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RESEARCH ARTICLE

SOIL STABILIZATION WITH LIME AND SAWDUST AND ITS NUMERICAL ANALYSIS

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Abstract

Due to population growth and rapid industrialization, requirement for new construction sites and transportation routes is increasing worldwide every day. The use of waste materials in different engineering applications not only contributes to the economy of the country but also becomes a determinant in reducing the effects of environmental pollution. In this study, the suitability of the use of easily obtainable lime and sawdust is discussed for soil stabilization. In the laboratory research phase, the effects of the use of sawdust and lime were investigated on soil bearing capacity problems. Artificial neural network and regression analysis were carried out on the test results. As the conclusion of the study, it is suggested that the use of lime and sawdust is a low-cost and easy-to find alternative additives in soil stabilization. The study also highlights the environmental advantages of utilizing biodegradable and non-toxic materials in soil improvement techniques. Furthermore, the combination of mechanical testing and predictive modeling strengthens the reliability of the findings, offering a scientific basis for practical implementation.

Keywords

Soil Stabilization,
Lime,
Sawdust,
ANN,
Regression

Time Scale of Article

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1. INTRODUCTION

Due to population growth and rapid industrialization, construction on new sites is increasing day by day. Lands that were previously considered unsuitable for transportation or building projects are now being utilized for new investments as part of urbanization efforts. In such cases, soil problems such as low bearing capacity have been frequently encountered. The lack of favorable soil conditions has encouraged the search for soil improvement methods. Innovations in materials, equipment, and design methods have made soil improvement techniques more effective and economical [1]. Attempts to

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enhance soil properties through stabilization methods have become common in many countries today [2].

In cases where traditional soil stabilization methods are costly, the use of waste materials or economical additives presents an alternative approach. Soil stabilization using waste materials has been increasingly employed to enhance soil engineering properties in a cost-effective and sustainable manner. Various waste materials, including waste calcium carbide (WCC), wood ash (WA), cow bone ash (BA), sawdust ash (SDA), sawdust (SD), and lime, have been investigated for their effectiveness in improving soil strength, plasticity, and load-bearing capacity. In one study, WCC and WA were mixed with natural soil at specific ratios, and their stabilization effects were evaluated through Atterberg limits, compaction properties, and California Bearing Ratio (CBR) tests. The results indicated that these materials reduced the liquid limit and shrinkage, increased the optimum moisture content, slightly decreased the maximum dry density, and significantly improved CBR values, demonstrating that WCC and WA provide an economical and sustainable stabilization method [3].

Similarly, lateritic soil stabilization was examined using cow bone ash (BA) and sawdust ash (SDA) in varying proportions (2%, 4%, 6%, and 8%). Geotechnical testing, including Atterberg limits, compaction, and CBR assessments, revealed that the optimal mix of 4% BA and 2% SDA significantly improved soil strength by increasing the maximum dry density and CBR while reducing moisture content, proving their suitability as cost-effective stabilizers for lateritic subgrade soils in road construction [4]. Another study focused on problematic laterite soil, where SDA was first incorporated, followed by an optimum amount of lime (4%), determined using the Eades and Grim method. Geotechnical tests, including compaction, unconfined compressive strength (UCS), and CBR, showed that SDA increased the optimum moisture content while reducing the maximum dry density, and when combined with lime, it formed cementitious compounds that significantly enhanced the soil's strength and load-bearing capacity [5]. Additionally, an investigation comparing raw sawdust (SD) and SDA as soil stabilizers aimed to determine whether SD could serve as an alternative to SDA, reducing incineration and air pollution. Clayey soil was stabilized with SD and SDA at varying proportions (2%, 5%, 8%, 12%, 15%, and 20%), followed by Atterberg limits, modified Proctor, and Direct Shear tests. The findings showed that both SD and SDA reduced the plasticity index and maximum dry unit weight while increasing optimum moisture content, with 5% SD providing the highest bearing capacity improvement (31.89%), making SD a more effective and environmentally friendly stabilizer than its incinerated counterpart [6].

The use of waste materials in different engineering applications contributes both to the national economy and plays a crucial role in reducing environmental pollution. Waste disposal through proper methods is essential for nature conservation in both rural and urban areas. Waste materials from various industries are frequently utilized, particularly in road construction and embankment fillings. The insufficient bearing capacity of such fills can lead to serious consequences, including economic losses, structural failures, and even potential loss of life and property if not properly stabilized. Therefore, the disposal of waste materials by incorporating them into the construction sector is seen as a sustainable and practical solution [7-10]. With the increasing number of scientific studies today, different waste materials are continuously being evaluated for new engineering applications, contributing to both sustainability and economic development.

The leading methods for soil stabilization involve cement or chemical stabilization, using cementitious materials such as lime, fly ash, and sludge [11-15]. Additionally, cement and polymeric materials are widely used as grout mixes with some additives—particularly waste materials—to reduce costs while achieving improved engineering properties with early strength gain [16]. Furthermore, research findings suggest that cement kiln powder, when added to peat soil, enhances its geotechnical properties [17-18].

Various alternative materials such as gas concrete [19], marble powder [20], biopolymer xanthan sand, synthetic fiber, rubber waste, silica fume, and lime [21-26] have also been explored for their positive effects on the mechanical and physical properties of problematic soils. Particularly in lime stabilization, it has been observed that the elasticity modulus of stabilized clay increases [27], and that a combination of lime and pozzolana significantly enhances the compaction and strength of soft clay soils [28-29].

Swelling clay soils, which absorb water and expand in volume, exert pressure on structures, leading to deformations if not adequately stabilized. When light structures fail to compensate for swelling pressures, significant damages can occur. To mitigate this issue, lime treatment is commonly used, triggering chemical reactions that alter the soil's microstructure. The addition of lime to clay soils leads to a cation exchange process, where Ca^{2+} and Mg^{2+} ions replace Na^{+} or K^{+} ions in the clay matrix. This reaction, known as flocculation-agglomeration, causes clay particles to aggregate and form larger structures, effectively reducing plasticity and increasing strength. As a result, the soil loses its clay-like behavior and transitions from a plastic to a solid state, significantly enhancing its bearing capacity, strength, and elasticity modulus. Lime stabilization is widely applied in clay-rich fills, particularly in road construction [21-26].

Recently, the use of sawdust as a waste material in various applications has gained attention [30-31]. Studies indicate that sawdust enhances the strength of binding agents such as cement, fly ash, and lime. Soil stabilization using lime and sawdust is conducted by mixing the soil with lime-sawdust or lime-sawdust slurry, followed by compaction. Lime and sawdust mixtures are particularly effective for high-plasticity and cohesive soils, offering both short-term and long-term improvements. In the short term, sawdust addition enhances flocculation-agglomeration, leading to an immediate strength increase, reduced plasticity, improved workability, and decreased swelling potential. In the long term, reactions between lime and sawdust further contribute to strength enhancement. Additionally, lime alters the compaction characteristics of the soil, improving its overall stability.

Sawdust is a by-product or waste product of woodworking operations. It can be found easily worldwide. It has been reported that approximately 500 million tons/year of waste sawdust are produced in Japan and only 20% of this waste is recycled. Lime is a inorganic-based binding material when mixed with water. Approximately 500 thousand tons are produced annually in the world.

In this study, the suitability of easily available lime and sawdust for soil stabilization is investigated. The selection of these materials is based on their cost-effectiveness and accessibility. Lime is an inexpensive, widely available stabilizer, while sawdust is an abundant by-product of the wood processing industry. Laboratory studies were conducted to examine the effects of sawdust and lime on soil bearing capacity, and a numerical model was developed using artificial neural networks and regression analysis to predict the behavior of stabilized soils. The results of this research aim to provide a sustainable and efficient stabilization method, utilizing waste materials to improve soil properties while reducing environmental impacts.

2. METHOD AND MATERIAL

The study was conducted in Eskisehir Technical University Soil Mechanics Laboratory, Turkey. Five different natural soil samples are taken from two different locations in Eskisehir, Turkey. All soil index tests are conducted to determine the soil properties. The results of the experiments performed according to the ASTM standards on the soil samples are given in Table 1.

Table.1 Experiment results of the soil samples

Notations	w (%)	Gs (g/cm³)	Grain size distribution (%)			Consistency limits (%)	
			Gravel	Sand	Silt & Clay	LL	PL
Sample-1	16.40	2.55	3	13	84	37	24
Sample-2	23.81	2.50	1	7	92	39	25

Waste sawdust was obtained from a wood factory operating in the provincial centre of Eskisehir. And lime was obtained from a lime factory from Eskisehir. In the study. the addition of sawdust was kept constant at 0.5% and 1.0% by weight. while the lime ratio was applied at % 0.5. % 1.0. % 2.0. % 5.0. % 10.0. % 15.0 and 20.0%. Technical specifications of lime are min: 80% $Ca(OH)_2$, Fineness: 0% above 150 microns.

The reconstituted soil samples having 7cm diameter and 14 cm long were prepared. Compaction parameters for soil samples were determined and reference samples were prepared with optimum water content. Although the optimum water content value was determined as 20% for Sample-1 and 22% for Sample-2. water content was applied as 25% and 30% respectively. Thus. it is aimed to determine whether the improvement can be achieved in the soft consistency of the soil. Unconfined compression tests were conducted on reconstituted samples. The experiments were repeated 3 times and the results are averaged. The tests were performed according to the ASTM standards.

3.EXPERIMENTAL RESULTS

A maximum stress value of 321 kPa was observed in the unconfined compression test on Sample-1 and it was observed as 312 kPa for Sample-2. The results of the unconfined compression test of the soil samples together with the lime and sawdust mixtures concerning Sample-1 were presented in Figure 1 and Figure 2. The results of the unconfined compression test of soil samples together with lime and sawdust mixtures concerning Sample-2 were presented in Figure 3 and Figure 4.

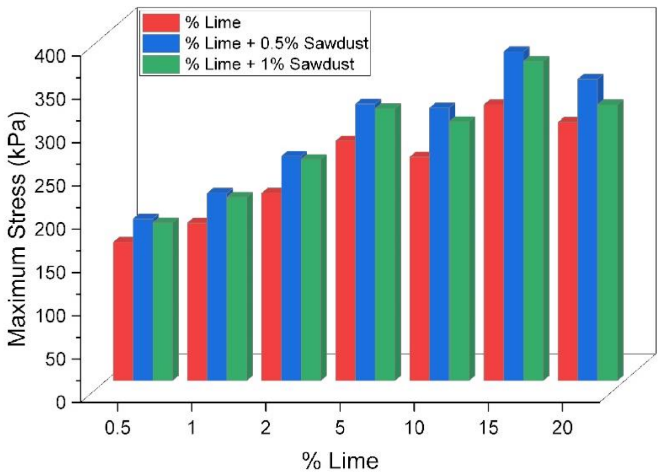


Figure 1. Unconfined compression test results with 25% water content concerning Sample-1

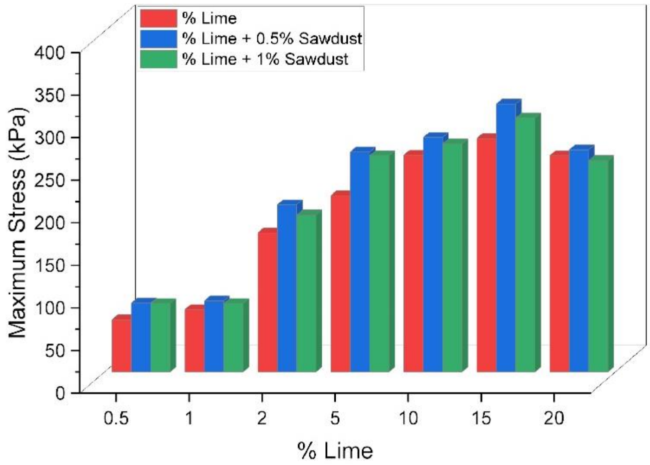


Figure 2. Unconfined compression test results with 30 % water content concerning Sample-1

Test results showed that sample from Sample-1 prepared with 30% Water + 15% Lime + 0.5% and 1% sawdust. maximum stress was determined as 275.3 kPa for lime. 299.2 kPa and 315.8 kPa for the sawdust. In the same soil. for the samples with 25% water + 5% Lime + 0.5% and 1% sawdust. it was determined to be 260.6 kPa for lime. 590.5 kPa and 580.6 kPa for sawdust.

It is seen from the test. samples from Sample-2 that prepared with 30% water. the values increased up to 398.1 kPa with the addition of lime. and up to 435.4 kPa and 453.5 kPa with the addition of sawdust + lime. In the samples with 25% water + 5% Lime + 0.5% and 1% sawdust. the stress values were obtained as 423.9 kPa for lime. 511.4 kPa and 519.2 kPa for sawdust.

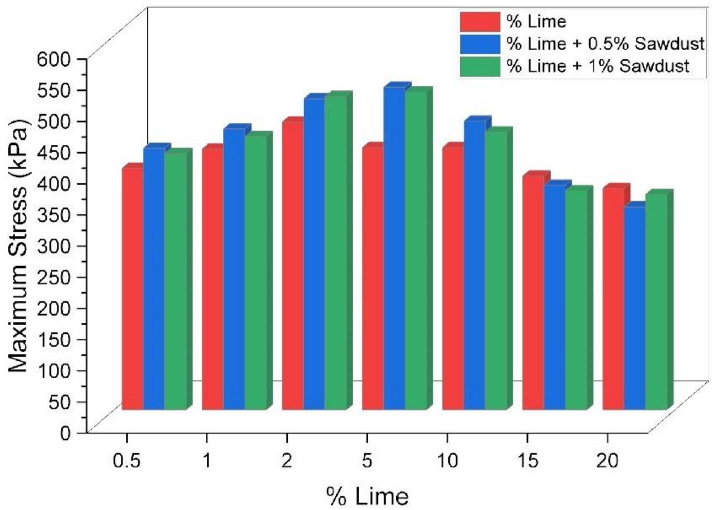


Figure 3. Unconfined compression test results with 25 % water content concerning Sample-2

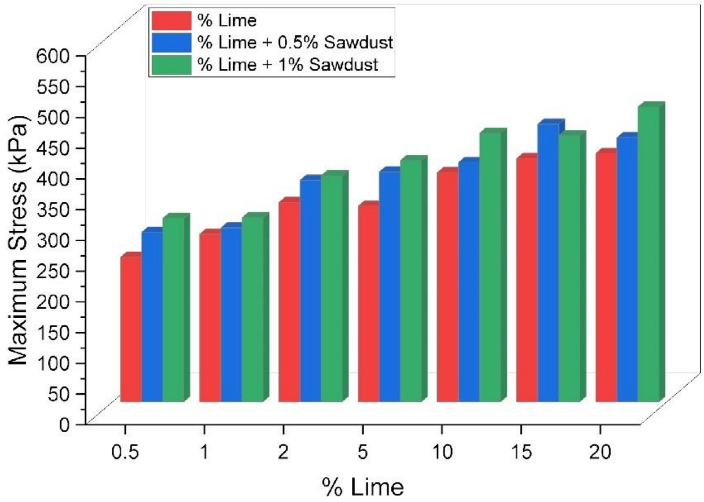


Figure 4. Unconfined compression test results with 30 % water content concerning Sample-2

4.NUMERICAL ANALYSIS

Artificial neural network (ANN) and multiple regression analysis (MRA) models were used on the test results of the samples to estimate the maximum unconfined compression test values of soils stabilized with lime and sawdust. In all models. water. lime and sawdust amounts were applied as percentages and the strength value was found as kPa.

4.1 Ann Model Development

In the development of the ANN model. a feed-forward neural network with a back-propagation training algorithm was employed due to its effectiveness as a general-purpose model [32-33]. The dataset for Sample-1. consisting of 45 data points. was divided into 30 for training. 6 for validation. and 9 for simulation. The performance of the model was validated by cross-checking the results against actual data.

The architecture of the neural network was carefully designed with three input neurons. a single hidden layer containing five neurons. and an output layer. The hyperbolic tangent sigmoid activation function was utilized for all layers. ensuring non-linearity and smooth transitions between nodes. The selection of five neurons in the hidden layer was based on iterative experimentation to balance the trade-off between model complexity and overfitting.

MATLAB's Neural Network Toolbox was used to perform the necessary computations and optimize the model. The statistical parameters for both training and simulation data are provided in Table 2 and Table 3. respectively. which further demonstrate the model's accuracy and reliability.

The chosen hyperparameters. including the learning rate and number of epochs. were fine-tuned through multiple trials to achieve the best performance. This approach ensured that the model effectively captured the underlying patterns in the data while avoiding overfitting. By providing detailed insights into the architecture and the rationale behind the parameter selection. this study aims to enhance the transparency and reproducibility of the ANN model.

Table 2. Statistical parameters of data set considered for training

	Sample-1				Sample-2			
	Mean	**Std. Dev.**	**Min**	**Max**	**Mean**	**Std. Dev.**	**Min**	**Max**
Water	27.64	2.53	25.00	30.00	27.64	2.53	25.00	30.00
Lime	9.56	0.32	0.50	30.00	8.15	7.67	0.50	20.00
Sawdust	0.54	0.40	0.00	1.00	0.53	0.41	0.00	1.00
Strength	238.44	76.64	75.20	370.40	390.28	63.24	274.80	519.20

Table 3. Statistical parameters of data set considered for simulation

	Sample-1				Sample-1			
	Mean	**Std. Dev.**	**Min**	**Max**	**Mean**	**Std. Dev.**	**Min**	**Max**
Water	27.78	2.64	25.00	30.00	27.50	2.67	25.00	30.00
Lime	7.44	6.87	0.50	20.00	8.44	6.65	0.50	20.00
Sawdust	0.33	0.43	0.00	1.00	0.44	0.42	0.00	1.00
Strength	209.08	103.93	63.00	380.50	413.80	88.41	236.60	511.40

The architecture of the artificial neural network used in the estimation of the strength of the soil samples reinforced with lime and sawdust is shown in Figure 5.

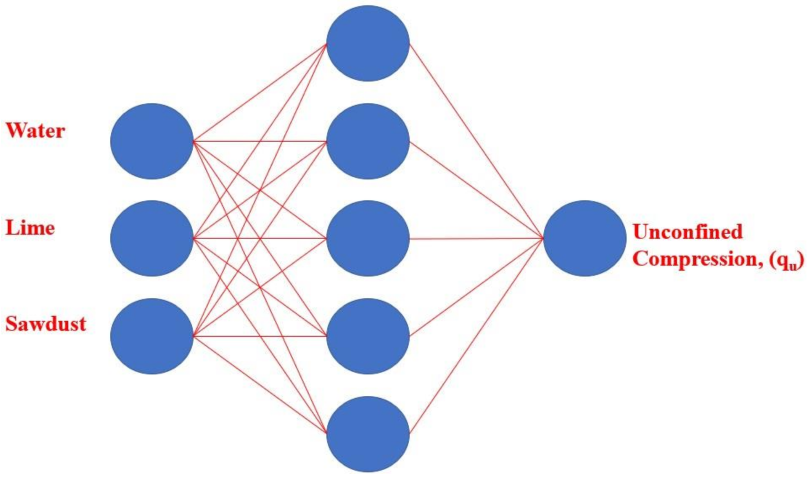


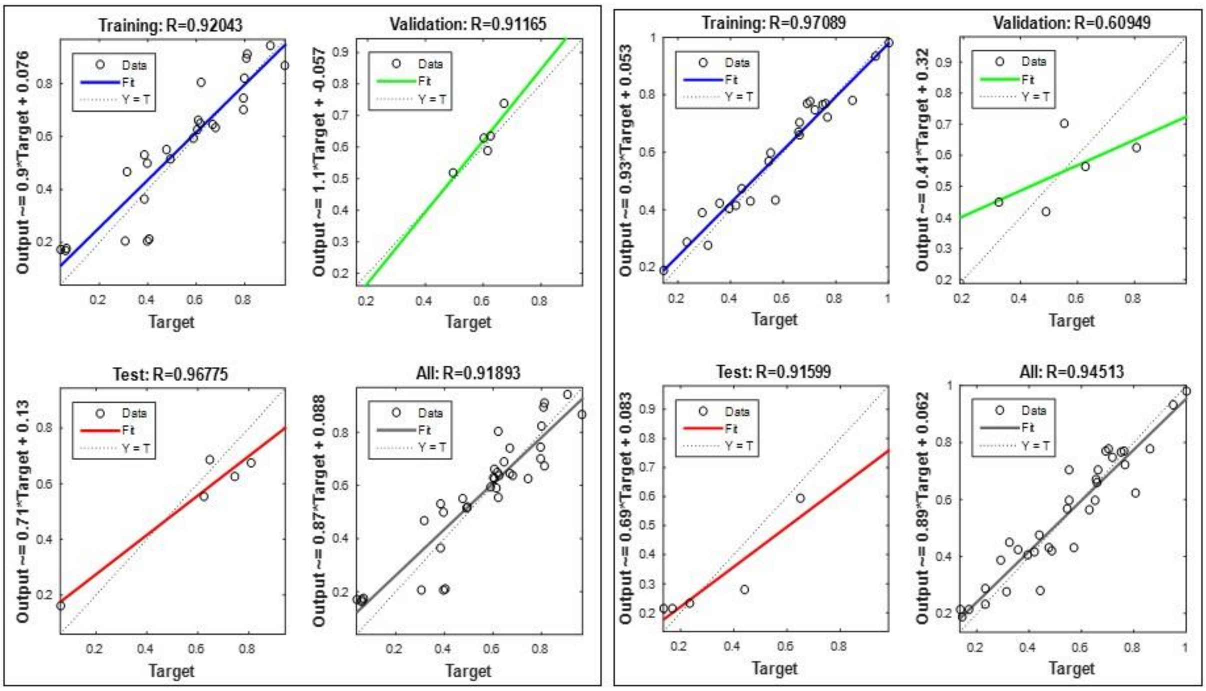
Figure 5. Architecture of the Neural Network model for prediction

The connection weights and biases of ANN model for prediction of unconfined compression of lime and sawdust stabilized soil are shown in Table 4.

Table 4. Connection weights and biases of ANN model for prediction

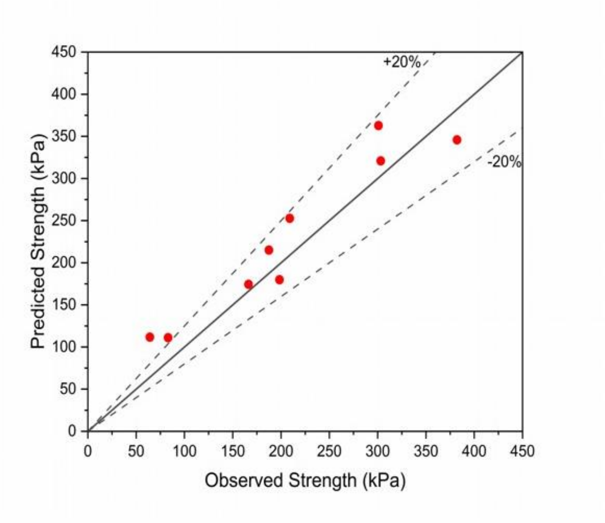
	Sample-1						Sample-2					
Neuron	Water	Lime	Sawdust	Strength	bhk	bo	Water	Lime	Sawdust	Strength	bhk	bo
Hidden neuron (k=1)	-1.512	-1.043	0.955	2.697	0.367	0.160	-1.258	-2.873	-0.644	-1.994	-3.330	-1.881
Hidden neuron (k=2)	-1.259	-2.006	0.036	-0.278	-1.161		-0.077	2.944	-0.280	1.699	3.503	
Hidden neuron (k=3)	2.639	0.022	-0.528	-0.278	-1.161		-1.169	-1.451	-2.227	-0.463	1.187	
Hidden neuron (k=4)	-1.972	1.782	0.115	-0.702	0.754		-1.070	-0.157	1.579	-0.912	-2.455	
Hidden neuron (k=5)	0.01	1.961	1.621	-2.091	-0.389		2.198	1.878	-0.209	-2.625	2.872	

The ANN model learning graphs of soil stabilized with lime and sawdust are shown in Figure 6. and the graph plotted between estimated and observed values are visualized in Figure 7. The estimated and actual observed values using the ANN model are nine simulation datasets for Sample-1 and eight for Sample-2.



a b

Figure 6. Learning outcome of ANN model: a) Sample-1 b) Sample-2



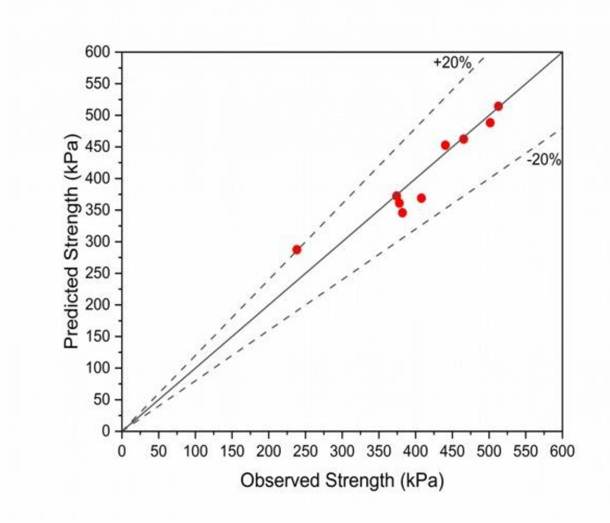


Figure 7. Simulation result of ANN model with predicted and observed values

It is observed that there is a high correlation between the observed and the estimated values. Coefficient of determination (R^2) value is 0.913 and coefficient of correlation (R) value is 0.956 for Sample-1. However. for Sample-2; R^2 value is 0.924 and R value is 0.961.

4.2 MRA Model Development

Multiple regression analysis (MRA) is one of the most widely used techniques to analyse multifactor data [34]. The MRA Model was developed using the SPSS software package as;

For Sample-1;

$$q_u = 654.859 – 18.021*W– 6.086*L + 42.983*S + 0.512*W*L – 0.673*W*S$$

For Sample-2;

$$q_u = 1257.116 – 32.402*W – 72.354*L – 80.771*S + 2.678*W*L + 3.932*W*S$$

- W: Water content (%)
- L: Amount of lime (%)
- S: Amount of sawdust (%)

Figure 8 shows the graph plotted between observed and predicted values. The predicted values were obtained through the MRA model. R2 value for Sample-1 is 0.879 with an R-value is 0.938 and R2 value is 0.791 with an R-value of 0.890 for Sample-2. If R ≥ is 0.8 value. there are two variables with strong correlation [35]. It can be argued that there is a significant correlation between the calculated and estimated values.

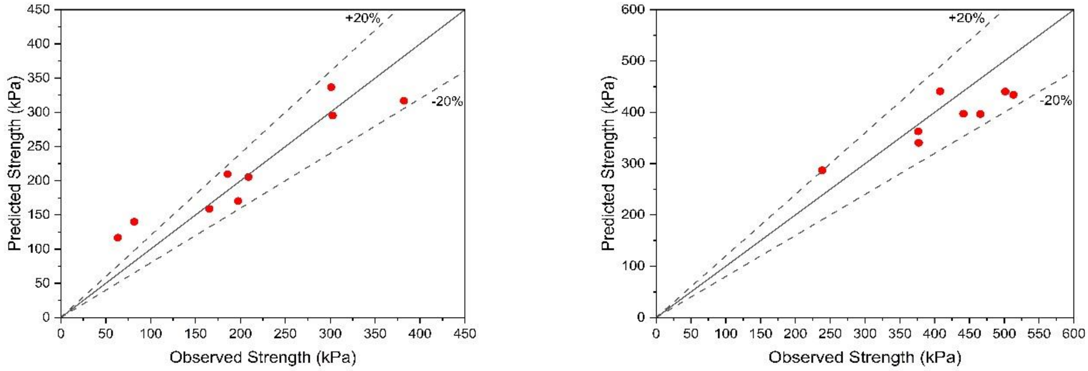


Figure 8. Simulation result of MRA model

4.3 MRA and ANN Comparison

A comparison of the predictive capabilities of the ANN and MRA model is shown in Table 5. Mean square error (MSE). mean absolute error (MAE). root mean square error (RMSE) and R^2 are considered as the parameters for comparison. The table indicated that the ANN model has less RMSE. MSE and MAE values and more R^2 than the MRA model.

Table 5. Comparison of the prediction capabilities of ANN and MRA Models

Soil Sample	Model	Data Set Used	RMSE (%)	MSE (%)	MAE (%)	R^2
Sample-1	ANN	9	2.413	5.823	9.885	0.914
	MRA	9	2.895	8.381	9.136	0.880
Sample-2	ANN	8	0.866	0.749	5.329	0.923
	MRA	8	1.250	1.561	11.289	0.791

The results show that the ANN model provides better results than the MRA model. The following summarizes the formulations used in the error calculations.

$$MSE = \frac{1}{n}\sum_{i}^{n} = 1e_t^2$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i}^{n} = 1e_t^2}$$

$$MAE = \frac{1}{n}\sum_{i}^{n} = 1|e^t|$$

5.CONCLUSION

One of the popular subjects in geotechnical engineering today is soil stabilization. The basis of soil stabilization works is to provide sufficient bearing capacity through additional additives to existing soil. Research studies are particularly focused on easy-to-find and low-cost additives.

In this study. soil stabilization was investigated through the addition of sawdust and lime. The main objective of this research is to find a suitable solution to the bearing capacity problems of soft soils. Lime. along with sawdust. can be used as waste materials to improve the soil. Unconfined compression tests were conducted on the prepared samples. Then. a numerical method was applied using an artificial neural network (ANN) and multiple regression analysis (MRA). The ANN model provided better results compared to the MRA model following the prediction modeling. The same simulation data were utilized in both the ANN and MRA models. When the MRA model was applied without simulation discretization. the R^2 value increased. However. common simulation data were selected and discretized to compare the models.

The findings indicate that this approach can serve as a low-cost and easy-to-find alternative for soil stabilization. Additionally. the environmental and economic impacts of sourcing lime and sawdust were considered. Lime. a widely available material. can enhance soil strength. while sawdust. as a by-product of the wood industry. provides a sustainable option for recycling waste. However. the potential limitations. such as the long-term durability of the stabilized soil and the variability in the quality of waste materials. need further investigation. Comparing these results with previous studies highlights the effectiveness of the ANN model in capturing complex relationships within the data. while the MRA model's performance improved with proper discretization.

Future research could explore the long-term performance of lime and sawdust-stabilized soils under varying environmental conditions. assess the scalability of this method for large-scale infrastructure projects. and investigate the environmental footprint of the materials used. Additionally. practical recommendations for field applications. such as optimal mixing ratios and curing times. should be developed to facilitate implementation in real-world scenarios.

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CONFLICT OF INTEREST

The authors stated that there are no conflicts of interest regarding the publication of this article.

CRediT AUTHOR STATEMENT

Mehmet İnanç Onur: Conceptualization, Supervision, **Janvier Hobonimana:** Investigation, Methodology, **Pınar Öztürk Kardoğan**: Formal analysis, Writing – Review & Editing, **Ahmet Erdağ:** Writing – Original Draft, Visualization, **Fatih Karaçor:** Software, Validation.

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