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Reliability Estimate of Strength Characteristics of Black Cotton Soil Pavement Sub-Base stabilized with Bagasse Ash and Cement Kiln Dust

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Abstract

Reliability of estimates of strength characteristic values from laboratory results for specimens compacted at the energy levels of British Standard Light (BSL), WestAfrican Standard (WAS) and British Standard Heavy (BSH)for compacted bagasse ash treated black cotton soil using cement kiln dust (CKD) as an activator was developed by incorporating data obtained fromUnconfined compressive strength(UCS) test gotten from the laboratory test to produce a predictive model. Data obtained were incorporated into a FORTRAN-basedfirst-order reliability program to obtain reliability index values. variable factors such as water content relative tooptimum (WRO), hydraulic modulus (HM), bagasse ash (BA), cement kiln dust (CKD), Tri-calcium silicate (C_3S), Di-calcium silicate(C_2S), and maximum dry density (MDD)do not produced acceptable safety index value of1.0 at the three energy levels namely BSL, WAS and BSH compactive effort at coefficient of variation (COV) ranges of 10-100% for the Unconfined compressive strength but they produces acceptable safety index value at the three energy level at coefficient of variation (COV) ranges of 10-100% for both California bearing ratio and resistance to loss in strength. Observed trends indicate that for unconfined compressive strength WRO, HM, CKD and MDD is greatly influenced by the COV and therefore must be strictly controlled in CKD/BA treated black cotton and California bearing ratio indicate that theCKD, C3S, C2S and MDD is greatly influenced by the COV and therefore must be strictly controlled in CKD/BA treated black cotton while for resistance to loss in strength indicate that theWRO, CKD, C3S, C2S and MDD is greatly influenced by the COV and therefore must be strictly controlled in CKD/BA treated black cotton. Stochastically, none ofthe compactive efforts can be used to model the 7 days unconfined compressive strength of compacted CKD/BA treated black cotton soil as a sub-base material for road pavement at all COV range because the safety index are lower than the acceptable 1.0 value. All the compactive effort, BSL, WAS and BSH compactive efforts can be used to model both California bearing ratio and resistance to loss in strength of compacted CKD/LBWA treated black cotton soil as sub-base material for road pavement at the variable ranges of COV between 10-100% at BSL, 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.

Keywords: Compaction, Compactor weight, Hydraulic Modulus, BagasseAsh, Black Cotton Soil, Cement Kiln Dust, ReliabilityAnalysis, Reliability Index, Unconfined Compressive Strength.

Introduction

The need to reduce the uncertainties in geotechnical engineering during design and construction in terms of the variable nature of soil and rock properties and other in situ conditions has become a major challenge because of the uncertainties about the reliability of design and construction methods, and uncertainties 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 (Yisa and Sani, 2014).

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; and with low rainfall, poor drainage and exceedingly great heat. The climate condition is such that the annual evapotranspiration exceeds precipitation (Chen, 1988; Nelson and Miller, 1992; Warren and Kirby, 2004). These soils are predominant in the Northeastern part of Nigeria occupying an area of about $10.4x10^4$ km (Ola, 1983).Black cotton soils owe their specific properties to the presence of swelling clay minerals, mainly montmorillonite. As a result of the wetting and drying, massive expansion and contraction of the clay minerals takes place. Contraction leads to the formation of the wide and deep cracks. Cracks measuring 70 mm wide and over 1m deep have been observed (Adeniji, 1991) and may extend up to 3 m or more in the case of high deposits. Surface material accumulates in these cracks during the dry season and is "swallowed" by the soil in the wet season, creating the 'self-mixing' or 'self-mulching' action of the black cotton soils.

These soils are poor materials to employ for highway or airfield construction because they contain high percentages of plastic clay. In areas where they occur, usually there are no suitable natural gravels or aggregates and most deposits cover a large significant area that avoiding them is not possible. Road construction over black cotton soils generally poses a major problem due to the inability of the soils to swell and shrink considerably with changes in moisture content, which consequently lead to low bearing values when wet and severe cracking when dry (Osinubi, 1995).

Bagasse ashtreated black cotton soil used on cement kiln dust as an activatorrecordedgreat improvement in terms of strength gain (Bello, 2014). The peak value of the treated soil at BSL, WAS and BSH compactive effortsfalls 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 byIngles and Metcalf (1972).

Strength is one of the major material properties of BCS that can be significantly affected by variability incomposition and admixtures. Engineering analyses and designs require the application of probabilistic methods as deterministicapproaches do not rigorously account for these uncertainties. Probability theory has been widely accepted and usedin engineering. The application of probability theory to engineering analysis requires the knowledge of somestatistical attributes of the relevant random variables such as their mean values and standard deviations (Kaymaz etal., 1998). One of such probabilistic methods is reliability analysis which has been used in geoenvironmentalengineering (Gilbert and Tang, 1995; Rowe and Fraser, 1995; Nwaiwu et al, 2009). Reliability analysis providesa frame work for establishing appropriate factors of safety and other design targets and leads to a better appreciationof the relative importance of uncertainties in different parameters (Christian and Baecher, 2001). Reliability analysiscan be used to assess the suitability of compacted bagasse ash treated black cotton soil used with cement kiln dust on unconfined compressive strength.

Reliability Index

Another measure of the adequacy of an engineering design is the reliability index, defined as

$$B = \mu / d \quad (1)$$

This can be interpreted as the number of sigma units (the number of standard deviation dx) between the mean valueof the safety margin.

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

and its critical value

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

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

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

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 ofrandomness. Probabilistic design is concerned with the probability that the structure will realize the functionsassigned 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 ofreliability analysis of any system or component is to ensure that r is never exceeded by s. In practice, r and s areusually functions of different basic variables. In order to investigate the effect of the variables on the performance ofthe 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:

$$g(t) = g(x1, x2\ldots.Xn) = r - s \tag{4}$$

Where x1 for I = 1, 2, 3,…………n, represent the basic design variables.

The limit state of the system can then be expressed as

$$G(t), - 0 \tag{5}$$

Reliability calculations provide a means of evaluating the combined effects of uncertainties and a mean ofdistinguishing between conditions where uncertainties are particularly high or low. In design evaluation involvingthe selection of a value for a soil parameter to be used for geotechnical analysis, reliability analysis, which involvesthe application of probabilistic concepts, is suitable for taking care of uncertainties (Duncan, 2000).

Soil reliability can be estimated from eq. (6) if the type of probability distribution function for K and its statisticalparameters (mean, standard deviation, variance, etc) are known. This is also possible only with the probability ofsurvival as given in eq. (7):

$$P_s = 1 - P_f \tag{6}$$

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:

1. When the 7 days UCS is less than the minimum value of 1720kN/m^2 specified by TRRL (1977), for sub base during its service period or design life.
2. When the CBR value is less than the minimum value of 30% specified by Nigerian General Specification (1997), for sub-base during its service period or design life.
3. When the resistance to loss in strength value is less than the minimum value of 80% specified by (Ola, 1983) based on 4 days soaking.

Theprobability of failure (P_f) can then be formulated as:

$$P_f = P\,\{S_c - S_o\,(WRO, HM, BA, CKD, C3S, C2S,\ E,\ MDD) \leq 0\,\} \tag{7}$$

where:

S_c = Expected Strength

S_o = Specified regulatory minimumstrength

WRO = Water with respect to optimum

HM = Hydraulic modulus

BA= Bagasse ash content

CKD=Cement kiln dust content

C_3S= Tri-Calcium Silicate

C_2S=Di-Calcium Silicate

E = Compactive Effort Index

MDD = Maximum Dry Density

Which are parameters affecting the unconfined compressive strengthand are used in predicting unconfined compressive strengthvalues basedon laboratory results and compound formations contents based on admixture combination ratio.

Materials and Methods

Database and Statistical Analysis

A database was compiled by extracting data on Bagasse ash stabilized black cotton soil using cement kiln dust as an activator from the laboratory test results of unpublished literature (Bello, 2014). The statistical characteristics of the material composition andcompaction variables for the black cotton soil are shown in Table 1.

Set-up of Numerical Experiments Reliability Analysis

The results of all laboratory experiments on strength and the parameters associated with strength were measured during the laboratory work. The various parameters measured include the followingunconfined compressive strength UCS, California bearing ratio CBR, resistance to loss in strength, water content with respect to optimum (WRO), hydraulic modulus HM, bagasse ash BA, cement kiln dust CKD, maximum dry density MDD,compactive effort index (E),and calculated compound compositions such as Tri-Calcium Silicate and Di-Calcium Silicate C_2S. Fundamentally, strength, watercontent with respect to optimum, maximum dry density C_2S and $C_4AF$are normally assumed to havea lognormal distribution (Eberemu, 2008; Stephen, 2010; Nwaiwu*et al,* 2009) .While BA and CKD has a normaldistribution (Eberemu, 2008; Stephen, 2010). The compactive effort index is an integer categoricalvariable describing compactive effort. It was assigned –1, 0 and 1 for British Standard light, West African Standardand British Standard heavy compactive efforts, respectively. These results were used to run a regression model forpredicting laboratory UCS results. The statistical analyses were carried out using the tools ofanalysis Mini-tab R15 software and the regression equation obtained for unconfined compressive strength, California bearing ratio and resistance to loss in strength isgiven in equation 8 to 10 bellow.

$$UCS(7) = -2687 - 22.3\,WRO - 58.4\,HM + 0.39\,BA + 121\,CKD - 21.2\,E + 2.64\,C3S + 2.84\,C2S + 1863\,MDD \qquad (8)$$

$$CBR(US) = -119 - 0.37\,WRO - 2.01\,HM + 0.082\,BA + 6.21\,CKD + 5.52\,E + 0.149\,C3S + 0.155\,C2S + 76.5\,MDD \qquad (9)$$

$$RESISTANCE\ TO\ LOSS\ IN\ STRENGTH = -40.4 + 1.02\,WRO - 0.758\,HM + 0.664\,BA + 6.97\,CKD + 4.29\,E - 0.107\,C3S - 0.0939\,C2S + 23.3\,MDD \qquad (10)$$

Reliability analysis is intended to assess the suitability of compacted bagasseash treated black cotton soilstrength characteristic for use as a sub grade 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 – bagasse 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 – bagasse ash – cement kiln dust mixtures were then incorporated into FORTRANprogrammes for a field based predictive model in order to evaluate reliability levels and to predict UCS, CBR and Resistance to loss in strength using the ‘first order reliability methods’ version 5.0 (FORM 5) (Gollwitzer*et al*., 1988). The inputdata 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 (%)
1a	Unconfined compressive Strength	Lognormal	7.6224E2	3.72E2	48.81
1b	California bearing ratio	Lognormal	3.822E1	2.11E1	55.21
1c	Resistance to loss in Strength	Lognormal	3.848E1	1.804E1	46.88
2	Water Content Relative to optimum (WRO)	Lognormal	1.583E1	1.901E0	12.01
3	Hydraulic modulus HM	Lognormal	1.138E0	1.586E0	139.37
4	Bagasse ash BA	Normal	5.0E0	3.435E0	68.7
5	Cement kiln dust CKD	Normal	4.0E0	2.844E0	71.1
6	Tri-calcium Silicate C_3S	Lognormal	1.911E2	2.15E2	112.51
7	Di-calcium Silicate C_2S	Lognormal	2.314E2	2.064E2	89.16
8	Maximum dry density MDD	Lognormal	1.7344E0	7.99E-2	4.61
9	Compactive effort E	Deterministic parameter	-1, 0, 1	-	-

Sensitivity analysis for each of the independent variables that affect strength was performed byvarying 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 variables evaluated that affect strength are: water content relative to optimum (WRO), hydraulic modulus HM, bagasse ash BA, cement kiln dust CKD, C_3S, C_2S, and Maximum dry density MDD; at compaction energy levels of British Standard light (BSL), West African Standard (WAS) andBritish Standard heavy (BSH) were obtained.

4. Results and Discussion

4.1 Unconfined Compressive Strength

Effect of Strength on Reliability Index

The effect of unconfined compressive strength on reliability indexas the coefficient of variation is varied when computed with a minimum value of 1710 kN/m^2 specified by TRRL (1977) is shown in Fig.1. Higher safety indices were recorded for higher compaction energies. Strength produced a linear decreasing relationship with coefficient of variation in the ranges 10-100% for all compactive effort. Safety index varied considerably which is an indication that variability of strength has drastic influence on the safety index. As COV increased from 10-100%, β value decreased from 0.83to 0.0268, 0.86 to 0.046 and 0.89 to 0.065 for BSL, WAS and BSH compactions, respectively.Similar trend of decreasing safety index as COV increases is reported by (Yisa and Sani, 2014).

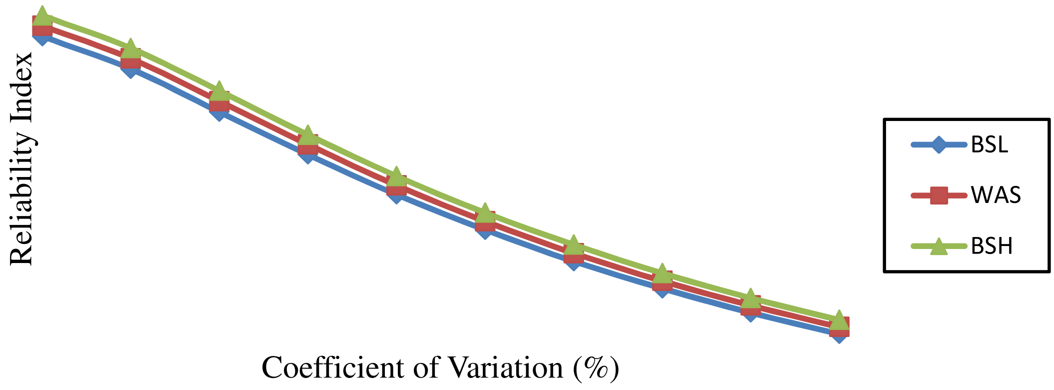

Fig.1: Variation of reliability index with coefficient of variation for 7 days unconfined compressive strength

Effect of Water Content Relative to Optimum on Reliability Indexon the 7 days unconfined compressive strength

The effect of water content relative to optimum on reliability indexas the coefficient of variation is varied is shown in Fig.2. Higher safety indices were recorded for higher compaction energies. Water content relative to optimum produced a linear decreasing relationship with coefficient of variation in the ranges 10-100%for BSL, WAS and BSH compactive effort respectively. Safety index varied considerably which is an indication that variability of WRO has drastic influence on the safety index. As COV increased from 10-100%, β value decreased from 0.73-0.56, 0.75 to 0.59 and 0.78to 0.62 for BSL, WAS and BSH compactions, respectively.

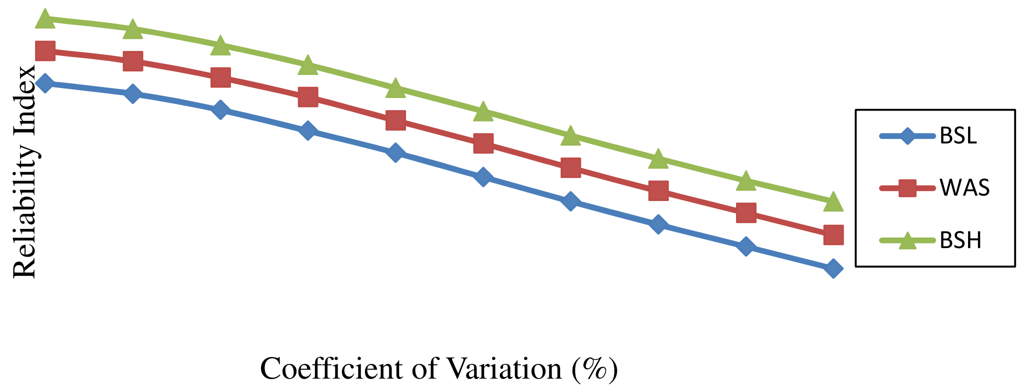

Fig.2: Variation of reliability index with coefficient of variation for water content relative to optimum

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

The effect of hydraulic moduluson reliability indexas the coefficient of variation is varied is shown in Fig.3. Higher safety indices were recorded for higher compaction energies. Hydraulic modulus produced a linear decreasing relationship with coefficient of variation in the ranges 10-100% for BSL, WAS and BSH compactive effort respectively.This is an indication that variability of hydraulic modulus has drastic influence on the safety index. As COV increased from 10-100%, β value decreased from 0.76 to 0.74, 0.79 to 0.76 and 0.82 to 0.79for BSL, WAS and BSH compactionsenergy respectively.

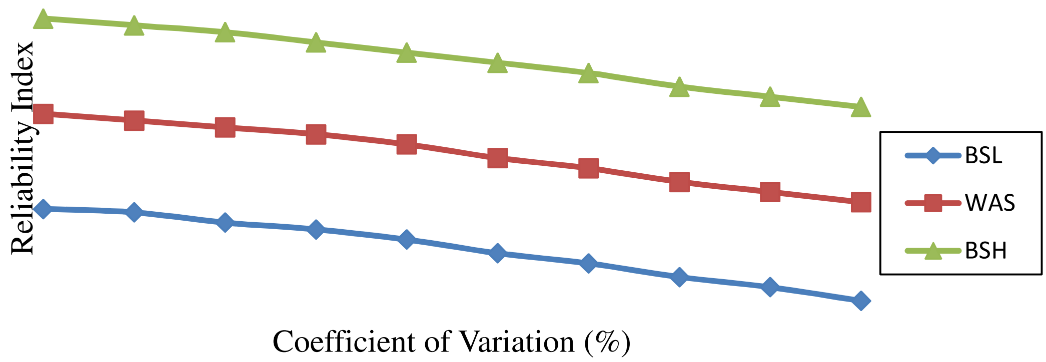

Fig.3: Variation of reliability index with coefficient of variation for hydraulic modulus

Effect of Bagasse Ash Content on Reliability Indexon the 7 days unconfined compressive strength

The effect of bagasse *ash content* on reliability indexas the coefficient of variation is varied is shown in Fig.4. Higher safety indices were recorded for higher compaction energies. Bagasse *ash content* produced a linear relationship with coefficient of variation in the range 10-100% for BSL, WAS and BSH compactive effort only, while reliability or safety index remained constant. This is an indication that variability of bagasse ash has no drastic influence on the safety index. As COV increased from 10-100%, β value remain constant at 0.72,0.75 and 0.78for BSL, WAS and BSH compactions, respectively.

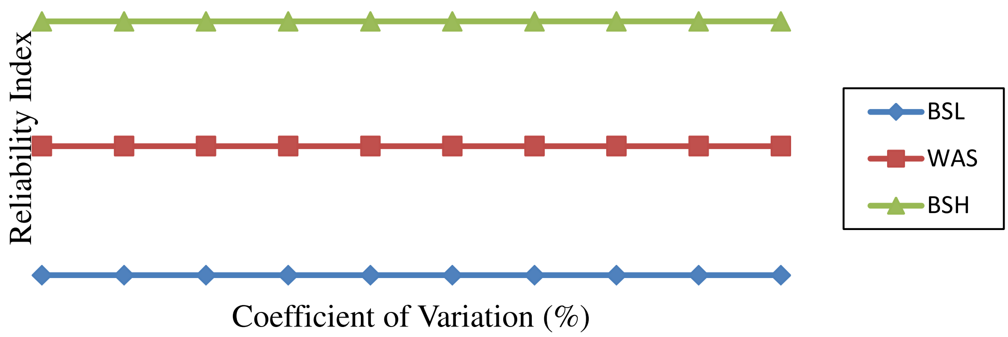

Fig.4: Variation of reliability index with coefficient of variation for bagasse ash

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

The effect of cement kiln dust content on reliability indexas 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 decreasing relationship with coefficient of variation in the range 10-100% for BSL, WAS and BSH compactive effort. This is an indication that variability of cement kiln dust contenthassome drastic influence on the safety index.As COV increased from 10-100%, β value decreased from 0.81-0.66,0.84-0.68 and 0.87-0.71 for BSL, WAS and BSH compactions, respectively.

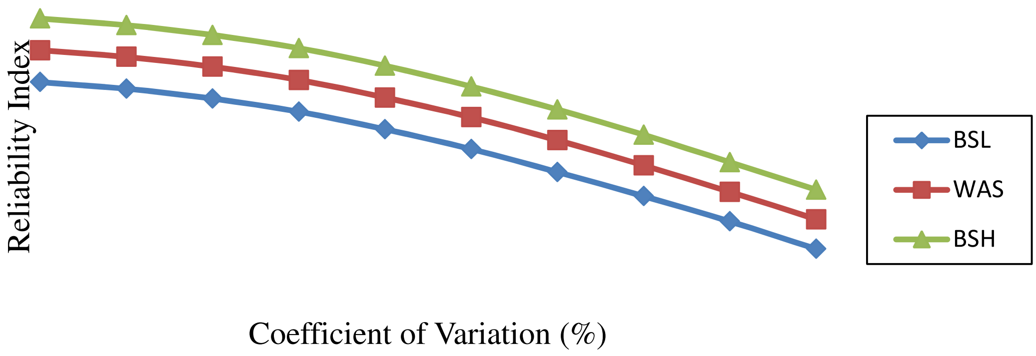

Fig.5: Variation of reliability index with coefficient of variation for cement kiln dust

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

The effect of Tr*i-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. Tr*i-calcium silicate* content produced a linear increasing relationship with coefficient of variation in 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 Tr*i-calcium silicate* content has no effects on the safety index. As COV increased from 10-100%, β valuealso increased from 0.57 to 0.70,0.60 to 0.73and 0.64 to 0.76 for BSL, WAS and BSH compactions respectively.

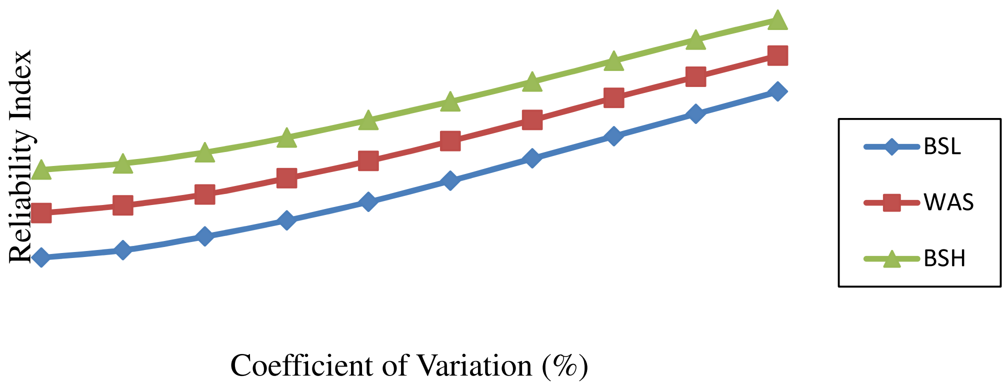

Fig.6: Variation of reliability index with coefficient of variation for tri- calcium silicate C_3S

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

The effect of Di-*Calciumsilicate 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. *Di-Calcium silicate content*produced a linear increasing relationship with coefficient of variation in the ranges 10-100%for BSL, WAS and BSH compactive effort. Safety index varied considerably which is an indication that variability of *Di-Calcium silicate content*has no drastic influence on the safety index. As COV increased from 10-100%, β value increased from 0.52-0.64, 0.55-0.67 and 0.59-0.70 forBSL, WAS and BSH compactions, respectively.

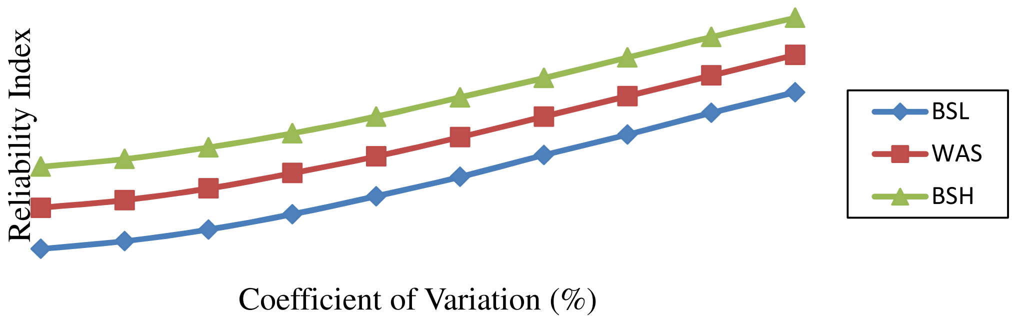

Fig.7: Variation of reliability index with coefficient of variation for di- calcium silicate C_2S

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.8. Higher safety indices were recorded for higher compaction energies. M*aximum dry density* 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. As COV increased from 10-100%, β value decreased from 0.69-0.58, 0.72-05.8 and 0.74-0.59 BSL, WAS and BSH compactions, respectively.

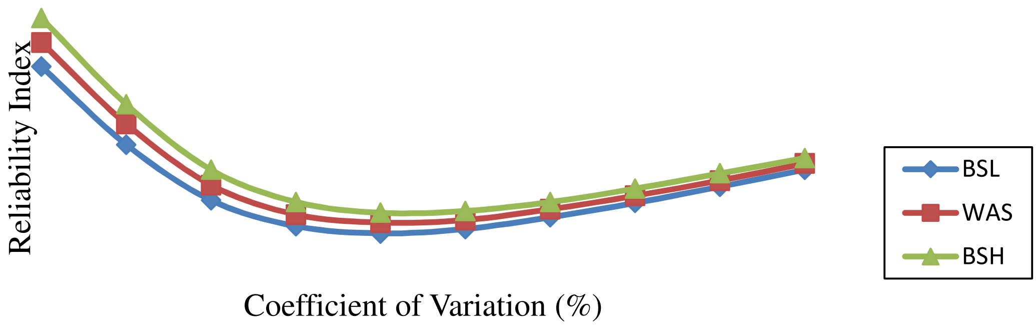

Fig.8: Variation of reliability index with coefficient of variation for maximum dry density

4.2 California bearing ratio

Effect of California Bearing Ratio on Reliability Index

The effect of California bearing ratio on reliability indexas the coefficient of variation is varied when computed with a minimum value of 30% specified by Nigerian general specification (1997) is shown in Fig.9. Higher safety indices were recorded for higher compaction energies. Safety index produced a linear decreasing relationship with coefficient of variation in the ranges 10-100% for all compactive effort. Safety index varied considerably which is an indication that variability of strength has drastic influence on the safety index. As COV increased from 10-100%, β value decreased from 1.01 to 0.967, 1.25 to 1.09 and 1.50 to 1.21 for BSL, WAS and

BSH compactions, respectively. Similar trend of decreasing safety index as COV increases is reported by (Yisa and Sani, 2014).

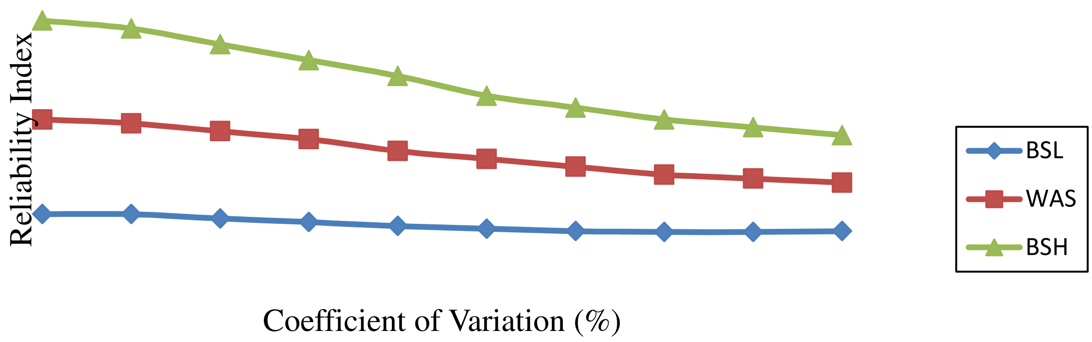

Fig.9: Variation of reliability index with coefficient of variation for California bearing ratio Unsoaked

Effect of Water Content Relative to Optimum on Reliability Indexon the California Bearing Ratio

The effect of water content relative to optimum on reliability indexas the coefficient of variation is varied is shown in Fig.10. Higher safety indices were recorded for higher compaction energies. Water content relative to optimum produced a linear increasing relationship with coefficient of variation in the ranges 10-100% for BSL, WAS and BSH compactive effort respectively. Safety index increases with increase in COVwhich is an indication that variability of WRO has no effect on the safety index. As COV increased from 10-100%, β value increased from 0.967-1.01, 1.13 to 1.17 and 1.28 to 1.31 for BSL, WAS and BSH compactions, respectively.

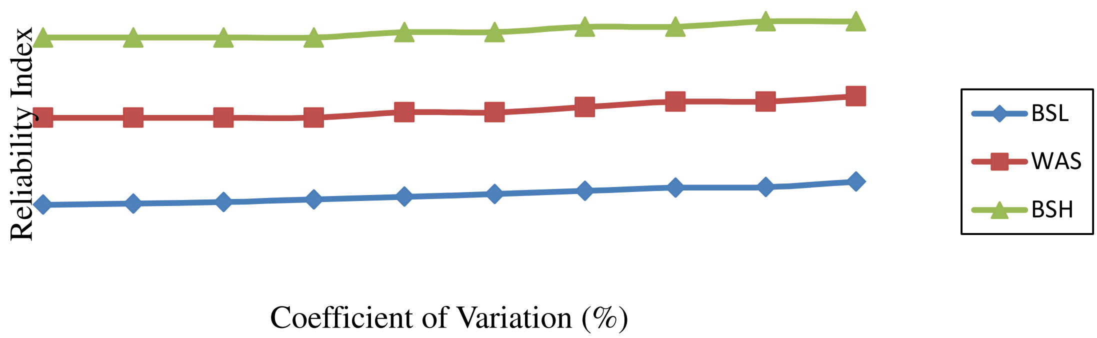

Fig.10: Variation of reliability index with coefficient of variation for water content relative to optimum

Effect of Hydraulic Modulus on Reliability Index on the California Bearing Ratio

The effect of hydraulic moduluson reliability indexas the coefficient of variation is varied is shown in Fig.11. Higher safety indices were recorded for higher compaction energies. Hydraulic modulus produced a linear increasing relationship with coefficient of variation in the ranges 10-100% for BSL, WAS and BSH compactive effort respectively. This is an indication that variability of hydraulic modulus has no drastic influence on the safety index. As COV increased from 10-100%, β value decreased from 0.94 to 0.959, 1.10 to 1.12 and 1.25 to 1.27 for BSL, WAS and BSH compactions energy respectively.

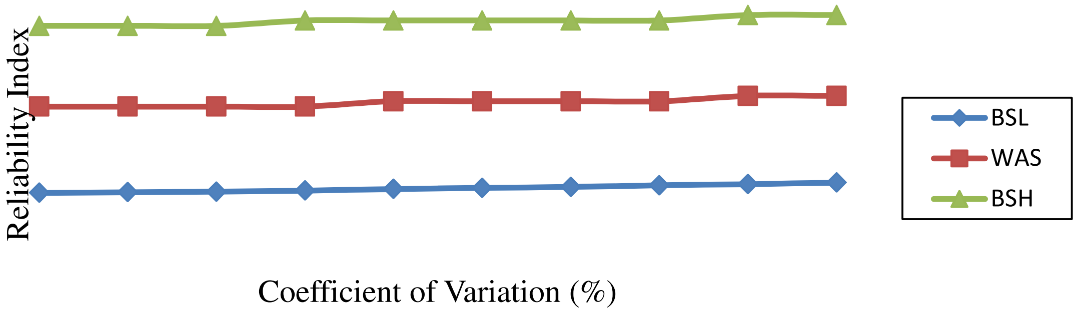

Fig.11: Variation of reliability index with coefficient of variation for hydraulic modulus

Effect of Bagasse Ash Content on Reliability Index on the California Bearing Ratio

The effect of bagasse *ash content* on reliability indexas the coefficient of variation is varied is shown in Fig.12. Higher safety indices were recorded for higher compaction energies. Bagasse *ash content* produced a linear relationship with coefficient of variation in the range 10-100% for BSL, WAS and BSH compactive effort, while reliability or safety index remained constant. This is an indication that variability of bagasse ash has no drastic influence on the safety index. As COV increased from 10-100%, β value remain constant at 0.967, 1.13 and 1.28 for BSL, WAS and BSH compactions, respectively.

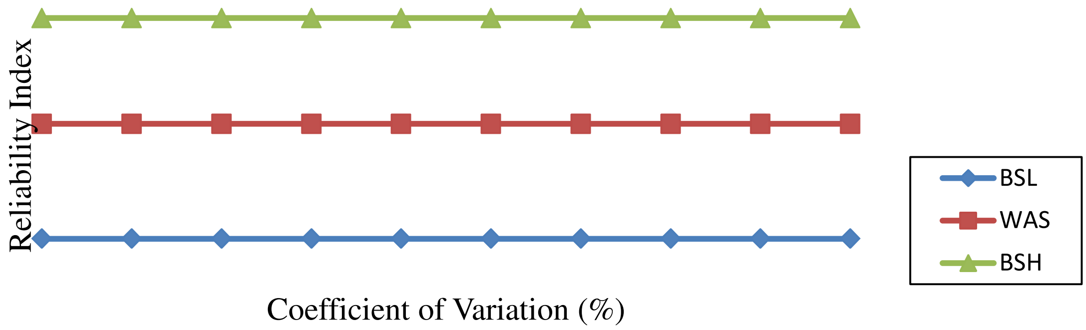

Fig.12: Variation of reliability index with coefficient of variation for bagasse ash

Effect of Cement Kiln Dust on Reliability Index on the California Bearing Ratio

The effect of cement kiln dust content on reliability indexas the coefficient of variation is varied is shown in Fig.13. Higher safety indices were recorded for higher compaction energies. Cement kiln dust content produced a linear decreasing relationship with coefficient of variation in the range 10-100% for BSL, WAS and BSH compactive effort. This is an indication that variability of cement kiln dust content has some drastic influence on the safety index. As COV increased from 10-100%, β value decreased from 1.11-0.856, 1.27-1.00 and 1.42 -1.15 for BSL, WAS and BSH compactions, respectively.

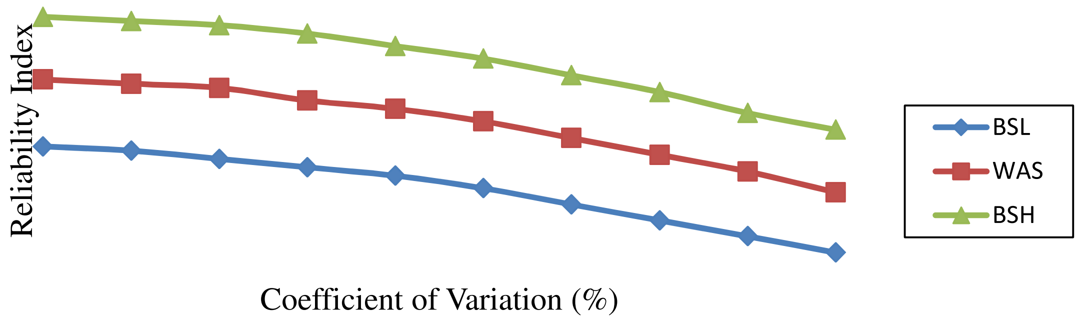

Fig.13: Variation of reliability index with coefficient of variation for cement kiln dust

Effect of Tri-calcium silicate on Reliability Index on the California Bearing Ratio

The effect of Tr*i-calcium silicate* content on reliability index as the coefficient of variation is varied is shown in Fig.14. Higher safety indices were recorded for higher compaction energies. Tr*i-calcium silicate* content produced a linear increasing relationship with coefficient of variation in the range 10-100% for BSL, WAS and BSH compactive effort. This is an indication that variability of Tr*i-calcium silicate* content has drastic effects on the safety index. As COV increased from 10-100%, β value also increased from 1.32 to 1.00, 1.46 to 1.16 and 1.60 to 1.31 for BSL, WAS and BSH compactions respectively.

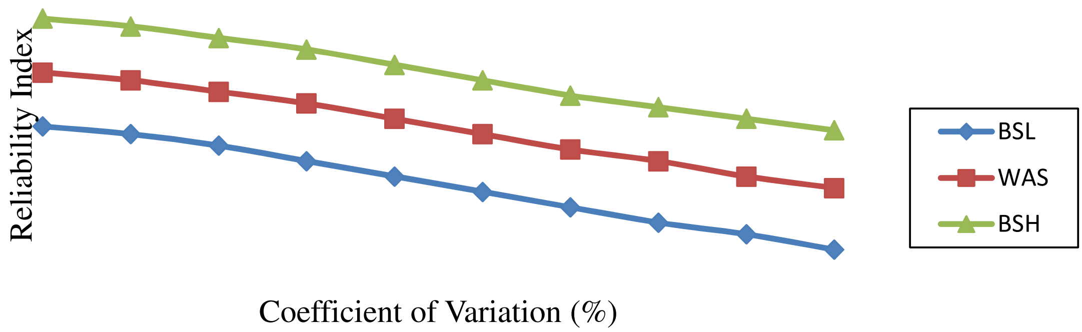

Fig.14: Variation of reliability index with coefficient of variation for tri- calcium silicate C_3S

Effect of Di-calcium silicate on Reliability Index on the California Bearing Ratio

The effect of Di-*Calcium silicate content* on reliability index as the coefficient of variation is varied is shown in Fig.15. Higher safety indices were recorded for higher compaction energies. *Di-Calcium silicate content*produced a linear decreasing relationship with coefficient of variation in the ranges 10-100% for BSL, WAS and BSH compactive effort. Safety index varied considerably which is an indication that variability of *Di-Calcium silicate content*has drastic influence on the safety index. As COV increased from 10-100%, β value increased from 1.28-1.07, 1.42-1.22 and 1.56-1.36 for BSL, WAS and BSH compactions, respectively.

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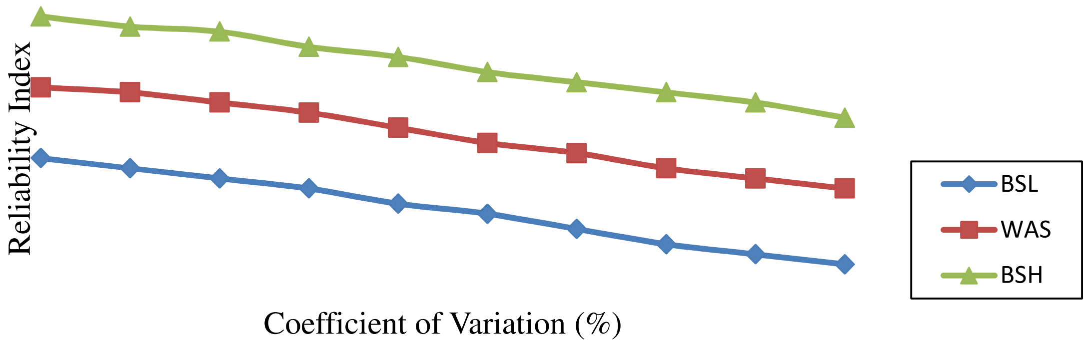

Fig.15: Variation of reliability index with coefficient of variation for di-calcium silicate C_2S

Effect of Maximum Dry Density on Reliability Index on the California Bearing Ratio

The effect of *maximum dry density* on reliability index as the coefficient of variation is varied is shown in Fig.16. Higher safety indices were recorded for higher compaction energies. M*aximum dry density* produced a linear decreasing relationship with coefficient of variation in the ranges 10-100% for BSL, WAS and BSH compactive effort. Safety index varied considerably which is an indication that variability of *maximum dry density* has drastic influence on the safety index. As COV increased from 10-100%, β value decreased from 0.901 to -0.0874, 1.06 to -0.0241 and 1.21 to 0.0419 BSL, WAS and BSH compactions, respectively.

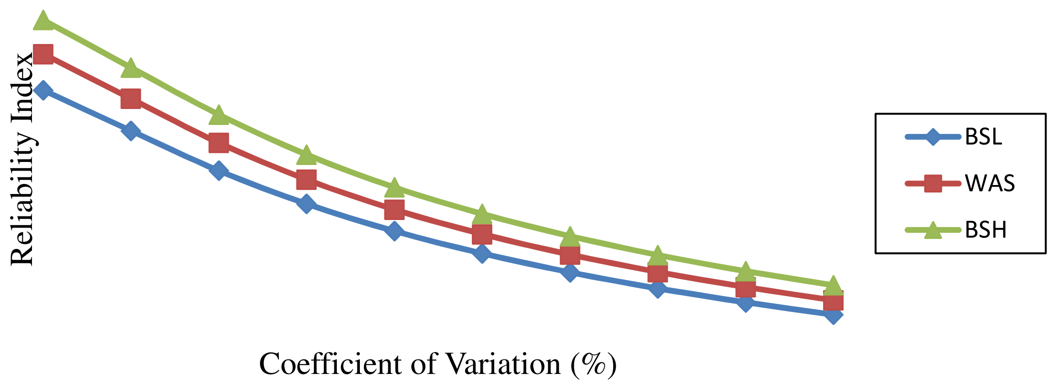

Fig.16: Variation of reliability index with coefficient of variation for maximum dry density

4.3 Resistance to loss in strength

Effect of Resistance to loss in Strength on Reliability Index

The effect of resistance to loss in strength on reliability indexas the coefficient of variation is varied when computed with a minimum value of 80% specified by (Ola, 1983) based on 4 days soakingis shown in Fig.17. Higher safety indices were recorded atlower compaction energies. Strength produced a linear decreasing relationship with coefficient of variation in the ranges 10-100% for all compactive effort. Safety index varied considerably which is an indication that variability of strength has drastic influence on the safety index. As COV increased from 10-100%, β value decreased from 2.70 to 0.974, 2.51 to 0.852 and 2.32 to 0.735 for BSL, WAS and BSH compactions, respectively.

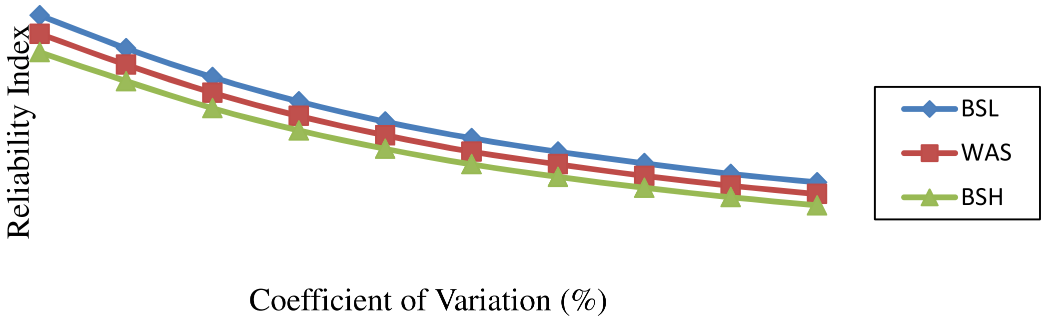

Fig.17: Variation of reliability index with coefficient of variation for resistance to loss in strenght

Effect of Water Content Relative to Optimum on Reliability Indexon the Resistance to loss in Strength

The effect of water content relative to optimum on reliability indexas the coefficient of variation is varied is shown in Fig.18. Higher safety indices were recorded atlower compaction energies. Water content relative to optimum produced a linear decreasing relationship with coefficient of variation in the ranges 10-100% for BSL, WAS and BSH compactive effort respectively. Safety index varied considerably which is an indication that variability of WRO has drastic influence on the safety index. As COV increased from 10-100%, β value decreased from 2.28-2.03, 2.11 to 1.93 and 1.95 to 1.83 for BSL, WAS and BSH compactions, respectively.

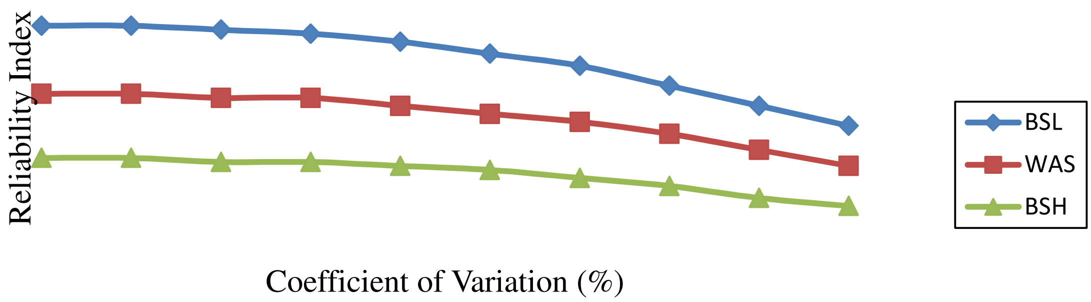

Fig.18: Variation of reliability index with coefficient of variation for water content relative to optimum

Effect of Hydraulic Modulus on Reliability Index on the Resistance to loss in Strength

The effect of hydraulic moduluson reliability indexas the coefficient of variation is varied is shown in Fig.19. Higher safety indices were recorded atlower compaction energies. Hydraulic modulus produced a linear relationship with coefficient of variation in the ranges 10-100% for BSL, WAS and BSH compactive effort respectively. This is an indication that variability of hydraulic modulus has no drastic influence on the safety index. As COV increased from 10-100%, β value remain approximately constant at 2.29, 2.13 and 1.96 for BSL, WAS and BSH compactions energy respectively.

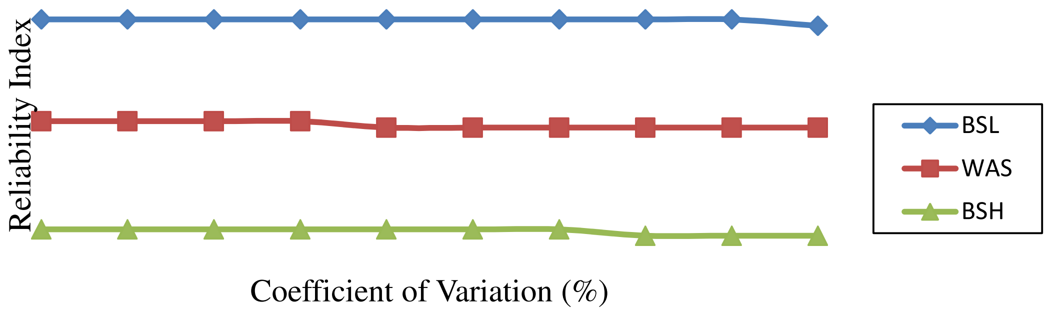

Fig.19: Variation of reliability index with coefficient of variation for hydraulic modulus

Effect of Bagasse Ash Content on Reliability Index on the Resistance to loss in Strength

The effect of bagasse *ash content* on reliability indexas the coefficient of variation is varied is shown in Fig.20. Higher safety indices were recorded atlower compaction energies. Bagasse *ash content* produced a linear relationship with coefficient of variation in 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 bagasse ash has no drastic influence on the safety index. As COV increased from 10-100%, β value decrease from 2.29 – 2.27, 2.12-2.10 and 1.95-1.94 for BSL, WAS and BSH compactions, respectively.

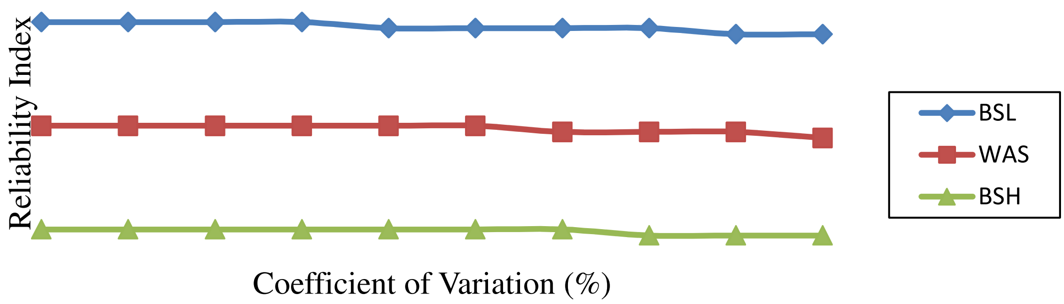

Fig.20: Variation of reliability index with coefficient of variation for bagasse ash

Effect of Cement Kiln Dust on Reliability Index on the Resistance to loss in Strength

The effect of cement kiln dust content on reliability indexas the coefficient of variation is varied is shown in Fig.21. Higher safety indices were recorded atlower compaction energies. Cement kiln dust content produced a linear decreasing relationship with coefficient of variation in the range 10-100% for BSL, WAS and BSH compactive effort. This is an indication that variability of cement kiln dust content has some drastic influence on the safety index. As COV increased from 10-100%, β value decreased from 3.66-1.82, 3.48-1.69 and 3.30-1.56 for BSL, WAS and BSH compactions, respectively.

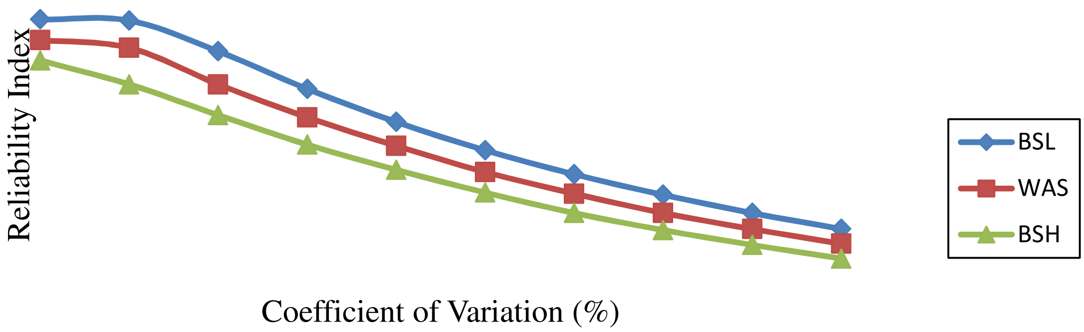

Fig.21: Variation of reliability index with coefficient of variation for cement kiln dust

Effect of Tri-calcium silicate on Reliability Index on the Resistance to loss in Strength

The effect of Tr*i-calcium silicate* content on reliability index as the coefficient of variation is varied is shown in Fig.22. Higher safety indices were recorded atlower compaction energies. Tr*i-calcium silicate* content produced a linear decreasing relationship with coefficient of variation in the range 10-100% for BSL, WAS and BSH compactive effort. This is an indication that variability of Tr*i-calcium silicate* content has drastic effects on the safety index. As COV increased from 10-100%, β value decreased from 2.70 to 2.31, 2.53 to 2.15 and 2.35 to 1.98 for BSL, WAS and BSH compactions respectively.

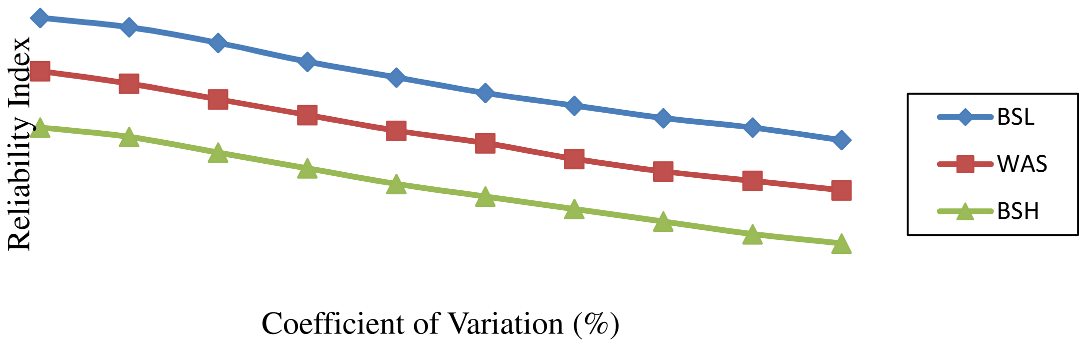

Fig.22: Variation of reliability index with coefficient of variation for tri-calcium silicate C_3S

Effect of Di-calcium silicate on Reliability Index on the Resistance to loss in Strength

The effect of Di-*Calcium silicate content* on reliability index as the coefficient of variation is varied is shown in Fig.23. Higher safety indices were recorded atlower compaction energies. *Di-Calcium silicate content*produced a linear decreasing relationship with coefficient of variation in the ranges 10-100% for BSL, WAS and BSH compactive effort. Safety index varied considerably which is an indication that variability of *Di-Calcium silicate content*has drastic influence on the safety index. As COV increased from 10-100%, β value increased from 2.56-2.36, 2.39-2.19 and 2.22-2.03 for BSL, WAS and BSH compactions, respectively.

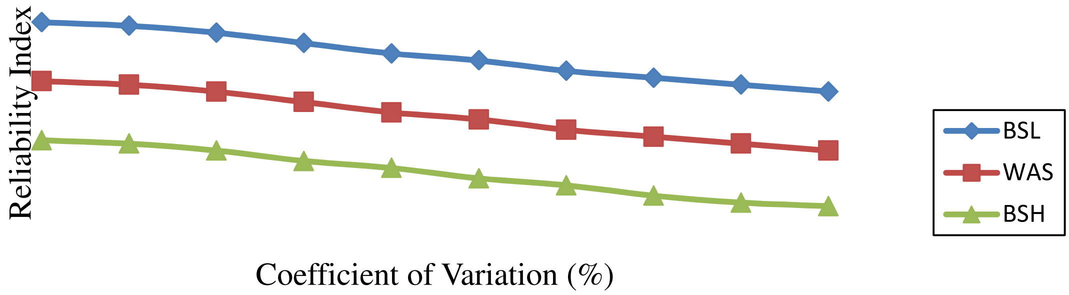

Fig.23: Variation of reliability index with coefficient of variation for di- calcium silicate C_2S

Effect of Maximum Dry Density on Reliability Index on the Resistance to loss in Strength

The effect of *maximum dry density* on reliability index as the coefficient of variation is varied is shown in Fig.24. Higher safety indices were recorded atlower compaction energies. M*aximum dry density* produced a linear decreasing relationship with coefficient of variation in the ranges 10-100% for BSL, WAS and BSH compactive effort. Safety index varied considerably which is an indication that variability of *maximum dry density* has drastic influence on the safety index. As COV increased from 10-100%, β value decreased from 2.26-1.45, 2.10-1.39 and 1.93-1.33 BSL, WAS and BSH compactions, respectively.

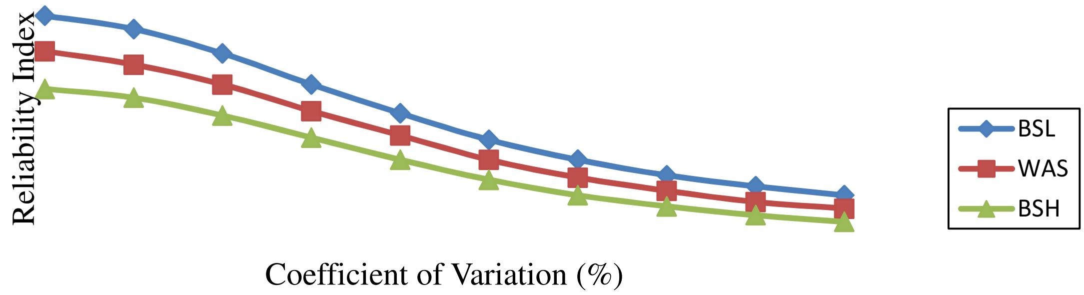

Fig.24: Variation of reliability index with coefficient of variation for maximum dry density

Statistical Significance of Safety Index Values

Statistical analysis of all the results obtained for the parameters (UCS, CBR, Resistance to loss in strength, W.R.O., HM, BA, CKD, C_3S, C_2S, 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 to 4.Using the F-distribution test at 95% level of significance compactive effort has significant effect on the outcome ofthe results recorded from the ANOVA test. Therefore care must be taken in ensuring that the compactive efforts thatproduced successful safety index are carefully monitored because they have influence on the value of the unconfined compressive strength, California bearing ratio and resistance to loss in strength. Table 2 shows that from the parameters, the one that has more significant effects on the unconfined compressive strength test is water content relative to optimum, then follow by bagasse ash, hydraulic modulus, cement kiln dust,di-calcium silicate, tri-calcium silicate and maximum dry density in descending order of their significance. Table 3 shows that from the parameters, the one that has more significant effects on the California bearing ratio test is bagasse ash, then follow by hydraulic conductivity, water with respect to optimum, cement kiln dust, di-calcium silicate, tri-calcium silicate and maximum dry density in the order of their significance. Table 4 shows that from the parameters, the one that has more significant effects on the resistance to loss in strength test is di-calcium silicate follow by bagasse ash, hydraulic conductivity, tri-calcium silicate, water with respect to optimum, cement kiln dust, and maximum dry density in descending order of their significance.

Table.2: Analysis of variance of reliability index values for unconfined compressive strength

Variable	Source of variation	Degree of freedom	F – value calculated	P – value	F–value critical	SS
UCS 7 Day curing	COV Compactive effort	9 2	18340.27 440.73	8.83E-34 5.15E-16	2.46 3.55	SS SS
Water content relative to optimum	COV Compactive effort	9 2	68792.54 58651.54	6.01E-39 4.71E-35	2.46 3.55	SS SS
Hydraulic modulus	COV Compactive effort	9 2	1903.583 58381	6.24E-25 4.91E-35	2.46 3.55	SS SS
Bagasse ash	COV Compactive effort	9 2	65535 65535	-- --	2.46 3.55	SS SS
Cement kiln dust	COV Compactive effort	9 2	12923.29 12031.61	2.06E-32 7.28E-29	2.46 3.55	SS SS
Tri-calcium silicate C_2S	COV Compactive effort	9 2	1235.597 2145.533	3.03E-23 3.87E-22	2.46 3.55	SS SS
Di-calcium silicate C_2S	COV Compactive effort	9 2	4178.607 7577.893	5.31E-28 4.65E-27	2.46 3.55	SS SS
Maximum dry density MDD	COV Compactive effort	9 2	241.0227 36.33714	6.84E-17 4.79E-07	2.46 3.55	SS SS

SS= statistically significant at 5% level

COV= Coefficient of variation

Table.3: Analysis of variance of reliability index values for California bearing ratio

Variable	Source of variation	Degree of freedom	F – value calculated	P – value	F–value critical	SS
California bearing ratio	COV Compactive effort	9 2	5.75 170.63	8.21E-4 1.99E-12	2.46 3.55	SS SS
Water content relative to optimum	COV Compactive effort	9 2	71.25 29026.55	3.13E-12 2.64E-32	2.46 3.55	SS SS
Hydraulic modulus	COV Compactive effort	9 2	35.05 55659.96	1.33E-09 7.55E-35	2.46 3.55	SS SS
Bagasse ash	COV Compactive effort	9 2	-2 1.59E+16	-- 6E-138	2.46 3.55	NS SS
Cement kiln dust	COV Compactive effort	9 2	1122.665 10389.25	7.17E-23 2.73E-28	2.46 3.55	SS SS
Tri-calcium silicate C_2S	COV Compactive effort	9 2	1201.351 7424.766	3.9E-23 5.59E-27	2.46 3.55	SS SS
Di-calcium silicate C_2S	COV Compactive effort	9 2	729.30 10000.29	3.44E-21 3.84E-28	2.46 3.55	SS SS
Maximum dry density MDD	COV Compactive effort	9 2	415.5078 103.12	5.3E-19 1.38E-10	2.46 3.55	SS SS

SS= statistically significant at 5% level

NS = Not statistically significant at 5% level

COV= Coefficient of variation

Table.4: Analysis of variance of reliability index values for resistance to loss in strength

Variable	Source of variation	Degree of freedom	F – value calculated	P – value	F–value critical	SS
Resistance to loss in strength	COV	9	1714.501	1.6E-24	2.46	SS
	Compactive effort	2	383.7975	1.74E-15	3.55	SS
Water content relative to optimum	COV	9	23.21142	3.89E-08	2.46	SS
	Compactive effort	2	377.9816	1.99E-15	3.55	SS
Hydraulic modulus	COV	9	3.23	1.65E-2	2.46	SS
	Compactive effort	2	24000.68	1.46E-31	3.55	SS
Bagasse ash	COV	9	9.81	2.61E-05	2.46	SS
	Compactive effort	2	24436.16	1.24E-31	3.55	SS
Cement kiln dust	COV	9	410.2383	5.94E-19	2.46	SS
	Compactive effort	2	127.6747	2.33E-11	3.55	SS
Tri-calcium silicate C_2S	COV	9	2068.478	2.96E-25	2.46	SS
	Compactive effort	2	11242.3	1.34E-28	3.55	SS
Di-calcium silicate C_2S	COV	9	1949	5.05E-25	2.46	SS
	Compactive effort	2	36505.29	3.36E-33	3.55	SS
Maximum dry density MDD	COV	9	139.37	8.8E-15	2.46	SS
	Compactive effort	2	74.69	1.92E-09	3.55	SS

SS= statistically significant at 5% level

COV= Coefficient of variation

Stochastical Model Assessment

The safety index obtained for the three compactive efforts BSL, WAS, and BSH for *the 7 days unconfined compressive strength, California bearing ratio and resistance to loss in strength are*tabulatedin Table 5 - 7. NKB Report (1978) specified a safety index value of 1.0 as the lowestvalue for serviceability limit state design (model 1) of structural components. As shown in table 5, none of the safety index value obtained met the 1.0 lowest value for serviceability limit state design for structural component. While the safety value in Table 6 and 7 met the 1.0 lowest values for serviceability limit state designs for structural component.

Table. 5: Stochastical Model Assessment of acceptable safety index for unconfined compressive strength test

Variables	Beta Value			Acceptable Range of COV (%)		
Factors	BSL	WAS	BSH	BSL	WAS	BSH
UCS 7 Day curing	0.83-0.03	0.86-0.05	0.89-0.07	Nil	Nil	Nil
Water content relative to optimum	0.73-0.57	0.75-0.60	0.78-0.62	Nil	Nil	Nil
Hydraulic modulus	0.76-0.74	0.79-0.76	0.82-0.79	Nil	Nil	Nil
Bagasse ash	0.72-0.72	0.75-0.75	0.78-0.78	Nil	Nil	Nil
Cement kiln dust	0.81-0.66	0.84-0.68	0.87-0.71	Nil	Nil	Nil
Tri-calcium silicate C_3S	0.57-0.70	0.60-0.73	0.64-0.76	Nil	Nil	Nil
Di-calcium silicate C_2S	0.52-0.64	0.55-0.67	0.59-0.70	Nil	Nil	Nil
Maximum dry density MDD	0.69-0.58	0.72-0.58	0.74-0.59	Nil	Nil	Nil

Table. 6: Stochastical Model Assessment of acceptable safety index for California bearing ratio

Variables Factors	Beta Value			Acceptable Range of COV (%)		
	BSL	WAS	BSH	BSL	WAS	BSH
CBR	1.01-0.97	1.25-1.09	1.50-1.21	10-20%	10-100%	10-100%
Water content relative to optimum	0.97-1.01	1.13-1.17	1.28-1.31	90-100%	10-100%	10-100%
Hydraulic modulus	0.94-0.96	1.10-1.12	1.25-1.27	Nil	10-100%	10-100%
Bagasse ash	0.97-0.97	1.13-1.13	1.28-1.28	Nil	10-100%	10-100%
Cement kiln dust	1.11-0.86	1.27-1.00	1.42-1.15	10-60%	10-100%	10-100%
Tri-calcium silicate C_3S	1.32-1.00	1.46-1.16	1.60-1.31	10-100%	10-100%	10-100%
Di-calcium silicate C_2S	1.28-1.07	1.42-1.22	1.56-1.36	10-100%	10-100%	10-100%
Maximum dry density MDD	0.9-0.087	1.1-0.024	1.21-0.04	Nil	10%	10-20%

Table. 7: Stochastical Model Assessment of acceptable safety index for resistance to loss in strength

Variables Factors	Beta Value			Acceptable Range of COV (%)		
	BSL	WAS	BSH	BSL	WAS	BSH
Resistance to loss in strength	2.70-0.97	2.51-0.85	2.32-0.74	10-100%	10-100%	10-100%
Water content relative to optimum	2.28-2.03	2.11-1.93	1.95-1.83	10-100%	10-100%	10-100%
Hydraulic modulus	2.29-2.28	2.13-2.12	1.96-1.95	10-100%	10-100%	10-100%
Bagasse ash	2.29-2.27	2.12-2.10	1.95-1.94	10-100%	10-100%	10-100%
Cement kiln dust	3.66-1.82	3.48-1.69	3.30-1.56	10-100%	10-100%	10-100%
Tri-calcium silicate C_3S	2.70-2.31	2.53-2.15	2.35-1.98	10-100%	10-100%	10-100%
Di-calcium silicate C_2S	2.56-2.36	2.39-2.19	2.22-2.03	10-100%	10-100%	10-100%
Maximum dry density MDD	2.26-1.45	2.10-1.39	1.93-1.33	10-100%	10-100%	10-100%

Conclusion

Reliability estimates for strength characteristics (unconfined compressive strength, California bearing ratio and resistance to los in strength) of compacted CKD/BA treated black cotton soil 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 indexes produced for the unconfined compressive strength were not satisfactory because the beta values obtained are lower than 1.0 specified for serviceability limit state design at the three compactive effort, while the safety indexes produced for califronia bearing ratio and resistance to loss in strength were satisfactory because the bata values obtained met the 1.0 specified for serviceability limit state design at the three compactive effort. Compositional factor and compound formations based on admixture combination ratiosuch as WRO, HM, CKD, BA, C3S, C2S and MDD do not produced acceptable safety index value of 1.0 at the three energy levels namely BSL, WAS and BSH compactive efforts at COV ranges of 10-100% for the unconfined compressive strength, but the compositional compound met the requirement for California bearing ratio and resistance to loss in strength. Observed trends for unconfined compressive strength indicate that theWRO, HM, CKD and MDD is greatly influenced by the COV and therefore must be strictly controlled in CKD/BA treated black cotton, while BA, C3S and C2S are not affected by COV because they are responsible for the strength gain in the soil – CKD – BA mixture.Observed trends for California bearing ratio indicate that theCKD, C3S, C2S and MDD is greatly influenced by the COV and therefore must be strictly controlled in CKD/BA treated black cotton, while WRO, HM and BA are not affected by COV because they are responsible for the strength gain in the soil – CKD – BA mixture.Observed trends for resistance to loss in strength indicate that theWRO, CKD, C3S, C2S and MDD is greatly influenced by the COV and therefore must be strictly controlled in CKD/BA treated black cotton whileHM and BA are not affected by COV.

Stochastically, none ofthe compactive efforts can be used to model the 7 days unconfined compressive strength of compacted CKD/BA treated black cotton soil as a sub-base material for road pavement at all COV range because the safety index are lower than the acceptable 1.0 value. All the compactive effort, BSL, WAS and BSH compactive efforts can be used to model both California bearing ratio and resistance to loss in strength of compacted CKD/LBWA treated black cotton soil as sub-base material for road pavement at the variable ranges of COV between 10-100% at BSL, 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.

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