

Effects of Natural Gravel and Lime on the Primary Characteristics of Red Soil as Construction Material for Low-Volume Road

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ABSTRACT: Soils are used extensively in road construction and their basic engineering properties are of great interest to road engineers as they reflect on the principal properties of the soil. The engineering properties of natural soils can be improved by soil stabilization whose methods fall into two broad categories, namely mechanical and chemical stabilization. This paper presents a laboratory study on the stabilization of red clay soil using natural gravel and hydrated lime as additives to improve some of its basic properties. The experimental work varied the amount of each additive where the gravel was varied in step percentages of 20% unto 100% while lime was varied with the plasticity of each soil admixture. The soils were tested for grading, chemical and mineralogical composition while the admixtures were tested for specific gravity, Atterberg limits, colloidal activity and free swell index. Based on USCS and AASHTO soil classification systems, the red soil classified as MH and A-7-5 respectively. Similarly, the natural gravel classified as GW and A-2-7 respectively. Both the red soil and gravel originated from basaltic rock and had almost similar chemical compositions dominated by silica at 40.7% and 50.8% respectively. The hydrated lime constituted mainly of calcium oxide 95.4%. The main mineral in the red soil was largely the inactive but stable kaolinite at 47.9% followed by microcline at 18.4%. The specific gravity for neat and lime-treated soil admixtures was 2.79-2.73 and 2.77-2.71 respectively; the specific gravity for the hydrated lime was 2.35. Similarly, the corresponding plasticity index for the soil admixtures was 30.1-17.6% and 12.0-6.6%. Further, linear shrinkage values for the neat and lime-treated soil admixtures were 15.7-8.6% and 8.2-3.3% respectively. The colloidal activity for the neat soil admixtures ranged from 0.37-2.1%. The free swell index varied with additives and ranged between 0% and 2.6% for soil-gravel admixtures and between 4% and 11.8% for soil-gravel-lime admixtures. Thus, the specific gravity and Atterberg limits of soil admixtures decreased with increasing gravel content and this dropped further at all levels with the addition of lime. The reverse happened with colloidal activity and free swell index.

KEYWORDS: Index Properties, Soil Composition, Soil classification, Mechanical Stabilization, Chemical Stabilization

I. INTRODUCTION

Authors in [1] and [2] reported that the birth of the road is lost in the mists of antiquity but the ancient Romans are credited as pioneers in modern road construction. Moreover, soils, gravel and binders like cement and lime are among the traditional road construction materials. However, authors in [3] and [4] reported that these materials are often scarce, non-renewable, costly, and impact negatively on the environment. According to many authors like [3], [5], [6], [7], [8] and [9], gravel is widely used in upgrading earth rural roads into gravel roads but have proved to be unsustainable and more expensive in the long term than paved roads. Author in [10] also reported that it is most expensive to construct roads in difficult terrains and mountainous area. Nevertheless, authors [3], [11] and [12] contended that rural roads are a key component of rural development and agricultural production. Therefore, lack of access to all weather road which

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makes transport difficult and costly and exposes rural populations, who are the majority in developing countries, to high levels of illiteracy, disease, unemployment and poverty as a result of slowed access to essential services. Thus, author in [8] proposed that the essential challenge for road engineers is how to provide and maintain rural roads on a sustainable basis with the limited resources available.

Nyeri County in Kenya's central highlands was selected as the study area based on reports by many authors like those in [13], [14], [15], [16], [17] and [18]. According to these authors, the county has a land area of 3,266 km² situated between the equator and latitude 0°38'45" south, and between longitudes 36°35'22" and 37°18'29" east. The authors added that the land has a great topographic variability marked by mountains, hills, steep ridges, deep river valleys, and a plateau all that lie at an altitude of between 1376 m and 5199 m above sea level. Moreover, the geology, relief, climate, human settlement, agriculture, and distribution of transport networks in the county are greatly influenced by its two conspicuous mountains – Mt Kenya and the Aberdare Ranges. The county receives strongly seasonal relief rainfall that occurs mostly at changes of the monsoon and ranges from 2200 mm on the higher volcanic country to 700 mm on the Laikipia Plateau. Much of the county also experiences moderate temperatures with a monthly mean of between 12.8°C and 20.8°C. Similarly, many geologists including [17], [18], [19] and [20] established that geology of the larger Kenya Highlands is grounded on the Basement System of the Precambrian or Archaean age. This is overlain by a variety of volcanic rocks ranging from the Simbara Series of Tertiary age, the Laikipian Basalts of Pliocene age, and the Mt Kenya Suite of Pleistocene age. These volcanic rocks are overlain by recent soil deposits of Quaternary age where Nyeri County is endowed with the dominant red soils in the highlands, and then the black soils, red lateritic earths and gravels in the lowlands.

II. RELATED WORK

Traditional road pavements rest on the native soil or subgrade and are extensively built with soils. There is a wide variety of soils throughout the world but not all soils are good for road construction. For this reason, authors in [7] and [6] contended that road engineers are interested in the basic engineering properties of natural soils for providing important information for quality control during construction operations. The red soil and gravel were then subjected to a laboratory investigation of their properties. Authors in [21] and [22] reported that red soils and gravel are common in the tropics and sub-tropics. The red soils are weathered from basalts in areas of high rainfall, and are spread over parts of Africa, South America and Southeast Asia. According to authors in [23] and [24], the red soils run deep and have high natural water content, clay content, plasticity, porosity, permeability, and high shear strength. However, the soils undergo irreversible property changes upon oven-drying and have low compressibility, volume change, dry density and allowable bearing capacity coupled with. Authors in [25], [26], [27] and [28] added that the engineering properties of these soils commonly characterize relatively coarse-grained soils and hence normally plot as silts below the A-line of plasticity chart. The soils are also highly resistant to erosion due to their strong mineralogical influence but they are difficult to handle and compact which make them poor and unpopular construction materials especially with first time engineers. Nevertheless, red soils consist principally of kaolinite minerals are therefore relatively stable and good as subgrade. According to authors in [22], formation of natural gravels, either on the ground surface or within a 30m depth, is favoured by low topographical reliefs like plateaus, savannahs, and by the more arid climate. Further, areas with natural gravels are characterized by scattered scrubby trees and sparse grass used mainly for pasture and hence they are often unknown in the vicinity of the fertile red soil deposits, except as rare and inaccessible rock outcrops mostly in deep river valleys and steep hillsides.

According to authors in [1] and [9], the availability of good cheap supplies of aggregates is limited in many developing countries and hence conventional road construction depends heavily on quarrying of non-renewable resources as borrow material. However, authors [12] and [13] contended that borrow material has adverse social, economic and environmental impacts like deforestation, land degradation, pollution, damage to haul routes, and increased hauling costs, energy and carbon footprint of the works. The production and distribution of conventional binders like lime and cement used in road construction have similar effects. Nonetheless, authors in [1], [6] and [9] reported that the process of soil stabilization was developed primarily for areas where these resources are difficult to obtain as it offers an alternative to the traditional "remove and replace" strategies commonly utilized by pavement engineers. They added that soil stabilization has been successfully utilized globally but appropriate field investigations, laboratory testing and

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mix design procedures are essential in ensuring its success. Moreover, the process not only offers the ability to alter and enhance the engineering characteristics of an unsuitable soil but also offers the engineer a more sustainable approach to pavement construction by utilizing poor local materials. Authors in [1], [29] and [30] reported that mechanical stabilization based on gradation of the native soil is the most economical and expedient method of altering the existing soil and also promotes use of local materials: It basically consists of blending and compaction of a correct mixture of materials with different gradations to produce a composite material superior to any of its components. Conversely, chemical stabilization uses conventional additives like lime and cement. However, author [30] proposed that chemical stabilization should be considered only when soil blending is not feasible or does not produce a satisfactory material. These methods of stabilization were combined when stabilizing the red soil with natural gravel and hydrated lime. This effort was not in vain as author [31] attested to the appreciable savings achieved in the cost of materials in countries like Kenya and Malawi where gravels have been successfully used for pavement construction and have even replaced stone as base course for paved roads.

III. MATERIALS AND METHODS

Materials

The red clay soil and the natural gravel were obtained in bulk as disturbed samples from two different climatic regions in Nyeri County. However, some bag samples were also taken in sealed plastic bags to prevent moisture loss. The residual red soil was obtained in Rukira area off Nyeri-Othaya Road C70 at an altitude of about 1820 m above sea level. It was dug out from a fresh vertical cutting at a depth of 1-2 m from ground level. Conversely, the natural gravel was obtained from a commercial quarry at the edge of Laikipia plateau near Nyaribo Market at an altitude of about 1730 m. It was mechanically excavated from the quarry face at approximately 20 m from the original ground level. The white high calcium hydrated lime was obtained over the counter as the *Rhino* brand manufactured by ARM Cement Limited of Nairobi to KS 1780-3:2010 and packed in 25 kg bags. The lime is recommended for use in soil stabilization and road construction.

Methods

Soil samples were collected in a manner outlined in [32] and then tested according to laboratory procedures given in [33]. As recommended by author in [34], care was taken to test the soils within 3 months of sampling to avoid altering properties of the residual soils. The soils were first air-dried and then pulverized thoroughly to facilitate their easy screening and mixing with lime and water as and when required. Further oven-drying of test materials was avoided except for the analyses of specific gravity and particle size distribution.

The air-dried and pulverized natural soils were screened through 425 μm sieve to obtain material for making test specimens. Neat soil admixtures were prepared by adding gravel fines to the neat red soil at 20% steps from 0% to 100%. Each soil admixture was then thoroughly mixed when dry and after adding lime and water as required. Individual soil admixtures were then tested for their respective index properties that included the specific gravity, free swell index, consistency limits, and colloidal activity. Moreover, the red soil and gravel were analysed for grain size by means of sieving and sedimentation methods to determine their physical composition or grading. The red soil, natural gravel and hydrated lime were also tested for their chemical composition using the x-ray fluorescence spectroscopy (XRF) method. However, only the red soil was subjected to x-ray diffraction (XRD) analysis for determination of its mineralogical composition. A mean value for three test runs was reported for parameters investigated except for the specialized and more expensive XRD analysis.

For lime-treatment, the amount of lime to be added in every soil admixture was determined graphically using a practical plasticity chart. This meant that lime content was not constant in all the soil admixtures but rather varied with plasticity of a particular admixture. The required lime contents were then added to the respective soil-gravel admixtures prepared at 20% steps of gravel content. Like with neat materials, the lime-soil-gravel admixtures were then mixed thoroughly when drying and after adding the mixing water. These lime-treated admixtures were then subjected to the same index tests as the neat soil admixtures and their mean value also reported.

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IV. EXPERIMENTAL RESULTS

Soil Composition

The XRF results for the chemical composition of red soil, natural gravel and hydrated lime are summarized in Table 1. This showed that the first three major chemical elements common to red soil were silica, alumina and iron. These were dominated by silica at 40.7% and 50.8 % respectively. The gravel also had an exceedingly high calcium oxide at 13.6%. Nevertheless, lime had a chemical composition different from that of soils and it contained calcium oxide at about 95.4% followed by alumina and phosphorous at 1.9% and 1.2% respectively. Results for the soils were comparable to those reported by authors in [21] and [18] for the red soil and gravel respectively. Moreover, a cation exchange would take place when lime was added to the red soil with calcium in the lime replacing some sodium in the soil, as postulated by authors in [7], changing the soil texture through particle flocculation. Similarly, a further pozzolanic reaction could occur in the long term in the soil-lime admixture due to the presence of silica and alumina responsible for the formation of a cementing material and significant increase in strength. Meanwhile, similarities in chemical composition of the red soil and gravel implied that they probably originated from a common parent rock with Nyeri area having the Laikipian Basalts as the most common type of rocks according to author in [17]. Further, authors in [35] described basalt as a fine-grained, extrusive and mafic igneous rock but geologists in [17] and [18] reported that the Laikipian basalts are generally dark grey in color often with a greenish tinge, and have a characteristic hackly fracture and widely spaced columnar jointing. These characteristics were evident at the Nyaribo quarry at the time of sampling where the underlying soft Nyeri tuffs were also quarried for building stone.

Table 1: Chemical composition of red soil, gravel and hydrated lime

| Element | Mean Percentage (%) | | |
|---|---------------------|----------------|---------------|
| | Red Soil | Natural Gravel | Hydrated Lime |
| Silica, SiO ₂ | 40.672 | 50.748 | - |
| Alumina, Al ₂ O ₃ | 26.649 | 13.413 | 1.858 |
| Iron, Fe ₂ O ₃ | 25.396 | 13.727 | 0.492 |
| Titanium, TiO ₂ | 4.018 | 3.526 | 0.058 |
| Sulphur, SO ₂ | 0.713 | 0.379 | 0.654 |
| Phosphorus, P ₂ O ₂ | 0.693 | 1.382 | 1.180 |
| Manganese, Mn ₂ O ₄ | 0.451 | 0.216 | 0.023 |
| Calcium, CaO | 0.429 | 13.622 | 95.371 |
| Potassium, K ₂ O | 0.226 | 2.494 | - |
| Zirconium, Zr | 0.200 | 0.070 | 0.028 |
| Cerium, Ce | 0.146 | - | - |
| Chloride, Cl | 0.078 | - | 0.110 |
| Total | 99.671 | 99.578 | 99.774 |

Only the red soil was tested for mineralogical composition. The XRD plot for the soil is presented in Figure 1 from which the dominant mineral was deduced to be kaolinite at 47.9% while other constituent minerals were 18.4% microcline, 12.6% albite, 11.6% quartz, and 9.5% hematite. The few peak reflections on the XRD plot represented these main constituent minerals. However, the XRD plot showed an absence of peak definition in the prominent kaolinite reflections as reported by authors in [36] for red soils developed over volcanic rocks in Kenya, inferring a poorly ordered crystalline structure indicative of disordered kaolinite or halloysite. The XRD results also differed from those of red soils reported by authors in [24] and [37] that showed low kaolinite content and 60-70% of halloysite.

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Other results obtained showed that organic and total carbon contents for the red soil were 0.33% and 0.35% respectively. The small difference indicated that the soil had not been subjected to any form of lime treatment in the past. According to author in [1], kaolinitic clays are very stable and their plasticity, cohesion, shrinkage and swelling are very low when compared with other silicate clays.

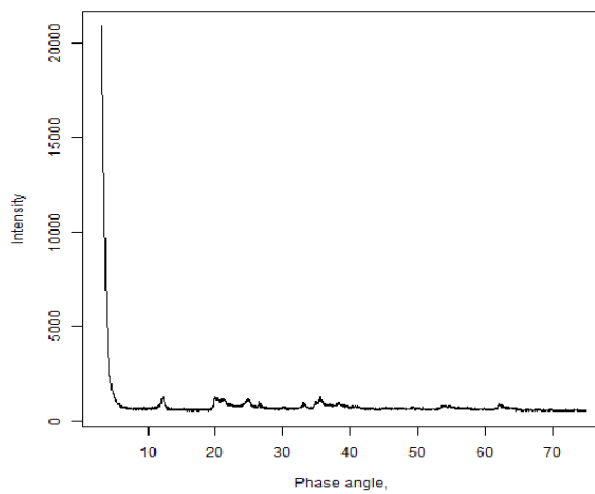


Figure 1: The XRD results for Nyeri red soil

The results for particle size distribution of the red soil and natural gravel are represented by the curves in Figure 2. Usually, a grading curve is cumulative in nature and shows the weighted particle size distribution in a soil. The spread and slope of the two curves infer well-graded soils and also served as the grading envelopes for any possible soil-gravel admixture. It was determined that the red soil had a maximum particle size of about 5mm and consisted of 34% clay, 18% silt, 46% sand and 2% fine gravel. Similarly, the natural gravel had a maximum particle size of about 50mm and comprised about 10% sand and 90% gravel. Thus, the red soil was described as silty SAND and the gravel as sandy GRAVEL. The grading coefficients were determinable only for the gravel and they were obtained as 9.2 and 2.3 for coefficients of uniformity and curvature respectively. In effect, the gravel satisfied the specifications by the authority in [38] for the minimum coefficient of uniformity and maximum particle size for subbase material of 5 and 63mm respectively.

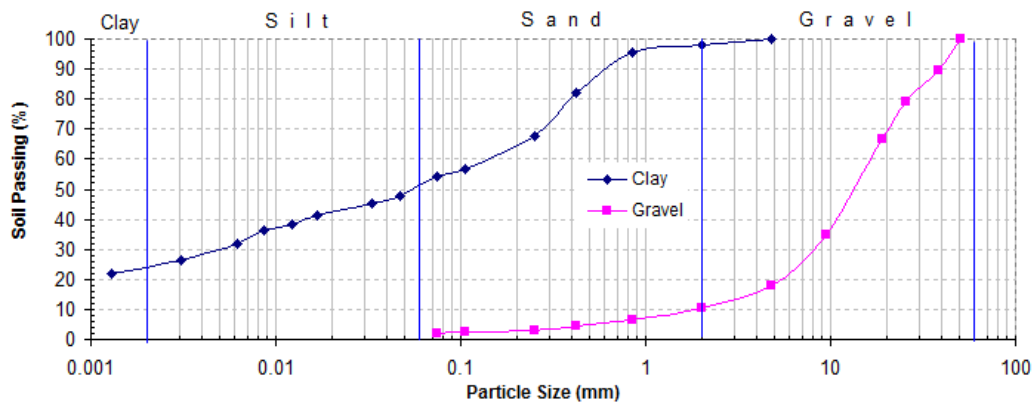


Figure 2: Gradation curves for red soil and natural gravel

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Soil Properties

Table 2 presents the summarized results of different soil properties shown for various soil admixtures. Most of the results show a progressive decline in values obtained for soil-gravel admixtures (denoted as RGN) with increasing gravel content in red soil except for the free swell index which increased in value. The same trend was also maintained for the lime-treated soil admixtures (denoted as RGT) but with a marked general drop except, again, for the free swell index which increased tremendously. When plotted, the results for RGT admixtures illustrated more regular changes in various parameters except for the free swell which changed abruptly especially after a gravel content of 60%. The Atterberg or consistency limits included the liquid and plastic limits, linear shrinkage and the related plasticity index. The liquid limit ranged 74.3-41.8% and 59.1-37.9 for the RGN and RGT soil admixtures respectively. Similarly, the respective plastic limit ranged 44.2-24.2% and 47.0-31.3%. These results demonstrated that the effect of an additive in soil is to lower liquid limit and raise plastic limit in order to reduce plasticity index, which is the arithmetic difference between liquid and plastic limits. As a result, the derived plasticity index (PI) was found to range 30.1-17.6% and 12.0-6.6% for the RGN and RGT soil admixtures respectively. The PI for the RGN soil admixtures was employed in the determination of lime content required for further plasticity reduction in the RGT soil admixtures. In effect, the initial lime content decreased with increasing gravel content and reducing amount of fines, and ranged 4.1%-1.88%. Similarly, the linear shrinkage dropped with increasing gravel content with further reduction observed upon the addition of hydrated lime. Therefore, the linear shrinkage ranged 15.7-8.6% and 8.2-3.3% for the RGN and RGT soil admixtures respectively. Considering the specifications given by authority in [38] for a subbase material, majority of all types of soil admixtures failed to satisfy a maximum PI of 4-12% for clayey and silty sands and 15% for gravel, and a maximum plastic modulus (PM) of 250% for all materials; PM is the product of PI and percent fines passing 425µm sieve and is meant to limit the amount fines present. As a result, only the RGT admixtures with at least 60% gravel content satisfied both plasticity requirements.

Table 2: Summarized results for index properties of soil admixtures

| Soil Admixture Type | | Soil-Gravel (RGN) | | | | | |
|----------------------|-----|------------------------|------|-------|-------|-------|-------|
| Gravel Content | (%) | 0 | 20 | 40 | 60 | 80 | 100 |
| Liquid Limit (Cone) | (%) | 74.3 | 67.3 | 60.2 | 53.5 | 46.8 | 41.8 |
| Plastic Limit | (%) | 44.2 | 42.2 | 38.2 | 33.9 | 28.8 | 24.2 |
| Linear Shrinkage | (%) | 15.7 | 12.4 | 11.3 | 10.2 | 9.5 | 8.6 |
| Plasticity Index | (%) | 30.1 | 25.1 | 22 | 19.7 | 18 | 17.6 |
| Initial Lime Content | (%) | 4.10 | 3.41 | 2.81 | 2.40 | 2.00 | 1.88 |
| Colloidal Activity | (%) | 0.37 | 0.38 | 0.45 | 0.60 | 1.10 | 2.10 |
| Free Swell Index | (%) | 0 | 0.36 | 0.71 | 1.24 | 1.94 | 2.63 |
| Specific Gravity | | 2.79 | 2.78 | 2.78 | 2.77 | 2.75 | 2.73 |
| Soil Admixture Type | | Lime-Soil-Gravel (RGT) | | | | | |
| Gravel Content | (%) | 0 | 20 | 40 | 60 | 80 | 100 |
| Liquid Limit (Cone) | (%) | 59.1 | 54.6 | 50.4 | 46.4 | 41.5 | 37.9 |
| Plastic Limit | (%) | 47.0 | 44 | 41.2 | 38.3 | 34.3 | 31.3 |
| Linear Shrinkage | (%) | 8.2 | 7.1 | 6.2 | 5.1 | 4.1 | 3.3 |
| Plasticity Index | (%) | 12.0 | 10.6 | 9.2 | 8.1 | 7.2 | 6.6 |
| Initial Lime Content | (%) | - | - | - | - | - | - |
| Colloidal Activity | (%) | - | - | - | - | - | - |
| Free Swell Index | (%) | 4.0 | 6.69 | 10.27 | 12.73 | 12.45 | 11.76 |
| Specific Gravity | | 2.77 | 2.76 | 2.76 | 2.75 | 2.73 | 2.71 |

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Other soil properties also shown in Table 2 include the colloidal activity, free swell index and specific gravity of solids. However, the colloidal activity (A), defined as the ratio of PI to clay fraction of a soil, was not determined for the RGT admixtures. The colloidal activity values increased with the gravel content and ranged between 0.37 and 2.1. Similarly, the free swell index generally increased with gravel content and ranged 0-2.63 and 4.0-11.76 for RGN and RGT soil admixtures respectively. Nevertheless, the specific gravity of soil admixtures decreased with increasing gravel content and further reduction was observed upon the addition lime into the RGT admixtures. In this respect the specific gravity values for the different soil admixtures ranged 2.79-2.73 and 2.77-2.71 for the RGN and RGT soil admixtures respectively. From these results, it was deduced that the red soil categorised as *inactive*, and the natural gravel as *active* after Skempton (1953) proposal. Moreover, the author in [1] reported that the predominant clay mineral present in a soil can be easily and inexpensively indicated from its activity. In effect, the main clay mineral in red soil was confirmed to be the kaolinite mineral where author in [29] related it to an activity of 0.35-0.50. Holtz and Gibbs (1956) also proposed free swell as the simplest and quickest laboratory technique available for establishing the swell behavior of a soil but the big difference between the RGN and RGT results suggested that the RGN were more stable than the RGT admixtures. It was further observed use lime as an additive had a reduction effect on specific gravity especially after about 60% gravel content. This reduction in specific gravity probably led to the slowed settlement of solids in either water or kerosene used in the test and resulted in the very high free swell index values for RGT admixtures.

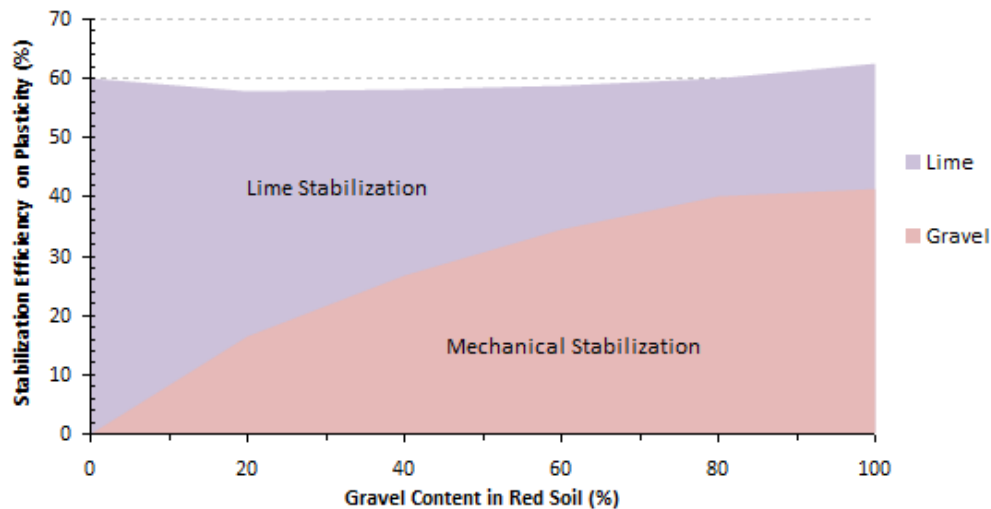


Figure 3: Double stabilization efficiency on plasticity of red soil

Figure 3 represents results of a deliberate attempt to express the efficiency of soil stabilization in reduction of the initial plasticity of the red soil. This was realized by determining the ratio of PI of a soil admixture to that of the original red soil which was expressed as a percentage. The figure demonstrates that the first step involving mechanical stabilization became more effective with increasing granular component in soil admixture. However, the second step of lime stabilization reduced in effect as the amount of fines in the admixture diminished. The results also indicate that the overall efficiency of double stabilization in improving the plasticity of red soil was limited to a maximum of about 60% regardless of the combination of the two additives. This indicates that none of the soil admixtures became non-plastic in the course of soil stabilization, which would have rendered them unfit for road construction.

V. CONCLUSION

The color, reactivity and nature of a soil is determined by its composition. Thus, the red soils got their color from the presence of ferric oxide as hematite while the gravel obtained its dark grey color largely from its high silica content of 50.8%. Moreover, the highly-weathered red soil was kaolinitic clay which classified as MH and A-7-5 according to the Unified Soil Classification System (USCS) and the AASHTO systems respectively. Similarly, the respective

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classification for the partially-weathered basaltic gravel was GW and A-2-7. The AASHTO system further rated the red soil and natural gravel as *poor* and *good* for subgrade respectively.

Gradation and plasticity of a soil also provide very useful guides to the behavior of disturbed soils when used as construction materials. According to authors in [28] and [39], soils rated as A6 or A7 by AASHTO system may be potentially expansive but red soils give little trouble as demonstrated by its zero value for free swell index. Further, most plots for soil properties a marked change at about 60% gravel content suggesting the limit of influence of the fine red soil. Coincidentally, any lime-treated soil admixture with at least 60% gravel content and not more than 3% lime satisfied the plasticity requirements for a subbase material. This effectively meant that a soil admixture with a maximum of 40% red soil, 3% lime, and at least 60% gravel content could be incorporated satisfactorily in subbase construction after double stabilization.

As illustrated in Figure 3, author in [1] opined that there is little or no value using lime with low cohesion or cohesionless sands and gravels unless a pozzolanic material is added. Moreover, as author in [29] proposed, the process of soil stabilization should not be evaluated on the basis of basic properties alone since certain engineering qualities are also essential in determination of a dense, impervious and strong composite construction material. Therefore, all stabilized materials that failed the plasticity criteria can be profitably employed in improved subgrades to reduce thickness and cost of road pavements.

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