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Machine Learning–Based Concrete Quality Prediction for Safe and Durable Infrastructure

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Abstract

Concrete remains the backbone of modern infrastructure, where structural safety, durability, and longevity are critical for societal resilience. Traditional quality assessment methods, including destructive and empirical testing, often fail to provide timely and accurate predictions of concrete performance under variable environmental conditions. Machine learning (ML) has emerged as a transformative tool, enabling data-driven prediction of concrete mechanical properties, durability, and long-term behavior. By analyzing complex relationships among material composition, curing conditions, and environmental exposure, ML models offer enhanced predictive accuracy, real-time monitoring capabilities, and optimization of mix designs. Advanced techniques such as ensemble learning, deep neural networks, and hybrid approaches facilitate multi-parameter evaluation, while feature selection and dimensionality reduction improve model efficiency and interpretability. Integration with sensor-based structural health monitoring systems further enhances infrastructure reliability and proactive maintenance strategies. This chapter presents a comprehensive overview of ML applications in concrete quality prediction, highlights critical research gaps, and outlines future directions for sustainable and durable infrastructure development. The findings demonstrate that predictive modeling using machine learning not only improves concrete performance evaluation but also supports climate-resilient and resource-efficient construction practices.

Keywords: Machine Learning, Concrete Quality Prediction, Durability, Structural Health Monitoring, Data-Driven Modeling, Sustainable Infrastructure.

Introduction

Concrete remains the primary construction material for modern infrastructure due to its versatility, strength, and cost-effectiveness [1]. Its performance under load, exposure, and long-term service conditions determines the safety, durability, and resilience of structures such as bridges, high-rise buildings, tunnels, and dams [2]. Structural failure caused by inadequate concrete quality has historically resulted in significant economic loss and endangerment of human life [3]. The assessment of concrete quality has traditionally relied on destructive testing methods, including compressive and flexural strength evaluation, or non-destructive techniques such as ultrasonic pulse velocity and rebound hammer tests. While these methods provide useful benchmarks for material performance, they are limited by time, labor intensity, and inability to capture complex interactions between mix constituents, environmental conditions, and curing processes [4]. Variations in aggregate properties, water-cement ratio, and admixture types introduce additional complexities, making conventional approaches insufficient for real-time predictive assessment. The growing need for rapid, accurate, and cost-efficient quality evaluation has led to the adoption of data-driven strategies capable of integrating multiple influencing factors simultaneously. The ability to predict concrete performance at early stages, during curing, or over the lifespan of a structure is critical for minimizing maintenance costs, optimizing resource usage, and ensuring long-term structural safety [5].

The introduction of machine learning (ML) into civil engineering has provided a paradigm shift from empirical evaluation methods toward intelligent predictive modeling [6]. Machine learning algorithms can uncover nonlinear and high-dimensional relationships among input variables, enabling accurate forecasting of mechanical properties such as compressive and tensile strength, flexural performance, shrinkage, and durability indicators [7]. Datasets collected from historical experiments, real-world construction projects, and sensor networks serve as the foundation for training predictive models that account for variations in environmental exposure, curing conditions, and material composition [8]. Regression-based approaches, including linear and polynomial regression, offer initial predictive capabilities but often fail to capture complex interactions between multiple features. Ensemble methods, including Random Forest and Gradient Boosting, alongside deep learning architectures such as artificial neural networks, enable superior predictive performance while accommodating large and heterogeneous datasets [9]. Hybrid models that integrate optimization algorithms, such as particle swarm optimization, further enhance prediction accuracy and allow simultaneous optimization of multiple concrete performance metrics. The integration of ML into quality assessment provides the capability to reduce dependency on time-consuming experimental testing while supporting proactive and data-driven decision-making in infrastructure design and management [10].