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MODELLING OPTIMAL UNCONFINED COMPRESSIVE STRENGTH OF GEOTEXTILE REINFORCED SOIL FOR FLEXIBLE FOUNDATION CONSTRUCTION

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Extreme vertex design (EVD) provides an efficient approach to mixture experiment design whereby the factor level possess multiple dependencies are expressed through component constraints formulation. EVD was deployed for the modeling UCS of a geogrid reinforced problematic soil aimed at checking the validity in subgrade construction. Geogrids are geosynthetic materials, which possess an open mesh-like structure and are mostly used for soil stabilization. Geogrids present permeable layer to support the soil and foundation by improving the stiffness characteristics. It is cheap compared to other construction materials and possesses unique light weight properties with greater strength improvement on the soil layer when used. Minitab 18 and Design Expert statistical software were utilized for the mixture design experiment computation. To fully explore the constrained region of the simplex, I-optimal designs with a special cubic design model were utilized to formulate the mixture component ratios at ten experimental runs. I-optimality and D-optimality of 0.39093 and 1747.474, respectively, were obtained with G-efficiency of 64.8%. The laboratory responses were taken together with the mixture ingredients as the system database for the model development. Statistical influence and diagnostics tests carried out on the generated EVD model indicated a good correlation with the experimental results. Graphical and numerical optimizations were incorporated using desirability functions that ranged from 0 to 1, which helped to arrive at the optimal combination of the mixture components. 0.2% of geogrid, 9.8% of water, and 90 % of soil yielded the optimal solution with a response of 41.270kN/m2 and a desirability score of 1.0. Model simulation was further carried out to test the model's applicability in subgrade construction with the results compared with the actual results using student's t-test and analysis of variance. The statistical results showed p-value>0.05 which indicates good correlation.

Keywords: constrained simplex method, design expert, extreme vertices, geogrid, soil, unconfined compressive strength

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INTRODUCTION

Geosynthetics are non-natural materials often used to improve soil's mechanical properties. They are obtained from petro-chemical polymer-based plastics (polymeric materials) which are inert biologically and would not decompose due to the actions of fungal, bacteria, and microorganisms (B. Indraratna et al. 2011). However, their chemical properties vary as most are totally inert while some are affected by sunlight and petrochemicals. They are incorporated with soil to achieve confinement, separation, and distribution of loads such as reinforcement for water pressure control and prevent soil movement while allowing water pass through the material. It can also be effectively utilized to prevent or reduce base coarse aggregates horizontal deformation and to resist asphalt reflective cracking (H. A. Alawaji, 2001). Construction of flexible road pavement with expansive subgrade soil most times requires higher thickness for constituting cross-section materials to safely carry the intending traffic loads without excessive and differential settlement of the subgrade (Salahudeen et al. 2014). Moreover, the flexible pavement could also deteriorate rapidly due to aggregated cross-section layers sinking into the expansive subgrade under traffic loads with increased moisture content. However, the introduction of geosynthetic layer between the problematic clayey subgrade materials and the aggregate layer (base and sub-base) can prevent the dreadful intermixing of the soft subgrade with the sub-base and base layer which results in road failure (I. Al.Qadi et al. 2018). The incorporation of geosynthetic materials can also provide significant gains in terms of thickness reduction of the pavement cross-section layers due to improved strength performance. Geogrid is a special type of geosynthetic material produced by stretching and extrusion of a high polymeric molecule (polyester, propylene or high density polyethylene (HDPE)). It possesses a number of apertures which are uniformly distributed between the transverse and longitudinal sections. Through the apertures, there is direct contact and bonding between the sheets of the geosynthetic materials and the soil particle (Bounsanti et al. 2012; A. Demir et al. 2012). With the use of weak soil in pavement construction, there is need to improve the unconfined compressive strength of the soil in order be able to withstand the axial traffic load. One of those methods includes the use of geogrids to reinforce the soil. However, the optimization of the utilization of these stabilization or soil reinforcement materials and the strength properties has become very important. Hence, the primary focus of this work was to apply the technique of extreme vertex design of experimental mixtures to optimize the UCS of the geogrid reinforced soil used as subgrade material. Extreme vertex design (EVD) method is a mixture design technique, which occupies a sub-portion or smaller space within the simplex. The technique is essential when the design factor space selected is not L-simplex design. This limitation is imposed by both lower and upper bound constraints in the factor levels when there is a high level of interdependencies between the mixture components (R. A. McLean and V. L. Anderson, 2012). The major objective of EVD method is to choose design points that appropriately cover the design space; this occurs as a result of additional constraints imposition of upper and lower boundary conditions on the mixture components which causes the design points occupying some portion of the simplex known as the constrained region. Extreme vertex design technique permits the imposition of additional boundary limits on the mixture component values by specifying upper bounds on

components and defining linear constraints for blends. The goal of using an extreme vertex design is to choose design points that adequately cover the design space (Damiri et al. 2016).

For q-component mixtures where the ith component proportion present in the mixture by xi, the factor space takes the shape of a regular (q-1) dimensional simplex due to the sum of one constraint presented in Eqn. 1. EVD method is flexible enough to deal with the imposition of additional constraints on the mixture components due to multiple dependencies between them. The lower and upper limit is denoted by Li and Ui respectively.as shown in Eqn. 2 and the sum of the mixture component ratios must be unity (J. A. Cornell, 2011).

$$\sum_{i=1}^{q} x_i = 1 \quad , \text{ i = 1, 2, 3... q} \quad 0 \le x_i \le 1 \tag{1}$$

$$0 \le L_i \le x_i \le U_i \le 1 \tag{2}$$

The mixture experiments objective is to develop mathematical model adequate where the factor levels $(x_1, x_2, x_3, ..., x_q)$ relates the desired response parameters. Commonly used Scheffe's method for data fitting which is expressed in Eqn. 3 for quadratic polynomial function (J. A. Cornell, 2011).

$$E(Y) = \sum_{i=1}^{q} \beta_i x_i + \sum \sum_{i<j}^{q} \beta_{ij} x_i x_j \tag{3}$$

And this is represented in matrix form as shown in Eqn. 4.

$$Y = X\beta + \varepsilon \tag{4}$$

Where X is $n \times k (\ge q)$ matrix and k is the number of model terms; Y is $n \times 1$ vector for the response parameter observations; ε is $n \times 1$ vector for the error function; and β is a $k \times 1$ vector for the predicted parameters (H. Scheffe, 1958; D. Jiang-Tong et al. 1999).

The error properties were assumed to possess the property expressed in Eqn. 5

$$E(\varepsilon) = 0, E(\varepsilon\varepsilon') = \sigma^2 I_n \tag{5}$$

Where σ^2 = the variance of the error function; I_n is an identity matrix.

The least square estimator for the predicted variables β is presented in Eqn. 6.

$$b = (X'X)^{-1} X'Y \tag{6}$$

The variance covariance matrix of the least squares estimator solution (b) is further expressed in Eqn. 7.

$$Var(b) = (X'X)^{-1}\sigma^2 \quad (7)$$

MATERIAL AND METHODS

Materials preparation

Expansive soil was collected at Edem Ekpenyong Street Anantigha, Calabar South Local Government Area of Cross River State, Nigeria. The geogrid (as presented in Fig. 1) was also obtained from Sermatech Construction Company in Calabar, Cross River State, Nigeria. Geogrids are spaced grid or open mesh-like synthetic materials of constituting polymers cemented integrally as shown in Fig. 1. They have mechanical strength characteristics than common geosynthetic materials and can only stretch to limit about 2% - 5% under loading condition (Guimaraes et al. 2017; Wang et al. 2010). The properties of the geogrid material used are shown in Table 1.



Fig. 1: Geogrid material

Table 1: Test geogrid properties

Aperture Size of Mesh (mm)	10 x 10
Shape of Aperture (mm)	Square
Tensile Strength (kN/m)	12.5
Color	Black
Structure	Bi-directional
Elongation at maximum load (%)	20.5
Unit Weight (N/m^2)	7.35
Thickness of Sheet (mm)	4
Raw Material	Polypropylene

Experimental Methods

The experimental programs for the investigative study were carried out upon the guiding requirements stipulated in BS 1924 (1990) and BS 1377 (1990) for the problematic clayey soil mechanical properties improvement using geosynthetic materials. Classification and general engineering properties derivation of the test soil were first achieved through specific gravity test, consistency limit, compaction test, sieve analysis, and unconfined compressive strength (UCS) test. This mixture experiment problem, which involves three component materials, namely; geogrid, water, and clayey soil, and because of the component constraint imposition at the

lower and upper boundary limits, the simplex is consequently constrained whereby the experimental points are situated at the vertices, interior and edges of the constrained region instead of the whole of the simplex (Aslam et al. 2020). Using I-optimal design computation with quadratic model design, the constrained experimental portion was adequately explored to generate the mixture components ratios and the number of experimental runs required. UCS tests were carried out in respect to the formulated ingredients proportions and the corresponding responses derived were utilized for the mechanical behavior modelling of the soil-geogrid blend. Statistical influences and diagnostic tests were carried out to validate the developed EVD model. Furthermore, graphical and numerical optimization is conducted using desirability function computation to maximize the output variable criteria with respect to the factor levels. The optimal combinations of the soil-geogrid blend for maximum mechanical response were determined in this process followed by simulation of the EVD model (W. Wangkamanon et al. 2018). The research program flowchart is presented in Fig. 2.

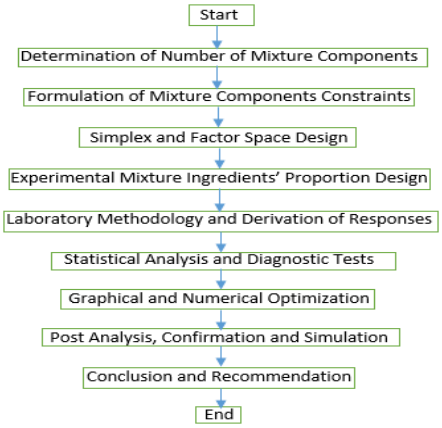


Fig. 2: Program flowchart

Unconfined Compressive Strength

The unconfined compressive strength (UCS) is the maximum axial compressive stress that a right-cylindrical sample of material can withstand under unconfined conditions. The purpose of this laboratory is to determine the unconfined compressive strength of a cohesive soil sample. In this test, a cylinder of soil without lateral support is tested to failure in simple compression at a constant rate of stream. The compressive load per unit area required to fail the specimen is called unconfirmed compressive strength of the soil in accordance with BS1377 (1990) with a setup presented in Fig. 3.



Fig. 3: Unconfined compressive strength experimental setup

Formulation of geotextile soil specimen mix proportions

The determination of the actual proportion of the mixture ingredients to be mixed for each particular experimental run and the total number of experimental runs were carried out here. The effective ratios obtained here form the fundamental base for the EVD model development to derive the optimal combination ratio for the soil-geogrid blend and achieve improvement in the problematic clayey soil engineering properties for flexible pavement construction. The mixture formulation computation was carried out with Design Expert 11 and Minitab 18 statistical software (Design Expert 11, 2018; Minitab 18, 2018).

Formulation of constraints

The mixture components are imposed with lower and upper bounds established through the properties of the ingredient materials which constitute the experimental soil-geogrid blend. In most cases, practical and environmental, economic, or physical considerations impose most of these boundary conditions. For the three-component mixture investigated in this research study, constituting of geogrid, water and problematic clayey soil to enhance its mechanical properties. From the relevant literatures (Zhou et al. 2012), the component constraints were formulated using single component constraints (SCC) are shown in Table 2.

Table 2: Design constraints

Mixture Coding:	Actual	
Low	Constraint	High
0.001	A:geogrid	0.002
0.098	B:water	0.150
0.848	C:soil	0.900
	A+B+C	1.000

Design of simplex and factor space

The developed constraints, which defined the upper and lower limits of the single component constraints imposed on the factor levels, cause the factor space to take a hyper-polyhedron simplex shape. The feasible experimental region within the simplex, termed the constrained space, is then obtained through the component constraints evaluation (Zhou et al. 2012). The degree of freedom evaluation is also conducted through design matrix computation for the design mixture using a quadratic model with U_pseudo mixture component coding as presented in Table 3. A minimum of 3 lacks of fit degrees of freedom (df) is required. This ensures a valid lack of fit test. Less df will result in a test that will not detect a lack of fit (Design Expert 11, 2018; Minitab 18, 2018).

Table 3: Design matrix evaluation for mixture quadratic model 3 factors: A, B, C with U_Pseudo Mixture

Degrees of Freedom for Evaluation	
Model	5
Residuals	4
Lack of Fit	*3*
Pure Error	*1*
Corr Total	9

The software further developed the contour plot of the 3- component simplex shown in Fig. 4, which diagrammatically displays the actual experimental points positioned within the constrained region. The information matrix measures showing the space type, leverages, and build types. Ten (10) runs were generated to improve on the optimality or efficiency of the model operation. Lack of fit was recorded on axialCB while the replicate point is situated at the center space of the feasible design space. The model build type was thus situated at the vertex and center-edge space type. Average leverage of 0.6 was calculated; this in effect raises concern for more design points to be located on these spaces of the simplex to reduce the lack of fit effect on the entire experimental space (Lawson and Erjavec, 2001).

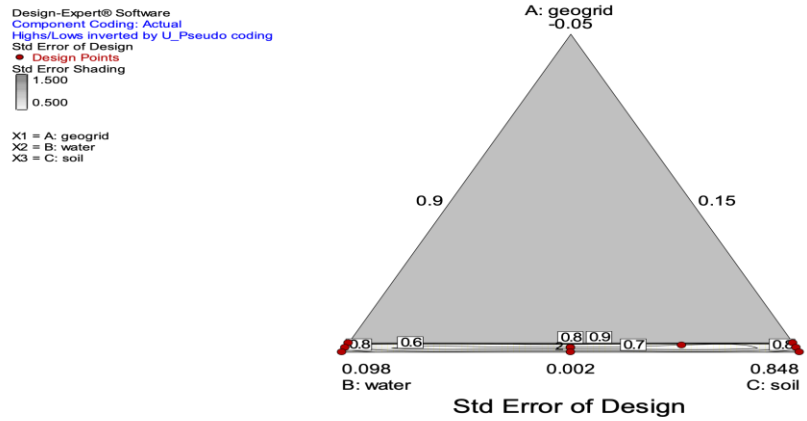


Fig. 4: Factor space simplex of a 3- component mixture experiment of water, soil, and geogrids.

The relevant data statistics for the design of experiments, multicollinearity design, scaled D-optimality, and I-optimal design computations were carried out using design expert software. D-optimality produces a design that best estimates the effects of the factors, which is particularly suited for screening studies. The algorithm picks points that minimize the volume of the confidence ellipsoid for the coefficients. I.e., it minimizes the determinant of the inverse matrix X'X, while I-optimal designs, also known as IV (integrated variance), provides a minimum average estimation of the variance across the experimental regions (U. Syafitri et al. 2015).

Design of experimental mix proportions

The number of experimental runs and the ingredients proportions were derived from the information matrix. Ten runs of experiments were derived in the process based on the imposed component constraints. The mixes and runs for the 3-component multi-constraints experimental design guide the preparation of specimens to be tested in the laboratory to achieve the responses (Xue et al. 2014; Alaneme et al. 2020).

RESULT DISCUSSION AND ANALYSIS

Test materials characterization

The general classification and engineering behavior of the soil is presented in Table 4. The results indicate that it possesses high plasticity and swelling potential; it is also poorly graded and exhibits expansive properties of soft materials. The

classification by AASHTO (1993) and USCS (ASTM, 1992) produced A-7 and CH, respectively, which indicates an unsuitable soil for engineering work with low CBR of 5 %, MDD of 1.28 Mg/m3 and OMC of 17 %. The studied soil has a specific gravity of 2.38 and from the grain size distribution of the unaltered soil, 38.24 % were passed through BS No. 200 sieve (75 µm aperture) (see Fig. 5). Plastic limit, liquid limit and plasticity index results of 20.53%, 54.23%, and 33.7. According to Federal Ministry of Works and Housing specification (FMWH, 1997), the soils not suitable for subgrade materials possess liquid limit and plasticity index values =< 30% and =< 13% respectively which implies that samples fall outside the required specification. However, a stabilization process is required to improve its properties to make it suitable for civil works (Bello et al. 2007).

Table 4: Basic properties of the test soil

Percentage Passing BS No. 200 Sieve (75 µm aperture)	38.24
Natural Moisture Content (%)	36.45
Dry Unit Weight (γ_d) (kN/m^3)	17.69
Specific Gravity	2.38
Liquid Limit (%)	54.23
Plastic Limit (%)	20.53
Plasticity Index (%)	33.7
OMC (%)	17
MDD (g/cm^3)	1.28
AASHTO	A-7
USCS	CH
CBR (%)	5
Unconfined Compressive Strength (UCS) (kN/m^2)	12.287

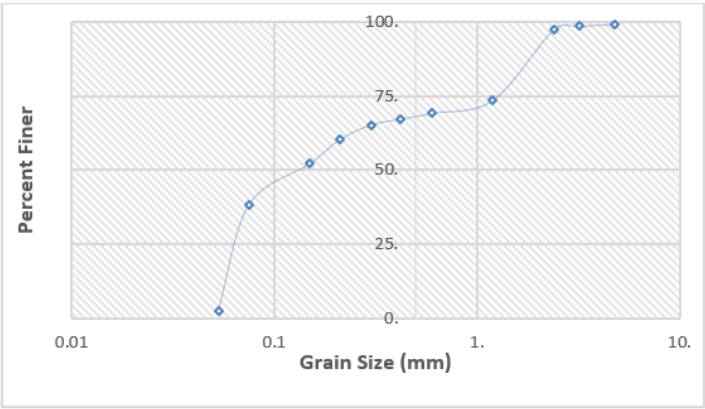


Fig. 5: Particle Size Distribution Graph

Unconfined Compressive Strength (UCS) test results

The experimental parameters utilized for the Unconfined Compressive Strength (UCS) test of the soil-geogrid blend with a proven ring factor of 0.0009kN are according to required standard (BS1377, 1990). The strain reading, corrected area, and stress values were then derived for each experimental run. The soils were further blended with geogrid at varying ratios according to the mixture ratio formulated and the results computations carried out with the derived dimension and cross-sectional area of the mold are presented below (K. C. Onyelowe et al. 2019a. 2019b);

From the computed values, the maximum result of 37.97 kN/m2 was obtained for test (run 4) while the minimum of 13.312 kN/m2 was obtained for test (run 1), which indicates a significant improvement on the soil's compressive strength properties in line with the federal Ministry of Works specification for subgrade materials. The result summary using percentage frequency statistics computation shows that 0.2% of geogrid, 9.8% of water and 90% of soil by weight produced the maximum response of 37.97kN/m2 for UCS target variable while 0.2% of geogrid, 15% of water and 84.8% of soil by weight produced the minimum response 13.312 kN/m2 for UCS (Zhou et al. 2012). The stress strain plot is presented in Fig. 6

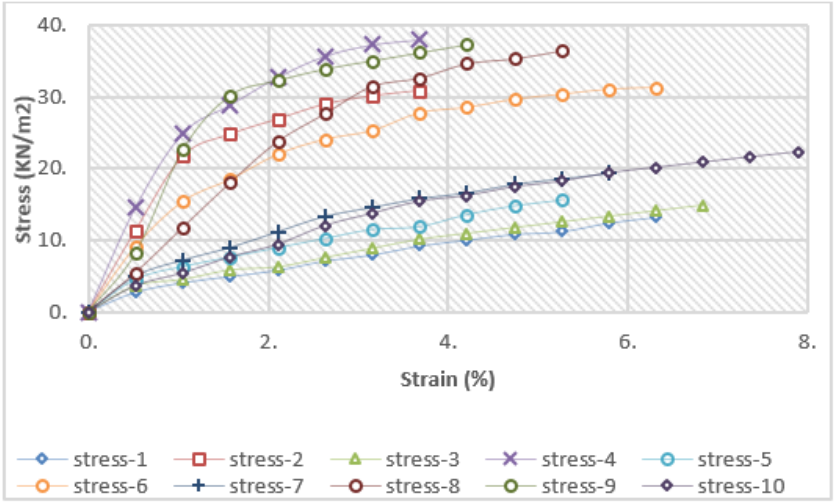


Fig. 6: UCS Stress vs. strain Plot

Model development and validation

For the analysis after experimental reports were obtained, the appropriate transformation which is quadratic (square root) and the response ranges from 5.13527 to 18.9128 with a ratio of max to min of 3.683 for CBR response (McLean and Anderson, 1966; Pinho-Lopes et al. 2018). Scheffe's models with intercepts built into the model coefficients are utilized for this mixture design. The transformation is required when the residual (error) is a function of the response magnitude (predicted results) and the transformation would be impactful unless the maximum to minimum ratio of the response parameter is very large (K. C. Onyelowe et al. 2019a; K. C. Onyelowe et al. 2019b, Alaneme et al. 2020). The fits summary, diagnostic tests, graphical and numerical optimization were carried out to determine the optimal combination proportion of the soil-geogrid blend to maximize the mechanical strength response. Post analysis, confirmation coefficient tables, and EVD model simulation were then executed to validate the model results using Design Expert 11 (2018) and Minitab 18 (2018) software.

Fit summary for UCS Response

The model fit summary statistics results indicated preference for quadratic model for CBR response with R-squared, predicted, adjusted and R-squared of 0.8367, 0.6417 and 0.79 respectively. The lack of fit test results presented a sum of squares of 1.09, a mean square of 0.18, and lack of fit p-value (Prob > F) of 0.8010.

Coefficient estimates and model equations for UCS

The estimates of components 'coefficient, standard error, degrees of freedom, variance inflation factor (VIF), and final equation in terms of L_pseudo component computation results are presented in Tables 5&6. VIF measures the extent to which the variance of the coefficient estimate (predictor) is inflated by a lack of orthogonality in the design points. If the factor is orthogonal with respect to all other factors in the model, then VIF = 1 (Pinho-Lopes et al. 2018; Bello et al. 2007).

Table 5: Final Equation in Terms of U_Pseudo Components

	*A	*B	*C	*AB	*AC	*BC
Sqrt(UCS) =	621.935	64.085	11.82484	-663.296	6315.46	3.10192

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels of the factors are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients (Design Expert 11, 2018; Minitab 18, 2018).

Table 6: Final equation in terms of U_Pseudo components

	*Geogrid	*Water	*Soils	Geogrid*Water	Geogrid*Soil	Water*Soil
Sqrt(UCS) =	2.36E+05	-615.29836	-3.1977	-2.45E+05	-2.35E+05	777.336

The equation in terms of actual factors can be used to make predictions about the response for given levels of each factor. Here, the levels should be specified in the original units for each factor. This equation should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor and the intercept is not at the center of the design space (J. A. Cornell, 2011).

Predicted vs. actual

This diagnostic plot shows the predicted EVD model response values on the y-axis against the actual values on the x-axis. This plot could also help to determine the value, or a group of values that are not estimated easily by the EVD model in terms of accuracy as presented in Fig. 7. The result deduced from the plotted results indicates a strong correlation between the experimental and the model predicted values with the plotted datasets ranging from about 3.5-6.5 (Pinho-Lopes et al. 2018; Bello et al. 2007).

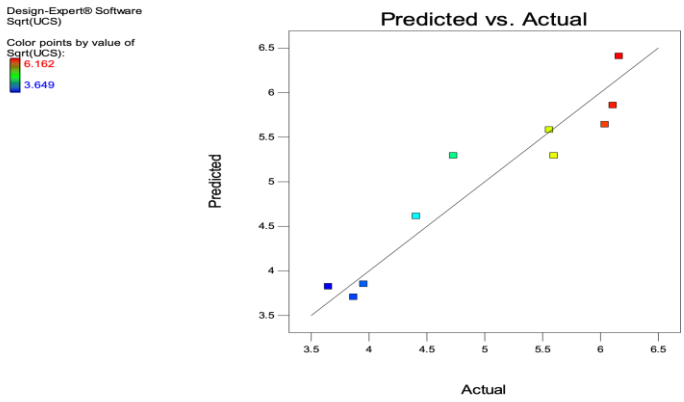


Fig. 7: Predicted vs. Actual UCS response

Optimization overview

Numerical optimization uses the model to search the factor space for the best trade-offs to achieve multiple goals. The optimization module searches for a combination of factor levels that simultaneously satisfy the criteria placed on each of the responses and factors. The goals that apply to both responses and factors were set to be in the range for the factors and maximize for the response where the lower limit is the lowest acceptable outcome and the upper limit is the desired best result.

In the desirability function computation, the solution with the highest score is preferentially taken as the optimal solution. A desirability criterion score of 1.0 and optimal ratio 0.002:0.098:0.9 for the fraction of geogrid, water and soil, respectively (J. Schwartz et al. 1981; Design Expert 11, 2018; Minitab 18, 2018).

Optimization ramps and bar graph

The numerical optimization ramps show the optimal solution graphical view with the optimal predictor parameter factor settings in red and the optimal response parameter factor in blue. This tool helps to make the required selection of the optimal solution in a graphical view presentation as shown in Fig. 11. Desirability value of 1.0 was calculated for the mixture component variables and the response variables, which indicate a robust model prediction of the mechanical behavior of soil-geogrid blend (Lawson and Erjavec, 2001; U. Syafitri et al. 2015; Ding et al. 1999).

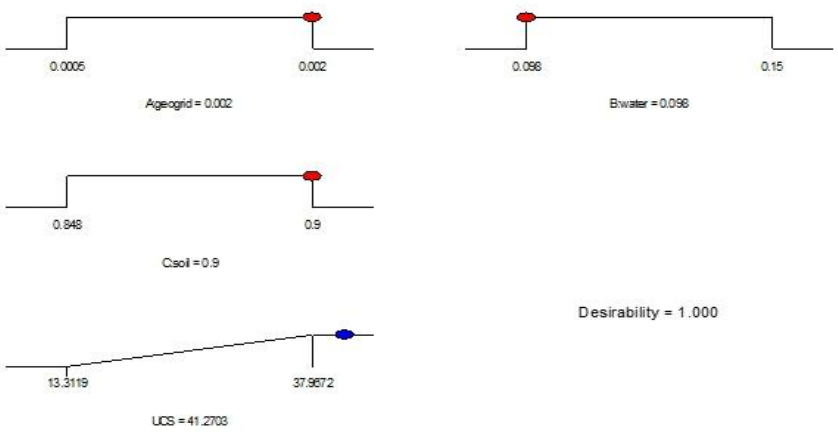


Fig. 8: Optimization Ramps

Optimization contour plot

The contour plot is an important tool for the visualization of the feasible experimental region's functional points in the iteration solution of mixture optimization (Design Expert 11, 2018; K. C. Onyelowe et al. 2019a). The contour plot for the optimal solution for the design points for UCS are ranging from 13.3119 to 37.9672 and the desirability points from 0 to 1. It is a graphical tool for the representation of 3-D surfaces by contour plotting in terms of constant slices in 2-D form as shown in Fig. 12.

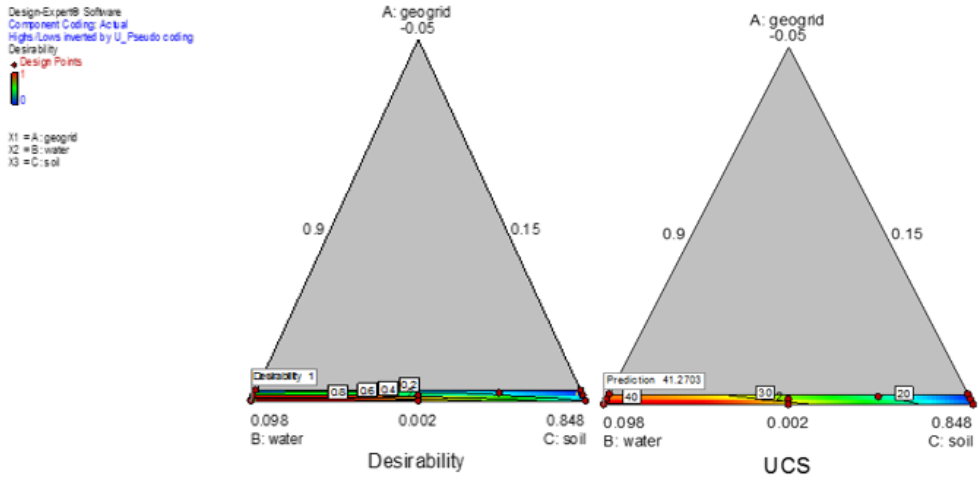


Fig. 12: Contour Plots for the Optimal Solution

CONCLUSION

In this research study, geogrids were utilized for engineering properties and modification of soil properties for civil engineering construction purposes. The research process involved the general engineering characterization of the test soil through experimental and laboratory processes to obtain the test soil's general engineering behavior and classification. The results obtained indicated high swelling potential and plasticity behavior with AASHTO classification of A-7 and unsuitable for engineering work. From the EVD optimization;

1. I-optimal design was utilized to explore the constrained factor space for the derivation of the run of experiments and mixture proportions formulation at the edges, center, interior, and vertex of the simplex. The mixture of experiment component is constrained by imposed restrictions on the sign of inequalities at the upper and lower region of the factor space to a sub-region of the equilateral triangle formed as a result of three component mixture simplex through the q-vertices with regular sides of (q-1) dimension where q is the total number of mixture ingredients. I-optimality and D-optimality of 0.39093 and 1747.474, respectively, was obtained with G-efficiency of 64.8%.

2. The responses were derived from the experimental runs utilized for statistical fit test, and diagnostic test computation using Design expert and Minitab 18 statistical software. This provides an analytical toolbox for the simulation and analysis of mixture experiments for test soil stabilization using geogrids. Incorporated in the toolbox are statistical tools and techniques like fit summary, model equations formulation with coefficients estimation, diagnostic plots

utilizing externally studentized residuals for regression model assumptions validation, and contour plots.

3. The numerical and graphical optimization process which locates the factor levels combinations which satisfy the criteria placed on the mixture components and the corresponding response parameters based on the model fitness evaluation through statistical analysis and equation simulation using desirability function was further conducted. A desirability score of 1 was calculated as the optimal solution with the optimal combination ratio of 0.002:0.0.98:0.9 for geogrid, water, and soil, respectively; and an optimal response of 41.270kN/m2 for UCS.

4. The results obtained from this research study on geotextile application for expansive soil UCS improvement indicated an improvement in the soil property at 0.2% by volume of geogrid, the generated strength value was greater than the minimum value specified by the American Association of State Highway and Transport officials (AASHTO) for the mechanical properties of soil.

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