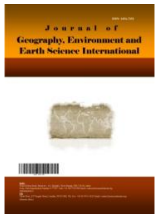

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Chemical Stabilization of Black Cotton Clay and Laterite Soil Using Drycon Powder for Suitability as Construction Materials

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Authors' contributions

This work was carried out in collaboration between both authors. Author LPC being the Supervisor. Author FSA designed the study and performed the statistical analysis. Author LPC wrote the protocol and drafted the manuscript. Both authors managed the analyses of the study and the literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

This paper used drycon powder (DP) as stabilization additive for improving the engineering properties of problem soils, specifically, black cotton clay (BCC) and laterite soil (LS), for use as a road construction material. The study was carried out in some parts of the Greater Accra Region of Ghana, through the conduction of index properties tests such as gradation, Atterberg limits, California bearing ratio (CBR), Compaction characteristics and X-ray diffraction (XRD) on the problem soils. CBR, Atterberg limits and environmental quality tests were specifically conducted on DP stabilized soils for comparative analysis. Gradation results revealed 38% fines for BCC and 14% fines for LS. X-ray diffraction analysis revealed the presence of quartz and montmorillonite in BCC, and quartz and kaolinite in LS. Generally, the results of the various tests conducted revealed that DP has the potential of improving the engineering properties of problem soils with significant strength improvement. It can also be inferred from the results that, DP is environmental friendly soil stabilizer.

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Keywords: Drycon powder; stabilization; problem soils; environmental quality; atterberg limits.

1. INTRODUCTION

Drycon Powder (composed of Portland cement, silica sand, silicon, carbon dioxide and some traces of chromic acid), is soil stabilization additive, recently introduced into the construction industry, believed to be environmental and user friendly. Black cotton clays, on the other hand, are potentially expansive soils and thus considered as problematic/problem soils as they are susceptible to volumetric changes. As such, they are capable of causing cracks when dry or swell when in wet conditions [1]. These properties in soils can cause extensive damage to engineered structures. Laterites are highly weathered soils formed by the concentration of hydrated oxides of iron and aluminium [2]. These LSs are mostly gravelly and exhibit high laboratory and field compaction densities [2]. However, they perform poorly under adverse traffic and moisture conditions [2]. Such behaviour of soils can cause severe damage to engineered structures. Both soils (BCC and LS) prevail widely in the study area. Considering the vast existence of these soils and the problems they pose to engineered structures built in/on them, it is important to effectively stabilize the soils so that, any structure founded on them can stand the test of time. The main focus of stabilizing soil is to change its intrinsic properties to give the desired effect. Soil stabilization is considered very effective and successful if upon altering the properties of the soil, its strength and durability are enhanced significantly without compromising the environmental consequences as a result of the introduction of chemical additives.

Generally, the state of increasing population with its attended rapid developmental agenda has resulted in high demands for construction of homes, roads and other engineering structures worldwide. These structures are mostly built on or in soils. However, in many cases, the availability of high-quality soils for construction is often limited by the existence of problem soils at construction sites. These soils tend to cause structural failures of engineered structures founded on them. The situation of problem soils is precarious in the study area compounded by the vast existence of such soils in scattered locations. Very often, engineers are left with the only choice of using locally available materials for construction projects. However, in projects locations where problem soils exist, such soils are excavated, removed and replaced with superior imported backfill materials. These imported materials are at times transported from very distant locations, which are mostly capital intensive and thus take up a significant portion of the budget cost of such projects. Under such conditions, it is prudent to develop a cost-effective, yet a sustainable approach to salvaging the situation. Stabilizing or otherwise improving the locally available soils to achieve the required engineering properties of the soils can provide an immediate and better option of curtailing the situation with minimum cost.

Several chemical soils stabilization methods are available in the literature [3–10]. These techniques are used in various ways to improve the engineering properties of problem soils in particular. The problem soils in this study are the black cotton clay (BCC) and Laterite Soil (LS). Black cotton clays have been reported to occur in substantial quantities in parts of Ghana and are considered problematic soils due to their expansive nature [1,11]. In some literature, laterites have been defined concerning the silica (SiO_2) to sesquioxides (Fe_2O_3 + Al_2O_3) content ratios. Content ratios of between 1.33 and 2 are indicative of laterite soils and those greater than 2 signify non-laterite soils [2]. Various investigative studies have also been conducted on both types of problem soils in parts of the Greater Accra Region [E.g. 2,11–14]. However, these studies have been addressed under various objectives, different from those of this present study. For example, Akayuli et al. [11] evaluated the black cotton soil for use as clay liner in tailings dam construction. The results yielded favourable findings though marginal failure results of specific gravity and liquid limit requirements of typical clay liner systems were also obtained. However, Gidigasu [1] and Achampong et al. [2] conducted similar studies related to soil stabilization on problem soils. While Gidigasu [1] considered the use of three stabilizing agents viz: the quarry dust, pozzolana and pozzolana-cement to address the soil stabilization problem of BCC, Achampong et al. [2] used lime and cement as additives for soil stabilization of LS. Conclusions thus arrived at from the results of the former investigator's study suggest the pozzolana-cement as being the most effective stabilizer for the black cotton soils. Whereas conclusion from results of the latter study revealed the addition of 6% lime as being more suitable for stabilizing the laterite soil as per the specifications of the Ministry of Transportation (MoT) [15] document. Nonetheless, the objective of this current study is to effectively stabilize the problem soils with due regards to cost-effectiveness and environmental considerations which are possibly not the main focus of the other studies. Aside from that, this current study considers stabilizing both potential problem soils, which are prevalence in the study area. Settling on the use of DP for stabilization of the problem soils in the study area is thus not a misplaced priority.

Against this background of cost-effectiveness and environmental considerations, this paper investigated the use of DP as stabilization additive for improving the engineering properties of black cotton clay (BCC) and laterite soils (LS) through the determination of strength properties of DP stabilized soils for use as a road construction material.

1.1 Study Area and Its Environmental Setting

Samples for the study were obtained from the Greater Accra Region of Ghana. The region, being the custodian of the capital city, Accra, is one of the sixteen administrative regions of Ghana. It is located between longitudes (0°31'3" W and 0°37'55" E) and latitudes (5°28'42" N and 6°6'11" N) and shares boundaries to the west, north and east by the following regions respectively: Central, Eastern and Volta Regions; and to the south by the Gulf of Guinea (Fig. 1 (a)).

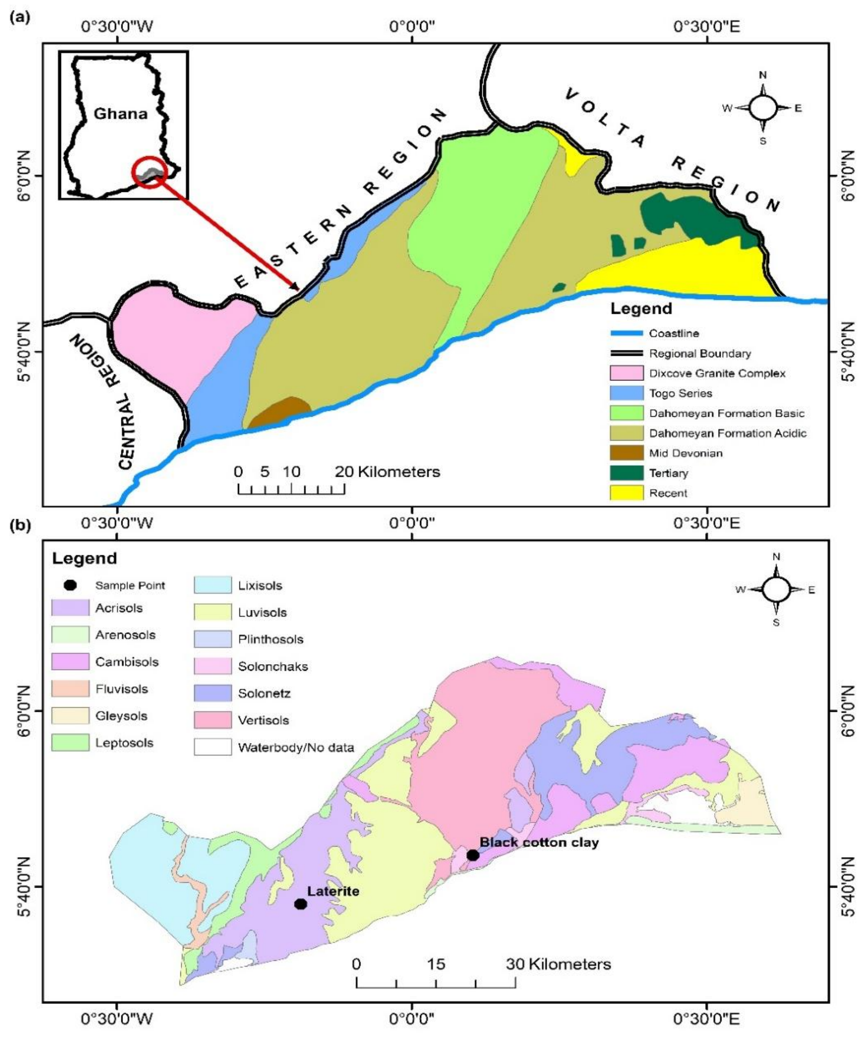

Fig. 1. Location of the study area: (a) geology and (b) Soil types with samples locations

Topographically, the area forms part of the coastal plains varying from flat to gently undulating slopes that rise to 75 m above means sea level at the foothills with a few isolated hills and rock outcrops.

There are three broad vegetation zones in the Accra Metropolitan area, which comprise of shrubland, grassland and coastal lands. The shrubland occurs in the western outskirts and the north towards the Aburi Hills. It consists of dense clusters of small trees and shrubs. The grassland is made up of a mixture of species found in the undergrowth of forests and are short. The coastal zone comprises of two vegetation types. Mangroves, comprising of two dominant species, are found in the tidal zone of all estuaries sand lagoons. Salt tolerant grass species cover substantial low-lying areas surrounding the lagoons [16] Coastal savannah shrubs interspersed with thickets mainly cover the region.

The area is characterized by two main seasons: the rainy and dry seasons. There are two rainy seasons [17]: The major rainy season, which occurs between April and July, while the minor season occurs between September and November. The rainy season is followed by a prolonged dry season which spans from December to March. The mean monthly temperature ranges from 24.7°C in August to 33°C in March, with an annual average temperature of 26.8°C.

1.2 Geological Setting and Soil Distribution

The geology of the area (Fig. 1 (a)) consists of Precambrian Dahomeyan formations, which have been classified into Acidic Dahomeyan, Alkalicgneiss with Basic intrusives and the Meta basics respectively. The Dahomeyan formations are northeast-southwest belts trending east of Togo. These are highly metamorphosed and are associated with many thermo-tectonic activities. The formation commonly consists of rocks of mica schists, granodiorites, granites gneiss and amphibolites [18]. Gneisses with garnet, pyroxene and scapolite occur more in the Dahomeyan rocks. Metamorphism is generally in the amphibolite facies, as indicated by the occurrence of index minerals such as garnet, sillimanite, kyanite and staurolite in rocks of suitable composition [19].

The rocks are overlain by unconsolidated and poorly consolidated sediments and soils. They include laterite soil (LS), gravels, clay, fluvial or lacustrine sediments. Soils within the sampling points are black cotton clay (BCC) and laterites soils (LS). According to the FAO/UNESCO [20] soils classification systems, the soil samples are located within the vertisols and Acrisols respectively (Fig. 1(b)).

2. MATERIALS AND METHODS

To grasp the theme of work at a glance, a flowchart of the methodological design is provided below (Fig. 2).

2.1 Desk Study and Terrain Evaluation

As indicated by Cooper [21], a literature review is aimed at obtaining a detailed account of the topic being studied. In this study, a thorough review of the relevant literature was conducted on the geology of the study area. The literature review provided the necessary baseline information pertinent to the research. The literature review was followed by terrain evaluation or reconnaissance survey. The terrain evaluation involved making initial trips to the field, making observations of features and ground truth verification to ascertain findings during the desk study. Such observations included: accessibility to the site, types of soil, conditions of the drainage system, engineering structures on site, topography and vegetation type. This phase also involved identifying or earmarking possible areas and locations for the collection of field samples following the BSI standards [22].

2.2 Field Investigations

The desk study and terrain evaluation were followed by field investigations, which involved collecting soil samples of different soil types from different locations for laboratory analyses. Before the collection of soil samples, test pits were excavated using pickaxe and shovel to collect disturbed soil samples. The location of each sampling station was recorded with the help of a Global Positioning System (GPS) device. Disturbed samples of two different soil types: Black cotton clay (BCC) and laterite soil (LS) were collected from different locations in the study area for determination of index properties, compaction and mineralogical characteristics. These soils were collected at a depth of 1 m, well packed, labelled and transported to the laboratory for analysis following the BS5930 code of practice for site investigations [22].

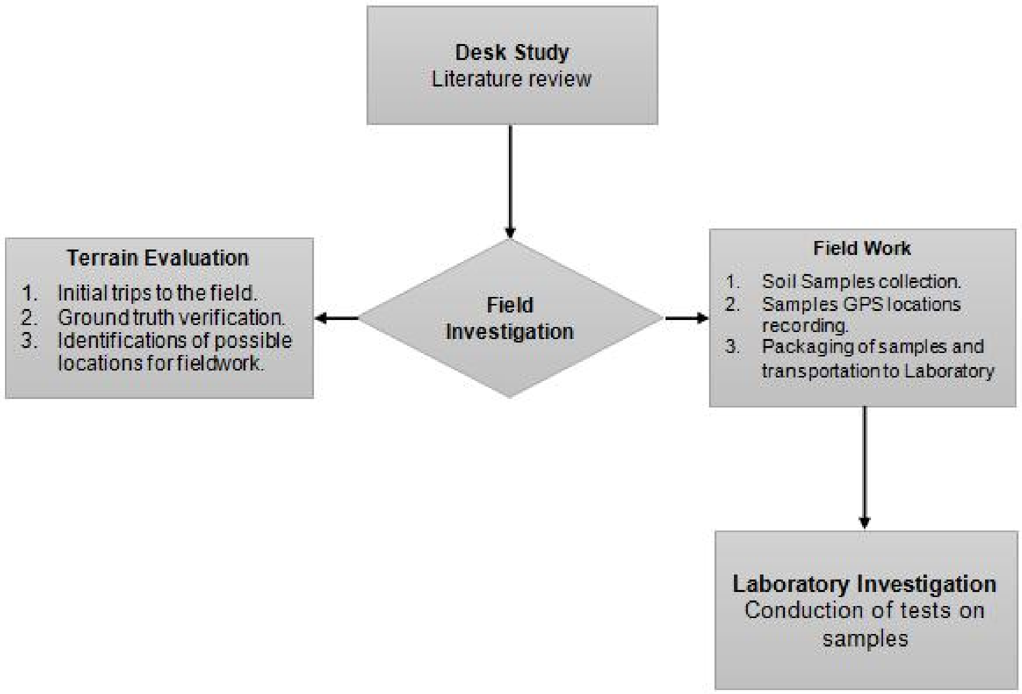

Fig. 2. Flowchart of overall methods used in investigations

2.3 Experimental Investigations

The retrieved soil samples from the test pits in their natural state were subjected to various laboratory analyses at the soils laboratory of Sonitra Ghana limited. The tests conducted on the retrieved soils samples include gradation, consistency (Atterberg) limits, compaction and California bearing ratio (CBR) following the BS 1377 [23–25].

Determination of swelling and shrinkage potentials of soil is key to assessing the viability of soils for engineering works. The swelling potential is dependent on such factors including the plasticity index, the clay minerals content, the fine fraction content and the liquid limit. Thus, conduction of gradation and consistency limits tests helped in the determination of swelling potential. The swelling potentials of the soils were assessed using Djedid et al. [26] model (Table 1).

Knowledge of the mineralogical composition and geotechnical characteristics of road construction material is important to make an informed decision on the contained mineralogical constituents of the material, as clay minerals have detrimental effects on such materials. In this study, the mineralogical composition of the soils was determined using X-ray diffraction (XRD) method at the Department of Physics, University of Ghana. In this method, mineral species identified by X-ray diffraction analysis were compared with theoretical known peaks to ascertain how well their diffraction pattern

Table 1. Swelling potentials of soils according to their plasticity index, liquid limit and soil used to classify the swelling potential of the soils studied fractions (Source modified by researchers [26])

PI (%)	%<2ųm	%74ųm	LL(%)	Swelling potential
>35	>95	>95	>60	very high
22-35	60-95	60-95	40-60	High
18-22	30-60	30-60	30-40	Moderate
<18	<30	<30	<30	Low

resembled the diffraction patterns of minerals found. Some portions of the soil samples were treated with DP meant for stabilizing the soils. The stabilized soils were carefully prepared by initially calculating the right amount of DP and then smoothly blending it with the soils using a hand trowel.

3. RESULTS AND DISCUSSION

Results of the laboratory investigations carried out on soil samples collected from the field for the various tests are presented below:

3.1 Particle Sizes Distribution and Physical Properties of Soils

The grading properties of the untreated soils used in this study are presented in Fig. 3. The results indicate that the percentage of fines for BCC and LS are respectively 38% and 14%. Using the American Association of State Highway and Transportation Officials (AASHTO) soils classification system as contained in literature [E.g. 27,28], the BCC can be considered as belonging to the silts-clay materials category, as more than 35% of the particles are fines, while the LS being granular materials since less than 35% fines. However, the consistency characteristics of the soils (Table 1) show that the LL and PI for BCC are respectively 27.25% and 14.39%, while the LL and PI values for LS are 34.10% and 14.10% respectively. With these data, BCC can be classified as A-6 (1) and the LS as A-2-6. The AASHTO classification, thus, suggests BCC as being clayey soil and the LS clayey sand or clayey gravel consistent with the analyses described in Liu and Evett [27] and Amer et al. [28]. For use as subgrade materials, both soils can be rated as being fair to poor and indeed justified as problem soils that need to be stabilized for any meaningful road construction works. To further ascertain the status of these soils, the Unified Soil Classification System (USCS) [29,30] classified both soils as SC, but with the LS containing some substantial amounts of gravel consistent with the classification by AASHTO though not completely consistent for BCC.

However, the stabilized soils did not show any significant change in the particle sizes distribution. Suggesting that, DP preserved the treated soil and increases the bonding characteristics. The gradations are the same as those of the untreated soils. However, Table 2 showed changes in the consistency characteristics of the treated soils. There is a significant reduction in the plasticity index of the treated soils. Comparing the results of Djedid et al. [26] model (Table 1) to the gradation results in Fig. 3 and the PI values in Table 2 of the untreated soils, the BCC can be classified as soil with low swelling potential. The LS is also classified as soil with moderate to low swelling potential. Reduction in the PI of the treated soils suggests that DP tends to reduce the swelling potential of soils. Generally, the lower the plasticity index, the lower the potential to shrink or swell as the soils undergo moisture content fluctuations [31]. The overall effects of DP on the consistency characteristics of the soils used are illustrated in Fig. 4. The results of this study showed improved soils properties more than those reported by Gidigasu et al. [13], particularly results of the swell potentials observed in BCC.

3.2 Soils Mineralogy

Results of X-ray diffraction analysis conducted on the untreated soils are presented in Fig. 5. The minerals identified in BCC were quartz (Qtz) and montmorillonite (Mnt) (Fig. 5 (a)), and those identified in LS were Qtz and kaolinite (Knt) (Fig. 5 (b)). As reported in Aksu et al. [32], montmorillonite has a 2:1 layer structure with a large base exchange capacity which readily adsorbs Na^+ and other cations. These Interlayer cations are variably hydrated thus, resulting in the swelling characteristic of montmorillonite. In contrast, kaolinite has a 1:1 layer structure with a small base exchange capacity and with little capability of absorbing other cations. This makes kaolinite less or non-swelling as compared to montmorillonite. The presence of these clay minerals in soils gives the characteristic swelling potentials of soils. The results suggest that BCC is of a higher swelling potential than LS.

3.3 Chemical and Organic Constituents of DP

Results of heavy metals and volatile organic compounds analyses (Table 3) indicate that the constituents in DP were within the limits set by the Ghana Environmental Protection Agency for the concentration of these substances in cement products. It can, therefore, be inferred that DP is environmentally friendly and does not contribute to the leaching of heavy metals and organic compounds into the environment. Hence, DP can safely be used as stabilization additive.

3.4 Strength Characteristics

Compaction characteristics of the untreated soils as presented in Table 2 show MDD of 1.97 Kg/m^3 with OMC of 9.5% for BCC and MDD of 2.21 Kg/m^3 with OMC of 5.6% for laterite. The CBR values for untreated clay (BCC) and LS are 8% and 36% respectively. However, CBR values in the range of 3% to 12% are considered poor to fair. This, therefore, suggests that BCC belongs to fair consistency while the laterite belonging to a good consistency.

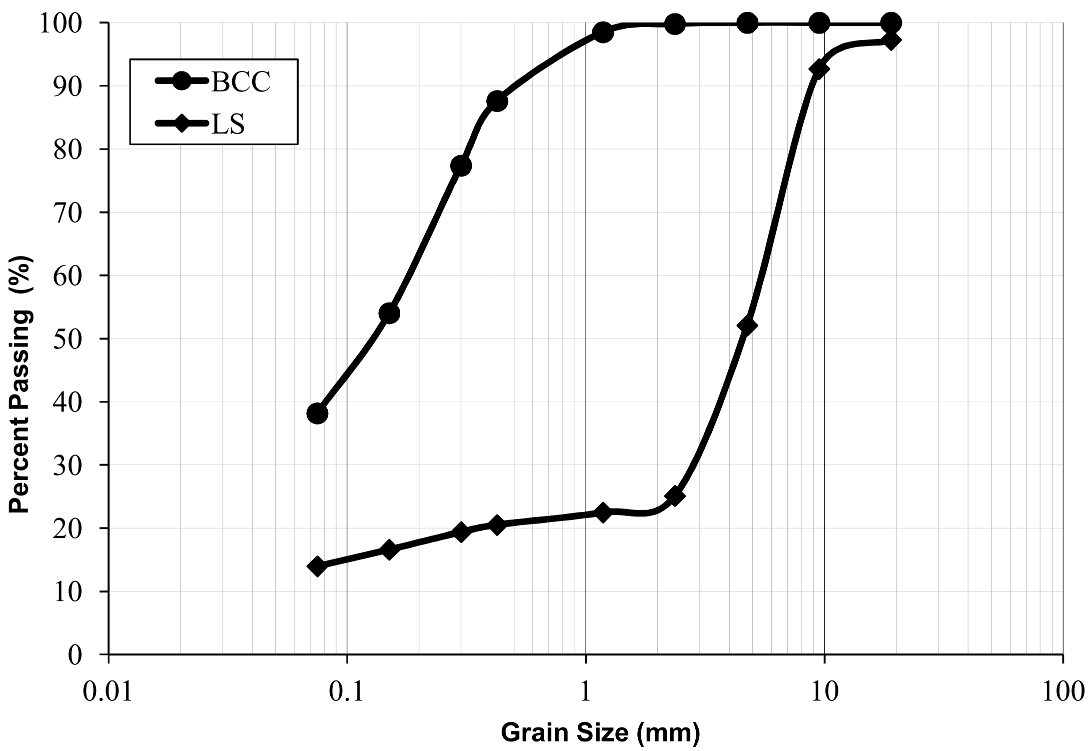

Fig. 3. Particle sizes distribution of soils used in the study

Table 2. Summary of laboratory test results

Category	Property	Untreated soil				Treated Soil			
		BCC	Re-marks	LS	Re-marks	BCC	Re-marks	LS	Re-marks
	Minerals	Mnt		Knt					
Atterberg Limits	LL (%)	27.25	√	34.1	×	27.19	√	30	√
	PL (%)	12.86		20		17.7		17.7	
	PI (%)	14.39		14.1		9.49		12.4	
Compaction Characteristics	OMC (%)	9.5		5.6		-		-	
	MDD (Kg/m^3)	1.97		2.21		-		-	
	CBR at 95%	8	×	36	√	50	√	96	√
Classification	AASHTO	A-6 (1)		A-2-6		-		-	
	USCS	SC		SC		SC		SC	

BCC: - Black Cotton Clay, LS: - Laterite Soil, LL: - Liquid Limit, PL: - Plastic Limit, PI: - Plasticity Index, Mnt: - Montmorillonite, Knt: - Kaolinite, Ministry of Transportation (MoT)[15] material requirement.
√: In agreement, ×: Not in agreement

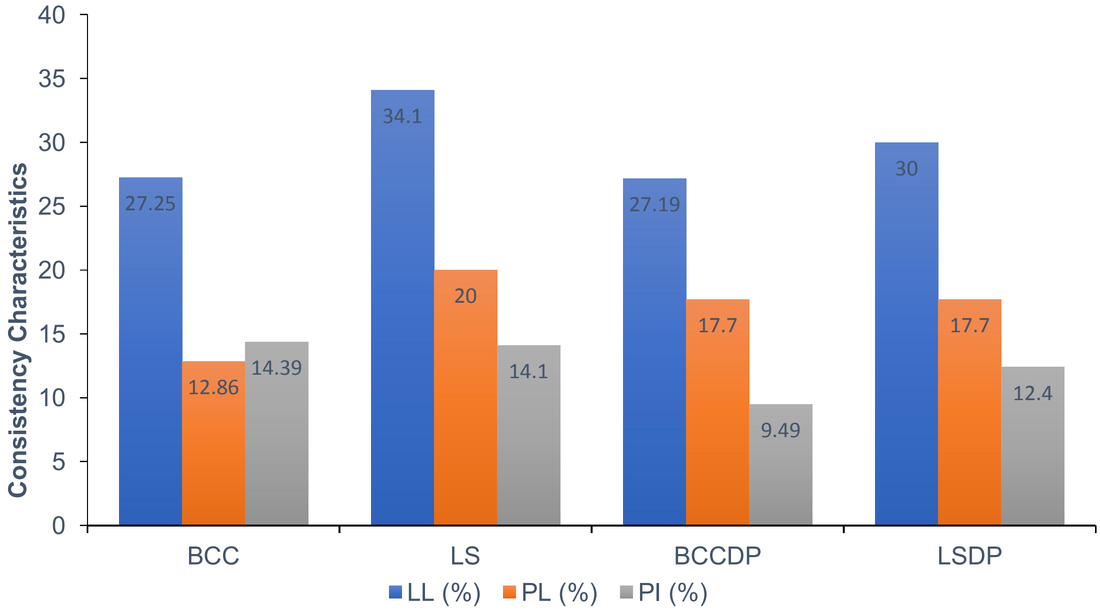

Fig. 4. Effects of Drycon powder on consistency limits of soils used

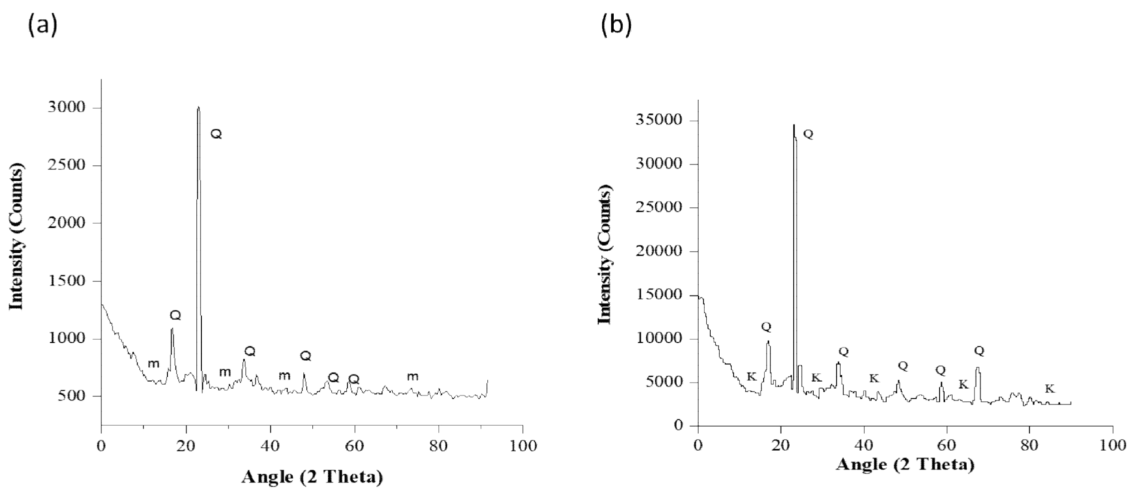

Fig. 5. (a) Diffractogram of untreated BCC (b) Diffractogram of untreated LS

Table 3. Results of heavy metals and volatile organic compounds analysis

Test code	Parameters	Values	Remarks
HEM	Lead (Pb)	0.001	√
	Cadmium (Cd)	Not detected	√
	Zinc (Zn)	0.02	√
	Mercury (Hg)	Not Detected	√
	Copper (Cu)	0.011	√
	Chromium (Cr)	0.003	√
VOC	Volatile Organic Compounds	0	√

Ghana Environmental protection regulatory standards material requirement. √: In agreement, ×: Not in agreement. All values are in (%) except VOC in (g/l), HEM: - Heavy Metals

For the treated clay (BCCDP) and treated laterite (LSDP), the CBR values are respectively 50% and 96%. However, CBR values in the range of 6% to 56% are considered fair to good and those in the range of 74% to 165% are considered good to excellent. It thus, suggests that BCCDP and LSDP belong to the good and excellent consistency. Generally, Lower CBR of clay as compared to laterite is due to its low quality attributed to the strength of the clay fraction and the mineral montmorillonite. The general effect of DP stabilization on CBR can better be observed by normalization. The CBR values for treated soils were normalized by the values for untreated soils. This is simply the ratio of the CBR values for treated soils to those for untreated soils, and it is referred to as 'CBR gain'. The CBR gain for BCCDP was generally higher than the CBR gain for LSDP. The higher value for BCCDP could be attributed to the higher plasticity of the clay. Generally, the CBR values of the treated soils have increased 2 to 6 times of the untreated soils, indicating that, DP has the capability of increasing the strength properties of problem soils. Comparing the strength properties of DP stabilized soils with other stabilizing additive used by different authors [14,33] in the study area, it can be concluded that DP stabilized soils showed significant improvement in strength properties compared to other known methods.

4. CONCLUSION

Based on the results of laboratory analyses of soil samples obtained from the study area and in line with the set objectives for the study, the following conclusions can be drawn:

- The selected soils were indeed problem soils as inferred from the results of gradation analysis and consistency characteristics of the soils. The AASHTO classification of A-6 (1) for BCC and A-2-6 for LS indicated the soils being problem soils which need to be stabilized for any meaningful engineering works.
- The Drycon powder has an effect on the properties of soil as revealed by the significant reduction in the plasticity index of the soils. The lower the plasticity index, the lower the potential of soils to swell or shrink, an important property of great concerns to engineers.
- The low values of heavy metals and volatile organic compounds within recommended limits suggest that DP is not only just a stabilization additive but also environmental friendly material. Therefore the choice of DP for this study was very relevant.
- Drycon powder stabilized soils showed significant improvement in strength properties as compared to other stabilizing additives used by other researchers in the study area.
- Generally, DP enhanced the properties of the treated soils with significant improvement in strength properties. It is safe and can be used for soil improvement in highway construction. The application of the chemical additive to subgrade soils has good impacts as an alternative to maximizing productivity and at the same time ensuring the sustainability of subgrade soils.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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