limit. The addition of PG has almost no effect on the plasticity of the soil. Due to the addition of 0.25% PG, there is a reduction in the liquid limit of the soil from 63.76% to 50.96%. On further increase in PG, there is a slight increase in liquid limit to 53.13% for 2% PG addition. This effect is directly reflected on the plasticity of the stabilized soil as evident from the similarity in the curves. However, it can be noticed that the least plasticity of 18.88% is achieved at 0.25% PG. However, for all values of PG addition, the plasticity of the stabilized soil is less than that of pure lime stabilized soil. For all additions of PG, the plasticity index of stabilized soils lay in the range of 18.88% to 19.45% whereas the plasticity of 3% lime stabilized soil was 31.2%. In a similar study performed by James and Pandian [40], the addition of ceramic dust (CD) as an additive to lime resulted in an increase in plastic limit initially followed by decrease on further addition of CD. The plasticity index decreased significantly when the lime content was below ICL.

Figure 4 shows the effect of PG on the plasticity of 5.5% lime stabilized soil. At 5.5% lime stabilization, the addition

FIGURE 3: Effect of PG on the plasticity of 3% lime stabilized soil.

of PG resulted in an initial decrease in liquid limit of the stabilized soil, followed by an increase in liquid limit of the same on further addition of PG. The liquid limit reduced to 48.92% for 0.25% PG addition, which increased thereon to 53.67% for 2% PG addition. According to Sivapullaiah and Jha [41], the reduction in liquid limit on addition of lime to fly ash stabilized soil is due to replacement of sodium ions with calcium ions, reduction in diffused double layer, and increase in electrolyte concentration of pore fluid. PG, which is chemically calcium sulphate, also acts as a source of calcium ions, thus contributing to similar effects on the soil. On the other hand, the addition of PG resulted in an overall increase in the plastic limit after a slight dip for 0.25% addition of PG. The plastic limit of 5.5% lime stabilized soil decreased from 37.24% to 36.4% for 0.25% PG addition but increased on further addition of PG to 40.06% for 2% PG addition. The combined result of this can be seen in an initial decrease in plasticity index followed by an increase, due to rise in liquid limit. However, the overall increased plasticity index was still below the plasticity of 5.5% lime stabilized soil. On closer observation, low plasticity levels of 12.52% and 11.57% were seen for 0.25% and 0.5% PG addition, respectively. In an earlier work, addition of CD to ICL content resulted in significant plasticity reduction at only one particular dosage of CD [40].

The effect of PG on 7% lime stabilized soil is shown in Figure 5. It is evident that addition of PG to 7% lime stabilized soil achieves reduction in plasticity by modifying both liquid limit and plastic limit. Addition of PG to 7% lime stabilized soil results in an initial increase in liquid limit which reduces and then stabilizes at higher PG content. The least liquid limit value of 46.75% was achieved at 1% PG addition. Kumar et al. [19] found that addition of 8% PG to 8% lime stabilized bentonite resulted in an increase in the liquid limit of the stabilized soil. Effect of PG on plastic limit is consistent increase with increase in PG content. Plastic limit steadily increased from 36.47% for pure lime stabilized soil to 43.22% for 2% PG addition. As a result of this, there is a significant reduction in plasticity of the soil, with higher reduction at

FIGURE 4: Effect of PG on the plasticity of 5.5% lime stabilized soil.

FIGURE 5: Effect of PG on the plasticity of 7% lime stabilized soil.

higher PG contents of 1% and 2%. For 1% PG addition, the plasticity is just around 4%. Kumar et al. [19] found that addition of PG on the plasticity of lime stabilized bentonite was marginal. Nwadiogbu and Salahdeen [42] found that the combination of lime and locust bean waste ash resulted in an increase in plastic limit and reduction in plasticity when compared to plain locust bean waste ash stabilization.

Figure 6 compares the plasticity of all three lime-PG stabilized soil combinations. The reduction in plasticity is greater with greater lime content. Considering all three lime contents, it can be seen that, at lower lime contents of 3% and 5.5%, the reduction in plasticity is at lower dosage of PG whereas, at higher lime content of 7%, the reduction in plasticity shifts to the higher side of PG addition. This trend exhibited by the plasticity characteristics is consistent with the trends exhibited by the strength of PG admixed lime stabilized soil [39]. In that study, James and Pandian found 0.25%, 0.5%, and 1% PG to be the optimal doses for 3%, 5.5%, and 7% lime stabilized soil, respectively, for maximum strength. In the present investigation, the optimal plasticity

FIGURE 6: Comparison of plasticity of lime stabilized soil admixed with PG.

FIGURE 7: Locations of lime-PG stabilized soil combinations on plasticity chart.

values are also achieved at the abovementioned doses of PG to lime.

Figure 7 shows the plot of various combinations of lime-PG stabilized soil on the plasticity chart of BIS classification. The virgin soil plot lies above the A-line in the plasticity chart as shown. However, addition of lime immediately improves the properties of the soil and changes its classification. It can be seen that even addition of 3% lime to soil results in its classification changing from clay to silt of high plasticity. All combinations of PG with LICI content plots are in the zone of silt of high plasticity. In the case of 5.5% lime, there is a further reduction in plasticity but still plots are in the same zone in a cluster below the cluster of LICI-PG combinations, the exceptions being 0.25% and 0.5% PG with LICI content.

This along with 7% lime-PG combination plots is in the zone of silt of intermediate plasticity. The exception in the case of 7% lime stabilization is 0.25% PG which lies on the border line of zones of high and intermediate plasticity. In the case of lime with PG, it can be noticed that, generally, the lime content is responsible for shift in both liquid limit and plasticity, whereas the effect of PG varies with lime content. At lower lime contents of L1CL and ICL, PG influences liquid limit more than plasticity as seen from the horizontal shifting of the plot points. James et al. [17] found that when PG was used as a standalone stabilizer for an expansive soil, it influenced liquid limit more than plastic limit. In the case of OLC, PG influences both liquid limit and plasticity as seen from the diagonal shifting of plot points. In the plasticity chart, the shifting of plot points reveals that lime has significant contribution in altering plasticity when compared to PG. However, the point being professed is that PG is still capable of reducing the plasticity of lime stabilized soil further. Calik and Sadoglu [43] found that addition of lime to soil-perlite system resulted in its classification changing from high plastic clay to silt of medium to high plasticity. James et al. [17] found that addition of 50% PG to an expansive soil resulted in the classification changing from high plastic clay to low plastic silt. Kalkan [44] found that the addition of 30% silica fume to an expansive soil resulted in the classification changing from high plastic clay to low plastic clay group. Sabat [2] found that addition of up to 30% CD to an expansive soil resulted in a change in classification from high plastic clay to low plastic clay. In the present case, however, due to the presence of lime, the dosage of PG is small compared to the aforementioned works, wherein large quantities of waste materials were added for achieving a change in classification. Thus, it can be concluded that PG as an auxiliary additive to lime stabilization of expansive soils can further augment the already pronounced effect of lime in altering plasticity. But this effect of PG reduces when the lime content increases as seen from the distance of the amended plot points for the three lime contents considered in the study.

3.2. Effect of PG on Swell-Shrink of Lime Stabilized Soil. The swell-shrink characteristic of any soil is a very good indicator of its volume change behavior. A soil with poor swell-shrink characteristics is usually problematic and difficult to deal with. Ito and Azam [45] concluded in their study that the swelling properties at a given initial degree of saturation can be estimated using the results of the free swelling test and the swell-shrink test in conjunction. In the present study, a simple free swell test and shrinkage limit test were adopted to study the swell-shrink nature of the soil. Figure 8 shows the free swell of lime stabilized soil.

It can be seen that addition of PG to lime stabilized soil does influence its swell. Addition of 0.25% PG to L1CL lime content results in a reduction in swell of the soil, but any further increase in the PG content results in increase in swell of the stabilized soil. However, at higher lime contents of 5.5% and 7%, the influence of PG is marginal. The effect of increasing PG results in an initial increase in swell but as the PG content reaches the optimal dosage, there is a reduction

FIGURE 8: Free swell of lime stabilized soil admixed with PG.

in swell. However, the swell is of the same order as that of pure lime stabilized soil. In the case of 3% lime stabilized soil, the swell reduces from 50% to 31.8% for 0.5% addition of PG, whereas, for 5.5% and 7% lime stabilized soil, the least swell occurred at 1% dosage of PG. In the case of 5.5% lime-PG stabilization, the swell reduces from 24.6% to 23.6% while, for 7% lime-PG stabilization, the same changes from 8% to 7.1%. Though the optimal dosages are slightly off from earlier established values, the general trend of low PG dose at lower lime content and higher PG dosage at higher lime content for achieving swell control is still maintained. Earlier James et al. [17] found that expansive soil modified by PG as a standalone stabilizer reduced the free swell of the soil from 100% to 20% on addition of 50% PG. Seco et al. [46] found the addition of either of 5% natural gypsum and 5% rice husk ash produced swell control comparable to that of 4% lime. Sabat and Nanda [47] found that addition of 25% marble dust to 10% rice husk ash stabilized soil produced no swell pressure. James and Pandian [40] found that addition of CD to lime stabilized soil resulted in a significant reduction in free swell of the soil at low lime content. Yilmaz and Civelekoglu [1] found that 10% gypsum was capable of reducing the swell of bentonite from 64.9% to 19.8%.

The results of the free swell test, wherein 0.25% addition of PG resulted in an increase in the free swell at 5.5% and 7% lime stabilization, was not in agreement with the results of plasticity tests. The free swell index test being a very simple test produces results of lesser accuracy when compared to other swell potential tests. In order to understand whether there were any big deviations in the individual test data for 0.25% PG addition due to experimental error resulting in errors in the average, the standard deviations (SD) of the free swell test data were calculated. The SD of 0.25% PG with 3% lime was the least at 3.53 when compared to the maximum of 7.07 for 1% and 2% PG. In the case of 5.5% and 7% lime stabilization, the corresponding SD for 0.25% PG were 4.77 and 1.84 against maximum values of 19.24 and 6.18 for 2% and 0.5% PG, respectively. The SD of 0.25% was the lowest among the four PG combinations for both 3% and 7% lime

FIGURE 9: Shrinkage limit of lime stabilized soil admixed with PG.

stabilization while it was the second lowest in the case of 5.5% lime stabilization. Thus, it can be seen that the SD of 0.25% PG combination showed the least variation indicating more closeness of individual results of all combinations, signifying reduced error due to scattering of data points. More accurate swell potential tests can reveal the true reason behind the retrograde trend in free swell tests.

Figure 9 shows the shrinkage limit of lime stabilized soil admixed with PG. It can be seen that addition of PG to lime stabilized soil increases the shrinkage limit of the soil. The increase in shrinkage limit is nominal at low lime content whereas, at higher lime contents of 5.5% and 7%, the increase is significant. However, the variation between the two is marginal. At 3% lime content, the shrinkage limit of the soil increases steadily from 17.3% to 18.9% for 2% addition of PG. For 5.5% lime stabilization, addition of PG results in the shrinkage limit increasing from 27.2% to 32.9% for 2% addition of PG, which is an increase of 5.7%. At 7% lime stabilization, it can be seen that PG alteration results in an increase in the shrinkage limit from 30.7% to 34% for 1% PG addition. Increase in shrinkage limit results in a reduction in the range over which the soil can undergo shrinkage on loss of moisture. Thus, addition of PG reduces the volume change zone of lime stabilized soil even further. James et al. [17] found that addition of PG to an expansive soil resulted in an increase in the shrinkage limit of the soil. Okagbue [48] found that addition of wood ash to expansive soil resulted in the reduction of linear shrinkage similar to that of lime stabilized soils. He also cited earlier work establishing the fact that coating of clay clasts by calcium silicate gel formed during pozzolanic reactions as a reason for reduced swelling and shrinkage. When compared to standalone PG stabilization, the presence of lime with PG results in small quantities of PG being sufficient for altering the swell-shrink nature of the soil due to pozzolanic reactions.

3.3. Microstructural Study of PG Admixed Lime Stabilized Soil. Figure 10 shows the comparison of the microstructure

of soil stabilized with varying content of lime with optimal dosage of PG. There is a clear indication that addition of PG results in a modification in the microstructure of the stabilized soil. At 3% lime with 0.25% PG, it can be seen that there is an aggregation of the soil particles. At 5.5% lime stabilization with 0.5% PG, the aggregation of soil particles is more pronounced due to more lime and PG available for reaction. At 7% lime stabilized soil with 1% PG, the soil matrix exhibits a dense, compact mass-like microstructure.

Literature reveals that addition of PG to lime soil stabilization results in the formation of a mineral called ettringite [49–52], which has been reported to be responsible for both poor performance and enhanced strength gain. Another reason for the improved microstructure is due to the presence of PG which quickens pozzolanic reactions [49–51]. In the present investigation, addition of PG to lime stabilized soil produced positive results in terms of plasticity and swell-shrink. The microstructure reveals that there is a significant change in the soil structure due to addition of lime and PG. A lot of earlier works report that ettringite mineral formed in lime/cement stabilized sulphate rich soils has a slender needle/rod shaped structure [41, 53–56]. Closer observation and comparison of the microstructure with earlier literature reveals what seems to be the onset of formation of ettringite mineral in the present study as shown in Figure 11. However, the theory of formation of ettringite can be better investigated and reinforced by means of mineralogical studies using XRD analysis.

4. Conclusion

In this study, PG was used as an additive to lime stabilized soil in order to study its effect on the plasticity and swell-shrink of lime stabilized soil and understand the changes taking place in the system. Based on the results of the tests and literature, the following can be concluded:

- (i) Addition of PG resulted in the improvement of plasticity characteristics due to reduction in liquid limit and increase in plastic limit. At lower lime contents of 3% and 5.5%, the plasticity improvement was achieved by reduction in liquid limit without much influence on the plasticity whereas, at higher lime content of 7%, PG influenced both liquid limit and plastic limit to achieve reduction in plasticity. Despite the improvements to the plasticity of the stabilized soil, the scale of improvements is smaller compared to those achieved by lime.
- (ii) At lower lime content, optimal improvement in plasticity was achieved at lower PG dosage whereas, at higher lime content, the optimal improvement was achieved at higher PG content, which was in agreement with the strength results achieved in an earlier study, reinforcing the fact that more PG utilization takes place with increasing lime content, in the pozzolanic reactions.
- (iii) Addition of lime-PG combinations to the soil resulted in a change in classification of the soil from high plastic clay to silt of intermediate plasticity. However, the

FIGURE 10: Microstructure of soil stabilized with (a) 3% lime + 0.25% PG; (b) 5.5% lime + 0.5% PG; (c) 7% lime + 1% PG.

FIGURE 11: Possible onset of formation of ettringite in soil stabilized with 7% lime and 1% PG.

PG content and, hence, its contribution in achieving this change are low in the presence of lime due to the dominance of the latter.

- (iv) Addition of PG to lime stabilized soil resulted in an improvement in the swell-shrink nature of the soil. The reduction in swell achieved was only significant at low lime content whereas, at higher lime content of 5.5% and 7%, the reduction in free swell was marginal. Addition of PG to lime stabilized soil increased the shrinkage limit of the soil, which was nominal at low lime content of 3% but significant at higher lime contents of 5.5% and 7%.
- (v) Introduction of PG to lime stabilized soil hastens pozzolanic reactions which results in a change in

the microstructure of the stabilized soil to a dense compact mass. The changes in the microstructure increase with increase in lime-PG content of the stabilized soil.

Thus, it can be seen that addition of PG to lime stabilized soil can beneficially improve the plasticity, swell-shrink nature, and microstructure of the stabilized soil resulting in an improvement in the behavior of the stabilized soil.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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