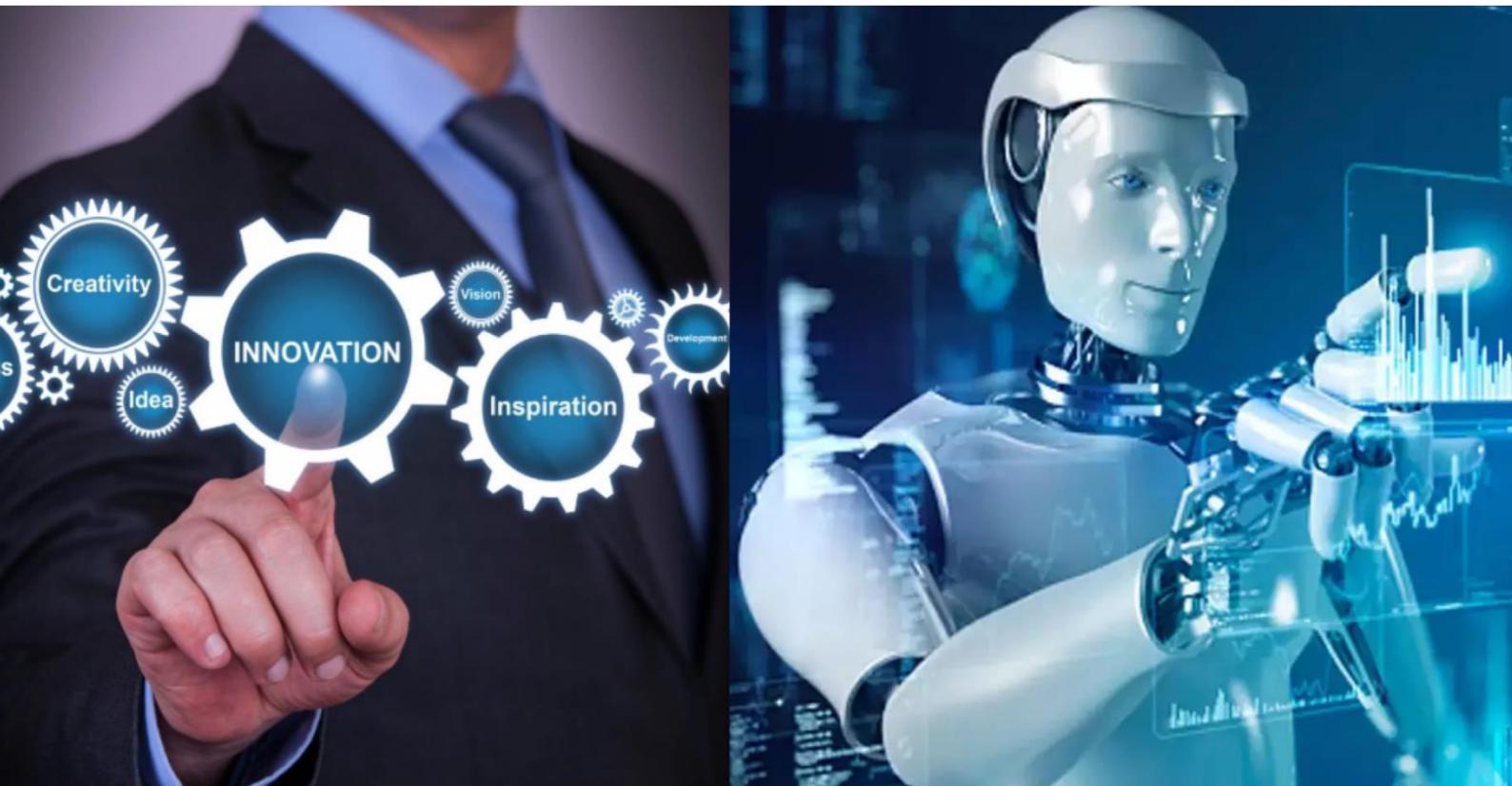




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Prediction of Carbonation Depth using Machine Learning Concept

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ABSTRACT: Carbonation-induced deterioration remains a critical durability issue in reinforced concrete structures, as it directly affects the long-term performance and safety of built infrastructure. Over the past few decades, extensive research has been conducted to understand carbonation mechanisms and to develop models for predicting carbonation depth. Traditional approaches, largely based on empirical relationships and diffusion theory, have provided useful insights but often show limited accuracy when applied to diverse materials, exposure conditions, and service environments. As a result, there has been growing interest in data-driven techniques that can better represent the complex and nonlinear nature of the carbonation process.

This literature review critically examines recent studies on carbonation depth prediction, with particular emphasis on the emerging application of machine learning methods. The review synthesizes findings related to commonly used input parameters, experimental datasets, and modeling techniques, including artificial neural networks, support vector machines, and ensemble learning approaches. Comparisons between conventional prediction models and machine learning-based frameworks are discussed to highlight their respective strengths and limitations. Overall, the reviewed studies indicate that machine learning models consistently demonstrate improved predictive capability and adaptability. The paper concludes by identifying existing research gaps and outlining future directions for developing robust, transparent, and practical carbonation prediction models for durability-based concrete design.

KEYWORDS: Carbonation Process, Machine Learning, concrete.

I. INTRODUCTION

Carbonation is widely recognized as a key factor affecting the long-term durability of reinforced concrete structures. As carbon dioxide gradually penetrates the concrete cover, it reacts with hydration products and lowers the alkalinity of the pore solution, which can eventually lead to corrosion of embedded steel reinforcement. Accurately estimating carbonation depth is therefore essential for evaluating service life and ensuring the safety of concrete structures. Traditionally, researchers have relied on empirical relationships and diffusion-based models to predict carbonation progress. Although these models are simple and convenient, they often struggle to represent the complex influence of material composition, curing conditions, and environmental variability observed in real structures.

With the increasing availability of experimental data and advances in computational tools, machine learning has emerged as an effective alternative for carbonation depth prediction. Unlike conventional approaches, machine learning models learn directly from data and are capable of capturing nonlinear interactions among multiple influencing parameters. Studies applying techniques such as artificial neural networks, support vector machines, and ensemble-based algorithms have reported noticeable improvements in prediction accuracy compared to traditional models. Moreover, these data-driven methods provide additional insights by identifying the most influential factors governing carbonation, such as exposure duration, water-cement ratio, compressive strength, and relative humidity. As a result, machine learning-based approaches are increasingly viewed as practical and reliable tools for durability assessment and performance-based concrete design.

II. LITERATURE SURVEY

D.P.P. Meddage, Isuri Fonseka et al “An explainable machine learning approach to predict the compressive strength of graphene oxide-based concrete”

Earlier research on carbonation depth in concrete has largely been based on empirical and semi-empirical models developed from Fick's diffusion theory. These models usually consider a limited set of parameters, such as exposure time, water-cement ratio, and compressive strength. Although they are simple to apply, their predictive capability often decreases when concrete is exposed to varying environmental conditions or when modern mix designs are used. This is mainly because such models assume linear relationships and uniform material behavior, which rarely represent real-world concrete performance accurately.

In response to these limitations, recent studies have increasingly adopted machine learning techniques to predict carbonation depth. Methods including artificial neural networks, support vector machines, random forest, and gradient boosting have shown improved accuracy by capturing complex and nonlinear interactions among material properties and environmental factors. Comparative investigations generally indicate that ensemble-based models outperform both traditional regression approaches and single ML algorithms, particularly when large and diverse datasets are involved. Building on these findings, the present study demonstrates that advanced ensemble methods, especially extreme gradient boosting, provide more reliable and consistent predictions of carbonation depth. In addition to improved accuracy, the study highlights the importance of model interpretability by identifying key governing parameters such as exposure duration, water-cement ratio, and compressive strength. This combined focus on prediction and understanding makes machine learning-based approaches more practical for durability assessment and service-life prediction of concrete structures.

Y. Asghari, S.E. Mohammadyan-Yasouj et. al. “3D Printing and Implementation of Engineered Cementitious Composites - A Review”

Recent advances in 3D concrete printing have highlighted its potential to transform construction practices by enabling automated, formwork-free fabrication of structural elements. Despite these advantages, the practical application of 3D printed concrete remains constrained by low tensile capacity, brittle behavior, and difficulties associated with conventional steel reinforcement. To overcome these limitations, researchers have increasingly explored Engineered Cementitious Composites (ECC) as an alternative material due to their inherent ductility, strain-hardening behavior, and fine crack control. ECC's unique composition, characterized by the absence of coarse aggregates and the presence of short fibers, makes it particularly suitable for extrusion-based printing processes while also offering enhanced structural reliability without traditional reinforcement.

Existing studies on 3D printed ECC primarily focus on optimizing mix design and printing parameters to achieve adequate pumpability, extrudability, and buildability without compromising mechanical performance. Findings consistently show that fiber type, volume fraction, and orientation strongly influence the tensile behavior and anisotropy of printed elements. In many cases, printed ECC exhibits improved tensile strength and strain capacity along the printing direction due to fiber alignment induced during extrusion, although weaker interlayer bonding remains a concern. While mechanical performance has been extensively examined, research on long-term durability and environmental resistance of printed ECC is still limited. Preliminary evidence suggests that the tight crack widths and self-healing capability of ECC may offset some durability concerns related to layered construction, but further investigation is required to validate this behavior under realistic service conditions.

Yaser Gamil et al. “Machine learning in concrete technology: A review of current researches, trends, and applications”

Recent studies have shown a growing interest in applying machine learning techniques to concrete technology, particularly for predicting mechanical and durability-related properties. Traditional empirical and regression-based models often struggle to capture the complex and nonlinear relationships between mix composition, curing conditions, and environmental exposure. To address these challenges, researchers have increasingly adopted machine learning algorithms such as artificial neural networks, support vector machines, decision trees, and ensemble models. These approaches have demonstrated improved accuracy and flexibility across a wide range of applications, including strength prediction, durability assessment, and service-life estimation. However, despite their promising performance, many studies highlight the need for larger and more diverse datasets, improved model

interpretability, and better integration of domain knowledge to ensure reliable and practical implementation in real-world concrete design.

Tzu-Han Wen, Terry Y.P. Yuen et.al. "A case study on early-age cracking of high-strength concrete construction by coupled thermal-mechanical analysis and field monitoring"

Early-age cracking remains a common concern in high-strength concrete, particularly in large structural elements where heat generation, restraint conditions, and rapid strength development interact unfavorably. Previous studies have shown that such cracking is mainly driven by thermal stresses, autogenous shrinkage, and inadequate curing practices, which often develop within the first few days after casting. Although high-strength concrete offers superior mechanical performance, its low water–binder ratio and dense microstructure make it more susceptible to early-age cracking compared to conventional concrete. Case-based investigations highlight that a lack of temperature control, delayed curing, and construction-related constraints can significantly increase crack risk. These findings emphasize the importance of proper mix design, early-age monitoring, and site-specific mitigation measures to improve crack resistance and long-term durability.

Peyman Sadeghi, Amirhossein Karimi et.al. "A comprehensive evaluation of damping, vibration, and dynamic modulus in reclaimed asphalt pavement: The role of rejuvenators, polymer, temperature, and aging"

The dynamic behavior of concrete structures, particularly in terms of vibration response and damping characteristics, has received increasing attention in recent years due to growing concerns over serviceability, comfort, and structural safety. Previous studies have shown that factors such as material composition, structural configuration, loading frequency, and boundary conditions significantly influence vibration performance. While conventional analytical and experimental approaches have provided valuable insights, they often struggle to represent real structural behavior under complex dynamic loading. Recent case-based investigations highlight the importance of comprehensive evaluation methods that combine experimental observations with numerical analysis to better capture damping mechanisms and dynamic response. These studies underline the need for improved modeling strategies and material optimization to enhance vibration control and overall structural performance.

Jilin Wang, Songpo Huang et.al. " A comprehensive study on the impact of direct electric curing on the performance of molybdenum tailings in cementitious materials"

In recent years, direct electric curing has attracted attention as an alternative method for accelerating early-age strength development in concrete, especially under cold or unfavorable curing conditions. Previous studies indicate that the application of electric current enhances hydration by generating internal heat, leading to faster strength gain and reduced setting time. Compared to conventional curing methods, electric curing offers better control over temperature distribution within the concrete mass, which can help limit thermal gradients and associated cracking. However, research also points out that excessive current intensity or prolonged exposure may adversely affect microstructure and long-term durability. These findings highlight the need for optimized electrical parameters to balance early-age performance with long-term structural integrity.

Pei Zhao, Shenghua Shi et.al."Analysis of strength size effect and failure mechanism of asphalt mixtures based on discrete element method"

The influence of specimen size on the strength and failure behavior of concrete has been widely recognized in the literature, particularly for high-strength and quasi-brittle materials. Earlier studies have shown that as structural size increases, nominal strength tends to decrease due to stress redistribution, microcrack localization, and fracture process zone development. While classical strength-based theories provide simplified explanations, they often fail to fully capture the transition from distributed cracking to localized failure observed in larger specimens. Recent experimental and analytical investigations emphasize the role of fracture mechanics in explaining size-dependent behavior, highlighting how crack initiation, propagation, and energy dissipation govern failure mechanisms. These findings underline the importance of considering size effects in both experimental interpretation and structural design to ensure safe and reliable performance.

N. Subhash Chandran, P. Manikandan et.al. " Application of Taguchi approach to optimize the waste glass powder in developing eco-friendly ternary blended aluminosilicate matrix"

Recent studies have increasingly focused on the use of waste-derived aluminosilicate materials to develop eco-friendly geopolymers as alternatives to ordinary Portland cement. Among these, waste glass powder (WGP) has attracted attention due to its high amorphous silica content and widespread availability. However, optimizing its use in multi-component geopolymers remains a challenge because of the complex interactions between binder constituents and activator parameters. To address this, Chandran et al. employed the Taguchi optimization approach to systematically evaluate the influence of WGP, fly ash, and alkali concentration on the workability and compressive strength of a ternary GGBS-based geopolymers. Their findings demonstrated that WGP plays a dominant role in governing both fresh and hardened properties, with an optimum replacement level around 30 % yielding enhanced strength and a dense microstructure, as confirmed through SEM-EDS analysis.

Yuan Gao, Yuhui Zhou et.al. "A probabilistic investigation of long-term field performance of warm mix asphalt pavements"

Recent field- and laboratory-based studies consistently show that warm mix asphalt (WMA) can deliver performance comparable to conventional hot mix asphalt (HMA) while offering clear environmental benefits. Earlier research largely focused on laboratory indicators such as rutting resistance, moisture susceptibility, and fatigue behavior, often reporting mixed outcomes depending on the WMA technology and additive used. While some studies observed improved rutting resistance or reduced moisture damage with foamed or chemical WMA, others reported slightly higher deformation or cracking under certain mix designs. A key limitation across much of this literature is its reliance on short-term testing or isolated field trials, which do not fully capture the combined effects of traffic loading, climate, construction quality, and aging on long-term pavement behavior.

Farzaneh Elyasigorji, Habib Tabatabai et.al. " Assessment of select direct and indirect pozzolanic reactivity test outcomes with robust regression and ranking analysis"

Recent studies emphasize that relying on a single test method to evaluate pozzolanic reactivity often leads to incomplete or even misleading conclusions, particularly when assessing emerging or waste-derived supplementary cementitious materials. Traditional approaches such as the strength activity index and Frattini test remain widely used, yet they are time-consuming and sensitive to material variability. As a result, several researchers have explored alternative direct and indirect techniques—including thermogravimetric analysis, calorimetry, electrical conductivity, pH variation, and ultrasonic pulse velocity—to capture different aspects of pozzolanic behavior. These methods highlight the strong influence of particle size, amorphous silica content, and curing age on lime consumption and strength development, confirming that reactivity is governed by both chemical and physical characteristics rather than composition alone.

More recent literature has shifted toward comparative and statistical evaluations of test methods to identify faster and more reliable indicators of pozzolanic activity. Studies employing correlation and ranking analyses demonstrate that certain rapid techniques, such as electrical conductivity and calorimetry, show strong agreement with conventional long-term tests, suggesting their potential as practical alternatives for early screening. Robust statistical approaches further reveal that some commonly used methods may be disproportionately affected by data outliers, underscoring the need for multi-method assessment frameworks. Overall, current research supports the use of integrated testing strategies to improve confidence in pozzolanic reactivity assessment, particularly when incorporating unconventional or recycled materials into sustainable concrete systems.

Weiying Liang, Zheng Chen et.al. "A three-phase model based on boundary element method for simulation of chloride diffusion in concrete"

Understanding the mechanical behavior of concrete and similar composite materials requires models that can realistically represent the interaction between aggregates, mortar matrix, and interfacial transition zones. Earlier numerical approaches often relied on simplified two-phase assumptions, which limited their ability to capture crack initiation and propagation accurately. In response, recent studies have introduced three-phase modeling frameworks that explicitly consider the role of the interfacial zone, leading to more realistic predictions of stress distribution and failure mechanisms. Boundary element-based formulations, in particular, have shown promise due to their efficiency in handling complex boundaries and fracture processes. These developments highlight the

growing shift toward more physically representative modeling techniques to better understand damage evolution in heterogeneous cementitious materials.

Milana Cimesa , Mohamed A. Moustafa et.al. "Axial behavior of UHPC columns with new emerging mixtures and varying confinement"

Ultra-high-performance concrete (UHPC) has gained increasing attention for column applications due to its exceptional compressive strength, dense microstructure, and enhanced confinement efficiency. Previous studies have shown that UHPC columns exhibit significantly improved axial load capacity and deformation resistance compared to normal-strength and high-strength concrete columns, even with reduced cross-sectional dimensions. Recent experimental investigations highlight the strong influence of confinement type, reinforcement detailing, and loading eccentricity on failure mode and ductility. While UHPC columns generally demonstrate a more stable post-peak response and delayed crushing, the use of emerging reinforcement systems introduces new interaction mechanisms that are not yet fully understood. These findings underline the need for continued experimental and analytical research to establish reliable design guidelines for UHPC column systems.

Mohammad Froozanfar, Saber Moradi et.al. "Cyclic response sensitivity of coupled composite plate shear walls/ concrete filled (CC-PSWs/CF)"

The cyclic behavior of coupled composite structural components has received growing attention due to their increasing use in seismic-resistant design. Previous studies indicate that the interaction between different materials and connection details plays a critical role in governing stiffness degradation, energy dissipation, and overall cyclic stability. Experimental and numerical investigations have shown that variations in geometry, loading protocol, and material properties can significantly influence hysteretic response and failure progression. While coupled composite systems often demonstrate improved strength and ductility compared to conventional configurations, their cyclic performance remains sensitive to damage accumulation and interface behavior. These observations highlight the need for careful detailing and realistic cyclic evaluation to ensure reliable seismic performance.

Mesfer M. Al-Zahrani et.al. "Durability of concrete-embedded GFRP bars after 20 years of tidal zone exposure: Correlation with accelerated aging tests"

The long-term durability of glass fiber-reinforced polymer (GFRP) bars embedded in concrete has been widely investigated as an alternative to conventional steel reinforcement, particularly for marine and chloride-rich environments. Field studies have generally shown that GFRP bars retain a substantial portion of their mechanical properties even after prolonged exposure, with most degradation confined to the surface layers rather than the bar core. However, laboratory-based accelerated aging tests often predict more severe deterioration than that observed in real structures, raising concerns about their direct applicability to service-life predictions. Recent research has therefore emphasized the importance of correlating accelerated conditioning results with long-term field performance to better represent actual degradation mechanisms and improve durability assessment models for GFRP-reinforced concrete systems.

III. OBJECTIVE

- To collect and compile a comprehensive dataset of carbonation depth in concrete under different conditions.
- To develop and train machine learning models (ANN, Random Forest, XGBoost, etc.) for predicting carbonation depth.
- To identify the most influential parameters (e.g., w/c ratio, SCM content, curing conditions, exposure environment).
- To validate and compare ML predictions against traditional empirical models.
- To propose a practical ML-based prediction tool for durability design of concrete structures.

IV. CONCLUSION

The literature indicates that traditional models for predicting carbonation depth, while conceptually important, often fail to account for the complex and nonlinear nature of carbonation in concrete. Recent studies demonstrate that machine learning techniques provide improved prediction accuracy by effectively capturing interactions among material, environmental, and exposure parameters. However, challenges such as limited data availability, lack of model

transparency, and issues with generalization remain. Overall, the review highlights the strong potential of machine learning-based approaches for reliable carbonation depth prediction and emphasizes the need for hybrid, explainable, and standardized modeling frameworks in future research.

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