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Effect of phosphogypsum on strength of lime stabilized expansive soil

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Scientific paper - Preliminary note

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Effect of phosphogypsum on strength of lime stabilized expansive soil

The use of phosphogypsum as an additive to lime, to enhance its performance in soil stabilization, is analyzed in this paper. Phosphogypsum is a by-product of the phosphate rock processing during production of phosphoric acid. Expansive soil samples used in this paper were stabilized using three different lime proportions: initial lime consumption, optimum lime content, and less than initial lime consumption. The results reveal that the addition of phosphogypsum to lime led to improvement of both the early and late strength of stabiliszd soil.

Key words:
expansive soil, lime stabilization, initial consumption of lime, optimum lime content, phosphogypsum, uniaxial compressive strength

Prethodno priopćenje

Jijo James, P. Kasinatha Pandian

Utjecaj fosfogipsa na čvrstoću ekspanzivnog tla stabiliziranog vapnom

U ovom radu ispituje se upotreba fosfogipsa (kao aditiva vapnu kako bi se poboljšao učinak vapna u stabilizaciji tla. Fosfogips je nusproizvod koji nastaje u procesu obrade fosfatne stijene tijekom proizvodnje fosforne kiseline. Uzorci ekspanzivnog tla upotrijebljeni u ovom radu, stabilizirani su pomoću tri različita udjela vapna: inicijalnog udjela vapna, optimalnog udjela vapna i udjela vapna manjega od inicijalnog. Rezultati su pokazali da je dodatak fosfogipsa vapnu poboljšao ne samo ranu nego i kasnu čvrstoću stabiliziranog tla.

Ključne riječi:
ekspanzivno tlo, stabilizacija tla vapnom, inicijalni udio vapna, optimalni udio vapna, fosfogips, jednoosna tlačna čvrstoća

Vorherige Mitteilung

Jijo James, P. Kasinatha Pandian

Einfluss von Phosphorgips auf die Festigkeit durch Kalk kalkverstärkter expansiver Böden

In dieser Arbeit wird die Anwendung von Phosphorgips als Zusatzstoff in der Anwendung von Kalk untersucht, um eine verbesserte Bodenstabilisierung zu erzielen. Phosphorgips ist ein Nebenprodukt, das im Verarbeitungsprozess von Phosphatgestein zur Herstellung von Phosphorsäure entsteht. Die bearbeiteten Proben expansiven Bodens sind mit drei verschiedenen Kalkanteilen stabilisiert worden: mit initialem Kalkanteil, mit optimalem Kalkanteil und mit einem Kalkanteil unter dem initialen Wert. Die Ergebnisse haben gezeigt, dass der Zusatz von Phosphorgips in der Anwendung von Kalk nicht nur die frühe, sondern auch die späte Festigkeit des stabilisierten Bodens verbessert.

Schlüsselwörter:
expansiver Boden, Kalkstabilisierung, initialer Kalkanteil, Phosphorgips, einachsige Druckfestigkeit

1. Introduction

Expansive soils pose a major challenge to civil engineers all over the world as they cause severe distress to structures constructed on them [1]. These soils are characterized by an enormous volume change due to the presence of a highly active montmorillonite group of minerals [2]. The process of soil stabilization is carried out in order to improve performance of such soils. Soil stabilization involves addition of a binder to improve mechanical and chemical properties of the soil [3]. Chemical additives have been used in soil stabilization for several years with varying levels of success. The effectiveness of these additives depends on the soil condition, stabilizer properties, and type of construction [4]. Several additives have been used in soil stabilization like lime, cement, polymers, salts, surfactants, and mixture of more than one of the above. But lime is most commonly used for stabilization of expansive soil as it improves mechanical properties of the soil [1]. Lime stabilization has been covered in literature quite extensively [5-11]. Several researchers have even analysed the utilization of waste materials in soil stabilization, including pumice waste [12], ceramic dust [13], cement waste dust [14], ceramic tile waste [15], rice straw ash [16], glass waste [17], to name just a few. However, research has shown that the combination of conventional stabilizers like lime and cement along with additives, usually industrial waste materials, has produced better results [18–25]. This work concentrates on the use of an industrial waste viz. Phosphogypsum (PG), as an additive to lime. Earlier work on PG shows that it has been used as binder [26], soil stabilizer [20, 27, 28] and as filler for bricks [29].

The primary objective of this study is to understand the effect of PG on the stabilization potential of lime applied to an expansive soil. This was studied by testing the UCC (Unconfined compressive) strength of lime stabilized soil by admixing it with varying quantities of PG.

2. Materials and methods

The materials that were used in this study include natural soil to be improved, lime as primary stabilizer, and phosphogypsum as an admixture.

2.1. Natural soil

The natural soil used for the study was obtained from Thatthamanji Village in Thiruvallur District of Tamil Nadu, India. Soil properties were tested in laboratory, and the corresponding results are summarized in Table 1.

2.2. Lime

Lime is a general term that is used to refer to the following three types – quick lime (CaO, Calcium Oxide), slaked or hydrated lime ($Ca(OH)_2$, Calcium Hydroxide), and carbonate lime ($CaCO_3$, Calcium Carbonate) [37]. Calcium hydroxide is the most widely used chemical stabilizer for clay soil subgrades [38]. Limestone or carbonate lime is not chemically reactive enough to lead to soil stabilization [39]. However, the addition of carbonate lime results in the improvement of soil strength through physical interaction. Soil stabilization using calcium carbonate obtained from egg shell powder resulted in the increase in the UCC strength of soil [40]. The mechanism of lime stabilization involves:

- ion exchange and flocculation [41],
- Pozzolanic reactions [41],
- Carbonation [9].

The lime adopted for the study was laboratory grade lime with 95 % purity manufactured by Nice Chemicals Pvt. Ltd., India.

Table 1. Properties of soil

S. No.	Property	Value	Standards
1	Liquid limit	68 %	IS 2720 Part 5 [30]
2	Plastic limit	27 %	
3	Plasticity index	41 %	-
4	Shrinkage limit	10 %	IS 2720 Part 6 [31]
5	Specific gravity	2,76	IS 2720 Part 3 [32]
6	% gravel	0	IS 2720 Part 4 [33]
7	% sand	2,5	
8	% silt	60,5	
9	% clay	37	
10	Maximum dry density	15,3 kN/m^3	IS 2720 Part 7 [34]
11	Optimum moisture content	25 %	
12	UCC strength	115,8 kPa	IS 2720 Part 10 [35]
13	Soil classification	CH	IS 1498 [36]

Laboratory grade lime offered better control over the test results because of the consistency in its composition. The composition of the lime provided by the manufacturer is given in Table 2.

Table 2. Composition of lime

S. No.	Component	Component [%]
1	Assay	95
2	Chloride	0,01
3	Sulphate	0,2
4	Arsenic	0,0004
5	Lead	0,001
6	Insoluble matter	1

2.3. Phosphogypsum

Phosphogypsum (PG) is a waste by-product from the processing of phosphate rock by wet acid method in fertilizer production, which currently accounts for over 90 % of phosphoric acid production [20, 42]. PG has been used as set controller in the manufacture of Portland cement, as a raw material for clinker, as a secondary binder with lime and cement, in the production of artificial aggregates, and in road stabilization [27]. The worldwide production of PG is estimated to be in the range of 100-280 Million tonnes per year [42, 43]. This calculation is based on the general rule that 4.5-5 tonnes of PG is generated for every ton of phosphoric acid produced [42, 44, 45].
PG production in India is 11 Million tonnes per annum [45]. Up to 15 % of the world PG production is used in the manufacture of building materials [42, 43]. The low utilization of PG may be due to naturally occurring radioactive materials including Ra-226 [20, 27, 42, 46]. It is even banned in several countries [42]. However, in 2009, the Atomic Energy Regulation Board of India approved PG use for construction purposes provided the activity concentration of Ra-226 in it is less than 1.0 Bq/g [45]. Shweikani et al. [47] found that radiation due to addition of PG in cement is within the prescribed international standards for construction materials. PG utilization in soil stabilization by Degirmenci et al. [20] involved its use in combination with cement and, later on, Degirmenci [27] utilized only PG for stabilization of adobe, whereas in this study PG has been used as an additive to lime. The utilization of PG in both aforementioned cases was more than 2.5 %, whereas in the present study, the maximum dosage of PG was limited to 2 % thereby limiting the study to understanding the effects of PG on lime at low dosage levels. However, Ghosh adopted in his study [48] the combination of lime and PG for stabilization of pond ash, where the PG content was within 1 %.
The PG used in the study was obtained from the Coromandel International Limited fertilizer plant, located in Ennore, north of Chennai, India. In this study, PG finer than 75 micron, Indian Standards sieve, was used as an admixture. Also, the grain size distribution of this fraction was analyzed on this fraction in accordance with Bureau of Indian Standards (BIS) code [33]. This analysis revealed 88.3 % silt size fractions and 11.7 % clay size fractions. The specific gravity of PG was determined as 2.48, in accordance with BIS code [32], which lies in the range of 2.3 to 2.6 for PG [45]. Typical composition of PG in India is given in table 3.

Table 3. Chemical composition of PG in India [45]

Parameter	Composition [%]
$H_2O_{cryst.}$	18,0
SO_2	43,6
CaO	32,0
MgO	0,40
$Al_2O_3 + Fe_2O_3$	1,82
$SiO_{2\ ins.\ in\ HCl}$	1,64
Na_2O	0,36
$P_2O_{5\ total}$	1,03
F_{total}	0,76
Organic matter	0,26

2.4. Methodology

The preparation of soil samples for the study was done in accordance with BIS code [49]. The soil was air dried, cleaned, pulverized to break clumps, and then sieved as per the requirement of the test. The soil was then tested for its properties, and classified as per BIS Classification [36] (Table 1). Three trial lime contents were identified for the stabilization of soil viz. the Optimum Lime Content (OLC), Initial Consumption of Lime (ICL), and the trial lime content less than ICL (LICL). Nasrizar et al. [50] state that there are three phases in the relationship between strength and lime content, the first phase for the lime content less than ICL, the second phase for the lime content above ICL but less than OLC, and the third phase, lime content above OLC. ICL was determined from Eades and Grim pH Test [51]. OLC was obtained by conducting UCC tests in accordance with BIS code [35] on soil at its optimum moisture content and maximum dry density, with increasing lime content and cured for a period of 2 days in sealed polythene bags. The lime content at which the stabilized soil developed maximum UCC strength was taken as the OLC. Ciancio et al. [52] determined the OLC using UCC tests on lime stabilized earth cured for 28 days. Sivapullaiah et al. [53] determined earlier the OLC using UCC tests on soil stabilized with increasing lime contents, for various curing periods, with a minimum curing period of 1 day. There have also been instances where researchers found ICL and adopted trial values higher than ICL for the study [41, 54–56]. However, trial percentages of PG were fixed at random. The expansive soil was mixed with combinations of lime (3 %, 5.5 %, and 7 %) and PG (0.25 %, 0.5 %, 1 %, and 2 %) by dry weight of soil. The UCC specimens were then prepared in a steel mould of 38mm

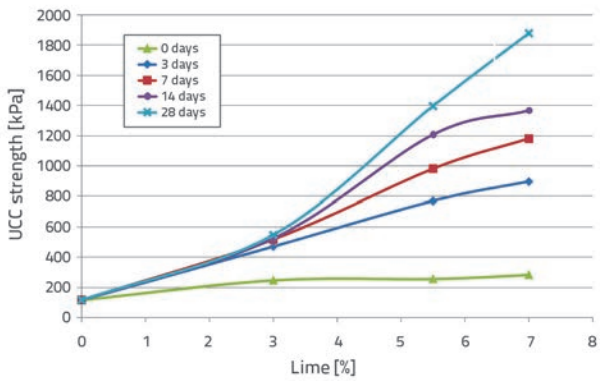

Figure 1. Variation of UCC strength with lime content over different curing periods

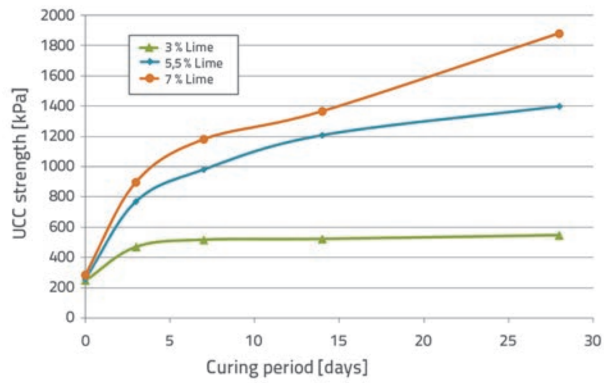

Figure 2. Variation of UCC strength with curing period for different lime contents

internal diameter and 76 mm height using static compaction [57–59]. The prepared samples were cured for the periods of 2 hours, 3, 7, 14, and 28 days in air tight sealed polythene covers to prevent loss of moisture. ASTM [60] states that any curing period can be specified but usually 7, 28 and 90 days of curing is adopted. Nasrizar et al. [50, 55] had adopted curing periods of 2 hours, 7, 14, 28, and 90 days. Al-Mukhtar et al. [1, 61] adopted a minimum curing period of 1.5 hours (period of fast exchange) for studying properties of the lime-stabilized expansive soil. After the specified curing period, the samples were subjected to a gradually increasing axial compression load until failure. All specimens were tested at a strain rate of 0.625 mm/minute. Bhuvaneshwari et al. [62] adopted a strain rate of 0.5 mm/minute, whereas Dash and Hossain [8] adopted a strain rate of 1.25 mm/minute. Muhmed and Wanatowski [11] adopted a strain rate of 1 % per minute.

3. Results and discussion

The lowest percentage of lime in soil that gives a pH of 12.4 is the approximate lime percentage for stabilizing the soil [51]. During lime stabilization reactions, the highly alkaline soil pH (soil pH of 12.4) promotes dissolution of siliceous and aluminous compounds from the clay mineral lattice. The compounds dissolved from the clay mineral lattice react with calcium ions in pore water to form calcium silicate hydrate and calcium aluminate hydrate gels, which coat the soil particles and subsequently crystallize to bond them [57]. Based on this, ICL for the soil was determined as 5.5 %. ICL values as low as 2 % [11, 54] and in some cases even up to 8 % [10] for organic soils have been reported. The OLC determined from UCC tests amounted to 7 %. The trial LICL content was adopted as 3 % in order to study the strength of lime stabilized soil below the ICL.

3.1. Effect of lime on soil

The stabilization of soil by addition of lime results in an increase in soil strength. It has been concluded that lime stabilization of clayey soils results in an increase in strength of the stabilized soil with an increase in lime content and curing period [5, 11, 23]. In the present study, the addition of lime to soil has also resulted in an increase in the strength of the soil with an increase in lime content as shown in Figure 1, and with the curing period as shown in Figure 2.

3.2. Effect of phosphogypsum on lime stabilized soil

In order to study the effect of PG on the development of strength of lime stabilized soil, the soil to be stabilized with lime was admixed with increasing contents of PG. To facilitate understanding of the PG effect on strength gain, the effects of PG quantum and the curing period were analysed with reference to three lime contents.

3.2.1. Effect of phosphogypsum quantum on lime stabilized soil

The soil to be stabilized was admixed with increasing quantity of PG along with 3 % of lime to see its influence on the strength gain of soil. The same was repeated with the other two lime contents. Figure 3 shows the variation of UCC strength of 3 % lime stabilized soil with %PG for different curing periods.

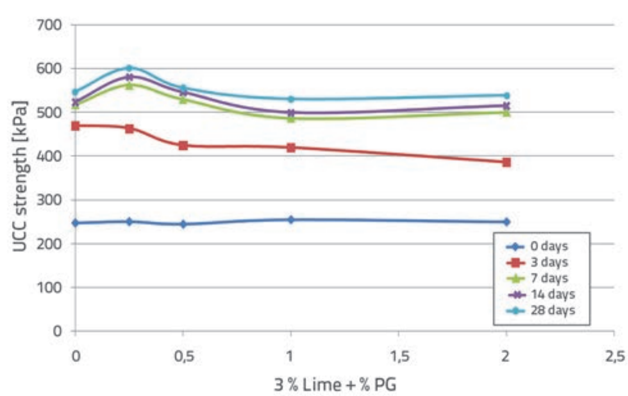

Figure 3. Variation of UCC strength of 3 % lime stabilized soil with % phosphogypsum

At 3 % lime, which is less than the ICL, the strength gain reduced with curing period. A significant drop in strength gain occurred beyond 7 days as seen from the closely spaced strength curves for 7, 14, and 28 days of curing. This may be due to the fact that 3 % is LICL, which is insufficient for raising the pH and stabilizing the soil. It is documented in literature that the lime content of more than ICL results in an increase in strength of the lime-stabilized soil [55]. At a PG content of 0.25 %, the maximum strength, beyond which the strength gain stabilizes, was achieved. 0.25 % addition of PG to lime soil mix resulted in a strength gain of close to 10 % when compared to the plain lime-stabilized soil with the strength increasing from 547.48 kPa to 601.66 kPa at 28 days of curing. Thus PG is capable of raising the strength of the soil even when lime content is LICL.

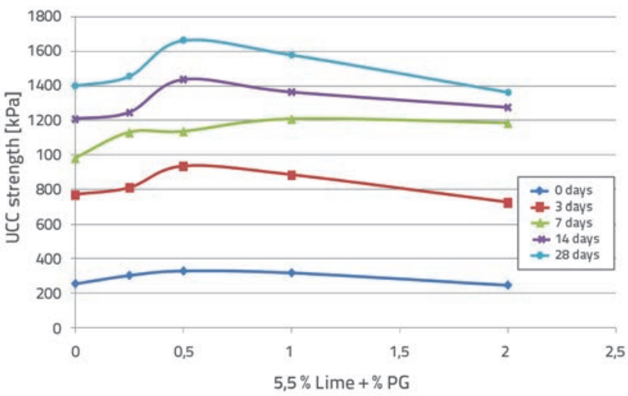

Figure 4. Variation of UCC strength of 5.5 % lime stabilized soil with % phosphogypsum

Figure 4 shows the UCC strength of the 5.5 % lime stabilized soil admixed with PG. Comparing the performance from Figure 3, it can be seen that ICL content performs better when compared to that of the LICL content. For 5.5 % addition of lime to soil, admixed with PG, the maximum strength was obtained at 0.5 % admixture. The strength of lime stabilized soil jumped from 1398.77 kPa to 1663.8 kPa at 28 days of curing. The difference amounts to a gain in strength of close to 19 %.

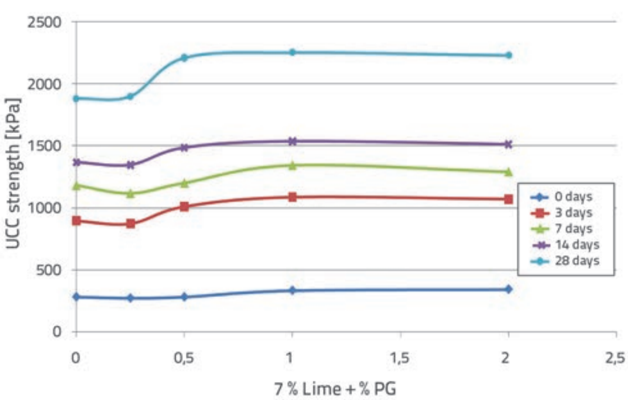

Figure 5. Variation of UCC strength of 7 % lime stabilized soil with % phosphogypsum

Figure 5 shows the UCC strength of 7 % lime stabilized soil amended with PG. At 7 % lime stabilization, the addition of PG has resulted in even higher strengths when compared to 3 % or 5.5 %. In this case, the maximum strength was obtained for 1 % PG amendment. The strength of the soil increased from 1881.45 kPa to 2251.07 kPa upon 1 % PG addition to 7 % lime stabilized soil, which is a gain of 19.6 %.

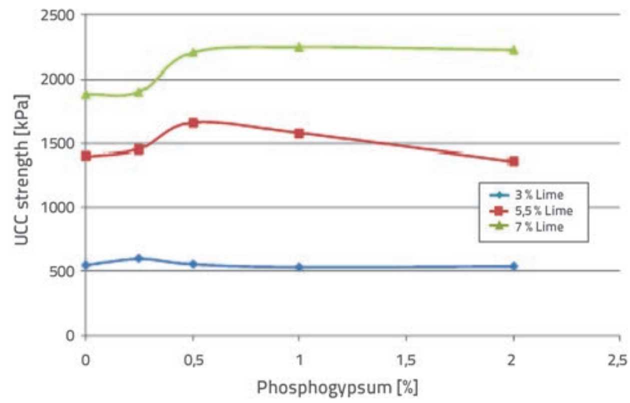

Figure 6. Variation of 28 days UCC strength of lime stabilized soil with % phosphogypsum

Figure 6 compares the strength curves of the three lime contents adopted for soil stabilization. It can be seen that, with an increase in lime content, the maximum strength is obtained at a higher PG dosage. It may be postulated that when more lime is available, more PG gets involved in the soil lime reactions resulting in higher utilization of PG in soil stabilization. The maximum percentage gain in UCC strength was obtained for OLC at 1 % PG addition. Ghosh [48] found that PG contribution to bearing ratio was more prominent at lower lime contents under soaked conditions. However, in unsoaked conditions, the PG contribution increased with an increase in lime content and then stabilized or reduced on further increase. The present study is in agreement with the above work. Krishnan et al. [28] found that at constant fly ash (FA), content an increasing PG content resulted in an increased strength of the FA stabilized expansive soil. Shen et al. [63] found that the addition of 2.5 % PG to 1:1 ratio steel slag – FA road base increased its strength from around 4.5MPa to 8.4MPa. With the addition of an optimum PG content, lime-FA mixtures produced 80-90 % higher strength than without PG [26].

3.2.2. Effect of curing period on phosphogypsum admixed lime stabilized soil

In order to understand the strength development of lime stabilized soil admixed with PG, it is also necessary to understand curing and its effect on the contribution of PG to strength development. Figure 7 shows the variation in strength development of lime stabilized soil with and without an optimum PG dosage for the various lime contents.

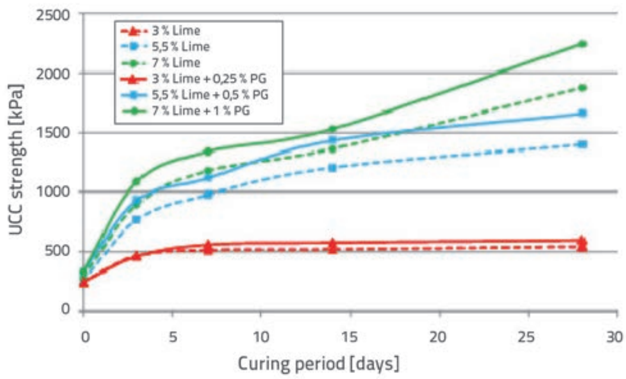

Figure 7. Comparison of UCC strength with curing period of lime stabilized soil with and without phosphogypsum

It is clear that at lower lime content of 3 %, the addition of PG results in more or less stable strength gain with increasing curing periods. However, the gain is not significant in comparison with higher lime content. The early strength development is also not significant at 3 % lime stabilization of soil. At 5.5 % lime stabilization, the addition of PG to the soil has resulted in a strength gain of 21.3 % over lime stabilized soil without PG at an early age of 3 days. At 7 days, the same is 14 % in comparison. At 7 % lime stabilization, the addition of PG to soil has resulted in a strength gain of 21.4 % at 3 days. At 7 days, the strength gain was almost like that of 5.5 % lime stabilization at 13.9 %. At 28 days of curing, the final strength gain for 5.5 % and 7 % lime was close to each other at 19 % and 19.6 %, respectively. However, in comparison with the early strength gain at 3 days, the strength gain at 28 days was lesser by around 2 % for both ICL and OLC contents. The results are similar to what Ghosh [48] found in his study, namely, that the addition of PG to lime stabilized pond ash had greater gain in bearing ratio at 7 days of curing than 28 days of curing for unsoaked specimens. The addition of PG results in an enhanced early strength when sufficient lime is available. According to Krishnan et al. [28], increasing PG content resulted in higher early strength of the FA stabilized expansive soil. It can be seen that the late strength gain is lesser than the early strength gain. The late strength development in PG-lime-FA systems depends, not only on the calcined PG content, but also on the ratio of calcined PG to lime [64].

3.2.3 Mechanism of phosphogypsum admixed lime stabilization of soil

The mechanism that results in the development of strength in PG admixed lime stabilized soils can be attributed to the formation of ettringite (AFt). Several researchers have reported the formation of AFt in PG admixed systems as a reason behind the early strength gain [26, 63–65]. Pozzolanic reactions are hastened by the presence of PG [26, 63, 64]. Formation of AFt needs a high pH environment [6] which in the present case is enabled by the presence of lime. With an increasing curing period, PG is consumed in the formation of AFt. Huang and Lin [65] reported an increase in the peaks of AFt and reduction in peaks of gypsum, indicating the consumption of PG in AFt formation in X-Ray Diffraction (XRD) studies. The precipitation of AFt as small crystals rather than large clumps was responsible for the gain in strength due to filling up of pores. It can be postulated that when PG levels go beyond the optimal dosage, more AFt in large clusters are formed, which may be responsible for the decrease in strength.

4. Conclusion

The study involved understanding the effect of PG addition on the strength of lime stabilized soil. Based on the test results, the following can be concluded.

- Addition of PG to lime in soil stabilization increased ultimate strength gain of the soil when compared to that of the lime stabilized soil.
- PG addition to lime resulted in significant early strength gain of the stabilized soil.
- With increasing lime content, more PG content was required to develop higher strength, indicating the utilization of PG in the pozzolanic reactions.
- However, less than 2 % of PG was required for strength gain as higher PG content resulted in an increase in the PG to lime ratio, reducing the development of late strength.
- PG can be used as an effective admixture to improve lime stabilization of expansive soil.

The strength development in PG lime systems can be further studied in detail through Scanning Electron Microscopy and XRD studies to corroborate the proposed mechanism.

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REFERENCES

[1] Al-mukhtar, M., Khattab, S., Alcover, J.: Microstructure and geotechnical properties of lime-treated expansive clayey soil, *Eng. Geol.*, 139 (2012), pp. 17–27.

[2] Sridharan, A., Prakash, K.: Classification procedures for expansive soils, *Proc. ICE - Geotech. Eng.*, 143 (2000) 4, pp. 235–240.

[3] Castro-Fresno, D., Movilla-Quesada, D., Vega-Zamanillo, Á., Calzada-Pérez, M.: Lime Stabilization of bentonite sludge from tunnel boring, *Appl. Clay Sci.*, 51 (2011) 3, pp. 250–257.

[4] Al-Rawas, A., Taha, R., Nelson, J., Al- Shab, T., Al-Siyabi, H.: A Comparative Evaluation of Various Additives Used in the Stabilization of Expansive Soils, *ASTM Geotech. Test. J.*, 25 (2002) 2, pp. 199–209.

[5] Bell, F.: Lime stabilization of clay minerals and soils, *Eng. Geol.*, 42 (1996) 4, pp. 223–237.

[6] Rajasekaran, G.: Sulphate attack and ettringite formation in the lime and cement stabilized marine clays, *Ocean Eng.*, 32 (2005) 8, pp. 1133–1159.

[7] Al-Mukhtar, M., Lasledj, A., Alcover, J.: Behaviour and mineralogy changes in lime-treated expansive soil at 20°C, *Appl. Clay Sci.*, 50 (2010) 2, pp. 191–198.

[8] Dash, S., Hussain, M.: Lime Stabilization of Soils: Reappraisal, *J. Mater. Civ. Eng.*, 24 (2011) 6, pp. 707–714.

[9] Metelková, Z., Boháč, J., Přikryl, R., Sedlářová, I.: Maturation of loess treated with variable lime admixture: Pore space textural evolution and related phase changes, *Appl. Clay Sci.*, 61 (2012), pp. 37–43.

[10] Saride, S., Puppala, A., Chikyala, S.: Swell-shrink and strength behaviors of lime and cement stabilized expansive organic clays, *Appl. Clay Sci.*, 85 (2013), pp. 39–45.

[11] Muhmed, A., Wanatowski, D.: Effect of Lime Stabilisation on the Strength and Microstructure of Clay, *IOSR J. Mech. Civ. Eng.*, 6 (2013) 3, pp. 87–94.

[12] Saltan, M., Kavlak, Y., Ertem, F.: Utilization of Pumice Waste for Clayey Subgrade of Pavements, *J. Mater. Civ. Eng.*, 23 (2011) 12, pp. 1616–1623.

[13] Sabat, A.: Stabilization of Expansive Soil Using Waste Ceramic Dust, *Electron. J. Geotech. Eng.*, 17 (2012) Bund. Z, pp. 3915–3926.

[14] Oza, J., Gundaliya, P.: Study of Black Cotton Soil Characteristics with Cement Waste Dust and Lime, *Procedia Eng.*, 51 (2013), pp. 110–118.

[15] Ameta, N., Wayal, A., Hiranandani, P.: Stabilization of Dune Sand with Ceramic Tile Waste as Admixture, *Am. J. Eng. Res.*, 02 (2013) 09, pp. 133–139.

[16] Anupam, A., Kumar, P., Ransinchung, G.: Use of Various Agricultural and Industrial Waste Materials in Road Construction, *Procedia - Soc. Behav. Sci.*, 104 (2013), pp. 264–273.

[17] Fauzi, A., Mohd, W., Wan, N., Rahman, A., Jauhari, Z.: Utilization Waste Material as Stabilizer on Kuantan Clayey Soil Stabilization, *Procedia Eng.*, 53 (2013), pp. 42–47.

[18] Ji-ru, Z., Xing, C.: Stabilization of Expansive Soil by Lime and Fly Ash, *J. Wuhan Univ. Technol. - Mater. Sci. Ed.*, 17 (2002) 4, pp. 73–77.

[19] Jha, J., Gill, K.: Effect of Rice Husk Ash on Lime Stabilization, *J. Inst. Eng.*, 87 (2006), pp. 33–39.

[20] Degirmenci, N., Okucu, A., Turabi, A.: Application of phosphogypsum in soil stabilization, *Build. Environ.*, 42 (2007) 9, pp. 3393–3398.

[21] Kavak, A., Bilgen, G., Faruk Capar, O.: Using Ground Granulated Blast Furnace Slag with Seawater as Soil Additives in Lime-Clay Stabilization, *J. ASTM Int.*, 8 (2011) 7, pp. 1–12.

[22] Alavéz-Ramírez, R., Montes-García, P., Martínez-Reyes, J., Altamirano-Juárez, D., Gochi-Ponce, Y.: The use of sugarcane bagasse ash and lime to improve the durability and mechanical properties of compacted soil blocks, *Constr. Build. Mater.*, 34 (2012), pp. 296–305.

[23] Harichane, K., Ghrici, M., Kenai, S.: Effect of the combination of lime and natural pozzolana on the compaction and strength of soft clayey soils: a preliminary study, *Environ. Earth Sci.*, 66 (2012) 8, pp. 2197–2205.

[24] Obuzor, G., Kinuthia, J., Robinson, R.: Enhancing the durability of flooded low-capacity soils by utilizing lime-activated ground granulated blastfurnace slag (GGBS), *Eng. Geol.*, 123 (2011) 3, pp. 179–186.

[25] James, J., Lakshmi, S., Pandian, P., Aravindan, S.: Effect of Lime on the Index Properties of Rice Husk Ash Stabilized Soil, *Int. J. Appl. Eng. Res.*, 9 (2014) 18, pp. 4263–4272.

[26] Shen, W., Zhou, M., Zhao, Q.: Study on lime-fly ash-phosphogypsum binder, *Constr. Build. Mater.*, 21 (2007) 7, pp. 1480–1485.

[27] Degirmenci, N.: The using of waste phosphogypsum and natural gypsum in adobe stabilization, *Constr. Build. Mater.*, 22 (2008) 6, pp. 1220–1224.

[28] Krishnan, D., Janani, V., Ravichandran, P., Annadurai, R., Gunturi, M.: Effect of Fly Ash and PhosphoGypsum on Properties of Expansive Soils, *Int. J. Sci. Eng. Technol.*, 3 (2014) 5, pp. 592–596.

[29] Ajam, L., Ben, M., Sfar, H., El, R.: Characterization of the Tunisian phosphogypsum and its valorization in clay bricks, *Constr. Build. Mater.*, 23 (2009) 10, pp. 3240–3247.

[30] BIS: IS 2720 *Methods of Test for Soils*: Part 5 - Determination of Liquid and Plastic Limit, India, 1985.

[31] BIS: IS 2720 *Methods of Test for Soils*: Part 6 - Determination of Shrinkage Factors, India, 1972.

[32] BIS: IS 2720 *Methods of Test for Soils*: Part 3 - Determination of Specific Gravity/Section 1 Fine Grained Soils, India, 1980.

[33] BIS: IS 2720 *Methods of Test for Soils:* Part 4 - Grain Size Analysis, India, 1985.

[34] BIS: IS 2720 *Methods of Test for Soils*: Part 7 - Determination of Water Content-Dry Density Relation Using Light Compaction, India, 1980.

[35] BIS: IS 2720 *Methods of Test for Soils*: Part 10 - Determination of Unconfined Compressive Strength, India, 1991.

[36] BIS: IS 1498 *Classification and Identification of Soils for General Engineering Purposes*, India, 1970.

[37] Literature Review: Stabilised Sub-Bases for Heavily Trafficked Roads, *Transport Research Laboratory*, Berkshire, UK, 2003.

[38] Petry, T., Little, D.: Review of Stabilization of Clays and Expansive Soils in Pavements and Lightly Loaded Structures - History, Practice, and Future, *J. Mater. Civ. Eng.*, 14 (2002) 6, pp. 447-460.

[39] Lime-Treated Soil Construction Manual: Lime Stabilization & Lime Modification, *National Lime Association*, Arlington, Virginia, US, 2004.

[40] James, J., Pandian, P.: Performance Study on Soil Stabilisation

using Natural Materials, *Int. J. Earth Sci. Eng.*, 06 (2013) 01, pp. 194–203.

[41] Bhuvaneswari, S., Thyagaraj, T., Robinson, R., Gandhi, S.: Alternative Technique to Induce Faster Lime Stabilization Reaction in Deeper Expansive Strata, *Indian Geotechnical Conference – 2010*, *GEOtrendz*, Mumbai, pp. 609–612,2010.

[42] Tayibi, H., Choura, M., Lopez, F., Alguacil, F., Lopez-Delgado, A.: Environmental impact and management of phosphogypsum, *J. Environ. Manage.*, 90 (2009) 8, pp. 2377–2386.

[43] Reijnders, L.: Cleaner phosphogypsum, coal combustion ashes and waste incineration ashes for application in building materials : A review, *Build. Environ.*, 42 (2007) 2, pp. 1036–1042.

[44] Rusch, K., Guo, T., Seals, R.: Stabilization of phosphogypsum using class C fly ash and lime : assessment of the potential for marine applications, *J. Hazard. Mater.*, 93 (2002) 2, pp. 167–186.

[45] Guidelines for Management and Handling of Phosphogypsum Generated from Phosphoric Acid Plants (Final Draft), *Central Pollution Control Bord,*New Delhi, India, 2012.

[46] Değirmenci, N.: Utilization of phosphogypsum as raw and calcined material in manufacturing of building products, *Constr. Build. Mater.*, 22 (2008) 8, pp. 1857–1862.

[47] Shweikani, R., Kousa, M., Mizban, F.: The use of phosphogypsum in Syrian cement industry: Radiation dose to public, *Ann. Nucl. Energy*, 54 (2013), pp. 197–201.

[48] Ghosh, A.: Compaction Characteristics and Bearing Ratio of Pond Ash Stabilized with Lime and Phosphogypsum, *J. Mater. Civ. Eng.*, 22 (2010) 4, pp. 343–351.

[49] BIS: IS 2720 *Methods of Test For Soils*:Part 1 - Preparation of Dry Soil Sample for Various Tests, India, 1983.

[50] Nasrizar, A., Ilamparuthi, K., Muttharam, M.: Quantitative Models for Strength of Lime Treated Expansive Soil, American Society of Civil Engineers, *GeoCongress 2012*, Oakland, California, pp. 978–987, 2012.

[51] *ASTM*: D6276 Standard Test Method for Using pH to Estimate the Soil-Lime Proportion Requirement, United States, 1999.

[52] Ciancio, D., Beckett, C., Carraro, J.: Optimum lime content identification for lime-stabilised rammed earth, *Constr. Build. Mater.*, 53 (2014), pp. 59–65.

[53] Sivapullaiah, P., Katageri, B., Herkal, R.: Enhancement of Strength of Soft Soils with Fly Ash and Lime, *First Sri Lankan Geotechnical Society International Conference on Soil and Rock Engineering*, Colombo, Sri Lanka, pp. 1–6, 2007.

[54] Maaitah, O.: Soil Stabilization by Chemical Agent, *Geotech. Geol. Eng.*, 30 (2012) 6, pp. 1345–1356.

[55] Nazrizar, A., Muttharam, M., Illamparuthi, K.: Role of Lime Content on Soil-Lime Reaction under Thermal Curing, *Indian Geotechnical Conference – 2010, GEOtrendz*, Mumbai, pp. 595 – 598, 2010.

[56] Nasrizar, A., Muttharam, M., Illamparuthi, K.: Effect of placement water content on the strength of temperature cured lime treated expansive soil, *GeoShanghai 2010*, Shanghai, pp. 174–180, 2010.

[57] Rao, S., Shivananda, P: Role of curing temperature in progress of lime-soil reactions, *Geotech. Geol. Eng.*, 23 (2005) 1, pp. 79–85.

[58] Kolay, P., Aminur, M., Taib, S., Mohd Zain, M.: Stabilization of Tropical Peat Soil from Sarawak with Different Stabilizing Agents, *Geotech. Geol. Eng.*, 29 (2011) 6, pp. 1135–1141.

[59] Thyagaraj, T., Rao, S., Sai Suresh, P., Salini, U.: Laboratory Studies on Stabilization of an Expansive Soil by Lime Precipitation Technique, *J. Mater. Civ. Eng.*, 24 (2012) 8, pp. 1067–1075.

[60] *ASTM*: D 5102 Standard Test Method for Unconfined Compressive Strength of Compacted Soil-Lime Mixtures, United States, 1996.

[61] Al-Mukhtar, M., Lasledj, A., Alcover, J.: Lime consumption of different clayey soils, *Appl. Clay Sci.*, 95 (2014), pp. 133–145.

[62] Bhuvaneshwari, S., Robinson, R., Gandhi, S.: Behaviour of Lime Treated Cured Expansive Soil Composites, *Indian Geotech. J.*, (2013) pp. 1–16.

[63] Shen, W., Zhou, M., Ma, W., Hu, J., Cai, Z.: Investigation on the application of steel slag-fly ash-phosphogypsum solidified material as road base material, *J. Hazard. Mater.*, 164 (2009) 1, pp. 99–104.

[64] Min, Y., Jueshi, Q., Ying, P.: Activation of fly ash–lime systems using calcined phosphogypsum," *Constr. Build. Mater.*, 22 (2008) 5, pp. 1004–1008.

[65] Huang, Y., Lin, Z.: Investigation on phosphogypsum–steel slag–granulated blast-furnace slag–limestone cement, *Constr. Build. Mater.*, 24 (2010) 7, pp. 1296–1301.