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Stress-Strain Characteristics and Mineralogy of an Expansive Soil Stabilized Using Lime and Phosphogypsum

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Featured Application: This study attempts to identify optimal dosage ranges of lime and PG for maximizing the strength performance of stabilized expansive soils.

Abstract: The study involved the utilization of an industrial waste product, Phosphogypsum (PG) as an additive to lime for the stabilization of soil. Three lime dosages, viz. initial consumption of lime (ICL), optimum lime content (OLC) and less than ICL (LICL) were adopted for stabilizing the soil. The study investigated the stress-strain characteristics of soil composites stabilized with these three lime contents modified with optimum dosages of PG. Mineralogical studies were performed on the spent samples used for a series of determinations of unconfined compression strength tests with various combinations of lime and optimum PG content. The addition of an optimum dosage of PG resulted in an early strength gain of 8.8%, 14.1% and 13.9% and a delayed strength gain of 9.9%, 19% and 19.7% for 3%, 5.5% and 7% for the lime-stabilized soil, respectively. It was found that the addition of PG to the lime resulted in enhanced stiffness, residual strength and reduced brittleness due to the PG amendment of the stabilization reactions. However, in terms of the overall improvement of soil properties, the most favorable benefit was obtained by optimal PG modification of ICL rather than OLC. Microanalysis of the X-ray diffraction scatter also supported the results revealed through stress-strain characteristics. ICL with its optimal PG dosage showed a better progression of pozzolanic reactions when compared to the other two in terms of reduction of peaks of soil minerals and increase in peaks of CSH.

Keywords: lime stabilization; phosphogypsum; expansive soil; initial consumption of lime; optimum lime content

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1. Introduction

Almost all civil construction and related ground development activities are carried out on soils. Rapid development and population growth have resulted in the reclamation and reuse of land areas having poor mechanical characteristics from the point of view of geotechnical engineering [1]. Expansive soils are those soils which have poor volume stability when they come into contact with water [2]. This volume instability, which is caused by moisture ingress, can lead to the development of uplift pressures on overlying structures (such as in-sidewalks, basement floors, driveways, pipelines and foundations); hence resulting in the severe cracking and ultimate collapse of the structures [3]. Chemical stabilization of the soil is the modification of the soil by the use of stabilizing agents (in the form of powder, slurry, or liquid) to improve its suitability as an engineering material. Lime-stabilization is the most common technique adopted for the stabilization of expansive soils and in recent times it has been adopted in combination with industrial solid wastes, resulting in a greater improvement of properties [4]. One such industrial solid waste is Phosphogypsum (PG). It is a waste by-product from fertilizer manufactured by the wet acid method [5,6]. A total of 200–250 million tons of PG are estimated to be generated worldwide per annum [7]. India generates around 12 million tons per annum with re-utilization rates of 40–45% in building materials [8]. PG has been extensively researched for use in building materials and soil modification. Focus on the utilization of PG in soil engineering applications has increased in the recent past [9–14]. It has also been used as a binary additive to cement as well as for lime-stabilization of soils [6,15–20]. In all the investigations adopting the combinations of lime and PG, very few researchers have focused on understanding the effect of the addition of PG to lime in lime-PG systems. In the case of the combination of lime-PG in soil stabilization, such investigations are very scarce. Most previous studies explored the improvement in the strength and bearing of the stabilized soil due to the addition of PG. Only a few investigators have made attempts at analyzing the effects of lime-PG combinations on the soil by performing some detailed studies at the micro level. For instance, Shen et. al. [21] investigated the performance of a fly ash-lime-PG binder on stabilized soil, while Min et al. [22], evaluated the activation of fly ash-lime systems using PG for soil stabilization. On the other hand, James and Pandian [23] focused on the plasticity and swell-shrink characteristics of lime-PG stabilized soil. Both Shen et al. [21] and Min et al. [22] concluded that the addition of PG to lime/lime-fly ash systems accelerated the pozzolanic reactions. Min et al. [22] also stated that the development of late strength depended on the ratio of the PG to the lime, resulting in a decrease in the late strength with an increase in the ratio. James and Pandian [23] concluded that the addition of PG to lime improved its plasticity and swell-shrink behavior. They also found that there is an increase in the utilization of PG with an increase in lime content. At the microstructural level, they found that the addition of PG to lime resulted in a dense compact microstructure. Ghosh and Subbarao [24] studied the microstructural development of fly ash modified with lime and gypsum. They concluded that the addition of small quantities of gypsum to lime was sufficient for the enhancement of strength gain at the early curing stage and that the addition of gypsum reduced strength loss due to soaking. It is evident from the foregoing studies that the addition of small-quantities of PG to lime-stabilized soil systems can accelerate pozzolanic reactions but that this, in turn, depends on the ratio of the PG to the lime used. Although the stress-strain characteristics of stabilized soils have only been studied by several researchers, the effect of the inclusion of binary additives, particularly PG, on the stress-strain behavior of lime-stabilized soils [16,25] is very limited. Moreover, the micro level response and behavior of lime-PG systems, especially when the lime-PG combination is used in soil for its stabilization, are quite limited. Thus, this research attempts to focus on the influence of PG on the stress-strain characteristics and the attendant mineralogical changes that are likely to occur due to the stabilization of an expansive soil with the use of a combination of lime and PG.

2. Materials

The materials that were used in this study include natural soil, hydrated lime and Phosphogypsum. The natural soil was obtained from Thataimanji Village in the Tiruvallur district of Tamil Nadu, India. The basic properties of the soil are shown in Table 1.

Table 1. Properties of the Virgin Expansive Soil [20].

Property	Value
Liquid Limit	68%
Plastic Limit	27%
Plasticity Index	41%
Shrinkage Limit	10%
Specific Gravity	2.76
% Sand	2.5
% Silt	60.5
% Clay	37
Maximum Dry Density	15.3 kN/m^3
Optimum Moisture Content	25%
Unconfined Compressive Strength (UCS)	115.8 kPa
Soil pH	6.53
Soil classification	CH

The lime adopted in the study was laboratory-grade hydrated lime manufactured by Nice Chemicals India Private Limited. The PG used in this study was sourced from the fertilizer plant of Coromandel International Limited, located in Ennore, north of Chennai, India. The chemical compositions of the materials used in this investigation as determined from an earlier investigation [23] are shown in Table 2.

Table 2. Chemical Composition of Materials.

Oxide	Soil (%)	Lime (%)	PG (%)
Al_2O_3	18.818	0.053	0.649
CaO	2.297	72.767	35.728
Fe_2O_3	7.484	0.037	4.88
K_2O	2.288	0.003	0.042
MgO	1.737	14.604	0.661
MnO	0.035	0.004	0.001
Na_2O	1.415	0.047	0.106
P_2O_5	0.043	0.005	10.701
SiO_2	63.615	0.245	16.957
TiO_2	0.876	0.003	0.015
SO_3	0.207	0.048	4.598

3. Methodology

The experimental methodology adopted in the present investigation involved various stages including preparation of the soil, fixing of the lime and PG contents, preparation and testing of UCS samples and mineralogical investigation.

3.1. Material Preparation

The soil and PG were collected from their source locations and transported to the geotechnical engineering laboratory where the investigation was carried out. As mentioned in Section 2, lime was procured from a supplier of chemicals and laboratory reagents. The soil was prepared for various laboratory tests in accordance with the Bureau of Indian Standards (BIS) code [26]. The PG was air-dried to remove any extraneous moisture that was acquired at the dump site. The large clods of PG were broken down, pounded to a finer fraction and mixed evenly to reduce variability. It was then sieved through a BIS 75-micron sieve and the fractions passing through the sieve were used in the investigation.

3.2. Fixing of Additive Dosage

Three lime doses were identified for the chemical stabilization of the soil sample. One was for the initial consumption of lime (ICL), determined by using the Eades and Grim pH test [27] following the procedure standardized in the ASTM code [28]. The optimum lime content (OLC) is defined as the lime content at which the soil will achieve maximum strength beyond which any further increase in the treatment level does not produce a significant increase in the strength [29]. The OLC was determined by performing a UCS test in accordance with the BIS code [30] on the soil mixed with an increasing lime content and cured for 2 days. The third lime content was randomly selected below the ICL and designated as less than the ICL (LICL) content. Ghosh and Subbarao [24], in their investigation, stated that small quantities of gypsum (0.5% and 1%) were adequate for enhancing the strength of lime-stabilized fly ash. Based on this guideline, the quantities of PG (0.25%, 0.5%, 1% and 2%) used were fixed randomly in such a manner that they were close to the suggested quantities. The PG dosages were used as auxiliary addendums and not as replacements for lime doses. It is also pertinent to add that other previous studies have used relatively higher quantities of PG. A total of 15 combinations of lime and PG were investigated of which only the control and optimum combinations have been reported here. Table 3 shows the combinations of lime and PG reported in this work.

Table 3. Lime and Optimum PG Combinations Used for Stabilization.

Lime (%)	PG (%)	Notation	Description
3	-	L1	3% Lime-Stabilized Soil
5.5	-	L2	5.5% Lime-Stabilized Soil
7	-	L3	7% Lime-Stabilized Soil
3	0.25	LP1	3% Lime + 0.25% PG-Stabilized Soil
5.5	0.5	LP2	5.5% Lime + 0.5% PG-Stabilized Soil
7	1	LP3	7% Lime + 1% PG-Stabilized Soil

3.3. Preparation of Samples and Strength Testing

UCS test samples of dimensions 38 mm × 76 mm were prepared by mixing soil, lime and PG in various proportions and then the mixture was cured for a period of 28 days to allow for the development of the chemical reactions needed for pozzolanic activities. The specimens were cast to a target density of 14.72 kN/m^3 and a moisture content of 25% was obtained from the compaction characteristics tests of soil and lime. The weights of soil, lime and PG were computed and weighed to obtain the aforementioned target density. They were initially mixed in dry conditions to obtain a uniform dry mix. The computed quantity of water to achieve the target moisture content was measured and added to the dry mix in stages to obtain a uniform wet mix. This wet mix was packed in the split mold in stages and statically compacted to obtain the sample. Manual mixing was adopted in both stages of mixing. Three samples (for each combination) were prepared to the target density and moisture content. The specimens were then ejected from the split mold and placed in a polythene cover and sealed for curing. At the end of the curing duration, the samples were subjected to a continuous axial loading at the rate of 0.625 mm/min until failure occurred.

3.4. Mineralogical Investigation

The spent UCS samples (failed specimens after strength test) were used for mineralogical investigations to understand the effect of the PG addition to the lime. These investigations were carried out at the Centre for Nanotechnology, Anna University, Chennai. The combinations of PG that gave the maximum strength with the three lime contents in the investigation were chosen for the mineralogical analysis. The mineralogical analysis was performed on the spent UCS samples after their preparation by air drying, followed by crushing and pulverization and sieving through a 75-micron sieve. X-Ray Diffraction (XRD) was performed in a benchtop diffractometer model Rigaku Miniflex 2C. X-rays of a wavelength of 1.54Å were adopted with a continuous mode Gonio scan between 2-theta positions of 10° and 90° with a scan step of 0.02° and a scan speed of 25 degrees/minute. A current of 10 mA and voltage of 30 kV was set in the generator. Scanning Electron Microscopy (SEM) was performed with a benchtop scanning electron microscope of model TESCAN Vega 3 SBU of Czech Make. The sample was prepared by gold sputtering using an EMITECH Gold Sputter coater SC7620 followed by an electron bombardment of the sample at an applied voltage of 10 kV after creating a vacuum in the sample chamber using a turbo molecular pump.

4. Results and Discussion

The three lime contents adopted in the investigation were 3%, 5.5% and 7% based on previously reported early strength [31] and delayed strength [20] results. This investigation focuses on the stress-strain characteristics and the mineralogical changes identified through XRD. The optimum dosages of PG for 3%, 5.5% and 7% lime-stabilized soil were 0.25%, 0.5% and 1%, respectively. Table 4 shows the various combinations discussed in the present work along with strength results.

Table 4. Strength of Lime and Optimum PG Combinations.

Combination	7 Days (kPa)	28 Days (kPa)
L1	517.69	547.48
L2	981.32	1398.77
L3	1181.26	1881.45
LP1	563.08	601.66
LP2	1119.23	1663.8
LP3	1345.34	2251.07

4.1. Stress-Strain Characteristics of Amended Stabilized Soil

From the data given in Table 3, it can be seen that the strength of 3% lime-stabilized soil increases from 517.69 kPa to 563.08 kPa on the addition of 0.25% PG. This amounts to an increase of 8.77% at 7 days of curing. When the lime content increases to 5.5%, the optimum PG content increases to 0.5%. At this dosage, the strength increases from 981.32 kPa to 1119.23 kPa, accounting for a 14.05% strength gain. At 7% lime dosage, 1% PG developed a maximum strength of 1345.34 kPa from 1181.26 kPa, a gain of 13.89%. When the curing period increases to 28 days, the percentage strength gains of 3%, 5.5% and 7% lime amended with 0.25%, 0.5% and 1% PG, respectively, amounted to 9.90%, 18.95% and 19.65%, respectively. Stress-strain curves and soil stiffness play an important role in settlement calculations. The stress-strain characteristics of the lime-stabilized soil are shown in Figure 1. The solid lines represent the stress-strain relationships of pure lime-stabilized soils, whereas the dashed lines represent the lime-stabilized soil specimens modified with their respective optimum doses of PG. The very first inference that can be obtained from Figure 1 is that the addition of lime to soil results in a change in stress-strain characteristics of the soil with an increase in lime content. The stress-strain behavior of the soil changes from plastic failure to brittle failure with an increase in the lime content, as is evident from the stress-strain curves for the three lime contents. There is also an increase in the stiffness of the soil with the strain corresponding to peak stress reducing with an increase in the lime content of the soil. For L1, the strain corresponding to peak stress is 0.021 which significantly reduces to 0.013 for L2 and L3. The second major inference that can be obtained from Figure 1 is that the addition of PG to the lime-soil system further increases the stiffness of the composite. This is true for lime contents up to 5.5%. Beyond 5.5% lime content the addition of PG does not contribute much to any increase in the stiffness of the system. The strain corresponding to peak stress for combinations LP1, LP2 and LP3 were 0.011, 0.011 and 0.013, respectively. To more accurately understand the stiffness behavior of the stabilized soil, the modulus of elasticity of the soil was determined and has been discussed in the next section.

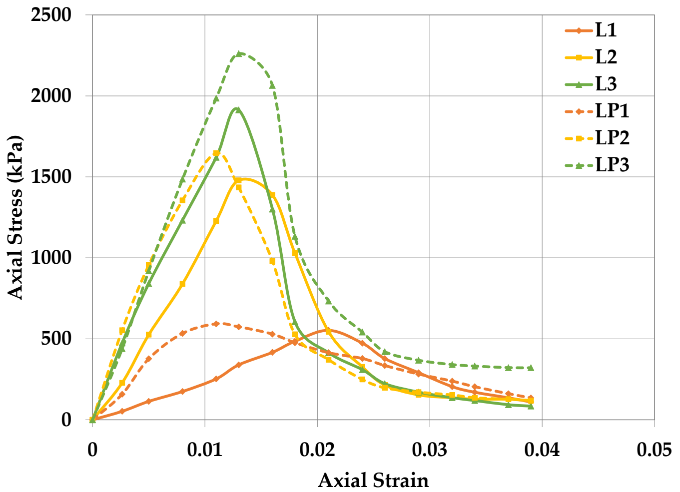

Figure 1. Stress-strain behavior of lime-stabilized soil with and without optimum PG content.

4.2. Moduli of PG Amended Lime-Stabilized Soil

The soil elastic modulus is defined as the slope of the stress-to-strain curve. The modulus plays an important role in settlement characteristics. An increase in the modulus value means that the settlement decreases. The moduli of the lime-stabilized soil amended with PG were determined from the stress-strain curves of the individual soil specimens. In this analysis, the initial tangent modulus was determined for the tangent drawn to the initial straight-line portion of the stress-strain curves of the individual specimens. Figure 2 shows the moduli of the stabilized soil composites. The modulus value for L1, L2 and L3 are 35,092.7, 107,199.3 and 145,287.3 kPa. LP1 showed a modulus value of 60,762.3 kPa. LP2 showed a modulus value of 140,337.7 kPa and LP3 gave a modulus value of 157,142.9 kPa. When the combinations LP1, LP2 and LP3 were compared, the contribution of PG toward the modulus in LP1 and LP2 was more when compared to that of LP3 (Figure 2). This indicates that when lime dosage lesser than ICL was used for stabilization, PG contributed a 73.15% increase in the modulus. This reduces to 30.92% and 8.16% for LP2 and LP3. Thus, it can be concluded that the contribution of PG in the augmentation of the modulus of the lime-stabilized soil is significant up to ICL and beyond which its contribution drastically reduces.

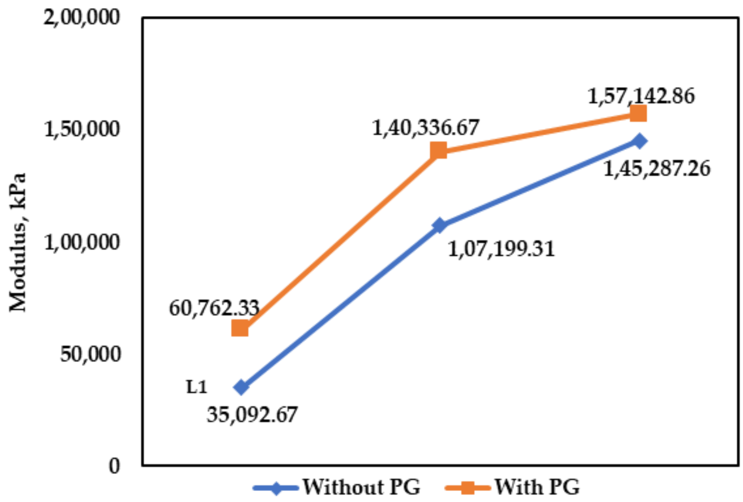

Figure 2. Contribution of PG to the modulus in lime modified soil.

4.3. Residual Strength of PG Amended Lime-Stabilized Soil

Residual strength of PG amended lime-stabilized soil is the strength calculated from the stress-strain graph of the soil as a result of static deviatoric stress. The fracture/breaking point of the modified soil under varying strain with constant stress gives the residual strength. From the Figure 1 it is observed that the soil underwent strain softening and where the soil is compacted at the maximum dry density it has started flocculating under varying strain, causing dilation. The value of residual strength increases with an increase in lime and PG content (Figure 3). Similar to the modulus behavior, the contribution of PG to the residual strength of the lime-stabilized soil is more when the lime content is lesser than the ICL, i.e., LP1. The increase in residual strength for LP1, LP2 and LP3 are 1.7, 1.36 and 1.29 times that of L1, L2 and L3, respectively. Thus, it can be concluded that the addition of optimum PG content to the lime-stabilization of expansive soils improves the residual strength of the soil. However, similar to the modulus, the contribution of PG toward an increase in residual strength decreases with the increase in lime content.

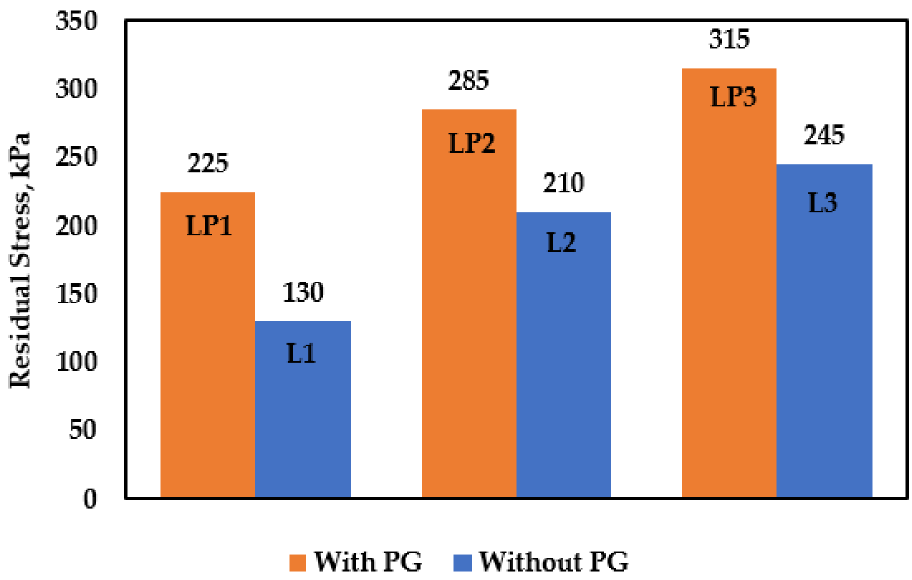

Figure 3. Influence of PG on the residual strength of lime-stabilized soil.

4.4. Brittleness Index of the Stabilized Soil

The parameters involved in determining the computation of the brittleness index (IB) are total and elastic strain (Equation (1)) from the stress-strain graph (Figure 4). This computation is based on the study done by Iqbal et al. [32].

$$I_B = (\text{Elastic Strain})/(\text{Total Strain}) \quad (1)$$

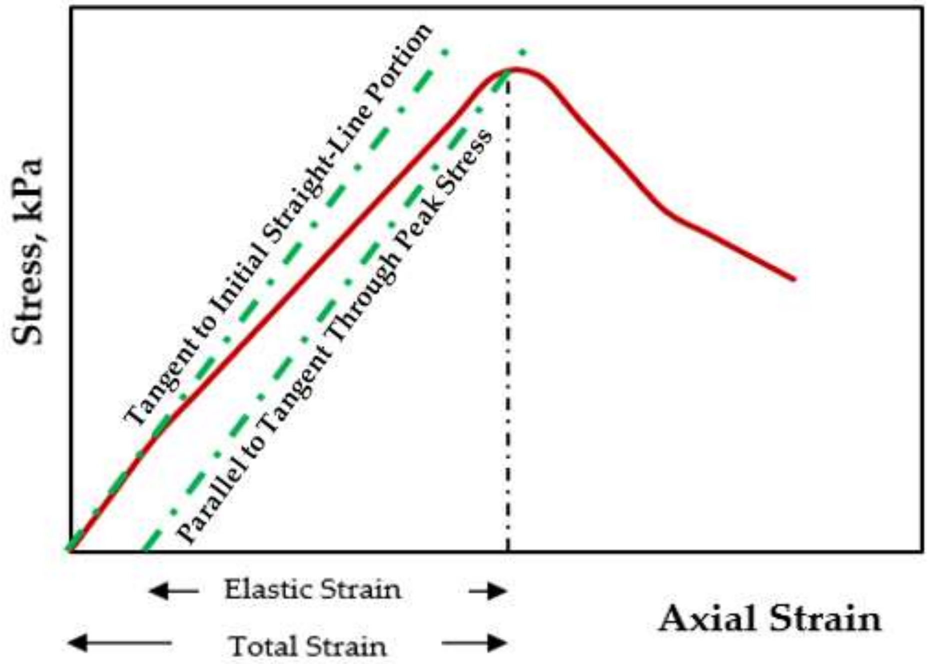

Figure 4. Computation of the brittleness index from a stress-strain curve.

Traditionally stabilized soil shows brittle behavior, which is often not very desirable for the structures constructed over such soils [33]. Thus, an attempt was made to understand the effect of PG on the I_B of the lime-stabilized soil. Figure 5 shows the variation in I_B values of the different stabilized soil combinations.

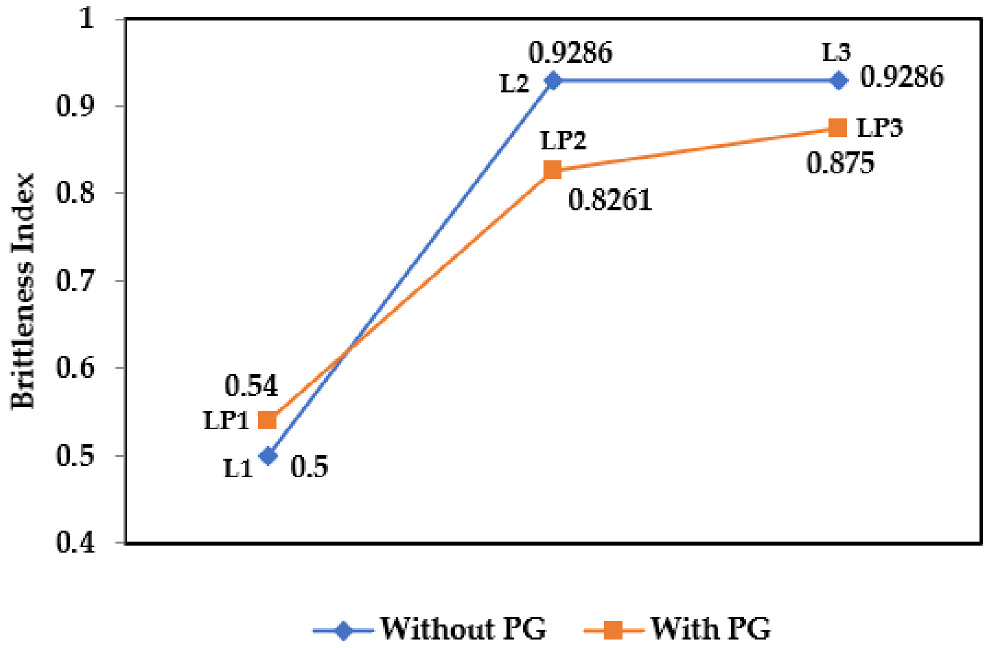

Figure 5. The brittleness Index of the lime-stabilized soil with and without PG.

The I_B values range between 0 to 1. I_B values of pure lime-stabilized soil combinations range from 0.5 to 0.93. Without any addition of PG, the I_B values for L1, L2 and L3 are 0.5, 0.93 and 0.93, respectively. When the lime is added beyond the ICL, I_B values computed from the stress-strain curve did not show any difference. The I_B values for LP1, LP2 and LP3 are 0.54, 0.83 and 0.875, respectively. For LP1, the I_B value is higher than L1. This may be due to PG augmenting the supply of the cations required for stabilization below the ICL content. However, the pattern differs for the increased percentage of 5.5% and 7% lime, which is the ICL and the OLC; the I_B values reduced with the addition of PG (Figure 5). This proves that with the addition of PG at and beyond the ICL combination, the I_B value reduces, making the soil less brittle. It can also be noted that the maximum benefit of PG on the desirable improvement of brittle behavior is at ICL rather than OLC. Thus, it can be concluded that the addition of PG to the lime-stabilization of an expansive soil improves the brittle behavior desirably when minimum lime content is available.

4.5. Mineralogy of PG Amended Lime-Stabilized Soil

Figure 6a–c shows the XRD scatter pattern of the soil specimens stabilized with their respective optimum dosages of PG. At the outset, it is clear from the scatter patterns that there is no sign of any significant change in the general pattern of the diffraction peaks in all three combinations. The increase in strength of the stabilized soil is due to the formation of calcium silicate hydrate minerals as seen from the XRD peaks of all three combinations of the stabilized composite. The formation of calcite also acts as a minor contributor to the development of the strength of the stabilized soil. The presence of quartz and montmorillonite from the original soil is also detected in the XRD patterns. However, a keen observation of the three patterns reveals that there are subtle differences in the diffraction patterns. An obvious difference is in the intensity of the most prominent peak of quartz in all three combinations. It is clear that the intensity of the specific peak at around 26.5° is different for the three combinations. To better understand the differences in the patterns a microanalysis of the peak intensities of the identified prominent peaks was performed. The prominent minerals identified in the virgin soil were quartz and montmorillonite at 2-theta angles of 20.8°, 26.6°, 39.4°, 40.2°, 50.1°, 68.3° and 19.8°, 27.9°, respectively. The pozzolanic reactions resulted in the formation of new minerals like ettringite, CSH and calcite. Ettringite was detected at a 2-theta value of 35.2° whereas CSH was detected at 2-theta values of 23.5°, 29.3°, 54.8° and 59.9°. Calcite was detected at a 2-theta value of 36.5°. The original intensity of quartz at 26.6° was 16,904 counts. However, this value was greatly reduced due to the stabilization process in the three combinations considered. For LP1, the intensity of quartz corresponding to 26.6° was 6681. This clearly indicates that the crystal structure of quartz is destroyed during the pozzolanic reactions, leading to the formation of new minerals. This intensity for LP2 was only 5496. This clearly indicates that there is better progress in pozzolanic reactions due to the increased lime and PG content, resulting in a reduction in the intensity of the quartz peak. For LP3, however, this intensity was 8950, which is comparatively higher than LP2. Thus, the destruction of quartz peaks is not as effective as in LP2. Similar behavior was also observed for the other quartz peaks as well. For the quartz peak at 20.8°, the intensity reduced from 4364 counts to 2114, 1968 and 2069 counts for LP1, LP2 and LP3, respectively. Thus, there is a clear indication that there is effective progress of pozzolanic reaction in LP2 when compared to the other two combinations as seen from the reduced peak intensities of quartz. Looking at the intensities of montmorillonite, it is 2278 at 2-theta of 19.8° for the virgin soil whereas this reduced to 1182, 1193 and 1262 counts for LP1, LP2 and LP3, respectively. However, the peak intensities do not differ sufficiently to gain a clear interpretation. At the other peak of 27.9°, the intensities reduced from 4825 to 2003, 1639 and 2362, respectively, for LP1, LP2 and LP3. Thus, in the case of montmorillonite as well, it is seen that there is a reduction in peak intensities of the mineral, indicating the effective progress of pozzolanic reactions, especially in LP2. Taking a look at the peak intensities of the minerals formed as a result of the pozzolanic reactions like ettringite, the intensity of ettringite increased with an increase in the lime content in the combinations. The peak intensities of ettringite at a 2-theta value of 35.2° were 971, 996 and 1108 for combinations LP1, LP2 and LP3, respectively. Looking at peak intensities of CSH at 23.5°, they also increased with an increase in the lime content; 1016, 1071 and 1152 counts for LP1, LP2 and LP3, respectively. At a 2-theta value of 29.3° as well, a similar trend was seen with intensities of 1062, 1153 and 1271 counts, respectively, for LP1, LP2 and LP3. Thus, there is an increase in the intensity of ettringite and CSH with an increase in the lime and PG content in the combinations which is the reason for the augmented strength of the stabilized soil composite. Moreover, comparing the three combinations, the XRD studies reveal that the destruction of soil minerals and the formation of reaction products is most prominent in the combination of ICL with 0.5% PG when compared to the other two. Thus, in the present study, the micro-level investigation clearly substantiates the behavior noticed in the stress-strain characteristics and reinforces the inference that the PG modification of lime-stabilization can be at its most advantageous at ICL rather than OLC. Figure 7 shows a higher resolution SEM image of 7% lime-stabilized soil amended with 1% PG reported in earlier work [23]. From the figure, it is clear that there are clusters of leaf-like formations indicating the development of CSH gel due to pozzolanic reactions. The formation of CSH is clearly evident from the XRD diffractograms. The SEM micrograph also shows the presence of folded solidified gel. The formation of a similar microstructure was also reported by Zhao et al. [34]. In the earlier work by James and Pandian [23] it was reported that the strength development may also be due to the possible onset of the formation of ettringite (Aft). Needle/rod-like formations, indicative of the onset of ettringite formation, are also seen in the micrograph. This is also supported by the presence of ettringite in the XRD diffractograms in the present study. The overall microstructure appears to be a dense mass-like structure with few micro and macro pores in the field of view. Zhao et al. [34] also report the formation of a dense compact microstructure due to stabilization. Higher-resolution SEM images of LP1 and LP2 (Figure 8) from an earlier investigation [23] have also been provided for comparison.

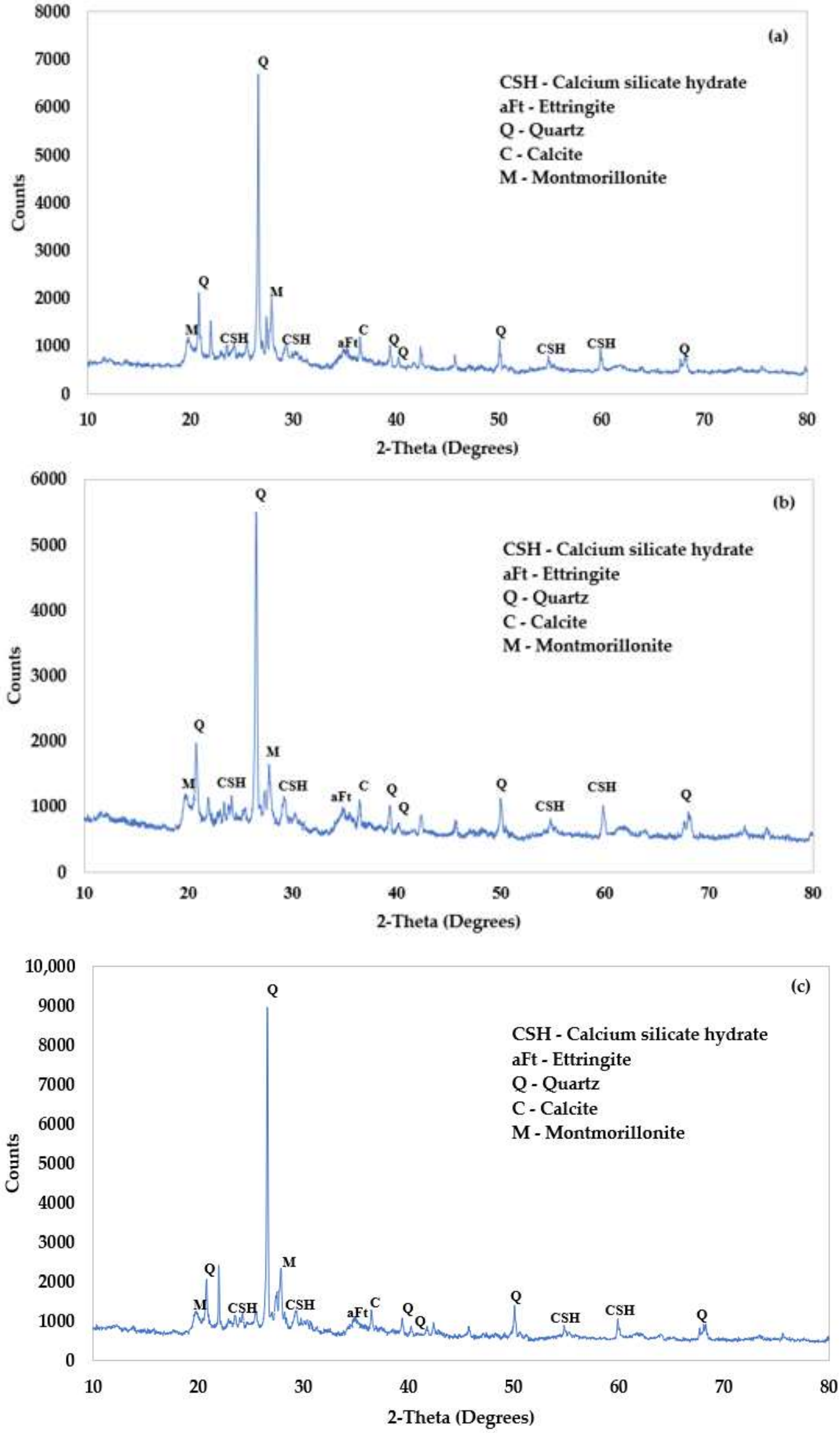

Figure 6. Mineralogy of (**a**) LP1 (**b**) LP2 and (**c**) LP3.

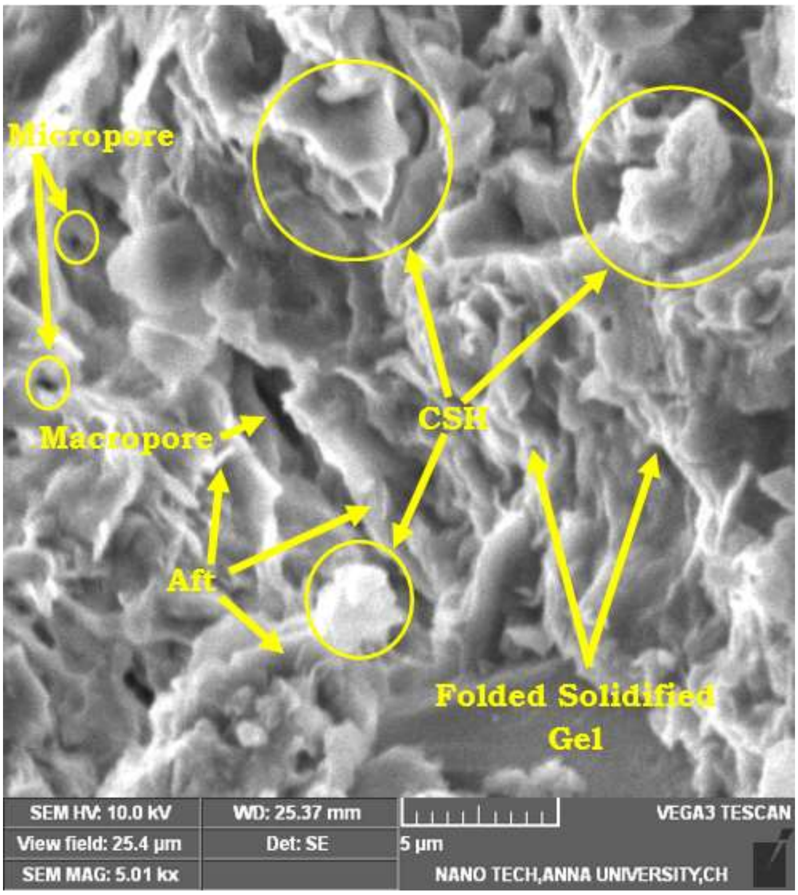

Figure 7. SEM Micrograph of LP3.

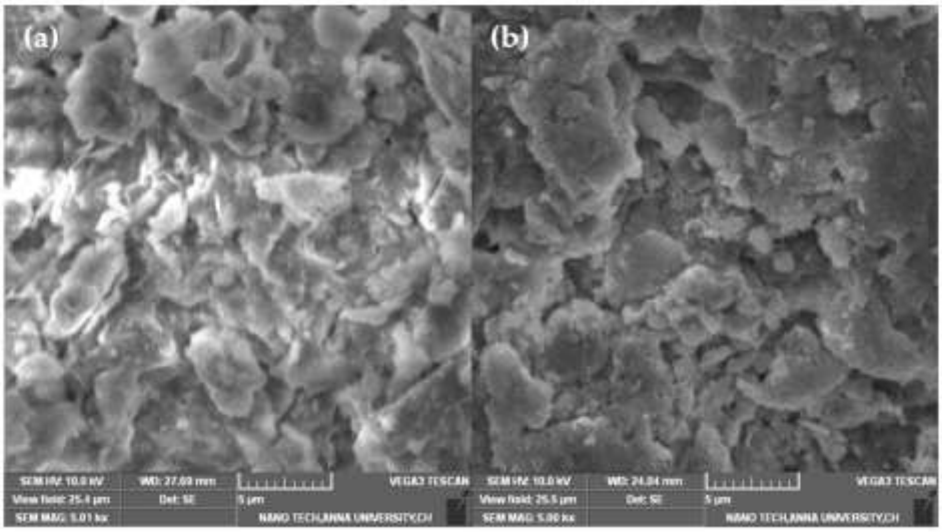

Figure 8. SEM Micrograph of (**a**) LP1 (**b**) LP2.

4.6. Effect of PG on Lime–Soil Reactions

The addition of PG to the lime-stabilization of soil results in modifications in the end products formed during the pozzolanic reactions. The primary constituent of PG is calcium sulfate ($CaSO_4.2H_2O$) [22]. As a result of this, sulfate ions are introduced into lime soil reactions. The mechanism of strength development due to the addition of PG can be attributed to the formation of the mineral ettringite. Several researchers have reported the formation of ettringite in lime sulfate systems [35–37]. In most of the cases, the ettringite formed was associated with swelling, resulting in the poor performance of the stabilized soils. However, several researchers who had earlier worked on PG admixed systems have attributed the formation of ettringite as the reason for the early strength gain [21,22,38,39]. With increasing curing periods, PG is consumed in the formation of ettringite. Huang and Lin [39] identified increasing peaks of ettringite coupled with decreasing peaks of gypsum in their X-ray diffraction study indicating the consumption of PG in PG-fly ash-limestone systems. PG also hastens the pozzolanic reaction in PG-lime-fly ash systems [21]. Min et al. [22] report that the formation of ettringite hastens the pozzolanic reactions. Huang and Lin [40] also reported increased strength in PG admixed cement systems due to the formation of ettringite. The formation of ettringite in sulfate systems is given by (2), (3) and (4) [22,38].

$$xCa(OH)_2 + SiO_2 + nH_2O \rightarrow xCaO{\cdot}SiO2{\cdot}(n+x)H_2O \tag{2}$$

$$yCa(OH)_2 + Al_2O_3 + nH_2O \rightarrow yCaO{\cdot}Al_2O_3{\cdot}(n+y)H_2O \tag{3}$$

$$\begin{gathered}3Ca(OH)_2 + Al_2O_3 + 3CaSO_4{\cdot}2H_2O + 26H_2O \rightarrow \\ 3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O\end{gathered} \tag{4}$$

Rajasekaran et al. [39] had also given a similar chemical reaction (5) for the formation of the ettringite in lime- or cement-stabilized sulfate-rich soils.

$$\begin{gathered}6Ca^{2+} + 2Al(OH)_4{}^{-} + 4(OH)^{-} + 3(SO4)^{2-} + 26H_2O \\ \rightarrow Ca_6[Al(OH)_6]_2{\cdot}.(SO_4)_3{\cdot}26H_2O\end{gathered} \tag{5}$$

It has been reported by researchers that ettringite formed in such stabilized soil systems has both positive as well as detrimental effects. Whether ettringite can cause expansive damage depends not only on the quantity but also on the condition under which ettringite forms. In a high CaO concentration solution, ettringite packs densely adjacent to other solid particle surfaces, and this gel tends to expand; in a low CaO concentration solution, ettringite is produced dispersedly, and this gel has less tendency to expand [39]. In the present work, the addition of PG to the lime-stabilized soil has resulted in an increase in the strength of the soil, and thereby it can be concluded that the reactive conditions in the soil have been favorable for the formation of ettringite that helps in better packing of pores in the stabilized soil matrix.

4.7. Discussion

Solid waste generation around the world has become an area of concern due to disposal problems. The PG generated from the fertilizer industry is no different. Although a lot of research has gone into its potential use in construction materials, its reutilization levels have been low. This could be due to the presence of naturally occurring radioactive materials in the waste [5,6,12,41]. However, with the Atomic Energy Regulation Board of India providing approval for the use of PG in construction [42], the research into the reuse of PG got a significant boost. Despite the approval, the reuse of material with traces of radioactive elements may have led to skepticism among construction industry professionals as well as common people. This is where its valorization in soil stabilization activities can prove comparatively beneficial, as it goes below the ground, thereby reducing the apprehensions of construction professionals. Lime-stabilization has been the go-to method for improving poor soils, especially expansive clays. The use of PG in soil stabilization has gained significant attention in recent years both as a primary stabilizer as well as an auxiliary addendum. There are a good number of scientific investigations that use the combination of lime and PG. However, the use of scientifically established lime contents of ICL and OLC, along with PG as an auxiliary addendum has not been given an in-depth study. By comparing three different lime contents with their optimal PG dosage, the present study has attempted to bring out the ideal range of lime content that needs to be utilized for obtaining maximum strength benefits when utilizing PG as an auxiliary additive. Moreover, the mineralogical investigations have also supported the strength results revealing that the maximum benefit of PG valorization can be obtained when lime dosage it closer to ICL rather than OLC, thereby reducing the lime requirement as well. This, along with earlier studies, has also proved that PG accelerates the strength gain by hastening the pozzolanic reactions. The mineralogical investigations in the present study have also supported this through changes noticed in peak intensities of soil minerals and new products formed due to the progress of pozzolanic reactions. The results of this investigation can prove useful in subgrade stabilization for road and railway projects wherein quick strength gain can be very beneficial in saving project execution time and cost. The current investigation focused on lime contents LICL, ICL and OLC. The course of future investigations can focus on identifying whether any variation in lime content between ICL and OLC can further augment the performance of lime-PG blended stabilization. Moreover, the application of this blend in road projects also requires durable performance. Future investigations can also focus on wetting-drying as well as freezing-thawing resistance of ICL- and OLC-stabilized soil modified with PG. This can further strengthen the knowledge of field practitioners in their application of the right amounts of lime and PG that can also resist variation is subgrade moisture contents due to changes in weather conditions.

5. Conclusions

Phosphorous is one of the most common fertilizers used in agriculture. The waste generated from this fertilizer industry is widely used in cement and road construction. An experimental study was carried out to understand the stress-strain behavior of PG in soil stabilization along with mineralogical changes. Lime is added as the primary stabilizer in three combinations: 3, 5.5 and 7% for various combinations of PG. The discussion mainly highlights the combinations of lime with their respective ideal PG combination. The following observations were made;

1. Addition of lime and PG to the soil for stabilization results in an increase in the peak stress and a reduction in the corresponding strain. Thus, it can be concluded that the stabilization of the expansive soil with a lime-PG combination increases the stiffness of the stabilized composite. The amendment of the lime-stabilized soil with PG further enhances the stiffness of the stabilized soil.
2. The modulus of soil influences the bearing capacity and settlement behaviors of foundations. The stabilization of the expansive soil with increasing lime content resulted in an increasing modulus of the stabilized soil. However, the amendment of the stabilization process using an optimal dosage of PG resulted in a further increase in the modulus of the stabilized soil. However, an increase in the modulus was pronounced when the lime content was less than or equal to the ICL. Thus, it can be concluded that the addition of an optimal dosage of PG to the lime-stabilization process can further enhance the modulus of the stabilized soil, resulting in improved performance and making it more attractive as an engineering material for foundation support.
3. The residual strength of the stabilized soil composites increases with the addition of optimum PG content; However, an increase in its residual strength is not very prominent for lime content beyond ICL. Thus, it can be concluded that optimum PG content is very effective in enhancing the residual strength of lime-stabilized soils for lime contents up to ICL.
4. The addition of an optimum dosage of PG results in a reduction in I_B values of the soil for ICL- and OLC-stabilized soils. Thus, it can be concluded that optimum PG amendment favorably improves the brittle behavior of the lime-stabilized composites when minimum lime content is available.
5. XRD investigations reveal the formation of CSH, ettringite and calcite in the P-amended lime-stabilized soils. However, a detailed look reveals that the reduction in intensities of the peaks of soil minerals, coupled with the peaks of new reaction

products is very prominent when 5.5% lime is amended with 0.5% PG. This is in line with the other characteristics of the stabilized soil obtained from its stress-strain curves. Thus, it can be concluded that hastening of the lime-soil reactions by PG, in the augmenting of the supply of calcium ions and contribution in the form of ettringite is best achieved when optimal dosages of PG are used to modify soils stabilized at their ICLs rather than OLCs.

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