Reliability Estimate of Strength Characteristics of Black Cotton Soil Pavement Sub-Base Stabilized with Locust Bean Waste Ash and Cement Kiln Dust

Osinubi K. J.[1],. Moses G [2] and Sani J. E.[2]

[1] Department of Civil Engineering, Ahmadu Bello University, Zaria
[2] Department of Civil Engineering, Nigeria Defence Academy, Kaduna
Corresponding Author's e-mail address:mgeorge@nda.edu.ng

Abstract

Reliability estimates of strength characteristic values for compacted locust bean waste ash treated black cotton soil using cement kiln dust as an activator for road sub-base material was generated from laboratory results for specimens compacted at the energy levels of British Standard Light, West African Standard and British Standard Heavy. A Model was developed by incorporating data obtained from unconfined compressive strength test obtained from the laboratory test to produce a predictive model. Data obtained were incorporated into a FORTRAN-based first-order reliability program to obtain reliability index values. Variable factors such as optimum moisture content, hydraulic modulus, locust bean waste ash content, cement kiln dust content, Di-calcium silicate (C_2S), Tetra Calcium Alumino-Ferrite (C_4AF), and maximum dry density produced acceptable safety index value of 1.0 at the energy levels of WAS and BSH compactive effort and they were achieved at coefficient of variation ranges of 10-100 %. Observed trends indicate that the CKD content, OMC and MDD is greatly influenced by the COV and therefore must be strictly controlled in CKD/LBWA treated black cotton soil for use as sub-base material in road pavements. Stochastically, WAS and BSH compactive efforts are the only energy levels that can be used to model the 7 days unconfined compressive strength of compacted CKD/LBWA treated black cotton soil for use as sub-base material in road pavement at the variable ranges of COV of 40-100 % and 10-100 % at WAS and BSH energy levels respectively.

Keywords: Compaction, Black Cotton Soil, Reliability Index, Unconfined Compressive Strength.

1. INTRODUCTION

Uncertainties of many types pervade the practice of geotechnical engineering and they include those due to the variable nature of soil and rock properties and other in-situ conditions. There are also about the reliability of design and construction methods, and those about the costs and benefits of proposed design strategies. Probability theory is a mathematical tool that can be used to formally include such uncertainties in an engineering design and to assess their implications on performance.

Black cotton soil (BCS) is an expansive soil that principally occurs in arid and semi arid regions of the tropical/temperate zones marked with dry and wet seasons; characterized by low rainfall, poor drainage and exceedingly great heat. The climate condition is such that the annual evapotranspiration exceeds precipitation (Nelson and Miller, 1992; Warren and Kirby, 2004). Black cotton soils are clays that are produced from the breakdown of basic igneous rocks where seasonal variation of weather is extreme. The Nigerian black cotton soils resulted from the weathering of shaly and clayey sediments and basaltic rocks. They contain more of montmorillonite with subsequent manifestation of swell properties and expansive tendencies (Ola, 1983).

Locust bean waste ash treated black cotton soil used on cement kiln dust as an activator recorded successful results in terms of increase in strength gain (Sani, 2012). The peak value of the treated soil at BSL compactive effort falls short of 1710 kN/m^2 specified by TRRL (1977) for base material but meet the requirement of 687–1373 kN/m^2 for sub-base as specified by Ingles and Metcalf (1972). The value obtained for WAS and BSH compactive effort on the other hand meet the requirements.

Strength is one of the major material properties of BCS that can be significantly affected by variability in composition and admixtures. Engineering analyses and designs require the application of probabilistic methods since deterministic approaches do not rigorously account for these uncertainties. Probability theory has been widely accepted and used in engineering. The application of probability theory to engineering analysis requires the knowledge of some statistical attributes of the relevant random variables such as their mean values and standard deviations (Kaymaz *et al.,* 1998). One of such probabilistic methods is reliability analysis which has been used in geoenvironmental engineering (Gilbert and Tang, 1995; Rowe and Fraser, 1995; Nwaiwu *et al.,* 2009). Reliability analysis provides a frame work for establishing appropriate factors of safety and other design targets and leads to a better appreciation of the relative importance of uncertainties in different parameters (Christian and Baecher, 2001). Therefore, the focus of these research work is to access the uncertainties based on the reliability analysis of compacted locust bean waste ash treated black cotton soil used with cement kiln dust as an activator for sub-base road pavement structures.

1.1 Reliability Index

A measure of the adequacy of an engineering design is the reliability index β, defined as:

$$\beta = \mu / s(x) \quad (1)$$

This can be interpreted as the number of sigma units (the number of standard deviation s(x)) between the mean value of the safety margin (E(s)).

$$E(s) = \mu \quad (2)$$

and its critical value

$$S = 0 \quad (3)$$

The reliability index of a system, "β" is defined as the ratio between the mean and standard deviation of the safety margin of the system.

By definition, the reliability index is the reciprocal of the coefficient of variation of the safety margin, that is $\beta = I/Vs$ (Kottegoda and Rosso, 1997).

1.2. Concept of First – Order Reliability Method (FORM)

The probabilistic and deterministic approaches to design differ in principle. Deterministic design is based on total 'discounting' of the contingency of failure. Design problems involve element of uncertainty; unpredictability of randomness. Probabilistic design is concerned with the probability that the structure will realize the functions assigned to it (Afolayan and Abubakar, 2003).

If 'r' is the strength capacity and 's' the compositional effect(s) of a system which are random variables, the main objective of reliability analysis of any system or component is to ensure that 'r' is never exceeded by 's'. In practice, 'r' and's' are usually functions of different basic variables. In order to investigate the effect of the variables on the performance of the system, a limit state equation in terms of the basic design variable is required (Afolayan and Abubakar, 2003).

This limit state equation is referred to as the performance or state function and expressed as: (Afolayan and Abubakar, 2003).

$$g(t) = g(x1, x2 \ldots . xn) = r - s \qquad (4)$$

where x_i for i = 1, 2, 3 ….n, represent the basic design variables.

The limit state of the system can then be expressed as

$$G\ (t) = g(x\ (t)) \qquad (5)$$

Reliability calculations provide a means of evaluating the combined effects of uncertainties and a mean of distinguishing between conditions where uncertainties are particularly high or low. In design evaluation involving the selection of a value for a soil parameter to be used for geotechnical analysis, reliability analysis, involving the application of probabilistic concepts, is suitable for taking care of uncertainties (Duncan, 2000). Thus, strength in term of unconfined compressive strength (UCS) and California bearing ratio (CBR) are taken to be the basic parameter for design of sub base or sub grade materials. (Ingles and Metcalf, (1972); TTRL, (1977); Osinubi, 1998a)

Soil reliability can be estimated from equation (6), if the type of probability distribution function for UCS and its statistical parameters (mean, standard deviation, variance, etc) are known. This is also possible only with the probability of survival expresses in as:

$$P_s = 1 - P_f \quad (6)$$

where P_s = probability of survival and P_f = probability of failure.

In the reliability analysis of compacted road pavement structure material, failure would occur when the 7 days UCS less than the minimum value of 687 kN/m^2 as specified by Ingles and Metcalf (1972), for sub base during service period or design life. A total of forty eight (48) data point per parameters was used in the analysis. The probability of failure (P_f) can then be formulated as:

$$P_f = P\,\{S_c - S_o\,(OMC, HM, CKD, LBWA, C3S, C4AF, E, MDD) \leq 0\,\} \quad (7)$$

where:

S_c = Expected Strength

S_o = Specified regulatory minimum strength

OMC = Water with respect to optimum

HM = Hydraulic modulus

CKD= Cement kiln dust content

LBWA= Locust bean waste ash content

C_2S= Di-Calcium Silicate

C_4AF= Tetra Calcium Alumino-Ferrite

MDD = Maximum Dry Density

E = Compactive Effort Index

The defined components in equation 7 above are parameters affecting the strength and are used in predicting strength values based on laboratory results and compound formations contents based on admixture combination ratios.

2. MATERIALS AND METHODS

2.1 Database and Statistical Analysis

The database was compiled by extracting data on Locust bean waste ash stabilized black cotton soil using cement kiln dust as an activator from the laboratory test results of unpublished literature (Sani, 2012). The statistical characteristics of the material composition and compaction variables for the black cotton soil are shown in Table 1.

2.2 Set-up of Numerical Experiments Reliability Analysis

Data from laboratory experiments for strength related parameters and deduced parameters associated with strength were estimated. The following parameters were measured experimentally: unconfined compressive strength UCS; optimum water content (OMC); cement kiln dust CKD; Locust bean waste ash LBWA; maximum dry density MDD; and compactive effort index (E). While the following associated shear strength parameters with respect to the stability and products of hydration were estimated from the oxide compositions of LBWA and CKD: Hydraulic modulus (HM); Di-Calcium Silicate (C_2S); Tetra Calcium Alumina-Ferrite (C_4AF). Shear strength, water content with respect to optimum, maximum dry density are normally assumed to have a lognormal distribution (Eberemu, 2008; Stephen, 2010; Gui *et al*., 2000; Nwaiwu *et al*, 2009). C_2S and C_4AF were also assumed to have a lognormal distribution, while, LBWA and CKD are normally distributed parameters (Eberemu, 2008; Stephen, 2010). The compactive effort index is an integer categorical variable describing compactive effort. It was assigned –1, 0 and 1 for British Standard light, West African Standard and British Standard heavy compactive efforts, respectively. The hydraulic modulus (*HM*) is generally defined as the ratio $CaO/(Al_2O_3\ SiO_2\ Fe_2O_3)$. Generally, for cement, if *HM is* lower than 1.7 then there will be insufficient strength but if *HM is* greater than 2.3, the there will be poor volumetric stability. (Moses and Afolayan, 2003). These results were used to run a regression model for predicting laboratory UCS results. The statistical analyses were carried out using statistical tools Mini-tab R15 software. Sensitivity analysis for each of the independent variables that affect strength was performed by varying the assumed values of coefficient of variation (COV) ranging from 10-100 % to obtain reliability indices (safety indices or β-values).

Reliability analysis is intended to assess the suitability of compacted locust bean waste ash treated black cotton soil strength characteristic for use as a sub-base material. This becomes necessary due to the variability that might exist from black cotton soil obtained from one location to another and the compositional content of the additives. The statistical characteristics of the relevant black cotton soil – locust bean waste ash – cement kiln dust as well as physical properties of their probability distribution functions types were established.

The relevant statistical properties for black cotton soil – locust bean waste ash – cement kiln dust mixtures were then incorporated into FORTRAN programmes for a field based predictive model in order to evaluate reliability levels and to predict UCS using the 'first order reliability methods' version 5.0 (FORM 5) (Gollwitzer *et al.*, 1988). The input data for the reliability analysis from the laboratory strength results are shown in Table. 1.

Table.1. Input data for reliability based design for eight independent variable using FORM 5 from laboratory measured strength.

S/No	Variables	Distribution type	Mean E(x)	Standard Deviation S(x)	Coefficient of Variation COV (%)
1	Strength Value	Lognormal	1.224 E3	3.953 E2	32.30
2	Optimum moisture content (OMC)	Lognormal	1.545 E1	2.698 E0	17.46
3	Hydraulic modulus HM	Lognormal	1.164 E0	1.587 E0	136.3
4	Locust bean waste ash LBWA	Normal	5.0 E0	3.435 E0	68.7
5	Cement kiln dust CKD	Normal	4.0 E0	2.844 E0	71.1
6	Di-calcium Silicate C_2S	Lognormal	2.38 E2	2.155 E2	90.55
7	Tetra calcium Alumina ferret C_4AF	Lognormal	1.3 E1	2.7 E0	20.77
8	Maximum dry density MDD	Lognormal	1.73 E0	7.6 E-2	4.39
9	Compactive effort E	Deterministic parameter	-1, 0, 1	-	-

Sensitivity analysis for each of the independent variables that affect strength was performed by varying the assumed values of coefficient of variation (COV) ranging from 10-100 % to obtain reliability indices (safety indices or β-values). The safety indices for the seven independent evaluated variables that affect strength are: Optimum Moisture Content (OMC), hydraulic modulus (HM), locust bean waste ash LBWA, cement kiln dust CKD, C_2S, C_4AF, and Maximum dry density MDD; at compaction energy levels of British Standard light (BSL), West African Standard (WAS) and British Standard heavy (BSH) were obtained.

3. RESULTS AND DISCUSSION

3.1 Unconfined Compressive Strength

3.1.1 Effect of Strength on Reliability Index

The effect of compressive strength on reliability index as the coefficient of variation is varied is shown in Fig.1. Higher safety indices were recorded for higher compaction energies. Strength produced a near linear decreasing relationship with coefficient of variation in the ranges 10-100 % for WAS and BSH compactive effort only while the observed trend for BSL is constant. Safety index varied considerably which is an indication that variability of strength has drastic influence on the safety index for road sub-base pavement structures. As COV increased from 10-100 %, β value decreased from 1.32 to 1.17 and 1.67 to 1.43 for WAS and BSH compactions, respectively while BSL compaction recorded slight increase in value from 0.844 to 0.855.

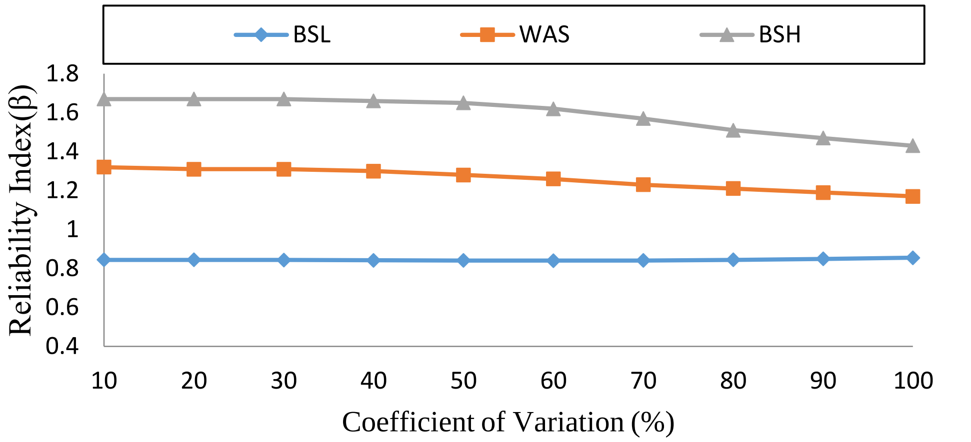

Fig.1: Variation of reliability index with coefficient of variation for 7 days unconfined compressive strength

3.1.2 Effect of Optimum Moisture Content on Reliability Index on the 7 days unconfined compressive strength

The effect of optimum moisture content on reliability index as the coefficient of variation is varied is shown in Fig.2. Higher safety indices were recorded for higher compaction energies. Optimum moisture content produced a linear decreasing relationship with coefficient of variation in the ranges 10-100 % for BSL, WAS and BSH compactive effort only. Safety index varied considerably which is an indication that variability of OMC has drastic influence on the safety index for road sub-base pavement structures. As COV increased from 10-100 %, β value decreased from 0.85-0.64, 1.32 to 1.17 and 1.67 to 1.43 for BSL, WAS and BSH compactions, respectively. Decreasing β values indicates that increasing COV will result in lower strength values at BSL, WAS and BSH compactive efforts.

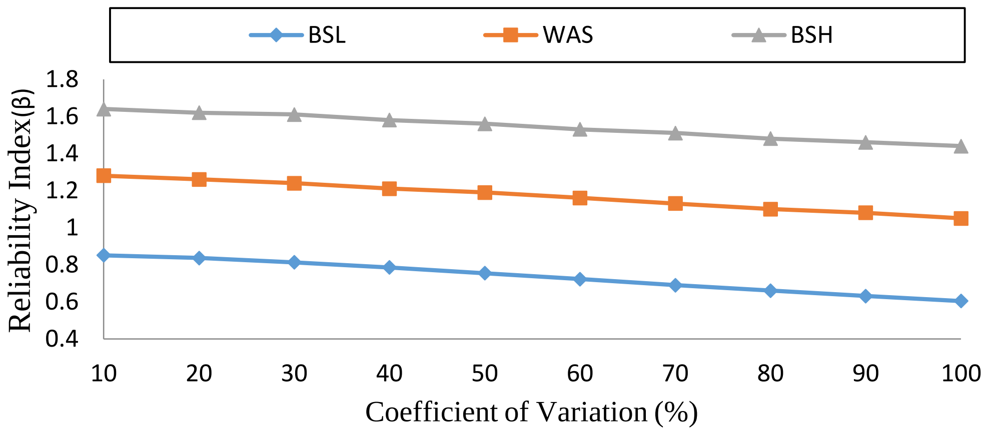

Fig.2: Variation of reliability index with coefficient of variation for water content relative to optimum

3.1.3 Effect of Hydraulic Modulus on Reliability Index on the 7 days unconfined compressive strength

The variation of the reliability index with the coefficient of variation of hydraulic modulus is shown in Fig.3. Higher safety indices were recorded for higher compaction energies. Hydraulic modulus produced a non-linear relationship with coefficient of variation within the range 10-100 % for BSL, WAS and BSH compactive effort, while reliability or safety index varied slightly. This is an indication that variability of hydraulic modulus has no drastic influence on the safety index. As COV did not vary considerably, except for slight increase in value from 0.73 to 0.80, 1.56 to 1.60 for WAS and BSH compactions, respectively for 10-100 %. This is an indication that increasing COV will result in higher strength values at WAS and BSH compactive efforts due to increasing safety index values. However, BSL compactive energy levels recorded slight decreases in β values from 1.25 to 1.14. Decreasing β values indicates that increasing COV will result in lower strength values at BSL. While increasing β values with increasing COV will result in higher strength values for WAS and BSH compactive efforts.

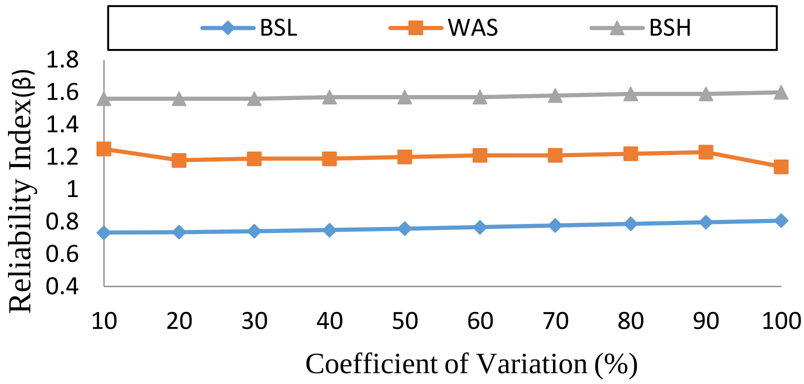

Fig.3: Variation of reliability index with coefficient of variation for hydraulic modulus

3.1.4 Effect of Locust Bean Waste Ash Content on Reliability Index on the 7 days unconfined compressive strength

The effect of *locust bean waste ash content* on reliability index as the coefficient of variation is varied is shown in Fig.4. Higher safety indices were recorded for higher compaction energies. L*ocust bean waste ash content* produced a constant relationship with coefficient of variation the range 10-100 % for BSL, WAS and BSH compactive effort respectively. This is an indication that variability of locust beans waste ash has no drastic influence on the safety index. As COV increased from 10-100 %, β value maintained constant values of 0.84, 1.27 and 1.63 for BSL, WAS and BSH compactions, respectively. Thus no effect is expected on the strength.

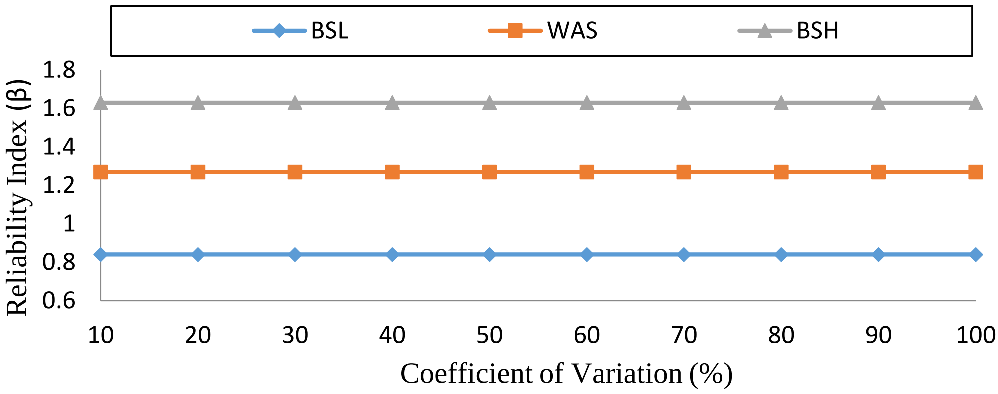

Fig.4: Variation of reliability index with coefficient of variation for locust bean waste ash

3.1.5 Effect of Cement Kiln Dust on Reliability Index on the 7 days unconfined compressive strength

The effect of cement kiln dust content on reliability index as the coefficient of variation is varied is shown in Fig.5. Higher safety indices were recorded for higher compaction energies. Cement kiln dust content produced a linear relationship with coefficient of variation the range 10-100 % for BSL, WAS and BSH compactive effort, while reliability or safety index varied. This is an indication that variability of cement kiln dust content has some influence on the safety index. As COV increased from 10-100 %, β value decreased from 0.87-0.81, 1.66-1.60 and 1.30 -1. 24 for BSL, WAS and BSH compactions, respectively. This is an indication that increasing COV with decreasing β value will result in lower strength values at BSL, WAS and BSH compactive efforts.

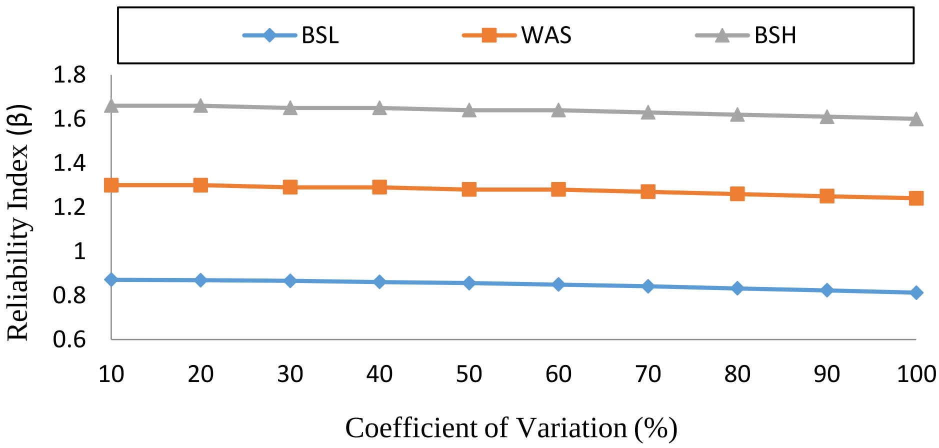

Fig.5: Variation of reliability index with coefficient of variation for cement kiln dust

3.1.6 Effect of Di-calcium silicate on Reliability Index on the 7 days unconfined compressive strength

The effect of *Di-calcium silicate* content on reliability index as the coefficient of variation is varied is shown in Fig.6. Higher safety indices were recorded for higher compaction energies.

Di-calcium silicate content produced a non-linear relationship with coefficient of variation the range 10-100 % for BSL, WAS and BSH compactive effort only, while reliability or safety index varied slightly. This is an indication that variability of *Di-calcium silicate* content has some slight influence on the safety index. As COV increased from 10-100 %, β value increased from 0.76 to 0.86 and 1.26 to 1.59 for BSL and BSH compactions, respectively while it decreases from 1.66 to 1.28 for WAS compaction energy. This is an indication that decreases in β values with increasing COV will result in lower strength values at WAS. While increasing β values with increasing COV will result in higher strength values for BSL and BSH compactive efforts.

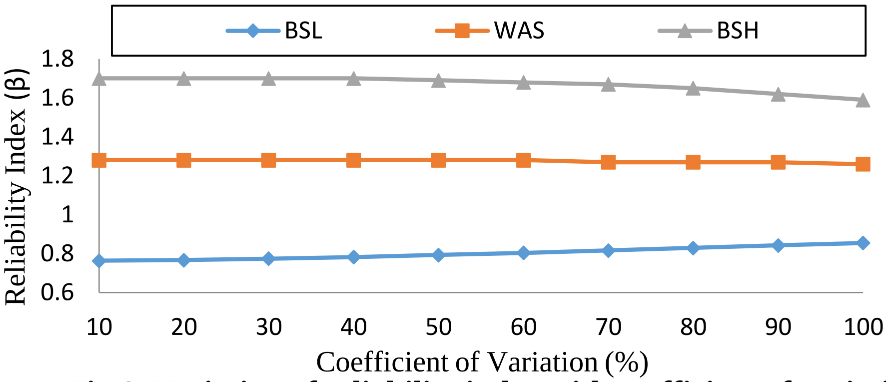

Fig.6: Variation of reliability index with coefficient of variation for di- calcium silicate C_2S

3.1.7 Effect of Tri-calcium Alumina Ferrite on Reliability Index on the 7 days unconfined compressive strength

The effect of *Tetra-Calcium Alumina-Ferrite content* on reliability index as the coefficient of variation is varied is shown in Fig.7. Higher safety indices were recorded for higher compaction energies. *Tetra-Calcium Alumina-Ferrite content* produced a linear relationship with coefficient of variation in the ranges 10-100 % for BSL, WAS and BSH compactive effort only. Safety index varied considerably which is an indication that variability of *Tetra-Calcium Alumina-Ferrite content* has drastic influence on the safety index for road sub-base pavement structures. As COV increased from 10-100 %, β value decreased from 0.89-0.32, 1.28-0.749 and 1.67-1.16 BSL, WAS and BSH compactions, respectively. This is an indication that decreases in β values with increasing COV will result in lower strength values all the energy levels.

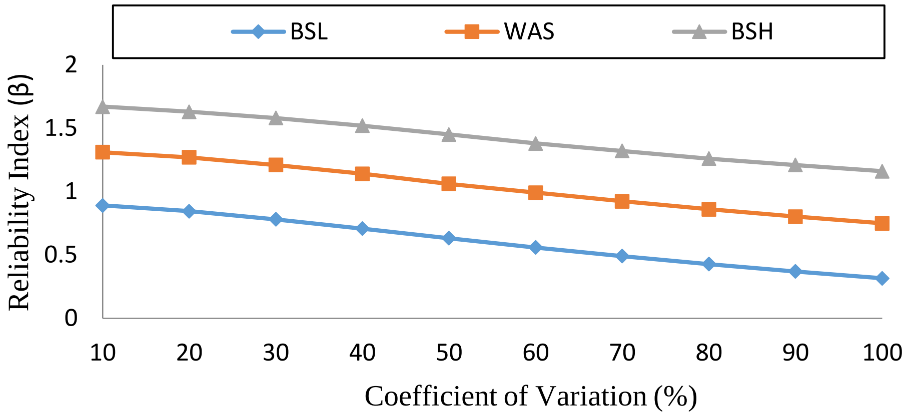

Fig.7: Variation of reliability index with coefficient of variation for tri- calcium aluminate ferrete C_4AF

3.1.8 Effect of Maximum Dry Density on Reliability Index on the 7 days unconfined compressive strength

The effect of *maximum dry density* on reliability index as the coefficient of variation is varied is shown in Fig.2. Higher safety indices were recorded for higher compaction energies. M*aximum dry density* to optimum produced a non-linear relationship with coefficient of variation in the ranges 10-100 % for BSL, WAS and BSH compactive effort only. Safety index varied considerably which is an indication that variability of *maximum dry density* has drastic influence on the safety index for road sub-base pavement structures. As COV increased from 10-100 %, β value decreased from 0.83-0.71, 1.25-0.87 and 1.62-1.04 BSL, WAS and BSH compactions, respectively. This is an indication that decreases in β values with increasing COV will result in lower strength values all the energy levels.

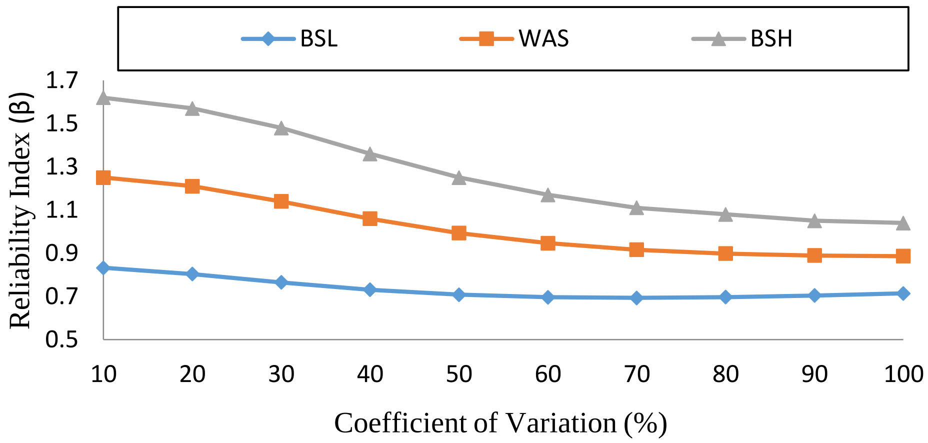

Fig.8: Variation of reliability index with coefficient of variation for maximum dry density

3.1.9 Statistical Significance of Safety Index Values

Statistical analysis of all the results obtained for the parameters (UCS, W.R.O., HM, LBWA, CKD, C_2S, C_4AF, and MDD) under consideration using the two-way analysis of variance (ANOVA) with respect to the compactive efforts produced statistically significant (SS) results as shown in Table 2. Using the F-distribution test at 95 % level of significance, compactive effort has significant effect on the outcome of the results recorded from the ANOVA test. Therefore, care must be taken in ensuring that the compactive efforts that produced successful safety index are carefully monitored during the construction of sub-grade or sub base materials.

Table.2: Analysis of variance of reliability index values

Variable	Source of variation	Degree of freedom	F – value calculated	P – value	F–value critical	SS
UCS 7 Day curing	COV	9	2.92	2.54 E-2	2.46	SS
	Compactive effort	2	605.83	3.1 E-17	3.55	SS
Optimum moisture content	COV	9	236.38	8.13 E-17	2.46	SS
	Compactive effort	2	20805.67	5.28 E-31	3.55	SS
Hydraulic modulus	COV	9	1.13	3.92 E-1	2.46	NS
	Compactive effort	2	2868.55	2.86 E-23	3.55	
Locust bean waste ash	COV	9	-2	-	2.46	NS
	Compactive effort	2	-2.1 E+16	-	3.55	NS
Cement kiln dust	COV	9	633.22	1.22 E-20	2.46	SS
	Compactive effort	2	778106.67	3.7 E-45	3.55	SS
Di-calcium silicate C_2S	COV	9	0.087	9.99 E-1	2.46	NS
	Compactive effort	2	1527.61	8.11 E-21	3.55	SS
Tri-calcium aluminate ferrete C_4AF	COV	9	779.98	1.88 E-21	2.46	SS
	Compactive effort	2	11588.31	1.02 E-28	3.55	SS
Maximum dry density MDD	COV	9	7.04	2.36 E-4	2.46	SS
	Compactive effort	2	93.56	3.08 E-10	3.55	SS

SS = Statistically significant at 5 % level
NS = Not Statistically significant at 5 % level
COV= Coefficient of variation

3.1.10 Stochastical Model Assessment on the 7 days unconfined compressive strength

The safety index obtained for the three compactive efforts BSL, WAS, and BSH for *the 7 days unconfined compressive strength are* tabulated in Table 3. NKB Report (1978) specified a safety index value of 1.0 as the lowest value for serviceability limit state design (model 1) of structural components.

Table. 3: Stochastical Model Assessment of acceptable safety index

Variables	Beta Value			Acceptable Range of COV (%)		
Factors	BSL	WAS	BSH	BSL	WAS	BSH
UCS 7 Day curing	0.84-0.86	1.32-1.17	1.67-1.43	Nil	10-100 %	10-100 %
Optimum moisture content	0.85-0.6	1.28-1.05	1.64-1.44	Nil	10-100 %	10-100 %
Hydraulic modulus	0.73-0.81	1.25-1.14	1.56-1.6	Nil	10-100 %	10-100 %
Locust bean waste ash	0.84-0.84	1.27-1.27	1.63-1.63	Nil	10-100 %	10-100 %
Cement kiln dust	0.87-0.81	1.3-1.26	1.66-1.6	Nil	10-100 %	10-100 %
Di-calcium silicate C_2S	0.76-0.86	1.28-1.26	1.7-1.59	Nil	10-100 %	10-100 %
Tri-calcium aluminate ferrete C_4AF	0.89-0.32	1.31-0.75	1.67-1.16	Nil	10-50 %	10-100 %
Maximum dry density MDD	0.83-0.71	1.25-0.89	1.62-1.04	Nil	10-40 %	10-100 %

4. CONCLUSION

Reliability estimates for 7 days unconfined compressive strength of compacted CKD/LBWA treated black cotton soil as sub-base material for road pavement was under taken by incorporating a predictive model. This was developed from the data obtained from laboratory results for specimens compacted at the energy levels of British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy (BSH), respectively. Results were incorporated into a FORTRAN-based first-order reliability program and safety index values obtained. Generally, the safety index produced satisfactory beta value of 1.0 as specified for serviceability limit state design at WAS and BSH compactive effort. Compositional factor and compound formations based on admixture combination ratio such as OMC, HM, CKD, LBWA, C3S, C4AF and MDD produced acceptable safety index value of 1.0 at the energy levels of WAS and BSH compactive efforts at COV ranges of 40-100 % and10-100 % at WAS and BSH compactive efforts respectively. Observed trends indicate that the CKD content, OMC and MDD is greatly influenced by the COV and therefore must be strictly controlled in CKD/LBWA treated black cotton soil as sub-base material for road pavement.

Stochastically, only WAS and BSH compactive efforts can be used to model the 7 days unconfined compressive strength of compacted CKD/LBWA treated black cotton soil as sub-base material for road pavement at the variable ranges of COV between 40-100 % and10-100 % at WAS and BSH compactive efforts respectively. Finally, care must be taken in ensuring that the compactive efforts required to produce successful safety index are carefully monitored during the construction.

References

Afolayan, J.O. and Abubakar, I. (2003), “Reliability analysis of reinforced concrete one-way slabs. The ultimate conditions”, *Nigerian Journal of Engineering,* 11(2), 28 – 31.

Benson C.H. (1993), “Probability distributions for hydraulic conductivity of compacted soil liners”, *Journal oj Geotechnical Engineering, ASCE*; 119(3): 471-486.

Christian, J.T. and Baccher, G. B. (2001). Discussion of factor of safety and reliability in Geotechnical Engineering, *Journal of Geotechnical and Geoenvironmental Engineering,* A.S.C.E., 127(8): 700-703.

Duncan, M.J. (2000). “Factors of safety and reliability in geotechnical engineering. “*Journal of Geotechnical Geoenenviromental Engineering,* ASCE, 126(), 307-316.

Eberemu, O. A. (2008). *Evaluation of compacted cement kiln dust treated laterite soil as hydraulic barriers in waste containment systems*. Unpublished Ph.D Dissertation submitted to the Department of Civil Engineering, Ahmadu Bello University, Zaria.

Gilbert, R.B., and Tang, W.H. (1995). “Reliability-based design for waste containment systems.” Geoenvironment 2000. Geotechnical Special Publication, ASCE, No. 6, New York : 499-513.

Gollwitzer, S., Abdo, T. and Rackwitz, R. (1988) First Order Reliability Method (FORM Version 5) Manual, Munich, 1- 47.

Gui, S., Zhang, R., Turner, J.P., and Zue, X. (2000). “Probabilistic slope stability analysis with stochastic Soil hydraulic conductivity.” Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 126(1): 1-9.

Kaymaz, I., McMahon, C. and Xianyi, M. (1998) Reliability based structural optimisation using the response surface method and Monte Carlo simulation. *8th Int. Machine Design and Production Conf. Ankara*.

Kotegoda M. and Rosso, R. (1997). *Statistics, probability, and reliability for civil and environmental engineers*. New York, McGraw-Hill.

Ingles, O. G. and Metcalf, J. B. (1972). *Soil Stabilization Principles and Practice,* Butterworths, Sydney.

Nelson, D. and Miller, J. (1992). *Expansive Soils: Problems and Practices in Foundation and Pavement Engineering.* John Wiley and Sons, Inc. New York.

NKB - Report No. 36. (1978) Recommendation for loading and safety regulations for structural design. Nordic Committee on Building Regulation.

Nwaiwu C.M.O., Afolayan J.O., and Osinubi K.J. (2009) Reliability Estimates of Field Hydraulic Conductivity of Compacted Lateritic Soils Continental Journal of Engineering Sciences 4:36–47.

Rowe, R.K. and Fraser, M.J. (1995) Effect of uncertainty in the assessment of the potential impact of waste disposal facilities. *Geoenvironment 2000, Geotechnical Special Publication No. 46, ASCE,* New York, 270 -284.

Sani, J. E. (2012). Locust Bean Waste Ash Stabilization of Black Cotton Soil Using Cement Kiln Dust as an Activator. Unpublished M.Sc Thesis submitted to the Department of Civil Engineering, Ahmadu Bello University, Zaria.

Stephen, I. T. (2010). *Evaluation of compacted cement kiln dust treated black cotton soil as\ hydraulic barriers in Waste containment systems*. Unpublished Ph.D Dissertation submitted to the Department of Civil Engineering Ahmadu Bello University, Zaria.
TRRL (1977), "A guide to the structural design of Bitumen surfaced Roads in tropical and Sub –
Tropical countries", Transport and Road Research Laboratory, Road Note 31, H. M. S. 0. London.
Warren, K. W. and Kirby, T. M. (2004). "Expansive clay soil: A widespread and costly geohazard." *Geostrata,* Geo-Institute of the American Society Civil Engineers, Jan pp. 24-28.