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Reliability Based Analysis of Ground Improvement Using a Polymeric Chemical Stabilizer

Bright Worlu[1], Ify L. Nwaogazie[2*]

[1]Centre for Geotechnical and Coastal Engineering Research, University of Port Harcourt, Port Harcourt, Nigeria
[2]Department of Civil and Environmental Engineering, University of Port Harcourt, Port Harcourt, Nigeria
Email: *ifynwaogazie@yahoo.com

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Abstract

In view of the challenges posed by the nature of expansive soil to structural stability which makes it necessary in some cases to improve the soils before structures can be placed on them, there is a need to investigate modern trends in ground improvement techniques in order to determine their reliability. This study is thus aimed at using the reliability based approach to analyze the use of polyvinyl alcohol (PVA) in combination with 1,2,3,4 Butane-tetracarboxylic acid (BTCA) for ground improvement. This study is necessary given the challenges posed by the nature of expansive soil to structural stability which makes it necessary in some cases to improve the soils before structures can be placed on them. Simplex lattice design was employed to build the design of experiment before experimental investigations were carried out on the PVA-BTCA treated soft soils. Reliability indices were computed on the basis of the 28th day unconfined compressive strength (UCS) of the treated soil. Reliability index models were developed using the Scheffe's technique and optimized using excel solver. From analysis of results, reliability model developed proved adequate at 5% level of significance. PVA-BTCA combination provided a potential reliability or probability of success of 99.936% at components combination of: 98.4256% for soil, 1.2352% for PVA, 0.3392% for BTCA and 15.9934% for water. It was therefore recommended that financial implications of using PVA-BTCA for stabilization be compared to those of conventional methods, in order to compare their performance-cost ratio.

Keywords

Reliability, Polyvinyl Alcohol (PVA), Butane-tetracarboxylic Acid (BTCA), Polymeric Chemical, Scheffe's Simplex Technique

1. Introduction

1.1. Basic Concepts

Ground improvement has always been one of the major thrust areas of geotechnical engineering. It is vertically crucial in the design of any structure in weak soil. Before any development or construction work for either civil structures or mining activities, it is crucial to know the local soil type, present and future use of the land area, required strengths for holding the above structural loads, and estimated cost of the project [1]. In case the soil of the selected site does not have desired structural properties, e.g., appropriate cohesion, internal angle of friction, bearing capacity, swelling factor, etc., it becomes necessary to improve these properties using external means. The effect of soil instability can be diverse, including cases of liquefaction, heaving, swelling, and plastic deformation [2]. The effects of unstable soil are correspondingly catastrophic, ranging from slope failures and foundation sinkage to total collapse of the tunnels and mine dumps, overlying buildings, and other structures [3].

The ground improvement as a sub-branch of the Geotechnical Engineering domain has made considerable advances since the practices began to develop in the mid-20th century. Most techniques have undergone drastic changes in terms of application and optimization.

Polyurethane (PU) is one of the four major organic polymeric binder used for soil improvement. The others are; Lignosulfonate, Epoxy resins and Polyacrylamide. There have been different researches on the use of PU for soil treatment and improvement.

Polyurethane (PU) is a polymer made up of Polyol (-OH) and Polyisocyanates (-NCO). Different types of Polyol and Polyisocyanates result in different varieties of polyurethane. Its rapid reaction time (usually between 30 to 120 seconds) and lightweight make it suitable for repairing highway pavement since it cannot be blocked for a long time. Groundwater or the presence of moisture in soil could be a limiting parameter for the use of polyurethane since the liberation of gas, which could be CO_2 due to the reaction between water and isocyanate or water vapor due to heat from the reaction of Polyol and Polyisocyanates [4].

[5] studied the effect of polyurethane mixed with polypropylene fiber on the tensile strength of sands. They found that curing of at least 12 h is required for solidification of the specimen and about 48h for stabilization. In the study, they showed that polyurethane helps in binding polypropylene with soil particles resulting in greater tensile strength, which could be 2 to 3 times initial tensile strength depending on the compaction.

[6] showed that rock-like strength could be achieved by polyurethane soil mixture without significantly increasing the weight of soil. With a 1:7 ratio of PU:Soil by weight, they achieved a much durable sample with unconfined compressive strength of more than 4 MPa with sandy silt. [7] studied the cracking and shrinkage behavior of bentonite clay with polyurethane and found an in-

crease in stiffness of the sample. Hydrophilic PU was more effective in controlling shrinkage distress.

[8] found PU more suitable for coarser material since it could lead to hydrofracturing in fine-grain clayey soil at the point of injection due to its viscosity. It was found that there was a significant increase in plastic strength under cyclic loading. At the same time, a decrease in the elastic property was also observed. [9] studied well-graded angular and subangular gravel stabilized with PU and concluded that with the addition of PU, there is increase cohesion without any reduction in angle of friction, unlike in some cases of fly ash. Compared to cement and lime-based stabilizers, it does not increase the brittleness and incorporate good post-failure strength. With 0% - 8% addition of hydrophobic PU and curing for 60 min, brittleness index [(peak deviatoric stress/residual deviatoric stress) − 1] for 0.5 MPa confining pressure varied from 0.01 to 0.29 whereas, in the case of lime/cemented gravel, it varied from 0.03 to 2.36. It was also noted that the failed specimen was intact after failure, and their behavior changes from contractive to dilative with the addition of PU.

Due to the challenges posed by the nature of expansive soil to stability of structures, it becomes imperative in some cases to improve the soils before structures are placed on them. There is also the need to investigate modern trends in ground improvement techniques such as use of geosynthetic materials, cement, lime, chemical polymers and other calcium based compounds in order to determine their reliability. This research thus seeks toinvestigatethe reliability in the application of poly (vinyl alcohol) (PVA) as a polymeric binder for stabilizing soft clay soils. PVA is the largest water-soluble biodegradable polymer chain that has excellent film forming and adhesive properties. It is also resistant to grease, oil, and solvent. It is highly hydrophilic and PVA solutions can be prepared easily by dissolving PVA in water. In this study PVA was used as the main stabilizing additive along with 1,2,3,4-Butane-tetracarboxylic acid (BTCA) as crosslinking agent. Furthermore, an optimization model was developed to predict the reliability index of PVA-BTCA stabilized soils.

Hasofer-Lind method which is also called first order reliability method was used for reliability analysis in this study. Geotechnical engineers deal with materials in which loads and resistances are combined and whose distributions and properties are not well known thereby bringing in uncertainties in design. These uncertainties can in geotechnical materials be tackled by an observational method [10] which is widely accepted and successful. This reliability method proposes a new definition for reliability index using geometric interpretation Statistical parameters which are normally described by their means, variances and covariance must include the properties of the geotechnical materials as well as their relationships. The determination of the statistical moment of performance function is basically the calculation of its mean and variance while the determination of the probability of failure can be less rigorous if the performance function has a well-defined probabilistic description like the normal distribution. For a geotechnical system with a load Q and resistance R the safety margin which is the performance function of the system M is expressed as:

$$M = R - Q \tag{1}$$

This method of reliability is centered on the assumption that both the load, Q and the resistance, R are normalized thereby leading to the normality of the safety margin, M. According to [10], reliability index β is given by the expression:

$$\beta = \frac{\mu_M}{\sigma_M} \tag{2}$$

where:

$$\mu_M = \mu_R - \mu_Q \tag{3}$$

And similarly, the variance of M (σ_M^2) is

$$\sigma_M^2 = \sigma_R^2 + \sigma_Q^2 - 2\rho RQ \cdot \sigma_R \cdot \sigma_Q \tag{4}$$

Combining Equations (3) and (4), gives:

$$\beta = \frac{\mu_R - \mu_Q}{\sqrt{\sigma_R^2 + \sigma_Q^2 - 2\rho RQ \cdot \sigma_R \cdot \sigma_Q}} \tag{5}$$

If the load and the resistance are not correlated, it then means the correlation coefficient ρ_{RQ} is zero and Equation (5) is reduced to:

$$\beta = \frac{\mu_R - \mu_Q}{\sqrt{\sigma_R^2 + \sigma_Q^2}} \tag{6}$$

From these mathematical expressions it can be deduced that as the Reliability index β increases, the probability of failure decreases thereby making the Reliability index β similar in behavior to the factor of safety.

$$R_e = 1 - P_f \tag{7}$$

1.2. Scheffe's Optimization Technique

In estimating and predicting the reliability of using PVA-BTCA in ground improvement, the Scheffe's optimization technique is employed. Several authors [11] [12] [13] [14] have carried out concrete mixture researches with development of mathematical models, most of which were based on Scheffe's Simplex theory.

[15] defined a simplex as a structural representation (shapes) of lines or planes joining assumed points of constituent materials of a mixture and which such points are equidistant from each other. According to [16], a (q, m) mixture, with q being the number of factors and m being the degree of assumed polynomial, the simplex coordinate system, X_i, and the number of design space points in the simplex lattice, N is defined by Equation (8) and Equation (9) respectively;

$$X_i = 0, \frac{1}{m}, \frac{2}{m}, \cdots, 1 \tag{8}$$

$$N=\frac{(q+m-1)!}{m!(q-1)!} \tag{9}$$

According to [17], mixture proportions are being represented in pseudo (theoretical) mix ratios. Pure substance exist at the vertices points and the method rely on the condition that the summation of all pseudo mix ratios at any point must be equal to 1. Mathematically:

$$\sum_{i=1}^{q} X_i = 1 \tag{10}$$

To achieve the condition of Equation (10), actual mix ratios must be converted to pseudo mix ratios. The relationship between pseudo and actual mix ratios, according to [17] is given by;

$$Z=[A]X \tag{11}$$

where: Z = column matrix of real component ratio.

X = column matrix of pseudo component ratio.

$[A]$ = coefficient matrix which is the transpose of the permutation matrix $[P]$.

The permutation matrix is obtained from experience derived from reviewed literatures and/or intelligent guesses of the mixture proportions of the factors or mix components. For a (q, m) mixture, the general form of the polynomial model is [17];

$$Y=b_0+\sum b_i x_i+\sum b_{ij} x_i x_j+\sum b_{ijk} x_i x_j x_k+\cdots+\sum b_{i1,i2,\cdots,im} x_{i1} x_{i2} x_{im} \tag{12}$$

where; $1 \le i \le q$, $1 \le i \le j \le q$, $1 \le i \le j \le k \le q$

b_0 is a constant coefficient.

This study employed this technique for the development of optimization or prediction models to predict the reliability indices based on some performance parameters of PVA-BTCA stabilized soft soil.

2. Materials and Methods

The soft soil whose properties is displayed in **Table 1** was treated using PVA in combination with 1,2,3,4 Butane Tetracarboxylic acid.

2.1. Building the Design of Experiment (DoE)

For (4, 2) mixtures, as employed in this study, X_i becomes 0, 1/2 and 1 while N becomes 10 for treatment procedures on application of Equations (8) and (9) respectively. This gives rise to the (4, 2) and simplex lattice presented in **Figure 1**. PVA was limited to 0.1% - 2% by weight of the dry soil and 1,2,3,4 BTCA was limited to 0.1% - 0.5% by weight of the dry soil. The water content was varied in the range of 10% - 20% by weight of stabilizer-soil mix for all stabilization processes. These range of values were used in the development of the permutation matrix $[P]$ resulting to; (0.998; 0.001; 0.001; 0.1), (0.99034; 0.00733; 0.00233; 0.133), (0.98266; 0.01367; 0.00367; 0.167), and (0.975; 0.02; 0.005; 0.2) for the PVA-BTCA stabilized soil to form **Table 2** and **Table 3**. **Table 2** and **Table 3** are

Table 1. Properties of soft soil.

Item	Value (description)
Specific gravity	2.65-representative of a fine grained material according to ASTM
Liquid limit	37.75%
Plastic limit	17.36%
Plasticity index	20.39%-a fine grained soil material with high plasticity
AASHTO classification	A-7-6clayey-siltymaterial
Grain distribution	
Silt	48.8%
Clay	50%
Fine sand	19.8%
Compaction characteristics	
Optimum moisture content (OMC)	14.2%
Maximum dry density (MDD)	1.29 g/cm^3
Specific gravity	1.58

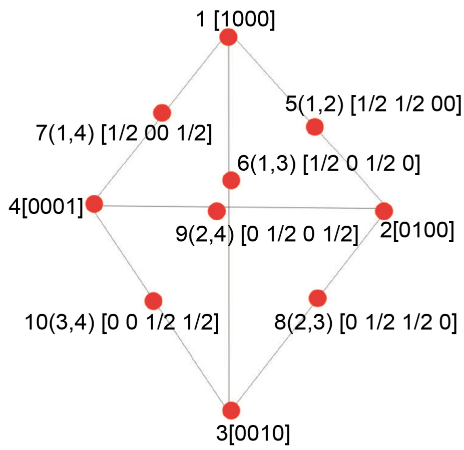

Figure 1. (4, 2) simplex lattice structure for polymeric chemical stabilized soft soil.

matrix mix design tables showing pseudo and actual components for the (4, 2) simplex lattice for trial and control mixes of PVA-BTCA stabilized soil. The number of the design space points *N*, translates to the minimum number of experimental runs required for development of optimization model of the modified soft soil. These actual mix components are arranged in the format, (soft soil; PVA; BTCA; water).

2.2. Experimental/Test Procedures

Unconfined Compressive Strength (UCS): this experiment was conducted in accordance to [18]. Readings of force (*F*) were taken from the proving ring dial

Table 2. Design table for trial mixes (PVA-BTCA soil mixes).

N	**Pseudo component⁺**				**Actual component**			
	X_1	X_2	X_3	X_4	Z_1	Z_2	Z_3	Z_4
1	1	0	0	0	0.998	0.001	0.001	0.100
2	0	1	0	0	0.99034	0.00733	0.00233	0.1330
3	0	0	1	0	0.98266	0.01367	0.00367	0.167
4	0	0	0	1	0.975	0.020	0.005	0.200
5	1/2	1/2	0	0	0.99417	0.004165	0.001665	0.1165
6	1/2	0	1/2	0	0.99033	0.007335	0.002335	0.1335
7	1/2	0	0	1/2	0.9865	0.0105	0.003	0.15
8	0	1/2	1/2	0	0.9865	0.0105	0.003	0.15
9	0	1/2	0	1/2	0.98267	0.013665	0.003665	0.1665
10	0	0	1/2	1/2	0.97883	0.016835	0.004335	0.1835

⁺Where; X_1, Z_1 = pseudo and actual component of soft soil; X_2, Z_2 = pseudo and actual component of PVA; X_3, Z_3 = pseudo and actual component of BTCA; X_4, Z_4 = pseudo and actual component of water.

Table 3. Design table for control mixes (PVA-BTCA soil mixes).

N	**Pseudo component⁺**				**Actual component**			
	X_1	X_2	X_3	X_4	Z_1	Z_2	Z_3	Z_4
1	0.25	0.25	0.25	0.25	0.9865	0.0105	0.003	0.15
2	0.2	0.2	0.3	0.3	0.984966	0.011767	0.003267	0.1567
3	0.3	0.3	0.2	0.2	0.988034	0.009233	0.002733	0.1433
4	0.2	0.2	0.2	0.4	0.9842	0.0124	0.0034	0.16
5	0.1	0.3	0.3	0.3	0.9842	0.0124	0.0034	0.16
6	0.35	0.3	0.2	0.15	0.989184	0.008283	0.002533	0.1383
7	0.15	0.45	0.15	0.25	0.986502	0.010499	0.002999	0.1499
8	0.25	0.2	0.3	0.25	0.986116	0.010817	0.003067	0.1517
9	0.4	0.1	0.35	0.15	0.988415	0.008918	0.002668	0.14175
10	0.45	0.25	0.2	0.1	0.990717	0.007017	0.002267	0.13165

⁺Where; X_1, Z_1 = pseudo and actual component of soft soil; X_2, Z_2 = pseudo and actual component of PVA; X_3, Z_3 = pseudo and actual component of BTCA; X_4, Z_4 = pseudo and actual component of water.

gauge and the stress applied to the ends of the sample (major principal stress) is computed according to Equation (13).

$$\sigma_1 = \frac{F}{A} \tag{13}$$

where: A is the cross-sectional area of the sample. The unconfined compressive strength was measured as the maximum value σ_1, which may or may not coincide with the maximum force measurement.

2.3. Reliability Index Optimization Model Development

For (4, 2) simplex problem (PVA-BTCA stabilization), the reduced second degree polynomial form of Equation (12)becomes;

$$\begin{aligned} Y = \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 + \alpha_4 X_4 + \alpha_{12} X_1 X_2 + \alpha_{13} X_1 X_3 \\ + \alpha_{14} X_1 X_4 + \alpha_{23} X_2 X_3 + \alpha_{24} X_2 X_4 + \alpha_{34} X_3 X_4 \end{aligned} \tag{14}$$

where; Y = Expected response, α_i, α_{ij} = Coefficients of the quadratic polynomial, X_i, X_j = Pseudo proportion of factors considered

According to Scheffe's simplex principle, the coefficients above can be determined from Equations (15).

$$\left.\begin{aligned} \alpha_i &= Y_i \\ \alpha_{ij} &= 4Y_{ij} - 2Y_i - 2Y_j \end{aligned}\right\} \tag{15}$$

2.4. Reliability Indices Optimization Models Validation

Reliability index models developed were subjected to F-test for validation. The F-value is given as the ratio of variance between the predicted response value and experimental value.

Mathematically, the F-test is represented by Equation (16):

$$F = \frac{S_1^2}{S_2^2} \tag{16}$$

where; S_1^2 = Larger of both variances

S_2^2 = Smaller of both variance

S^2 is obtained from Equation (17)

$$S^2 = \frac{1}{n-1}\left[\sum\left(Y - \bar{Y}\right)^2\right] \tag{17}$$

where: $\bar{Y}$ = Average mean of response, Y

Y = Means of response

The model developed was declared adequate if the F-value calculated in accordance to Equation (16) is less than tabulated value.

3. Results and Discussion

Table 4 presents the experimental results obtained for the UCS of stabilized or treated soil trial mixes. The reliability indices of these stabilized soft soils were determined using the information from Table 4.

3.1. Reliability Index Determination

Given the foregoing, constant mean load of 75 kPa was used in the UCS test, this becomes μ_Q. This constant load application results to a constant load deviation of 27.39 kPa, which becomes σ_Q. This results to a reliability index value of 2.07

Table 4. PVA-BTCA stabilized soil UCS test results for trial mixes.

N	Pseudo component+				Actual component+				Av. UCS (kPa)
	X_1	X_2	X_3	X_4	Z_1	Z_2	Z_3	Z_4	
1	1	0	0	0	0.998	0.001	0.001	0.100	261.48
2	0	1	0	0	0.99034	0.00733	0.00233	0.1330	433.37
3	0	0	1	0	0.98266	0.01367	0.00367	0.167	685.19
4	0	0	0	1	0.975	0.020	0.005	0.200	495.44
5	1/2	1/2	0	0	0.99417	0.004165	0.001665	0.1165	357.29
6	1/2	0	1/2	0	0.99033	0.007335	0.002335	0.1335	488.51
7	1/2	0	0	1/2	0.9865	0.0105	0.003	0.15	518.18
8	0	1/2	1/2	0	0.9865	0.0105	0.003	0.15	518.18
9	0	1/2	0	1/2	0.98267	0.013665	0.003665	0.1665	699.29
10	0	0	1/2	1/2	0.97883	0.016835	0.004335	0.1835	501.10

+Where; X_1, Z_1 = pseudo and actual component of soft soil; X_2, Z_2 = pseudo and actual component of PVA; X_3, Z_3 = pseudo and actual component of BTCA; X_4, Z_4 = pseudo and actual component of water.

by application of Equation (11). Similarly, other reliability indices were obtained as shown in Figure 2.

3.2. Reliability Indices Models' Development and Analysis

With the aid of Figure 2 in conjunction with Equation (15), the model coefficients for the reliability index of PVA-BTCA stabilized soil based on UCS were derived and model obtained as Equation (18):

$$\begin{aligned}\beta_{\text{PVA-BTCA(UCS)}} &= 2.07X_1 + 2.13X_2 + 3.10X_3 + 2.39X_4 + 0.16X_1X_2 + 1.54X_1X_3 \\ &\quad + 3.2X_1X_4 + 1.66X_2X_3 + 4.28X_2X_4 - 0.66X_3X_4\end{aligned} \tag{18}$$

3.3. Validation of Reliability Index Models

Figure 3 presents the reliability index values of PVA-BTCA stabilized soil based on UCS for the control mixes. Table 5 presents the F-statistics for validation of Equation (18) where the developed model was tested for adequacy at 5% level of significance. With the aid of Table 5 and Equation (16) the F-value was obtained as 2.47. Because F-cal (2.47) is less than F-tab (3.18), the model is considered adequate.

3.4. Optimization Analysis of the Components on the Reliability of Improved Soft Soil

Microsoft excel solver was used to optimize or combine components to yield the most reliable outcome. In optimization, there must be an objective function subjected to a set of constraints.

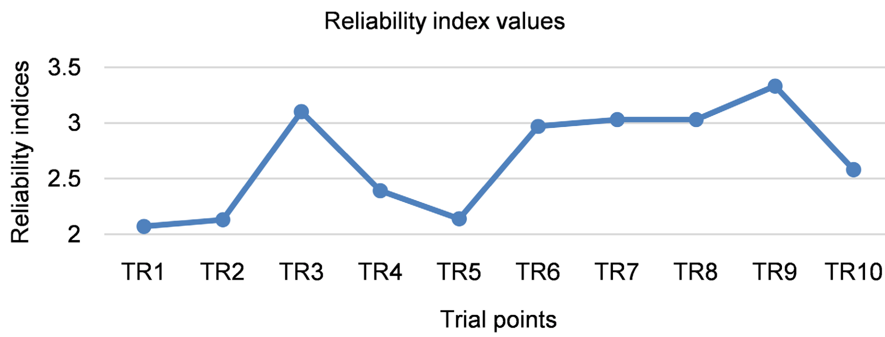

Figure 2. Reliability indices for PVA-BTCA soil mix.

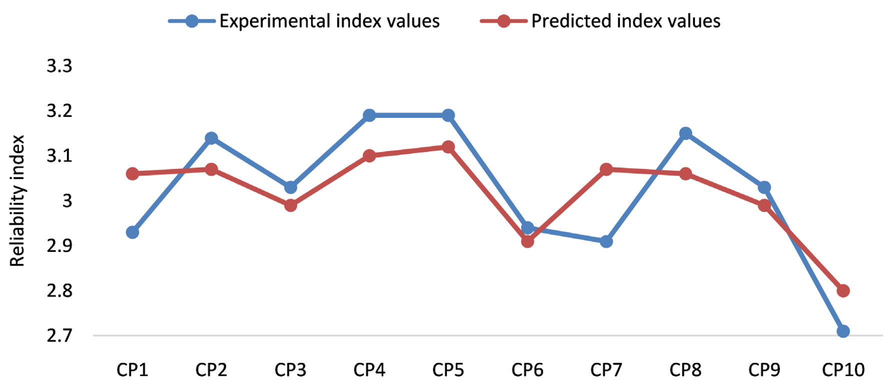

Figure 3. Experimental and Predicted reliability index values for control mixes.

Table 5. F-Statistics for validation of PVA-BTCA stabilized soil reliability index model based on UCS.

Exp.Value $= Y_e$	Model. Value $= Y_m$	$Y_e - \hat{Y}_e$	$Y_m - \hat{Y}_m$	$\left(Y_e - \hat{Y}_e\right)^2$	$\left(Y_m - \hat{Y}_m\right)^2$
2.93	3.06	−0.092	0.0438050	0.00846	0.0019189
3.14	3.07	0.118	0.0598550	0.01392	0.0035826
3.03	2.99	0.008	−0.0281450	6.4E−05	0.0007921
3.19	3.10	0.168	0.0810550	0.02822	0.0065699
3.19	3.12	0.168	0.1002550	0.02822	0.0100511
2.94	2.91	−0.082	−0.1079450	0.00672	0.0116521
2.91	3.07	−0.112	0.0508050	0.01254	0.0025811
3.15	3.06	0.128	0.0436550	0.01638	0.0019058
3.03	2.99	0.008	−0.0287950	6.4E−05	0.0008292
2.71	2.80	−0.312	−0.2145450	0.09734	0.0460296
$\hat{Y}_e = 3.022$	$\hat{Y}_m = 3.01495$			$\Sigma = 0.21196$	$\Sigma = 0.0859124$

Objective function;

Maximize*; *Equation **(18)**

Subjected to the following constraints;

$$X_1 + X_2 + X_3 + X_4 = 1 \tag{19a}$$

$$X_1, X_2, X_3, X_4 \geq 0 \tag{19b}$$

Using the constraints (Equations 19(a) & 19(b)), the pseudo proportions of PVA-BTCA soil components were obtained as; $X_1 = 0$; $X_2 = 0.207831$; $X_3 = 0.792169$, $X_4 = 0$; with Max(β) = 3.17. On application of the transformation equation, the actual or real components were obtained as: 98.4256% for soil, 1.2352% for PVA, 0.3392% &BTCA, and 15.9934% for water giving a reliability index value of 3.17.Using normal distribution table, this value of reliability index translates to a reliability of 0.99936 (99.936%).

4. Conclusion

The reliability index model developed for the PVA-BTCA soil proved adequate at 5% significance level from the validation analysis conducted. The optimum proportions of PVA-BTCA soil components are; 98.4256% for soil, 1.2352% for PVA, 0.3392% for BTCA, and 15.9934% for water. This results to an average reliability index value, β of 3.17. Using standard normal distribution table, this value of reliability index translates to a reliability of 0.99924 (99.924%). The reliability of PVA-BTCA in ground improvement should be checked against other conventional methods of ground improvement for effective comparisons.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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