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Original Research Article

Compaction and CBR Properties of Cement Stabilised Clay-Quarry Dust Mixtures

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Abstract

This paper presents the findings of a study on the compaction and CBR characteristics of cement stabilized clay-quarry dust mixtures, utilising the BS Light compaction energy. The study encompasses laboratory experiments, statistical analysis, and the development of empirical models to describe the geotechnical behaviour of these mixtures. Various proportions of quarry dust (0-50%) and cement (0-10%) were studied. The soil mixtures were subjected to classification tests, compaction tests, and soaked CBR tests. The results of the study showed that the addition of quarry dust and cement to the soil can significantly improve its Atterberg limits, compaction characteristics, and CBR. The addition of 50% quarry dust and 10% cement reduced the liquid limit by about 41.8% and the plasticity index by about 42%. The maximum dry unit weight increased with cement and quarry dust content, while the optimum moisture content reduced with the same. The CBR of the natural soil increased from 6.3% to 130% at 50% quarry dust and 10% cement content. The empirical models developed in this study can be used to predict the compaction characteristics and CBR of cement stabilized soil-quarry dust mixtures.

Keywords: California Bearing Ratio (CBR), cement stabilisation, compaction characteristics, quarry dust, sustainable construction.

INTRODUCTION

The process of maintaining or improving the geotechnical properties of naturally occurring soils using either physical or chemical techniques is known as soil stabilization. Stabilisation of soils aims to improve the geotechnical properties such as the dry unit weight, shear strength, CBR, unconfined compressive strength, compressibility, and other engineering properties. The overall aim is to improve the performance of in-situ sub-soils, foundations, highway pavements, embankments, slopes, etc. (Obianigwe and Ngene, 2018; Balkis and Macid, 2019). The efficient utilization of available resources and the pursuit of sustainable construction practices are critical considerations in the field of geotechnical engineering. Soil stabilization techniques play a crucial role in improving the engineering properties of soils, particularly in the construction of highways, embankments, and foundations. Cement stabilization has been widely employed as an effective method to enhance the strength and durability of marginal soils. However, the demand for cement as a stabilizing agent poses environmental concerns due to its high energy consumption and carbon emissions associated with its production (Kurda *et al.*, 2018; Paris *et al.*, 2016).

To address these concerns, researchers have explored alternative materials and additives that can reduce the cement content while maintaining or improving the engineering properties of stabilized soils. One such material is quarry dust, a byproduct generated during the crushing process of rocks in quarrying operations (Panchal *et al.*, 2019). Quarry dust is typically considered a waste material and is often stockpiled, causing environmental and land use issues. Incorporating quarry dust in soil stabilization provides an opportunity to address these environmental concerns while potentially improving the geotechnical properties of the stabilized soil. Quarry dusts are primarily made up of an excessive amount of fines that were generated as a byproduct of crushing, washing, and screening processes carried out at quarries. Their properties could vary depending on the source, but on the whole, they appear to be very stable in any particular location they are stockpiled. During the pulverizing process, enormous quantities of waste are produced, which, if not properly disposed of, could be harmful to the surrounding environment. It is common knowledge that they are a nuisance because they create "mole hills" that take up a wide breadth and immediate space within the quarry site. This creates a potentially hazardous working environment for quarry miners. Large amounts of resources are typically used in the process of disposing of and managing quarry dust wastes. This is done to both satisfy environmental standards and ensure that there is sufficient room for quarry activities to take place within the location.

Quarry dust as a granular material exhibits high shear strength, and this makes it beneficial for geotechnical applications (Soosan *et al.,* 2005). It also possesses high permeability, which means variation in moisture content does not significantly affect its behaviour (Soosan *et al.*, 2001a). Quarry dust also contains high aluminosilicate and as a result, it has shown to be useful in recent years as a replacement for cement when coupled with a blend of geopolymer cements (Onyelowe, 2019; Onyelowe *et al.,* 2021). Additionally, it has proven to be effective in a wide variety of geotechnical applications, including as base, sub-base, embankments, and backfill materials. It has ALSO been used as a substitute for sand in order to improve the qualities of lateritic soil (Soosan *et al.*, 2001b; Onyelowe, 2019; Onyelowe *et al.,* 2020; Onyelowe *et al.*, 2021). Previous studies (Eze-Uzomaka and Agbo, 2010; Rohini *et al.,* 2018; Arinze *et al.*, 2018) have investigated the geotechnical behavior of cement stabilized soil-quarry dust mixtures, focusing on various aspects such as compaction characteristics, strength development, and load-bearing capacity.

These investigations have provided valuable insights into the potential benefits and limitations of utilizing quarry dust as an additive in cement-stabilized soils. In the study by Rohini *et al.* (2018), the addition of quarry dust to expansive soil decreased the cohesion and increased the angle of internal friction. Eze-Uzomaka and Agbo (2010) carried out research to determine the suitability of quarry dust as improvement to cement stabilised laterites. Test results showed that liquid limit, plastic limit, plasticity index, and maximum dry density improved with increase in quarry dust content, in all the cement dosages used. Arinze *et al.* (2018) carried out investigation on the geotechnical properties of cement stabilised white clay-quarry dust mixtures. For white clays classified under A-7-5, it was observed that optimum mixtures can be obtained for maximum strength. Etim *et al.* (2021) investigated the effects of micro-sized quarry dust and reported an increase in the maximum dry unit weight, unconfined compressive strength, and CBR.

However, there is still a need for comprehensive studies that consider a wide range of cement and quarry dust contents to establish optimized mix proportions and evaluate the long-term performance of these mixtures. This paper aims to contribute to the existing body of knowledge by presenting an extensive investigation into the compaction and CBR characteristics of cement stabilized soil-quarry dust mixtures. The study encompasses laboratory experiments, statistical analysis, and the development of empirical models to describe the geotechnical behaviour of these mixtures. The findings of this research will be useful for the development of sustainable and cost-effective soil stabilization techniques in Civil Engineering applications.

MATERIALS AND METHODS

The non-lateritic soil (grey clays) used in this study was collected from a construction site at Amansea in Awka North Local Government Area of Anambra state (6°14’54” N, 7°8’5” E, 30m above sea level). Quarry dust was purchased in bags from a construction market in Agu Awka, Anambra State, while Portland Limestone Cement (Grade 42.5N) was purchased from local dealers in Awka. The general requirements and sample preparation was done according to the procedure described in BS 1377-1:1990. The in-situ appearance of the clay is shown in Figure 1.

Figure 1: Appearance of Amansea Clay in its natural state

In this study, the selected soil sample was partially replaced by 0%, 10%, 20%, 30%, 40%, and 50% quarry dust. These soil mixtures were then stabilised with 0%, 2%, 4%, 6%, 8%, and 10% Limestone Portland cement (Grade 42.5N). The stabilised soil mixtures were subjected to classification/index properties tests, compaction test using the BSL compaction energy, and soaked CBR test. Mechanical (sieve) analysis was used to obtain the particle-size distributions of the soil samples in accordance with BS 1377-2:1990. The Atterberg limit tests was carried out according to the procedure described in BS 1337-2:1990. BS Light compaction test was carried out according to BS 1377-4:1990. The determination of the California Bearing ratio of a soil is obtained by measuring the relationship between load and penetration when a cylindrical plunger of cross-sectional area 1935 mm^2 is made to penetrate the soil at a given rate. At any value of penetration, the CBR values are normally quoted for 2.50 mm and 5.00 mm penetration or average of both. However, the highest value is usually quoted. The CBR test has been carried out according to the procedure described in ASTM D1883-16 (2016).

RESULTS AND DISCUSSION

The index properties of the untreated clay soil are summarized in Table 1. The soil was classified as A-7-6 (clayey soil) according to the AASHTO classification system (AASHTO, 1986) and as CL (inorganic low plastic clay) using the USCS. As can be seen from Table 1, 54.9% of the sample passed through sieve No 200 (75 μm). The index properties of the natural soil suggests that it is unsuitable for base or sub-base construction in its untreated state, indicating the need of soil stabilization.

Table 1: Properties of the natural soil

Property	Value
Natural moisture content (%)	34.1
Percentage passing BS No 200 sieve (%)	54.9
Liquid Limit LL (%)	43.2
Plastic Limit PL (%)	25.6
Plasticity Index PI (%)	17.6
Specific gravity	2.46
AASHTO classification	A-7-6 (clayey soil)
USCS classification	CL (Inorganic low-plastic clay)
MDUW (BSL) (kN/m^3)	15.89
OMC (BSL) (%)	19.4
CBR (BSL) (%)	6.4
Colour	Grey
Subgrade rating	Poor

Atterberg Limits

The clay soil has a plasticity index of 17.6% and a liquid limit of 43.2%, thereby making it unsuitable for use as a subbase or base material (see Table 1). According to the Nigerian Federal Ministry of Works and Housing (FMWH, 1997) specifications, the liquid limit and plasticity index of earth materials to be used as base or sub-base materials should not have values exceeding 35% and 12% respectively. Figures 2 to 3 show that the Atterberg limit properties of the soil reduced as the quantity of quarry dust and cement increased. This can be attributed to the change in gradation due to the addition of quarry dust. The increase in quarry dust content can lead to a reduction in the proportions of clay in the soil, which can decrease the soil's plasticity. On the hand, the usage of water for the hydration reaction on addition of cement can also reduce the availability of free water in the mix for higher plasticity. The liquid limit, plastic limit, and plasticity index decreased from 43.2% to 31.8%, 25.6% to 18.0%, and 17.6% to 13.8%, respectively, which is more than a 27% reduction for each of the consistency limits taken into consideration, as quarry dust content increased from 0 to 50%. These results are consistent with the findings of some other researchers (Etim et al., 2021; Onyelowe and Okafor, 2013, Eze-Uzomaka and Agbo, 2010).

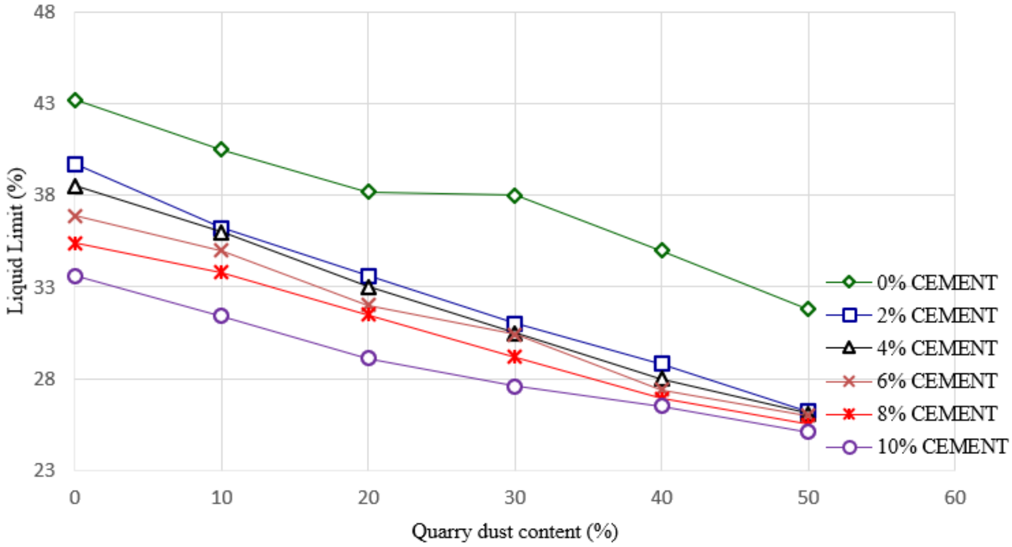

Figure 2: Variation of liquid limit with cement and quarry dust content

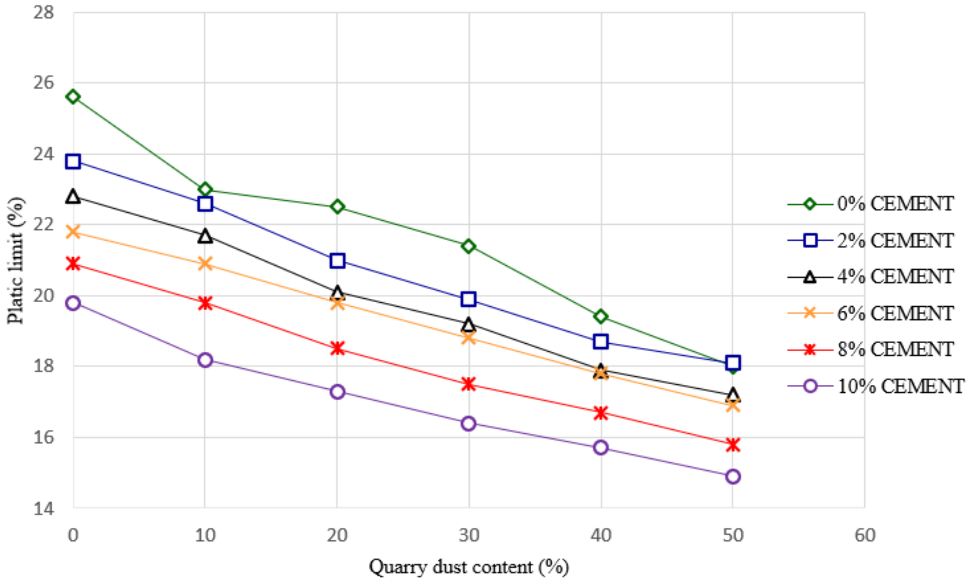

Figure 3: Variation of plastic limit with cement and quarry dust content

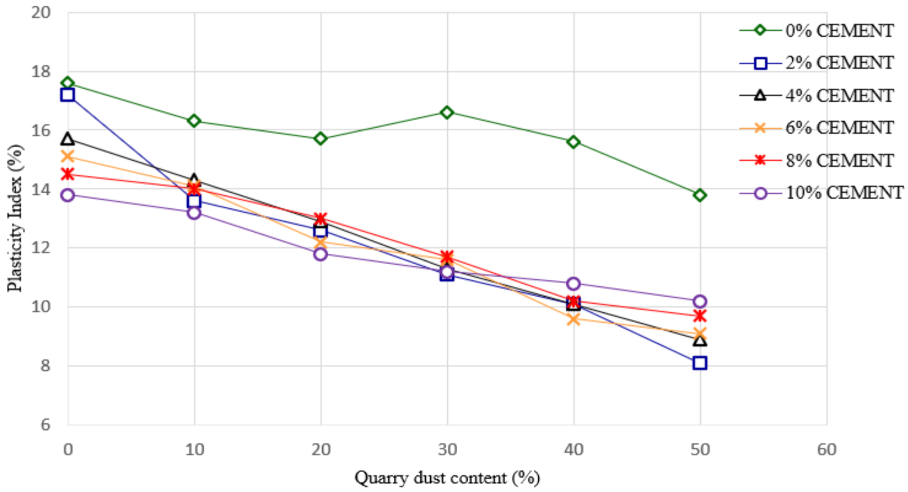

Figure 4: Variation of plasticity index with cement and quarry dust content

The study shows that quarry dust or cement alone was not sufficient to modify the Atterberg limits of the soil such that it meets FMWH specifications. However, the combination of cement and quarry dust improved the consistency limits of the clay soil starting from 30% quarry dust content and 2% cement. At 30% quarry dust content and 2% cement content, the liquid limit was 31% while the plasticity index was 11.1%. The lowest values of LL and PI were observed at 50% quarry dust and 10% cement content with values of 25.1% and 10.2% respectively. The relationships between the Atterberg limits and quarry dust/cement content are given by Equations (1) to (3).

$$LL = -0.740C_c - 0.2221QD + 41.39 \ (R^2 = 0.919;\ Adj.\ R^2 = 0.918) \quad (1)$$
$$PL = -0.442C_c - 0.112QD + 24.4627 \ (R^2 = 0.973;\ Adj.\ R^2 = 0.972) \quad (2)$$
$$PI = -0.293C_c - 0.111QD + 16.938 \ (R^2 = 0.734;\ Adj.\ R^2 = 0.718) \quad (3)$$

From the regression models shown in Equations (1 to 3), the Atterberg limits reduced with increase in cement and quarry dust content. The values of the coefficient of determination R^2 suggested that the equations can be used to predict the Atterberg limits of cement stabilized clay-quarry dust mixtures. The 3D variation of liquid limit with cement and quarry dust content for the clay is shown in Figure 5. The polynomial regression equations relating the consistency limits to the Atterberg limits of the clay soil are presented in Equations (4) to (6). The coefficient of determination (R^2) showed that polynomial regressions made better predictions compared to the multiple linear regression analysis.

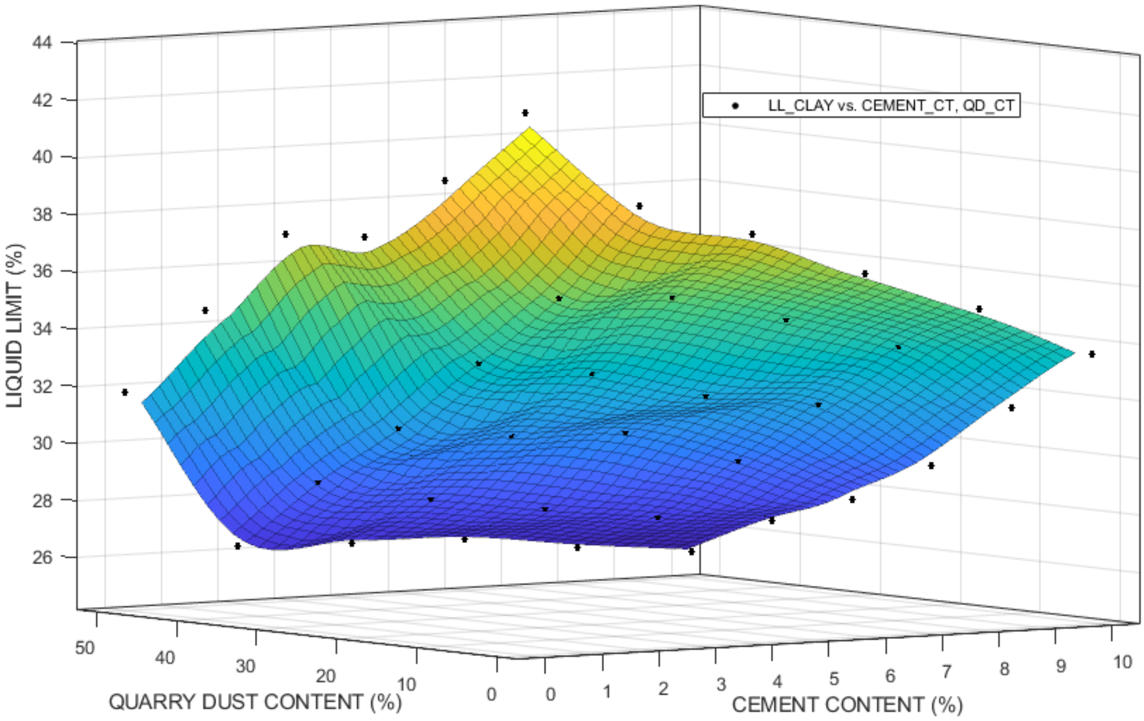

Figure 5: 3D variation of liquid limit with quarry dust and cement content

$$LL = 31.1 - 2.565C_c - 3.832QD + 0.9196C_c^2 + 0.3527C_cQD + 0.1616QD^2 \ (R^2 = 0.9515;\ Adj.\ R^2 = 0.9434;\ RMSE = 1.1439) \quad (4)$$
$$PL = 19.42 - 1.531C_c - 1.938QD + 0.1062C_c^2 + 0.262C_cQD + 0.1429QD^2 \ (R^2 = 0.9879;\ Adj.\ R^2 = 0.9859;\ RMSE = 0.2976) \quad (5)$$
$$PI = 11.683 - 1.017C_c - 1.9176QD + 0.907C_c^2 + 0.0943C_cQD + 0.0875QD^2 \ (R^2 = 0.839;\ Adj.\ R^2 = 0.8122;\ RMSE = 1.0976) \quad (6)$$

Compaction Properties

The unstabilized soil has an optimum moisture content of 13.2% and a maximum dry unit weight of 17.8 kN/m^3. With an increase in the percentages of quarry dust and cement, the soil's maximum dry unit weight gradually increases as shown in Figure 6. This supports earlier findings from combinations of soil and quarry dust (Eze-Uzomaka and Agbo 2010; Onyelowe and Okafor, 2013). The combination of 50% quarry dust and 10% cement produced the largest increase in the maximum dry unit weight, 20.9 kN/m^3. Eze-Uzomaka and Agbo (2010) suggested that the increase in maximum dry unit weight can be attributed to the finer particles of the quarry dust being packed more densely. The difference in the specific gravities of the composite materials (cement and quarry dust) is another factor that can influence the increase in the maximum dry unit weight. The addition of cement and quarry dust results in a composite material with a higher specific gravity and provides more evidence to support the rationale behind the increase maximum dry unit weight.

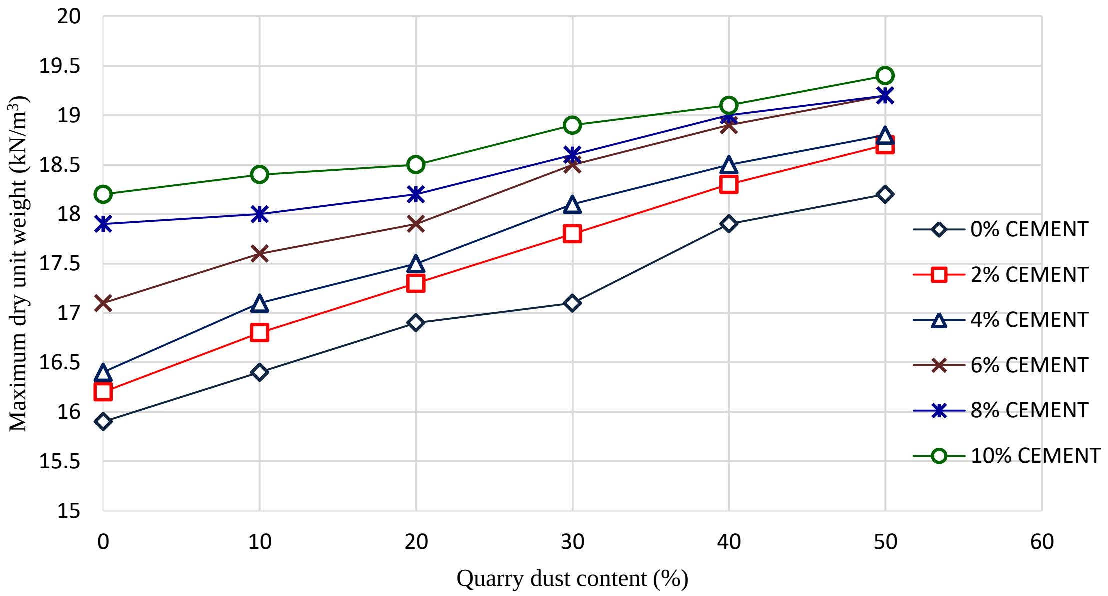

Figure 6: Variation of maximum dry unit weight with cement and quarry dust content

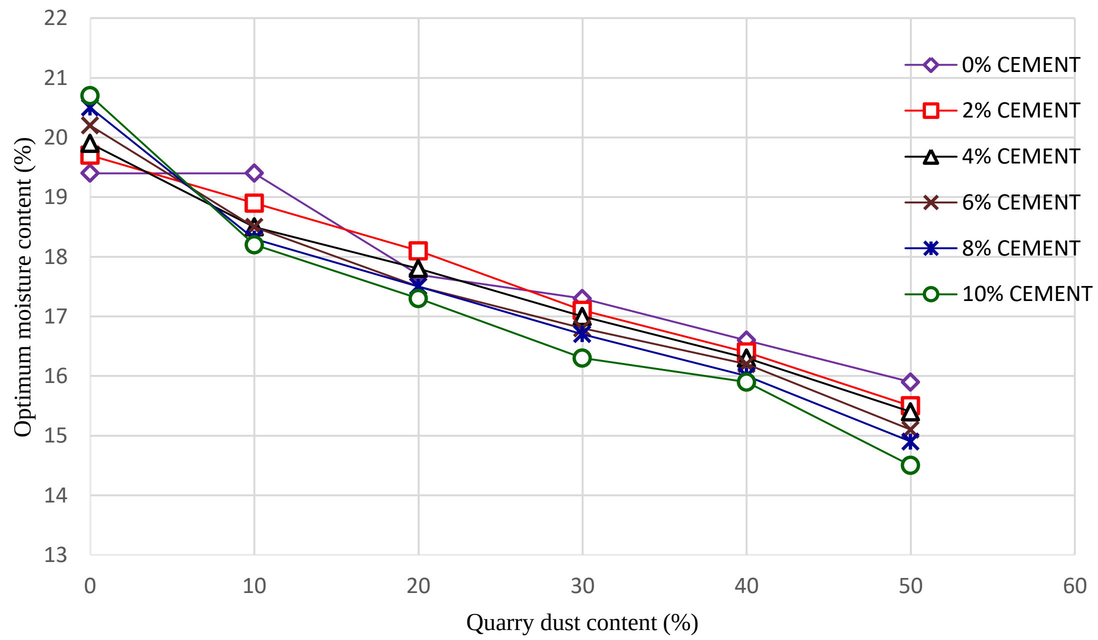

Figure 7: Variation of optimum moisture content with cement and quarry dust content

The effects of quarry dust and cement variations on the optimum soil moisture content are shown in Figure 7. The optimum moisture content of the soil was observed to decrease as the proportion of cement and quarry dust content increased. This finding is consistent with earlier research using quarry dust (Eze-uzoamaka and Agbo, 2010). According to Gupta and Kumar (2017), the additional water required for increased fineness and ensuing hydration reaction is what causes an increase in OMC in the case of cement-stabilized soils. The reduction in OMC may be explained by the heat of hydration and water demand of hydration reaction during the compaction process, which results in increased cohesion (binding) of the soil and quarry dust. The multiple linear regression equation for MDUW and OMC is shown in Equation (7) and Equation (8).

$$MDUW = 0.0399QD + 0.1683C_c + 16.117 \ (R^2 = 0.953; Adj.\ R^2 = 0.951) \quad (7)$$
$$OMC = -0.0907QD - 0.043C_c + 19.9 \ (R^2 = 0.943; Adj.\ R^2 = 0.939) \quad (8)$$

Where C_c is the cement content (%) and *QD* is the quarry dust content. The regression models suggest that the maximum dry unit weight increases with quarry dust and cement content, while the optimum moisture content reduces with cement and quarry dust content. The coefficient of correlation shows that a reliable prediction was made between the compaction characteristics and cement/quarry dust content.

CBR Properties

In its natural state, a CBR value of 6.3% was observed when the clay was compacted in its natural state at BSL compaction efforts (see Figure 8). From Figure 8, it was observed that the soaked CBR of the clay increased continuously with quarry dust content up to 50% addition. This behaviour could be attributed to the fact that extensive modification was not made to the gradation of the soil particles, such that it would lose its cohesion and undergo a reduction in shear strength when soaked in water. In a study by Arinze *et al*. (2018), a continuous increase in the soaked CBR value up to 50% replacement was observed when white clay was stabilized with quarry dust.

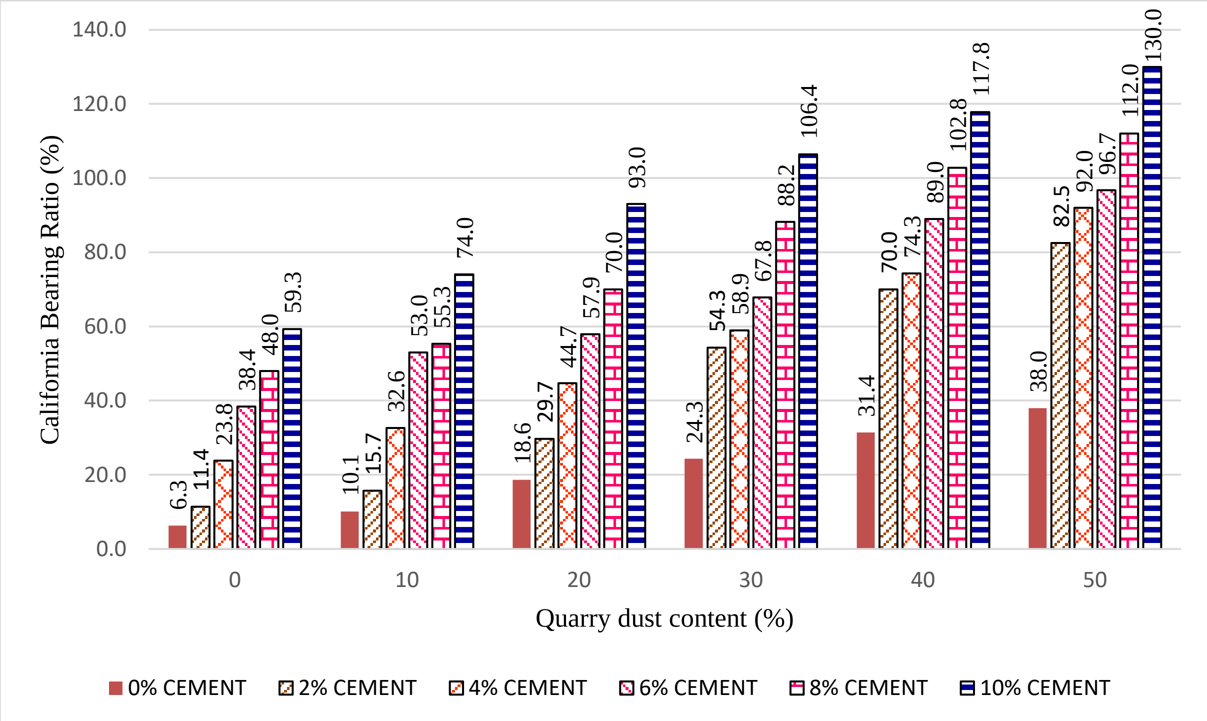

Figure 8: Variation of CBR with cement and quarry dust content

Furthermore, when the soil-quarry dust mixture (Amansea Clay) was stabilized with cement, a progressive improvement in strength was observed. The CBR of the soil peaked at 50% QD and 10% cement with a value of 130%. It is worthy of note that CBR values meeting the threshold of 180% for FMWH (1997) for soaked CBR were not met at the compaction effort employed.

The statistical evaluation of the CBR test results for all the compaction efforts are presented in Equation (9).

$$CBR = 1.257Q_D + 7.08C_c - 6.327 \ (R^2 = 0.962; Adjusted\ R^2 = 0.960) \quad (9)$$

With a coefficient of determination of 0.962, the regression model made a very good prediction of the relationship between the CBR and cement and quarry dust content.

CONCLUSION

The comprehensive investigation into the compaction and California Bearing Ratio (CBR) characteristics of cement stabilized soil-quarry dust mixtures has provided valuable insights into the potential of using quarry dust as an alternative to cement in soil stabilization. The key findings from the results are as follows:

(1) The addition of quarry dust and cement led to improvements in the engineering properties of the soil mixtures. As the quantity of quarry dust and

cement increased, the Atterberg limits of the soil decreased, indicating reduced plasticity and improved workability.

(2) The addition of cement and quarry dust also increased the maximum dry unit weight but reduced the optimum moisture content. At 50%QD and 10% Cement content, the maximum dry unit weight increased from 15.9 kN/m^3 to 19.4 kN/m^3 (a 22% increase) while the optimum moisture content reduced from 19.4% to 14.5% (a 25% reduction).

(3) The addition of cement and quarry dust also improved the CBR of the soil after 6 days curing. The CBR of the natural soil increased from 6.3% to 130% at 50% quarry dust and 10% cement content.

(4) The empirical models developed in this study can be used to predict the Atterberg limits, compaction characteristics and CBR of cement stabilized soil-quarry dust mixtures.

The findings of this study provide valuable insights into the use of quarry dust and cement as soil stabilizers. These findings can be used to develop more effective and sustainable soil stabilisation techniques for highway applications.

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