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Variable returns to scale DEA—Taguchi approach for ternary additives optimization in expansive soil subgrade enhancement

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Abstract

In this study, variable returns to scale (VRS) data envelopment analysis was integrated into the Taguchi approach to optimize ternary additives for expansive soil enhancement. The ternary additives selected were sawdust ash (SDA), quarry dust (QD) and ordinary Portland cement (OPC). The additives were set as the input variables while multiple responses obtained from the experiments performed with the Taguchi orthogonal array were set as the output variables. Each row in the orthogonal array were defined as a decision making unit (DMU) in the optimization process and output-oriented VRS model was used to obtain the efficiency score for each DMU. Next, benevolent formulation was utilized to obtain the multipliers for the inputs and outputs which were subsequently used to determine the cross efficiency scores for each DMU. The cross-efficiency scores were used to construct the cross-efficiency matrix. Thereafter, the mean cross-efficiency score (MCES) was determined for each DMU. Parameter level that maximizes the MCES was chosen as the optimal level for that parameter. Optimum combination of additives was found at A6 B2 C3. Lastly, confirmatory experiments performed by blending the soil with the optimum combination of additives showed the effectiveness of this method in the enhancement of expansive soil properties.

Keywords: Additives, Expansive soil, Data envelopment analysis, Optimization, Taguchi method, Variable returns to scale

Introduction

During construction of geotechnical and highway structures, a common setback often encountered in practice is the unsuitability of some natural materials such as expansive soil found in situ. Expansive soil is known to be widely distributed predominantly in parched regions [1–3]. It is associated with significant volume change due to its susceptibility to moisture variability. It has the propensity to swell and shrink depending on the prevailing moisture condition. Infrastructures constructed on it portend great georisk to the surrounding due to stability concerns of the infrastructures. Several palliative measures are usually sought after during construction to mitigate the dangers posed by the soil [4–11]. The commonly used palliative measure is the replacement strategy in which

the soil is expected to be replaced with suitable geomaterials. This measure is ideal when the soil strata is only surficial. However, in cases where the soil extends to considerable depth below the ground surface, soil stabilization technique, which is an economical palliative measure, is usually adopted.

Soil stabilization involves blending soil with suitable geomaterials under appropriate conditions to obtain a composite mixture with enhanced soil properties. Different soil stabilization schemes are frequently executed in practice but the ones to be applied on a particular site are usually decided principally by the highway or geotechnical engineer [2]. In addition, the geomaterials used for soil stabilization by engineers are selected based on their reported performance in several studies conducted by different researchers. The geomaterials are categorized into traditional and non-traditional additives. Some of the traditional additives include cement, lime, fly ash, et cetera while the non-traditional ones include cement kiln dust (CKD), sawdust ash (SDA), mine tailings, coal bottom ash, bagasse ash, sulphonated oil and others [12–15].

The use of traditional additives such as lime and cement has been reported to be efficient in the enhancement of the properties of expansive soils. However, a notable concern with their continuous usage is the environmental challenges associated with them. These environmental challenges include the increase in pH of the soil and carbon footprint which is not unconnected with their production. Adverse effect of the undue increase in the pH of the soil when treated with the traditional additives is rife in literature [16–19]. As a consequence, there has been a paradigm shift towards the utilization of additives which possesses little or no environmental challenge for expansive soil stabilization. Most recent studies utilize a combination of the traditional and non-traditional additives to limit the environmental challenges caused by the sole usage of the traditional additives.

In a study by Ikeagwuani et al. [1], a combination of lime and SDA were used to treat black cotton soil, which is an expansive soil. The result obtained show that the best performance was achieved when a combination of 4% lime and 16% SDA were added to the soil. Similarly, rice husk ash and calcium carbide residue were combined by Liu et al. [20] to treat an expansive soil and an improved performance of the soil was reported when the additives were added to it. In a related study conducted by Phanikumar and Raju [21] on the improvement of an expansive soil, cement and lime sludge were mixed together to treat the soil and it was discovered that the pozzolanic reaction that occurred between the two additives and the soil resulted in the improved performance observed in the soil. The improved performance became apparent when 10% cement and 12% lime sludge content were blended with the expansive soil. In a similar development, a combination of hydrated lime and lignosulphate was used by Ijaz et al. [22] to stabilize an expansive soil and it was reported that an optimal combination of 2.625% hydrated lime and 0.875% lignosulphate content yielded the desired improvement in the soil properties.

Despite the degree of successes recorded in the combination and usage of the traditional and non-traditional additives in expansive soil stabilization, the current mode of stabilization can best be described as trial and error method, which is neither cost nor time effective. Fortunately, optimization schemes can provide improved and robust approaches when integrated in the stabilization process [8]. However, their integration in soil stabilization techniques has only been reported in very few literatures to the

extent of the knowledge of the authors. The use of response surface methodology (RSM) has claimed some level of successes in expansive soil stabilization [23, 24]. Interestingly, other optimization schemes which exist in literature and are capable of optimizing additives for expansive soil stabilization can also be explored. One of such optimization schemes, which has proven to be robust in product development, is the Taguchi optimization method.

Taguchi optimization method

Taguchi optimization technique, which is a widely adopted analytical tool for quality product design, was developed by a Japanese quality control expert, Genichi Taguchi [25]. The method bears a unique advantage as it significantly reduces the number of experiments required for robust product development. This unique advantage makes it preferable to other methods of experimental design including the RSM and other classical design of experiment (DOE) methods. Taguchi method provides a systematic approach in the variation of process parameter levels to attain the target response value [26] unlike other DOE methods that are usually executed using either full or fractional factorial test designs. The full or fractional test designs have inherent shortcomings such as time and cost—intensive nature (in the case of full factorial designs) and the use of undefined rules which makes the method more or less a trial and error method (in the case of fractional factorial designs) [27–29].

Taguchi surmounted the shortcomings of the classical DOE methods by adopting the use of orthogonal array for experimental designs. The orthogonal array is an approach with a mathematical framework developed by Hadamard, a French mathematician [30]. It reduces the number of designed experiments to the barest minimum but still achieves a balanced design. This is because every possible combination of the process parameters is utilized for any two consecutive columns to produce a mutually orthogonal array [26]. The key quality control tool employed by the Taguchi optimization technique is the signal-to-noise (S/N) ratio, which ensures that the desired outcome for each quality characteristic is optimally targeted [30]. The combined utilization of orthogonal array and S/N ratio by the Taguchi optimization method makes it a robust approach and the preferred optimization technique in several fields. Using the vacuum membrane distillation method, phenolic wastewater was efficiently treated by optimization of the process parameters through the Taguchi method [31], which shows a successful application in wastewater engineering. The method was also applied in the field of environmental science for effective pesticide removal using zeolite modified soil [32]. Several other applications exist in literature [33–38].

Despite the level of successes recorded with the utilization of the Taguchi optimization method, it still exhibits the inherent limitation of single response optimization associated with every other DOE method. In order to circumvent this drawback when confronted with multiple response problems, the Taguchi method is usually integrated into some numerical and analytical techniques to achieve multiple response optimization [39–46]. However, most of the developed numerical and analytical techniques for Taguchi multiple response optimization present modest results due to their inherent shortcomings [47], which poses a huge setback to the wide acceptance of the Taguchi optimization method. As such, the need for more thorough approaches toward solving

the multiple response optimization becomes crucial. The present study explored the use of a thorough numerical technique known as variable returns to scale data envelopment analysis model for Taguchi multiple response optimization; involving expansive soil stabilization process.

Data envelopment analysis

Data envelopment analysis (DEA) is a nonparametric mathematical linear programming technique used for the assessment of relative efficiencies of an array of decision-making units (DMUs) that comprises multiple inputs and multiple outputs. It was developed by Charnes et al. [48] for the assessment of efficient (best practice) frontier and to distinguish efficient units from the inefficient ones based on the recorded input and output values. The DEA is a body of methodologies and concepts that have been integrated into a group of models that has different interpretive possibilities [49]. They include the constant returns to scale (CRS) model which is also known as the Charnes, Cooper and Rhodes (CCR) model; the Bankers, Cooper and Rhodes (BCC) model; the multiplicative models; the additive models and the slack based measure (SBM) models. The most common among these models are the CCR and the BCC models which are often referred to as the classical DEA models because they were the earliest forms of the DEA models.

The DEA models are broadly divided into two groups based on their orientation. They are the input-oriented models and the output-oriented models. In the input-oriented models, the DMU under evaluation can have a proportional reduction in its input level as it advances towards the efficient frontiers whilst retaining its outputs at their existing levels. In the output-oriented models, the DMU under evaluation can have a proportional increase in its output whilst retaining its inputs at their existing levels. The striking feature of the DEA is its flexibility in multiplier selection during the estimation of the efficiency of a DMU. During efficiency estimation, each DMU is allowed to choose multipliers (weights) for its multiple inputs and outputs that is highly favorable to it. The efficiency so obtained is the greatest efficiency the DMU can achieve. This feature made the DEA to be accepted globally in the measurement of efficiencies.

However, the problem with this flexibility feature is the inability to discriminate among efficient DMUs because several DMUs may lie at the efficient frontier. With more than one DMU lying at the efficient frontier, comparison among their efficiencies become a herculean task. Notably, comparison of the efficiencies of DMUs can only be adjudged to be fair if their efficiencies are calculated with similar set of weights. To put a stop to this problem, the concept of cross-efficiency evaluation, which was developed by Sexton et al. [50] and later expanded by Doyle & Green [51], was introduced as an extension to the DEA technique. This cross-efficiency concept discourages the idea of DMUs being self-evaluated only and encourages peer-evaluation in conjunction with the self-evaluation amongst the DMUs. The objective of the cross-efficiency concept is to utilize the set of weights chosen by the self-evaluated DMUs as a unique set of common weights for the estimation of the efficiencies of other DMUs. Thus, unrealistic weights obtained from the self-evaluated DMUs are obliterated when cross-efficiency evaluation is performed [52]. In addition, discrimination amongst the efficient DMUs is also vastly improved.

Notwithstanding the benefit of the cross-efficiency evaluation in the DEA, the problem of non-uniqueness of the optimal solutions in the classical DEA often limits its usage. To overcome this challenge, a secondary goal is usually incorporated into the traditional DEA. Several scholars have developed different secondary goals for the classical DEA models. Some of the secondary goals are the well established aggressive and benevolent formulation [51], neutral DEA concept [53], maxmin formulation [54] and the symmetric weight assignment approach [55]. Other secondary goals include the coordinate translation method [56], integration of SBM model in the DEA [57], target identification model [58] and the game cross-efficiency model which represents a Nash equilibrium point [59]. Some other scholars who have also contributed to the secondary goals include Liu [60], Ramon et al. [61] and Yang et al. [62].

Interestingly, the introduction of secondary goals to the DEA has led to its widespread utilization in various disciplines. Wu et al. [63] successfully utilized the concept of the cross efficiency evaluation for the measurement of performance of countries that participated in the summer Olympic from 1984 to 2004. Wu et al. [64] effectively employed cross-efficiency evaluation concept to assess the performance of different container ports situated in 12 different countries. Lim et al. [65] applied DEA cross-efficiency concept to choose stock portfolio in the Stock market of Korea. Gavgani & Zohrehbandia [66] used the concept of cross-efficiency for the assessment of performance of staff working in six nursing homes. Sun et al. [67] evaluated the efficiency of infrastructure investment of various capital cities in China using the cross-efficiency evaluation.

There are other numerous applications of the cross-efficiency concept in literature. However, it is highly necessary to note that cross efficiency concept is often utilized mainly for CRS models. This is largely due to the negative efficiency scores that are generated from the input-oriented BCC models. Negative scores are not reasonable and usually pose serious challenge in the estimation of the final efficiency of DMUs. Interestingly, its counterpart, the output-oriented BCC models, do not produce negative efficiency scores and by extension, reasonable weights are produced from it that can be utilized by practitioners especially geotechnical and highway engineers. Consequently, this study adopted the classical output-oriented BCC model together with the benevolent formulation as a secondary goal for the optimization of additives in the improvement of expansive soil. The BCC model was integrated into the Taguchi method in the optimization process.

BCC model

The BCC model, which was proposed by Banker, Cooper and Rhodes [68], is also known as the variable returns to scale (VRS) model. The VRS model is an extension of the CRS model. The difference between both models is that the assumption imposed on the CRS is relaxed in the VRS model. Data involved in the VRS model are much more enveloped than that of the CRS model. This result in the production of technical efficiencies that are equal to or even greater than those of the CRS model. Furthermore, efficiency variation with regards to its scale of operation are accounted for in the VRS model, and this lead to pure technical efficiency being measured in the VRS model [69]. BCC model is described as efficient if its efficiency is equal to unity; otherwise, it is described as inefficient.

The BCC model can be represented in the envelopment form or in the multiplier form whose orientation can either be input oriented or output oriented. One of these two orientations can be used for benchmarking depending on the goal of the decision maker [70]. However, in this study, the multiplier form of the output-oriented BCC model was utilized for the optimization process. The multiplier form, which was integrated into the Taguchi method for the optimization of additives for expansive soil enhancement, was utilized because it is best suited for geotechnical and highway engineering problems. In addition, it reflects the main objective of the optimization process which is to reduce or keep the inputs at their current level whilst seeking the maximization of the outputs. The equations for the multiplier form of input-oriented BCC model and output-oriented BCC model used for estimation of a DMU under evaluation DMU_k ($k \in \{1, \dots, n\}$), are expressed as shown in Eqs. (1) and (2).

Input-oriented multiplier BCC model

$$\begin{aligned}
 &\text{Maximize } \theta_{kk} = \frac{u_{0k} + \sum_{r=1}^s u_{rk} y_{rk}}{\sum_{i=1}^m v_{ik} x_{ik}} \\
 &\text{Subject to } \frac{u_{0k} + \sum_{r=1}^s u_{rk} y_{rj}}{\sum_{i=1}^m v_{ik} x_{ij}} \leq 1, j = 1, \dots, n, \\
 &u_{rk} \geq \varepsilon, r = 1, \dots, s \\
 &v_{ik} \geq \varepsilon, i = 1, \dots, m, \\
 &u_{0k} \text{ is unconstrained in sign}
 \end{aligned} \tag{1a}$$

Equation (1a), which is a fractional program can be expressed in the form of a linear program by using the transformation technique developed by Charnes [71].

$$\begin{aligned}
 &\text{Maximize } \theta_{kk} = u_{0k} + \sum_{r=1}^s u_{rk} y_{rk} \\
 &\text{Subject to } \sum_{r=1}^m v_{ik} x_{ik} = 1, \\
 &u_{0k} + \sum_{r=1}^s u_{rk} y_{rj} - \sum_{i=1}^m v_{ik} x_{ij} \leq 0, j = 1, \dots, n, \\
 &v_{ik} \geq \varepsilon, i = 1, \dots, m, \\
 &u_{0k} \text{ is unconstrained in sign}
 \end{aligned} \tag{1b}$$

Output-oriented multiplier BCC model

$$\begin{aligned}
&\text{Minimize } 1/\theta_{kk} = \frac{v_{0k} + \sum_{i=1}^m v_{ik}x_{ik}}{\sum_{r=1}^s u_{rk}y_{rk}} \\
&\text{Subject to } \frac{V_{0k} + \sum_{i=1}^m v_{ik}x_{ij}}{\sum_{r=1}^s u_{rk}y_{rj}} \geq 1, j = 1, \dots, n, \\
&\quad u_{rk} \geq \varepsilon, r = 1, \dots, s, \\
&\quad v_{ik} \geq \varepsilon, i = 1, \dots, m, \\
&\quad v_{0k} \text{ is unconstrained in sign}
\end{aligned} \tag{1b}$$

Equation (2a) which is also a fractional program can be expressed as a linear program by using the transformation technique developed by Charnes [71].

$$\begin{aligned}
&\text{Minimize } 1/\theta_{kk} = v_{0k} + \sum_{i=1}^m v_{ik}x_{ik} \\
&\text{Subject to } \sum_{r=1}^s u_{rk}y_{rk} = 1, \\
&\quad v_{0k} + \sum_{i=1}^m v_{ik}x_{ij} - \sum_{r=1}^s u_{rk}y_{rj} \geq 0, j = 1, \dots, n, \\
&\quad u_{rk} \geq \varepsilon, r = 1, \dots, s, \\
&\quad v_{ik} \geq \varepsilon, i = 1, \dots, m, \\
&\quad v_{0k} \text{ is unconstrained in sign}
\end{aligned} \tag{2a}$$

where,

x_{ij} denotes the input of each of the j th DMU (DMU_j)

y_{rj} denote the output of each of the j th DMU.

n represents the number of DMUs to be evaluated.

m represents the number of inputs used by each DMU_j

s signifies the number of outputs produced by each DMU_j

ε represents non-Archimedean infinitesimal.

v_{ik} signifies the input multiplier selected by DMU_k

u_{rk} signifies the output multiplier selected by DMU_k

θ_{kk} denotes the optimal efficiency of DMU_k

Methodology**Materials used**

The data used for analysis in this study was extracted from the study that was performed by Ikeagwuani [72]. Ikeagwuani [72] optimized ternary additives for the enhancement of expansive soil properties using the Taguchi method. The expansive soil, sawdust dust (SDA), quarry dust (QD) and ordinary Portland cement (OPC) were the additives used for the optimization.

Expansive soil

The expansive soil sample (Fig. 1) used for the investigation in the study conducted by Ikeagwuani [72] was collected from a borrow pit in Numan (9°29'10"LN, 12°02'36"LE), Adamawa State, Nigeria. Shortly after collection, the soil sample was pulverized with the aid of a pestle. Ikeagwuani [72] reported that the pulverization was done because the expansive soil was found to be in dried and firm condition when it was collected. The basic soil tests conducted on the natural expansive soil showed that the soil comprises 95.8% fine particles and 4.2% sand particles as shown in Table 1. The compaction characteristics of the expansive soil which include the optimum moisture content (OMC) and maximum dry density (MDD) were recorded as 23.4% and 1.55 g/cm³ respectively. The compaction characteristics were determined using the standard proctor mould. Atterberg limits performed on the soil using the procedure that was stated in BS 1377 (1990) Part 2 showed that the soil has a plastic limit of 23.6% and a high plasticity index of 43.5%. According to Garg [73] and Holtz & Gibbs [74] any soil that possesses a plasticity that exceeds 17% can be regarded as an extremely high plastic soil. The values of the unconfined compressive strength (UCS) and the California bearing ratio (CBR) of the soil as displayed in Table 1 showed that both values did not meet the minimum requirement for design of pavement as laid out in the Nigerian general specification for road and bridges. Furthermore, the soil was classified using the American association of state highway and transportation official [75] and the classification revealed that the soil fell under the A-7-6 group of soil. Chemical composition analysis was conducted on a representative sample of the soil using the X-ray fluorescence procedure (ARL-XRF Advant 1200 model) and the result is shown in Table 2 (Fig. 1).

Table 1 Expansive soil properties

S/No	Soil property	Description
1	Specific gravity	2.66
2	Fines	95.8%
3	Sand	4.2%
4	Natural moisture content	8.7%
5	Plastic limit	23.6%
6	Liquid limit	67.1%
7	Plasticity index	43.5%
8	Optimum moisture content (OMC)	23.4%
9	Maximum dry density (BSL)	1.546 g/cm ³
10	AASHTO classification	A-7-6 (33)
11	USCS classification	CH
12	UCS	152.482kN/m ²
13	DFS	71.59%
14	CBR	Unsoaked
		Soaked

Table 2 Chemical analysis of expansive soil, SDA, QD and OPC

Element oxide	Soil (%)	SDA (%)	QD (%)	OPC (%)
Silica (SiO ₂)	58.9	41.0	71.7	12
Iron oxide (Fe ₂ O ₃)	23.34	6.07	4.47	4.33
Alumina (Al ₂ O ₃)	9.85	-	14.7	-
Potash (K ₂ O)	-	10	2.7	-
Lime (CaO)	1.21	38.9	3.81	80.91
Magnesia (MgO)	-	-	-	-
Titanium oxide (TiO ₂)	3.07	0.36	1.37	0.16
Magnesium oxide (MnO)	0.03	0.42	-	0.03
SO ₃	-	0.89	-	1.4
V ₂ O ₅	0.04	0.02	0.02	-
Cr ₂ O ₃	0.02	-	-	-
CuO	0.06	0.06	0.04	0.02
ZnO	0.04	0.09	-	-
Ga ₂ O ₃	0.02	-	0.02	-
Rb ₂ O	0.08	0.17	0.06	-
SrO	0.16	0.62	0.21	0.90
Y ₂ O ₃	0.03	0.01	0.02	-
ZrO ₂	0.25	0.05	0.36	0.01
BaO	0.47	-	0.10	-
Eu ₂ O ₃	0.64	-	0.22	-
Re ₂ O ₇	0.05	-	-	-
IrO ₂	0.07	-	-	-
ThO ₂	0.07	-	-	-
Co ₃ O ₄	-	0.05	0.01	0.06
HgO	-	-	-	0.03
PbO	-	-	0.01	-
As ₂ O ₃	-	-	0.02	-
Loss on ignition				

Quarry dust

According to Ikeagwuani [72], the quarry dust (QD) used as one of the additives in the optimization process was obtained from Enugu (7° 32' 47"LN, 6° 27' 31"LE), Nigeria.

Fig. 1 Sample of the dried natural expansive soil

QD is an industrial waste product from quarry industries. It is liberated during the crushing of rock [76]. The QD is well known for his environmental pollution when it is discarded inappropriately [77]. Numerous scholars particularly in geotechnical and highway engineering constantly seek to recycle and harness the potential of QD in pavement design [77–81]. The chemical composition analysis of the QD utilized by Ikeagwuani [72] for the optimization process is presented in Table 2. The chemical composition analysis of QD as presented in Table 2 consists of a high percentage of silica.

Sawdust ash

Sawdust ash (SDA), which was the second additive utilized by Ikeagwuani [72] during the optimization process, was gotten from the residue produced after the incineration of sawdust collected from a dumpsite in Enugu. Ikeagwuani [72] reported that the sawdust was generated using dual-phase production process. The first phase involved the removal of impurities in the sawdust through manual sorting. The removed impurities were discarded and the sawdust was air-dried for a period of 7 d. The second phase involved the incineration stage. In this stage, the air-dried sawdust was gently inserted into a furnace whose heating temperature was set at 800 °C. The sawdust was burnt for 6 h in the furnace to generate the SDA which was permitted to cool for 24 h and subsequently made to pass through BS No. 200 test sieve. A representative sample of the cooled SDA was collected from the sieved ones and used for chemical composition analysis. The result of the chemical composition analysis of the SDA as reported by Ikeagwuani [72] is presented in Table 2.

Ordinary Portland cement

The ordinary Portland cement (OPC) which was the third and last additive utilized by Ikeagwuani [72] was sourced locally. The OPC grade was 32.5R and its chemical composition conforms with the specification stated in the ASTM C150 (ASTM, 2017) code. The oxide composition analysis of the OPC that was utilized by Ikeagwuani [72] is presented in Table 2

Methods

Laboratory testing procedures

The experimental procedure stated in BS 1377 [82] was employed by Ikeagwuani [72] for the evaluation of the basic soil properties of the expansive soil. Only the Differential free swell (DFS) test was evaluated with the experimental procedure stated in IS 2720, Part 40 [83]. The basic soil properties of the soil evaluated included compaction, UCS, specific gravity, Atterberg limits, CBR and natural moisture. BS 1377 [82] experimental procedure was also employed by Ikeagwuani [72] to evaluate the UCS and CBR, which were the first two responses considered in his study while the IS 2720, Part 40 [83] was utilized for the evaluation of the last response (DFS).

Compaction

Compaction test was executed as per BS 1377, Part 4 [84] experimental procedure for the determination of the OMC and MDD of the natural soil. The BS 1377, Part 4 [84]

experimental procedure was also used to execute the compaction test for the samples that were prepared with the various mix ratios obtained from the mixed level Taguchi orthogonal array. As reported by Ikeagwuani [72], a standard proctor mould whose volume was 0.001 m^3 along with a standard rammer whose weight was 2.5 kg were utilized for the test. The soil samples were poured into the mould in three layers and each layer was compacted by subjecting it to 27 blows with the help of the rammer. The rammer was permitted to fall under its own weight from a height of 300 mm.

CBR test

The CBR test was performed in accordance with BS 1377, Part 4 [84] experimental procedure. The test was done on soil samples prepared with the various mix ratios obtained from the mixed level Taguchi orthogonal array as well as on the natural expansive soil sample. Both unsoaked and soaked CBR tests were carried out for the natural expansive soil. The soaked CBR test was performed after immersing the natural expansive soil in water for 96 h. For the soil samples prepared with the various mix ratios gotten from the Taguchi orthogonal array, only unsoaked CBR test was performed on them. According to Ikeagwuani [72], the unsoaked CBR test was performed after curing the samples for 7 d in a humidity-controlled environment. Before performing the CBR test, two surcharge circular disks, whose combined weight was 4.5 kg, were gently placed on the soil samples and the entire assembly were placed onto the CBR machine loading frame. Axial force was applied to the soil samples through a 50 mm metallic plunger that was permitted to penetrate the soil samples at strain rate of 1.25 mm/min until failure occurred. Subsequently, the CBR values of the soil samples were estimated corresponding to settlements at 2.5 mm and 5 mm.

UCS test

As reported by Ikeagwuani [72], the UCS test was performed in accordance with the experimental guidelines stated in BS 1377, Part 7. Cylindrical soil samples whose height and diameter are 76 and 38 mm respectively were used to perform the UCS test. The test was performed on both the natural soil sample and the soil samples prepared with the mix ratios generated from the Taguchi mixed level orthogonal array. The soil samples were compacted in standard moulds with moisture content corresponding to their OMC. Extraction of the soil samples were carried out afterwards. The extracted samples were tightly sealed in polyethylene bags and left to cure for 28 d. After curing, the samples were placed in the loading frame of the UCS machine and then loaded axially at strain rate of 1.2 mm/min until it failed or reached 20% of the strain applied to it.

DFS test

IS 2720, Part 40 [83] experimental guideline was employed by Ikeagwuani [72] to perform the DFS test. The DFS test is used to determine the degree of expansiveness of soil samples containing expandable clay. It involves determining the volume change of two similar soil samples in which one of the soil sample is immersed in water (polar solvent) and the other sample is immersed in kerosene (non-polar solvent). According to Ikeagwuani [72], the soil samples used for the experiment were oven dried for 24 h prior to the test. After oven-drying, the soil samples were sieved using BS No. 36 test sieve. To

conduct the test, about 10 g of sample was collected from a sieved sample, poured into a transparent graduated cylinder containing water, and stirred thoroughly until it was perfectly mixed with the water. In the same vein, another 10 g of sample was collected from the sieved soil sample and poured into another transparent graduated cylinder containing kerosene. It was also stirred thoroughly with a stirrer until it was perfectly mixed with the kerosene. Both transparent graduated cylinders were allowed to stand undisturbed for 24 h and the soil sample degree of expansiveness was evaluated shortly after.

Optimization procedure

As pointed out earlier, this study utilized the data from the experiment performed by Ikeagwuani [72] on the optimization of ternary additives for the enhancement of the properties of expansive soil. Ikeagwuani [72] used the Taguchi approach to optimize the additives. Taguchi orthogonal mixed level array was selected by Ikeagwuani [72] for the design of experiment (DOE). The OPC together with the QD were assigned three levels each while only SDA was assigned six levels in the optimization process performed by Ikeagwuani [72] as depicted in Table 3. In Table 4, the Taguchi mixed level orthogonal array used by Ikeagwuani [72] for his optimization process is shown.

As noted earlier, Taguchi approach is only effective for the optimization of single response. Therefore, in order to optimize the ternary additives concurrently, this study proposed an approach which involves the integration of the output-oriented multiplier BCC model and benevolent formulation (secondary goal) into the Taguchi approach utilized by Ikeagwuani [72]. The following four steps were adopted for the concurrent optimization of the ternary additives.

Step 1: Definition of DMU and estimation of the mean responses.

In this initial step, each row in the Taguchi orthogonal array signifies a DMU_j . The rows consist of various mix ratios and their corresponding responses. The responses are determined by performing experiments in the laboratory. The total number of experiments in the Taguchi orthogonal array represents the total number of DMUs, n . The various mix ratios are set as the input variables while their corresponding responses are set as the output variables. Each additive ratio, in each row of the Taguchi orthogonal array, denotes an input, x_{ij} , for each DMU_j ; while each response, in each row of the Taguchi array, denotes an output, y_{rj} for each DMU_j . After defining the DMUs, the average value of each response are calculated.

Step 2: Evaluation of BCC-efficiency.

Step 2 involves the estimation of the relative BCC-efficiency, θ_{kk} , for each DMU. This is performed by solving Eq. (2b) which is the linear form of the output-oriented BCC model.

Step 3: Estimation of optimal weights and construction of cross-efficiency matrix.

Table 3 Additives with their assigned levels

S/N	Parameter (additive)	Parameter level					
		1	2	3	4	5	6
1	SDA	0	4	8	12	16	20
2	QD	0	10	20	-	-	-
3	OPC	2	5	8	-	-	-

Table 4 Layout of Taguchi mixed level orthogonal array

Number of experiment	Parameter values					
	Actual values			Coded values		
	SDA	QD	OPC	A	B	C
1	0	0	2	1	1	1
2	0	10	5	1	2	2
3	0	20	8	1	3	3
4	4	0	2	2	1	1
5	4	10	5	2	2	2
6	4	20	8	2	3	3
7	8	0	5	3	1	2
8	8	10	8	3	2	3
9	8	20	2	3	3	1
10	12	0	8	4	1	3
11	12	10	2	4	2	1
12	12	20	5	4	3	2
13	16	0	5	5	1	2
14	16	10	8	5	2	3
15	16	20	2	5	3	1
16	20	0	8	6	1	3
17	20	10	2	6	2	1
18	20	20	5	6	3	2

In this step, the benevolent formulation (Eq. (3)) proposed by Doyle & Green [51], is applied to estimate the optimal input and output weights, v_{ik}^* and u_{rk}^* as well as the optimal free variable, v_{ok}^* chosen by each DMU. Once the optimal weights and free variables are determined, they are used to generate cross-efficiency scores for each DMU_j . The cross-efficiency scores are calculated using the expression given in Eq. (4). Thereafter, the generated cross-efficiency scores are used to construct the cross-efficiency matrix and to obtain the mean cross efficiency scores (MCES), θ_j , for each DMU_j (Eq. 5). The MCES for each DMU_j is calculated as the arithmetic mean across each row. This is done to obtain the average appraisal of peers.

$$\begin{aligned}
 & \text{Minimize } 1/\theta_{kk} = \sum_{j=1, j \neq k}^n \left(v_{0k} + \sum_{i=1}^m v_{ik} x_{ik} \right) \\
 & \text{Subject to } \sum_{j=1, j \neq k}^n \sum_{r=1}^s u_{rk} y_{rk} = 1, \\
 & v_{0k} + \sum_{i=1}^m v_{ik} x_{ij} - \sum_{r=1}^s u_{rk} y_{rj} \geq 0, \quad j = 1, \dots, n, \\
 & v_{0k} + \sum_{i=1}^m v_{ik} x_{ik} - 1/\theta_{kk} \sum_{r=1}^s u_{rk} y_{rk} = 0, \\
 & u_{rk} \geq \varepsilon, \quad r = 1, \dots, s,
 \end{aligned} \tag{3}$$

$$v_{ik} \geq \varepsilon, i = 1 \dots m,$$

v_{0k} is unconstrained in sign

$$\theta_{kj} = \frac{v_{0k}^* + \sum_{i=1}^m v_{ik}^* x_{ij}}{\sum_{r=1}^s u_{rk}^* y_{rj}}, k, j = 1, 2 \dots, n \quad (4)$$

$$\theta_j = \frac{1}{n} \sum_{k=1}^n \theta_{kj} \quad (5)$$

Step 4: Parameter effect on the MCES.

The average efficiency scores for the various DMUs that appear on the same parameter level are determined in this last step. This is done by determining the level of any parameter level in which the MCES are maximized.

Results and discussion

Effect of the process parameters on the responses

The process parameter effect on the responses is displayed in Fig. 2. The result for the effect of the additives on the CBR in Fig. 2a suggests that changes in the quantity of the additives had a noticeable effect on the CBR. Judging from the maximum slope of the linear variations, the effect of the SDA was the most pronounced. The effect of the QD and OPC on the CBR appears to be roughly the same. As such, the quantity of the additive admixed with the soil for the three additives significantly influence the change in the CBR. For the UCS in Fig. 2b, it can be similarly concluded that the SDA had the most perceptible effect on the UCS based on the maximum slope. The effect of the OPC was also very pronounced, with the QD yielding the least effect on the UCS variation. The variation in DFS with change in the additives content is represented in Fig. 2c. The SDA clearly had the most significant effect on the DFS of the expansive soil. The effect of both QD and OPC appear to be less pronounced, with the maximum observed slope, typically having an effect below 10% in the DFS. The outcome of the result in Fig. 2 clearly indicates the influential role of the SDA in the expansive soil treatment. This could likely be due to its self-cementing ability as explicated subsequently.

Optimal combination for individual responses

The experiment data obtained from the study performed by Ikeagwuani [72] is presented in Table 5. Ikeagwuani [72] optimized the additives using the L18 Taguchi mixed level orthogonal array. The responses considered in the study were UCS, CBR and DFS. The values obtained for the responses after the optimization were 738.735kN/m², 50.04 and 3.69% for the UCS, CBR and DFS respectively. These values were found at three different conflicting combinations. The combinations were A3 B3 C3 (UCS), A6 B3 C3 (CBR) and A6 B3 C2 (DFS). This shows the ineffectiveness of Taguchi approach in the concurrent optimization of additives. In reality, geotechnical and highway engineers often seek to improve multiple properties of the soil.

Fig. 2 Plots of process parameter effect on **a** CBR, **b** UCS, **c** DFS

Remarkably, this present study was used to optimize the ternary additives concurrently by integrating the output-oriented BCC model and the benevolent formulation into the Taguchi method for the enhancement of the expansive soil properties.

Table 5 Experimental data

Expt. No	UCS			CBR			DFS			
1	229.11	237.14	296.68	12.23	10.86	27.57	23.78	54.12	55.15	53.57
2	407.75	361.60	459.05	26.22	30.58	21.77	24.35	45.18	45.98	44.38
3	617.41	552.78	724.66	33.03	-	34.03	32.30	29.53	28.57	30.30
4	363.08	246.20	171.18	21.61	23.70	19.70	25.44	43.30	43.93	42.70
5	701.92	424.63	639.86	33.30	28.60	34.48	32.58	27.62	28.50	26.44
6	644.39	698.88	-	46.23	45.43	45.95	43.42	32.00	31.12	33.33
7	710.28	756.21	800.30	30.17	27.41	36.30	36.32	22.02	22.86	21.23
8	674.93	526.44	441.33	26.76	-	19.69	51.19	32.67	31.66	33.15
9	488.83	475.93	528.82	36.55	34.35	38.78	33.93	19.05	19.63	18.78
10	513.51	634.70	-	35.10	31.95	22.50	31.23	31.82	32.50	30.69
11	196.79	280.08	242.31	36.23	34.89	33.54	34.85	22.07	22.58	21.63
12	660.80	633.02	286.96	49.22	44.39	48.20	43.50	13.64	14.81	12.89
13	422.39	274.89	485.91	43.61	38.23	36.37	38.31	11.62	11.91	11.16
14	453.29	324.02	-	43.19	37.66	42.30	37.18	26.52	27.32	25.74
15	322.34	373.88	370.38	38.22	35.81	39.59	35.73	25.65	25.60	25.84
16	399.71	429.12	335.22	55.93	51.79	38.05	48.55	8.70	9.75	7.63
17	248.09	284.80	397.48	34.69	-	39.85	38.93	25.22	26.11	24.39
18	462.49	417.59	393.78	38.36	36.46	53.78	32.43	8.43	8.37	8.30

Table 6 Mean response values

Experimental runs	DMU _j	Parameter			UCS (kN/m ²)	CBR (%)	DFS (%)
		SDA	QD	OPC			
1	DMU ₁	0	0	2	254.33	18.61	54.28
2	DMU ₂	0	10	5	409.47	24.11	45.18
3	DMU ₃	0	20	8	631.62	33.12	29.47
4	DMU ₄	4	0	2	260.15	22.61	43.31
5	DMU ₅	4	10	5	588.81	32.24	27.52
6	DMU ₆	4	20	8	671.64	45.26	32.15
7	DMU ₇	8	0	5	755.60	32.55	22.04
8	DMU ₈	8	10	8	547.57	32.55	32.49
9	DMU ₉	8	20	2	497.86	35.90	19.15
10	DMU ₁₀	12	0	8	574.11	30.20	31.67
11	DMU ₁₁	12	10	2	239.73	34.88	22.09
12	DMU ₁₂	12	20	5	526.92	46.33	13.78
13	DMU ₁₃	16	0	5	394.40	39.13	11.56
14	DMU ₁₄	16	10	8	388.65	40.08	26.53
15	DMU ₁₅	16	20	2	355.53	37.34	25.70
16	DMU ₁₆	20	0	8	388.02	48.58	8.69
17	DMU ₁₇	20	10	2	310.12	37.82	25.24
18	DMU ₁₈	20	20	5	424.63	40.26	8.37

Application of VRS DEA and benevolent formulation to Taguchi approach for additives optimization

The concurrent optimization of the additives was executed using a combination of DEA solver software and visual basic application (VBA) code as illustrated in the

Table 7 BCC-efficiency of DMUs

DMU_j	Inputs			Outputs			BCC-efficiency, θ_{kk}
	x_{1j}	x_{2j}	x_{3j}	y_{1j}	y_{2j}	y_{3j}	
DMU ₁	0	0	2	254.33	18.61	54.28	1.00
DMU ₂	0	10	5	409.47	24.11	45.18	1.00
DMU ₃	0	20	8	631.62	33.12	29.47	1.00
DMU ₄	4	0	2	260.15	22.61	43.31	1.00
DMU ₅	4	10	5	588.81	32.24	27.52	1.00
DMU ₆	4	20	8	671.64	45.26	32.15	1.00
DMU ₇	8	0	5	755.60	32.55	22.04	1.00
DMU ₈	8	10	8	547.57	32.55	32.49	1.08
DMU ₉	8	20	2	497.86	35.90	19.15	1.00
DMU ₁₀	12	0	8	574.11	32.76	31.67	1.00
DMU ₁₁	12	10	2	239.73	34.88	22.09	1.00
DMU ₁₂	12	20	5	526.92	46.33	13.78	1.00
DMU ₁₃	16	0	5	394.340	39.13	11.56	1.00
DMU ₁₄	16	10	8	388.65	40.08	26.53	1.07
DMU ₁₅	16	20	2	355.53	37.34	25.70	1.00
DMU ₁₆	20	0	8	388.02	52.09	8.69	1.00
DMU ₁₇	20	10	2	310.12	37.82	25.24	1.00
DMU ₁₈	20	20	5	424.63	40.26	8.37	1.15

Table 8 Optimal input and output weights

DMU_j	BCC-efficiency θ_{kk}	Input weights			Output weights			Free variable v_{ok}^*
		v_{1k}^*	v_{2k}^*	v_{3k}^*	u_{1k}^*	u_{2k}^*	u_{3k}^*	
DMU ₁	1.0000	0.00060	0.00053	0.00332	0.00001	0.00128	0.00027	0.03490
DMU ₂	1.0000	0.00066	0.00000	0.00000	0.00007	0.00000	0.00112	0.07756
DMU ₃	1.0000	0.00266	0.00000	0.00488	0.00007	0.00059	0.00024	0.03210
DMU ₄	1.0000	0.00064	0.00057	0.00351	0.00001	0.00131	0.00025	0.03365
DMU ₅	1.0000	0.00275	0.00038	0.00479	0.00004	0.00114	0.00000	0.02197
DMU ₆	1.0000	0.00062	0.00054	0.00343	0.00001	0.00133	0.00028	0.03609
DMU ₇	1.0000	0.00061	0.00053	0.00337	0.00001	0.00130	0.00028	0.03543
DMU ₈	1.0780	0.00000	0.00025	0.00000	0.00007	0.00000	0.00106	0.07513
DMU ₉	1.0000	0.00061	0.00053	0.00337	0.00001	0.00130	0.00028	0.03545
DMU ₁₀	1.0000	0.00000	0.00070	0.00089	0.00002	0.00094	0.00063	0.05485
DMU ₁₁	1.0000	0.00067	0.00050	0.00340	0.00001	0.00136	0.00028	0.03524
DMU ₁₂	1.0000	0.00059	0.00053	0.00340	0.00001	0.00131	0.00027	0.03659
DMU ₁₃	1.0000	0.00066	0.00116	0.00547	0.00001	0.00149	0.00005	0.02514
DMU ₁₄	1.0690	0.00000	0.00056	0.00000	0.00000	0.00108	0.00079	0.06287
DMU ₁₅	1.0000	0.00000	0.00014	0.00343	0.00003	0.00081	0.00055	0.04671
DMU ₁₆	1.0000	0.00062	0.00054	0.00343	0.00001	0.00132	0.00028	0.03606
DMU ₁₇	1.0000	0.00061	0.00054	0.00338	0.00001	0.00130	0.00028	0.03552
DMU ₁₈	1.1508	0.00000	0.00015	0.00424	0.00000	0.00167	0.00000	0.05331

following steps:

Step 1: In this first step, the mean values of each response (Table 6) were obtained after defining the DMUs which included the inputs and outputs variables. There were

three input variables, which were the three additives used by Ikeagwuani [72]. The inputs were SDA (x_{1j}), QD (x_{2j}) and OPC (x_{3j}). There were 18 different experiments in the Taguchi mixed level orthogonal array used in the study conducted by Ikeagwuani [72] and this corresponds to 18 different DMUs. The output variables, which were the responses, included UCS (y_{1j}), CBR (y_{2j}) and DFS (y_{3j}).

Step 2: In the second step, the BCC-efficiency for each DMU was calculated. The BCC-efficiency was calculated by using Eq. (2b) and the result is presented in Table 7.

Step 3: In this step, optimal input and output weights for each DMU as well as the free variables were determined for each DMU using the benevolent formulation expressed in Eq. (3). The results are displayed in Table 8. Next, the cross-efficiency scores, which were used for the construction of the cross-efficiencies matrix, were estimated using Eq. (4) and the results are presented in Table 9. Thereafter, the MCES for each DMU_j were determined using Eq. (5) and the results are shown in Table 9.

Step 4: The optimum combination of additives were determined in this last step. The MCES were determined for DMUs which are on the same parameter level. The parameter level that maximizes the MCES was adopted as the optimal level for that parameter. The results of the parameter level effect on the MCES are shown in Table 10 while the corresponding plots of the parameter level effect on the MCES are depicted in Fig. 3(a-c).

Experimental validation

The optimum combination of additives (A6 B2 C3) obtained from this study which involves the integration of VRS DEA and benevolent formulation into the Taguchi approach is absent in the experiment performed by Ikeagwuani [72]. This, therefore, necessitated the need to validate the proposed procedure through conducting confirmatory test. To conduct the confirmatory test, the optimum combination of additives was thoroughly blended with the expansive soil. The soil samples used for the UCS test were subjected to 28 d curing while the samples used for the unsoaked CBR confirmatory test were cured for 7 d. Both samples were cured in a humidity-controlled environment. The result obtained from the confirmatory test is presented in Table 11. Furthermore, other additives combinations close to the obtained optimum were also tested in the laboratory for confirmation. This was done to evaluate more closely, the uniqueness of the obtained optimal solution as the global optimal solution. The comparative test results are summarized in Table 12. For the concurrent optimization of the UCS, CBR and DFS, the achieved optimal solution based on the VRS DEA exhibited a superior performance.

In order to verify the suitability of the predicted responses from the VRS DEA Taguchi model, the predicted values and the values obtained from the experimental confirmatory test are shown in Table 13. It can be deduced that the VRS DEA Taguchi model slightly under predicted the responses, which is considered conservative. Moreover, the absolute percentage error values between the experimental and predicted responses are quite low, which provides further justification of the prediction accuracy; especially for the CBR that is a crucial pavement design parameter for subgrade and unbound granular materials.

Table 9 Cross-efficiencies matrix with the mean cross-efficiency score for each DMU_j

DMU_j	DMU_j																		θ_j
	DMU_1	DMU_2	DMU_3	DMU_4	DMU_5	DMU_6	DMU_7	DMU_8	DMU_9	DMU_{10}	DMU_{11}	DMU_{12}	DMU_{13}	DMU_{14}	DMU_{15}	DMU_{16}	DMU_{17}	DMU_{18}	
DMU_1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.020	1.084	1.000	1.000	1.000	1.000	1.983	1.060
DMU_2	1.186	1.000	1.049	1.203	1.126	1.186	1.186	1.021	1.186	1.121	1.192	1.196	1.501	1.111	1.121	1.186	1.186	1.883	1.202
DMU_3	1.248	1.040	1.000	1.270	1.070	1.248	1.248	1.075	1.248	1.223	1.261	1.249	1.597	1.258	1.197	1.248	1.248	1.628	1.242
DMU_4	1.005	1.222	1.249	1.000	1.171	1.005	1.005	1.177	1.005	1.057	1.005	1.021	1.000	1.075	1.052	1.005	1.005	1.632	1.094
DMU_5	1.066	1.153	1.000	1.072	1.000	1.066	1.066	1.116	1.066	1.120	1.081	1.069	1.196	1.214	1.069	1.066	1.066	1.409	1.105
DMU_6	1.000	1.000	1.000	1.015	1.000	1.000	1.000	1.000	1.000	1.000	1.003	1.000	1.242	1.000	1.000	1.000	1.000	1.191	1.025
DMU_7	1.000	1.114	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.037	1.000	1.000	1.200	1.000	1.000	1.000	1.367	1.040
DMU_8	1.260	1.144	1.409	1.281	1.450	1.260	1.260	1.078	1.260	1.116	1.278	1.260	1.530	1.129	1.206	1.260	1.260	1.629	1.282
DMU_9	1.000	1.528	1.037	1.000	1.000	1.000	1.000	1.472	1.000	1.271	1.000	1.000	1.080	1.378	1.000	1.000	1.000	1.079	1.102
DMU_{10}	1.202	1.167	1.529	1.217	1.536	1.202	1.202	1.030	1.202	1.000	1.231	1.203	1.357	1.044	1.172	1.202	1.202	1.590	1.238
DMU_{11}	1.011	2.109	1.724	1.005	1.382	1.011	1.011	1.946	1.011	1.239	1.000	1.017	1.000	1.246	1.134	1.011	1.011	1.085	1.220
DMU_{12}	1.002	1.706	1.303	1.007	1.166	1.002	1.002	1.581	1.002	1.172	1.000	1.000	1.110	1.220	1.061	1.002	1.002	1.000	1.130
DMU_{13}	1.058	2.265	1.844	1.053	1.483	1.058	1.058	1.913	1.058	1.146	1.066	1.060	1.000	1.228	1.245	1.058	1.058	1.137	1.266
DMU_{14}	1.212	1.593	1.980	1.227	1.759	1.212	1.212	1.417	1.212	1.113	1.213	1.212	1.397	1.069	1.256	1.212	1.212	1.322	1.324
DMU_{15}	1.048	1.688	1.585	1.053	1.459	1.048	1.048	1.552	1.048	1.213	1.043	1.047	1.151	1.225	1.000	1.048	1.048	1.0380	1.186
DMU_{16}	1.000	2.573	2.064	1.000	1.535	1.000	1.000	2.099	1.000	1.000	1.000	1.000	1.000	1.000	1.236	1.000	1.000	1.000	1.250
DMU_{17}	1.000	1.864	1.892	1.000	1.623	1.000	1.000	1.615	1.000	1.107	1.000	1.000	1.000	1.130	1.000	1.000	1.000	1.000	1.179
DMU_{18}	1.262	2.433	1.968	1.270	1.719	1.262	1.262	2.112	1.262	1.425	1.264	1.256	1.370	1.484	1.295	1.262	1.262	1.151	1.462

Table 10 Parameter effect on the mean cross-efficiency scores

Parameter	Physical meaning	Level					
		1	2	3	4	5	6
A	SDA	1.168	1.075	1.141	1.196	1.259	1.297
B	QD	1.158	1.219	1.191			
C	OPC	1.140	1.201	1.227			

Key: Values in bold colour represents optimal parameter level

Enhancement mechanism of the additives

OPC

The use of OPC as a cementing material is well established. The mechanisms of cementation often occur through both immediate strength gains on hydration and long term pozzolanic reactions. These ultimately result to the formation of cementitious compounds, mainly the CSH phases [85]. The formed compounds act as binding agents due to the cementation bonds formed. As shown in Table 2, the major chemical composition of the OPC is the CaO that is inherent in the active components of the OPC. These active components, which are principally responsible for its cementation reactions are the alite and belite.

QD

Quarry dusts are particles, mainly in granular form, which are known to improve the physical texture of any material blended with it. Quarry dust is often characterized by high specific gravity which imparts higher density [86] with potential for strength improvement. It is known to possess high shear strength and further improves the gradation of fine-grained soils, giving the soil a coarse granular and friction resistant structure [87, 88]. Moreover, it possesses fine fractions, which makes it a very good filler material that improves the soil pore structure [89]. The presence of significant amounts of SiO₂ and AlO₂ in its oxide composition (Table 2) further suggests that it is capable of partaking in pozzolanic reactions for the formation of cementitious compounds.

SDA

The SDA consist of extremely fine particles, which are rich in SiO₂, CaO and K₂O (Table 2). The presence of SiO₂ and CaO is a good indication of self-cementation ability [90] and thus can partake in pozzolanic reactions [91]. Moreover, the presence of K₂O and CaO indicates a good ionization potential for cation exchange as K⁺ and Ca²⁺ ions are exchangeable cations in the diffuse double layer of clays. As such, they possess the ability to initiate cation exchange process in clay minerals. The cation exchange process of Ca²⁺ causes flocculation, which makes the soil particles to be friable with higher potential for strength increment [2, 92]. In the case of kaolin-rich soils, ionization of K⁺ ions can facilitate the formation of K-feldspar, which imparts strength to the soil [93]. Moreover, for expansive soils rich in montmorillonite, the potential for clay mineral modification is expected due to the ionization of the potash present in the SDA.

Fig. 3 a–c Plots of parameter level effect on MCES

Table 11 Optimum combination of additives with their corresponding responses

Response	Optimum combination	Mean responses value
UCS	A6 B2 C3	864.31kN/m ²
CBR	A6 B2 C3	60.45%
DFS	A6 B2 C3	5.34%

Table 12 Comparison of optimal combination with other close combinations

S/N	Combination	UCS (kN/m ²)	CBR (%)	DFS (%)
1	A6 B2 C3*	864.31*	60.45*	5.34*
2	A6 B1 C2	854.476	48.91	25.38
3	A6 B3 C3	729.314	48.58	3.26
4	A6 B2 C2	889.281	44.50	20.25

* Represents the optimal combination

Table 13 Comparison of experimental and predicted values of the responses obtained from VRS-DEA Taguchi optimization

Response	Experimental	Predicted	Absolute % error
CBR (%)	60.45	53.96	0.107
UCS (kN/m ²)	864.31	758.68	0.122
DFS (%)	5.34	7.53	0.410

Optimum combination of additives effect on UCS, CBR and DFS

UCS

A significant change in the UCS was prevalent due to the addition of the optimum combination of additives to the soil. The UCS of the soil increased from an initial value of 152.5 kPa to a value of about 864.3 kPa, which represents an increment of 467%. The improvement can be explicated in terms of micro and macro level changes occasioned by the physical and chemical actions of the additives on the soil-additives matrix. The physical action of the QD particles resulted in physical modification through imparting an improved gradation and coarse-granular nature to the soil. This resulted in a more intense interlocking of the particles with higher shear resistance, which is a known characteristic of QD particles as per previous studies [14, 87].

The chemical actions which modified the soil microstructure were due to hydration and pozzolanic reactions of the cement and additives particles (SDA and QD), which are pozzolanic materials. The hydration reaction led to instant strength gain, while the pozzolanic reaction resulted in long-term strength gain. On addition of water to the soil additives mixture, hydration reaction is initiated due to the active chemical compounds in the cement, principally dicalcium silicate and tricalcium silicate [85]. This resulted in the formation of a metastable form of paste known as portlandite as shown in reaction Eq. 6 [85].

The portlandite reacts with the nano particles of silica and alumina present in the QD and SDA to form binding complexes, mainly those of C-S-H and C-A-H nanophases. Different binding phases of C-S-H can be formed such as the α -C-S-H, β -C-S-H and γ -C-S-H, depending on the Ca/Si ratio [94]. The properties of these nanostructures can reflect the changes in the macro level behavior of the soil-additives matrix [94–96]. The binding complexes crystallize further with time to form denser particles such

as globules, which can favorably seal the pores in the soil, thereby improving the soil strength as moisture ingress is impeded. Similar findings have been reported in other studies [20, 97].

During the curing period of the samples, pozzolanic reaction occurred, which further led to strength gain. Due to the presence of calcium and silicon oxides in the soil-additives mixture, C–S–H forms in the presence of moisture. With time, condensation of the C–S–H occurs in a similar way as the sol gel process of inorganic gels. Denser particles then result from the polymerization process which further imparted a higher strength to the soil through flocculation and agglomeration [95, 98–100].

CBR

The CBR showed considerable increment from a value of 9.4–60.5% due to the addition of optimum combination of additives to the soil. This shows an increase in CBR by as much as 544%. The physical action of the QD particles made the soil-additives matrix resistant to penetration because of the coarse-grained nature imparted to the soil. Furthermore, the fine particles in the QD acted as microfillers to fill up void spaces in the soil which facilitated compaction to achieve higher density. This also made the soil-additives matrix resistant to the penetrative force of the CBR plunger.

Chemical action occurred in the soil-additives matrix due to the presence of potash in the SDA particles which transformed the structure of the soil clay mineral. Dissolution of the potash in the presence of moisture, releases K^+ ions which are exchangeable with the weak hydrous ions of the adsorbed water in the diffuse double layer. This chemical action modifies the structure of montmorillonite clay mineral in the soil to that of illite due to affixation of K^+ ions in the clay interlayer. Illite clay has less affinity for moisture and hence more stable [101–103], which also explains the reason for the higher strength achieved.

DFS

On addition of the optimum combination of additives, the soil showed a minimal tendency to swell, as the DFS greatly declined from a value of 71.6–5.3%. This shows a tremendous drop of about 1251% in the DFS. The change in the swelling behavior is adduced to the physical and chemical actions of the additives. In addition to the lubrication of the fine particles of the additives with increased surface area, the chemical reactions which took place used up a substantial amount of the available moisture. Hence uptake of water for swelling greatly dropped. Also, the likelihood of swelling has been reported to drop in the presence of granular materials such as the QD particles [88, 104].

In a related development, the cation exchange process of higher valence cations like the Ca^{2+} balanced the ionic charge concentration within the clay-pore fluid media; and with the formation of cementitious compounds, the clay layer is made more stable. This in essence, resulted to the lower moisture affinity and drop in swelling observed. Similar observations have also been reported elsewhere [105, 106]. More so, the hydrophilic nature of the soil was further altered by the flocculation and agglomeration which occurred during the curing period, in addition to the clay mineral transformation previously explained. The volume change behavior of the soil is controlled due to flocculation and agglomeration phenomenon [106].

Conclusion

This study was used to integrate output-oriented VRS–DEA and benevolent formulation in Taguchi approach in order to optimize additives for the enhancement of expansive soil properties. The integration was done because Taguchi approach alone is incapable of optimizing multiple additives for expansive soil properties. After the optimization process, confirmatory experiments were conducted by blending the expansive soil with the optimum combination of additives. Based on the results obtained from the optimization process and the confirmatory test performed thereafter, the following conclusions can be drawn:

1. Significant improvement in the expansive soil was found when a combination of 20% SDA, 10% QD and 8% OPC (A6 B2 C3) were blended with it.
2. The DFS of the expansive soil, which reduced considerably when the optimum combination of additives was added to it, was adduced to the interplay between the micro-filler effect experienced in the mixture which was driven by the presence of the QD and the cementitious compound formation in the soil-additive matrix.
3. The CBR of the expansive soil that was combined with the optimum combination of additives increased significantly apparently due to the improved mechanical strength of the soil. The improved mechanical strength aroused from the micro-filler effect experienced between the reaction of the QD and the soil. Furthermore, cation exchange effect caused by the reaction between ionized potash in the SDA and the montmorillonite clay mineral also contributed to the significant improvement in the CBR.
4. The remarkable increase recorded in the UCS value when the optimum combination of additives was added to the expansive soil was attributed to the artificial formation of cementitious compound in the mixture. The cementitious compound was formed when the expansive soil reacted with hydrated SDA. Other factors that contributed to the increase in the value of the UCS included the formation of water-cement paste that was observed when the OPC reacted with the soil and the high resistance to shear exerted by the QD
5. Lastly, the output-oriented VRS model combined with the benevolent formulation and integrated into Taguchi method has shown that it is capable to optimize ternary additives for the enhancement of expansive soil

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Authors' contributions

CCI and DCN conceived and designed the experiment. CCI financed and performed the experiment, CCI worked on most of the technical details and implemented the numerical analysis. CCI and DCN contributed to the interpretation of experimental results. Both authors read and approved the final manuscript

Competing interests

The authors declare that they have no competing interests.

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