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Predicting the Mechanical and Durability Properties of Hybrid Green Concrete using Artificial Neural Networks and Weight of Evidence: A Comprehensive Review

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***Abstract* - The construction industry's pursuit of sustainability has intensified the development of green concrete incorporating multiple waste materials as partial cement replacements. However, the complex, non-linear relationships between mixture proportions and performance characteristics of these hybrid systems present significant challenges for traditional empirical modeling. This comprehensive review presents a data-driven framework integrating Weight of Evidence (WoE) and Artificial Neural Networks (ANN) to predict the mechanical and durability properties of hybrid green concrete containing combinations of industrial and agricultural wastes. The paper systematically analyzes how WoE methodology identifies and quantifies the influence of key mixture parameters including replacement types (Rice Husk Ash (RHA), Sugarcane Bagasse Ash (SCBA), Fly Ash, Waste Glass Powder (WGP)), replacement levels, water-binder ratios, and curing conditions on concrete performance. The review demonstrates how these prioritized factors then serve as optimized inputs for ANN models, creating highly accurate predictive systems for compressive strength, tensile strength, permeability, and chemical resistance. By synthesizing findings from extensive experimental studies on binary, ternary, and quaternary cement replacement systems, this review establishes that the WoE-ANN integration achieves prediction accuracies of 92-97% for mechanical properties and 85-90% for durability indicators, significantly outperforming conventional regression models. The framework provides researchers and practitioners with a powerful methodology for optimizing complex hybrid mixtures, accelerating the development of sustainable concrete formulations while ensuring reliable performance. This approach represents a paradigm shift from trial-and-error experimentation to intelligent, data-driven design of next-generation green construction materials.**

Keywords: Green Concrete, Artificial Neural Networks, Weight of Evidence, Mechanical Properties, Durability, Sustainable Construction, Predictive Modeling, Hybrid Concrete.

I. INTRODUCTION

The global cement industry accounts for approximately 8% of worldwide carbon dioxide emissions, creating an urgent need for sustainable alternatives in concrete production [1]. The incorporation of industrial and agricultural waste materials as partial cement replacements represents a promising strategy for reducing the environmental impact of concrete while addressing waste management challenges. Research has demonstrated the viability of individual waste materials such as Fly Ash [8], Rice Husk Ash [6], [18], Sugarcane Bagasse Ash [10], and Waste Glass Powder [2], [14] as supplementary cementitious materials. However, the growing complexity of modern concrete mixtures often involves combinations of these materials, creating hybrid systems with synergistic effects that are difficult to predict using conventional methods.

The behavior of hybrid green concrete involves intricate, non-linear relationships between mixture components and performance characteristics. Traditional empirical approaches and statistical regression models often fail to capture these complex interactions, leading to suboptimal mixture designs and unpredictable performance [4], [7]. This limitation has hampered the widespread adoption of advanced hybrid concrete systems in structural applications, where reliability and predictability are paramount.

Artificial Intelligence (AI) and Machine Learning (ML) techniques offer powerful alternatives for modeling complex material behavior. Among these, Artificial Neural Networks (ANN) have demonstrated exceptional capability in capturing non-linear relationships in construction materials [5], [23]. However, the effectiveness of ANN models depends critically on the selection of appropriate input parameters. The integration of Weight of Evidence (WoE) methodology, adapted from geospatial analysis and risk assessment, provides

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a robust framework for identifying the most influential factors before model development [22], [26].

This comprehensive review presents a systematic framework integrating WoE and ANN methodologies for predicting the mechanical and durability properties of hybrid green concrete. The paper examines: (1) the fundamental principles of WoE and its application in concrete science; (2) the architecture and training of ANN models for property prediction; (3) the synergistic integration of these methods for hybrid concrete optimization; and (4) the validation and practical implementation of the resulting predictive models. By synthesizing insights from recent research advances, this review provides a comprehensive methodology for accelerating the development and implementation of sustainable hybrid concrete systems.

II. HYBRID GREEN CONCRETE: MATERIALS AND MECHANISMS

A. Supplementary Cementitious Materials in Hybrid Systems

The effectiveness of hybrid concrete systems derives from the complementary properties of different waste materials when combined in optimal proportions:

Rice Husk Ash (RHA): characterized by high amorphous silica content (85-95%) and porous microstructure, RHA exhibits strong pozzolanic activity and pore-refinement capabilities. [18], [19] demonstrated that RHA replacement levels of 10-15% significantly enhance concrete strength and durability through secondary hydration reactions.

Sugarcane Bagasse Ash (SCBA): with moderate silica content and favorable particle size distribution, SCBA contributes to both pozzolanic reactions and microfiller effects. Research [6], [10] showed that SCBA can effectively replace 15-20% of cement while improving long-term strength development.

Fly Ash: a well-established pozzolanic material that enhances workability and long-term strength. Chagger et al. [8] documented the performance of Fly Ash in M30 concrete, with optimal replacement levels of 20-30% demonstrating excellent durability characteristics.

Waste Glass Powder (WGP): when ground to sufficient fineness (<75μm), WGP exhibits significant pozzolanic activity while mitigating alkali-silica reaction risks. Investigations by [2] and [14] established optimal replacement levels of 10-20% for maintaining mechanical properties while reducing environmental impact.

B. Synergistic Effects in Hybrid Combinations

The combination of multiple SCMs creates synergistic effects that enhance overall performance beyond what individual materials can achieve:

Binary Systems: Research by [4], [7] on SCBA and WPSA combinations demonstrated that optimal blends (10-15% total replacement) achieved compressive and tensile strengths comparable to conventional concrete, with enhanced durability characteristics.

Ternary Systems: Studies incorporating RHA, WPSA, and cement [19], [21] revealed that carefully balanced ternary systems could achieve replacement levels up to 25% while maintaining or improving mechanical properties through complementary reaction mechanisms.

Quaternary Systems: Advanced mixtures incorporating four or more SCMs represent the frontier of hybrid concrete research, offering the potential for even higher cement replacement levels while maintaining performance standards [13], [17].

The complexity of these interactions necessitates advanced modeling approaches to predict performance accurately and optimize mixture proportions.

III. WEIGHT OF EVIDENCE METHODOLOGY FOR FACTOR IDENTIFICATION

A. Fundamental Principles of WoE

Weight of Evidence is a quantitative method for evaluating the predictive power of different factors regarding a specific outcome. Originally developed for mineral exploration and environmental risk assessment [25], [26], WoE has been adapted for construction materials research to identify the most influential parameters affecting concrete performance.

The WoE approach involves three key steps:

1. **Variable Discretization:** Continuous input variables (e.g., replacement percentage, water-binder ratio) are divided into discrete classes or bins. This discretization enables the analysis of non-linear relationships between factors and outcomes.

2. **Weight Calculation:** For each class of each factor, the weight is calculated using the formula:

$$W_{ij} = \ln\left(\frac{P(F_{ij}|S)}{P(F_{ij}|N)}\right)$$

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Where $P(F_{ij} \mid S)$ is the probability of factor class j given the occurrence of outcome S (e.g., high strength), and $P(F_{ij} \mid N)$ is the probability given non-occurrence.

3. **Contrast Calculation:** The overall contrast C for each factor is computed as:

$$C = W^{+} - W^{-}$$

Where W^+ is the weight for the most favorable class and W^- is the weight for the least favorable class.

B. Application to Hybrid Concrete Systems

In the context of hybrid green concrete, WoE analysis helps identify which mixture parameters most significantly influence target properties:

Factor Selection: Based on extensive experimental literature [4], [7], [8], [19], key factors include:

- Cement content (kg/m³)
- Water-binder ratio
- Replacement types and proportions
- Aggregate characteristics
- Curing conditions and duration
- Chemical admixture dosage

Data Preparation: A comprehensive database is compiled from experimental studies, with each mixture represented as a case with specific factor values and measured outcomes.

WoE Analysis: For each target property (e.g., 28-day compressive strength > 40 MPa), the WoE method calculates weights for each factor class, identifying optimal ranges and threshold values.

C. Integration with Frequency Ratio and Information Value

WoE methodology can be enhanced through integration with related bivariate statistical methods:

Frequency Ratio (FR): FR analysis complements WoE by providing an intuitive measure of the relationship between factor classes and outcomes. The frequency ratio is calculated as:

$$FR = \frac{N_{class} / N_{total}}{S_{class} / S_{total}}$$

Where N_{class} is the number of outcome occurrences in the class, and S_{class} is the total number of cases in the class [26].

Information Value (IV): IV provides a single measure of a factor's overall predictive power, calculated as:

$$IV = \sum_{i=1}^{n} (P(F_i|S) - P(F_i|N)) \times W_i$$

Factors with IV > 0.3 are considered highly predictive and should be prioritized as ANN inputs [22], [25].

IV. ARTIFICIAL NEURAL NETWORKS FOR PROPERTY PREDICTION

A. ANN Architecture for Concrete Modeling

Artificial Neural Networks are computational models inspired by biological neural systems, capable of learning complex non-linear relationships from data. For hybrid concrete prediction, a multi-layer perceptron (MLP) architecture typically proves most effective:

Input Layer: Neurons representing the factors identified through WoE analysis as most influential. Based on comprehensive studies [4], [7], [19], these typically include:

- Cement content
- Water-binder ratio
- Individual replacement percentages (RHA, SCBA, Fly Ash, WGP)
- Total replacement percentage
- Curing time
- Chemical admixture dosage

Hidden Layers: One or more layers of processing neurons that extract features and learn complex relationships. Research by Thakur and Kumar [23] demonstrated that architectures with 1-2 hidden layers containing 5-15 neurons typically provide optimal performance for concrete property prediction.

Output Layer: Neurons representing target properties, which may include:

- Compressive strength at various ages
- Tensile strength
- Flexural strength
- Permeability coefficients
- Chemical resistance indices

B. Network Training and Validation

The development of robust ANN models involves careful training and validation procedures:

Data Partitioning: The compiled database is typically divided into training (70-80%), validation (10-15%), and testing (10-15%) subsets to ensure model generalizability [5], [23].

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Training Algorithms: Backpropagation algorithms, particularly Levenberg-Marquardt optimization, have proven effective for concrete property prediction, efficiently adjusting connection weights to minimize prediction errors [19], [23].

Performance Metrics: Model accuracy is evaluated using multiple metrics:

- Coefficient of determination (R^2)
- Root Mean Square Error (RMSE)
- Mean Absolute Error (MAE)
- Mean Absolute Percentage Error (MAPE)

Studies integrating WoE-preprocessed data typically report R^2 values of 0.92-0.97 for mechanical properties and 0.85-0.90 for durability indicators, significantly outperforming conventional models [4], [7], [23].

V. INTEGRATED WoE-ANN FRAMEWORK FOR HYBRID CONCRETE

The synergistic integration of WoE and ANN methodologies creates a powerful framework for predicting hybrid concrete performance:

A. Framework Architecture

The proposed integrated framework operates through five systematic phases:

Phase 1: Data Compilation

- Collection of experimental data from comprehensive studies on hybrid concrete [2], [4], [6], [7], [8], [14], [18], [19]
- Documentation of mixture proportions, curing conditions, and measured properties
- Quality control and normalization of data for consistency

Phase 2: WoE Analysis

- Discretization of continuous variables into meaningful classes
- Calculation of weights and contrasts for each factor-property relationship
- Identification of optimal ranges and threshold values
- Selection of most influential factors based on Information Value

Phase 3: ANN Model Development

- Architecture design based on WoE-identified factors
- Network training using optimized algorithms
- Validation against independent test data
- Sensitivity analysis to verify factor importance

Phase 4: Model Implementation

- Prediction of properties for new mixture designs
- Optimization of mixture proportions for target performance
- Identification of synergistic combinations
- Validation through limited experimental verification

Phase 5: Continuous Improvement

- Incorporation of new experimental data
- Model refinement and updating
- Expansion to additional property predictions

B. Advantage Over Conventional Methods

The integrated WoE-ANN framework offers significant advantages over traditional approaches:

- **Enhanced Accuracy:** By focusing on the most influential factors identified through WoE, ANN models achieve higher prediction accuracy than models using comprehensive but potentially redundant input sets [23], [26].
- **Interpretability:** The WoE component provides transparent insights into factor-property relationships, addressing the "black box" criticism often leveled against neural networks [5], [22].
- **Efficiency:** The reduction of input dimensionality through WoE preprocessing decreases computational requirements and training time while maintaining prediction quality [19], [25].
- **Robustness:** The framework demonstrates consistent performance across different concrete types and property predictions, making it widely applicable in concrete technology [4], [7].

VI. PREDICTION OF MECHANICAL PROPERTIES

A. Compressive Strength Modeling

Compressive strength represents the most critical mechanical property for structural concrete. The WoE-ANN framework has demonstrated exceptional capability in predicting compressive strength development in hybrid systems:

- **Factor Significance:** WoE analysis of comprehensive experimental data [4], [7], [8], [19] identifies water-binder ratio, total replacement percentage, and curing time as the most influential

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factors, with Information Values typically exceeding 0.4.

- **Model Performance:** ANN models trained on WoE-selected factors achieve R^2 values of 0.94-0.97 for 28-day compressive strength prediction, with MAPE typically below 5%. This represents a significant improvement over traditional regression models, which often achieve R^2 values of 0.75-0.85 for similar predictions [23].
- **Practical Applications:** The models enable accurate prediction of strength development curves, allowing optimization of formwork removal times and structural loading schedules for hybrid concrete structures [13], [19].

B. Tensile and Flexural Strength Prediction

While often correlated with compressive strength, tensile and flexural properties exhibit distinct relationships with mixture parameters:

- **Factor Analysis:** WoE studies reveal that fiber content, aggregate characteristics, and specific SCM types exert stronger influence on tensile properties than on compressive strength [4], [17].
- **Model Architecture:** Separate ANN models dedicated to tensile and flexural prediction, incorporating WoE-identified specialized factors, achieve prediction accuracies of R^2 = 0.91-0.95, substantially outperforming empirical code equations [4], [23].

VII. DURABILITY PROPERTY PREDICTION

A. Permeability and Transport Properties

Durability of concrete is fundamentally governed by its transport properties, which are strongly influenced by SCM combinations:

- **Critical Factors:** WoE analysis identifies particle size distribution of SCMs, total replacement level, and curing conditions as dominant factors affecting permeability, with IV values typically ranging 0.3-0.45 [14], [19].
- **Prediction Models:** ANN models for chloride permeability, water absorption, and gas permeability achieve R^2 values of 0.85-0.90, enabling reliable service life predictions for hybrid concrete in aggressive environments [13], [23].

B. Chemical Resistance

The resistance of hybrid concrete to chemical attacks depends critically on SCM combinations and proportions:

- **Sulfate Attack:** WoE studies identify C3A content, SCM composition, and permeability as key factors. ANN models incorporating these factors successfully predict expansion and strength loss in sulfate environments [8], [19].
- **Acid Resistance:** Models for acid attack incorporate pH sensitivity of SCMs and binder composition factors identified through WoE, achieving good correlation with experimental mass loss data [2], [14].

VIII. VALIDATION AND PRACTICAL IMPLEMENTATION

A. Experimental Validation

The predictive accuracy of WoE-ANN models requires rigorous experimental validation:

- **Independent Testing:** Models are validated against completely independent datasets not used in training or development [4], [7], [23].
- **Long-Term Performance:** Predictions are compared with long-term experimental results exceeding one year, verifying model reliability for service life prediction [13], [19].
- **Full-Scale Verification:** Selected optimal mixtures identified through the framework are cast in full-scale structural elements and monitored for performance validation [13], [22].
- **B. Practical Implementation Guidelines**
- Successful implementation of the WoE-ANN framework requires attention to several practical considerations:
- **Data Quality Assurance:** Implementation of strict protocols for data collection, normalization, and documentation to ensure model reliability [5], [23].
- **Model Updating Procedures:** Establishment of systematic procedures for incorporating new experimental results to continuously improve prediction accuracy [19], [25].
- **User Interface Development:** Creation of intuitive software interfaces that enable practicing engineers to utilize the models without specialized AI expertise [9], [13].

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IX. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Despite the significant advances represented by the WoE-ANN framework, several challenges and opportunities for improvement remain:

- **Data Scarcity for Complex Systems:** Limited experimental data for quaternary and higher hybrid systems constrains model development. Future research should prioritize systematic investigation of these complex mixtures [6], [10].
- **Long-Term Performance Prediction:** Accelerated testing methods correlated with long-term performance data are needed to enhance durability prediction models [13], [19].
- **Multi-Objective Optimization:** Integration of environmental impact assessment with performance prediction would enable truly sustainable mixture optimization [8], [14].
- **Uncertainty Quantification:** Development of methods to quantify and communicate prediction uncertainties would enhance implementation confidence [5], [23].
- **Industry Standardization:** Establishment of standardized protocols for data collection and model validation would facilitate wider adoption across the construction industry [9], [13].

Future research directions should focus on expanding the framework to incorporate additional sustainability metrics, developing real-time monitoring integration, and creating specialized applications for specific exposure conditions and performance requirements.

X. CONCLUSION

This comprehensive review has established the powerful capability of integrating Weight of Evidence and Artificial Neural Networks for predicting the mechanical and durability properties of hybrid green concrete. The WoE methodology provides a robust, transparent approach for identifying the most influential factors affecting concrete performance, while ANN models leverage these insights to achieve unprecedented prediction accuracy for complex hybrid systems.

The integrated framework represents a significant advancement beyond traditional empirical and statistical methods, enabling reliable prediction of synergistic effects in concrete containing multiple waste materials. By achieving prediction accuracies of 92-97% for mechanical properties and 85-90% for durability indicators, the approach provides engineers and researchers with a powerful tool for optimizing sustainable concrete mixtures while ensuring performance reliability.

The systematic application of this framework accelerates the development of advanced hybrid concrete systems, facilitating higher utilization of industrial and agricultural wastes in construction. This contributes substantially to the twin goals of reducing the environmental impact of concrete production and addressing waste management challenges.

As the construction industry continues its transition toward circular economy principles and sustainable development goals, data-driven approaches like the WoE-ANN framework will play an increasingly crucial role in balancing performance requirements with environmental responsibility. The continued refinement and expansion of these methodologies will support the development of next-generation construction materials that meet the dual imperatives of structural excellence and ecological stewardship.

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