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Effect of micro sized quarry dust particle on the compaction and strength properties of cement stabilized lateritic soil

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ABSTRACT

Laboratory investigation on the effect of micro sized quarry dust on engineering behaviour of cement stabilized lateritic soil was carried out. The specific concentration was on the effective way of curtailing, managing and disposing solid wastes generated from quarry activities by incorporating them as admixture in cement amelioration protocol of weak lateritic soil bound for sustainable subgrade material. In airfield, embankment, railways, pavement foundation structures, special attention/consideration/interest is continually laid on how moisture percolation affect the bearing capacity or strength of the subgrade layer. The quarry dust of 0 to 10 % was admixed with cement of 0 to 8 %, both in step increment of 2% by dry weight of the soil forming a combination matrix of twenty-five test specimens in an amelioration protocol. The test results show that quarry dust admixture steadily improved the plasticity index of cement stabilized soil through the reduction in plasticity index. The maximum dry density in most part of the test, improved with increase in percentage stabilizers blend for the individual corresponding optimum moisture content of the treated soil. The mechanical properties (California bearing ratio and unconfined compressive strength) of cemented lateritic soil increased significantly with increase in the micro sized quarry dust stabilizer. The resistance to loss in strength showed that more than 80 % durability values was recorded. The SEM/EDS analysis of the optimally stabilized specimen in contrast to untreated soil established the development of calcite as C-S-H and C-(A)-S-H. The formation of C-S-H and C-(A)-S-H which was also confirmed through the FTIR and XRD test was responsible for strength development.

1. Introduction

In many instances, lateritic soils which account for most compacted subgrade foundation may act dynamically as plastic or liquids when moisture finds their way through it. These process overtime affect largely the engineering behavior and durability performance of the subgrade material. Similarly, the availability of a high-quality soil with an excellent bearing capacity is often rare to come in contact with in many parts of the world (Hoy et al., 2016; Latifi et al., 2016a; 2016b). Nigeria, being a case study where road construction is carried out mostly with lateritic soils and in most cases, substantial information about the bearing capacity of the existing soil rarely exists coupled with the fact that they hardly meet the required standards for use as construction materials. These forces engineers to resort to the use of locally available soils in order to meet the criterion stipulated by the given project. In doing so, it is either they scarify the soil on site with a replacement which is usually an imported backfill materials, proven to be so expensive or they improve on the existing soil by method of stabilization in order to meet the stipulated properties of the materials (Karol, 2003; Alshawabkeh and Sheahan, 2002; Manso et al., 2013; Sukmak et al., 2013). Tropical regions, warm temperatures, appreciable amount of rainfall and the presence of deeper geologic deposits favors the formation of laterites as reported by (Eisazadeh et al., 2011; Latifi et al., 2014). The red coloration cum shades of brown in lateritic soils is made possible through the presence of iron oxides (Ojuri and Ogundipe 2012; Marto et al., 2013). Most lateritic soil deposits generally contain some appreciable amount of fine-grained soil due to significant process of soil weathering. The presence of these fines and some swelling clay minerals such as hydrated halloysite, vermiculite and montmorillonite render the lateritic soils deficient and problematic (Francis and Venantus, 2013). Due to these deficiencies, soil re-engineering scholars have come up with strategies in stabilizing these marginal soils through the application of the well-known traditional soil improving stabilizers such as cement, lime, fly ash

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(Chew et al., 2004; Basha et al., 2005; Billong et al., 2009; Horpibulsuk et al., 2010; Arulrajah et al., 2016). However, in recent times, these known traditional stabilizers especially cement have increased in price coupled with the greenhouse effect they release in large quantities into the environment (Faleschini et al., 2014; Ezziane et al., 2011). So, efforts are geared towards replacing Portland cement either partially or totally as a soil stabilizer. In a bid to achieve this, researchers have been motivated to harness the possibilities of utilizing solid waste materials in soft soil treatment and as admixture concrete, which includes: fly ash, sludge ash, steel slag, periwinkle shell ash (PSA), cement kiln dust (CKD), iron ore tailings (IOT), quarry dust, metakaolin, oyster shell ash (OSA), rice husk ash (RHA) etc. (Neeraj et al., 2012; Ayodele et al., 2016; Attah et al., 2020; Akinhumi, 2014; Etim et al., 2017a; Etim et al., 2019; Sreekrishnavilasam et al., 2006; Amadi and Eberemu 2013; Osinubi et al., 2015; Soosan et al., 2001a; Soosan et al., 2005a; Sridharan and Soosan, 2005; Moses et al., 2018; Moses et al., 2019; Sridharan et al., 2006; Attah et al., 2019b; Etim et al., 2020; Attah et al., 2019a; Attah et al., 2021b; Ekpo et al., 2020; Ekpo et al., 2021a; Onyelowe and Obianyo 2021; Onyelowe et al., 2019, Alaneme et al., 2021). Recent researches in these areas have shown a considerable improvement in geotechnical properties of the soil.

Similarly, as the scope of resilient and sustainable pavement expands, a rising amount of reprocessed materials and industrial wastes have gain relevance and have been used in specific areas of soil amelioration and re-engineering of pavement sub-layers. This are particularly geared toward the provision of sustainable pavement structure. Substantial resources are being deployed to dispose of these waste materials in order to satisfy environmental restrictions. The construction industry and in particular the pavement industry have used several of these waste to preserve natural resources. Some of such waste to include but not limited to waste glass and quarry fines also regarded as quarry dust. Far reaching results have also been obtained in the use of some this waste in engineering application. In the light of this, waste glass powder (WGP) admixed with hydrated lime (HL) in varying ratios has offered improved consistency, mechanical properties and durability which acted as a controlled low strength material as stabilizing agent in backfill materials (Xiao et al., 2021). The mechanical properties of WGP-based geopolymer stabilized specimen was significantly improved (Xiao et al., 2020).

Quarry dust are solid wastes generated during crushing operations. They comprise chiefly of overabundance fines produced during pulverizing, washing and screening operations at quarries. Their properties might shift with the source yet moderately they appear to be consistent at a specific site. Immense amounts of these waste gather during pulverizing tasks which whenever left unutilized might be deleterious to the environment. They are often known to constitute nuisance, forming "mole hill" that occupy large expanse and immediate space within the quarry site which could stand risky for quarry miners. Also, in a bid to securing adequate space for quarry activities within its spot and to satisfy environmental regulations, huge resources are most often than not expended in disposing and management of quarry dust wastes. Soosan et al. (2005) reported that in India, an estimate of around 200 million tons of by-products of quarry is being produced every year which constitute around 20–25 % of the yield of every rubble crusher unit. Studies conducted by (ASTM, 1978) has shown that other than its effective use in realizing a cost-effective pavement construction, quarry dust likewise has high aluminosilicate content which is reliant upon the high pozzolanic properties it shows. This trait renders it helpful in recent times as a supplanting for cement combined with the blend of geopolymer cements (Liang et al., 2018; Onyelowe, 2019, Onyelowe et al., 2021). It has also found its usefulness in a high number of geotechnical applications such as sub-base, embankments and backfill. Furthermore, it has been used as a replacement for sand as a way of improving the properties of the lateritic soil (Soosan et al., 2001b; Onyelowe, 2019; Onyelowe et al., 2020; Onyelowe et al., 2021).

Portland cement on the other hand is one of the commonest and widely accepted traditional soil improving additives either as single or mixed stabilizer binders Khemissa and Mahamedi, 2015; Osinubi et al., 2015). Portland cement is essentially made up of calcium-silicates and calcium-aluminates such that when combined with water, hydration occurs leading to the formation of cementing compounds of calcium silicate hydrate (C-S-H) and calcium-aluminate-silicate-hydrate (C-A-S-H) inclusive of excess calcium hydroxide $Ca(OH)_2$ (Myers et al., 2017). Due to the cementitious material as well as the $Ca(OH)_2$ formed, Portland cement has been effective in treating both granular and fine-grained soils, as well as aggregates and miscellaneous materials. This has resulted into some lateritic soils stabilized with cement being utilized as a highway pavement layer, earth building materials and as backfill material (Ola, 1974; Awoyera and Akinwumi, 2014) in tropical and subtropical nations because of their accessibility. Nonetheless, because of the conceivable increase in cost and ecological effects caused during production through the release of greenhouse gases which depletes the ozone layer, it is crucial to sort for a partial or all out substitution of Portland cement as a soil stabilizing agent. Also, the use of single non-conventional additive may not be efficient to rejuvenate the expected geotechnical properties of soft soils and this has invigorated the incorporation of multi-additives or additives blended with imported stabilizers such as lime-IOT (Etim et al., 2017a), cement-IOT (Osinubi et al., 2015), CKD-rice husk ash (Attah et al., 2021c), CKD-metakaolin (Attah et al., 2021a; Attah et al., 2021d), hydrated lime-RHA (Alaneme et al., 2020a; Alaneme et al., 2020b), CKD- PSA (Ekpo et al., 2021), cement-PSA (Etim et al., 2021a), OSA-lime and OSA-cement blends (Etim et al., 2021b) and lime-PSA (Etim et al., 2021c). The optimal blends obtained from their studies showed that the resultant effect of using multi-additives optimal blends in stabilization protocol of soft soil is greater than the effect either one of them have established by itself. Amadi (2014) reported that one of the stabilizers in the mixture could easily substitutes for the lack of efficacy of the other in treatment of a specific feature or properties of a given soil.

Moving onward, recent studies has shown that cement-quarry dust (CQD) admixtures are a viable stabilizer in improving the CBR and other geotechnical properties of the soil (Sridharan et al., 2005; Sridharan et al., 2006; Soosan et al., 2005; Eze-Uzomaka and Agbo, 2010; Nayak and Sarvade, 2012; Nweke and Okogbue, 2017; Onyelowe et al., 2019). However, there are no known studies that has been reported in open literature that compares or evaluate the differences in compaction behaviour coupled with other qualitative analysis in CQD treated lateritic soil. Hence, this study becomes crucial. Furthermore, this research work will highlight the changes in microstructural behaviour of the specimen in order to close the gap of the existing studies on the effect of CQD on lateritic soil. The specific objectives are to evaluate the effect of the compactive efforts of British Standard light, BSL (standard Proctor); West African Standard (WAS) and British Standard heavy, BSH (modified Proctor) on strength properties of the CQD treated soil as road material. In this study, CQD will be presumed to be advantageous and to be an alternative to the costly traditional soil stabilizing additives such as bitumen, cement and lime. This will achieve two goals: improving the soil and disposing of waste in a healthy manner. More so, the outcome of this study is expected to pave way for the wide-scale use and comprehensive management of quarry fines waste in construction industry.

2. Materials and methods

2.1. Materials

The disturbed lateritic soil utilized for this investigation was collected from Mkpat Enin LGA of Akwa Ibom State. The study location map from where samples were collected is shown in Fig. 1. The top soil

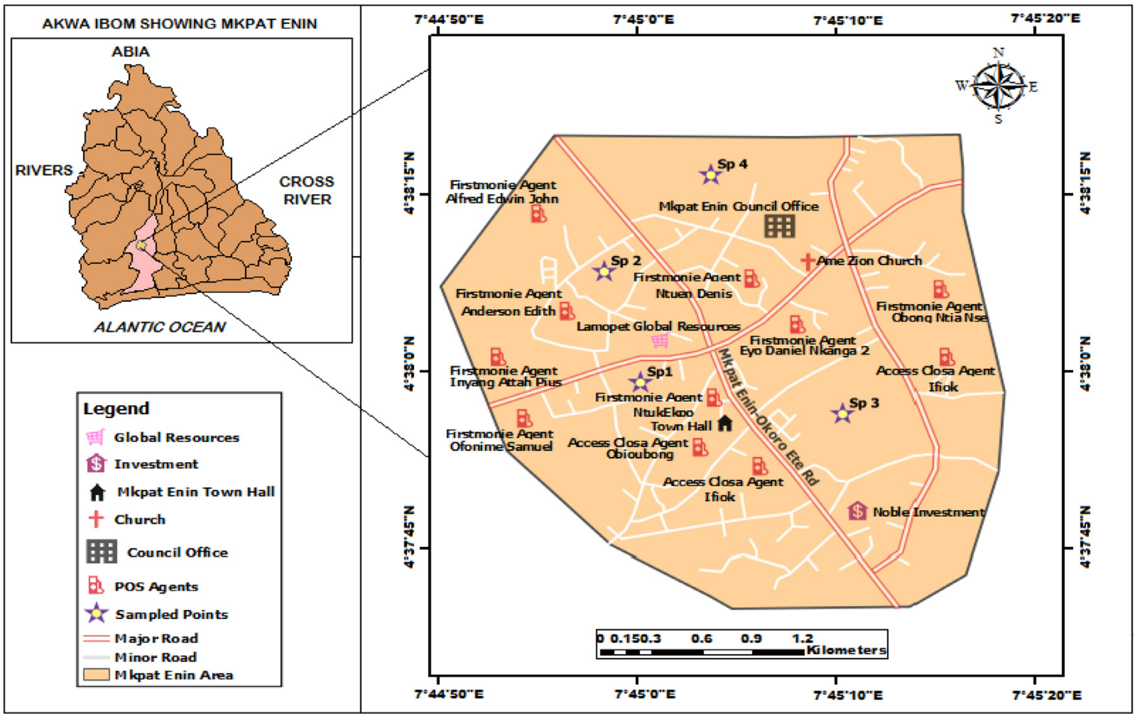


Fig. 1. Map of study area showing sampling point.

was excavated to a depth of about 0.5 m in order to remove organic matter which might impair the behavioral pattern of the soil. The representative sample utilized for this investigation was a mixture of specimen from each of sample point indicated by SP1, SP2 SP3 and SP4. These points were critical locations within the study area. The soil was carefully sealed in plastic bags to curtail moisture loss before being transported to the laboratory for moisture content determination. The cement used in this study is a grade 32 Portland limestone cement after here denote as "C" is commonly used for construction purposes in Nigeria. It was obtained from a commercial open market which was produced according to the specifications of Nigeria Industrial Standards (2003). The quarry dust (QD) was obtained from Peter stone construction company quarry sites in Uyo, Akwa Ibom State. The material was then sieved through 0.075 µm sieve according to ASTM 98 D422-63 and combined with the required percentages of the soil–cement matrix.Nigerian Industrial Standards, 2003.

2.2. Methods

2.2.1. Physicochemical analysis

The oxide composition of the specimens which comprises of the lateritic soil, Portland limestone cement (C) and quarry dust (QD) were determined by Niton^{TM} XL3t XRF analyser using the X-ray Fluorescence (XRF) technique.

2.2.2. Index properties

The particle size distribution (PSD) was determined through the use of mechanical sieves as outlined in the procedures described in ASTM D 422–63 (1998). The natural moisture content, specific gravity and Atterberg's limits (liquid limit, LL and plastic limit, PL) otherwise known as the index properties of the soil were determined according to ASTM D 2216, ASTM D 854–02, and ASTM D423-66 (1972) and ASTM D424 (1954). The 425 µm sieve was used in determining the Atterberg limits. The plasticity index (PI) of the soil was obtained. The results obtained from the Atterberg's limits and PSD were used in classifying the soil according to American Association of State Highway and Transport Officials (AASHTO, 1986).

2.2.3. Compaction

Compaction of the untreated soil and optimally stabilized soil were done through BSL, WAS and BSH compactive efforts according to the procedures outlined in ASTM D 698 in different percentages of the admixtures.

2.2.4. Unconfined compression strength test

Lateritic soil was treated with cement at 0–8 % and quarry dust at 0–10 % each, at increments of 2 %. Using the procedures described in ASTM D 2166, the untreated and treated soils were subjected to unconfined compression strength (UCS) tests to determine the lateritic soil's stress–strain behaviour. The soil–cement-quarry dust mixtures based on the moisture-density relationship at BSL, WAS, and BSH as described in section 2.2.3 at their different optimum moisture contents were extruded from moulds cored in a steel coring ring of height 76 mm and internal diameter 38 mm, after which they were sealed in a membrane and dried for 7, 14 and 28 days prior to testing. For each soil-CQD mixture, two samples were taken and the average values were determined. The UCS was calculated as:

$$\mathrm{UCS} = \frac{\mathrm{Loadatfailure}}{\mathrm{Crosssectionalarea}} \tag{1}$$

2.2.5. California bearing ratio

The California bearing ratio (CBR) was conducted according to the procedure stated in ASTM D 2850. Using 2360 cm^3 mould, the soil-CQD samples were mixed at their different OMC for the three compaction energies. For six (6) days, the compacted specimens were tightly packed in plastic bags. Following the expiration of the 6-day period, the specimen was immersed in water for 48 h before testing, as required by Nigeria General Specifications (1997). Penetrations was achieved at 2.5 mm and 5.0 mm – the higher value of the two is taken as the CBR provided they are within the acceptable limits of 10% of each other. The CBR was then obtained using Eq. (2):

$$\mathrm{CBR} = \frac{\mathrm{Measuredload}}{\mathrm{Standardload}} \mathrm{x}100\% \tag{2}$$

2.2.6. Microanalysis

The PHENON WORLD scanning electron microscope (SEM) was used to identify the changes in morphological and structural behaviour of the treated and optimally stabilized soil-CQD at different magnification levels. There are a lot of software applications attached to the PHENON WORLD SEM such as the energy dispersive X-ray spectrometers (EDS) used for rapid elemental analyses of small particles which is usually presented in form of a plot energy in kiloelectronvolt (keV) on the X-axis and the intensity in counting phantons per electronvolt (cps/eV) on the Y-axis at different zones of the scanned samples. Since there are prejudices inherent in manual optical analysis, automated SEM-EDS analyses helps to remove such with a more rapid and accurate results (Brian, 2013). The overall quality of results output are most often than not a function of the equipment settings or calibration. Furthermore, in investigating the behavioural changes in functional groups of the soil, the Fourier transformation Infrared (FTIR) via the Agilent Technologies using the Transmittance Method principles with a range of 650–4000 cm^{-1} on a background scan and resolution of 16 and 8, respectively was employed. XRD was also used to validate the mineralogical modifications in the stabilized specimen.

Table 1
Properties of the untreated soil.

Property	Quantity
Natural moisture content (%)	20.54
Percentage passing BS No 200 sieve (%)	52.4
LL (%)	42.6
PL (%)	24.06
PI (%)	18.54
Specific gravity (%)	2.55
Linear shrinkage (%)	9.2
AASHTO classification	A-7-6 (8)
USCS	CL
MDD (Mg/m^3)	
BSL	1.655
WAS	1.700
BSH	1.805
OMC (%)	
BSL	21.0
WAS	20.5
BSH	19.2
UCS (kN/m^2)	
BSL	201.53
WAS	425.35
BSH	565.80
CBR (48-hr. soaking) (%)	
BSL	8.04
WAS	10.30
BSH	14.39
Dominant clay mineral	Kaolinite
Colour	Reddish-brown

3. Results and discussion

3.1. Properties of materials

Summarized in Table 1 is the index properties of the untreated soil, while the particle size distribution curve is presented in Fig. 2. AASHTO classification system (AASHTO, 1986), classified the soil as an A-7–6 (8) which is indicated by the 55.3 % passing the 200 μm sieve size. The Unified Soil Classification System, USCS (ASTM, 1992) classifies the soil as inorganic clay with low plasticity (CL). The very stiff consistency nature of the soil is in tandem with the findings of (Das, 2000) as obtained from the UCS value. The predominant clay mineral is kaolinite and mixed layer kaolinite/quartz and goethite minerals (Etim et al., 2019). In its untreated state, the soil's tests demonstrate that it is unfit for construction, pointing to the need for soil stabilization.

3.2. Chemical composition of soil, cement and quarry dust

As presented in Table 2, the chemical composition of lateritic soil, quarry dust, Portland limestone cement are displayed. The quarry dust is rich in SiO_2 (45.4%), while the Portland limestone cement is rich in CaO (61.14 %) and deficient in SiO_2 (21.40%). Quarry dust's high shear strength makes it an excellent geotechnical material (Soosan et al., 2005; Eze-Uzomaka and Agbo 2010; Amadi, 2011). Its exceptional high shear strength allows it to deliver more Si^{2+} to the entire stabilization mechanism.

3.3. Effect of CQD on the Atterberg limits

The behaviour of CQD admixtures on lateritic soils are presented in Table 3. The plasticity index (PI) of the natural soil was 18.54 %. This was considered as inorganic clay of low plasticity which is not fit and desirable as construction materials. The addition of CQD to this soil causes a general decreasing trend in LL and PI with a corresponding increase in PL for varying QD contents. Further treatment with CQD led to a drastic decrease in PI with the minimum value of 7.87 % at 8 % cement and 10 % QD. Similarly, the maximum percentage increase in PL was 5.7 % at 8 % QD contents. The general reduction in LL and PI may have been attributed to cation exchange reaction which exist between the CaO in the cement and water in the CQD soil.

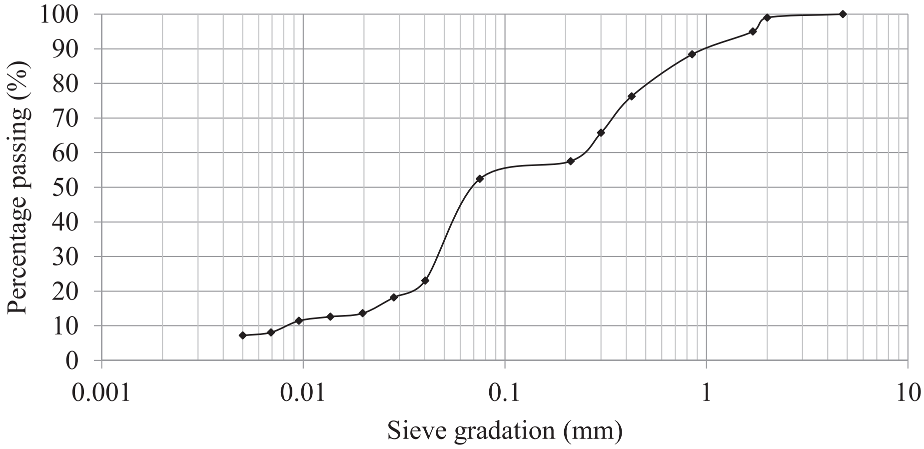


Fig. 2. Particle size distribution curve of the natural soil.

Table 2
Chemical composition of materials used.

Chemical (% Oxide concentration)	Chemical compositions by weight (%)		
	Lateritic soil	Portland lime stone cement*	Quarry dust
Lime (CaO)	1.25	61.14	14.3
Magnesium oxide (MgO)	–	1.35	3.54
Potassium oxide (K_2O)	0.35	0.48	4.35
Silica (SiO_2)	30.2	21.40	45.4
Sulphur oxide (SO_3)	0.63	2.53	0.55
Sodium oxide (Na_2O)	–	0.24	–
Alumina (Al_2O_3)	26.5	5.03	15.52
Iron oxide (Fe_2O_3)	23.2	4.40	6.53
Phosphorous pentoxide (P_2O_5)	0.05	–	–
Tin oxide (TiO_2)	0.72	–	2.65
Loss on Ignition (LOI)	7.45	1.29	0.37

[*] Attah et al., (2018).

Table 3
Effect of soil-cement-quarry dust admixtures on liquid limits.

CEMENT						
	LL					
QUD		0	2	4	6	8
	0	42.60	41.80	41.00	39.23	38.20
	2	41.20	40.25	39.25	38.24	37.40
	4	40.10	38.30	39.62	38.20	38.00
	6	39.50	38.10	38.20	37.00	36.15
	8	39.60	39.10	38.50	37.80	36.10
	10	38.40	38.25	37.20	36.50	35.70
	PL					
QUD	0	24.06	25.07	25.14	25.00	26.67
	2	24.60	25.20	25.75	25.60	26.80
	4	24.95	25.82	26.15	26.00	26.70
	6	24.58	25.40	26.50	25.80	27.30
	8	25.42	25.60	26.85	26.40	27.42
	10	25.30	25.70	27.23	26.70	27.83
	PI					
QUD	0	18.54	16.73	15.86	14.23	11.53
	2	16.60	15.05	13.50	12.64	10.60
	4	15.15	12.48	13.47	12.20	11.30
	6	14.92	12.70	11.70	11.20	8.85
	8	15.18	13.50	11.65	11.40	8.68
	10	13.10	12.55	9.97	9.80	7.87

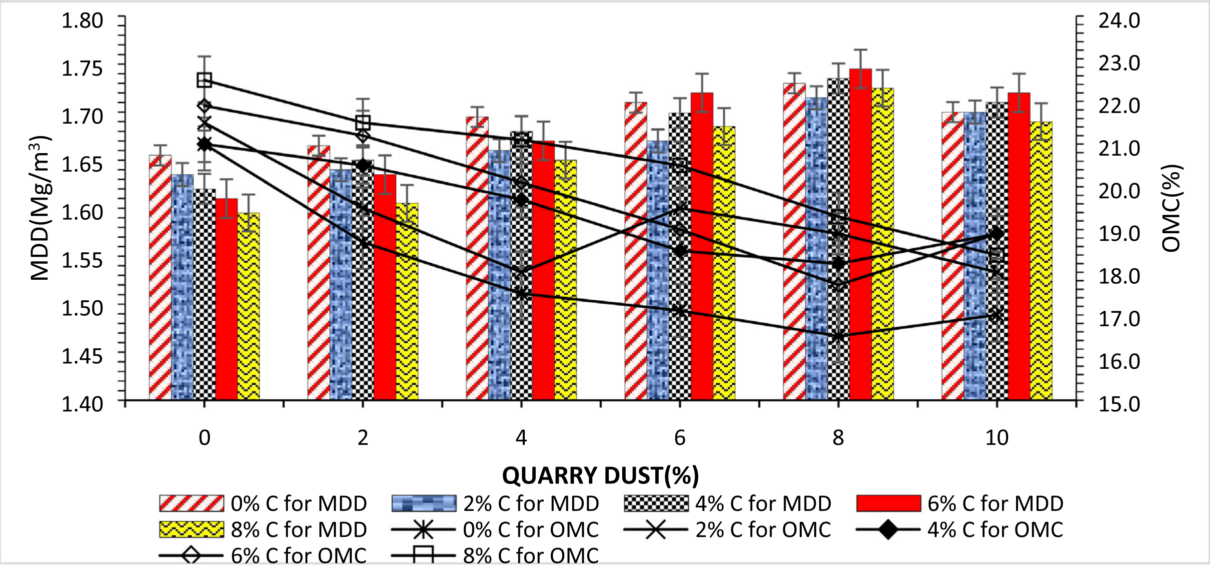


Fig. 3. Compaction properties of soil-cement-quarry dust admixtures (BSL).

The Ca^{2+} released by the cement is absorbed by some of the soil's clay particles, which replaces the lower valence electrons of Na^{+} in the soil, causing a suppression of the soil's diffuse double layer and making the soil flocculated and more workable (Osinubi, 1995; Abood et al., 2007; Parsons and Kneebone, 2005; Muntohar, 2002; Sharma and Lewis, 1994; Akinwumi, 2014; Etim et al., 2021a; Etim et al., 2021b). Furthermore, Sharma and Lewis (1994) found that increasing the concentration of cations causes a decrease in net repelling forces, which results in flocculation of clay particles and a decrease in Atterberg's limits. Flocculated soil structures generally exhibit low plasticity characteristics and high shear strength, so the enhancement in soil properties can be attributed primarily to the physicochemical interaction of soil particles with additives.

3.4. Compaction characteristics

Figs. 3-5 show the respective variations in maximum dry density (MDD) and optimum moisture content (OMC) of soil–cement mixtures with quarry dust for the three different compactive activities (BSL, WAS, and BSH). For all of the cement contents analyzed, the MDD increased with the increase in quarry dust. The MDD for BSL, WAS, and BSH varied from 1.655 to 1.745 Mg/m^3, 1.700 to 1.820 Mg/m^3, and 1.800 to 1.920 Mg/m^3, respectively, on treatment with CQD admixtures. During the process of the addition of water, a reaction between the cement and water increases the hardness of the soil matrix, which in turn increases the weight of the soil/CQD matrix. The increase in MDD for all the compactive efforts could also be related to dynamic loading, which increases the soil's density, increasing dry density and reducing void spaces. The lime-rich cement and silica (SiO_2)-rich quarry dust combine to produce an increase in MDD, thereby shifting the soil's orientation from an edge-to-face to a more compact orientation (Iorliam et al., 2012; Osinubi et al., 2015, Moses, 2008, and Al-Amoudi, 1994). The higher specific gravities of cement and quarry dust (2.98 and 2.67) might have replaced the soil with a lower specific gravity of 2.55. This may have contributed to the MDD showing an increasing trend for all three compactive efforts

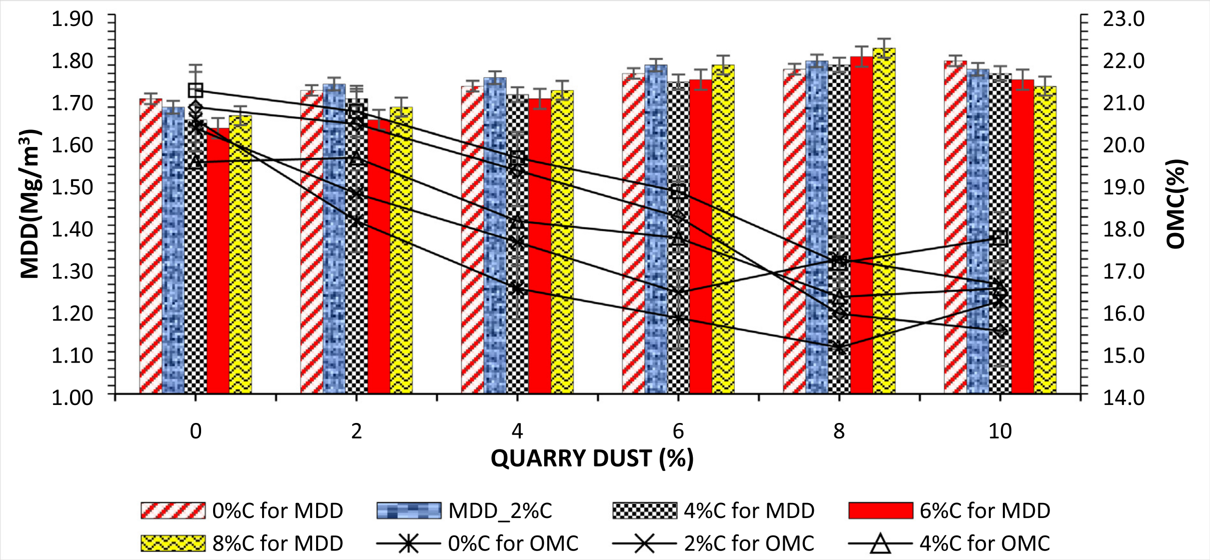


Fig. 4. Compaction properties of soil-cement-quarry dust admixtures (WAS).

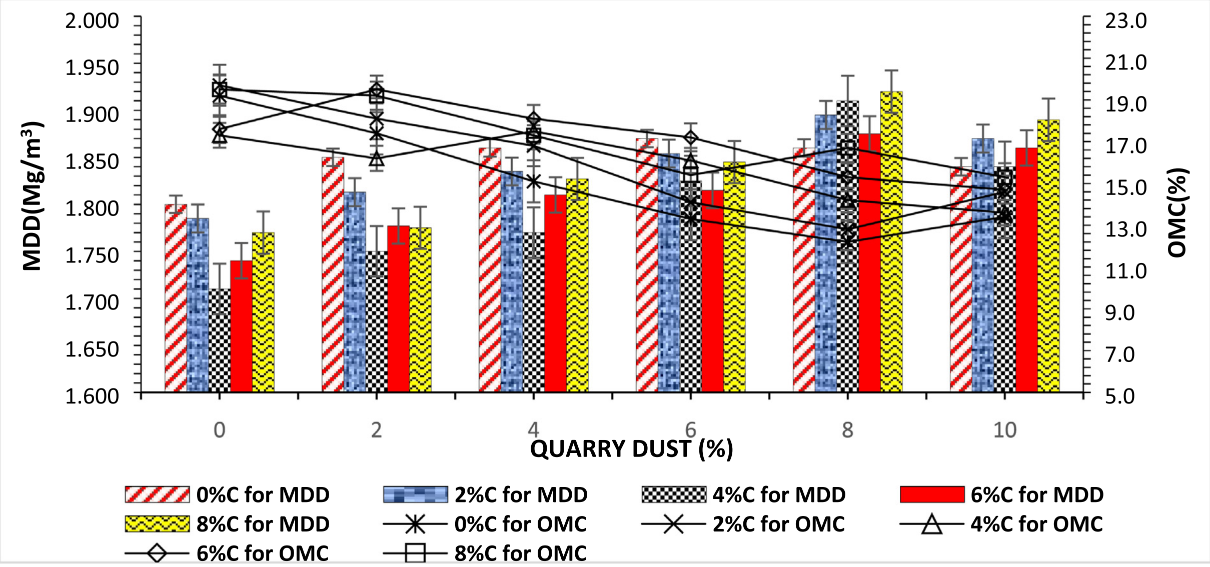


Fig. 5. Compaction properties of soil-cement-quarry dust admixtures (BSH).

with a corresponding decrease in OMC. The decrease in OMC could be attributed to the cohesiveness of the soil and quarry dust due to a higher heat of hydration rate as compaction increases, which causes less demand for water by various cations released from the admixtures. The decrease in OMC could also be attributed to self-drying in which all the water was used, leading to poor hydration. If no water movement is allowed to or from the CQD paste, the hydration reaction will consume the water until little or no more is left to coat the surface of the solid, thereby reducing the relative humidity of the paste within (Osinubi and Stephen, 2007; Moses et al., 2012; Ijimdiya et al., 2014).

3.5. Unconfined compressive strength

The plot of UCS-soil CQD contents for curing ages, 7, 14, and 28 days for BSL, WAS, and BSH is illustrated in Figs. 6-8. The results of BSL, WAS, and BSH compaction energies as presented in Fig. 6, show that for all cement contents up to 8 %, a slight increase in the UCS peaked at 8 % quarry dust contents. For the three compactive efforts, this percentage increase was 803.4, 424.5, and 351.6 %. For BSL, WAS, and BSH, peak strength was 2542.63, 2875.84 and 2983.24 kN/m^2 at 8% quarry dust for the 14-day curing period

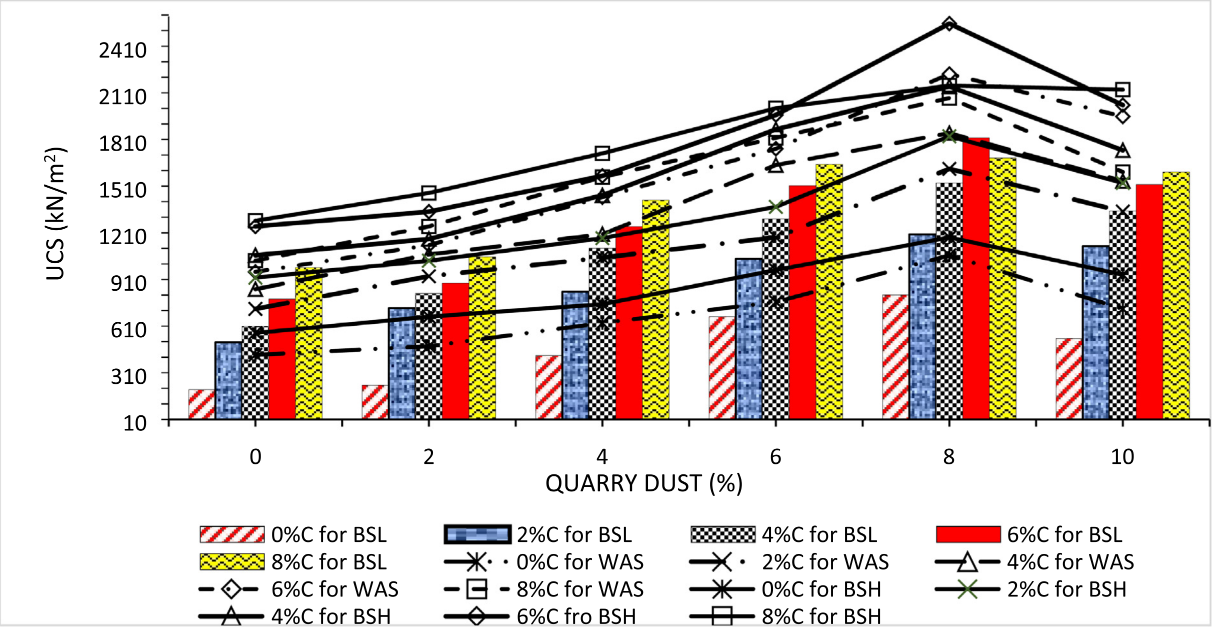


Fig. 6. 7 days UCS of lateritic soil-CQD mixtures.

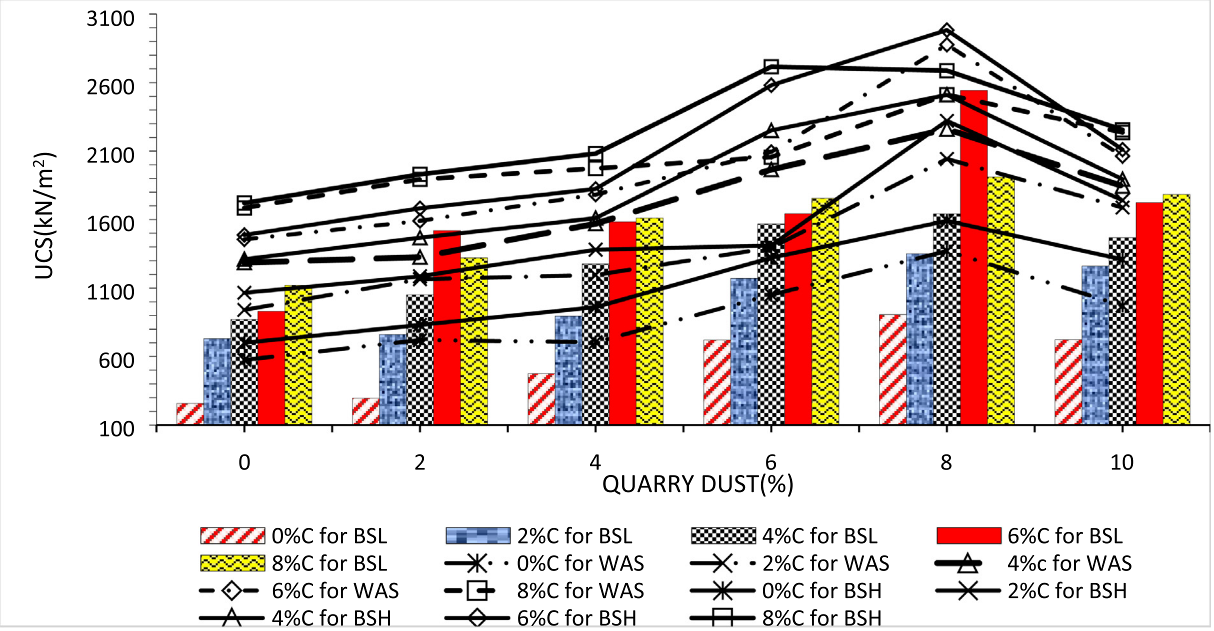


Fig. 7. 14 days UCS of lateritic soil-CQD mixtures.

(see Fig. 7). For the three compactive efforts, the 28-day curing period rose to a peak value of 2754.78, 3050.64, and 3247.11 kN/m^2 (see Fig. 8). The increase in UCS values for all the tested compactive efforts could be attributed to an exchangeable cation reaction, in which Ca^{2+} from the cement displaces the smaller valence electron of Na^+ in the soil, causing the formation of flocs (Puppala et al., 2006; Moses and Saminu, 2012; Salahudeen et al., 2014; Amadi and Okeiyi, 2017). Quarry dust, which is mainly SiO_2 and Al_2O_3, similarly interacts with $Ca(OH)_2$ from the cement to form calcium aluminate silicate hydrate (C-A-S-H) and calcium silicate hydrate (C-S-H). Okagbue and Ochulor (2007) attributed the soils' composition, clay minerology, and particle size distribution as contributing factors to the soil strength gain. The equation below explains the reaction mechanism within the soil matrix, whereby the Ca^{2+} from the cement in the presence of SiO_2 and Al_2O_3 triggers C-S-H and C-A-S-H gels that activate the binding forces within the soil composite and increase soil strength (Amadi and Okeiyi, 2017; Li et al., 2019).

$$Ca^{2+} + 2(OH)^- + SiO_2 \rightarrow CSH \tag{3}$$

$$Ca^{2+} + 2(OH)^- + SiO_2.Al_2O_3 \rightarrow CASH \tag{3}$$

Based on the result of the UCS values obtained for specimen cured for 7 days as recommended by Singh (1991), TRRL (1997) and Nigerian General Specifications (1997), only the optimal blend of 6% cement/8% quarry dust met the strength requirement of 1720 kN/m^2, recommeneded as benchmark for effective soil stabilization

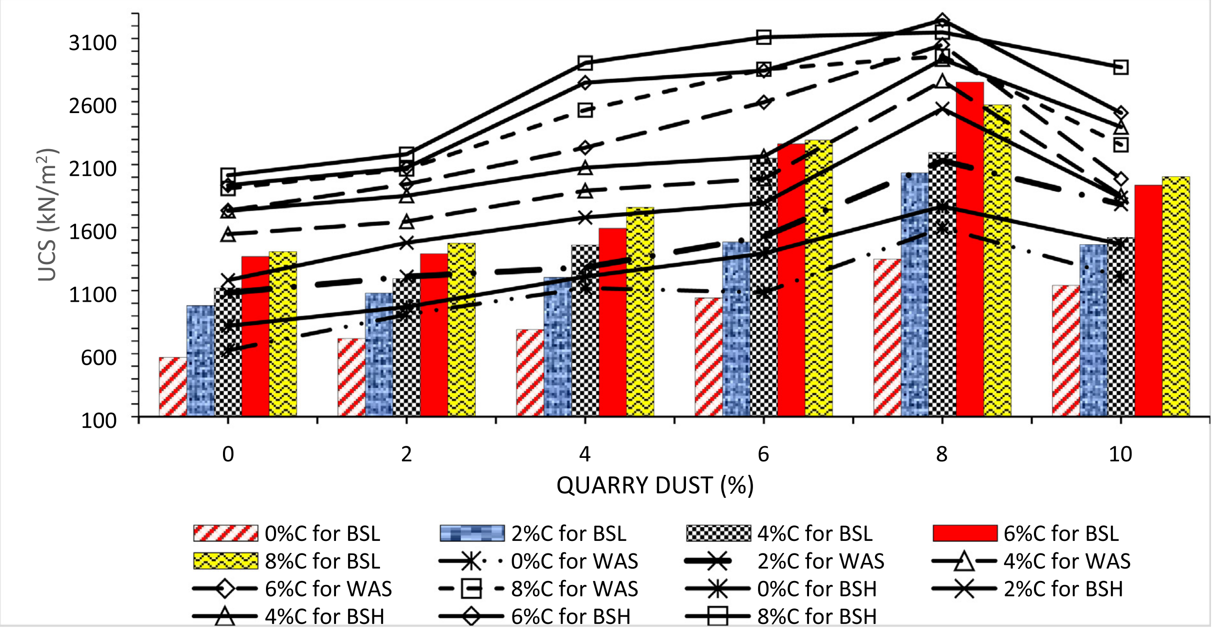


Fig. 8. 28 days UCS of lateritic soil-CQD mixtures.

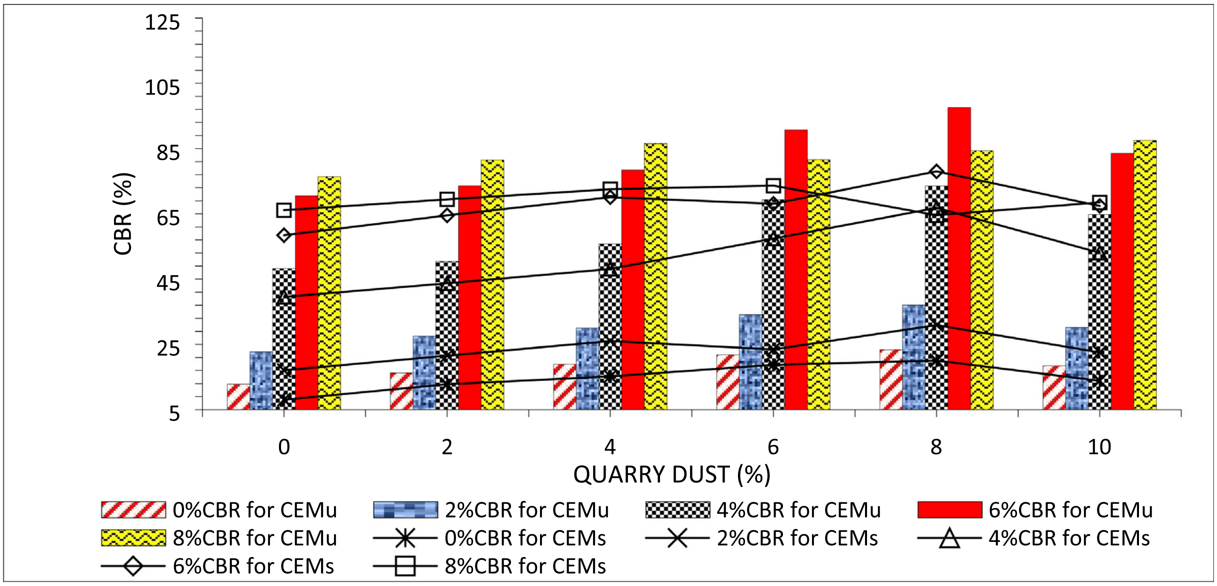


Fig. 9. Variation of CBR (unsoaked & soaked) of lateritic soil-CQD mixtures for BSL.

with cement. This information could serve as a basis for developing a sustainable sub-base construction materials where quary dust is used as admixture.

3.6. California bearing ratio and resistance to loss in strength

Presented in Figs. 9 and 11, we show the variation in California bearing ratio (CBR) of lateritic soil-cement mixtures with quarry dust for BSL, WAS, and BSH (unsoaked and soaked) conditions. The unsoaked CBR values increased steadily to a peak strength of 97.62, 101.60, and 107.60 % for BSL, WAS, and BSH, respectively, with a further decrease after adding the quarry dust. The reduction in unsoaked CBR values beyond 8% could be due to the addition of quarry dust that changes the grading of the soil, leading to reductions in the bonding particles of the clay structure, thereby reducing the soil's shear strength. On the other hand, the soaked CBR progressively increased from 8.04, 10.30 and 14.39 % to a peak strength of 78.04, 88.42, and 98.52 % for the three compacting efforts (BSL, WAS, and BSH), the percentages of which are 870.65, 758.45, and 584.78 % in the order of the compactive efforts. The reduction in the soaked CBR relative to the unsoaked CBR may be due to the penetration of water during soaking, which could have weakened the cohesive forces in the soil structure generated by the formation of CSH and CAH. In addition, the failure under load of the soil particle matrix caused by the fineness of the CQD admixture might have also contributed to the reduction in the soaked CBR. The Nigerian General Specifications (1997) recommend a CBR value of 180% for cement stabilization; however, when compacted to optimal moisture and 100% WAS compaction, CBR (unsoaked) values of 80 % and CBR (soaked) values of 30 % are required for bases and subbases (Gidigasu, 1982; Gidigasu and Dogbey, 1980; Osinubi, 2001). For BSL, WAS, and BSH, the CBR (unsoaked) tests revealed that requirements for base course material

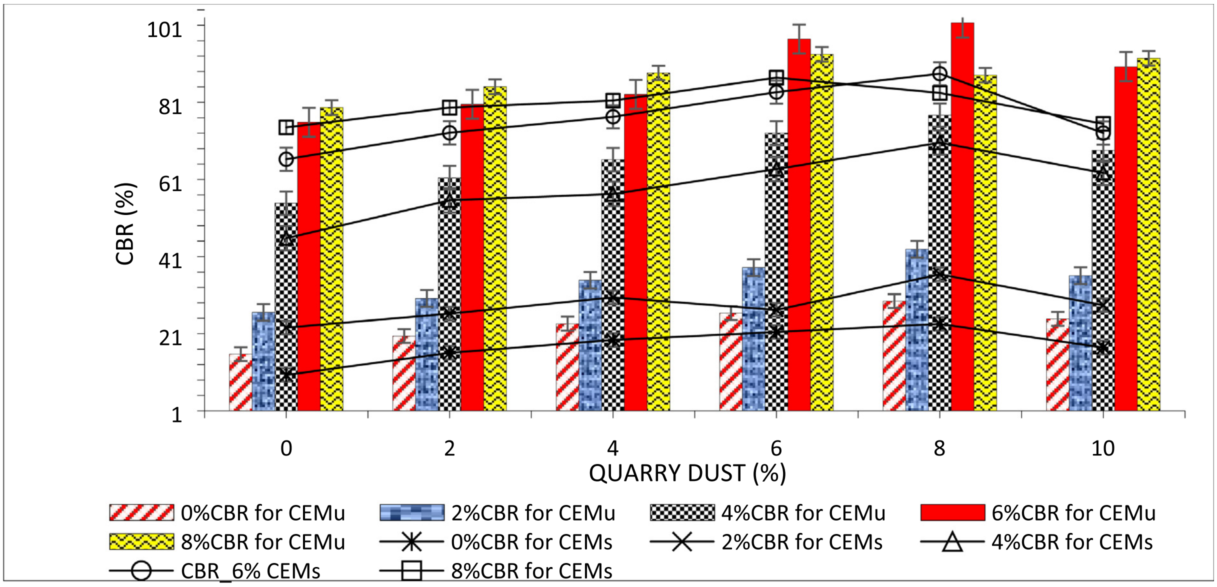


Fig. 10. Variation of CBR (unsoaked & soaked) of lateritic soil-CQD mixtures for WAS.

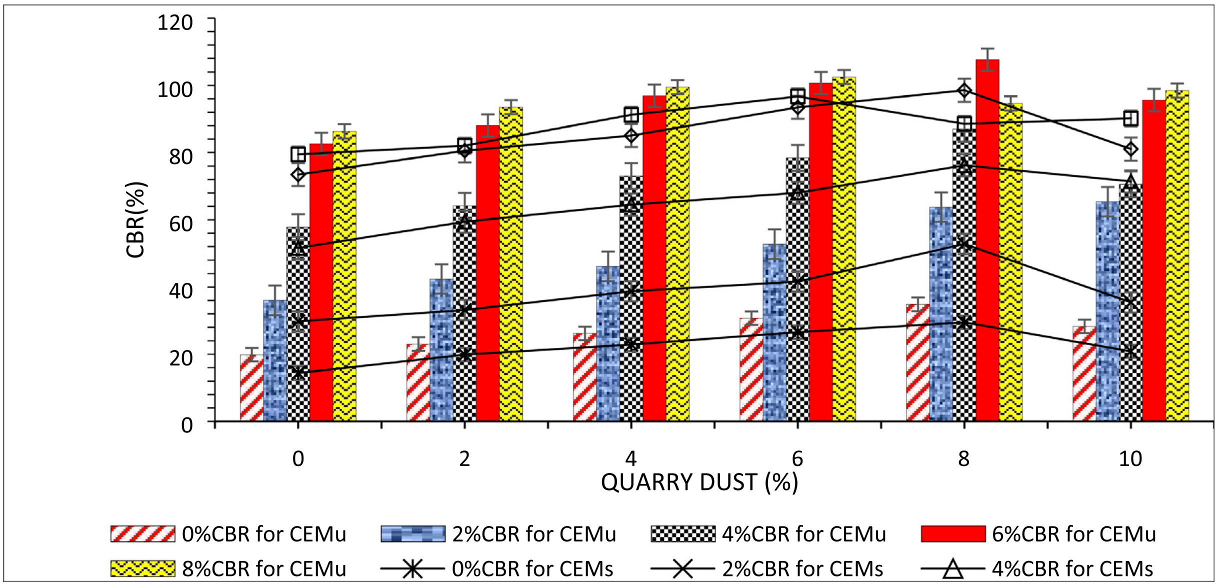


Fig. 11. Variation of CBR (unsoaked & soaked) of lateritic soil-CQD for BSH.

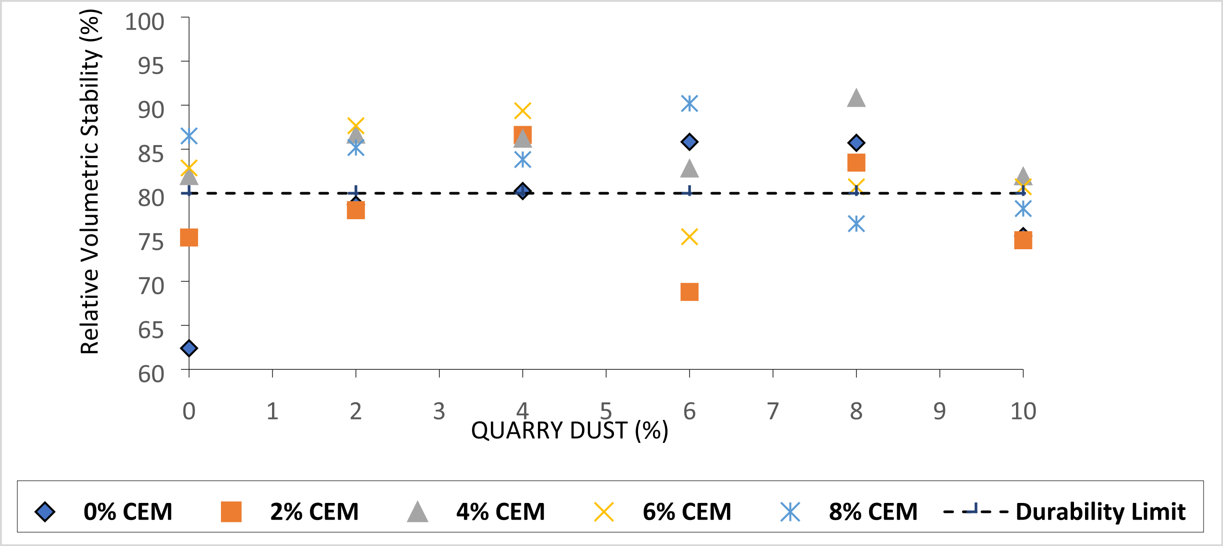


Fig. 12. Relative volumetric stability variations of lateritic soil-CQD mixtures.

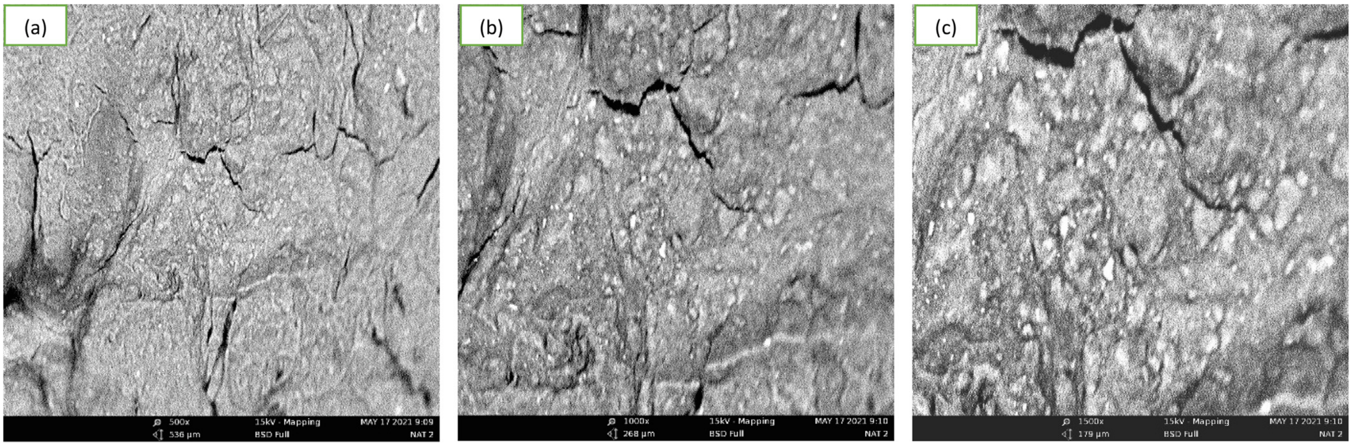


Fig. 13. SEM of natural soil at (a) 500 × (b) 1000 × and (a) 1500 × magnification.

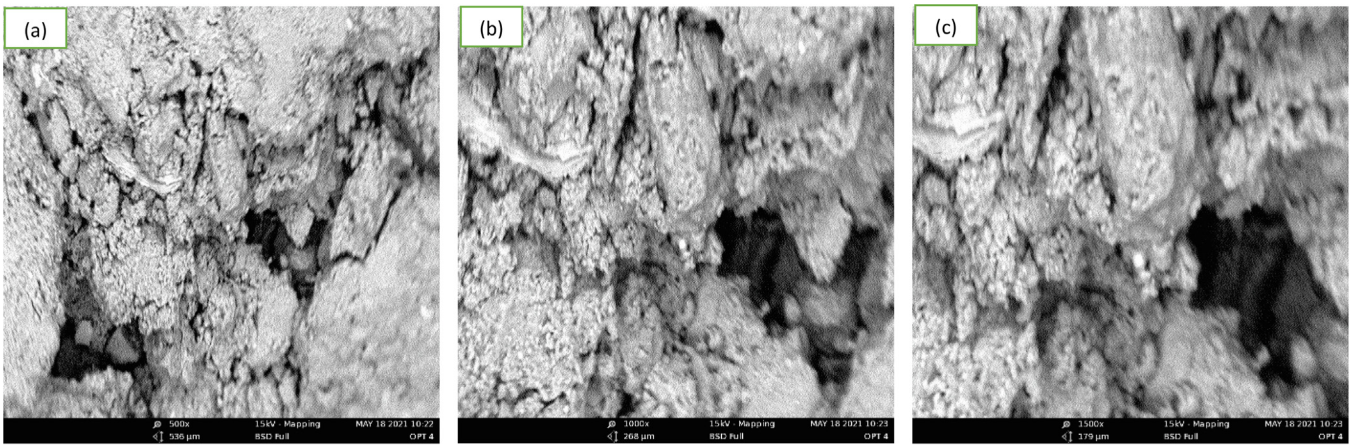
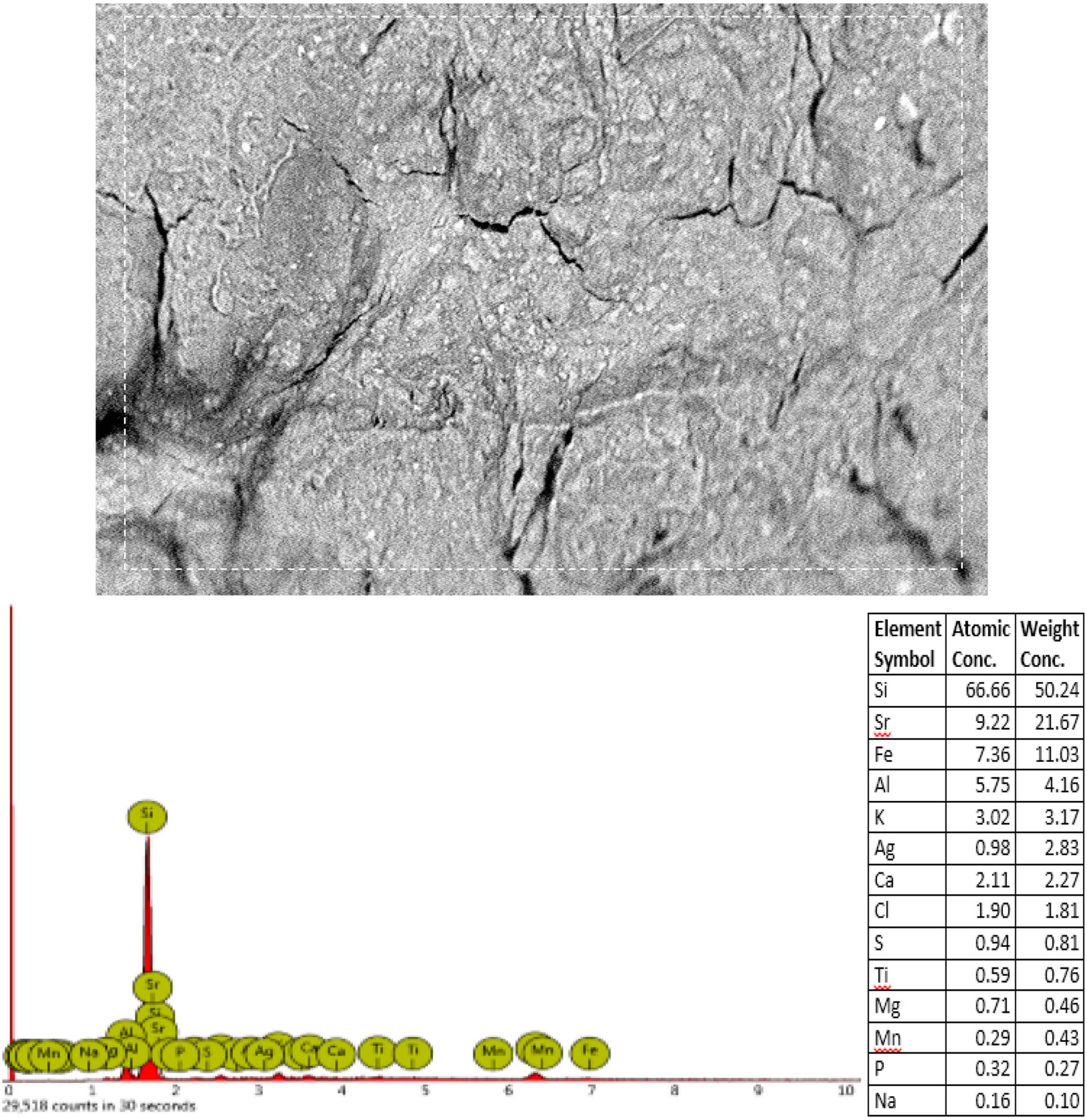


Fig. 14. SEM of optimal blend 6% cement/8% quarry treated specimen at (a) 500 × (b) 1000 × and (a) 1500 × magnifications.

were met at a cement/quarry dust blend of 6% and 8% at a peak value of 97.62 %, 100 % and 100 %, respectively. At optimum blend (6% cement/8% quarry dust), values of 78.04 %, 88.42 % and 98.54 % were observed for BSL, WAS, and BSH. However, the peak soaked CBR values for the three compaction efforts met the 20 ~ 30 % requirement for use as sub base materials on the basis of clause 6201 of the General Specification for Roads and Bridges. The relative volumetric stability or durability of the soil-CQD admixtures is shown in Fig. 12. In the most part of the test, the relative volumetric stability or durability of soil-CQD admixtures was more than 80%. The results showed that soil-COQ admixture would provide a robust subgrade material that could handle the increasing capillary action of water from the pavement's top and bottom subgrade layers.

4. Microstructural interplay

The paradigm shift towards the deployment of micro-morphological investigations like scanning electron microscopy (SEM), Fourier transformation Infrared (FTIR) and X-ray Diffractometer (XRD) has been found very useful with much emphasis in soil treatment studies (Osinubi et al., 2015; Etim et al., 2017a; Sani et al., 2018; Etim et al., 2020; Attah and Etim, 2020; Ekpo et al., 2020; Etim et al.,



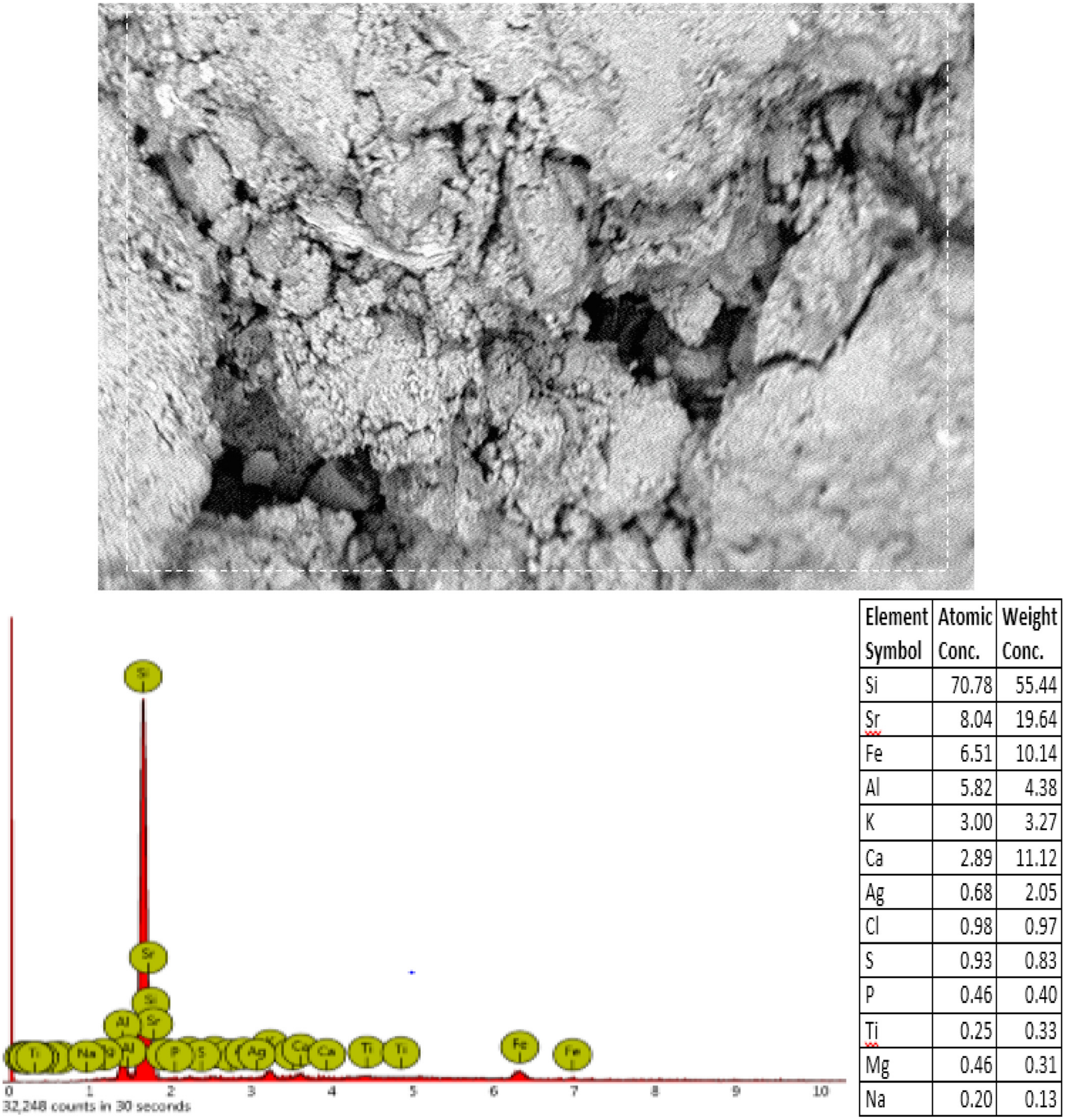
Element Symbol	Atomic Conc.	Weight Conc.
Si	66.66	50.24
Sr	9.22	21.67
Fe	7.36	11.03
Al	5.75	4.16
K	3.02	3.17
Ag	0.98	2.83
Ca	2.11	2.27
Cl	1.90	1.81
S	0.94	0.81
Ti	0.59	0.76
Mg	0.71	0.46
Mn	0.29	0.43
P	0.32	0.27
Na	0.16	0.10

Fig. 15. EDX of natural soil obtained from map source of 500× magnification output.

2021b). They are basically used in exploring in-depth analysis that substantiate mechanical properties of specimen relative to their chemical composition, physicochemical interaction, fabric reorientation and morphological characteristics.

4.1. Scanning electron morphology

The SEM images of both the unaltered and CQD altered soil viewed at 500x, 1000x and 1500x magnifications are displayed in Fig. 13(a-c) and Fig. 14(a-c). For the unaltered soil, there is a dominance of white tissues which could be linked with the unaltered soil material having high clay-silt content. Interestingly, at a higher magnification of 1500x the whitish clothed structure became more visible. Looking at Fig. 14, the incorporation of CQD blend into the soil activated the reduction of whitish clothed structure noticed in the unaltered soil. It is evident that blending CQD initiated the flocculation protocols which is noticeable in the altered soil and this outcome could as well be linked with the variations of pore sizes detected in the fibre histogram of the tested soil materials. On a general note, the detected disparities noticed between the untreated and CQD treated soil confirms the disbandment of some clay minerals which in return activates the formation of new compounds. Interestingly, the newly built com-



Element Symbol	Atomic Conc.	Weight Conc.
Si	70.78	55.44
Sr	8.04	19.64
Fe	6.51	10.14
Al	5.82	4.38
K	3.00	3.27
Ca	2.89	11.12
Ag	0.68	2.05
Cl	0.98	0.97
S	0.93	0.83
P	0.46	0.40
Ti	0.25	0.33
Mg	0.46	0.31
Na	0.20	0.13

Fig. 16. EDX of 6% cement/8% quarry optimally treated specimen obtained from map source of 500× magnification output.

pounds are sourced from the combative elements domicile in CQD blend and enhancement in strength could as well be attributed to these elements (Etim et al., 2017b; Attah et al., 2021).

4.2. Energy-Dispersive X-ray outcomes

The energy dispersive x-ray (EDX) application is an integral system embedded in the scanning electron microscopy examination. It generates both the morphological views and variation peaks of elemental concentrations of the tested sample. The outcomes of EDX assessment on the unaltered and CQD mixtures are displayed in Figs. 15 and 16. The whitish surface noticed in the EDX revalidates the SEM morphology. The atomic and weight concentration of chemical composition is shown on the right-hand side of the EDX. While the report acknowledged the unclear EDX spectra which might not be unconnected with the setting or calibration of the equipment as earlier mentioned, it is our hope that the element numerical values which are provided at the right hand side of the EDX has clearly depict the several band concentrations and therefore dismiss any reservation that might come from the indistinctiveness of the shown EDX. The case of the untreated specimen showed insignificant calcium compared to the higher calcium observed in treated specimen. This confirms calcite in the appearance of C-S-H and C-A-H. Also, the peak elemental composition discovered in the natural soil material is silica with traces of strontium, iron and aluminium (Fig. 15). On the other hand, the CQD ameliorated soil samples had similar elemental composition compared to untreated soil material, but the quantification percentages were at variance. The increase in silicon content in the treated soil could be concomitant with the presence silica in the deficient soil and stabilization binding agents (Fig. 16). Remarkably, the iron and aluminium contents decreased in the CQD-soil mixtures and this might not be unconnected with establishment of new compounds and modifications of miner-

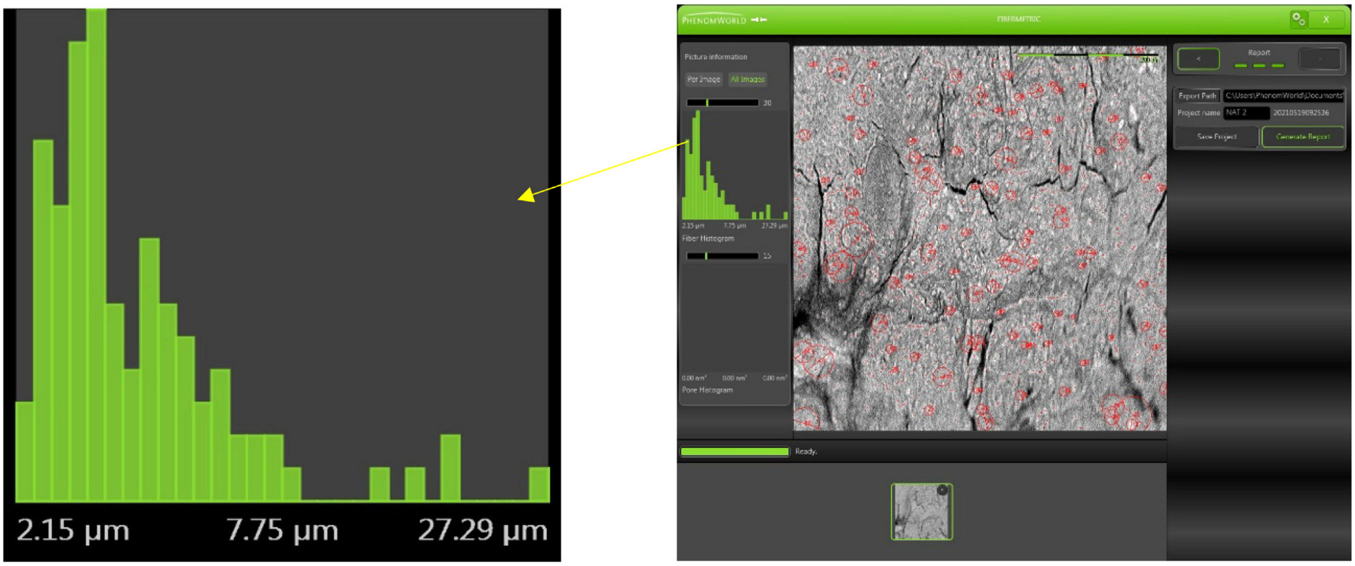


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Fig. 17. Fibemetric distribution of a natural soil.

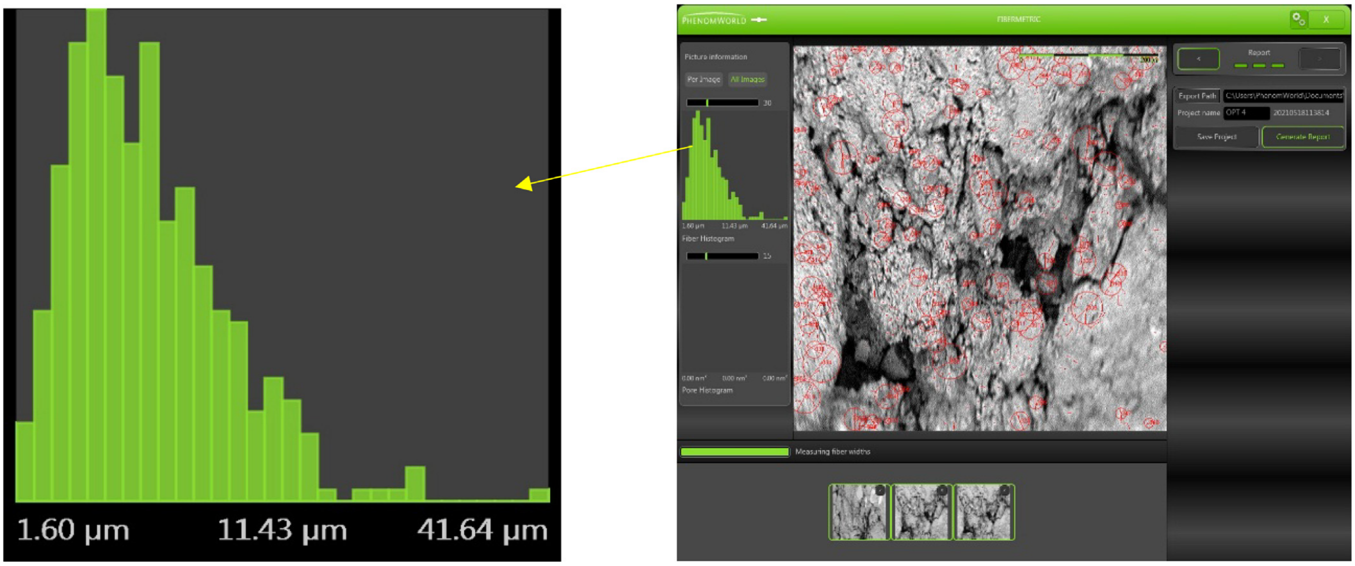

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Fig. 18. Fibemetric distribution of 6% cement/8% quarry optimally treated specimen.

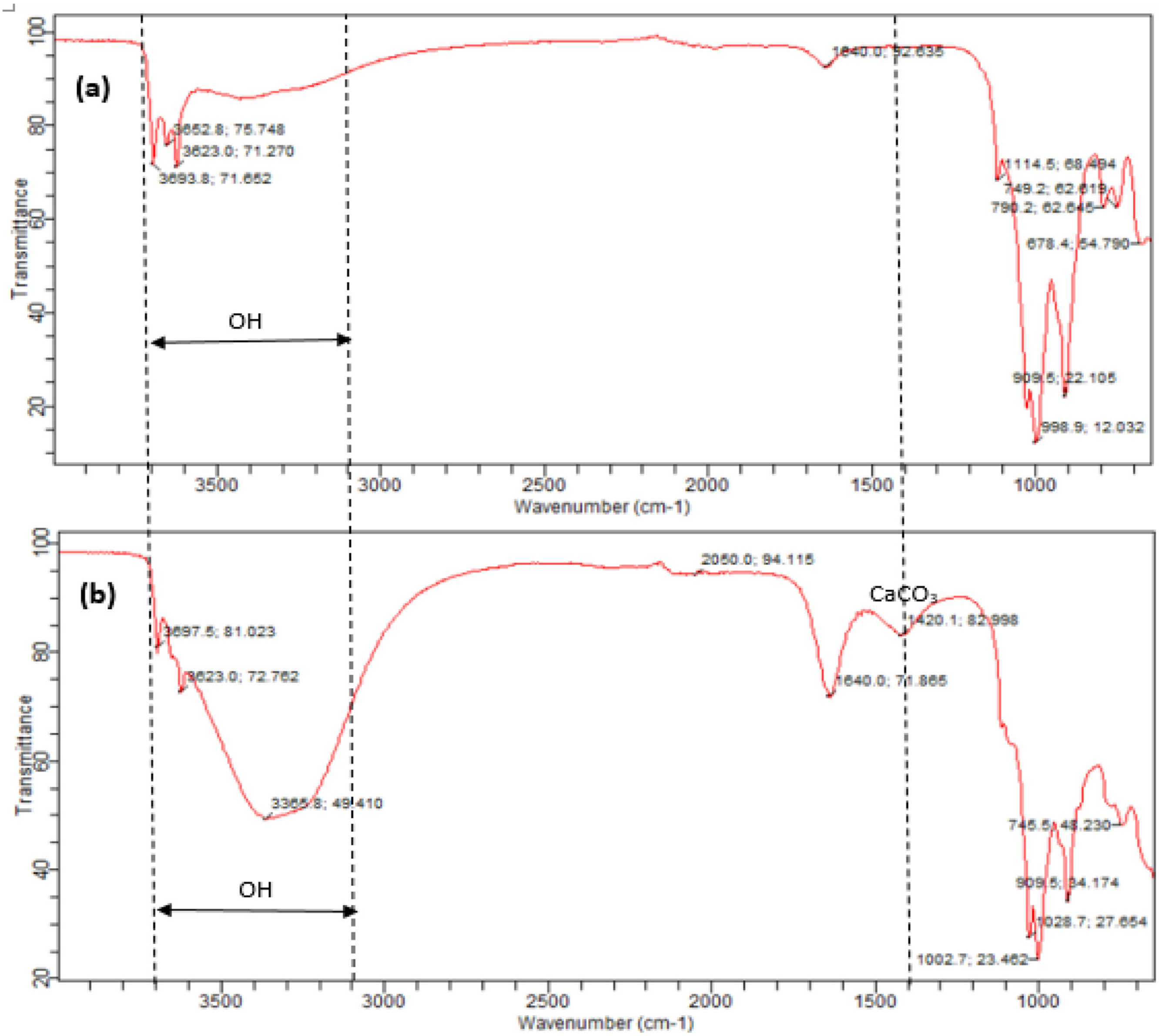

Fig. 19. FTIR of (a) unaltered soil and (b) 6% cement/8% quarry optimally treated specimen.

alogical compounds. This could as well give the verdict of strength enhancement of the treated soil materials.

4.3. Fibre histogram assessment

The variation of histograms viewed via scanning electron microscopy of the natural soil and soil-CQD mixtures are presented in Figs. 17 and 18. For the natural soil, the fibre height was as high as 2.15 µm compared to a low fibre height of 1.60 µm recorded for the CQD ameliorated specimen. The incorporation of CQD blend into the deficient soil material stimulated the reduction in fiber height of soil fabrics. The flocculation exercise with the clay structure due to incorporation of additives might trigger the reduction in fibre height of soil fabrics. Secondly, the alteration in terms particle fractions of the soil mixtures could as well be responsible of the noticed reduction of length of soil fabrics. The results are in conformity with the findings of Etim et al., (2021b) and Osinubi et al., (2015).

4.4. Fourier transformation Infrared

The minerals characterization exercise based on Fourier Transformation Infrared (FTIR) wavelengths of unaltered and CQD altered soil is presented in Fig. 19(a and b). In the case of the soil specimen without CDQ content, the recorded wavelength of 678.4 cm^{-1} depicts a Si-O-Si bending formation whereas 1640 cm^{-1} transmittance wavelength could be interconnected with H-O–H distortion of water in the parent material (Madejova and Komadel 2001). The untreated soil exhibited a wavelength of 3652.8 cm^{-1} which depicts a relatively feeble band and this might be as a result of the traces of clay minerals in the parent soil (Chipera and Bish, 2001).The presence of CQD in the soil material resulted in a significant modification of the functional minerals within the soil structure and is visible via the FTIR band. These wavebands validates the recorded diminishing trend in plasticity properties as well as the increasing trend of strength behavior of the treated soil. For the CQD treated soil mixtures, the much weaker wave bands of 2050, 1640 and 1420 cm^{-1} may perhaps be linked with the build-ups of crystalline. The IR transmittance values of 3697, 3623 and 3365 cm^{-1} are in conformity with the stretching of OH structural hydroxyl groups (Sharma et al., 2017; Etim et al., 2021a; 2021b; 2021c).

4.5. XRD analysis

The XRD of the unaltered soil is presented in Fig. 20. The unaltered soil shows precise reflections at 2theta values that varies with several peak intensity of the XRD pattern for kaolinite clay mixed with layers of vermiculite, goethite and quartz. Typical of some of the peak obtained are that of 12.4° and 25.1° (conforming to the d-spacing value of 7.15A, which matches the basal reflections from [001]). This indicate that the natural soil is predominantly a characteristics kaolinite mineral. Also varying peaks that indicate basal and prism were observed at varying 2theta degree.

The XRD of treated specimen (soil + 6%cement/8%quarry dust) cured 28 days is shown in Fig. 21. The intesnsities varies due to the influence of quarry dust and cement on the soil. The $2\theta = 32.3^{\circ}$ (Latifi et al., 2016a; 2016b; Kim et al., 2007; Etim et al., 2021a; 2021b; 2021c) and $2\theta = 34.4$ and 47.8° (Latifi et al., 2016a; 2016b; Etim et al., 2021a; 2021b; 2021c; JCPDS, 1995; Wu et al., 2016; Yi et al., 2015) are as a result of calcium slicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-S-H), respectively. Li et al., 2020 and Richardson (2014) reported that the structural C-A-S-H and C-S-H are model structures for the binding phase of specimen (concrete or soil), which eventually account for the high mechanical strength earlier reported from experimental obervations.

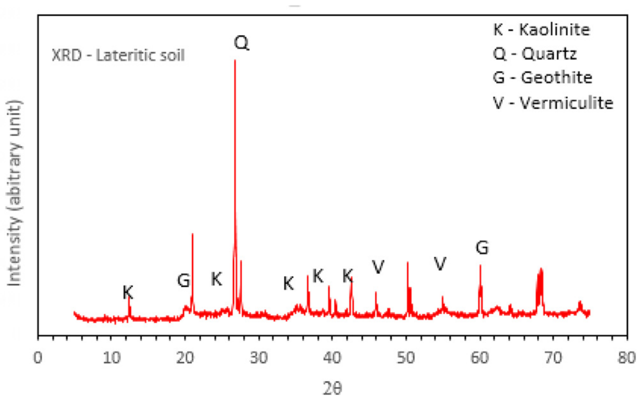

Fig. 20. XRD of the natural soil.

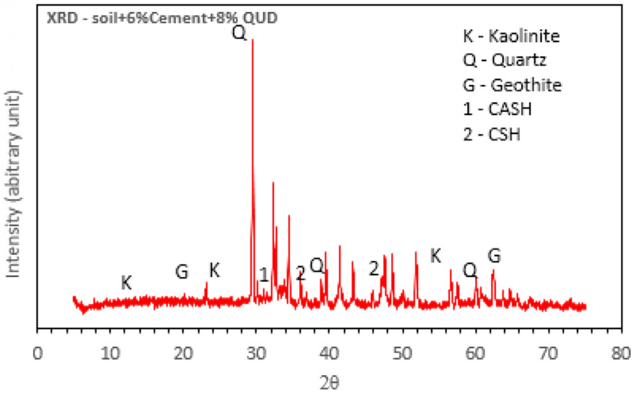

Fig. 21. XRD of treated soil.

5. Conclusion

The lateritic soil used in this study was classified as A-7–6 (8) or CL soil in the AASHTO and USCS classification systems, respectively. Transportation Research Board and Nigerian General Specification both provided criteria for use as subgrade material. With a corresponding increase in bearing capacity (CBR_U and CBR_S) and UCS (7, 14, and 28 days) for all compaction energies considered, the soil's plasticity index values were increased by addition of CQD admixtures to meet the 12 % requirement in the Nigeria General Specifications for subbase materials. The maximum strength of UCS at 7 days of curing was 1820.67, 2230.76 and 2554.96 kN/m^2 for BSL, WAS, and BSH, respectively; after 14 days the UCS was 2542.63, 2875.84, and 2983.24 kN/m^2 for BSL, WAS, and BSH, respectively and while after 28 days curing period the UCS for the three compactive efforts, was 2754.78, 3050.64 and 3247.11 kN/m^2, respectively. For CBR_U, CBR_S, and UCS values for all curing periods at different compaction energies, the maximum strength was reached at 6% cement/8% quarry dust; the resistance to strength loss was greater than 80%. On this basis, lateritic soil treated with 6% cement/8% quarry dust fulfilled the strength requirements of the Transportation Research Board and Nigerian General Specification for use as a pavement material. The combination of this optimal mixture of additives, which is a cheaper alternative compared to using cement only, could be used in stabilization protocol of a soil which has the same geotechnical properties as the one under consideration so as to render them suitable for use as a subgrade pavement material. The CSH and CASH structural assemblages obtained from microstructural studies of soil-CQD specimen are binding effect from hydration mechanism which paves way for the field application of quarry dust in cement amelioration protocol for pavement industry.

CRediT authorship contribution statement

Roland Kufre Etim: Conceptualization. **David Ufot Ekpo:** Conceptualization. **Imoh Christopher Attah:** Conceptualization. **Kennedy Chibuzor Onyelowe:** Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

All the data sets generated during the findings of this research study are included in the manuscript.

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