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Influence of Compaction Delay on the CBR and Compaction Behaviour of Cement-treated Lateritic Gravels

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ABSTRACT

The effect of cement content, compaction energy and compaction delay on cement-treated lateritic gravels from north-eastern Nigeria was investigated in this study. The natural and cement-treated soils were subjected to classification, compaction and California Bearing Ratio (CBR) tests according to British standards. To investigate the effect of cement content, cement was added in the range of 2-10% by dry weight of the soil, while compaction was delayed by 1 hour, 3 hours and 5 hours, respectively. The results showed that the maximum dry unit weight (MDUW) increased with cement content and delay in compaction time. At low cement content and for all compaction energies, the highest values of MDUW were observed at 3 hours delay time, while the MDUW dropped at 5 hours delay time. However, no significant trend was observed on the effect of cement content, compaction energy, and compaction delay on the optimum moisture content (OMC). The CBR value of the soil was observed to reduce with cement content and delay in compaction time. This behaviour was attributed to the high coarse fraction of the lateritic gravel.

KEYWORDS: Lateritic gravel, Compaction, CBR, Compaction delay, Cement stabilization, Compaction energy.

INTRODUCTION

Soil stabilization is the process of improving or maintaining the geotechnical properties of natural soils using chemical or physical means. In tropical or sub-tropical regions of the world, lateritic materials are very abundant and are widely utilized in road, airfield, embankment, dam and foundation construction (Netterberg, 2014; Hagos, 2017; Komolafe and Osinubi, 2019; Osinubi and Nwaiwu, 2006). Laterite is produced by the weathering of rocks in a humid tropical region where there is high temperature and distinct wet and dry seasons. This weathering process results in a parent material that is chemically enriched with aluminium and iron oxides with predominantly kaolinitic materials and reduced silica content due to leaching (Netterberg, 2014; Tuncer, 1976). The processes described above usually produce red, brown, yellow or purple materials, with red being the predominant colour.

There is no universally accepted definition of the word laterite (Netterberg, 2014; Tuncer, 1976). Vallerga et al. (1969; in Gidigasu, 1976), however, pointed out that the most important consideration for engineering purposes is "*not what its name is, but what its significant geotechnical characteristics and engineering behaviour are*". Gidigasu (1976) defined laterite as "*all the reddish residual and non-residual tropically weathered soils, which genetically form a chain of materials ranging from decomposed rock through clays to sesquioxide-rich crusts*".

Different researchers have proposed different methods for the classification of laterites. According to Blight (1997), the aim of this system of classification is to divide residual soils into common groups of similar formation and/or composition with expected similar engineering properties. Charman (1988) used the degree of concretionary development to classify lateritic materials. This classification model was based on the

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physical variation of laterites from soil to rock-like material, as shown in Table 1. Lateritic gravels based on Charman's classification are nodular laterites with distinct hard nodules present as separate materials. According to Krinitzsky et al. (1976), lateritic gravels are identified to be poorly sorted, strongly fine-skewed, leptokurtic and on average, contain approximately 12 percent fines. They are formed by the hydrolytic destruction of primary silicate minerals in warm, tropical to sub-tropical weathering environments which exhibit distinct wet and dry seasons and are generally free-draining (Krinitzsky et al., 1976). Lyon and Associates Inc. (1971) described lateritic gravels as having particle sizes between 2 mm and 60 mm.

Table 1. **Charman's recommended classification system for laterites (Charman, 1988)**

Age	Recommended Name	Characteristics	Equivalent terms in literature
Immature (young)	Plinthite	Soil fabric containing a significant amount of laterite material. Hydrated oxides present at the expense of some soil material. Unhardened, no nodules present, but may be a slight evidence of nodular development.	Plinthite, laterite, lateritic clay
	Nodular Laterite	Distinct hard nodules present as separate particles.	Laterite gravel, ironstone gravel, pisolitic gravel, concretionary gravel
	Honeycomb Laterite	Nodules have coalesced to form a porous structure which may be filled with soil material.	Vesicular laterite, pisolitic iron-stone, vermicular ironstone, cellular ironstone, spaced pisolitic laterite
Mature (old)	Hardpan Laterite Boulder	Indurated laterite layer, massive and tough.	Ferricrete, ironstone, laterite crust, vermiform laterite, packed pisolitic laterite
	Boulder Laterite	May be honeycomb or hardpan, but is the result of weathering of a pre-existing layer and may display brecciated appearance.	

In a research work carried out in southern Cameroon, Zame et al. (2017) reported that the 50 samples of lateritic gravels studied fell into AASHTO classification A-2-7, which can be described as silty/ clayey gravel or sand. Another study in Uganda by Bhatta (2010) classified 89 out of the 90 samples studied as A-2-7 with just one sample classified as A-2-6. According to Bhatta (2010), the most remarkable characteristic of the lateritic gravels is that they are all gap-graded, with the pisoliths ranging between 6 mm and 20 mm in size embedded in a matrix of fine-textured red soil.

Lateritic gravel studied in eastern Cameroon by Onana et al. (2015) were found to contain kaolinite (34 wt.%), hematite (24 wt.%), goethite (13 wt.%), quartz (11 wt.%), gibbsite (10 wt.%) and anatase (wt.%) without swelling clay minerals such as smectites. In south-western Nigeria, Alao (1983) studied three varieties of laterites (clay, gravel and crust) and reported that they are composed of kaolinite and illite clay minerals with some quartz and feldspar rich in SiO_2 (45%), Fe_2O_3 (16%) and Al_20_3 (10%).

The assumption of bulk relative density (BRD) for soils can be very misleading for nodular laterites due to the differences in the physical properties of their fines and coarse contents. It has been identified that the specific gravity of the iron-rich coarse fraction of nodular laterites is between 3.0 and 3.5 and sometimes it can be very much higher. The fines fraction of nodular laterites is usually made up of kaolinite clay minerals with smaller values of specific gravity of about 2.7 (Netterberg, 2014).

The application of the conventional particle size distribution curve to nodular laterites will not be representative of the actual packing and mechanical stability of the entire material. This is due to the differences or variations in the bulk relative density. A typical particle size distribution curve represents the percentage of the particles of constant bulk relative density retained on successive sieve sizes. The application of this technique to nodular laterites will exaggerate any gap grading in the material and underestimate the volume content of the coarser particles in the material.

It is important, therefore, that when carrying out particle size distribution analysis of nodular laterites, the material and its composition should be inspected and a decision taken on whether to determine the BRD of the fine and coarse fractions separately. It is important that the grading of particle sizes be assessed using volume and mass proportions when the specific gravities of the fine and coarse fractions are significantly different. When nodular laterites are graded by mass, they tend to appear to be poorly graded, showing a deficiency of sand fraction and a high value of fines (Netterberg, 2014; Qian et al., 2015). However, an improvement may be observed if the mass gradings are corrected to a volumetric basis (which is what really matters).

In their natural states, laterites may or may not meet the requirements as road pavement materials (Joel and Edeh, 2014; Odumade and Ezeah, 2019). In a situation where laterites do not meet the minimum requirements, they may be improved through stabilization using chemicals, such as lime, cement and industrial wastes, such as fly ash, quarry dust, ground granulated blast furnace slag, … etc. Other materials, such as cement kiln dust, unground cement clinker, sand and cement have also been used to improve the geotechnical properties of weak soils such as black cotton soils (Devendra and Kumar, 2020; Nwaiwu et al., 2022). Crushed concrete has also been suggested as an alternative sustainable stabilizer for improving soft clay soils (Karkush and Yassin, 2020).

Cement is the most attractive material for chemical stabilization due to its wide availability and early strength gain when compared with other chemicals (Pasupuleti et al., 2015; Naveena et al., 2013; Athanasopoulou, 2016). Different researchers have also identified cement as the most widely used material for soil stabilization in the world (Arshad et al., 2018; Sitaram and Purushotham, 2012; Saaldedin and Siddiqua, 2013).

Odumade and Ezeah (2019) stabilized A-5(4) and A-5(12) lateritic soils with 2-14% Limestone Portland Cement and reported that the maximum dry unit weight, CBR and unconfined compression strength increased with cement content, while the optimum moisture content reduced with cement content. Bhatta (2010) reported an increase in CBR and unconfined compression strength (UCS) when lateritic gravels are stabilized with 2-4% cement. In another study by Prasad and Reddy (2012), the maximum dry density and optimum moisture content of cement-stabilized clayey gravel increased slightly with cement content, while the CBR increased linearly with cement content too.

Millogo et al. (2008) studied the microstructure and strength characteristic of cement-gravely laterite mixtures and reported that the addition of cement resulted in the formation of 1.4 nm-tobermorite, ettringite, iron oxyhydroxide, portlandite and calcite. The formation of tobermorite led to a noticeable reduction of particle segregation and improved mechanical strength.

Standard construction methodology requires that stabilized soils be compacted immediately after mixing on site. However, unforeseen circumstances, such as breakdown of machinery, injury to workers, bad weather or other forms of disruption, can lead to delay in compaction after mixing on site. Research works have shown that delay in compaction can negatively affect the strength properties of stabilized soils (Osinubi, 1998; Osinubi and Nwaiwu, 2006; Okonkwo, 2009; Bello, 2011; Mujedu et al., 2016; Osuolale et al., 2017; Nazari et al., 2021).

Reviewing literature surveyed shows a little consideration of the strength behaviour of cement-stabilized lateritic gravel. Furthermore, the influence of compaction delay on the strength behaviour of cement-stabilized lateritic gravel has not been investigated. The aim of this study is to investigate the effect of compaction delay on the compaction and CBR properties of cement-stabilized lateritic gravels from north-eastern Nigeria.

MATERIALS AND METHODS

Lateritic gravel was collected from a borrow pit along Damagum road, Potiskum, Yobe State in north-eastern Nigeria using an open digging method at a depth of 1.5m - 2m from the existing surface. The samples were obtained in a disturbed state. According to Du-Preez and Barber (1965), lateritic gravels in the location are of an extensive lateritic capped erosion surface which predated the Chad Formation in north-eastern Nigeria. The laterite surface was reported to be Pliocene in age. Geographically, the geology of the study area could be related to two major formations which are the Kerri-Kerri Formation (older of the laterite caps) and a younger one that postdates the Chad Formation. According to Abubakar et al. (2019), the palaeocurrent analysis of the Kerri–Kerri Formation suggested southwestern direction, which indicates that the sediments were sourced from the north-eastern direction.

Limestone Portland Cement (Grade 32.5R) was used in the study for stabilization of the gravely laterite and was purchased from the local market. The cement conforms to the specifications of cement CEM II according to EN 197-1 standard.

The soil samples were prepared in accordance with the specifications of BS 1377-1:1990. Subsequently, the natural soils were subjected to index properties tests, such as specific gravity, sieve analysis, natural moisture content tests, Atterberg limits and linear shrinkage according to the specifications of BS 1377-1:1990 for the purpose of classification. Physico-chemical tests (soil pH and electrical conductivity) were carried out according to BS 1377-3:1990. The soil sample was also subjected to compaction tests using British Standard Light (BSL), British Standard Heavy (BSH) and West African Standard (WAS) compaction efforts. The procedures for BSL and BSH compaction are described in BS 1377-4:1990, while the procedure for West African Standard compaction effort is described in Nwaiwu and Osinubi (2006). CBR tests were done in accordance with BS 1377-9:1990. Cement was added in the range of 2-10% by weight of the dry soil and the effect on the strength properties was observed. Furthermore, the compaction was delayed after mixing for 1, 3 and 5 hours in order to study the effect of compaction delay.

RESULTS AND DISCUSSION

Natural Soils

The properties of the natural soil are shown in Table 2. A plasticity index of 5.8% and liquid limit of less than 35% show that the natural soil meets the requirements for base and sub-base materials according to the specifications of the Federal Ministry of Works for Highway Construction in Nigeria (Nigerian General Specification, 1997). A free swell value of 35% however suggested that the fines content of the lateritic gravel can undergo a moderate to a high degree of expansiveness (Murthy, 2012). This can inspire the need for treatment with cement. At BSH compaction energy, the unsoaked CBR value of the natural soil was 84%, while at BSL compaction energy, the unsoaked CBR value was 74%.

Table 2. Properties of the natural soil

Property	Value
Fines content	19.42%
Sand content	18.08%
Gravel content	62.5%
Liquid limit (L_L)	24.70%
Plastic limit (P_L)	18.9%
Plasticity index (P_I)	5.8%
Linear shrinkage (L_S)	5.02%
Natural moisture content (M_c)	1.69%
Specific gravity (G_s)	2.77
Electrical conductivity	0.06
pH	5.73
Free swell	35%
Maximum dry unit weight (BSH)	20.59 kN/m^3
Maximum dry unit weight (WAS)	20.4 kN/m^3
Maximum dry unit weight (BSL)	20.1 kN/m^3
Optimum moisture content (BSH)	9.6 %
Optimum moisture content (WAS)	8.0 %
Optimum moisture content (BSL)	9.8 %
CBR (BSH)	84 %
CBR (BSL)	74%
Classification	A-2-4

Compaction Characteristics

When cement was added to the natural soil in the range of 2-10%, the maximum dry unit weight (MDUW) increased with cement content for all the compactive efforts studied. This is consistent with previous studies on the effect of cement on the maximum dry density of lateritic soils (Prasad and Reddy, 2012; Ogundipe and Adekanmi, 2019).

The highest value of MDUW was observed at 10% cement content using BSH compaction energy, where the value increased from 20.59 kN/m³ to 22.8 kN/m³. The variation of maximum dry unit weight with cement content without any delay in compaction is shown in Figure 1.

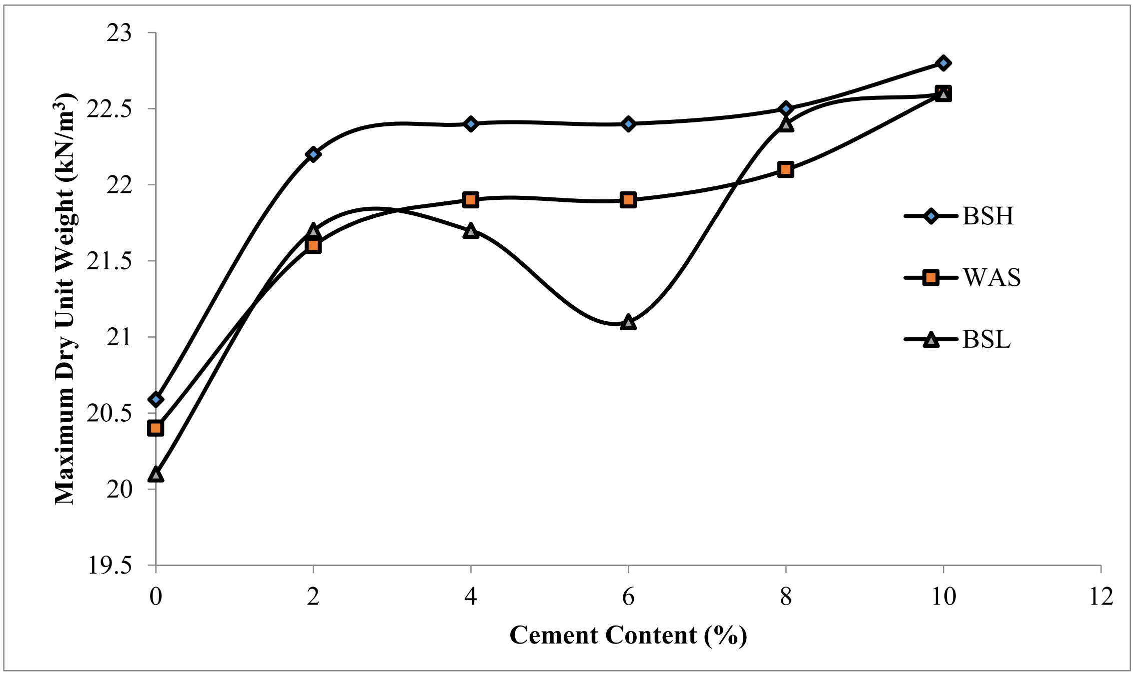

Figure (1): Variation of maximum dry unit weight with cement content for all the compactive energies

However, the variation of optimum moisture content with cement content showed an erratic trend across the different compaction energies, as shown in Figure 2.

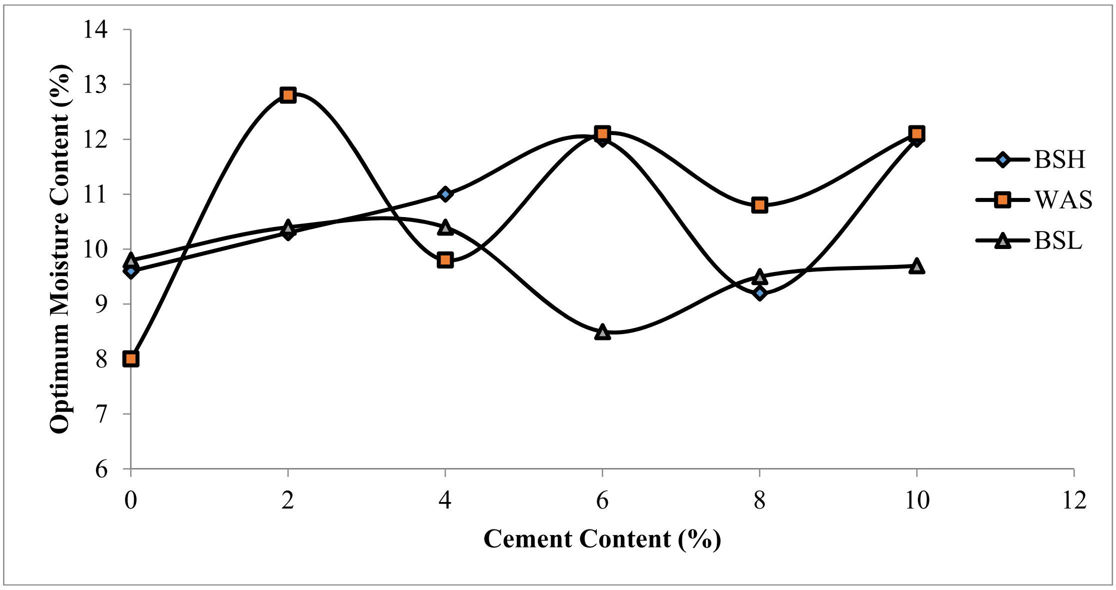

Figure (2): Variation of optimum moisture content with cement content for all the compactive energies

The relationship between the maximum dry unit weight (*MDUW*) in kN/m^3, log of compactive effort (*LogE*) in kNm/m^3 and cement content (C_E) in percentage can be described using the relationship in Equation (1);

$$MDUW = 0.183C_E + 0.85LogE + 18.803 \quad (Adj\ R^2 = 0.693) \qquad (1)$$

Cement content and compactive effort were found to be statistically significant to the maximum dry unit weight obtained at 95% confidence level.

CBR Characteristics

For the two compactive efforts (BSL and BSH) studied, the CBR reduced with cement content, as shown in Figure 3. For BSH compactive energy, the CBR value reduced from 84% to 64% when the cement content was increased to 10%, while for BSL compactive effort, the CBR reduced from 74% to 52%. This is inconsistent with previous studies on the effect of cement on the CBR of lateritic soils (Bhatta, 2010; Rashid *et al*., 2013; Prasad and Reddy, 2012; Ogundipe and Adekanmi, 2019).

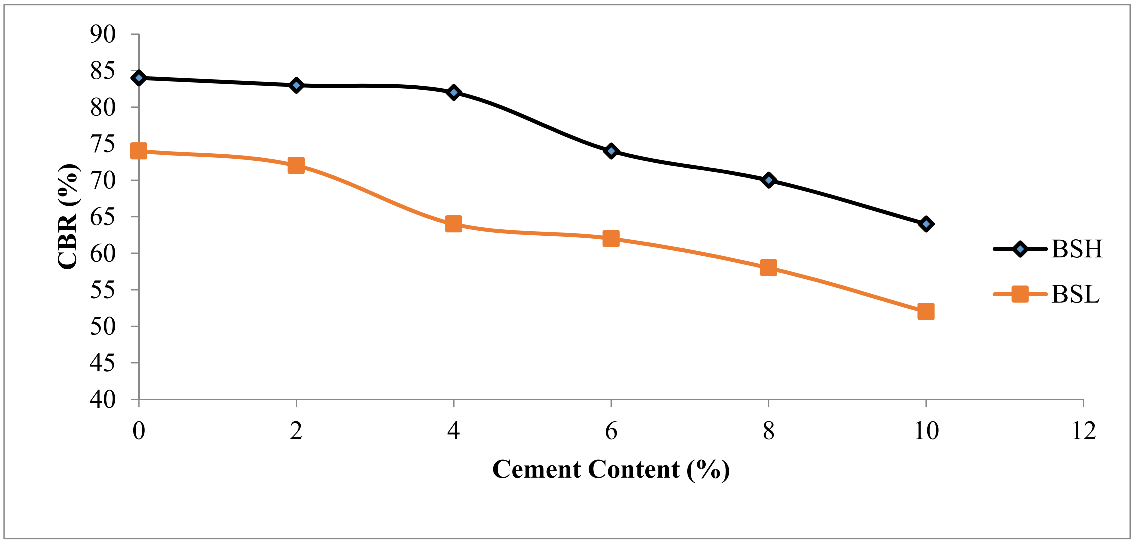

Figure (3): Variation of CBR with cement content for all the compactive energies

The relationship between the CBR in percentage, log of compactive effort (*LogE*) in kNm/m^3 and cement content (C_E) in percentage can be described using the relationship in Equation (2);

$$CBR = -2.15C_E + 19.125LogE + 21.211 \quad (Adj\ R^2 = 0.965) \qquad (2)$$

Effect of Compaction Delay on Compaction Characteristics

From the study, the maximum dry unit weight (MDUW) of the cement-treated lateritic gravel was observed to increase with delay in compaction time for all the compactive efforts. This was found to be inconsistent with previous studies on the compaction delay of cement-stabilized lateritic soils (Okonkwo, 2009; Bello, 2011; Prasad and Reddy, 2012; Mujedu et al., 2016). For BSH compactive effort, the highest value of MDUW was observed at 10% cement content at 5-hour delay. However, at low cement content (2 - 6%), 3-hour delay gave the highest value of MDUW, as shown in Figure 4.

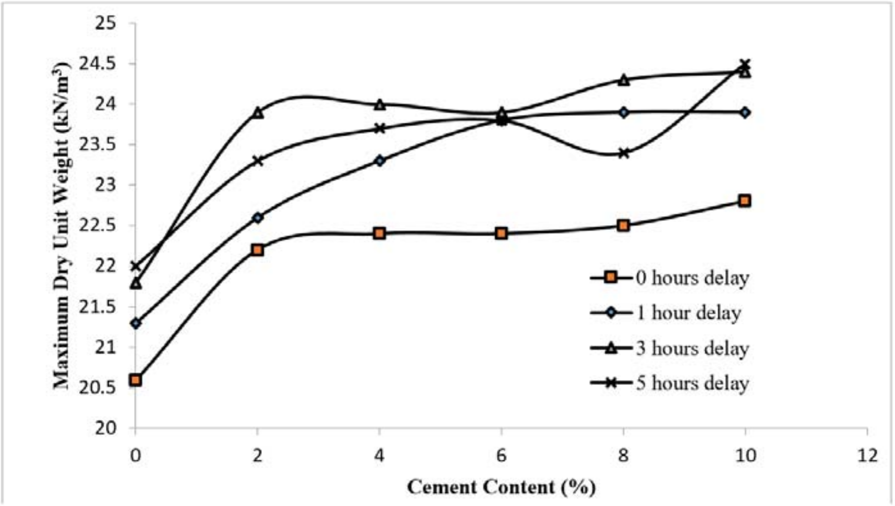

Figure (4): Effect of compaction delay on maximum dry unit weight of cement-stabilized lateritic gravel at BSH compaction effort

At WAS compaction energy, the highest value of MDUW was observed at 3-hour delay for high and low cement contents, as shown in Figure 5. The same behaviour was observed in BSL compaction energy, as shown in Figure 6. No significant trend was observed for the effect of compaction delay on optimum moisture content.

Some researchers have pointed out the effect of pre-treatment on the strength characteristics of lateritic gravels. For instance, the method of preparation and testing, such as oven drying, sun-drying, re-use of compacted samples and compaction energy, can affect the strength properties of compacted lateritic gravels (Netterberg, 2014). During compaction, the particle size distribution of nodular laterites is observed to be considerably altered, which can affect the behaviour of the samples at different stages.

Due to the high gravel content of the soil (62.5%), delay in compaction favoured strength gain in terms of the maximum dry unit weight. At the onset of hydration and initial setting on the addition of cement, the matrix will not have enough sand and fines content to bind the coarse fraction together. With a delay in compaction, the cement mortar gains strength and cohesion which on subsequent compaction densifies the soil better.

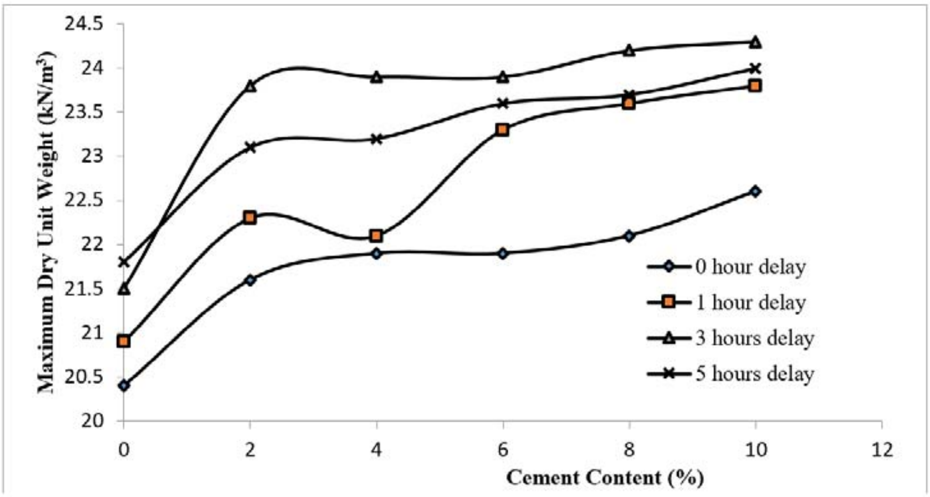

Figure (5): Effect of compaction delay on maximum dry unit weight of cement-stabilized lateritic gravel at WAS compaction effort

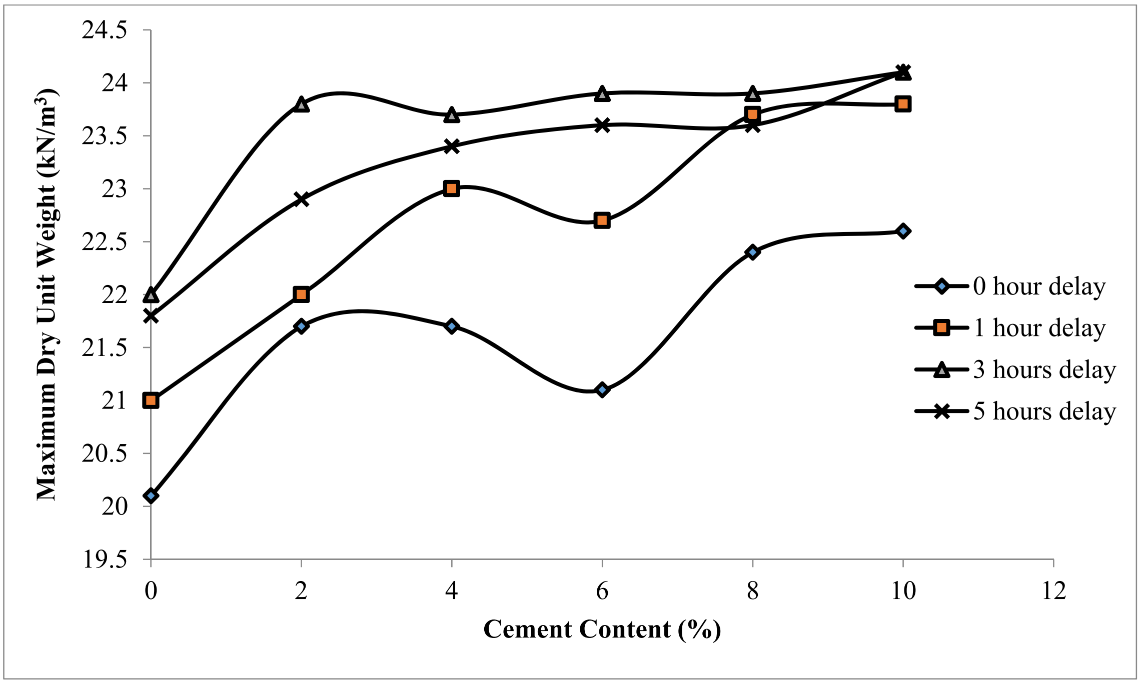

Figure (6): Effect of compaction delay on maximum dry unit weight of cement-stabilized lateritic gravel at BSL compaction effort

The relationship between the maximum dry unit weight *MDUW* (kN/m^3), log of compaction energy *LogE* (kNm/m^3), cement content C_E (%) and delay in compaction time T_C (hours) is given in Equation (3);

$$MDUW = 0.211C_E + 0.608LogE + 0.291T_C + 19.311 \quad (Adjusted\ R^2 = 0.699) \qquad (3)$$

Table 3. ANOVA table for MDUW and compaction delay time

	Compaction Delay (hours)		DOF	Calculated F-value	p-value	Critical F-value
Maximum dry unit weight	0 hour	Cement Content	5	31.4267	8.33E-06	3.325835
		Compaction Energy	2	8.05227	0.008249	4.102821
Maximum dry unit weight	1 hour	Cement Content	5	36.29851	4.26E-06	3.325835
		Compaction Energy	2	4.552239	0.039294	4.102821
Maximum dry unit weight	3 hours	Cement Content	5	108.0233	2.28E-08	3.325835
		Compaction Energy	2	1.55814	0.257601	4.102821
Maximum dry unit weight	5 hours	Cement Content	5	72.48498	1.58E-07	3.325835
		Compaction Energy	2	3.626609	0.065411	4.102821

Table 4. ANOVA table for OMC and compaction delay time

	Compaction Delay (hours)		DOF	Calculated F-Value	p-value	Critical F-value
Optimum moisture content	0 hour	Cement Content	5	1.364596	0.315226	3.325835
		Compaction Energy	2	1.623462	0.245146	4.102821
Optimum moisture content	1 hour	Cement Content	5	0.976822	0.476737	3.325835
		Compaction Energy	2	0.333842	0.723851	4.102821
Optimum moisture content	3 hours	Cement Content	5	2.276453	0.125657	3.325835
		Compaction Energy	2	0.598934	0.567967	4.102821
Optimum moisture content	5 hours	Cement Content	5	0.582481	0.71359	3.325835
		Compaction Energy	2	6.107195	0.018485	4.102821

From Table 3, it can be seen that at 0-hour and 1-hour compaction delay time, the cement content and compaction energy were statistically significant on the MDUW of the soil at a 95% confidence level. However, at higher delay times, the effects of compaction energy were observed not to be statistically significant on the MDUW. However, the effects of cement content and compaction energy were found not to be statistically significant on the optimum moisture except for compaction energy at 5-hour delay time, as shown in Table 4.

Effect of Compaction Delay on CBR

Across all the compactive efforts employed in the study (BSL and BSH), the CBR value of the soil was observed to reduce with cement content and delay in compaction. At BSH compaction energy, the lowest CBR value was observed at 10% cement content and 3-hour delay in compaction, where the CBR reduced from 84% to 24%, as shown in Figure 7. The same trend was observed for BSL compaction energy, where the CBR reduced from 74% to 17%, as shown in Figure 8.

The reduction in CBR with compaction delay is consistent with previous studies, while the reduction in CBR with cement content is not (Okonkwo, 2009; Bello, 2011; Mujedu *et al.*, 2016). This same behaviour has been attributed to very slow setting time and unusual reaction of the cement with the clay minerals present in the clay.

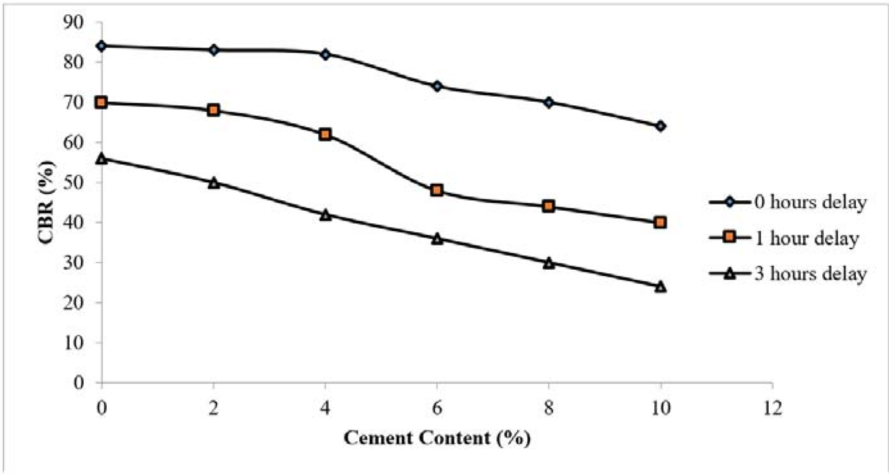

Figure (7): Effect of compaction delay on CBR of cement-stabilized lateritic gravel at BSH compaction effort

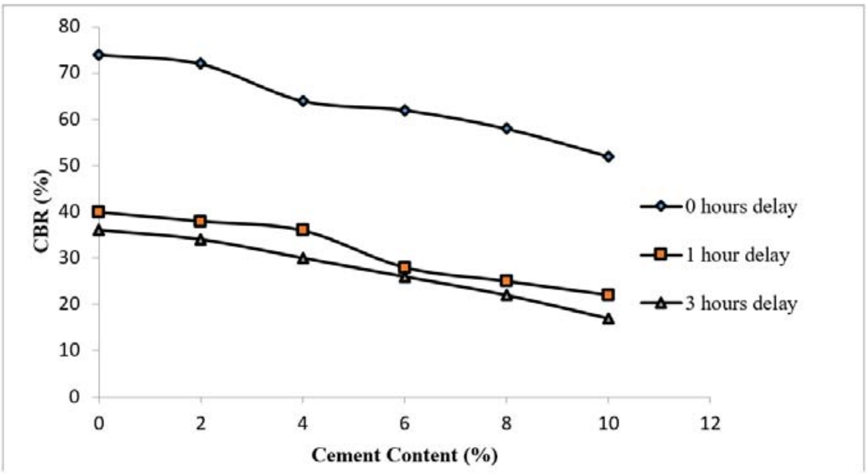

Figure (8): Effect of compaction delay on CBR of cement-stabilized lateritic gravel at BSL compaction effort

The relationship between the CBR (%), log of compaction energy $LogE$ (kNm/m^3), cement content C_E (%) and delay in compaction time T_C (hours) is given in Equation (4);

$$CBR = -2.464C_E + 24.734LogE - 11.083T_C - 0.824 \quad (Adjusted\ R^2 = 0.834) \tag{4}$$

Table 5. ANOVA table for MDUW and compaction delay time

	Compaction Delay (hours)		DOF	Calculated F-value	p-value	Critical F-value
CBR	0 hour	Cement Content	5	33.43882	0.000756	5.050329
		Compaction Energy	1	118.6709	0.000113	6.607891
CBR	1 hour	Cement Content	5	13.61505	0.006172	5.050329
		Compaction Energy	1	111.4995	0.000132	6.607891
CBR	3 hours	Cement Content	5	14.93858	0.005001	5.050329
		Compaction Energy	1	35.5741	0.001896	6.607891

From Table 5, it can be seen that at all compaction delay times, the cement content and compaction energy were statistically significant on the CBR of the soil at a 95% confidence level.

CONCLUSIONS

From the study conducted on the effect of compaction delay on the CBR and compaction characteristics of cement-treated lateritic gravels, the following conclusions were reached:

(1) In their natural states, the studied lateritic gravels satisfied the requirements of sub-base and base materials according to the Nigerian Highway Specifications (1997).

(2) When treated with cement and compacted using different compaction energies (BSL, WAS and BSH), the maximum dry unit weight of the lateritic gravel increased with cement content and with delay in compaction time across all the compaction energies.

(3) When treated with cement and compacted using BSL and BSH compaction energies, the CBR values reduced with cement content and delay in compaction time.

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