Reliability Evaluation of Compacted Tropical Red Soil Admixed with Waste Wood Ash for Use as Road Construction Material

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Abstract: A first-order reliability program (FORM) was applied to evaluate the potential of Tropical Red Soil (lateritic soil) admixed with waste wood ash (WWA) and compacted with British Standard Light (BSL) energy for use as road construction material. Regression models were developed from laboratory data using Mini-tab R15 software which served as limit state equations for the reliability analysis. Using the developed models for compaction characteristics, and a well-known distributions for the related soil parameters, safety indices were calculated considering compaction characteristics (maximum dry density, MDD and optimum moisture content, OMC) as dependent variables and the soil parameters (content of WWA, content of clay, content of silt, content of sand and specific gravity as independent variables). The results revealed that safety index is influenced by alteration in the soil parameters. Results shows that content of clay, content of silt, content of sand and specific gravity are significantly affected by the change in coefficient of variation (COV) and for that reason must be firmly controlled in lateritic soil-waste wood ash (WWA) mixtures compacted with BSL energy for use in road pavement as sub-base material. It was evident from the safety index that WWA content has little effect as its value almost continued unchanged at all COV values used. Stochastically, the BSL energy used did not yield satisfactory safety index value of 1.0 as recommended by the Nordic Committee on Building Regulation. Hence, higher energy level with better additives having higher potency such as cement, lime or bitumen is suggested to model compaction characteristics of lateritic soil-waste wood ash (WWA) mixtures for road pavement purpose as sub-base material for 10-100% variation in COV.

Keywords: Reliability analysis, Coefficient of variation, Safety index, Lateritic soil, Waste wood ash.

1. Introduction

The general behaviour of an engineering structure most times relies on the capacity of the imposed load, strength and stiffness of the structure. The performance of an engineering structure is determined by their requirement which need to be satisfied [1]. The requirements include reliability of the structure against collapse, or failure. The application of reliability approach to assess the performance of a system has been successfully applied in civil engineering [2-4]. [5] Reported that design, construction and management of any building should meet the safety requirements of functionality, economy and aesthetics. For engineering
structure subjected to loading, its response to load is governed by the kind and degree of the load imposed, the strength and its structural stiffness [6].

Current approach uses the mechanism of reliability assessment in different engineering applications, with varying degree of success in many engineering applications [7]. Prior to the coming of reliability optimization, structural inspection and repair programs were totally based on previous engineering experiences. Also, probability theory using the knowledge of statistics like mean, standard deviations and coefficient of variations are employed, has shown to be increasingly successful in many engineering projects [8]. The concept of Probability Theory has gain wide acceptance in many engineering applications.

Lateritic soils are residual soils formed by the breakdown of rocks made from silicate materials after leaching and thereafter washing away of alkaline earth materials, silica and alkali that occur from the processes of weathering. Laterites are self-possessed oxides of metals likes iron, aluminium and other metals oxides that are smallest soluble constituents of the rocks [9-11]. Seasonal expansion and contraction of lateritic soils due to variation in weather conditions marks them incompatible for engineering use in their natural form. The high fee for industrially produced soil improvement materials like cement, lime has led to examination of the effect of agricultural waste such as waste wood ash (WWA) on the engineering properties of deficient soils. WWA has been used in many engineering applications and recorded positive results [12-15].

The measurement of uncertainties in the field of science and engineering has been generally successful. The application of these probabilistic methods has been fruitful in many structural and geotechnical engineering designs [16]. A First Order Reliability Method (FORM) incorporated in FORTRAN program was used to evaluate the potentials of lateritic soil – WWA mixtures as road construction material. This investigation focused on a process established for evaluating the potential of lateritic soil admixed with WWA on the compaction characteristics (MDD and OMC) for use as road construction materials by reviewing the effects of WWA content, content of clay, content of silt, content of sand, specific gravity and COV on the safety indices for lateritic soil compacted with BSL compaction energy.

2. Theoretical background

2.1 Reliability/Safety Index

Probabilistic technique of design is troubled based on the possibility that a structure will recognize the functions allotted to it. The measure of the competence of design in engineering is named reliability/safety index, $\beta$. This is defined by the expression.

$$\beta = \frac{\mu}{d}$$  \hspace{1cm} (1)

where $\mu$ is the mean value of the safety margin and $d$ is the standard deviation. The critical values defined as

$$E(s) = \mu$$  \hspace{1cm} (2)

and $S = 0$  \hspace{1cm} (3)

But $\beta$ defined as reliability index, is the inverse of COV, $V_s$ of the safety margin. [17] Defined reliability index, $\beta$ as

$$\beta = \frac{1}{V_s}$$  \hspace{1cm} (4)
2.2 Theory of First – Order Reliability Method (FORM)

The theory of FORM is founded on the deterministic and probabilistic methods of design which vary in principle for diverse engineering applications. The deterministic approach of design relies on complete discounting of the likelihood of failure [18]. Design challenges include element of ambiguity; unpredictability of randomness. Probabilistic design is characterised by the likelihood that the structure will recognize the purpose allotted to it [19]. If the strength capability denoted by $R$ and the compositional influence denoted by $S$ for the system which are all random variables, the aim of reliability study of any component is the assurance that $R$ did not exceed $S$. In practical case, $R$ and $S$ are regularly defined functions of dissimilar independent parameters. To examine the influence of the variables on the performance of the system, a limit state equation derived with relation to the design variable is develop [19].

This limit state equation or state function is expressed as:

$$G(t) = G(X_1X_2X_3X_n) = R - S$$

(5)

Where $X_i$ for $I = 1, 2, 3 \ldots n$, signify design variables.

The system’s limit state is defined as:

$$G(t) = 0$$

(6)

[20] Reported that reliability designs offer a way of assessing the joint properties of uncertainties and a means of differentiating circumstances where indecisions are predominantly high or low. In the evaluation of design problems involving the choice of soil parameter and its values for geotechnical analysis, reliability analysis, which involves the use of probabilistic theories, is appropriate to take care of uncertainties [20].

Soil reliability can be predictable from equation (7) if the category of likelihood of distribution function for $K$ and its statistics are defined. However, it is also promising only with the likelihood of survival as assumed in equation (8):

$$P_s = 1 - P_f$$

(7)

Where

$P_s$ = survival probability; $P_f$ = failure probability

Failure probability ($P_f$) well-defined as:

$$P_f = P(K_e - K_o(WWA, G_s, SA, SI and CL) < 0)$$

(8)

where:

$K_e$ = expected compaction characteristics (MDD and OMC).

$K_o$ = compaction characteristics (MDD and OMC) of natural soil.

Failure probability on the independent variables; Content of waste wood ash (WWA), Specific gravity (Gs), content of sand (SA), content of silt (SI) and content of clay(CL), as parameters influencing the compaction
characteristics (MDD and OMC) and are used in calculating compaction characteristics values founded on results generated in the laboratory.

3. Material and Methods

3.1 Database for analysis
A database was generated by using data from literature(12). Summary of statistical characteristics used are shown in table 1.

3.2 Set-up for reliability analysis
Laboratory experiments on compaction characteristics, particle size and specific gravity test were determined in the laboratory. Parameters measured comprises compaction characteristics (Maximum dry density, MDD; optimum moisture content, OMC); Content of waste wood ash(WWA), Specific gravity(Gs), content of sand(SA), content of silt(SI) and content of clay(CL). Fundamentally, MDD and OMC are assumed to have a lognormal distribution [18-19, 21]. While content of waste wood ash(WWA), specific gravity(Gs), content of sand(SA), content of silt(SI) and content of clay(CL) are assumed to have a normal distribution. These results were used to develop a regression model for predicting laboratory compaction characteristics. The input data for reliability design for compaction characteristics is presented in table 1. The statistical examinations was done with Mini-tab R15 software and the regression equations for MDD OMC are given in equations 9 and 10 respectively.

Table 1. Input parameters for reliability analysis using FORM 5

| S/No | Variables            | Type of Distribution | Mean E(x) | Standard deviation S(x) | Coefficient of Variation COV (%) |
|------|----------------------|----------------------|-----------|-------------------------|---------------------------------|
| 1    | Maximum dry density  | Lognormal            | 1.71      | 0.020                   | 1.152                           |
| 2    | Optimum moisture content | Lognormal       | 16.33     | 0.320                   | 1.960                           |
| 3    | Waste wood ash       | Normal               | 5.00      | 3.740                   | 74.800                          |
| 4    | Specific gravity     | Normal               | 2.59      | 0.029                   | 1.135                           |
| 5    | Content of sand      | Normal               | 39.21     | 1.367                   | 3.486                           |
| 6    | Content of silt      | Normal               | 29.61     | 0.788                   | 2.661                           |
| 7    | Content of clay      | Normal               | 30.53     | 1.022                   | 3.348                           |

\[
MDD = -6.11 - 0.00633WWA + 0.916Gs + 0.0427SA + 0.0621SI + 0.0641CL \quad (9)
\]

\[
OMC = -197 - 0.22WWA + 6.93Gs + 1.43SA + 2.27SI + 2.39CL \quad (10)
\]

Where MDD = Maximum dry density, OMC = Optimum moisture content, WWA = Waste wood ash content, Gs = Specific gravity, SA = Content of sand, SI = Content of silt and CL = Content of clay.

4. Results and Discussion

4.1 Influence of MDD and OMC on safety index
Change in safety index for MDD and OMC of lateritic soil-WWA mixtures with COV is shown in figure 1. The safety index reduced meaningfully with rise in the COV for both MDD and OMC. It is evident from the results that both MDD and OMC have significant effect on safety index when used as sub-base materials for road pavement. Similar behaviour was observed by [18]. The values ranged from -0.407 to 0.0182 and -0.379 to 0.0563 for MDD and OMC respectively. Also values of -0.4 to 0.0673 and -0.386 to 0.0317 were
gotten for MDD and OMC respectively when calculated with MDD and OMC values of 1.72 Mg/m$^3$ and 16.2% for the untreated soil (see figure 1). Lesser safety indices were noted for the MDD of the modified soil than the untreated soil (i.e natural soil). However, in the case of OMC, higher safety indices were noted for the modified soil than the untreated soil which depicts enhancement on the compaction characteristics of the soil with WWA content.

Figure 1. Graph of safety index with COV for the effect of MDD and OMC on compaction characteristics of WWA modified lateritic soil.

4.2 Influence of waste wood ash on safety index

A change in reliability index with COV is shown in figure 2 for content of WWA. The safety index remained nearly constant for both MDD and OMC as the COV increased from 10 – 100%. The constancy in the safety index is a sign that WWA has no major influence on the compaction properties of the treated soil for use as sub-base materials for road pavement. The values ranged from 0.109 to 0.114 and 0.0806 to 0.0842 for MDD and OMC respectively. Also values of 0.2 to 0.208 and 0.0542 to 0.0566 were obtained for MDD and OMC respectively when computed with MDD and OMC values of 1.72 Mg/m$^3$ and 16.2% for the untreated soil (see figure 2). It was observed that higher safety index was recorded for MDD of the modified soil over the untreated soil which depict that the inclusion of WWA improved only the MDD of the soil and have no impact on the OMC. The implication of higher density for the modified soil helps its suitability for pavement application as higher density lateritic soil has higher bearing capacity that low density soil.
4.3 Influence of specific gravity on safety index

The impact of specific gravity on safety index as COV is changed is shown in figure 3. Specific gravity formed a linear decreasing result with COV in the ranges 10-100% for both MDD and OMC compacted using BSL energy. Safety index changed extensively which suggest that change in specific gravity has drastic influence on the safety index when used for road pavement as sub-base materials. As COV rise from 10-100%, β value/safety index decreased from 0.0464 – 0.00507 and 0.0741– 0.0166 for MDD and OMC respectively. Also values of 0.00928 to 0.085 and 0.0112 to 0.0498 were gotten for MDD and OMC respectively when computed with MDD and OMC values of 1.72Mg/m³ and 16.2% for the untreated soil(see figure 3). It is evident from the result obtained that lower safety index (for both MDD and OMC) was recorded for the untreated soil when compared with that of the modified soil which indicate that addition of WWA to the soil improved its specific gravity for use as sub-base materials for road pavement.
4.4 Influence of content of sand on safety index

Change in safety index for content of sand for lateritic soil – WWA mixtures with COV is shown in figure 4. Safety index decreased linearly at decreasing rate. As COV rises from 10 - 100 %, values decreased in the consistent ranges of 0.0632 – 0.00717 and 0.0474 – 0.00544 for MDD and OMC respectively. It is clear that alterations in the content of sand influenced compaction characteristics meaningfully seen in the changes in safety indices. This is a suggestion that the content of sand is an element that must be monitored during field construction of flexible pavement using WWA modified lateritic soil as pavement material. Safety indices of 0.0132 to 0.116 and 0.00365 to 0.0319 were gotten for MDD and OMC, respectively when calculated with MDD and OMC values of 1.72 Mg/m³ and 16.2% for the untreated soil (see figure 4).
The impact of content of silt on safety index as the COV is changed is shown in figure 5. Content of silt formed a linear diminishing relationship with COV that varied from 10 –100% for MDD and OMC respectively. Safety index varied extensively which is a sign that change in content of silt has severe impact on the safety index. As COV rise from 10–100%, safety index declined from 0.058 to 0.00654 and 0.0409 to 0.00454 for MDD and OMC respectively. Safety index of 0.012 to 0.106 and 0.00305 to 0.0275 were gotten for MDD and OMC respectively when computed with MDD and OMC values of 1.72 Mg/m$^3$ and 16.2% for the untreated soil (see figure 5).

![Graph of safety index with COV for the effect of content of silt on compaction characteristics of WWA treated lateritic soil.](image)

**Figure 5.** Graph of safety index with COV for the effect of content of silt on compaction characteristics of WWA treated lateritic soil.

4.6 **Influence of content of clay on safety index**

The impact of content of clay on safety index as the COV is changed is shown in figure 6. Content of clay gave rise to a linear declining trend with COV in the range 10-100% for MDD and OMC respectively. This suggests that changes in content of clay have drastic effects on the safety index when used for road pavement sub-base materials. As COV rise from 10-100%, safety index declined from 0.0563 to 0.00616 and 0.0391 to 0.00418 for MDD and OMC respectively when compacted using BSL compaction energy. Also values of 0.0113 to 0.103 and 0.00218 to 0.0263 were observed for MDD and OMC respectively when computed with MDD and OMC values of 1.72 Mg/m$^3$ and 16.2% for the untreated soil (see figure 6).
Figure 6. Graph of safety index with COV for the effect of content of clay on compaction characteristics of WWA treated lateritic soil

4.7 Analysis of variance for safety index values

A single factor analysis of variance (ANOVA) for the soil parameters (MDD, OMC, Gs, SA, SI and CL with respect to Waste wood ash (WWA) content gave rise to statistically significant (SS) results as revealed in table 2. F-distribution test at 95% level of significance for WWA has significant effect as revealed in the ANOVA test. Hence caution must be taken in certifying that an optimum blend of WWA content is added to the soil that will produce successful safety index and should be carefully supervised because they have impact on the compaction characteristics. Table 2 shows that all the parameters have almost similar significant effects on the compaction characteristics.

Table 2. ANOVA test on safety index values for compaction characteristics of WWA treated lateritic soil.

| Property          | Variable | Source of Variation | Degree of freedom | F-value calculated | P-value          | F-value calculated | Remark |
|-------------------|----------|---------------------|-------------------|-------------------|------------------|-------------------|--------|
| Compaction        | MDD      | WWA                 | 1                 | 33.268756         | 1.819E-05        | 4.4138734         | SS     |
| characteristics    | OMC      | WWA                 | 1                 | 33.21923          | 1.835E-05        | 4.4138734         | SS     |
| Specific gravity  | MDD      | WWA                 | 1                 | 32.982797         | 1.916E-05        | 4.4138734         | SS     |
|                   | OMC      | WWA                 | 1                 | 32.957425         | 1.924E-05        | 4.4138734         | SS     |
| Sand content       | MDD      | WWA                 | 1                 | 32.976002         | 1.918E-05        | 4.4138734         | SS     |
|                   | OMC      | WWA                 | 1                 | 32.981906         | 1.916E-05        | 4.4138734         | SS     |
| Silt content       | MDD      | WWA                 | 1                 | 32.97808          | 1.917E-05        | 4.4138734         | SS     |
|                   | OMC      | WWA                 | 1                 | 32.984697         | 1.915E-05        | 4.4138734         | SS     |
| Clay content       | MDD      | WWA                 | 1                 | 32.979117         | 1.917E-05        | 4.4138734         | SS     |
|                   | OMC      | WWA                 | 1                 | 32.985689         | 1.915E-05        | 4.4138734         | SS     |

SS = Significant effect
4.8 Stochastic model examination

Safety index gotten for the compaction characteristics with respects to the various parameters considered are presented in table 3. Nordic Committee on Building Regulation [22] itemized a safety index value of 1.0 as the least value for serviceability limit state design of structural components. Table 3 revealed that all the safety indices did not meet the 1.0 least value for serviceability limit state design for structural component.

| Variables          | Beta Value | Acceptable Range of COV (%) |
|--------------------|------------|-----------------------------|
| Compaction         |            |                             |
| characteristics    |            |                             |
| MDD                | -0.407 to 0.0182 | Nil                      |
| OMC                | -0.379 to 0.0563 | Nil                      |
| Waste wood ash     |            |                             |
| MDD                | 0.109 to 0.144  | Nil                      |
| OMC                | 0.0806 to 0.0842 | Nil                      |
| Specific gravity   |            |                             |
| MDD                | 0.00507 to 0.0464 | Nil                      |
| OMC                | 0.0166 to 0.0741 | Nil                      |
| Sand content       |            |                             |
| MDD                | 0.00717 to 0.0632 | Nil                      |
| OMC                | 0.00544 to 0.0474 | Nil                      |
| Silt content       |            |                             |
| MDD                | 0.00654 to 0.058  | Nil                      |
| OMC                | 0.00454 to 0.0409 | Nil                      |
| Clay content       |            |                             |
| MDD                | 0.00616 to 0.0563 | Nil                      |
| OMC                | 0.00418 to 0.0391 | Nil                      |

5. Conclusion

The statistical analysis of WWA modified lateritic soil were conducted and related with those from which the regression models were developed. Using regression models for compaction characteristics, safety indices were computed. Results shows that the content of clay, content of silt, content of sand and specific gravity are significantly affected by the COV and hence must be strictly monitored in WWA mixtures compacted with British Standard light for road pavements purposes. WWA content has little effect as its value nearly stayed constant at all values of COV used. Stochastically, result obtained did not produce acceptable safety index value of 1.0 as recommended by the Nordic Committee on Building Regulation. Therefore attention must be provided in ensuring that an optimum blend of WWA content is added to the soil that will produced successful safety index and have to be prudently checked since they have impact on the compaction characteristics. It is recommended that higher energy level with more effective additives such as cement, bitumen be applied to model compaction characteristics of lateritic soil-waste wood ash (WWA) mixtures for use as road pavement sub-base material.
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