Reliability Estimates of Field Hydraulic Conductivity of Compacted Bagasse Ash Treated Foundry Sand

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Abstract

Reliability estimates of field hydraulic conductivity values of compacted bagasse ash treated foundry sand as landfill liners was under taken by incorporating a predictive model for hydraulic conductivity, which was developed from data obtained from laboratory results for specimens compacted at the energy levels of Standard Proctor (BSL), West African standard (WAS) and British standard heavy (BSH). These results were incorporated into a FORTRAN-based first-order reliability program to obtain reliability index values. variable factors such as water content relative to optimum, degree of saturation, bagasse ash content and percentage fines produced acceptable safety index value of 1.0 at the energy levels of BSL, WAS and BSH compactive effort and they were achieved at COV ranges of 10-100%. Observed trends indicate that the degree of saturation and bagasse ash content are greatly influenced by the COV and therefore must be strictly controlled in bagasse-foundry sand mixtures for use in covers and liners in waste containment facilities. While, recorded trend for water content relative to optimum and percentage fines indicates that this variables do not significantly affect the reliability index of bagasse-foundry sand mixtures for use in covers and liners. Stochastic assessment of the model gave reliability index values in the range of 0.703-0.958, 0.935-1.188 and 1.165-1.416 at the compactive efforts of BSL, WAS, and BSH, respectively. Successful safety index values were recorded at WAS and BSH compactive efforts, therefore, only these two energy levels can be used to model the hydraulic conductivity behavior of bagasse ash treated foundry sand for landfill liners at COV ranges of 50-100% and 10-100%, respectively. Furthermore, using the F-distribution test at 95% level of significance, it was observed that the compactive effort has significant effect on the outcome of the recorded reliability index values from the ANOVA test. Therefore, care must be taken in ensuring that the compactive efforts that produced successful safety indices are carefully monitored during the construction of liner in waste containment facilities. The trend of the recorded results showed that reliability index (**β**) produced value of 1.0 which is considered adequate for serviceability limit state design.

Keywords: Compaction, Compactor weight, Hydraulic conductivity, Bagasse ash treated foundry sand Reliability analysis, Reliability index, Soil composition, Soil liners

1. Introduction

Compacted bagasse ash treated foundry sand have proven to be successful as an integral component of lining systems for municipal waste landfills (Osinubi and Moses, 2011; Osinubi and Moses, 2012). The hydraulic conductivity of compacted liner material is required to be sufficiently low, usually less than 1 x 10^{-9}m/s (Daniel, 1993b; Benson et. al., 1994), as the primary purpose of such compacted bagasse treated foundry sand liner material is to impede the flow of fluids. Hydraulic conductivity is taken as the basic parameter for design and for characterizing liner performance and reliability (Bogardi *et al*., 1989). The variability in the properties of foundry sand from one foundry to another is well documented in literatures (AFS, 1991; Moses, 2012; Okeke and Sadjere, 1991). As with other materials, this variability introduces uncertainties in engineering designs involving the use of foundry sand.

Hydraulic conductivity is one of the material properties of soils that are significantly affected by this variability in composition. Engineering analyses and designs require the application of probabilistic methods as 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 (e.g., 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). Reliability analysis can be used to assess the suitability of compacted bagasse ash treated foundry sand for use as liners and covers in waste containment structures.

2. Theoritical Background

2.1 *Factor of Safety*

The assessment of risk and safety of engineering systems are traditionally based on allowable factor of safety; these are estimated from previous experience with the behaviour (a particular or from observed responses of similar systems). A conventional measure of the safety factor taken by engineers is the ratio of the assumed nominal values of capacity x and demand y (Kotegoda and Rosso, 1997, Duncan, 2000).

$$Z = x/y \tag{1}$$

The decimal on a sytem often results from a number of uncertain components such as wind reading, pollutant loads etc. Because of thenominal values of both the capacity x and the demand y cannot be determined with certainty, the capacity and demand functions must be considered as probability distribution. Hence the safety factor given by the ratio z = x/y of the two random variables X and Y is also a random variable.

The safety factor of a system, treated as a random variable and defined as Z=X/Y is the ratio between capacity X and demand Y for the system.

The inadequacy of the system to meet the demand as measured by the probability of failure, associated with that portion of the distribution of the safety ratio wherein it becomes less tan unity, that is, the portion in which

$$Z+X/Y < 1 \tag{2}$$

The probability P_r of system failure is thus given by (Kottegoda and Rosso, 1997)

$$Pr = P_r [Z <1] – F_2(1) \tag{3}$$

The corresponding probability of non failure is

$$R = 1- P_r = Pr[Z<1] = 1 – F_2(1) \tag{4}$$

which can be interpreted as survival probability or simply reliability. When the joint probability distribution of X and Y is known, the reliability of the system can be evaluated by determining the cdf of X/Y. There is zero probability of failure (pr=0) and a reliability of 100 percent (r=1) only if the maximum demand Y_{max} does not exceed the minimum capacity X_{min}, so that the two distributions do not overlap.

2.2 *Safety Margin*

If the maximum demand Y_{max} exceeds the minimum capacity X_{min}., the distributions overlap and there is a non zero probability of failure. To assess this probability, one can take the difference between capacities and demand (Kottegoda and Rosso, 1997).

$$S = X – Y \tag{5}$$

which is usually referred to as the safety margin. Because X and Y are random, the safety margin is also a random variable.

Safety margin of a system is the random difference S = X – Y between capacity X and demand Y of the system. The inadequacy of the system to meet the demand, as measured by Pr is associated with that portion of the distribution of the safety margin wherein S takes the negative values, i.e. the portion in which

$$S = X - Y < O \quad (6)$$

Thus

$$\{r=Pr[\{X - Y\} < 0] = Pr[S<P\} \quad (7)$$

And the corresponding reliability is

$$R = 1 - Pr = Pr [(X - Y\} > 0] = Pr(S>0] \quad (8)$$

When the joint probability distribution of X and Y is known, the reliability of the system can be evaluated by determining the cumulative distribution function (CDF) of X – Y.

2.3 *Reliability Index*

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

$$\beta = \mu/d \quad (9)$$

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

$$E(s) = \mu \quad (10)$$

and its critical value

$$S= O \quad (11)$$

The reliability index of a system, denoted by 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 β = I/Vs (Kottegoda and Rosso, 1997).

2.4 *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 loading 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:

$$g(t) = g(x1, x2....Xn) = r - s \quad (12)$$

Where x1 for I = 1.2….n, represent the basic design variables.

The limit state of the system can then be expressed as

$$G(t), - 0 \quad (13)$$

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, which involves the application of probabilistic concepts, is suitable for taking care of uncertainties (Duncan, 2000). Thus, hydraulic conductivity is taken to be the basic parameter for design and for characterizing liner performance and reliability. Bogardi et al. (1989) defined soil liner reliability as a probabilistic measure of assurance of post-construction performance characterized by hydraulic conductivity, k.

$$R = P(K_c < K_o) \quad (14)$$

where K_o is the specified hydraulic conductivity limit, such as I x 10^{-9}m/s and K_c is the expected value Furthermore soil liner reliability could be based on other performance parameters, such as the travel time of pollutants through the liner. This is possible only in terms of probability, $P(K<K_o)$.

Soil reliability can be estimated from eq. (15) if the type of probability distribution function for K and its statistical parameters (mean, standard deviation, variance, etc) are known. This is also possible only with the probability of survival as given in eq. (16):

$$P_s = I\text{-}P_f \quad (15)$$

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

In the reliability analysis of compacted soil liners, failure would occur when the liner hydraulic conductivity is equal or greater than the regulatory maximum (1 x 10^{-9}m/s), during its service period or design life. The probability of failure (P_f) can then be formulated as:

$$P_f = P\{K_c - K_o(S_i, PL, C, E) \leq 0\} \quad (16)$$

where: K_c = Expected hydraulic conductivity

K_o = Specified regulatory maximum hydraulic conductivity

S_i = Initial degree of saturation

PI = Plasticity index

C = Clay content

E = Compactive Effort Index.

which are parameters affecting the hydraulic conductivity and used in predicting hydraulic conductivity values based on laboratory results. The limit state function hydraulic conductivity can then be formulated as

$$g(\underline{X}) = Ink_o - Ink_c \quad (17)$$

Failure is said to occur if K_o is less than K_c , for construyction quality control purposes, a regression equation would be required to link point-scale hydraulic conductivity to relevant soil properties, even though hydraulic conductivity is a spatially averaged property (Benson et al., 1994a).

Benson and Trast (1995) developed the following regression model for predicting hydraulic conductivity on the basis of soil composition and structure using laboratory test data:

$$InK_c = -15.0 - 0.087S_i - 0.054PI + 0.022C + 0.91E + c \quad (18)$$

where k is in unit of m/s; C is clay content is any percentage less than 2µm; S_i is degree of initial saturation; PI is plasticity index, E is an integer categorical variable describing compactive effort index, and c is a random error term.

Benson and Trast (1995) concluded from their result that the most signification factors affecting hydraulic conductivity are (in decreasing order of importance):

1. initial saturation
2. compactive effort
3. plasticity index
4. clay content.

Generally, soil hydraulic conductivity decreases with increases in initial saturation, plasticity index and compactive effort but increases with reducing clay content. Benson et al (1994b) reported that a simple regression model was developed based on data extracted from construction documentation reports from 67 landfills in North America where only compacted soil liners constructed with natural clays were considered. Wang and Huang (1984) and Boadu (2000) proposed other regression models for predicting hydraulic conductivity. These are based on laboratory test data for a variety of non-lateritic soils mostly occurring in North America.

3. Materials and Methods

3.1 *Database and Statistical Analysis*

A database was compiled by extracting data on foundry sand from laboratory test results of published literature (e.g Osinubi and Moses, 2011; Osinubi and Moses, 2012). The statistical characteristics of the material composition and compaction variables for foundry sand are shown in Table 1.

3.2 *Statistical Distributions of Variables*

Hydraulic conductivity is usually assumed to be lognormally distributed (Harrop - Williams, 1985; Bogardi et al., 1989; Benson, 1993). Although alternative distributions have been proposed by Harrop - Williams (1985) and Benson (1993), the two parameter lognormal distribution type was adopted here for hydraulic conductivity.

A Kolmogorov-Smirnov (K-S) goodness-of-fit test on the foundry sand-bagasse ash mixtures properties as well as on the compactor weight (sheeps foot rollers only from Benson et al., 1994) indicates that degree of initial saturation are lognormally distributed, while the compactor weight has a Weibull (extreme value Type III) distribution. The distribution type for each variable as stated above was used in this study, although there are also some alternative distribution types.

3.3 *Set-up of Numerical Experiments Reliability Analysis*

The results of all laboratory experiments on hydraulic conductivity and the parameters associated with hydraulic conductivity were measured during the laboratory work. The various parameters measured include the following hydraulic conductivity (k), water content with respect to optimum (WRO), initial degree of saturation (S_i), percentage fines (PF), bagasse ash content , and compactive effort index (E). Fundamentally, hydraulic conductivity, water content with respect to optimum, initial degree of saturation (S_i) and bagasse ash content is normally assumed to have a lognormal distribution (Benson, 1993; Harrop-Williams, 1985; Eberemu, 2008; Stephen, 2010; Benson and Daniel, 1994a. 1994b; Borgadi, *et al*., 1989; Gui *et al*., 2000; Nwaiwu *et al,* 2009) .While percentage fines (PF) has a normal distribution (Eberemu, 2008; Bello, 2010; 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. These results were used to run a regression model for predicting laboratory hydraulic conductivity results. The statistical analyses were carried out using the tools of analysis Mini-tab R15 software.

Reliability analysis can be used to assess the suitability of compacted bagasse ash treated foundry sand for use as liners and covers in waste containment structure. This becomes necessary due to the variability that might exist from foundry sands obtained from one foundry to another. The statistical characteristics of the relevant foundry sand-bagasse ash mixtures as well as physical properties of their probability distribution functions types were established. The relevant statistical properties for foundry sand-bagasse ash mixtures were then incorporated into FORTRAN programmes for a field based predictive model in order to evaluate reliability levels and to predict hydraulic conductivities 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 hydraulic conductivity results are shown in Table. 1.

Sensitivity analysis for each of the independent variables that affect hydraulic conductivity 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 four independent variables evaluated that affect hydraulic conductivity are: water content relative to optimum ((WRO), degree of saturation, bagasse ash content and percentage fines) at compaction energy levels of British Standard light (BSL), West African Standard (WAS) and British Standard heavy (BSH) were obtained.

Table.1. Input data for reliability based design for five independent variable using FORM 5 from laboratory measured hydraulic conductivity.

S/No	Variables	Distribution type	Mean E(x)	Standard Deviation S(x)	Coefficient of Variation COV (%)
1.	Maximum Hydraulic Conductivity (K)	Log normal	1.23E-08	2.1E-08	170.73
1b.	Lnk	Log normal (=3)	19.65	1.97	-10.1
2.	Water Content Relative to Optimum (WRO)	Log normal (=3)	1	2.26	225.50
3.	Degree of Saturation (Sr)	Log normal (=3)	75.67	13.67	18.54
4.	Percentage Fines (PF)	Normal (=2)	27.7	1.71	6.16
5.	Bagasse Ash Content	Log normal (=2)	4	2.85	71.3
6.	Compactive Effort Index (E)	Deterministic Parameter	-1,0,1	-	-

4. Results and Discussion

4.1 *Effect of Hydraulic Conductivity on Reliability Index*

The effect of hydraulic conductivity on reliability index for various coefficients of variation is shown in Fig.1. Hydraulic conductivity varied non-linearly as the coefficient of variation increased in the range 10-100%, while reliability or safety index recorded an increase in value. It was observed that β values increased in the ranges 0.703-0.958, 0.935-1.188 and 1.165-1.416 for BSL, WAS and BSH compactions, respectively. Generally, higher compactive energy levels produced higher safety index as COV increased in the range 10-100% which indicates that the better hydraulic conductivity values of liner material will be obtained at higher compactive efforts. The negative beta values obtained at all the three compactive effort indicate that the liner material is not safe at those specific COV values.

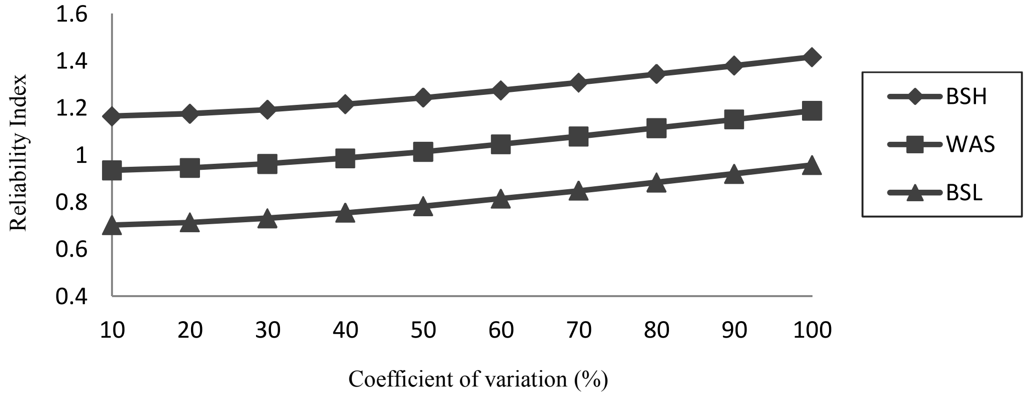

Fig.1: Variation of reliability index with coefficient of variation for hydraulic conductivity

4.2 *Effect of Water Content Relative to Optimum on Reliability Index*

The effect of water content relative to optimum on reliability index as the coefficient of variation is varied is shown in Fig.2. Water content relative to optimum produced a linear relationship with coefficient of variation the range 10-100%, while reliability or safety index varied slightly. This is an indication that variability of WRO has no drastic influence on the safety index similar results were reported by Stephen (2009). As COV increased from 10-100%, β value increased from 2.333-2.368, 2.556-2.589 and 2.777-2.807 for BSL, WAS and BSH compactions, respectively. Generally, higher safety indices were recorded for higher compaction energies.

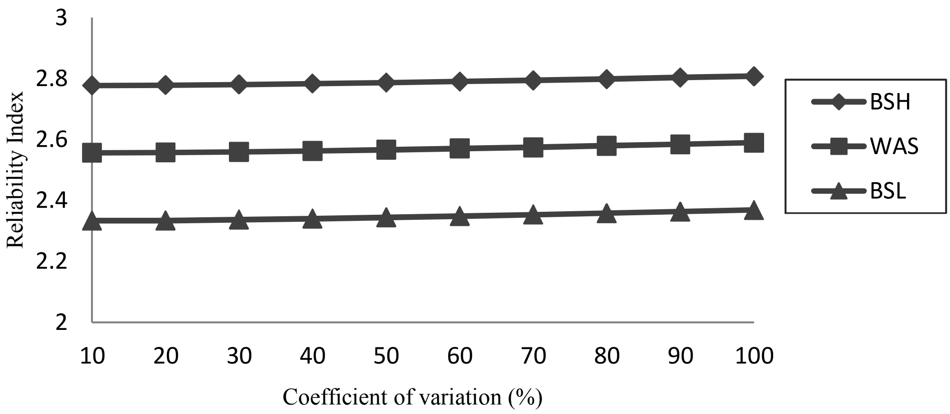

Fig.2: Variation of reliability index with coefficient of variation for water content relative to optimum

4.3 *Effect of Degree of Saturation on Reliability Index*

The effect of degree of saturation on reliability index as the coefficient of variation is varied is shown in Fig.3. The degree of saturation varied non-linearly as the coefficient of variation in the range 10-100%, while, reliability or safety index decreased. Generally, higher compactive efforts produced higher safety indices. The trends recorded are consistent with the findings of Benson et al., (1994; 1999). As COV increased from 10-100%, β value decreased in the corresponding ranges 2.427-1.249, 2.679-1.297 and 2.854-1.344 for BSL, WAS and BSH compactions, respectively. The rapid change in safety index as COV in the range 10-100% is an indication that hydraulic conductivity is significantly influenced by changes in initial degree of saturation. A similar trend was reported by

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Eberemu (2007). It implies that the initial degree of saturation must be carefully controlled when compacting soils

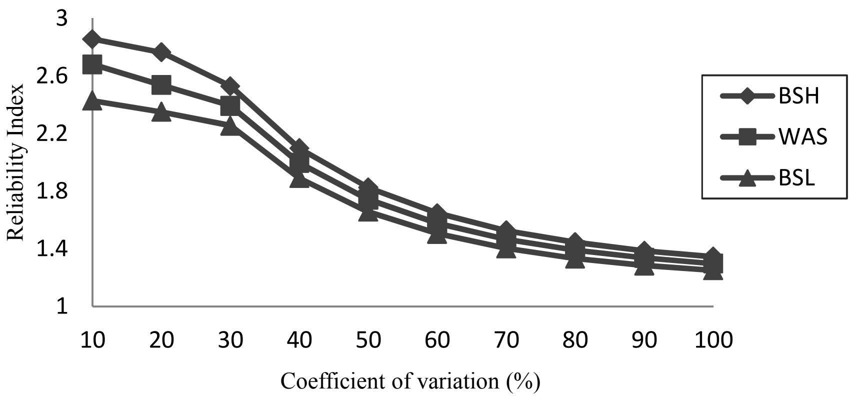

Fig.3: Variation of reliability index with coefficient of variation for degree of saturation

for use as covers and liners in waste containment facilities.

4.4 *Effect of Bagasse Ash Content on Reliability Index*

The effect of bagasse ash content on safety index as the coefficient of variation is varied is shown in Fig.4. Bagasse ash content varied non-linearly as the coefficient of variation increased from 10-100%, reliability or safety index decreased significantly especially in the 60- 100% range of COV values. Generally higher compactions energies produced higher safety indices. As COV increased from 10-100%, β value correspondingly decreased in the ranges 2.667-1.715, 2.724-1.841 and 2.778-1.889 for BSL, WAS and BSH compactions, respectively. The rapid change in safety index as COV is varied from 10-100% is an indication that hydraulic conductivity is significantly influenced by changes in bagasse ash content contrary to the finding of Stephen (2007). Therefore, when compacting bagasse-foundry sand mixtures for use in covers and liners in waste containment facilities the bagasse ash content must be strictly controlled.

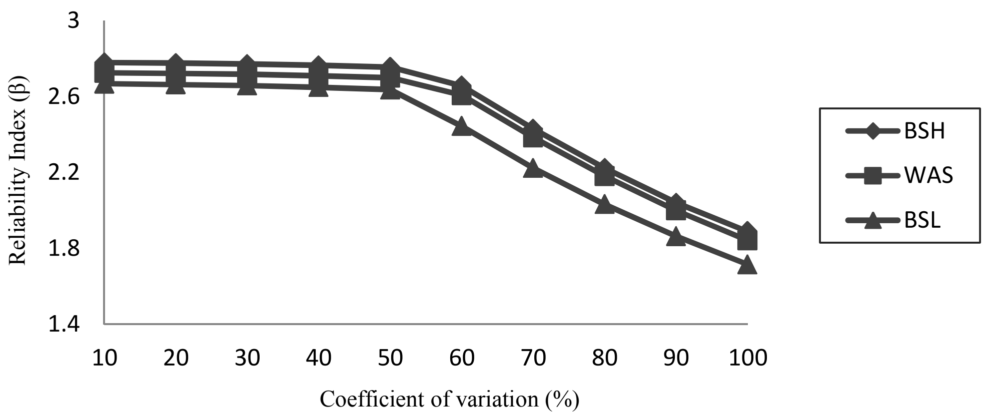

Fig.4: Variation of reliability index with coefficient of variation for bagasse ash content

4.5 *Effect of Percentage Fines on Reliability Index*

The effect of percentage fines on the safety index as the coefficient of variation is varied is shown in Fig.5. Percentage fines produced a linear relationship as the coefficient of variation increased in the range in the range 10-

100%, while reliability or safety index varied slightly as β value decreased in the range 2.133-2.092, 2.356-2.311 and 2.577-2.528 for BSL, WAS and BSH compactions, respectively. It was generally observed that higher compaction energies recorded higher safety indices. From the results attained shows that percentage fines has no significant effect on reliability index.

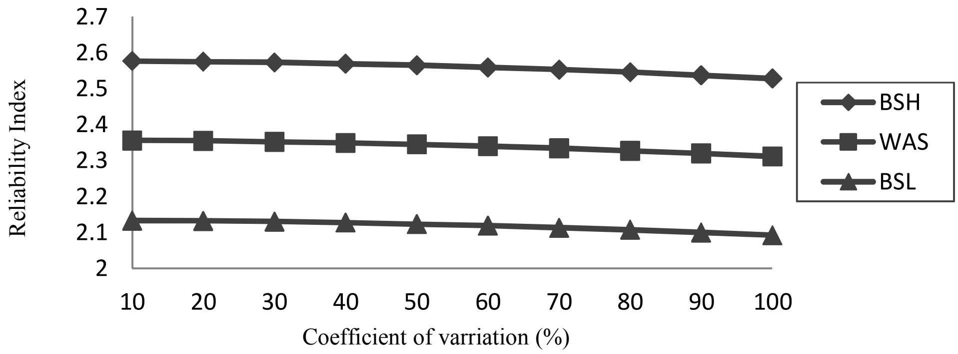

Fig.5: Variation of reliability index with coefficient of variation for percentage fines

4.6 *Statistical Significance of Safety Index Values*

Statistical analysis of all the results obtained for the parameters (hydraulic conductivity, W.R.O., degree of saturation, bagasse ash content and percentage fines) 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 indices are carefully monitored during the construction of liner in waste containment facilities.

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)**
Hydraulic conductivity	COV	9	24443	8.89×10^{-128}	2.46	SS
	Compactive effort	2	549349		3.55	SS
Water Content Relative Optimum	COV	9	89	5.92×10^{-10}	2.46	SS
	Compactive effort		120451		3.55	SS
Degree of Saturation	COV	9	28	7.82×10^{-8}	2.46	SS
	Compactive effort	2	27		3.55	SS
Bagasse Ash Content	COV	9	535	9.31×10^{-5}	2.46	SS
	Compactive effort	2	89		3.55	SS

Percentage Fines	COV	9	396	9.82×10^{-8}	2.46	SS
	Compactive effort	2	265798		3.55	SS

SS= Statistically significant at 5% level

COV= Coefficient of variation

4.7 *Stochastical Model Assessment*

The safety indices obtained for the three compactive efforts BSL, WAS, and BSH are in the ranges 0.703-0.958, 0.935-1.188 and 1.165-1.416 respectively. 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 **Factors**	**Beta Values**			**Acceptable Ranges of COV (%)**		
	BSL	**WAS**	**BSH**	**BSL**	**WAS**	**BSH**
Hydraulic conductivity (k)	0.70-0.96	0.94-1.19	1.17-1.43	Nil	50-100	10-100
Water content relative to optimum	2.33-2.37	2.57-2.59	2.78-2.81	10-100	10-100	10-100
Initial degree of saturation	1.30-2.43	1.30-2.68	1.34-2.85	10-100	10-100	10-30
Bagasse ash content	1.72-2.67	1.84-2.72	1.89-2.78	10-100	10-100	10-100
Percentage fines	2.09-2.13	2.31-2.36	2.53-2.58	10-100	10-100	10-100

5. *Conclusion*

Reliability estimates of hydraulic conductivity of compacted bagasse ash treated foundry sand as landfill liners was under taken by incorporating a predictive model for hydraulic conductivity, which was developed from data obtained from laboratory results for specimens compacted at the energy levels of Standard Proctor (BSL), West African standard (WAS) and British standard heavy (BSH). 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 for hydraulic conductivity at compactive efforts of WAS and BSH. Compositional factor such as water content relative to optimum produced acceptable safety index value of 1.0 at the energy levels of BSL, WAS and BSH compactive efforts, and they were achieved at COV ranges of 10-100% and 10-100% respectively. Observed trends indicate that the degree of saturation and bagasse ash content is greatly influenced by the COV and therefore must be strictly controlled in bagasse-foundry sand mixtures for use in covers and liners in waste containment facilities. Stochastical assessment of the model obtained at the three compactive efforts of BSL, WAS, and BSH gave safety indices in ranges 0.703-0.958, 0.935-1.188 and 1.165-1.416. Generally, it was observed that higher compaction energies recorded higher safety indices.

Stochastically, WAS and BSH compactive efforts can be used to model the hydraulic conductivity behavior of bagasse ash treated foundry sand for landfill liners at the variable ranges of 50-100% and 10-100% COV, respectively. Furthermore, using the F-distribution test at 95% level of significance, it was observed that compactive effort had significant effect on the outcome of the results recorded from the analysis of the ANOVA test obtained. Therefore, care must be taken in ensuring that the compactive efforts required to produced successful safety indices are carefully monitored during the construction of liner in waste containment facilities.

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