

Investigating and machine learning predicting the Impact of Nandina domestica Roots on the Unconfined Compressive Strength of unsaturated silty clay

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Investigating and machine learning predicting the Impact of *Nandina domestica* Roots on the Unconfined Compressive Strength of unsaturated silty clay

Abstract:

Bio-stabilization of soil using natural vegetation offers a sustainable and cost-effective approach to slope management and erosion control. Furthermore, soft computing technologies are necessary since experimental research is often challenging, and time consuming. This article discusses the modelling and the performance of nonlinear and Random Forest (RF) model for predict UCS ultimate stress and trajectory of root-soil stress-strain. *Nandina domestica* is particularly promising due to its hardness and low maintenance requirements, making it an economical and sustainable option for soil bio-stabilization. Using compressive strength, the effects of moisture content, root weight density (RWD), and root diameter (RD) on soil reinforcement were evaluated. 144 silty clay soil samples reinforced with four RWD (1, 2, 3 and 4 gr/cm³) and three RD (1, 2 and 3 mm) in four moisture conditions (20, 25, 30, and 35%) was considered to determine the UCS. The proposed nonlinear model demonstrated acceptable predictive accuracy ($R^2 = 0.84$) with RMSE=8.7 kPa and MAE=7.13 kPa values predicted the contribution of *Nandina domestica* roots to soil ultimate UCS reinforcement. The data was split into three sections for the development of the RF model: the training data set (70%), the testing data set (15%) and the testing unseen data set (15%). The proposed model accurately predicted the trajectory of unknown data root-soil stress-strain and contribution of *Nandina domestica* roots to soil reinforcement, exhibiting strong performance with $R^2 = 0.97$, RMSE = 3 kPa, and MAE = 1.8 kPa.

Keyword: Root-soil composite, Unconfined compressive strength, Random Forest, *Nandina domestica* Roots

1. Introduction

Silty clay soils, characterized by their fine-grained texture, low permeability, and limited strength, typically exhibit poor performance under loading and settlement, demonstrating restricted compressive strength. This inherent weakness often constrains their safe application in various geotechnical projects [1]. While soil improvement techniques, both mechanical and chemical, are widely employed, they frequently present drawbacks such as high costs, environmental concerns, and the need for specialized equipment. Common mechanical methods include compaction, preloading, and stone columns, while chemical stabilization typically involves additives like lime or cement. However, these approaches can be expensive, environmentally disruptive, and demand complex machinery[2].

The fibrous and branched root systems of herbaceous plants and shrubs are particularly effective in stabilizing surface soil layers and augmenting soil resistance to compressive and shear loads due to their efficient interaction with soil particles [3, 4]. This effect becomes even more significant in moist soils or regions with high rainfall, where the complex interplay between moisture, root distribution, and soil strength acts synergistically. In this context, *Nandina domestica* (Nandina) stands out as a shrub species with a fibrous, extensive, and dense root system, demonstrating high potential for improving soil mechanical properties. The structural characteristics of its roots enhance physical engagement with soil particles, limiting displacement and increasing soil cohesion [5, 6].

Under natural conditions, failure in rooted soils primarily occurs under vertical loads, especially in surface soil layers where herbaceous plant roots are established. In these layers, lateral stress is negligible and can typically be disregarded. Numerous studies have indicated that although roots create a form of lateral confinement within the soil-root complex, during the isolation of a sample for testing, the confining effect of internal and external roots tends to cancel each other out. This results in a final state equivalent to a triaxial test with zero lateral pressure. Therefore, the unconfined compression test is a suitable method for evaluating the impact of surface roots on increasing soil strength[7].

Theoretically, the unconfined compression test is a simplified version of the triaxial compression test based on the Mohr-Coulomb theory, where the internal friction angle is assumed to be zero, and the soil's shear strength is considered to be solely due to cohesion[8]. This characteristic makes the unconfined compression test a scientifically sound and practical option, particularly for assessing the soil-stabilizing capacity of fibrous roots in natural and moist conditions. Consequently, this study employed the unconfined compression test as an appropriate method for evaluating the behaviour of fine-grained soils under conditions of no lateral pressure.

The objective of this research is to investigate the influence of varying moisture content, root weight, and root thickness of *Nandina domestica* on the unconfined compressive strength of clayey silt soil and accurate predict of UCS ultimate stress and trajectory of root-soil stress-strain using nonlinear and RF models.

2. Materials and methods

2.1. Plant characteristics

Nandina, commonly known as heavenly bamboo, is a member of the Berberidaceae family native to East Asia. This ornamental plant is valued for its evergreen foliage, white flower clusters, and red berries. It is recognized as a hardy species, adaptable to various environmental conditions, including drought, cold, and partial shade. The plant is hardy in USDA zones 6 through 9. *Nandina* shrubs typically grow to an average height of 60 to 180 cm, with a crown spread of 60 to 120 cm[9-11]. Their roots extend to depths of 30 to 60 cm, spreading laterally, which makes them effective for erosion control on slopes.

The soil and *Nandina domestica* plants studied were sampled from the Karaj Seed and Seedling Centre in Iran (35° 47' 1" N, 50° 56' 41" E). Karaj has an average annual rainfall of approximately 250 mm. The summers are hot, dry, and clear, while winters are extremely cold, snowy, and mostly clear. Throughout the year, temperatures typically range from -2.2°C to 34.5°C and rarely drop below -8°C or rise above 37°C [12].

Soil particle size distribution was analysed using sieve analysis for coarse particles and hydrometer testing for fine particles. The particle size distribution of the studied soil is shown in Table 1. According to the Unified Soil Classification System (USCS), the soil is classified as well-graded silty clay (ML). The basic physical and chemical properties of the soil are detailed in Table 1.

2.2. Soil sampling

To ensure consistent and accurate results, the following sample preparation and testing methodology was meticulously followed. First, soil samples were oven-dried at 105°C for 24 hours to eliminate all moisture. The dried soil was then mixed uniformly with the predetermined weight of roots (1, 2, 3, 4 gr/cm³) for each experimental condition and the calculated amount of water to achieve target moisture contents of 20%, 25%, 30%, and 35%. To ensure homogeneous moisture distribution and stable samples, these mixtures were sealed in containers with plastic wrap and allowed to equilibrate for 24 hours.

Subsequently, all samples were carefully compacted into unconfined compression test molds, maintaining a consistent bulk density of 1.6 gr/cm³. The unconfined compression test was then initiated for each sample. In total, 144 unconfined compression tests were conducted on soil samples containing roots, along with 12 tests on root-

free control samples. Each experimental condition was replicated three times to ensure the reliability and validity of the results, allowing for a robust assessment of the effects of roots and moisture on soil properties.

2.3. Measurement of soil Unconfined Compressive Strength

To determine the unconfined compressive strength of the soil, we employed the unconfined compression test, a simplified version of the triaxial compression test. Cylindrical metal molds with a diameter of 3.8 cm and a height of 8.9 cm were used for sample preparation. To maintain the natural soil density across all samples, a specific weight of 150.6 grams was uniformly placed into each mold. This included both root-free soil samples and soil samples containing roots at various moisture contents.

Once prepared, the samples were subjected to loading in an unconfined compression testing machine at a constant strain rate of 1 mm/min. For samples that failed before reaching 15% axial strain, the peak compressive strength was recorded as the unconfined compressive strength. For samples that did not fail by 15% axial strain (typically observed in samples with higher moisture content), the stress at 15% axial strain was considered as the unconfined compressive strength.

2.4. RF Regression model

This study utilized a RF Regression model to predict soil reinforcement from plant and soil parameters (W, RWD, RD, and Strain). The raw strain-stress data was first meticulously parsed and structured, with metadata extracted to create a tidy dataset. To prepare the data for modeling, all features were standardized using StandardScaler, preventing larger-scale variables from dominating the learning process. The dataset was then strategically divided into training (70%), validation (15%), and final test (15%) sets to ensure robust model development and an unbiased assessment of its generalization performance on completely unseen data.

An initial RF Regressor was trained on the 70% training set, and its performance was evaluated on the validation set using Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), and R-squared (R²). To optimize the model's predictive capabilities, Randomized Search Cross-Validation was performed on the training data. This process systematically explored a predefined range of hyperparameters, including the number of estimators, maximum features, and minimum samples per leaf, using 5-fold cross-validation. The model was then refitted with the best identified hyperparameters. Finally, the optimized model's performance was rigorously assessed on the truly unseen 15% final test set, with its predictions visually compared against actual values through a scatter plot.

2.5. Evaluation of the performance of the corrected Wu Waldron model

The performance of the models was assessed using the following statistical parameters:

Coefficient of determination (R^2): This coefficient measures the proportion of variance in the observed data explained by the model [13].

$$R^2 = \frac{[\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P})]^2}{\sum_{i=1}^n (O_i - \bar{O})^2 \sum_{i=1}^n (P_i - \bar{P})^2} \quad (5)$$

Root mean squared error (RMSE): Quantifies the average magnitude of prediction errors [14].

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (O_i - P_i)^2} \quad (6)$$

Mean absolute error (MAE): This metric provides the average of absolute errors, offering an easy-to-interpret measure of prediction accuracy [14].

$$MAE = \frac{1}{n} \sum_{i=1}^n |O_i - P_i| \quad (7)$$

In the equations above, P_i represents the predicted value, O_i represents the observed value, $\bar{O}$ is the mean of the observed values, $\bar{P}$ is the mean of the predicted values, and n is the number of samples.

2.6. Statistical analysis

Python software was used for analysis, correlation analysis, and regression analysis of the test parameters.

3. Results and discussion

3.1. unconfined compressive stress-strain curves

unconfined compressive stress-strain curves for rooted soils were plotted at three root diameter (3 columns) and four moisture content (4 row), along with the corresponding curves for bare control soils (RWD=0 gr in fig 1). These curves, drawn up to the maximum compressive stress corresponding to 15% horizontal displacement, in general differ significantly between rooted and bare soils, demonstrating that the presence of roots enhances soil strength and delays failure (fig 1). The soil-root system consistently exhibited failure at higher compressive stresses compared to the bare soils, indicating greater resistance and stability.

Moisture content significantly influences soil cohesion and friction angle, highlighting its effect on root-soil interactions [15, 16]. At a 20% moisture content, the presence of roots led to an average 53% increase in compressive strength compared to root-free soil. For higher moisture contents, specifically 25%, 30%, and 35%, the root-reinforced soil exhibited improvements of 54%, 18%, and 19% in compressive strength, respectively.

Regarding the influence of root thickness, the average improvement in clayey silt soil across all moisture contents was 62% for 1 mm thick roots, 31% for 2 mm thick roots, and 16% for 3 mm thick roots. This trend suggests that thinner roots, particularly those around 1 mm in diameter, are more effective in enhancing compressive strength. This superior performance of thinner roots could be attributed to their more fibrous nature, which likely allows for greater water absorption and better regulation of moisture within the soil matrix, thereby mitigating the detrimental effects of higher moisture content on soil strength.

Research on plant root systems indicates that root diameter generally decreases with depth, with finer roots exhibiting higher respiration rates and nitrogen concentrations [17]. Thinner roots at greater depths exhibit higher tensile strength, compensating for their reduced volume and weight, as noted by Pregitzer, Laskowski [17] and Ghestem, Sidle and Stokes [18]. This is consistent with findings from Xing, Zhang [15] and Zhu, Mao [19], who reported that thicker roots enhance resistance but are less effective at minimizing displacement compared to dense, thinner root networks.

3.2. Interaction of UCS and RWD and water on 3D map

To investigate the simultaneous effect of moisture content and root density on the unconfined compressive strength of silty clay, the results of testing samples with thicknesses of 1, 2, and 3 mm were plotted separately. According to the 3D figures, with increasing RD, the maximum soil pressure decreased, indicating the importance of finer roots in soil strengthening.

In addition, at a thickness of 1 mm (Fig 2-a) compared to a thickness of 2 and 3 mm (Fig 2-b, c), the difference in resistance between different moisture conditions and root volume is greater and they are more affected by moisture reduction and root growth, indicating a lower moisture absorption ability of finer roots.

From the slope of moisture and RWD, it can be said that with increasing RWD and decreasing moisture content, the uniaxial compressive strength of the soil increases.

3.3. non-linear model for soil-root UCS

Compressive strength of the soil-root system decreases with increasing moisture content. Additionally, an increase in root weight unlike root diameter enhances the resistance of the root-soil system. Based on the feature importance analysis performed using the RF Regressor, moisture content, root weight density (RWD), and root diameter (RD) were found to contribute 69.9%, 19.4%, and 10.7% respectively to the variation in the unconfined compressive strength (UCS) results. Accordingly, the relationship was quantified through Equation (1). the equation for the UCS of the root-soil complex was as follows:

$$F(Kpa) = (160.64 + (1.11^W) + (-5.7(RD) + (9.62(RWD) + (-5.23(W))) \quad (1)$$

where F is the ultimate unconfined compressive strength (kPa); W is the moisture content (%); RWD is the root weight density (gr/100 cm³); RD is the root diameter (mm).

R^2 for the model was 0.84, and the RMSE=8.7 kPa and MAE=7.13 kPa were acceptable and indicating good model performance. A comparison of the actual and predicted values for root-reinforced soils shows that they align closely with the 1:1 line (Fig 3). This demonstrates that the model can accurately predict the effects of *Nandina* roots on the UCS of silty clay soils. Therefore, it is recommended to estimate the UCS of *Nandina* shrub systems in silty clay soils. For other cases with different plant species or soil properties, further research is necessary.

3.4. RF model for soil-root compression behaviour

The experimental results of the UCS tests on root-soil, discussed in the previous section, indicate that the relationship between compressive strength and strain is nonlinear. similar behaviour has been observed in numerous studies on root-soil interactions across various plant species.

Therefore, it appears that a RF model with perfectly plastic behaviour at the ultimate state could be effectively employed for numerically simulating the Compressive behaviour of root-soil systems. The prediction results of this model at different strains and moisture conditions and different RWD and RD against actual experiments (unseen data) are shown in Figure 4. The RF algorithm trains efficiently, generalizes well, and remains robust even with incomplete data due to its parallel structure and random sampling[20]. The proposed models accurately predicted the contribution of *Nandina domestica* roots to soil reinforcement, exhibiting strong performance with $R^2 = 0.97$, RMSE = 3 kPa, and MAE = 1.8 kPa.

4. Conclusion

This study demonstrates the significant role of *Nandina domestica* roots in enhancing the compressive strength of unsaturated silty clay soils. The experimental results show that root systems improve soil Unconfined compressive strength compared to unreinforced soils.

The nonlinear model with $R^2 = 0.84$ and acceptable RMSE=8.7 kPa and MAE=7.13 kPa metrics, accurately predicted the contribution of *Nandina domestica* roots to soil UCS reinforcement. Moreover, this model can be calibrated for different conditions and datasets, allowing for adaptation based on regional data. In summary, increasing moisture reduced the UCS of both bare and root-reinforced soils. However, root-reinforced soils significantly contributed to improving soil strength under higher moisture conditions.

The analysis revealed that the compressive stress-strain behaviour of root-soil interactions follows a nonlinear pattern, which was effectively modelled using a RF approach. The RF model, which incorporates the nonlinear elastic perfectly plastic behaviour of root-soil interactions, provided excellent predictions of compressive behaviour across varying conditions of soil moisture content, RWD and RD. This approach, as illustrated by the analytical solutions, closely matched experimental data, confirming its reliability for simulating root-soil interactions in silty clay soils. The proposed models accurately predicted the contribution of *Nandina domestica* roots to soil reinforcement, exhibiting strong performance with $R^2 = 0.97$, RMSE = 3 kPa, and MAE = 1.8 kPa.

In conclusion, the combination of the nonlinear model and RF model provides a robust framework for understanding and quantifying the role of root systems in soil stabilization. Future research should focus on refining the proposed model by incorporating additional environmental and soil parameters, to enhance its predictive capability. Further validation through large-scale field testing is essential to assess its reliability under

diverse conditions. Additionally, expanding its application to different soil types and plant species will improve its adaptability for erosion control and slope stabilization.

Declarations

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Ethics Declaration

Not applicable.

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305 **List of tables:**

306 Table 1. index properties of the Soil

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337 **Tables:**

338 Table 1. index properties of the Soil

PH	EC (μS)	Bulk density (gr/cm^3)	Plastic limit (%)	Liquid limit (%)	Particle size distribution (%)		
					Sand	Silt	Clay
					0.075 - 4.75 mm	0.002- 0.075 mm	0.002mm <
6 – 7.5	49.4	1.6	27.3	37.7	44.5	37.5	18

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Fig. 1. Unconfined compressive stress-strain results. W represents the moisture content and RD represents the root diameter and 0 to 4 gr represents the root weight density of every diagram.

Fig. 2. 3D surface plot of the unconfined compressive strength under the combined of moisture content and root weight density (a) for RD of 1mm (b) for RD of 2mm (c) for RD of 3mm.

Fig.3. Ratio of the nonlinear Predicted UCS to the measured UCS

Fig. 4. Ratio of the Random Forest Predicted UCS to the measured UCS

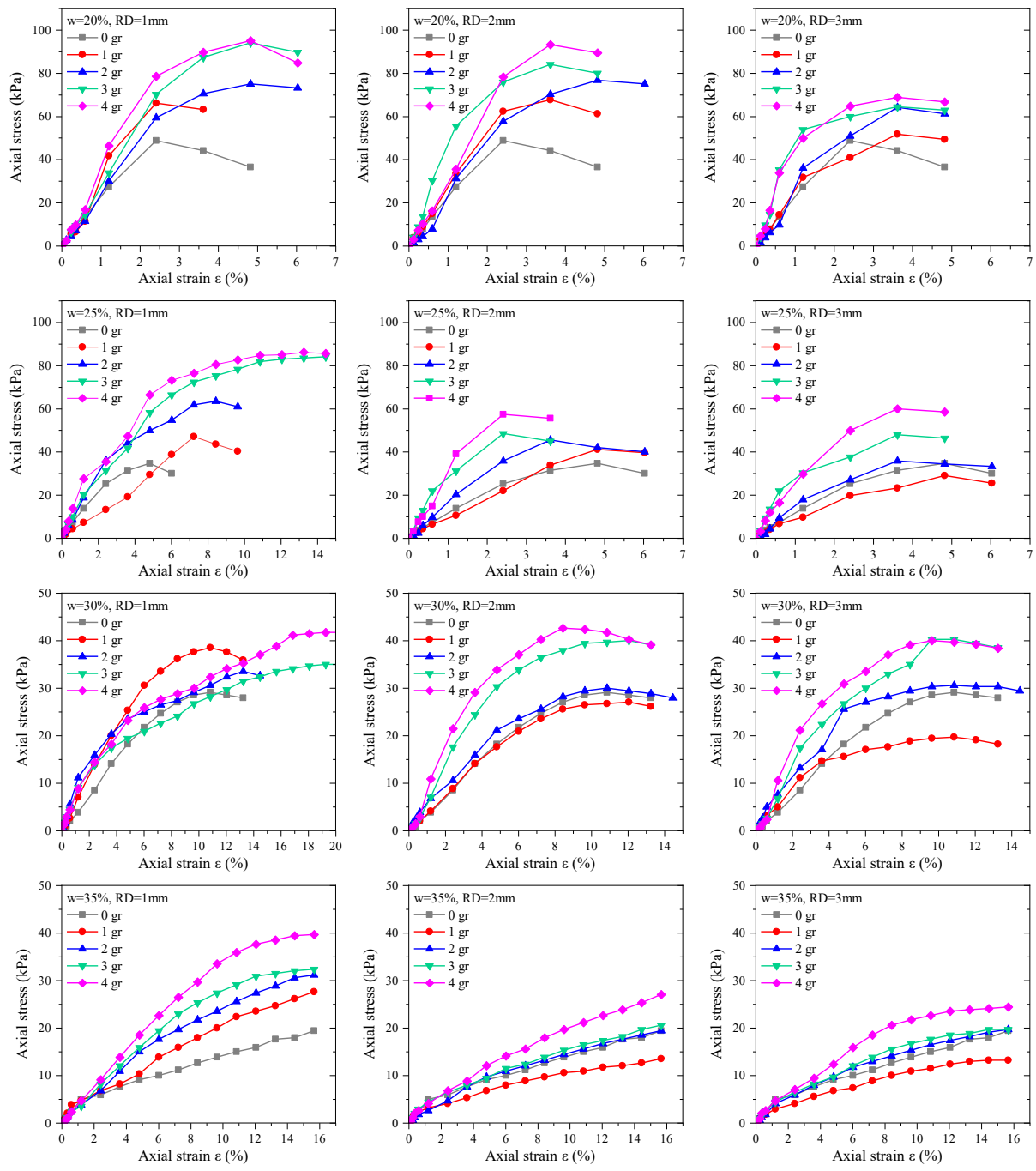
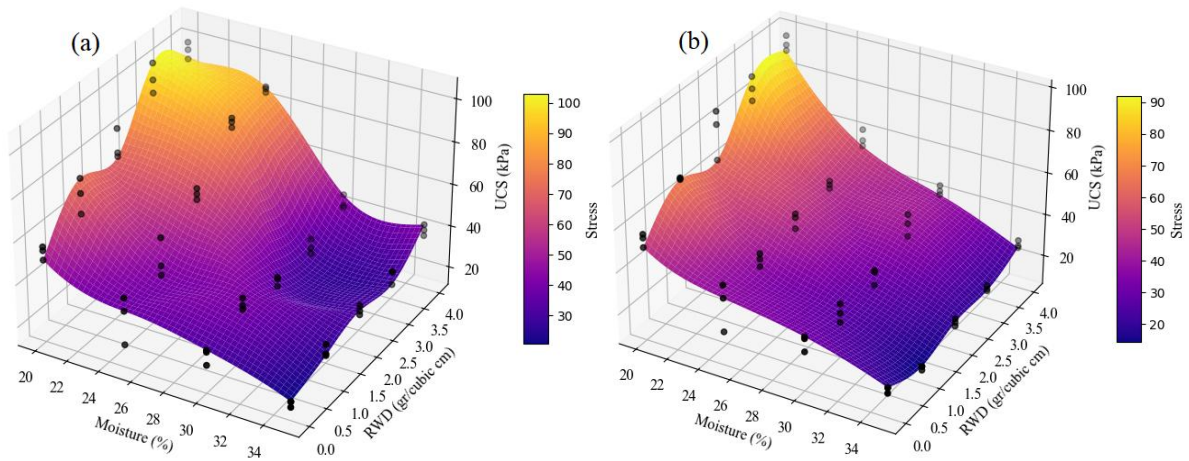
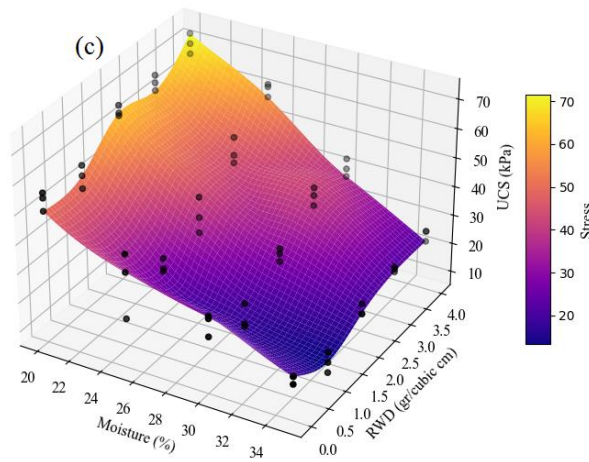


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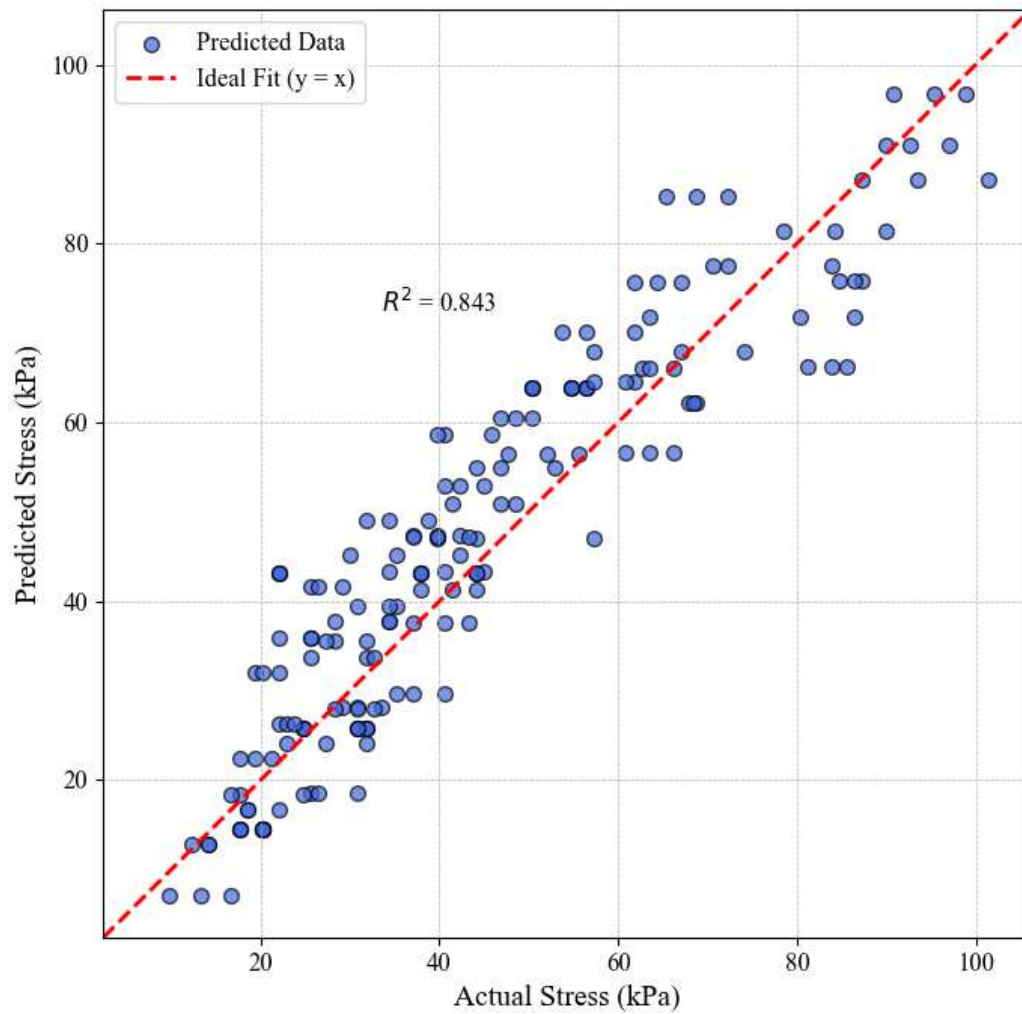
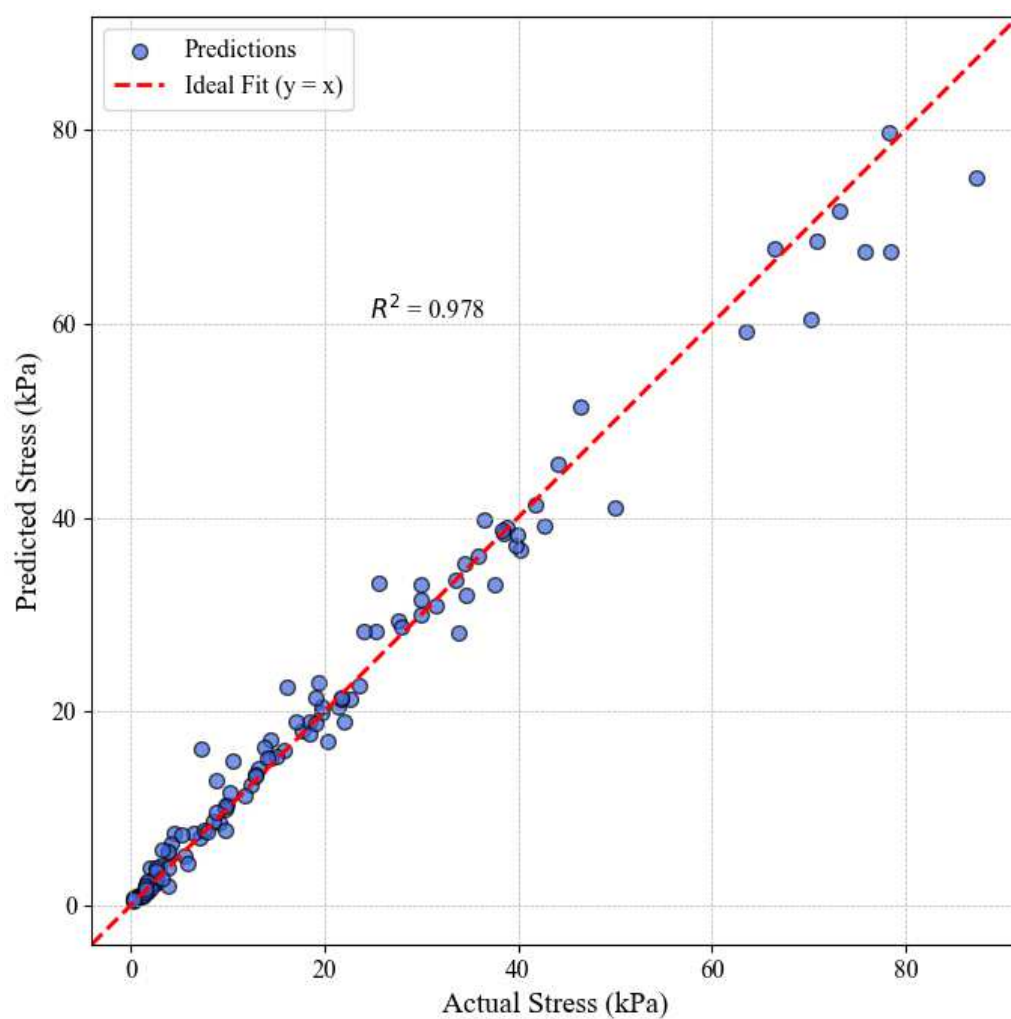


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