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Performance Evaluation of Sustainable Soil Stabilization Process Using Waste Materials

Muhammad Aamir [1], Zarnish Mahmood [1], Aqsa Nisar [1], Amjad Farid [1], Tanveer Ahmed Khan [2,*], Mudassir Abbas [1], Muhammad Ismaeel [1], Syyed Adnan Raheel Shah [1,*] and Muhammad Waseem [3]

1 Department of Civil Engineering, Pakistan Institute of Engineering and Technology, Multan 60000, Pakistan; 2kx5civil127@piet.edu.pk (M.A.); 2kx5civil141@piet.edu.pk (Z.M.); 2kx5civil140@piet.edu.pk (A.N.); 2kx5civil110@piet.edu.pk (A.F.); mabbas@piet.edu.pk (M.A); muhammadismaeel@piet.edu.pk (M.I.)
2 Department of Building & Archi Engineering, Bahauddin Zakariya University, Multan 60000, Pakistan
3 Department of Environmental Chemistry, Bayreuth Centre for Ecology and Environmental Research, University of Bayreuth, 95440 Bayreuth, Germany; muhammad.waseem@uni-bayreuth.de
* Correspondence: tanveerkhan@bzu.edu.pk (T.A.K.); syyed.adnanraheelshah@uhasselt.be (S.A.R.S.); Tel.: +92-30-0791-4248 (S.A.R.S.)

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Abstract: The process of soil stabilization is a fundamental requirement before road infrastructure development is possible. Different binding materials have been used worldwide as soil stabilizers. In this study, water treatment waste (i.e., alum sludge (AS)) was used as a soil stabilizer. Alum sludge can work not only as a low-cost soil stabilizer but also can solve the problem of waste management at a large scale. Utilization of alum waste can be a sustainable solution and environmentally friendly exercise. Thus, in consideration of the pozzolanic properties of alum, it was applied as a binder, similar to cement or lime, to stabilize the soil with the addition of 2%, 4%, 6%, 8%, and 10% of dry soil by weight. To analyze the resulting improvement in soil strength, the California Bearing Ratio (CBR) test was conducted in addition to three other tests (i.e., particle size analysis, Atterberg's limits test, and modified proctor test). The soil bearing ratio was significantly improved from 6.53% to 16.86% at the optimum level of an 8% addition of alum sludge. Furthermore, the artificial neural networks (ANNs) technique was applied to study the correlations between the CBR and the physical properties of soil, which showed that, at 8% optimum alum sludge, maximum dry density, optimum moisture content, and plasticity index were also at maximum levels. This study will help in providing an eco-friendly soil stabilization process as well as a waste management solution.

Keywords: sustainable; stabilization; strength improvement; waste management; processes

1. Introduction

Water treatment is an essential process before the consumption of groundwater. There has been a significant increase in the production of sewage sludge, which has increased from 180,000 m^3/day to 400,000 m^3/day in different parts of the world [1]. Such a large amount of sewage sludge is very difficult to dump by landfill, farm use, or even incineration. Researchers have used sewage sludge as a replacement of cement and have concluded that some cement can be replaced by different percentages of sludge for different engineering applications (e.g., geotechnical engineering) [2]. Generally, cement in the 12% range has been used as a soil stabilizer. According to the Unified Soil Classification System (USCS), if an additive is effective enough to change the soil type from mild to low plastic, it can act as a suitable replacement for cement [3]. Furthermore, replacing cement by incinerated sewage sludge ash was tested for soil improvement. Soil swelling of A4 soil (following the American Association of

State Highway and Transportation Officials (AAHSTO) classification system) was reduced; incinerated sewage sludge ash also enhanced the California Bearing Ratio (CBR) of soil [4]. In 2007, sludge ash was used along with hydrated lime. The results were encouraging because the unconfined compressive strength of soil increased between three to seven times; however, swelling behavior remained the same [5]. Sewage sludge ash mixed with cement was added to soil to improve its quality. Results indicated that the compressive strength has been improved. Accordingly, sewage can be a suitable replacement for cement or any expensive chemical stabilizer [6]. Soil stabilization has been carried out by the addition of different materials, such as Bagasse ash [7–11], rice husk ash [12], lime [13], fly ash [14,15], fuel oil fly ash [16], cement [17], coal ash [18], granulated blast furnace slag [19–22], and cement kiln dust [23–25]. Previously, the effective impact of potassium alum was observed on monazite in contrast with bastnaesite during flotation separation because of the special adsorption of hydrolyzed aluminum species [26]. Another waste material (i.e., thermally activated alum sludge ash), used as a binder in concrete formations, can also be used as a soil stabilizer [27]. Alum belongs to the class of aluminum hydroxide minerals, which are the main component of bauxite, the principal ore of aluminum. The solid Al $(OH)_3$ gibbsite is then calcined (heated to over 1100 °C) to obtain aluminum oxide [28,29]. Alum ($XAl(SO_4)_2{\cdot}12H_2O$) is a type of chemical compound that is a hydrated double sulfate salt of aluminum. The X refers to the monovalent cations, which are either potassium (K^+), ammonium (NH^{4+}) or sodium (Na^+). The alum generally used to treat the wastewater before disposal is potassium alum [30,31]. This material is available in bulk but has a waste management issue (i.e., it is difficult to dump).

This paper focuses on the issue of soil stabilization using a low-cost stabilizer. The review of published literature reveals that alum sludge not only has binder properties but also is found in bulk as waste from plants using alum for water treatment. Alum has a reputation as a cleaning effluent for the safe and environment friendly disposal of wastewater. This paper emphasizes the improvement of soil strength by adding a single additive, alum sludge, leading to a sustainable and environment friendly approach for this necessary task. The study addresses two major issues, i.e., soil stabilization and waste management.

2. Waste Materials and the Circular Economy Principle

The concept of a waste recycling approach and the circular economy has proven to be a positive way to analyze social, economic, and environmental impacts [32]. The use of bio-based products, especially those dumped as waste materials, offers a promising future to inexpensive, easily available, and environmentally favorable additives (i.e., alum sludge) [33]. The utilization of waste for stabilization of soil will not only lead to sustainable development but also help to achieve circular economy goals. The benefits of circular economy and its relation to sustainable development has already been studied [32]. The recycling of goods and materials will help to solve energy resource problems. Cycles related to water and nutrients discarded by one can be a resource for others [34]. Theories of circular economies and manageability are increasingly taking root in the scholarly community, engineering industry, as well among policymakers; however, the relationship between the two ideas remains under debate. The connection between the ideas has not yet been expressed in writing, which obscures its theoretical potential and the utility of these methodologies in both research and practice [35]. Circular economy specialists have proposed that studies aimed to help the administrations dealing with waste utilization and the economy should be encouraged. In Europe, noteworthy advances have been accomplished in estimating externalities by applying methods that account for the environmental and economic relations of reusing products. The financial evaluations have come into play as a result of interdisciplinary research, which urges the reconsideration of an ecological approach as an important element in business models [36]. Thus, utilization of waste resources, like alum sludge, for development of new infrastructures can lead to both economical and environmentally friendly development processes. Furthermore, policymakers often link waste management with financial sustainability [37]; recent innovations in this field have introduced the terminology of green finance to attain environmentally sustainable solutions [37]. This concept has also been discussed within the European Union [38]. Accordingly, policymakers, if they focus on exploring the connection between the circular economy principle and waste management, can open a treasure of green finance possibilities [39]. Moreover, if concepts of renewable energy are attached to this phenomenon, investors might consider the risk involved in investing before financial decision making [40]. Accordingly, it is necessary to focus on this theme of circular economy to develop a sustainable green finance-based infrastructure development strategy.

3. Materials and Methods

3.1. Experimental Framework

A stepwise pattern of research is in the flowchart presented in Figure 1. The chart illustrates the process of utilization of waste for the stabilization of soil. The experimental program enlists the series of tests following the American Society for Testing and Materials (ASTM) and American Association of State Highway and Transportation Officials (AASHTO) standards, as shown in Figure 1.

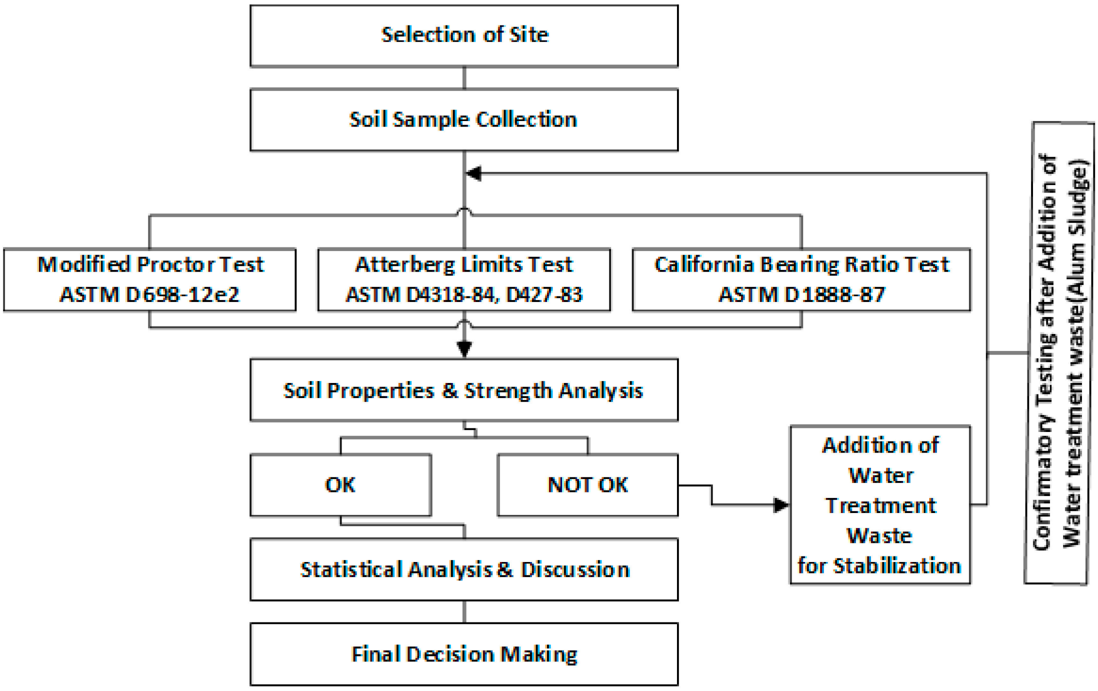


Figure 1. A research framework for the experimental stud.

The stepwise plan comprises:

Step 1: Site Selection and Soil Sample Collection;
Step 2: Soil Stabilizer (Alum Sludge) Addition;
Step 3: Particle Size Analysis;
Step 4: Atterberg Limits Tests and Modified Proctor Test;
Step 5: California Bearing Ratio (CBR) Test;
Step 6: Statistical Analysis-Application of ANNs;
Step 7: Profile Analysis of Soil and Decision Making.

3.2. Site Selection and Sample Collection

The soil sample was taken from Nandipur (Gujranwala, Pakistan) and its properties were studied using AASHTO and USCS standards. According to AASHTO classification, the soil sample was A-7-6 soil; particle size analysis is shown in Figure 2. Conditions that determined the soil as A-7-6 soil was its plasticity index, which must be greater than its liquid limit minus 30 (PI > LL−30). This type of soil is called clayey soil. Physical properties when no additive was added to the soil are shown in Table 2. According to USCS standards, the soil sample was determined to be inorganic fat clay (group CH). The necessary condition to be satisfied was that 50% or more soil particles pass through sieve number 200 or 0.075-mm sieve. The liquid limit of the soil sample needed to be greater than or equivalent to 50.

3.3. Soil Stabilizer (Alum Sludge) Addition

Alum sludge (composition given in Table 1) was added to the soil sample to attain better strength of soil. Alum sludge is basically a waste product produced by water treatment plants. The grey-colored alum sludge, which exists in slurry form, is used in dry and crushed form. Water treatment includes the removal of various compounds from water, particularly AL_2O_3, Fe_2O_3, SiO_2, CaO, MgO, Na_2O, K_2O, and other miscellaneous compounds in case of sludge. The samples were prepared with different percentages, i.e., 0%, 2%, 4%, 6%, 8%, and 10% of dry weight of soil. The alum sludge used for experiments was dried at 100 °C and then crushed and passed through sieve number #325 prior its addition to the soil sample. The soil was oven-dried at 110 °C before each test was performed and alum sludge was added to it.

Table 1. The composition of alum sludge.

Components	Percentage
Al_2O_3	37.85%
Fe_2O_3	14.97%
CaO	1.20%
MgO	0.60%
Na_2O	0.86%
K_2O	1.73%
SiO_2	28.91%
TiO_2	0.92%
SO_3	0.78%
Rb_2O	0.04%
P_2O_5	0.42%
Others	0.95%
Loss on ignition	10.77%

3.4. Particle Size Analysis

The soil sample collected for the study had liquid limit of 54% as described above. Moreover, according to Burmister [41], the soil of Nandipur can be classified as highly plastic soil because the plasticity index falls between 20 and 40 (calculated as 34). Particle size analysis is shown in Figure 2 for the soil before and after addition of alum sludge.

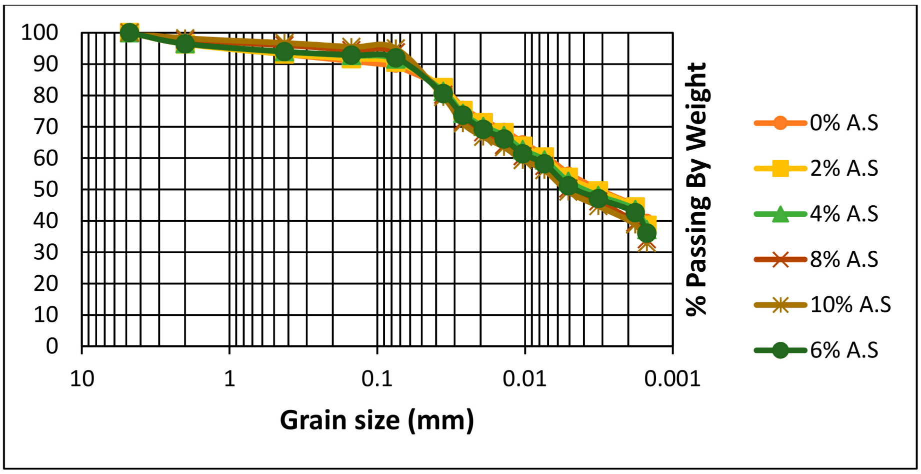


Figure 2. Particle size analysis of soil sample before and after the addition of alum sludge.

3.5. Atterberg Limits Tests and Modified Proctor Test

Basic testing of soil for physical properties began with the application of Atterberg Limits Tests which included plastic limit (PL) and liquid limit (LL). Depending on its water content, a soil may manifest in one of four states: strong, semi-strong, plastic, and fluid. These limits were defined by Albert Atterberg, a Swedish agriculturist in 1911 [1]. The Proctor compaction test is a lab strategy for tentatively deciding the ideal dampness content at which a given soil type will be most thick and achieve its maximum dry density. The test is named for Ralph R. Delegate, who, in 1933, demonstrated that the dry density of a soil for a given compactive effort relies upon the measure of water a given amount of soil contains amid soil compaction. This test focuses on the calculation of maximum dry density (MDD) and optimum moisture content (OMC). The physical properties of under study soil based on Atterberg Limit test and Modified Proctor test are shown in Table 2.

Table 2. Physical properties of soil samples.

Sample	Alum Sludge (%)	USCS Symbol	OMC (%)	MDD (lb/ft^3)	MDD (KN/m^3)	LL (%)	PL (%)	PI (%)
S 1	0	CH	21	111.7	17.55	56	21	35
S 2	0	CH	20	112.5	17.67	54	20	34
S 3	0	CH	20.5	112.1	17.61	55	22.2	32.8

3.6. California Bearing Ratio (CBR)

Previously, maximum dry density (MDD), moisture content (MC), plasticity index (PI), and liquid limit (LL) were used to determine the CBR values of a soil by statistical models, which were only applicable over certain areas. Moreover, the studies predicted a statistical relationship between CBR and index properties of soil [42]. Prior research discovered a correlation between CBR and plasticity index where the soil was cohesive [43–45]. The correlation of CBR with soil grain distribution and plasticity has also been investigated. A correlation between the plasticity index and CBR was suggested as Equation (1);

$$\text{CBR} = (\#2.4\ \text{mm})/\log\,(\text{PI})\ (\text{LL}) \quad (1)$$

where #2.4 mm is the sieve size (2.4 mm British Standard (BS) sieve) for percentage passing, PI is plasticity index, and LL denotes liquid limit. Agarwal and Ghanekar [45] discovered an improved correlation between Atterberg limits and CBR when optimum moisture content was also added as a variable [45]. The correlation worked for preliminary identification of material is expressed as Equation (2).

$$\text{CBR} = 2 - 16 \times \log\,(\text{OMC}) + 0.07\ (\text{LL}) \quad (2)$$

Maximum dry density and optimum moisture content have been seen as independent variables in several equations of CBR [46]. The relationship between the CBR and various classification parameters was investigated in existing models for some Natal soil by Stephen [47]. The fine-grained plastic soil, tested for CBR value, was correlated to the gradation by percentage passing from No. 200 US sieve and PI. The work was done in [48], and it predicted the following Equation (3):

$$\mathrm{CBR} = 75\ /\ (1 + 0.728(\mathrm{wPI})) \tag{3}$$

where #200 is US sieve for percentage passing, and PI is plasticity index. California bearing ratio (CBR) is one of the most important strength determination parameters of soil. CBR testing is followed according to ASTM D1883-05 standards. In contrast, ASTM D4429 is used for the sampling or testing in the field. The AASHTO T193 illustrates the CBR testing. The CBR was determined for different moisture levels, minimum OMC (dry side of OMC), OMC, and maximum OMC (wet side of OMC), as shown in Table 3.

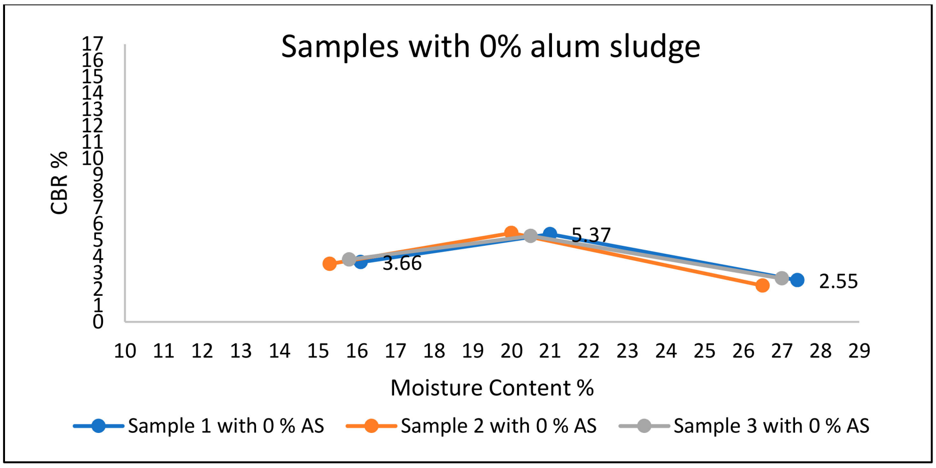
Table 3. California Bearing Ratio (CBR) values at different moisture contents for the experimental soils.

Sample	Sample Detail	Moisture Content (%)	Sample	Sample Detail	Moisture Content (%)
S-1	S-1-Optimum	21	S-10	S-10-Optimum	16.2
	S-1-Dry	16.1		S-10-Dry	11.7
	S-1-Wet	27.4		S-10-Wet	21.8
S-2	S-2-Optimum	20	S-11	S-11-Optimum	16.5
	S-2-Dry	15.3		S-11-Dry	12
	S-2-Wet	26.5		S-11-Wet	20.6
S-3	S-3-Optimum	20.5	S-12	S-12-Optimum	16.6
	S-3-Dry	15.8		S-12-Dry	12.4
	S-3-Wet	27		S-12-Wet	21.6
S-4	S-4-Optimum	19	S-13	S-13-Optimum	15.8
	S-4-Dry	13.7		S-13-Dry	11.6
	S-4-Wet	21.5		S-13-Wet	20.7
S-5	S-5-Optimum	18	S-14	S-14-Optimum	16
	S-5-Dry	12.6		S-14-Dry	12.5
	S-5-Wet	21.2		S-14-Wet	21
S-6	S-6-Optimum	18.6	S-15	S-15-Optimum	16.1
	S-6-Dry	13.4		S-15-Dry	12.8
	S-6-Wet	20.9		S-15-Wet	20.2
S-7	S-7-Optimum	17.4	S-16	S-16-Optimum	19.5
	S-7-Dry	13.8		S-16-Dry	12.9
	S-7-Wet	21.3		S-16-Wet	22.1
S-8	S-8-Optimum	17	S-17	S-17-Optimum	19
	S-8-Dry	12.1		S-17-Dry	10.4
	S-8-Wet	22.8		S-17-Wet	21
S-9	S-9-Optimum	17.5	S-18	S-18-Optimum	19.2
	S-9-Dry	12.9		S-18-Dry	13.6
	S-9-Wet	22.5		S-18-Wet	22.8

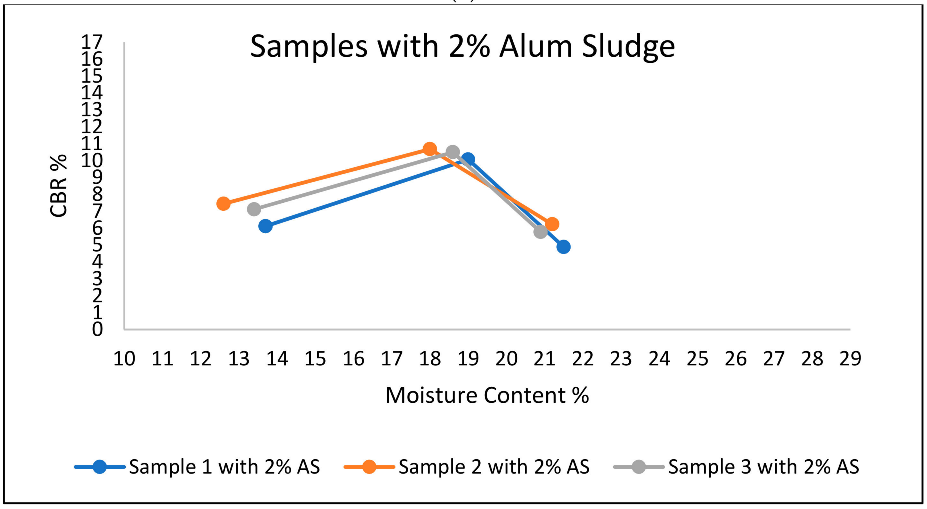
4. Results and Discussion

4.1. Impact of Alum Sludge Addition on California Bearing Ratio (CBR)

As discussed, CBR was calculated for different moisture levels and by adding different percentages of alum sludge to the soil. The molds were prepared with different percentages to determine the soil stabilization along with the effect of OMC, MDD, and PI. CBR versus Moisture Content can be observed in Figure 3 for all 18 samples.



(**a**)



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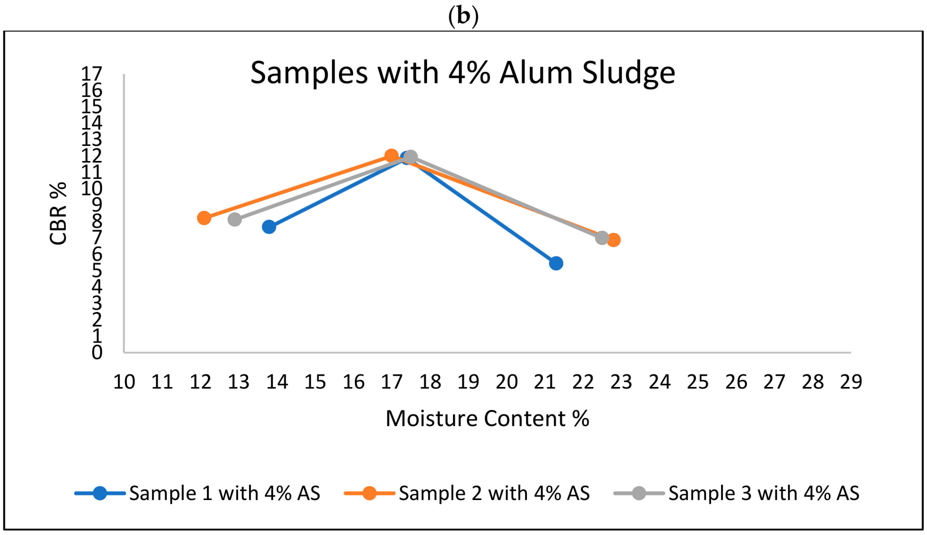
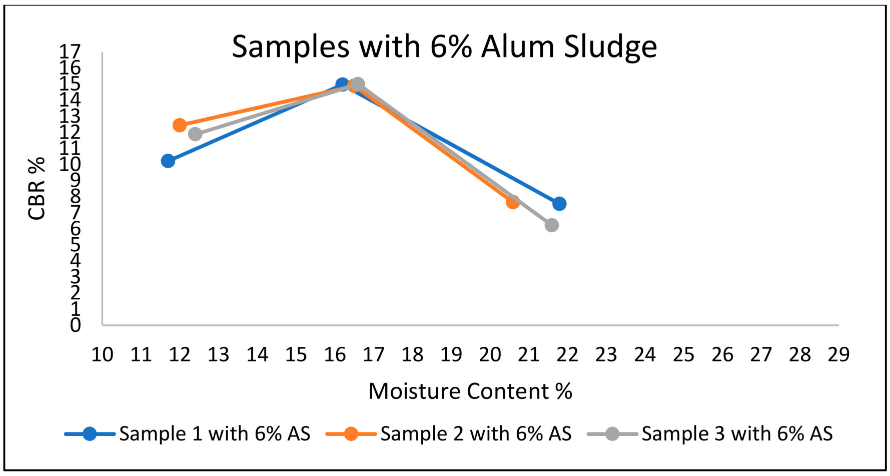


(**c**)

Figure 3. *Cont.*



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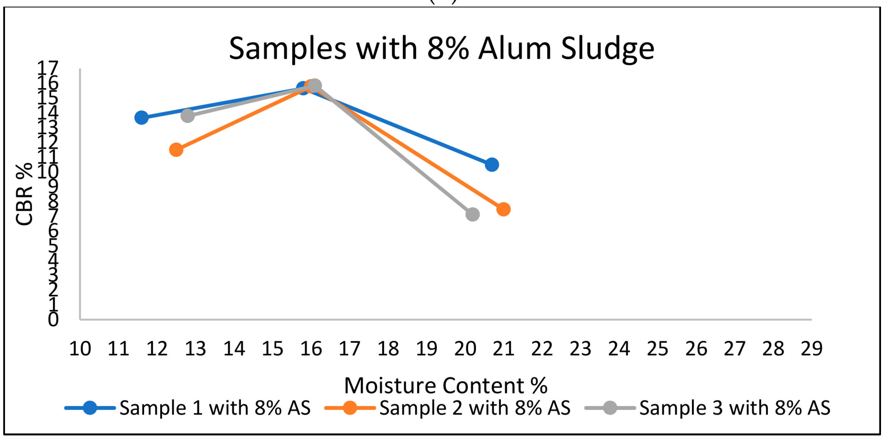

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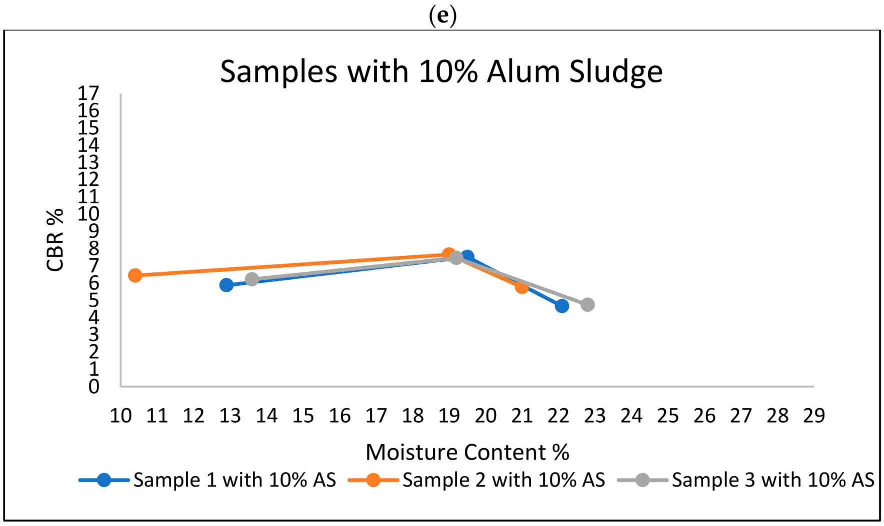

(**f**)

Figure 3. (**a**) The CBR versus the moisture content for soil sample at 0% addition of alum sludge; (**b**) The CBR versus the moisture content for soil sample at 2% addition of alum sludge. (**c**) The CBR versus the moisture content for soil sample at 4% addition of alum sludge; (**d**) The CBR versus the moisture content for soil sample at 6% addition of alum sludge; (**e**) The CBR versus the moisture content for soil sample at 8% addition of alum sludge; (**f**) The CBR versus the moisture content for soil sample at 10% addition of alum sludge.

The graph seen in Figure 3a illustrates the CBR when alum sludge was not added to soil. Three samples were made to cross check and validate the results. At an average optimum moisture content (about 20.5%), the average CBR recorded was 5.35%, which is very low. Thus, a stabilizer was needed to increase the soil strength.

The graph seen in Figure 3b shows the rise in CBR value when 2% of alum sludge was added to the soil. At 2% of the alum sludge concentration in soil, the average moisture content for three samples decreased from 20.5% to 18.5%. In contrast, the average CBR almost doubled, increasing from 5.3%5 to 10.4%. The result demonstrated that the addition of alum sludge efficiently increased the soil strength.

Figure 3c shows the change in CBR with 4% addition of alum sludge. In comparison with the sample in which 2% alum sludge was added, CBR improved from 10.4% to an average of 11.93%. In contrast, the average optimum moisture content decreased from 18.5% to approximately 17.3%. When compared with the results of the soil CBR when no alum sludge was added, the strength was more than doubled (from 5.35% to 11.93%) and the average optimum moisture content dropped from 20.5% to 17.3%.

The graph seen in Figure 3d, with 6% addition of alum sludge illustrates the improvement in strength of soil as CBR percentage increased from 11.93% (average CBR obtained at 4% addition of alum sludge on optimum moisture content) to 14.95%. The optimum moisture content reduced from 17.3% to 16.4%.

Figure 3e demonstrates a large increase in CBR value when compared with the soil with no alum sludge. In this case, when 8% of alum sludge was added to soil, CBR percentage increased three-fold, i.e., it increased from 5.35% to 15.75%. When compared with 6% addition of sludge, the strength improved from 14.95% to 15.75%. On the other hand, the optimum moisture content reduced from an average of 20.5% to 15.9% when compared with soil with no alum sludge.

Figure 3f displays an increase of alum sludge from 8% to 10%. The average optimum moisture content recorded was 19.23%, which was greater than the percentage in which 2% of AS (18.5), 4% of AS (17.3), 6% of AS (16.4), and 8% of AS (15.9) were added. When compared with soil with no alum sludge, this was slightly decreased, i.e., from 20.5% to 19.23%. The CBR value also decreased and it was observed that CBR declined from 15.75% (soil with 8% addition of alum sludge) to 7.54%. The descending CBR value (7.54%) was still greater than the CBR of soil with no addition of alum sludge (5.35%). Results indicate that an increase in percentage of alum sludge in soil up to 8% improved the soil strength thrice the original.

4.2. Application of Artificial Neural Networks (ANNs)

The human brain consists of a complex neuron network that efficiently works together to perform body functions. Artificial neural networks (ANNs) have been considered by the researchers to solve complex engineering problems because it follows the concept of human brain working mechanism [9,10]. The composition of ANNs models can vary for architecture, learning rules, and self-organization. For the prediction of California bearing ratio (CBR), four parameters were considered as alum sludge (%): plasticity index, optimum moisture content, and maximum dry density. Data is presented in Table 4.

Table 4. Data description of properties of soil.

Variable	Description	Mean	SD	Min.	Med.	Max.
CBR	California Bearing Ratio	12.19	3.801	6.53	13	16.86
AS (%)	Alum Sludge	5	3.515	0	5	10
PI	Plasticity Index	17.6	11.72	0	16.84	35
OMC	Optimum Moisture Content	17.994	1.659	15.8	17.75	21
MDD	Max. Dry Density	114.06	1.63	111.7	114.4	116.4

The ANN model consists of four variables, i.e., four nodes with one hidden layer and one independent variable selected as the California bearing ratio (CBR). As CBR is considered the most prominent factor to identify the strength of soil, the relationship among the four independent variables, i.e., MDD, OMC, PI, and AS, has been analyzed to identify the impact of these parameters on CBR. ANNs also provide an opportunity to analyze the relationships with a higher degree of accuracy.

The model developed for the study is shown in Figure 4. It has four nodes connecting the independent variables with one dependent variable. K-folded mechanisms have been adopted in this model by dividing the data set into five segments for training and validation; estimates are shown in Table 5.

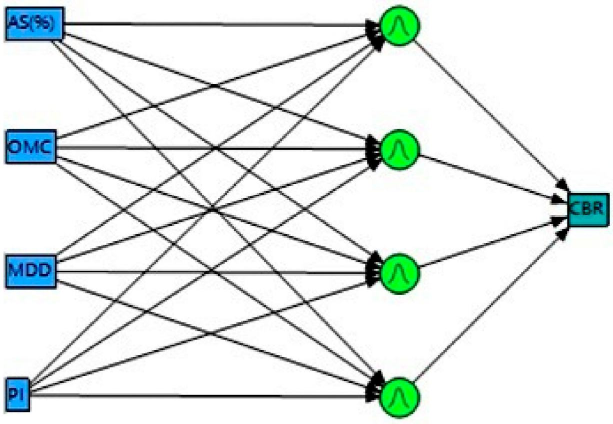

Figure 4. Artificial Neural Networks (ANNs) structure of CBR Prediction.

4.3. Model Parameters

The strength of the developed model was tested using root-mean-square error (RMSE) between the actual and predicted values and the coefficient of determination (R^2) [11] to determine the accuracy of the forecast of the system.

$$\mathrm{RMSE} = \sqrt{\left(\frac{1}{N}\sum_{n=1}^{N}(\mathrm{actual} - \mathrm{predicted})^2\right)} \tag{4}$$

$$R^2 = 1 - \frac{SSE}{SS_y} \tag{5}$$

In Equation (5), SSE denotes the sum of squared errors of prediction and SSy is the total variation. Apart from the use of absolute difference instead of squared difference, mean absolute error is similar to root mean square. The coefficient of determination (R^2) is commonly used to compare the performance of a model. If an output is considered more accurate, it yields an R^2 of 1; in contrast, a poor fit brings about 0 [49]. The backward propagation of the errors in the neural system is a popular technique for improving model performance. A certain number of nodes in hidden layer and the number of hidden layers to obtain a system with a slightly better prediction capacity is also of interest. A general guideline or several subjective structures can be used as the choice of hidden layers, the number of nodes, and the one that provides the best execution [50]. Parametric estimates are presented in Table 5.

Table 5. Parameter estimates of ANN models for CBR prediction.

Parameter	H1_1	H1_2	H1_3	H1_4
AS (%)	0.778894	0.586618	0.034067	−0.36091
OMC	−0.67213	−0.02785	0.14313	−0.10689
MDD	−0.45533	0.020422	−1.21731	−0.01654
PI	−0.654	0.001748	−0.74646	0.076513
Intercept	1.451715	−0.92283	−1.35736	-0.05674
CBR	2.342307	8.766582	−0.16405	2.38735

Data has been divided into 5-segments following the K-folded mechanisms' JMP software provides an analysis option according to which it automatically divides data into five segments. It then develops a model on four sections and validates on the fifth section. Table 6 shows that data, which consisted of

18 samples. Out of those samples, it considered 15 data points as training values and three other data points as validation values.

Table 6. Model Strength Evaluation of Training and Validation Data.

Estimates	Training	Validation	Remarks
R^2	0.9997552	1.0000000000	V. Good
RMSE	0.0582346	0.0000000007	V. Good
Sum Freq	15	3	As per standard

Graphical representation seen in Figure 5 depicts the CBR which predicted an almost perfect identification of CBR actual, as R^2 value was almost 1 for both sections of data.

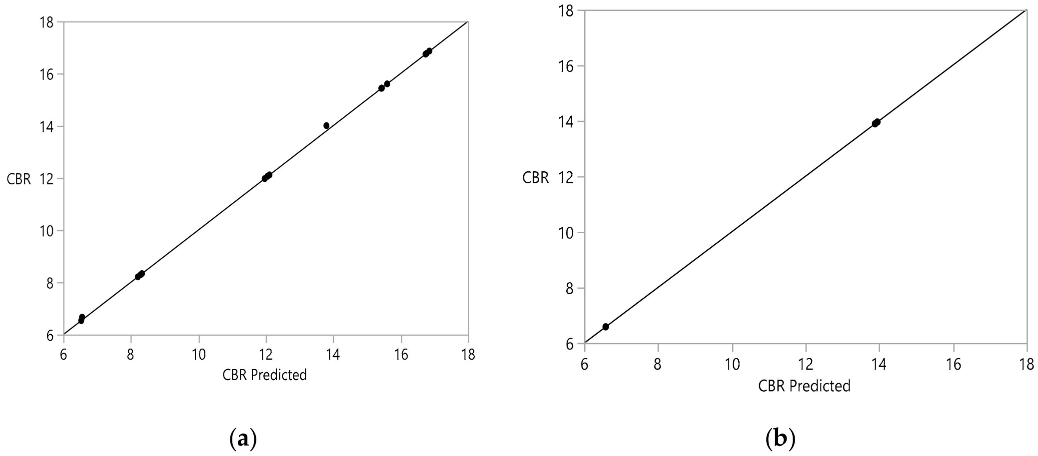

Figure 5. Training and Validation Data Plot for CBR Predicted versus Actual CBR. (**a**) Training; (**b**) Validation.

4.4. Impact Analysis of Variables

The strength behavior of soil samples before and after addition of water treatment waste can be seen in Figure 6. As the moisture content of the soil sample tended to increase, a decrease in CBR was observed. The decline was primarily due to the reduction of shear strength. The CBR value was maximum when the moisture content was at OMC as well as the addition of 8% of water treatment waste, i.e., alum sludge (AS). The alum sludge also affected the value of CBR; however, at 10% addition of AS, plastic index reduces. Accordingly, CBR value also tended to decrease. This determines the soil behavior towards the additive, i.e., alum sludge and moisture content.

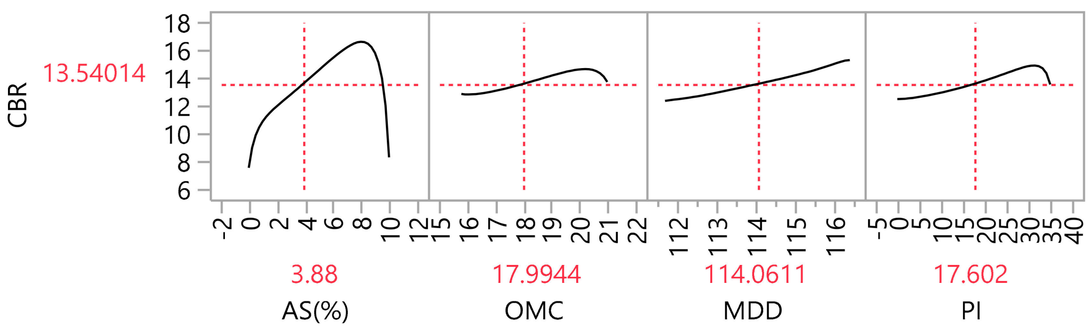

Figure 6. Variable Analysis Profile.

4.5. Interactional Profile Analysis

Interactional profile, as seen in Figure 7, demonstrates that the increase in alum sludge concentration up to 8% stimulated an initial increase in CBR but a subsequent decline is observed after that level. The CBR increased until the soil achieved optimum moisture content; when the moisture content moved toward the wet side, California bearing ratio started to decrease. The maximum dry density was directly related to the CBR, which contrasted with the plasticity index that exhibited an inverse relation to the CBR.

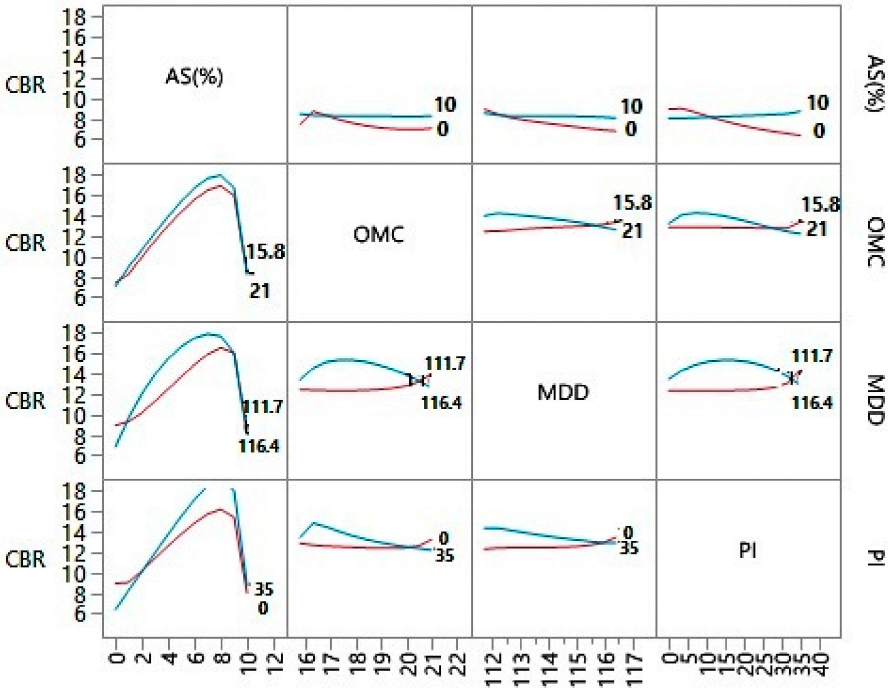

Figure 7. Interactional Profile Analysis for CBR.

4.6. Variable Importance Analysis

Identification of important variables was also a key target of priority analysis, as presented in Table 7. It cannot be considered that, by addition of alum sludge, CBR will continue in an increasing trend because, at a certain optimum level, it reaches the highest CBR value. After that point, it may start to reduce the strength level. The addition of alum sludge to the soil considerably affected the plastic limit of the soil. The plastic limit gradually increased up 8% with the addition of alum sludge. The physical properties of the soil are directly related to its strength. When the plastic limit declined after 8%, the soil's CBR (strength) also decreased. Accordingly, by focusing on AS addition and PI value, it was concluded to be one of the better options.

Table 7. Variable Priority Analysis.

Variables	Main Effect	Total Effect	Visuals
AS (%)	0.918	0.977	
PI	0.02	0.058	
OMC	0.011	0.039	
MDD	0.012	0.034	

5. Practical Implications of the Study

Soil stabilization is an essential step to any sort of infrastructure development and construction. As discussed above, different materials have been used for this purpose. Cement is one of the most frequently used and manufactured additives. In this study, alum sludge was added to soil to produce an environmentally friendly, economically reliable, and sustainable stabilization. The results clearly illustrate that the addition of alum sludge to soil increased soil strength as indicated via the improvement of CBR. For future studies, it is recommended that, before applying any mechanical effort, such as the application of roller compaction procedure, alum sludge should be mixed into the soil. Accordingly, as has been identified in this study, a lower compaction effort will be required to compact the soil before road construction. The world is moving towards sustainable development and circular economies, with the concept that the waste of one can be useful to others. Accordingly, the utilization of waste materials can be helpful to a country to maintain development without the production of additional waste. Alum sludge is convenient and available and can easily be used for stabilization. Alum sludge is recommended for use in both dry and crushed forms. Some precautionary measures include the need to cover one's face before using alum sludge; because crushed alum sludge is very fine and easy to inhale. Although the material has no harmful effect on either the human body or the environment, future studies should be conducted to investigate these aspects. Policymakers relevant to road construction can use this soil stabilizer to produce a low-cost stabilization, which can potentially save considerable expense during road construction projects. Furthermore, the issue of waste management for alum sludge will also be solved.

6. Conclusions and Future Recommendations

This paper focuses on soil stabilization by using water treatment waste, i.e., alum sludge (AS). The improvement of physical properties of soil can lead to the enhancement of its bearing capacity. Alum sludge was added to soil to improve the strength of weak soil with a very low bearing capacity. The addition of alum sludge significantly increased the CBR of soil. In the field, certain factors such as constant load application, changes to the water table, varied environmental conditions, and climatic changes over time may cause the moisture content of the soil to increase or decrease. The benefit of stabilized soil in such conditions strengthens the foundation of structures. CBR was calculated for three moisture contents: minimum moisture content (dry side of OMC), optimum moisture content, and maximum moisture content (wet side of OMC). The effect of OMC and alum sludge percentages was significant and changed the CBR of weak, clay-like soil, which was used for the purposes of the experiment. The average optimum moisture content recorded was 19.23%, which was greater than the percentage in which 2% of AS (18.5), 4% of AS (17.3), 6% of AS (16.4), and 8% of AS (15.9) were added. In comparison with soil with no alum sludge, moisture content decreased slightly, i.e., from 20.5% to 19.23%. CBR value also decreased, and it was observed that CBR declined from 15.75% (soil with 8% addition of alum sludge) to 7.54%. However, the diminished CBR (7.54%) was still greater than the CBR of soil to which no alum sludge was added (5.35%). Results indicate that increase in percentage of soil up to 8% improved the soil strength thrice the untreated soil. The influence of addition of alum sludge was visible, increasing CBR with a corresponding increasing percentage of alum sludge up to the optimum addition level of 8%. Furthermore, the application of artificial neural networks (ANNs) also help in exploring the relationship between physical properties and strength parameters of soils. During the pre-analysis phase, ANNs helped to control the focus ingredients to maintain the target variables, i.e., CBR in this case. This research can help during the soil stabilization of road construction projects at large scales. As a low-cost solution, it can easily replace other stabilizers such as cement; it also offers a sustainable waste management solution.

The research is a step towards sustainable development and circular economies. The results have proven that the addition of alum sludge was not merely utilization of waste material but can help to increase soil strength. Future studies should focus on the compaction properties and energy used to improve soil strength with reference to the addition of alum sludge. This will illustrate five major benefits: (i) Strength improvement of soil, (ii) eco-friendly stabilization, (iii) low-cost stabilization with reference to material, (iv) low-cost stabilization with reference to compaction effort/energy saving, and (v) waste management. The water treatment waste material is easily available and inexpensive; accordingly, it has a great scope for practical use in the future.

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Notation

CBR	California bearing ratio
PI	Plasticity index
LL	Liquid Limit
MC	Moisture Content
MDD	Maximum dry density
OMC	Optimum moisture content
USCS	Unified soil classification system
AASHTO	American Association of State Highway and Transportation Officials

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