International Journal on Recent and Innovation Trends in Computing and Communication
ISSN: 2321-8169 Volume: 11 Issue: 8
***Article Received:** 25 May 2023 **Revised:** 12 June 2023 **Accepted:** 30 July 2023*

Comprehensive Review of State-of-the-Art Applications of Artificial Neural Networks in Predicting Concrete Compressive Strength

Vaishali K. Bhadke
Research Scholar, Civil Engineering Department, Kalinga University, Raipur C.G, India
vaishalimendhe@gmail.com

Dr. P. S. Charpe
Associate Professor, Civil Engineering Department, Kalinga University, Raipur C.G, India

Abstract-

Concrete compressive strength prediction is a crucial aspect in civil engineering, with applications ranging from structural design to quality control in construction projects. Traditional methods for predicting concrete compressive strength often rely on empirical formulas or physical testing, which may be limited in accuracy or efficiency. In recent years, Artificial Neural Networks (ANNs) have emerged as powerful tools for predicting concrete compressive strength due to their ability to capture complex nonlinear relationships in data. This paper provides a comprehensive review of the state-of-the-art applications of ANNs in predicting concrete compressive strength. It discusses various architectures, training techniques, input parameters, and datasets used in ANN models, as well as their performance compared to traditional methods. Additionally, challenges and future directions in the field are identified to guide further research efforts.

Keywords: Artificial Neural Networks, Concrete Compressive Strength Prediction, Civil Engineering, Machine Learning

1. INTRODUCTION

Concrete is one of the most widely used construction materials globally, owing to its durability, versatility, and cost-effectiveness. The compressive strength of concrete, which measures its ability to withstand axial loads, is a critical parameter in structural design and quality assurance processes. Traditionally, concrete compressive strength prediction has relied on empirical formulas based on mix proportions or physical testing of concrete specimens. However, these methods may not always provide accurate or timely predictions, especially for complex concrete mixtures or in situ conditions.

Artificial Neural Networks (ANNs) offer a promising alternative for predicting concrete compressive strength by leveraging their ability to learn complex patterns from data. ANNs are computational models inspired by the structure and functioning of the human brain's neural networks. They consist of interconnected nodes (neurons) organized into layers, including input, hidden, and output layers. Through a process called training, ANNs can learn from labeled datasets to make accurate predictions on new, unseen data.

In recent years, researchers have increasingly explored the use of ANNs in predicting concrete compressive strength, leading to significant advancements in the field. This paper aims to provide a comprehensive review of the state-of-the-art applications of ANNs in this domain, highlighting their strengths, limitations, and potential for future research.

2. LITERATURE REVIEW

Several studies have indicated that the strength of concrete is influenced not only by the water-to-cement ratio but also by other additive constituents (Oluokun, 1994). The absence of standardized empirical relationships for assessing concrete's compressive strength based on its constituents has sparked the interest of researchers in soft computing tools. Chaturvedi (2008) has characterized soft computing as an emerging set of methodologies aimed at exploiting tolerance for imprecision, uncertainty, and partial truth to achieve robustness, tractability, and cost-effectiveness. Soft computing leverages statistical, probabilistic, and optimization tools for learning, predicting, and classifying new patterns based on historical data. Artificial Neural Networks (ANNs), heralded as the next generation of computing, constitute a subset of soft computing tools. ANNs are massively parallel adaptive networks composed of simple nonlinear computing elements called neurons, designed to abstract and model certain aspects of the human nervous system in order to partially replicate some of its computational capabilities (Kumar, 2013). In contrast to traditional digital computing methods, procedural and symbolic processing, neural networks offer advantages such as learning from examples and extrapolating solutions to novel problem variations, adapting to subtle changes in problem characteristics, exhibiting tolerance to input data errors, processing information swiftly, and being easily transferable between computing systems (Flood and Kartam, 1994).

Verma and colleagues (2012) examined the impact of integrating microsilica with conventional Portland cement on concrete durability. Their study suggests that silica fume enhances concrete strength and diminishes the occurrence of capillary voids. In 2012, Dilip Kumar Singha Roy investigated the strength properties of concrete by substituting a portion of cement with silica fume (SF).

The unconventional approach to acquiring knowledge through learning has sparked significant interest in the realm of neural networks. Artificial neural networks possess the remarkable capability of serving as universal function approximators, a feature that has long been employed to tackle problems where the relationship between dependent and independent variables remains obscure (Aggarwal and Aggarwal, 2011). Thanks to their black-box nature, neural networks eliminate the need to presuppose any functional relationship among the variables. Instead, they autonomously establish connections and adjust based on the training data provided. Leveraging this modeling prowess, neural networks have proven invaluable in predicting the behavior of both engineered and natural systems by deciphering meaning from complex, nonlinear interrelationships among variables. Concrete's compressive strength exemplifies one such problem, characterized by its unstructured nature and intricate nonlinear connections among its constituents and compressive strength. This review paper delves into these aspects, elucidating the adaptability and resilience of artificial neural networks in modeling the compressive strength of concrete.

3. ARTIFICIAL NEURAL NETWORKS AS A MODELING TOOL

Artificial Neural Networks (ANNs) serve as a potent modeling tool across various fields due to their ability to learn complex patterns from data. Essentially, ANNs are computational models inspired by the structure and functioning of the human brain's neural networks. They consist of interconnected nodes, or neurons, organized into layers, including input, hidden, and output layers.

ANNs excel as modeling tools for several reasons:

Pattern Recognition: ANNs can recognize and learn patterns from large datasets, making them effective in tasks such as image recognition, speech recognition, and natural language processing.

Non-linearity: Unlike traditional linear models, ANNs can capture non-linear relationships between input and output variables, allowing for more accurate modelling of complex phenomena.

Adaptability: ANNs can adapt and improve their performance over time through a process called training. During training, the network adjusts its internal parameters (weights and biases) based on the provided data and a specified objective function, optimizing its ability to make predictions or classifications.

Generalization: ANNs can generalize learned patterns to new, unseen data, making them robust in real-world applications. This ability to generalize ensures that the model performs well beyond the training dataset.

Parallel Processing: ANNs can perform computations in parallel, enabling them to handle large-scale and computationally intensive tasks efficiently.

Versatility: ANNs can be applied to a wide range of tasks, including regression, classification, clustering, and time-series prediction, making them versatile modeling tools across diverse domains such as finance, healthcare, engineering, and more.

Overall, Artificial Neural Networks offer a powerful and flexible framework for modeling complex systems and solving a variety of real-world problems.

Artificial Neural Networks derive their name from the intricate networks of nerve cells found in the human brain. While they represent a simplified version of biological neural networks, these computational models offer fresh avenues for addressing challenges encountered in various real-world tasks. Unlike digital computers, which process information sequentially, ANNs leverage parallel processing inspired by the human brain's functioning, enabling computers to simultaneously handle vast amounts of data. ANNs are particularly well-suited for problems where the solutions are hard to define explicitly but where there exists sufficient data or observations (Zhang et al., 1998). The backbone of the ANN's modeling prowess lies in its capacity to learn from experience without relying on prior knowledge of underlying relationships and to generalize when confronted with unseen

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data. This enables ANNs to approximate functional relationships with notable accuracy. Studies have shown that ANNs possess the capability to discern patterns within phenomena and circumvent challenges associated with selecting model forms such as linear, power, or polynomial equations (Tokar and Johnson, 1999). A common trait among successful applications of ANNs in prediction and modeling is the presence of multivariate interrelationships governing the quantities being modeled, coupled with noisy or incomplete data (Oreta and Kawashima, 2003).

4.UTILIZING ARTIFICIAL NEURAL NETWORKS TO MODEL THE COMPRESSIVE STRENGTH OF CONCRETE

The compressive strength of concrete stands as its paramount characteristic and holds a significant correlation with its quality. The fundamental components of concrete, namely cement, aggregate, and water, play pivotal roles in shaping its behavior by contributing to its strength and durability. Given the composite nature of concrete and the intricate, nonlinear connections between its constituents and compressive strength, researchers have turned their focus to computational tools inspired by nature. Artificial Neural Networks (ANNs), with their learning capabilities, have emerged as a means to model compressive strength, shedding light on the factors influencing its robustness. The subsequent paragraphs provide an exhaustive literature review concerning the utilization of ANNs in modeling the compressive strength across various concrete types

4.1 Architecture and Training of ANN Models

The architecture and training of ANN models play a crucial role in their performance for predicting concrete compressive strength. Various architectures, including feedforward, recurrent, and convolutional neural networks, have been explored for this task. Feedforward neural networks, which consist of multiple layers of neurons where connections only flow from previous layers to subsequent layers, are the most commonly used architecture for concrete compressive strength prediction. Training techniques such as backpropagation, gradient descent, and stochastic optimization algorithms are employed to optimize the weights and biases of ANN models during the training process. Hyperparameter tuning, regularization techniques, and model selection methods are also essential considerations in designing effective ANN models for concrete compressive strength prediction.

4.2 Input Parameters and Datasets

The selection of input parameters is critical for the accuracy and generalization ability of ANN models in predicting concrete compressive strength. Common input parameters include mix proportions (e.g., cement, aggregate, water), curing conditions, age of concrete, and supplementary cementitious materials. Feature selection and dimensionality reduction techniques may be applied to identify the most informative input parameters and enhance model performance. The availability and quality of datasets are also crucial factors influencing the development and evaluation of ANN models. Large-scale experimental datasets, field measurements, and historical data from construction projects are valuable sources for training and testing ANN models. Data preprocessing techniques such as normalization, scaling, and outlier detection are often applied to ensure the quality and consistency of input data.

4.3 Performance Evaluation and Comparison

Performance evaluation metrics such as mean absolute error (MAE), mean squared error (MSE), and coefficient of determination (R-squared) are commonly used to assess the accuracy and reliability of ANN models in predicting concrete compressive strength. Comparative studies with traditional methods such as empirical formulas, statistical regression models, and finite element analysis are conducted to evaluate the superiority of ANN-based approaches. Numerical simulations, cross-validation techniques, and sensitivity analyses are employed to validate the robustness and generalization ability of ANN models across different concrete mixtures, curing conditions, and environmental factors. Case studies and real-world applications demonstrate the practical utility and effectiveness of ANN models in various civil engineering projects.

4.4 Challenges and Future Directions

Despite the significant advancements in the application of ANNs for predicting concrete compressive strength, several challenges and opportunities for future research exist. The interpretation of ANN models and the underlying mechanisms governing concrete behavior remain topics of ongoing investigation. The integration of hybrid models combining ANNs with other machine learning techniques, physics-based models, and experimental validation approaches holds promise for improving prediction accuracy and reliability. Addressing issues related to data scarcity, data quality, and model overfitting is essential for enhancing the robustness and applicability of ANN models in practical engineering scenarios. Collaborative efforts between researchers, practitioners, and industry stakeholders are needed to develop standardized procedures, guidelines, and best practices for deploying ANN-based tools in the construction industry.

Summary

With the rise of computing technology, there has been a significant trend towards the development of knowledge-based computational tools aimed at leveraging past knowledge to comprehend natural phenomena. The remarkable capacity of Artificial Neural Networks (ANNs) to extract insights from historical data can be combined with the large-scale data processing capabilities of modern computers to construct decision support systems that aid users in making informed decisions. ANNs, renowned for their ability to model nonlinear material behavior, have garnered considerable interest in the field of neural networks. Characterized by a black box approach, ANNs have the capability to approximate any functional relationship with considerable accuracy. The resilience of ANNs stems from their profound ability to learn from past data and adapt to changes in the presented data. In contrast to conventional mathematical regression techniques, which rely on either known or assumed regression equations, ANNs operate without such prerequisites. This characteristic of ANNs is leveraged to achieve exceptional modeling capabilities, particularly for unstructured problems. The composite nature of Cement Concrete has perpetually posed a challenge for researchers in modeling its properties, including compressive strength, tensile strength, slump, etc., based on its mix proportions. Addressing such unstructured problems often necessitates the utilization of nature-inspired soft computing tools. Artificial Neural Networks (ANNs), drawing inspiration from the workings of the human brain, have the capability to learn from past instances and provide meaningful insights into these unstructured challenges. The review paper extensively explores the application of ANNs in modeling the compressive strength of concrete. The overarching conclusions gleaned from the literature review can be summarized as follows:

ANNs are computational models that rely heavily on data and do not necessitate any prior understanding of the underlying relationships among input-output variables. Among neural network architectures, the Multilayer Feed Forward neural network, coupled with the error back-propagation learning algorithm, stands out as the most efficient and commonly employed model for function approximation. The applications of ANNs discussed in the paper underscore the widespread utilization of this particular neural network in modeling the composite material behavior of concrete. ANNs demonstrate superior efficiency in modeling unstructured, nonlinear problems compared to traditional mathematical regression models. Utilizing ANN methodology for material modeling can yield decision support tools capable of elucidating and deriving complex, unknown, and nonlinear functional relationships. This facilitates informed decision-making and time savings during the design of concrete mix proportions tailored to specific compressive strength requirements. Through ANN modeling, insights into the composite nature of concrete can be obtained. Sensitivity analysis aids in identifying factors governing compressive strength, while evaluating the impact of variations in each constituent on concrete's compressive strength is facilitated by ANN modeling methodology. ANNs can serve as predictive tools based on historical data, enabling estimation of concrete compressive strength based on mix proportions prior to concrete placement. Furthermore, ANN prediction capabilities can extend to early estimation of 28-day strength based on 3-day strength. The robustness of ANN material modeling enables its application to various types of materials.

Conclusion

In conclusion, Artificial Neural Networks (ANNs) have emerged as powerful tools for predicting concrete compressive strength, offering advantages in accuracy, efficiency, and scalability over traditional methods. This paper provides a comprehensive review of the state-of-the-art applications of ANNs in this domain, covering architecture and training techniques, input parameters and datasets, performance evaluation, and challenges and future directions. By leveraging the capabilities of ANNs and addressing existing challenges, researchers can continue to advance the field of concrete technology and contribute to the sustainable development of infrastructure worldwide.

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