Research Article

Geotechnical Properties and Microstructure of Lime-Fly Ash-Phosphogypsum-Stabilized Soil

Tebogo Pilgrene Mashifana ⬤,[1,2] **Felix Ndubisi Okonta,[2] and Freeman Ntuli[1]**

[1]*Department of Chemical Engineering, University of Johannesburg, P.O. Box 17011, Doornfontein 2088, South Africa*
[2]*Department of Civil Engineering Sciences, University of Johannesburg, P.O. Box 524, Auckland Park 2000, South Africa*

Correspondence should be addressed to Tebogo Pilgrene Mashifana; tmashifana@uj.ac.za

The use of industrial waste as a potential stabilizer of marginal construction materials is cost effective. Phosphogypsum and fly ash are industrial wastes generated in very large quantities and readily available in South Africa. In order to explore the potential stabilization of vastly abundant expansive soil using larger quantity phosphogypsum waste as a potential modifier, composites with a mixture of lime-fly ash-phosphogypsum-basic oxygen furnace slag were developed. However because of the presence of radionuclide, it was necessary to treat the phosphogypsum waste with mild citric acid. The effect of the acid treatment on the geotechnical properties and microstructure of expansive soil stabilized with phosphogypsum-lime-fly ash-basic oxygen furnace slag (PG-LFA-BOF) paste was evaluated, in comparison with the untreated phosphogypsum. Expansive soil stabilized with acid-treated PG-LFA-BOF paste exhibited better geotechnical properties; in particular, the high strength mobilized was associated primarily with the formation of various calcium magnesium silicide and coating by calcium silicate hydrate and calcium aluminate hydrate. The soil microstructure was improved due to the formation of hydration products. The stabilized expansive soil met the specification for road subgrades and subbase. Stabilization of expansive soils with phosphogypsum, fly ash, and basic oxygen fly ash does not only improve engineering properties of soil but also provides a solution in relation to disposal and environmental pollution challenges.

1. Introduction

Expansive soils are widely distributed throughout the world [1, 2] and tend to change greatly in volume with variation in water content. Expansive soils are extremely problematic and form a wide range of problems related to geotechnical engineering [3]. The greatest challenge is the high montmorillonite mineral content in the soil. Due to this problem, expansive soils need to be modified or stabilized in order to render it suitable for construction applications [3].

This soil type is abundant in arid zones with conditions suitable for the formation of clayey minerals of mainly the smectite group such as montmorillonite or illites [2, 4, 5]. Large specific area and high cation exchange capacity (CEC) are the characteristics associated with the expansive soils [5, 6]. These soils are extremely difficult to handle during construction and have very poor strength and low bearing capacity [3]. Three factors readily contribute to the swelling of these soils, namely, local environmental conditions, the engineering factors of the soil, and geology. Geology primarily determines the presence of expansive clay minerals. Among the engineering factors included are the soil moisture content, plasticity, and dry density. The most important local environmental conditions to consider are the amount of the clay fraction in the soil, its initial moisture conditions, and confining pressure [2]. The great volume changes associated of these types of soil are amongst the major causes of disasters worldwide due to the extensive damages caused to the structures and infrastructure [7–11], when built on top of the expansive soil. Chen et al. refer to these types of soils as "calamitous soils" [9], which is the soil with special characteristics in relation to shrinking, swelling,

fissures, and strength reduction. Expansive soils are also associated with swelling when they absorb water and shrink upon evaporation of water [12]. Stabilized expansive soil can be used as a backfill material; in 2015, Sun et al. utilized bentonite as a potential buffer/backfill material for deeply buried geological disposal system to isolate high-level radioactive waste [13].

Phosphogypsum and fly ash are normally discharged to the environment without any treatment leading to environmental contamination, occupation of considerable land, and pollution of soil and water [14]. These two industrial wastes, fly ash and phosphogypsum are produced by thermal power plants and phosphoric acid production companies, respectively [15]. An estimated 100–280 million tons of PG was generated worldwide per annum [16], and although excess of 35 million tons of fly ash is produced in South Africa, only 3 million tons were utilized. Currently only a relatively little amount of PG is utilized for building and civil engineering applications due to the presence of radionuclides [17–21]. Waste PG was treated with citric acid to reduce its radionuclides and render the material applicable for civil engineering works. To enhance the geotechnical properties of PG, both the raw and treated PG were then stabilized with fly ash, lime, and basic oxygen furnace slag before they were used further. The composites developed from different proportions of raw and acid-treated phosphogypsum, fly ash, lime, and basic oxygen furnace slag were then investigated as potential stabilizers for bentonite-rich reconstituted soils (expansive soil). The main objective of this study was to stabilize expansive soil by enhancing its geotechnical properties, using voluminous phosphogypsum waste and other wastes such as fly ash and basic oxygen furnace slag.

2. Materials and Methods

2.1. Materials. The raw phosphogypsum was obtained from a phosphoric acid manufacturing plant in South Africa. The treated phosphogypsum was produced by treating the raw phosphogypsum with mild citric acid to reduce its radioactivity. The effect of stirring speed on the leaching of raw PG with citric acid was studied by investigating the speed of 200, 400, and 600 rpm. For the leaching reagent concentration, citric acid was varied from 0.25 M, 0.5 M, to 0.75 M. The effect of temperature was also studied and temperature was set at 25°C, 30°C, and 40°C. The optimum operating conditions were the concentration of 0.5 M, stirring speed of 200 rpm, and temperature of 25°C. The major contributor to the radioactivity of phosphogypsum was ^{232}thorium with a concentration of 290 Bq/kg, which resulted into the following activity indexes: $I_1 = 1.405$, $I_2 = 0.505$, and $I_3 = 0.217$. Thorium radioactivity was reduced to 121 Bq/kg after treatment. Acid-treated phosphogypsum yielded the following activity indexes: $I_1 = 1.386$, $I_2 = 0.136$, and $I_3 = 0.055$, removing any limitation for the material to be used in building, construction of street or playground, and for landfilling. I_1, I_2, and I_3 are the activity indexes for materials intended for use in building construction, material used in road, street, playgrounds, and related construction work, and material used for landfilling,

respectively. Expansive soil was reconstituted in the laboratory by blending sand, kaolin, bentonite, and gravel.

2.2. Samples Preparation. The expansive soil utilized consists of 40% bentonite, 35% sand, 20% kaolin, and 5% gravel. The raw PG and the treated PG were stabilized with LFA and BOF slag. The developed binders with the PG proportion of 50% for both raw and treated PG were prepared separately with a mix design containing the following composition: PG 50%, FA 30%, and L 20% for raw PG and PG 50%, FA 10%, L 10%, and BOF slag 30% for treated PG. Stabilized raw PG mobilized unconfined compressive strength of 4.8 MPa, and stabilized acid-treated composites mobilized strength of 1.5 MPa (without BOF slag), both at 50% PG content. To further stabilize the treated PG, basic oxygen furnace slag was added in order to improve the strength. The application of the raw and treated PG composites separately as stabilizer using different proportions was investigated to the ratio of the expansive soil: 1 : 9, 2 : 8, 3 : 7, 4 : 6, and 5 : 5. Ratios from 10% to 50% stabilizers were investigated. The maximum dry density (MDD) and optimum moisture content (OMC) at different stabilizers to expansive soil were determined. The specimens were then cast in a $100 \times 100 \times 100$ mm^3 moulds.

To ensure that the composites developed are environmentally friendly and will not leach back to the environment, they were subjected to the toxicity characteristic leaching procedure (TLCP). The composites for the raw and treated PG were milled after determining UCS and leached with an extraction buffer of acetic acid and sodium hydroxide (pH 4.93 ± 0.05) at a liquid/solid ratio of 20 : 1. A thermostatic shaker was used for the extraction, and the cured composites were subjected to 24 hours shaking at 25 ± 2°C. After 24 hours, three samples were taken per test conducted and filtered. The leachate was analysed using the inductively coupled plasma-optical emission spectrometer (ICP-OES) to determine the concentration of leached heavy metals. The results obtained showed the concentration of the heavy metals in the leachate ranging between 0.01 and 6.59 ppm, indicating a lower leachability of the composites and that they are environmentally friendly and have no potential contaminating the environment.

2.3. Curing, Determination of Unconfined Compressive Strength, Atterberg Limit Tests, and Microstructure. The specimens were cured for 7 days in a chamber at the temperature of 40°C. After the curing process, the UCS of the specimens was determined in accordance with ASTM method D698 [22]. The liquid limit and plastic limit tests were performed on the expansive soil and the stabilized soil, following the ASTM D4318 method [23]. The expansive soil and stabilized soils were characterized using XRF, XRD, and SEM to study the chemical composition, mineralogy, and the morphology of the microstructures, respectively.

2.4. Properties of Expansive Soil. Tables 1 and 2 present the results for the raw and treated PG chemical composition and the properties of expansive soil, respectively.

TABLE 1: Chemical composition of raw PG, lime, fly ash, treated PG, and BOF.

Component (%)	F	Al_2O_3	SiO	P_2O	SO_3	CaO	TiO	Fe_2O_3	MgO	MnO	CrO_3	Radionuclides
Raw PG	1.06	0.23	1.37	1.28	51	44		0.121				0.62
L		0.28	0.5	0.03	0.2	73		0.225				
FA		28	48	0.73	0.6	5.1	2.47	4.83				
Treated PG		0.09	0.86	0.72	54	43		0.05				0.41
BOF slag		4.67	14.1	1.21		44	0.27	28.47	3.53	2.84	0.05	

TABLE 2: Properties of expansive soil.

	Sand (%)	Bentonite (%)	Gravel (%)	Kaolin (%)	pH	Density (g/cm^3)	Plastic limit (%)	Liquid limit (%)	Plastic index (%)	UCS (MPa)
Expansive soil	35	20	5	40	10.3	2.55	74.5	94.9	20.40	0.15

The raw phosphogypsum was mainly laden with calcium oxide and sulphur trioxide, and the semiqualitative results using XRD indicated traces of radionuclides. The actual radioactivity showing the concentration of radionuclides was measured by a gamma ray spectrometer. Treating PG with citric acid resulted into a reduction of contaminants such as flourides, phosphorus, and radionuclides, which has a potential to hinder strength development of the material. Calcium oxide was predominant in the hydrated lime utilized. Fly ash consisted of constituent such as silica, calcium oxide, ferrous iron, and titanium oxide [24]. The high wt.% of sulphate measured in both the raw and treated materials may have a detrimental effect on the strength development of the material. Although sulphate slightly increased after the treatment of PG, it was drastically reduced after curing. The relative proportion of sulphate was reduced from 51 wt.% to 35.21 wt.%, 32.88 wt.%, 26.15 wt.%, and 20.82 wt.%, for raw PG 30, 40, 50, and 60, respectively, and from 54 wt.% to 20.19 wt.%, 24.67 wt.%, 28.23 wt.%, and 30.42 wt.% for treated PG 30, 40, 50, and 60 composites, respectively.

The expansive soil had the UCS of 0.15 MPa, and it is a basic material with a pH of 10.32. The properties of soil also show a clay mineral with high plastic and liquid limits indicating the high water adsorption capability of the soil. The specific density of the expansive soil was measured to be 2.55 g/cm^3.

The respective MDD and OMC results with the increment in content of raw and treated PG stabilizers are presented in Table 3.

An increment in the stabilizers content for both raw and treated PG resulted in the decrease in MDD. The expansive soil had a MDD of 1765 kg/m^3, and raw and treated PG had MDDs of 1204 kg/m^3 and 1100 kg/m^3, respectively, leading to an overall reduction in density when the expansive soil was stabilized. The lower expansive soil dry density may have less swelling potential when compared to expansive soil with a higher dry density. The OMC however increased with increasing stabilizers content, and this may be due to the mineralogical composition especially the presence and specific surface of the montmorillonite and calcium-silica reactions [25]. The increase in OMC indicates an increased demand for water for curing and strength development.

TABLE 3: MDD and OMC with raw and treated PG stabilizers.

Stabilizer (%)	0	10	20	30	40	50
MDD (kg/m^3), raw PG	1765	1702	1683	1674	1663	1618
OMC (%)	13	18	21	24	28	30
MDD (kg/m^3), treated PG	1765	1647	1619	1501	1404	1314
OMC (%)	11	15	17	22	25	28

Particle agglomeration together with voids left by water is also responsible for the decrease in MDD [26].

2.5. Relative Density and pH of Expansive Soil. The relative density and pH of expansive soil before and after stabilization are shown in Table 4.

An increment in both the raw and treated PG stabilizer contents resulted in the increase in pH. The soil stabilized with treated PG possesses higher pH as compared to that with raw PG, and this is attributed to the availability of hydrogen ions in the lime which interact with alkalinity hence increasing the pH. The pH proves to have played a role on the higher strengths developed with treated PG as a stabilizer as the pozzolanic reactions are triggered at a higher pH of 12.

The relative density results for stabilized soil with raw PG show an increasing trend with the increase in the stabilizer content. The stabilized soil densities obtained with treated PG are higher than those of the raw PG. The treated PG contains slag, and the specific gravity of steel slags depends on their chemical composition, mineralogy, and particle structure. The presence of high iron oxide contents in the slags makes them to have specific gravity values larger than those of natural soils/aggregates [27]. Pozzolanic reactions are hastened by the presence of PG [28–30]. Pozzolanic reactions require a high pH environment [31] which in the present case is enabled by the presence of lime and calcium from slag for the treated PG stabilizer.

3. Results and Discussion

3.1. Atterberg Limits of Stabilized Soil by Raw PG-LFA and Treated PG-LFA. Figures 1(a) and 1(b) depict the liquid

TABLE 4: pH and specific density of expansive soil (raw PG and treated PG).

Stabilizer (%)	pH		Specific density (g/cm^3)	
	Raw PG	Treated PG	Raw PG	Treated PG
0	10.32	10.32	2.652	2.652
10	10.52	11.55	2.666	2.669
20	10.37	11.63	2.673	2.678
30	10.73	11.91	2.678	2.688
40	11.01	12.23	2.681	2.697
50	11.53	12.57	2.685	2.698

TABLE 5: PI of stabilized soil.

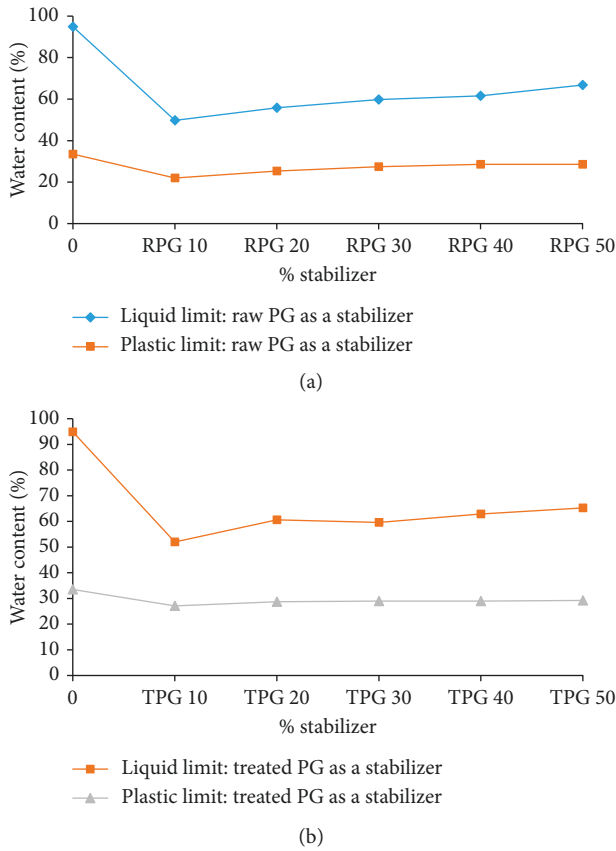| % stabilized	PI-raw PG	PI-treated PG
0	61.4	61.4
10	27.27	24.9
20	30.50	31.86
30	32.29	30.60
40	33.06	33.93
50	38.18	36.06

(a)

(b)

FIGURE 1: Liquid limit and plastic limits of soil samples that were stabilized by (a) raw PG-LFA and (b) treated PG-LFA-BOF.

limit and plastic limit of the soil stabilized with raw and treated PG.

The expansive soil initially had a liquid limit of 94.90%, and a 42% reduction in the liquid limit is observed at the highest PG content of 50%. The plastic limit decreased from 33.50% to 28.59%. A significant decrease in the liquid limit from 94.90% to 65.26% was achieved. Plastic limit decreased steadily by 25.45% with the increment in PG content to 50%, when comparing the expansive and stabilized soil. It is also evident that the effect of treated PG stabilizer on plasticity is through the liquid limit modification. In 2014, Kumar et al. studied the engineering properties of soil stabilized with lime and phosphogypsum and reported that increment of PG content increased both the liquid and plastic limits [19].

The increment in the stabilizer content from 10 to 50% resulted in the increase in both liquid and plastic limits. The effect herein is directly reflected on the plasticity of the stabilized soil as evident from the similarity in the gradually increasing plasticity. The overall plastic index of stabilized soil has decreased by 61% and 70% for maximum content of the raw and treated PG stabilizers, respectively. The reduction in plasticity is greater with the treated PG stabilizer; this is attributed to the lime content available sources used. The overall liquid limit, plastic limit, and plasticity index of the stabilized soil are less than those of the expansive soil. The reduction in the liquid limit is due to replacement of sodium ions with calcium ions, reduction in diffused double layer, and increase in electrolyte concentration of pore fluid. Phosphogypsum which is chemically calcium sulphate also acts as a source of calcium ions, thus contributing to similar effects on the expansive soil [32]. When the amount of phosphogypsum in mixture increases, the plastic limit value gradually rises. With the focus of utilizing voluminous waste PG for the stabilization of expansive soils, the higher quantity of PG can be used, even though the trends reveal that 10% stabilization in the optimum and shows a gradual increment in PL and LL thereafter. In the study conducted by James et al., in investigating the strength and index properties of phosphogypsum stabilized expansive soil, they found that addition of up to 50% PG has resulted in an increase in the plastic limit from 25.16% to 28.19% only, a mere 3.03% upon 50% addition of PG [33].

The PI of the unstabilized and stabilized soil with raw and treated PG is reported in Table 5.

The PIs of the stabilized soil using the raw PG and treated PG contents that yielded highest strength show a PI reduction of 90% and 70%, respectively. Ji-ru and Xing found that a change of expansive soil texture takes place when lime and fly ash are mixed with expansive soil [34]. The plastic limit increases by mixing lime, and liquid limit decreases by mixing fly ash, which decreases the plasticity index.

The plasticity chart showing the classification of the expansive and stabilized soil is presented in Figure 2. The figure shows that there is a change in the classification of the stabilized soil when comparing with the unstabilized soil. The expansive soil was initially classified as CE material exhibiting an extremely high plasticity material with high liquid limit and high plastic index. The raw and treated PG stabilized soils with a stabilizer content of 10–50% fall mainly under CL-CH region, displaying a medium to high plasticity behaviour. Both the stabilizers utilized in the study greatly improved the expansive soil properties. There is
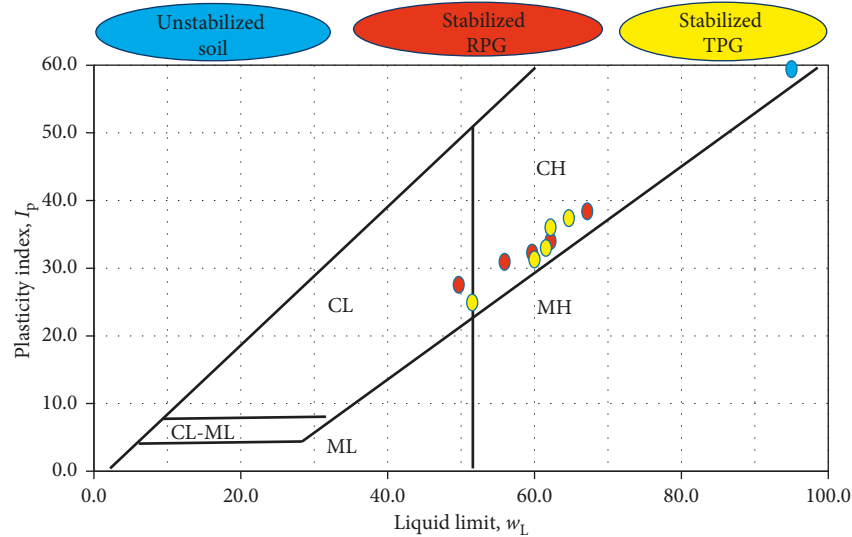
Figure 2: Plasticity chart for the stabilized soil.

a significant and distinct improvement in the soil properties which has resulted in a change in soil classification from clay of high plasticity to low plasticity, and similar results were obtained by James and Pandian [35]. CL is of low plasticity. They are used as subgrade pavement materials because of their low swelling and shrinkage potential. The addition of PG-LFA and PG-LFA-BOF effectively converts the soil from an expansive clay to a clay of low expansivity. The local TRH4 specification recommends low plasiticity clayey soils (CLs) as good candidate materials for modified pavement subgrade.

3.2. Unconfined Compressive Strength (UCS)-Stabilization of Expansive Soil with the Raw and Treated PG. The results for the unconfined compressive strength of the expansive soil stabilized with the raw and treated PG are presented in Figures 3(a) and 3(b).

The expansive soil initially had the UCS of 0.15 MPa, and stabilization with 10–50% raw PG improved the strength. The optimum strength is observed at the stabilizer content of 30%, and an increment in the stabilization material above to 40% and 50% resulted into strength reduction by 13% and 43%, respectively. James et al. also found that, in the stabilization of expansive soil, the optimum PG content that yielded the highest strength of $250 \, \text{kN/m}^2$ was 40%; thereafter, there was a reduction in the strength with increment of PG content [33]. Lime in excess can remain unreacted and act as weak filler in the compacted lime-fly ash-phosphogypsum composites, resulting in reduction of strength [36]. Also, insufficient lime to raise the pH and stabilize soils contributes greatly to strength reduction. The strength development for lime-fly ash-phosphogypsum specimen depends on a number of factors and lime-fly ash ratio being one of the most important factors affecting strength. Both the raw and treated PG stabilizers prepared at the PG content of 50%. The lime to fly ash ratio was 0.6 for the raw PG and 1 for the treated PG specimen. Lime

and fly ash in the treated PG were partially replaced by BOF which played a significant role in maintaining an improving strength. In the study conducted by Sivapullaiah and Jha on the induced strength behaviour of fly ash-lime-stabilized expansive soil, the change in strength behaviour was studied at different curing periods [32]. The researchers found that the variations in the strength of soil with curing period were due to cation exchange and flocculation initially, and binding of particles with cementitious compounds formed after curing. Early strength development was initially observed; thereafter, there was a decrease in strength due to annoyance of clay matrix with the increase in size of ettringite needle. The decrease in UCS after stabilization with 30% raw PG is attributed to excess lime content in the stabilizer. Therefore, raw PG stabilized with lime and fly ash can improve the geotechnical properties of expansive soil by increasing the unconfined compressive strengths of the soil, when added up to 30%.

In the unconfined compressive strength of the stabilized composite developed from treated PG-lime-fly ash-basic oxygen furnace slag, a significant improvement on the strength of expansive soil with increase in binder content was evident. The maximum UCS of 1.65 MPa was mobilized by composite with 50% binder. Basic oxygen furnace slag as a well-known aggregate in civil engineering for building and road construction has existing free lime, coming from the raw material and precipitated lime from molten slag [37]. The lime to fly ash ratio was higher in the treated PG content, but there is evidence of lime consumption during the curing process. In this case due to the lime consumption, the access lime in the slag played a significant role in the improvement of the strength by maintaining the lime-fly ash ratio. The XRD results showed that the BOF slag constitute of magnesium ferrite ($MgFe_2O_4$) and larnite (Ca_2SiO_4). Larnite has silica and calcium which plays a significant role in the strength development, and it had the higher intensity. The calcium and silica in the slag supplemented quartz and lime and promoted higher strengths in the treated PG. The results
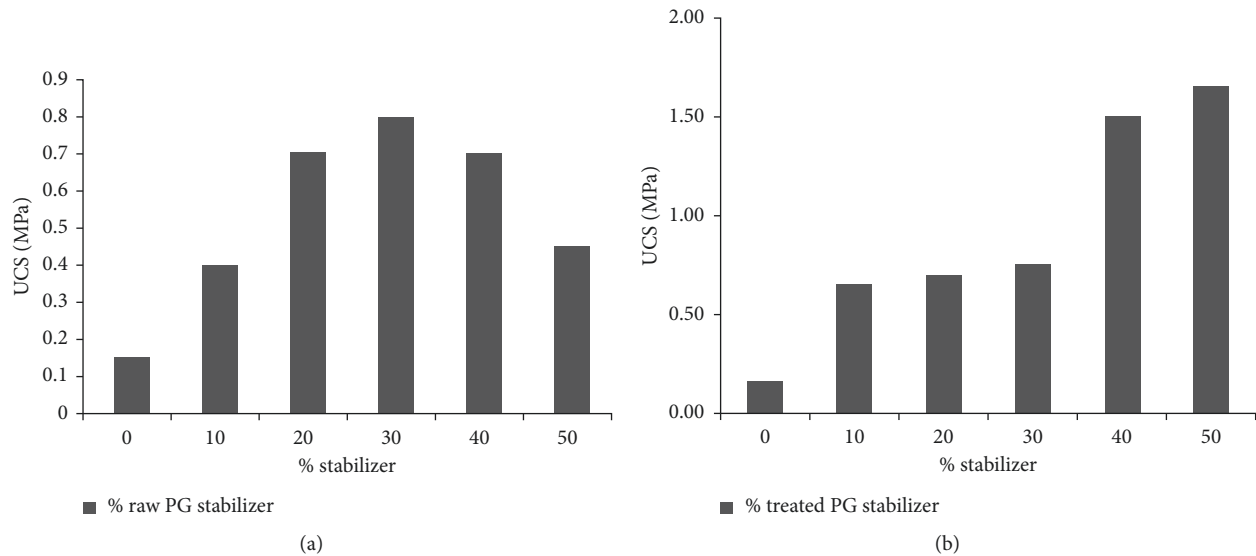
FIGURE 3: Stabilization of expansive soil with (a) raw PG and (b) treated PG.

obtained agree with the results reported by Tossavainen et al., who have reported the same predominant phases on BOF slag [38].

Comparing the two composites developed, it is evident that the treated PG composites perform better than the raw PG. The UCS of the raw PG composite increased by up to 30%, while continuous improvement in UCS was evident from acid-treated PG composite. According to the results, using treated PG for the development of a potential binder results in voluminous usage of the PG. Thus, the reactivity of treated PG composite in expansive soil stabilization was highly relative to raw PG binder and allowed for utilization of greater percentage of PG for pozzolanic reaction. The rearrangement of clay matrix and suppression of sulphate effects with formation of cementitious compounds are observed and found to be the main responsible factors for strength recovered [32].

3.3. XRD Analysis of Soil with Raw and Treated PG Stabilizers. The mineralogy of the expansive and stabilized soils with raw and treated PG determined by XRD is presented in Figures 4(a) and 4(b).

The predominant phases in the expansive soil (unstabilized) are those of montmorillonite $8(KAl_4(SiAl)O_{10}(OH)_4)$, bentonite $(Ca_{0.06}Na_{0.21}K_{0.27})$ $(A_{11.64})$, kaolinite $(Al_2(Si_2O_5)(OD)_4)$, and quartz (SiO_2). The presence of montmorillonite mineral in the soil is responsible for the expansive characteristics of the soil [28]. Stabilization of expansive soil with raw PG and curing for 7 days formed new hydration products of feldspar $(Al_2Si_2O_8)$. The strength gain in the raw PG stabilized soil was due to the new hydration product formed.

New products of calcium magnesium silicide (CaMgSi), sillimanite $(Al_2(SiO_4)O)$, kaolinite $(Al_2(Si_2O_5)(OD)_4)$, feldspar $(Al_2Si_2O_8)$, and trikalsilite $((KNa)AlSiO_4)$ were formed. The higher strength gain of treated PG stabilized

soil was primarily caused by the formation of various calcium magnesium silicide phases. The exact products formed, however, depend on the type of soil mineralogy and the reaction conditions including temperature, moisture, and curing conditions [39]. The highly alkaline stabilized soil with treated PG 50 at the pH of 12.57 stimulated the dissolution of siliceous and aluminous compounds from the soil mineral lattice. The compounds dissolved from the clay mineral lattice reacted with calcium ions in the pore water to form calcium silicate hydrate and calcium aluminate hydrate which coat the soil particles and subsequently crystallize to bond them [40], and hence, the significant strength is improved.

3.4. SEM Micrograph Analysis of Soil with Raw and Treated PG Stabilizers. The SEM results are presented in Figure 5.

The expansive soil structure shows a discontinuous structure, where the voids are more visible because of the absence of hydration products. The stabilized soil by raw PG 50 reveals that needle-like shape and euhedral to subhedral crystals were formed after curing. The EDS results showed the majority of silicon (Si) and aluminium (Al) minerals and trace amounts of potassium (K) and sodium (Na) minerals in the stabilized soil. The orientation of the soil particles in the soil mass and the spacing between particles will influence the manner in which the particles interact [41]. SEM results show a formation of more larger particles in the stabilized soil by treated PG. The hydration products in this case are not empty but intermixed and occupied by hardened epoxy structure. The micrographs also demonstrate the evidence of development of a more compact structure after curing time. The EDS analysis showed the presence of Ca and Si in the stabilized soil with treated PG, indicating presence of C-S-H, the main cementing product responsible for strength gain [42, 43]. Also peaks of Al, Fe, and Mg are
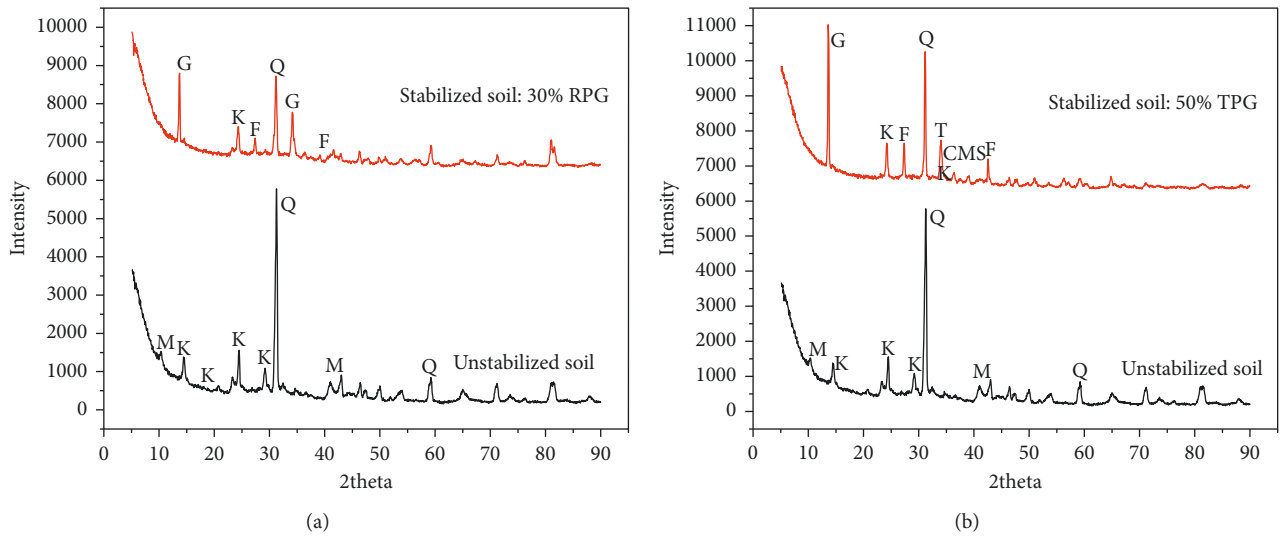
(a)

(b)

FIGURE 4: Mineralogy of expansive soil and stabilized soil by (a) raw PG (M: montmorillonite; B: bentonite; Q: quartz; G: gypsum; K: kaolinite; F: feldspar) and (b) treated PG (M: montmorillonite; B: bentonite; Q: quartz; G: gypsum; K: kaolinite; F: feldspar; TK: trikalsilite; CMS: calcium magnesium silicide; S: sillimanite).
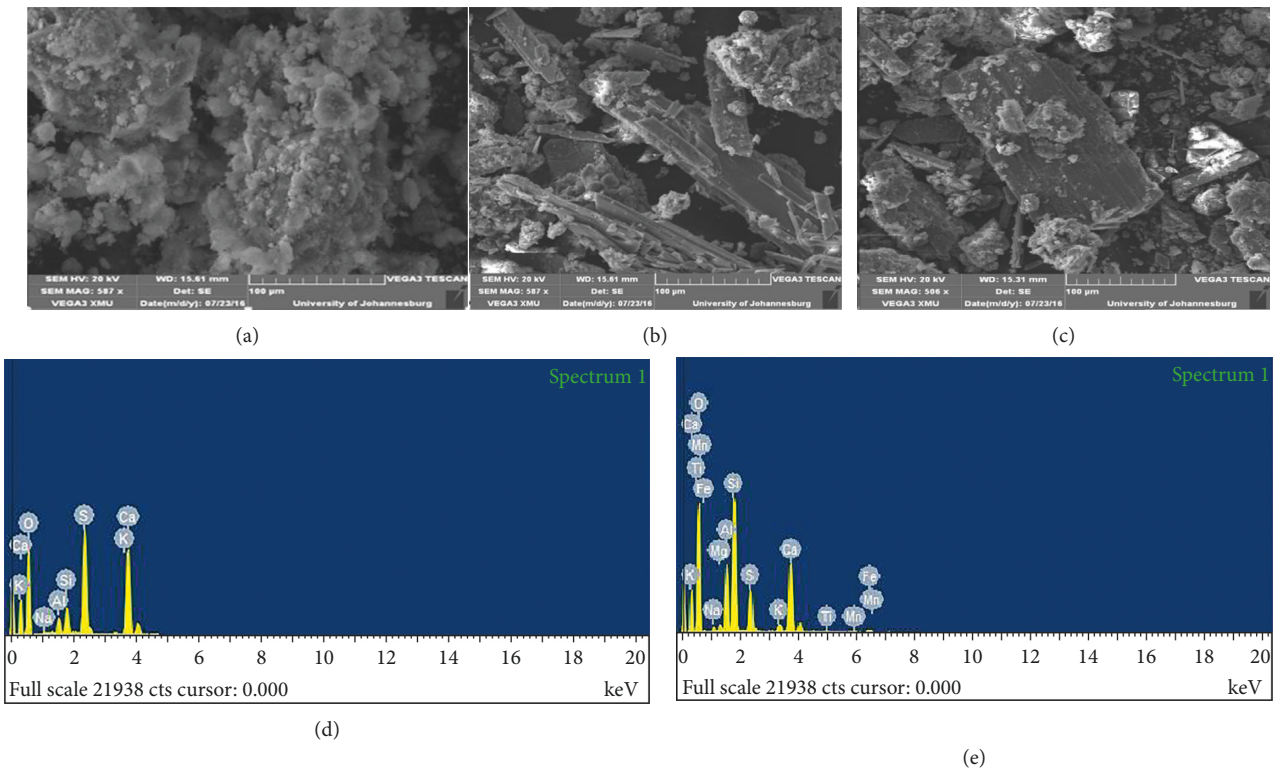

(a)

(b)

(c)

(d)

(e)

FIGURE 5: SEM micrograph and EDS of (a) expansive soil, (b) stabilized soil by raw PG, and (c) stabilized soil by treated PG. EDS of (d) stabilized soil by raw PG and (e) stabilized soil by treated PG.

visible in the material, constituents initially available in slag. The scanning electron microscope image of treated PG stabilized soil also shows that due to BOF slag, the material mainly consists of larger subrounded to angular particles with the surface having a rough surface texture.

BOF slag larger particles increased the contact between the particles cementing the particles together and increasing the UCS. The EDS shows that the elements detected were in accordance with the XRF results presented in Table 1.

4. Conclusion

Bentonite-rich soils can be simultaneously modified by mechanical and chemical stabilization. Residual industrial waste PG was treated with mild citric acid to reduce the radionuclides and then progressively modified with LFA-BOF. Expansive soil was then stabilized with the raw and treated PG binders. Both the raw and acid-treated stabilizers improved the geotechnical properties of the expansive soil by improving its liquid limit, plastic limit, and unconfined compressive strength. When treated PG-LFA was added to the expansive soil, the predominant hydration products formed contributed significantly to strength improvements. Curing resulted in the formation of harder and larger particles which also contributed to the strengths of the soils, and the hydration reaction products formed are responsible for the change in microstructure and improvement in physical and mechanical properties. The liquid limit and plastic limit of the expansive soil were reduced by both the raw and treated PG stabilizers, which implies improved plasticity characteristics of the soil. According to ASTM D4609 [44], an increase in the UCS of 345 kPa or more is considered an effective soil stabilization. In this study, the improvements of 650 kPa to 1500 kPa were achieved with LFA-modified raw and LFA-BOF-treated PG, respectively. The stabilized composite with UCS >750 kPa is suitable for the development of road subgrades and subbase in accordance with South African Roads TRH4 specifications. Fly ash-lime-basic oxygen slag stabilized PG can be used in larger quantities, up to 50% PG as a stabilizer for stabilizing expansive soils and enhancing the properties of soil. The analysis of the environmental impacts of the products produced shows an extremely low contaminants leachability back to the environment; thus the products will not contaminate the environment should leaching occur. The concentrations for all the measured elements are within the stipulated standards by the South African Department of Water and Sanitation [45].

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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