Effects of continuous leaching on engineering properties of lime-stabilized lateritic soils

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Abstract: This research investigates the performance of lime-stabilized lateritic subgrades under continuous leaching by focusing on changes in the engineering properties of the natural soil together with those treated with varying proportions of lime. Geotechnical tests conducted include California bearing ratio (CBR), Atterberg limits, particle size analysis and Proctor compaction tests. The leaching test was conducted in a constant-head cylindrical Perspex tank for a period of 28 days. X-ray diffraction analysis was conducted on the extracted leachates coupled with other physicochemical tests such as pH, electrical conductivity ($EC$), and calcium and potassium concentrations. The experimental results indicate that the highest CBR value of 47.1\% was obtained from the mixture containing 5\% lime after a curing period of 7 days. Further increase in the amount of lime resulted in a decrease in CBR, except for the 10\% soil-lime mixture which had a CBR value of 31.4\% after a curing period of 28 days. Physicochemical analyses showed a significant decrease in $EC$, calcium and potassium concentrations from the pore fluid of the soil-lime mixtures. The results suggest that the potential for strength loss was higher in the mixtures stabilized below their optimum lime contents than in those stabilized above their optimum lime contents.

Keywords: Lateritic soil, Calcium concentration, Column leaching test, Pavement deterioration, California bearing ratio

1. Introduction
Distresses in flexible pavements remain a major problem in many tropical and subtropical regions of the world. These problems are attributed to a number of causative factors such as traffic loading, characteristic properties of pavement materials, nature and type of subgrade, and climatic factors - temperature and moisture conditions [1]. Among these, climatic factors coupled with the type of subgrade, are by far the most contributing factors to pavement deterioration, especially in humid tropical wetlands, where the influence of high-intensity rainfalls on road pavements founded on lateritic soils leads to moisture-induced distresses that develop into potholes or depressions under repeated traffic loading and water infiltration (Figure 1).

Lateritic soils cover large parts of Southern Nigeria - a wet tropical region with average annual temperature and precipitation of 27°C and 1800 mm, respectively. These soils have been widely used as sub-bases and subgrades for the construction of highways, airports, landfill liners, and as fill materials in earth dam foundations [2-5]. However, lateritic soils are relatively unstable; they are usually characterized by medium to high plasticity index and low California bearing ratio (CBR) values [6,7].
Furthermore, these soils undergo irreversible changes upon continuous exposure to moisture, leading to aggregation on drying and permanent water loss during hydration, and thus results in changes in their index properties. Hence, lateritic soils pose significant threat to the service life of highway pavements due to their instability under seasonal changes in climate, especially in wet tropical regions [4,8].

Lime stabilization and other calcium-based treatment methods have been used to improve the engineering properties of lateritic soils and expansive clays [9-11]. The process involves the addition of lime to lateritic soils in the presence of moisture. This triggers a pozzolanic reaction which results in the exchange of cations, flocculation, agglomeration, and the formation of new cementitious compounds such as calcium-silicate-hydrates (CSH) and calcium-aluminate-hydrates (CAH). The reaction ultimately improves the soil by causing a reduction in plasticity, swelling potential, linear shrinkage, and leads to an increase in workability, bearing capacity and resilient modulus [12-14].

Although significant increases in shear strength and resilient modulus have been achieved in soils stabilized with an optimum amount of lime required for maximum modification; however, the service life of lime-stabilized pavement subgrades tends to decrease under adverse conditions brought about by continuous water ingress, mostly in humid tropical regions [15-17]. Therefore, this research aims at investigating the influence of continuous leaching on the performance and service life of lime-stabilized lateritic soils for use as sub-bases and subgrades in the design and construction of pavement infrastructure.

2. Materials and Methods

2.1. Materials

The lateritic soil used in this research was obtained from a borrow site (6°40'51"N, 3°9'10"E) along Idiroko road, in Ado-Odo/Ota Local Government Area of Ogun State, Southwest Nigeria. The soil samples were air-dried for a minimum of 7 days and passed through sieve No. 4 to remove any rock, root or plant debris. A summary of the geotechnical properties of the lateritic soil is given in Table 1. The soil was stabilized with a 50-kg industry grade quicklime (calcium oxide) procured for this research. The pulverized quicklime has the following chemical constituents: CaO (92%), MgO (2.2%), SiO$_2$ (1.3%), Mn$_2$O$_3$ (1.2%), Fe$_2$O$_3$ (0.4%), Al$_2$O$_3$ (0.5%), CO$_2$ (1.5%), while the sum of SO$_3$, P$_2$SO$_5$, and free carbon are less than 0.07% [18]. To achieve the main objectives of this research, various percentages of lime were mixed with the lateritic soil in proportions that were marginally equal to or above the minimum amount of available lime (lime modification optimum - LMO) required to attain a pH of 12.4, in accordance with ASTM D6276-19 standards [19]. Hence, the soil samples were prepared by adding various percentages of lime in the range of 5, 10, 15 and 20% by weight of dry lateritic soil.
Table 1. Geotechnical properties of the lateritic soil.

| Property                  | Value |
|---------------------------|-------|
| Percent passing sieve No. 200 | 53    |
| Liquid limit (%)          | 49    |
| Plastic limit (%)         | 21    |
| Plasticity index (%)      | 28    |
| AASHTO A-7-6              |       |
| OMC (%)                   | 16    |
| MDD (kN/m$^3$)            | 17.95 |
| CBR (unsoaked) (%)        | 5     |

2.2. Methods

2.2.1. Geotechnical tests

Laboratory tests on the liquid limit (LL), plastic limit (PL) and plasticity index (PI) of the various soil-lime mixtures were determined at room temperature in accordance with ASTM D4318-17e1 standards [20]. The particle size distribution curves of the various soil-lime mixtures were determined using a combination of the sieve and hydrometer methods in accordance with ASTM D6913 and ASTM D7928-17 standards, respectively [21,22] (Figure 2). Standard Proctor compaction tests were carried out to determine the maximum dry density (MDD) and optimum moisture content (OMC) of the various soil-lime mixtures following British Standard BS 1924-2 [23]. Furthermore, California bearing ratio (CBR) tests were carried out in accordance with ASTM D1883-16 [24] standards under soaked condition. The specimens were soaked for a period of 3, 7, 14, and 28 days to simulate the effects of water ingress on the performance of the lime-stabilized lateritic soils for use as subgrades for the design and construction of pavements.

2.2.2. Column leaching tests

The effects of continuous leaching on the engineering behaviour of the stabilized soils were simulated in the laboratory using two cylindrical Perspex cells of height and diameter, 25 and 8 cm, respectively. The treated soils were placed in the leaching columns using the moist tamping method. The leaching columns have an inlet (top) and outlet (bottom) valves for the control of fluid in and out of the cells. The inlet valve was connected to a water main through a rubber hose, while the leachates were collected through the outlet valve via a rubber hose at intervals of 3, 7, 14 and 28 days. Water circulation through the columns was set to simulate infiltration- and percolation-induced deterioration of subgrades; hence no excess confining pressure was induced on the flow. A constant hydraulic gradient was maintained in all the columns throughout the duration of the experiment. The leachate samples were analyzed for cation concentrations, essentially calcium and potassium ions (Ca$^{2+}$ and K$^+$) using the Palintest 8000 photometer. Similarly, the pH and electrical conductivity (EC) of the leachates were determined immediately upon collection using a multi-parameter (Oakton) PCTestr 35 series. X-ray diffraction (XRD) analysis was performed on the leachates to determine the variation of the primary mineral constituents at various leaching cycles. All the tests were performed in the Geotechnical and Environmental Engineering laboratories of Covenant University, Nigeria following standard procedures.
### 3. Results and Discussion

#### 3.1. Effect of lime on the plasticity of the soil

Table 2 shows the variation of the liquid limit ($LL$), plastic limit ($PL$) and plasticity index ($PI$) of the soil at various lime contents. The addition of 5% lime to the natural soil caused its $LL$ and $PI$ to reduce from 49 to 33.9% and 28 to 5.6%, respectively. This reduction in the plasticity of the soil has been ascribed to the flocculation-agglomeration process that increased the workability of the soil. However, a significant increase in the soil’s plasticity was observed as the lime content increased from 10 to 20%. This marginal increase in $LL$ and $PI$ at higher lime contents has been observed in residual soils containing silicate minerals such as illite, kaolinite and montmorillonite [6]. Similar trends have also been reported by [25] and [26] on lime stabilization of residual soils.

#### Table 2. Variation of Atterberg limits test results in the stabilized and unstabilized soils.

| Lime (%) | Liquid limit (%) | Plastic limit (%) | Plasticity index (%) |
|----------|------------------|-------------------|----------------------|
| 0        | 49               | 21                | 28                   |
| 5        | 33.9             | 28.3              | 5.6                  |
| 10       | 38.9             | 31.2              | 7.7                  |
| 15       | 42.3             | 33.2              | 9.1                  |
| 20       | 47.5             | 37.3              | 10.2                 |

#### 3.2. Compaction and California Bearing Ratio

Figure 3 shows the compaction curves of the soil specimens at different lime contents. The maximum dry unit weight and optimum moisture content of the lateritic soil were 17.95kN/m$^3$ and 16%, respectively. However, the maximum dry unit weight of the stabilized soils decreased from 17 to 14.1kN/m$^3$ as lime content increased from 5 to 20%. Expectedly, the optimum moisture content of the soil increased from 18 to 23% as lime content increased from 5 to 20%. The observed reduction in dry unit weight could be attributed to the cation exchange reaction that led to a reduction in the diffuse double layer size, which consequently reduced the dry unit weight of the stabilized soils [13].

![Figure 2. Particle size distribution curves of the soil-lime mixtures.](image-url)
Figure 4 shows the CBR test results of the soil specimens at different mix ratios and curing periods. Preliminary tests revealed that the unsoaked CBR value of the lateritic soil was 5% (see Table 1). However, soaking the lateritic soil for a minimum of 7 and 28 days reduced its CBR to 1.5 and 0.7%, respectively. In contrast, the test results show that the soil specimen containing 10% lime had the highest CBR value of 20.5% after a curing period of 3 days. However, the results show that within 7 days of curing, the CBR value of the 5% soil-lime mixture increased from 15.4% to a maximum value of 47.1%. The result thus indicates that the lime stabilization optimum (LSO) of the lateritic soil could be between 4 and 8%. However, the CBR value of the 5% soil-lime mixture at 28 days curing period decreased by 57% from the initial value of 47.1 to 20.1%. The overall trend of the results indicates that within a curing period of 7 and 28 days, the strength of the treated soils reached an asymptotic value and thereafter decreased with an increase in lime content. Furthermore, the CBR results indicate that the stabilized soils meet the minimum CBR value required for use as subgrades for the design of flexible pavement infrastructure, as recommended by the Federal Ministry of Works [27].

3.3. Electrical Conductivity

Figure 5 shows the variation of electrical conductivity (EC) of the leachates at different mix ratios and leaching periods. The results indicate that after a leaching period of 3 days, the EC of the lateritic soil increased from 8.5mS/cm to 10.9, 11.8, 12.3 and 12.5mS/cm, for the soil specimens mixed with 5, 10, 15 and 20% lime, respectively. The immediate increase in the EC of the soils has been ascribed to the high alkaline environment (pH≥10.5) produced by the dissolution of lime to yield calcium (Ca\textsuperscript{2+}) and hydroxyl ions (OH\textsuperscript{-}). The trend of the results indicates that the EC of the soils decreased as the leaching time increased from 3 to 28 days. The specimens mixed with 5 and 10% lime decreased from 10.9 and 11.8% to 9.4 and 10.3%, respectively, while the specimens mixed with 15 and 20% lime showed a percentage decrease of 13 and 11.2%, respectively. The gradual decrease in EC of the soil specimens has been attributed to the removal (leaching) of unused calcium from the pore fluid or the depletion of calcium (Ca\textsuperscript{2+}) and hydroxyl ions (OH\textsuperscript{-}) from the pore fluid. Similar trends have been reported by [28], [29] and [30].

3.4. Calcium and Potassium Concentrations

Figure 6 shows the trends of calcium concentrations in the leachates obtained from the various soil-lime mixtures. The concentration of calcium in the lateritic soil slightly decreased from 85 to 82mg/l as the leaching time increased from 3 to 28 days. The results evidently indicate that the amount of leached calcium increased with an increase in lime content. Furthermore, the leachates collected from the stabilized soils show a general decrease in calcium concentration as the leaching time increased from 3
to 28 days. The rate of decrease in calcium concentration was highest in the soil mixed with 5% lime and lowest in the soil mixed with 20% lime. This phenomenon has been attributed to the rapid depletion of calcium in the soils stabilized at or below their LMO due to a decrease in the cation exchange process brought about by a decrease in pH of the pore fluid. In contrast, the soils stabilized above their LMO maintained a high alkaline environment required for long-term pozzolanic reactions, which produced cementitious compounds that improved the shear strength of the soils [31-33]. The rapid decrease in concentration of calcium from the pore fluid of the soil treated with 5% lime can be associated with the evolution of the shear strength of the soil, which was evident from the soil’s CBR values that rapidly increased from 15.4 to 47.1%, and thereafter decreased to 20.1% as the curing period increased from 3 to 28 days. Figure 7 shows the trends of potassium concentrations in the leachates obtained from the stabilized and unstabilized soils.

**Figure 5.** Variation of electrical conductivity of the leachates at different mix ratios and curing periods.

**Figure 6.** Trends of calcium concentrations in the leachates at different mix ratios and curing periods.

**Figure 7.** Trends of potassium concentrations in the leachates at different mix ratios and curing periods.
The results of Figure 7 show that potassium concentration in the natural soil initially increased from 9.6 to 12 mg/l and sharply decreased to 1.7 mg/l as the leaching time increased from 3 to 28 days. However, potassium concentrations were highest in the leachate obtained from the soils mixed with 20% lime and lowest in the soil mixed with 5% lime. Similarly, potassium concentrations decreased as the leaching period increased from 3 to 28 days. Laterites are known to contain high sesquioxides of iron and aluminium, in addition to some essential silicate minerals including microcline, muscovite, illite, and kaolinite (Figure 8). Hence, the addition of lime to the soils leads to the dissolution of the silicate minerals, which leads to the availability of potassium in the pore fluid of the soils [31]. Therefore, the overall trend of the result shows that the leachability of calcium and potassium ions from the pore fluid was faster in the soil treated with a smaller amount of lime (5% lime) and slower in soils treated with higher amounts of lime (10, 15 and 20% lime). The gradual decrease in EC, pH, and Ca\(^{2+}\) and K\(^{+}\) ions from the pore fluid of the stabilized soils has the potential to cause detrimental changes on the shear strength of the soils. Similar results have been reported by [31] and [32] who combined experimental investigations and predictive modelling to determine the service life of pavements subjected to repeated leaching cycles.

![Figure 8. X-ray diffraction spectrum of the natural soil after 3 days of continuous leaching. Cl = chlorite, G = goethite, K = kaolinite, M = magnetite, Qz = quartz.](image)

4. Conclusions
This research investigated the effects of continuous leaching on the engineering properties of lime stabilized lateritic soils, with emphasis on the variations of electrical conductivity (EC), calcium and potassium concentrations in the leachates. The lateritic soil was stabilized with quicklime (calcium oxide) in the range of 5, 10, 15, and 20%. Geotechnical tests such as Atterberg limits tests, standard Proctor compaction tests and California bearing ratio (CBR) tests were used to evaluate the engineering properties of the stabilized and unstabilized soils. Column leaching tests were carried out on the soil samples, while the physico-chemical properties of the extracted leachates were analyzed using standard analytical devices. Based on the test results, the following conclusions can be drawn:

- High EC values were observed in soils stabilized with high amounts of lime than in those stabilized with low amounts of lime. This high EC values can be attributed to the high alkaline environment created by the dissolution of lime to yield calcium (Ca\(^{2+}\)) and hydroxyl ions (OH\(^{-}\)), which led to cation exchange processes that resulted in the formation of CAH – a cementitious compound that caused a significant increase in the engineering properties of the stabilized soils.

- A minimum curing period of 7 days was enough to increase the CBR value of the soil mixed with 5% lime to 47.1%. However, this value decreased to 20.1% after a curing period of 28 days. All the CBR values of the stabilized soils were above the minimum standard required for
use as subgrades in pavement design and construction, as recommended by the Federal Ministry of Works.

- The addition of 5% lime to the lateritic soil decreased the plasticity index (PI) of the natural soil from 28% to 5.6%. However, further increase in lime content to 15 and 20% caused a marginal increase in PI to 9.1 and 10.2%, respectively.

- The high concentration of excess calcium in the leachates at a curing period of 3 days is indicative of the initial dissolution of lime in the soil-lime mixtures to free up Ca\(^{2+}\) ions, which were thereafter used in the cation exchange process. Subsequent pozzolanic reaction caused a significant reduction in calcium concentration in all the leachates.

- Whilst an immediate reduction in shear strength of the stabilized soils was not observed. The gradual decrease in pH and EC of the pore fluid and the subsequent removal of calcium under repeated leaching cycles could inadvertently cause a reduction in the design life of pavements, especially in soils stabilized at or below their optimum lime contents.

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