



# A Review of Machine Learning Applications in Performance Prediction and Intelligent Optimization Design of Recycled Concrete

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**ABSTRACT:** Recycled concrete is a promising route for construction-waste utilization and low-carbon civil engineering, but its performance is difficult to predict because recycled aggregates introduce variable old mortar, water absorption, gradation and interfacial properties. This review summarizes recent machine learning applications in recycled concrete performance prediction and intelligent mix design, with emphasis on workability, mechanical properties, durability and multi-objective optimization. Models such as random forest, support vector machine, XGBoost, LightGBM, artificial neural networks and deep learning can capture nonlinear relationships between material parameters and target properties more effectively than conventional empirical approaches. Their use also enables data-driven optimization of strength, durability, cost and carbon emissions. However, reliable implementation remains limited by heterogeneous databases, incomplete feature descriptions, weak extrapolation ability and insufficient interpretability. Future progress requires standardized datasets, mechanism-informed features, interpretable modelling and independent experimental validation.

**KEYWORDS:** recycled concrete; machine learning; performance prediction; mix design; durability.

## I. INTRODUCTION

On 22 September 2020, China explicitly proposed the goals of achieving carbon peaking by 2030 and carbon neutrality by 2060. From the perspective of building materials, the output of solid waste has increased with large-scale demolition and renovation in the construction sector. Studies have shown that the comprehensive utilization of 1 t of construction waste can reduce carbon dioxide emissions by approximately 0.698 t. Concrete is also one of the largest sources of carbon emissions in construction materials, and its production accounts for about 8% of global carbon dioxide emissions [1].

Recycled concrete [2] is a green material produced by processing, crushing and grading waste concrete blocks into recycled aggregates, which are then mixed according to a designed proportion and gradation to replace part of the natural aggregate in concrete. The promotion and application of recycled concrete is an important measure for addressing the increasing scarcity of natural aggregates and the environmental pollution caused by construction waste. It is therefore significant for reducing ecological pressure. As early as 1946, the former Soviet scholar Gluzhge [3] investigated the feasibility of producing recycled aggregates from waste concrete. Since the mid-twentieth century, Japan, the United States and several European countries have successively carried out research and development on recycled concrete, with early studies focusing mainly on recycled aggregates and the mechanical properties of recycled concrete [4-11]. Recycled concrete can exhibit structural performance similar to that of ordinary concrete. However, because recycled aggregates have complex sources, recycled concrete usually shows greater variability and poorer durability, chloride resistance and carbonation resistance than ordinary concrete [12]. Existing studies indicate that these disadvantages can be improved by adjusting aggregate gradation, incorporating admixtures or adding fibres.

Traditional experimental design methods are often limited to a small number of influencing variables and cannot reasonably or accurately evaluate the strength development of recycled concrete in a comprehensive manner [13]. Their applicability and reliability usually require repeated trial mixing, which inevitably consumes materials and time [14]. With the rapid development of artificial intelligence, machine learning has shown broad application potential in engineering materials as an effective tool for handling large-scale and high-dimensional nonlinear data [15]. By making full use of historical experimental data, machine learning can identify complex mappings between inputs and outputs and construct accurate and stable prediction models. Owing to its strong pattern recognition and nonlinear fitting capabilities, machine learning can improve experimental efficiency and reduce experimental costs, and has been widely applied to the prediction of concrete strength [16]. At present, researchers are increasingly using machine learning to predict the properties of recycled concrete. These studies show that machine learning improves the accuracy of recycled concrete performance prediction and provides support for its wider application [17-19].

### MACHINE LEARNING ALGORITHMS

The development of machine learning entered its early exploratory stage in the 1940s and can be traced back to research on artificial neural networks. In 1943, Warren McCulloch and Walter Pitts proposed a hierarchical neural network model [20], which established a theoretical computational model for neural networks and laid the foundation for the development of machine learning. In 1950, Alan Turing proposed the well-known Turing test, making artificial intelligence an important research topic in computer science. In 1959, A. M. Samuel of IBM developed a checkers program with learning ability, which provided an early demonstration of machine learning capability. From the 1980s to the 1990s, machine learning entered a period of revival and development. The first International Machine Learning Workshop was held at Carnegie Mellon University in 1980, marking the rise of machine learning research worldwide [21]. During this period, new methods such as support vector machines were proposed. The development of statistical learning theory made machine learning methods more robust, while improvements in computational power promoted their applications. After the twenty-first century, machine learning entered a period of rapid expansion. In 2006, Geoffrey Hinton and Ruslan Salakhutdinov published a paper [22] proposing a deep learning model. The main idea was that artificial neural networks with multiple hidden layers have strong feature learning capability and that layer-wise initialization can overcome training difficulty and enable global network optimization. This model opened a new era of deep neural network-based machine learning. In 2012, Hinton's research team won the ImageNet competition, one of the most influential competitions in computer vision, using a deep learning model. This marked another important stage in the development of deep learning. The basic workflow of applying machine learning to problem analysis is shown in Figure 1 [23].

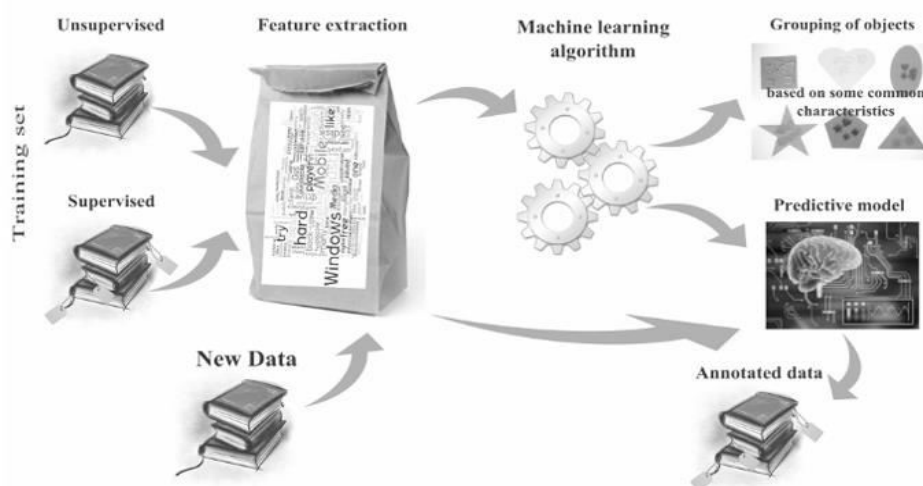


Fig. 1. Typical workflow of machine learning

### 1.1 Random Forest

Random forest classification (RFC) is an ensemble classification model composed of many decision tree classifiers  $\{h(X, \Theta_k), k = 1, \dots\}$ , in which the parameter sets  $\{\Theta_k\}$  are independent and identically distributed random vectors. For a given independent variable  $X$ , each decision tree classifier casts one vote to select the optimal

classification result. The basic idea of RFC is as follows. First, bootstrap sampling is used to draw  $k$  samples from the original training set, and each sample has the same size as the original training set. Second,  $k$  decision tree models are built from the  $k$  samples to obtain  $k$  classification results. Finally, the final class of each record is determined by voting among the  $k$  results, as shown in Figure 2 [24].

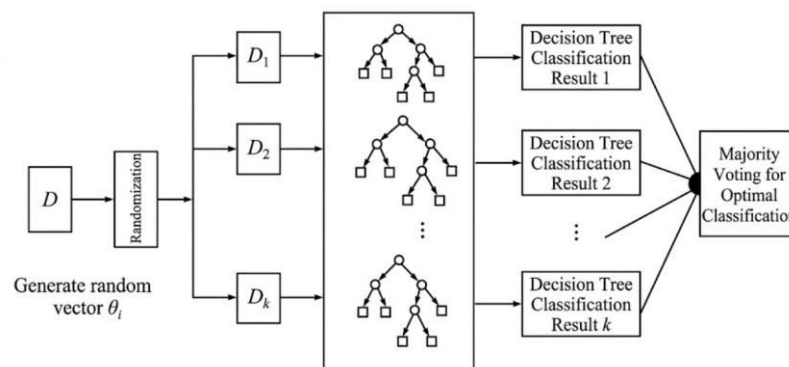


Fig. 2. Schematic diagram of RFC

In addition to random forest, support vector machine, gradient boosting tree, XGBoost, LightGBM, artificial neural network, deep learning, genetic algorithm and automated machine learning are also commonly used in recycled concrete performance prediction. These algorithms differ in their data requirements, nonlinear fitting ability, parameter sensitivity, training efficiency and interpretability. Therefore, the model should be selected according to the prediction target and the size of the database.

### 1.2 Support Vector Machine

Support vector regression (SVR) maps low-dimensional input variables into a high-dimensional feature space through kernel functions and constructs a regression function based on the principle of structural risk minimization. For recycled concrete datasets with limited sample size and nonlinear relationships, SVR has good small-sample learning and generalization capability. Its limitations are that the kernel function, penalty coefficient and insensitive loss parameter strongly affect prediction results. Parameter optimization also increases computational cost, and the model has limited interpretability.

### 1.3 Gradient Boosting, XGBoost and LightGBM

Gradient boosting models improve the fitting ability for complex nonlinear relationships by sequentially building weak learners and correcting the residuals from the previous iteration. XGBoost introduces regularization into the objective function and improves model stability through column sampling, pruning and parallel computing. LightGBM uses histogram-based splitting and leaf-wise growth, making it suitable for larger datasets. In recent years, gradient boosting models have been widely used to predict compressive strength, elastic modulus, slump, carbonation depth and chloride penetration resistance of recycled concrete, and they usually show high prediction accuracy [25]. However, these models have many parameters. If the training set does not cover the relevant variable range, overfitting or unreliable extrapolation may still occur.

### 1.4 Artificial Neural Networks and Deep Learning

Artificial neural networks establish complex mappings through weighted connections among the input layer, hidden layers and output layer, and they are among the earliest methods used for concrete material property prediction. Back-propagation neural networks can fit nonlinear functions, but they are sensitive to initial weights, learning rate and local minima. Deep learning models improve feature representation by increasing network depth and are suitable for cases with high-dimensional variables or large databases. For recycled concrete, neural networks can simultaneously account for multiple coupled factors, including water-to-binder ratio, recycled aggregate replacement ratio, aggregate water absorption, curing age, mineral admixtures and chemical admixtures. Nevertheless, their training requires large and high-quality datasets, and their internal mechanisms are difficult to interpret.

### 1.5 Intelligent Optimization Algorithms and AutoML

Genetic algorithms, particle swarm optimization, grey wolf optimization, Bayesian optimization and NSGA-II are often coupled with machine learning models. On the one hand, these algorithms can be used for hyperparameter optimization to improve prediction accuracy. On the other hand, trained prediction models can serve as surrogate models for optimizing mix proportions across multiple objectives, including strength, cost, carbon emissions, durability and material consumption [26,33,34]. AutoML automates feature processing, model selection and parameter tuning, reducing the difficulty of model construction. However, the results still need to be examined using material mechanisms to avoid mix designs that perform well statistically but violate engineering common sense.

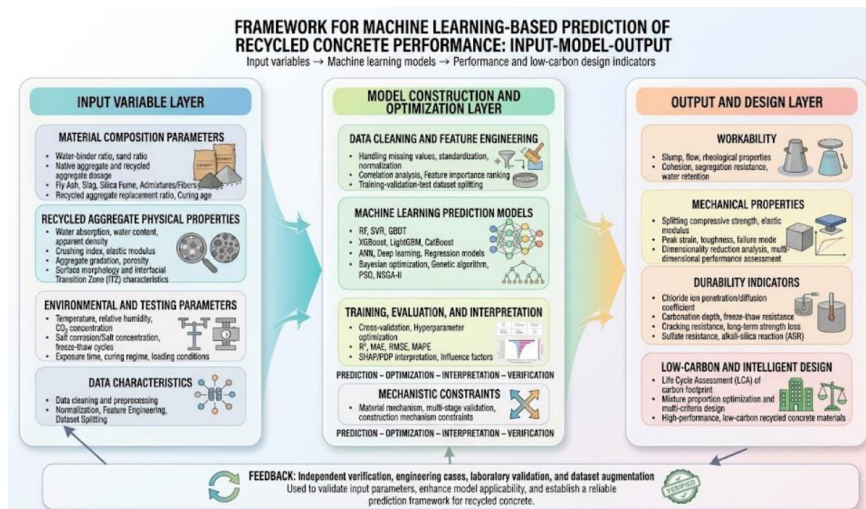


Fig. 3. Input-model-output framework for machine learning-based performance prediction of recycled concrete

## II. RESEARCH STATUS OF MACHINE LEARNING IN RECYCLED CONCRETE PERFORMANCE PREDICTION AND DESIGN

As shown in Figure 3, recycled concrete performance prediction usually takes material composition, recycled aggregate properties and service environment parameters as inputs. Models such as RF, SVR, XGBoost and ANN are then used to establish nonlinear mappings and output key design indicators related to workability, mechanical properties, durability and low-carbon mix proportion design. This framework shows that the role of machine learning in recycled concrete is not limited to single strength prediction, but can be extended to multi-performance evaluation and intelligent design.

### 2.1 Machine Learning-Based Studies on the Workability of Recycled Concrete

The workability of recycled concrete mainly includes slump, spread, flowability, cohesiveness and water retention, which directly affect transportation, casting and forming quality. Compared with ordinary concrete, recycled aggregate has a rougher surface, higher porosity and higher water absorption. Attached old mortar also changes the rheological behaviour of the fresh mixture. Therefore, water-to-binder ratio, superplasticizer dosage, recycled aggregate replacement ratio, aggregate moisture condition and fine aggregate proportion interact in a more complex manner. It is difficult to predict fresh properties reliably using only empirical mix proportioning or single-factor tests.

Existing studies usually use water-to-binder ratio, cement content, natural aggregate content, recycled aggregate content, recycled aggregate water absorption, maximum aggregate size, mineral admixtures, fibre or rubber particle content and chemical admixture dosage as input variables. Slump or flowability is then used as the output variable to establish prediction models such as RF, SVR, XGBoost and ANN [27]. The results show that ensemble learning models have strong capability for capturing nonlinear features and often outperform traditional regression models under small-sample and multivariable conditions. Feature importance analyses further indicate that water-to-binder ratio, admixture dosage, recycled aggregate replacement ratio and aggregate water absorption are often key factors affecting workability [28].

It should be noted that workability data are strongly affected by testing methods, mixing time, aggregate pre-wetting state and environmental temperature and humidity. Directly combining data from different studies may therefore introduce systematic bias. Future research should strengthen the standardization of fresh-property databases, clearly record the moisture condition of recycled aggregates and the type of admixture, and incorporate physical constraints or rheological parameters into machine learning models to improve applicability under practical construction conditions.

### 2.2 Machine Learning-Based Studies on the Mechanical Properties of Recycled Concrete

Compressive strength is one of the most important mechanical properties of recycled concrete. It is affected by many factors, including cement grade, aggregate replacement ratio, water-to-cement ratio, aggregate quality, admixtures, construction conditions, curing temperature and humidity. These influencing factors are high-dimensional and complex. Ordinary linear or nonlinear regression analysis is often unable to reveal the mapping between strength and feature variables accurately. Therefore, robust machine learning models are needed for analysis and prediction.

In civil engineering, many researchers have applied machine learning to the prediction of concrete material properties. BP neural networks are among the earliest and most widely studied algorithms. Liao Xiaohui [29] established a prediction model for the compressive strength of recycled concrete based on a BP network, and the predicted values were generally consistent with the measured results. Golafshani and Behnood [30] used four soft computing methods to predict the elastic modulus of recycled concrete, and the results showed that all proposed models could successfully predict elastic modulus and fit the experimental data well. In recent years, Yao Xiaojun et al. [31] investigated Bayesian-optimized Gaussian process regression and found that it achieved higher accuracy than Gaussian process regression, support vector regression, random forest regression and artificial neural networks for predicting compressive strength and elastic modulus, with correlation coefficients of 0.91 and 0.93, respectively. Zhang Xinyi et al. [32] proposed a TPE-XGBoost model for predicting the compressive strength of recycled coarse aggregate concrete and optimized model parameters using Bayesian optimization based on tree-structured Parzen estimators. The results showed that this model had higher prediction accuracy and generalization ability than random forest, k-nearest neighbour regression, support vector regression and gradient boosting decision tree models. Gao Wei [33] predicted the compressive strength of recycled concrete using deep learning. The results showed that, compared with traditional neural network models, the deep learning model had advantages in prediction accuracy, efficiency and generalization ability and could be used as a new method for strength estimation of recycled concrete.

### 2.3 Machine Learning-Based Studies on Mix Proportion Design of Recycled Concrete

Mix proportion design is a core step in the engineering application of recycled concrete. Its objective is not only to satisfy strength requirements, but also to consider workability, durability, economy and low-carbon performance. Traditional mix proportion design usually relies on empirical formulas and trial mixing. When recycled aggregate replacement ratio, water absorption, mineral admixtures and chemical admixtures vary simultaneously, the number of trial mixes increases substantially, and it is difficult to obtain a global optimum. Machine learning can establish surrogate models between material composition and performance based on existing experimental databases, and optimization algorithms can then be used to search for mix proportions that satisfy specified constraints.

Existing studies commonly use water, cement, sand, natural coarse aggregate, recycled coarse aggregate, fly ash, slag, silica fume, superplasticizer, curing age and recycled aggregate properties as inputs. Compressive strength, splitting tensile strength, slump, chloride penetration index, cost and carbon emissions are used as outputs or optimization objectives [27,34]. On this basis, genetic algorithms, particle swarm optimization, grey wolf optimization and NSGA-II can be used to optimize strength maximization, cost minimization, carbon emission reduction and durability improvement simultaneously [35]. Figure 4 summarizes the machine learning-based optimization process for recycled concrete mix proportions. It usually involves database construction, key feature selection, performance prediction model training, and the generation of candidate mix proportions by combining multi-objective optimization algorithms with engineering constraints. These studies promote the transition of recycled concrete research from performance prediction to performance design.

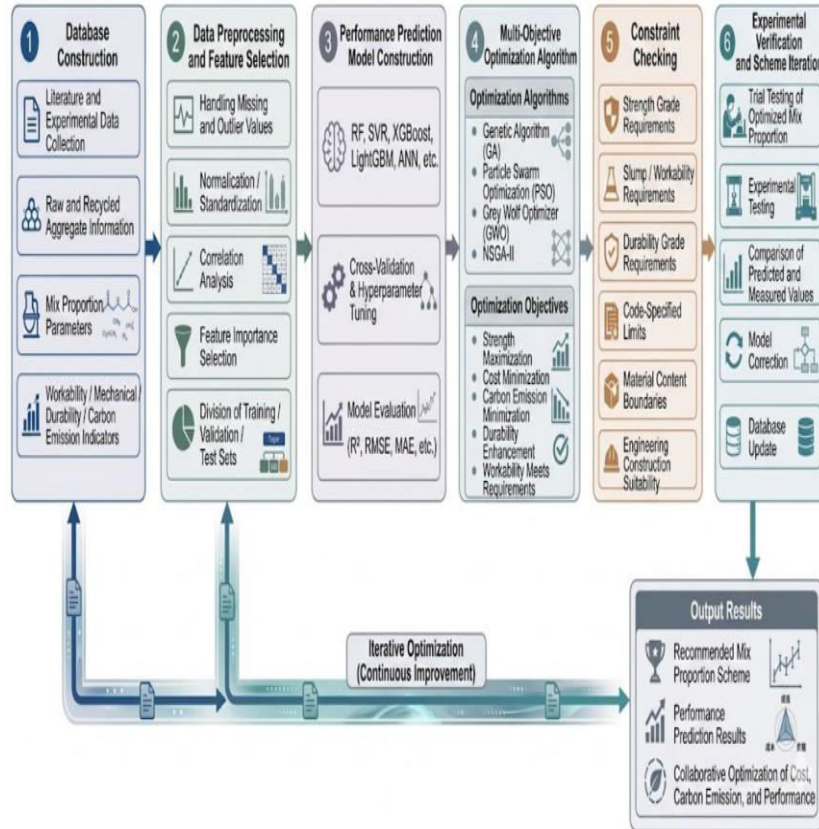


Fig. 4. Machine learning-based optimization process for recycled concrete mix proportions

However, the engineering applicability of optimized mix proportions still requires further verification. Machine learning models essentially perform interpolation within the distribution of the training data. When an optimization algorithm proposes material dosages outside the database coverage, the prediction results may become unreliable. Therefore, mix proportion design studies should set reasonable material dosage boundaries and construction constraints, and optimized schemes should be verified through independent experiments. Code requirements, durability grades, construction slump requirements and life-cycle assessment indicators should also be incorporated into models so that the optimization results are closer to practical engineering needs.

#### 2.4 Machine Learning-Based Studies on Durability of Recycled Concrete

Durability is an important factor limiting the large-scale structural application of recycled concrete. Because recycled aggregates have higher porosity and water absorption, and because old mortar and new mortar form multiple interfacial transition zones, recycled concrete is usually more sensitive than ordinary concrete to chloride penetration, carbonation, freeze-thaw damage and sulfate attack [36]. Durability deterioration is affected by material composition, environmental temperature and humidity, exposure time, curing regime and loading state, and it therefore shows long-term and multivariable coupling characteristics.

Machine learning applications in recycled concrete durability prediction mainly focus on chloride penetration, carbonation depth, freeze-thaw damage and impermeability. For chloride penetration, studies usually use water-to-binder ratio, cement content, recycled aggregate replacement ratio, mineral admixtures, curing age, chemical admixtures and aggregate water absorption as input variables. Models such as RF, SVR, XGBoost and ANN are then used to predict electric flux, chloride diffusion coefficient or chloride resistance grade [37]. Related studies show that ensemble learning models can effectively identify the effects of water-to-binder ratio, recycled aggregate content and binder composition on chloride transport, and can be combined with durability design [38].

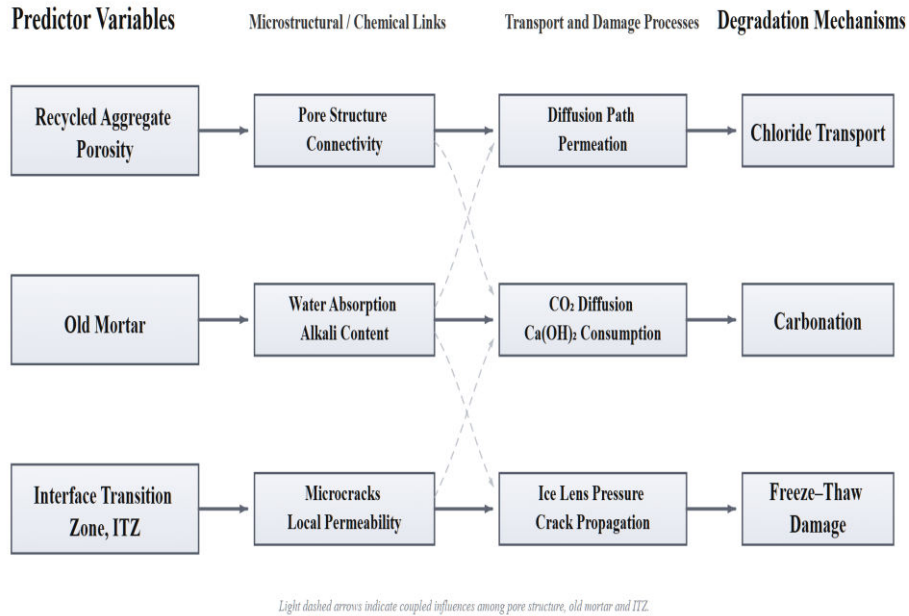


Fig. 5. Relationship between durability prediction variables and deterioration mechanisms of recycled concrete

As shown in Figure 5, the durability deterioration of recycled concrete is associated with recycled aggregate porosity, old mortar content, interfacial transition zone structure and external environment. Transforming these mechanistic factors into machine learning input variables can improve the specificity of predictions for chloride penetration, carbonation depth and freeze-thaw damage.

For carbonation performance, existing studies have developed ANN, SVR, DT, RF, XGBoost and LightGBM models based on datasets containing material and environmental parameters to predict carbonation depth of recycled concrete [39]. Model analyses usually show that water-to-binder ratio, exposure time, relative humidity, carbon dioxide concentration, recycled aggregate replacement ratio and mineral admixture type are important factors affecting carbonation depth. Compared with empirical formulas, machine learning models can handle nonlinearity and interactions, but their reliability depends on the completeness of exposure environment data and long-term experimental data.

Overall, durability prediction depends more strongly on long-term data accumulation than mechanical-property prediction. Existing databases often suffer from limited sample size, inconsistent test protocols and unclear environmental boundaries, which restrict model generalization. Future research should establish durability databases covering multiple regions, exposure environments and ages, and should combine material microstructure, pore characteristics and transport mechanisms with machine learning models to improve the credibility of durability prediction.

### III. ADVANTAGES AND LIMITATIONS OF MACHINE LEARNING IN RECYCLED CONCRETE PERFORMANCE DESIGN

In the prediction of mechanical properties of recycled aggregate concrete, commonly used machine learning models include support vector machine (SVM), decision tree, random forest and neural network [39-43]. SVM is widely used in recycled aggregate concrete performance prediction because of its advantages in small-sample and nonlinear data processing. However, its parameter selection is difficult, and model training can be time-consuming, which limits its applicability. Decision tree models are easy to understand and interpret, but they are prone to overfitting. Random forest improves model stability and prediction accuracy by constructing multiple decision trees. Neural networks, especially deep learning models, perform well in predicting the complex properties of recycled aggregate concrete because of their strong nonlinear fitting ability. However, they also require substantial computational resources and

training data. Comparing the advantages and disadvantages of different models can help select the most suitable model for a specific recycled aggregate concrete performance prediction task, as shown in Table 1.

**Table 1 Applicability comparison of common machine learning algorithms in recycled concrete performance prediction**

Algorithm	Principle	Advantages	Limitations
SVM	Maximizes the classification margin	Supports multiple kernel functions	Difficult parameter tuning
Decision Tree	Recursive data partitioning	Handles multiple data types	Prone to overfitting
Random Forest	Ensemble learning method	Strong resistance to overfitting	Long training and prediction time
Neural Network	Simulates biological neural networks	Strong learning capability	Difficult to interpret
Linear Regression	Models linear relationships	Simple and easy to understand	Limited to linear relationships
Logistic Regression	Regression model for classification	Can be extended to multiple variables	Limited to binary classification

Algorithm	Principle	Advantages	Limitations
k-Nearest Neighbors	Classification and regression method	No assumption on data distribution is required	Not suitable for high-dimensional data
Naive Bayes	Bayes' theorem	High computational efficiency	Strongly affected by data volume
Ensemble Learning	Combines multiple weak learners	High prediction accuracy	Long training time

#### IV. CONCLUSION

Machine learning provides an effective data-driven approach for recycled concrete performance prediction. Existing studies show that BP neural networks, support vector machines, random forests, XGBoost, LightGBM, CatBoost and deep learning models can be used to predict compressive strength, elastic modulus, slump, chloride penetration resistance and carbonation depth of recycled concrete. Compared with traditional empirical formulas, machine learning models have advantages in handling multivariable, nonlinear and strongly coupled relationships, and can improve the efficiency and accuracy of recycled concrete performance prediction.

The combination of machine learning and intelligent optimization algorithms promotes the transition of recycled concrete research from performance prediction to performance design. By coupling prediction models with genetic algorithms, particle swarm optimization, grey wolf optimization and NSGA-II, multi-objective optimization can be carried out among strength, workability, durability, cost and carbon emissions. This provides a new technical pathway for low-carbon design, material consumption control and engineering application of recycled concrete.

Current machine learning studies on recycled concrete still have clear limitations. Existing databases are mostly derived from different literature sources and experimental conditions. Differences in material sources, recycled aggregate quality, specimen size, curing regime and testing method may lead to data noise and model bias. Meanwhile, some studies overemphasize prediction accuracy but lack external data validation and engineering experimental verification. The generalization ability of models across different material systems and real engineering scenarios therefore requires further examination.

Future research should strengthen standardized databases and interpretable models. On the one hand, open databases covering different recycled aggregate sources, replacement ratios, curing ages, environmental conditions and durability indicators should be established, and key features such as recycled aggregate water absorption, crushing index, old mortar content and pore structure should be improved. On the other hand, interpretable methods such as SHAP and PDP should be introduced to clarify the effects of key input variables on model predictions, so that data-driven models can be cross-validated against material mechanisms and engineering experience.

Overall, machine learning cannot replace material testing and mechanistic analysis. Instead, it should be used as an auxiliary tool connecting experimental data, performance prediction, mix proportion optimization and engineering verification. Only by integrating data-driven methods with physical mechanisms, code constraints and independent experimental validation can the credibility of model predictions be improved, thereby promoting recycled concrete toward more reliable, economical and low-carbon engineering applications.

#### V. FUNDING

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