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Original Research Article

Predicting and Optimizing Compressive Strength of Tuffcrete Concrete Using Artificial Neural Networks

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Abstract

Tuffcrete concrete (ATC) has emerged as a promising material in modern civil engineering due to its enhanced durability and eco-friendly composition. This study presents the development of Artificial Neural Network (ANN) models to predict and optimize the compressive strength of Tuffcrete concrete based on experimental data. The dataset consists of 21 input features, including mix proportions (e.g., cement content, water-cement ratio, aggregate size distribution), material properties (e.g., tuffcrete polymer, slag content), and process parameters (e.g., mixing time, compaction level). The ANN models were trained and validated using these features to accurately forecast the compressive strength of Tuffcrete concrete under various conditions. The study demonstrates the model's ability to capture nonlinear relationships between input variables and compressive strength, achieving high accuracy metrics (e.g., R^2 and RMSE). Furthermore, optimization techniques were employed to identify the optimal mix design for maximizing compressive strength. Results reveal critical insights into the interplay between material properties and mechanical performance, paving the way for efficient mix designs tailored for specific applications. This work contributes to the advancement of machine learning applications in civil engineering, providing a robust framework for performance prediction and optimization of sustainable construction materials.

Keywords: Compressive Strength, Tuffcrete Concrete, Artificial Neural Networks (ANNs), Predictive Modeling, Mechanical Properties, Concrete Optimization.

INTRODUCTION

Background on Tuffcrete Concrete as a Sustainable Construction Material

Concrete remains one of the most widely used materials in construction due to its durability, versatility, and cost-effectiveness, but its high carbon footprint has raised environmental concerns. The development of alternative eco-friendly materials, such as Tuffcrete, has gained momentum in sustainable construction (Awodiji & Sule, 2023; Silva *et al*., 2023). In recent years, Tuffcrete concrete has emerged as a promising sustainable alternative, integrating tuff as a supplementary material to reduce environmental impact while enhancing mechanical properties. One of the critical mechanical properties that dictate concrete's utility is compressive strength, which influences structural stability and design parameters (Li *et al*., 2023; Silva *et al*., 2022). Tuffcrete, a volcanic tuff-based concrete, offers distinct advantages, including enhanced pozzolanic activity, superior durability, and reduced dependency on traditional Portland cement. These features position it as a viable solution for reducing greenhouse gas emissions and conserving natural resources (Khasauov *et al*., 2020; Radlińska & Li, 2022). Previous studies have demonstrated the potential of using Tuffcrete in structural applications due to its high compressive and flexural strengths, coupled with cost-effectiveness (Awodiji & Sule, 2023).

In addition to its environmental benefits, Tuffcrete's mechanical properties make it a suitable candidate for modern construction needs. By incorporating recycled aggregates and pozzolanic materials, Tuffcrete not only minimizes construction waste but also enhances its mechanical properties, as observed in studies on sustainable self-compacting concrete (de-Prado-Gil *et al*., 2022). These advancements align with global goals for resource-efficient and sustainable infrastructure development.

Importance of Compressive Strength in Concrete Applications

Compressive strength is a critical parameter for evaluating the structural performance and durability of concrete. It directly influences the design, safety, and longevity of infrastructure projects. Achieving optimal compressive strength depends on various factors, including mix design, curing conditions, and the type of materials used (Silva *et al*., 2023; Barbhuiya & Sharif, 2022). For innovative materials like Tuffcrete, understanding the interplay of these factors is vital to unlocking its full potential in construction applications (Sarfarazi *et al*., 2024).

The significance of compressive strength extends beyond structural applications, encompassing cost-effectiveness and sustainability. Enhanced strength allows for the optimization of mix proportions, reducing the overall material usage while maintaining safety standards (Khasauov *et al*., 2020). Furthermore, compressive strength serves as a key performance indicator for evaluating the efficacy of supplementary cementitious materials, such as recycled aggregates, in sustainable concrete production (de-Prado-Gil *et al*., 2022).

Overview of Artificial Neural Networks in Predictive Modeling and Optimization

The application of Artificial Neural Networks (ANNs) in civil engineering has revolutionized predictive modeling, offering unparalleled accuracy and adaptability. Unlike traditional statistical approaches, ANNs can capture complex, nonlinear relationships in datasets, making them highly suitable for predicting concrete properties like compressive strength (Barbhuiya & Sharif, 2022). Recent studies have successfully employed ANN models to predict strength characteristics in various concrete types, including self-compacting and recycled aggregate concretes (de-Prado-Gil *et al*., 2022; Silva *et al*., 2023). Moreover, ensemble and hybrid machine learning models have demonstrated improved prediction accuracy by leveraging the strengths of multiple algorithms (Sarfarazi *et al*., 2024).

Explainable AI techniques further enhance the applicability of ANNs by identifying critical factors influencing compressive strength. Sensitivity analysis and feature importance rankings derived from ANN models enable researchers to optimize mix designs effectively (Radlińska & Li, 2022). Such advancements facilitate the development of sustainable concrete materials like Tuffcrete, aligning with industry trends toward intelligent and data-driven construction practices (Barbhuiya & Sharif, 2022).

Objectives

This study aims to harness the predictive and optimization capabilities of ANNs to evaluate and enhance the compressive strength of Tuffcrete concrete. Specifically, the objectives are:

1. To predict compressive strength based on key mix design variables using ANN models.
2. To optimize mix proportions for achieving high compressive strength in Tuffcrete concrete.
3. To validate the proposed ANN model through experimental datasets and comparative analyses with traditional methods.
4. To advance the understanding of sustainable concrete materials and their mechanical properties through data-driven insights.

By addressing these objectives, this research contributes to the broader discourse on sustainable construction materials and their integration into modern engineering practices.

MATERIALS AND METHODS

Experimental Details:

a. Aggregates

i. Coarse Aggregates

Two grades of coarse aggregates; medium size coarse aggregate of maximum size 12.5 mm and coarse aggregate of maximum size 20mm conforming to EN 12620 were employed. Aggregates were sourced from Akamkpa in Cross Rivers State and bought at Mile 3, building material market at Diobu, Port Harcourt.

ii. Fine Aggregates

Fine River sand was sourced from Imo River which was purchased in Mile 3 building material market in Diobu, Port Harcourt, Nigeria. The standard is in conformance to (EN 12620).

b. Portland Cement

The Grade 42.5N Dangote Portland Cement containing 15% limestone was used for the investigation. This cement conformed to the Nigeria International Standard (NIS 444:2018). The cement was acquired at the building material market located at Diobu, Port Harcourt, Nigeria.

c. Water

Water which is fit for drinking and obtained from the Civil Engineering Laboratory of Rivers State University was adopted for the study.

d. Axion Rigid Tuffcrete Powder (ARTP)

A low viscosity, high performance water reducer and advanced high early age strength plasticizer (AXION TUFFCRETE) which conformed to EN 934-2 was used in the study. This was purchased at Km 1/2 Aba Express Road, Port Harcourt, Rivers State.

e. Axion Tuffcrete Liquid Polymer (ATLP)

Axion Liquid Polymer acts as a performance-enhancing additive in concrete, primarily affecting the material's mechanical properties, durability, and workability. This material was obtained from Km 1/2 Aba Express Road, Port Harcourt, Rivers State. Methodology for obtaining mechanical properties.

Artificial Neural Network Architecture:

a. Model Architecture Design

A feedforward neural network architecture was employed in this study. The network consisted of an input layer, multiple hidden layers, and an output layer. The number of hidden layers and neurons was optimized through trial and error to minimize prediction errors. The model was designed to predict a specific property based on the following fifteen (15) input parameters that include; Coarse Aggregate Content (kg/m3), Water-Cement Ratio, Fine Aggregate Content (kg/m3), Coarse Aggregate Content (kg/m3), Tuffcrete Cement (kg/m3), Dry Mass (M1 (kg), Wet Mass (M2 (kg), Tuffcrete Polymer (kg/m3), Density (Kg/m3), Age of Concrete (days), Aggregate Size Distribution, Slag Content (kg/m3), Mixing Time (minutes), and Compaction Level (%).While, the network output was the compressive strength predicted. This design was carried out using the neural network toolbox in Matlab R2024A.

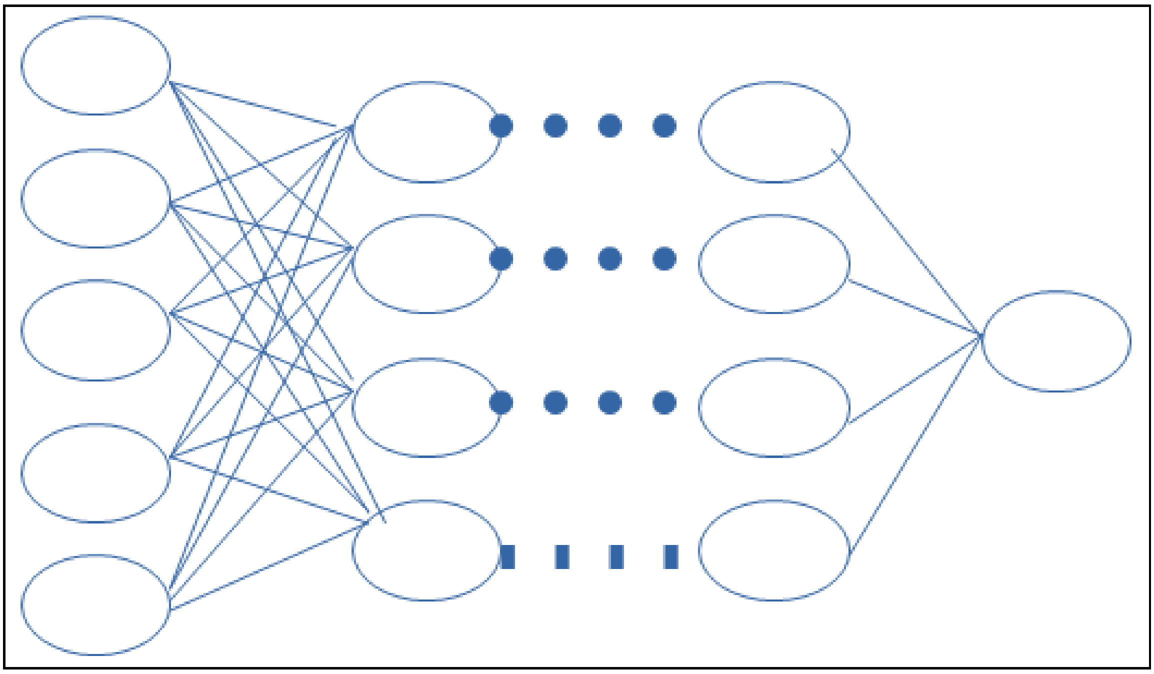


Figure 3.1: ANN architecture

b. Feature Selection and Input Representation

Data preprocessing techniques, such as normalisation or standardisation, where applied to ensure that input features are within a similar scale and range, which aided in the training process. The range scaling (min-max scaling) (-1, 1) was used for normalisation of the results, which aided in the training process. It scales the data so that the minimum and maximum values are -1 and 1, keeping the data within a specific range, which improved the training speed and stability in neural networks.

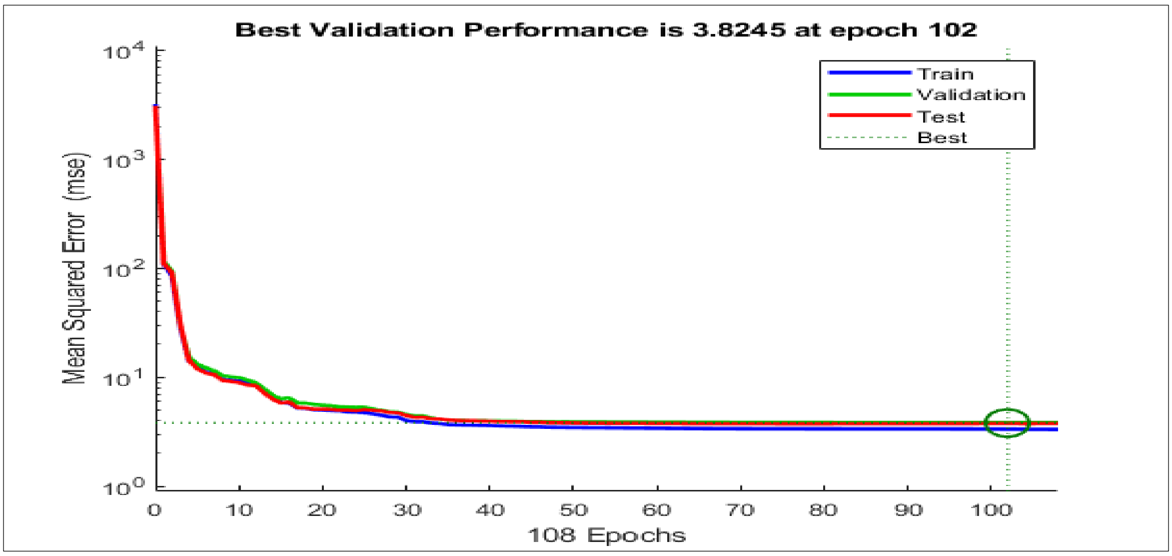
c. Training Process

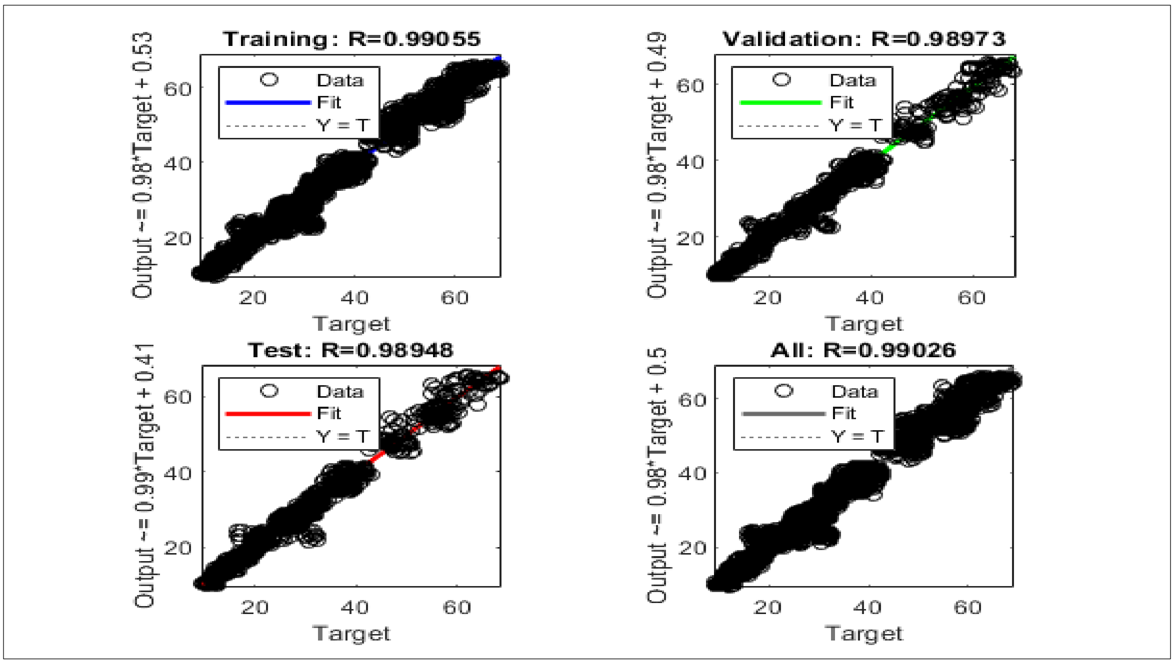
During the training phase, the ANN models learnt to map input features to their desired output (i.e., the mechanical properties) through an iterative optimisation process. The back propagation algorithm was used to updating the network’s weights and biases based on the error between predicted and actual outputs. This process helped to minimize the loss function.

The ANN models were trained using 7,980 samples of the 8,000 dataset. This was obtained from the 225 sample data obtained experimentally, extract from existing literature and MATLAB R2024a augmentation. The model used only 70% (5600) of it was used for the actual training process, 15% for testing and the other 15% for validating the networks, (1,190 each). The tanh activation function was applied to the hidden layers, while a linear activation function was used in the output layer.

RESULTS

The result obtained from the laboratory investigation on the compressive strength of ATC are presented. These results show that highest 28-day compressive strength of 64.3 MPa was obtained from mix ratio 1:0.7:1.13 at w/c ratio of 0.35 and percentage addition of ATWP of 20%. Meanwhile, the lowest 28-day strength of 13.92MPa was attained at 1:0.62:1.1 mix ratio at 0.45 w/c ratio having ATWP inclusion of 0%.





DISCUSSION

Compressive strength of the concretes shows that at a water-cement ratio of 0.35, the mix with 20% Tuffcrete exhibits the highest compressive strength of 64.3 MPa at 28 days, while the mixes without Tuffcrete (0%) show a significantly lower strength of 22.81 MPa. Similarly, at a water-cement ratio of 0.40, the highest compressive strength (55.41 MPa) was achieved with 20% Tuffcrete, and the lowest (16.89 MPa) without Tuffcrete. For the water-cement ratio of 0.45, compressive strength decreases, but the mix with 20% Tuffcrete still reaches a considerable strength of 47.41 MPa, compared to just 13.92 MPa without Tuffcrete.

CONCLUSION

This study successfully developed neural network models capable of accurately predicting the compressive strength, The models exhibited strong generalization across training, validation, and test sets, as evidenced by the high correlation coefficients R-values close to 0.99 for compressive strength. The performance of the models confirms the practical application in predicting the mechanical properties of concrete materials with partial replacement by Axion Tuffcrete.

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