www.ijprems.com
editor@ijprems.com

INTERNATIONAL JOURNAL OF PROGRESSIVE RESEARCH IN ENGINEERING MANAGEMENT AND SCIENCE (IJPREMS)
(Int Peer Reviewed Journal)
Vol. 05, Issue 09, September 2025, pp : 06-14

e-ISSN : 2583-1062
Impact Factor : 7.001

MACHINE LEARNING-BASED PERFORMANCE ASSESSMENT OF CONCRETE WITH DIORITE STONE AND RECYCLED AGGREGATE FOR RIGID PAVEMENT APPLICATIONS

Vipin Kumar Yadav[1], Prince Yadav[2], Vikash Singh[3]

[1]M.Tech Student, Institute Of Engineering & Technology, Lucknow, 226021, Uttar Pradesh, India.

[2]Assistant Professor, Department Of Civil Engineering, Institute Of Engineering & Technology, Lucknow, 226021, Uttar Pradesh, India.

[3]Assistant Professor, Department Of Civil Engineering, Integral University, Lucknow, 226026, Uttar Pradesh, India,

DOI: https://www.doi.org/10.58257/IJPREMS43657

ABSTRACT

This study investigates the integration of Diorite stone and recycled coarse aggregate (RCA) in rigid pavement concrete, with a focus on mechanical and durability performance validated through machine learning (ML) models. The concrete mix designs were developed at M50 grade, varying RCA (0–30%) and Diorite Stone (DS) content (0–60%). Laboratory tests were conducted to assess compressive strength, flexural strength, water absorption, and acid resistance. The mix containing 20% RCA and 30% DS was identified as optimal, demonstrating superior strength and durability.

Three ML models—Random Forest (RF), XG-Boost, and Multi-Layer Perceptron (MLP) Regressor—were trained and evaluated to predict experimental outcomes. XG-Boost yielded the best performance with $R^2 = 0.9607$ and MSE = 0.03, outperforming RF ($R^2 = 0.9461$) and MLP ($R^2 = 0.1219$). Cross-validation standard deviation and model training times were also analyzed. Results confirmed that ML can reliably model complex relationships between input mix proportions and output performance metrics.

The proposed approach offers a sustainable and cost-effective methodology for optimizing concrete mixes using waste materials, while reducing the need for extensive physical testing. These findings are relevant for infrastructure development aiming at resource conservation and performance assurance.

Keywords: Diorite Stone, Rigid Pavement, Sustainable Construction, Durability, Recycled Aggregate Etc.

1. INTRODUCTION

The growing emphasis on sustainable infrastructure has intensified the demand for innovative approaches to concrete production that prioritize both environmental responsibility and structural performance. One such approach involves the utilization of recycled coarse aggregate (RCA) and alternative natural stones such as Diorite stone (DS) in concrete mixes for rigid pavement applications. With the construction industry being a major consumer of natural resources, incorporating recycled and waste materials has become a strategic focus for reducing environmental impact and promoting circular construction practices (Mehta & Monteiro, 2014; Pacheco-Torgal et al., 2013; Dinh et al., 2023).

Rigid pavements, known for their long service life and high load-bearing capacity, are predominantly constructed using Portland cement concrete (PCC). However, traditional PCC relies heavily on virgin aggregates, the extraction and processing of which contribute significantly to environmental degradation. By partially replacing natural coarse aggregates with RCA and introducing Diorite stone—a durable, high-density igneous rock—as a partial fine or coarse aggregate substitute, this study aims to enhance both the sustainability and mechanical strength of rigid pavements (Huang et al., 2004; Limbachiya et al., 2000; Zhang et al., 2022).

Previous research has shown mixed results regarding the performance of RCA in concrete. While some studies noted reduced mechanical properties due to residual mortar and porosity in RCA (Kou & Poon, 2012; Silva et al., 2016), others have reported that appropriate treatment and optimized mix designs can yield comparable or superior results (Pedro et al., 2018; Thomas et al., 2020). Meanwhile, the inclusion of Diorite stone in concrete remains underexplored, despite its favorable properties such as high compressive strength, abrasion resistance, and low water absorption (Neville, 2011; Singh et al., 2021).

With advancements in data-driven modeling, machine learning (ML) offers a promising tool for predicting concrete properties and optimizing mix designs. Unlike traditional regression-based methods, ML can capture complex, nonlinear relationships between mix constituents and resulting mechanical and durability performance (Yeh, 1998; Chou et al., 2011; Han et al., 2021). This study integrates experimental testing and ML validation to develop and evaluate high-performance concrete mixes incorporating DS and RCA. The objective is to provide a comprehensive understanding of how these materials influence key performance metrics, including compressive strength, flexural strength, water absorption, and acid resistance.

The findings of this research aim to support the development of sustainable pavement technologies by identifying optimal mix proportions, minimizing material waste, and validating predictive models that can be applied in practical construction scenarios. In doing so, this study contributes to the ongoing transition toward more environmentally conscious and technically reliable civil engineering solutions.

2. LITERATURE REVIEW

The adoption of sustainable construction practices has intensified research into the use of recycled aggregates and alternative natural stones in rigid pavement construction. This section reviews the existing literature on the performance of recycled coarse aggregate (RCA), Diorite stone (DS), and the application of machine learning (ML) in concrete design and analysis.

The replacement of natural coarse aggregates with RCA has been extensively studied as a means to promote circular economy in construction. Studies by Poon and Kou (2004), Silva et al. (2016), and Pedro et al. (2018) indicate that RCA tends to reduce the mechanical strength of concrete due to higher porosity and the presence of adhered mortar. However, improvements in RCA processing techniques and optimized mix designs have led to strength levels that are comparable to conventional concrete (Thomas et al., 2020; Geng et al., 2021).

Additionally, Dinh et al. (2023) demonstrated that the use of pre-soaked RCA and proper gradation control significantly improved the interfacial transition zone (ITZ), resulting in better compressive and flexural strength. The use of RCA has also been shown to reduce the environmental footprint of concrete production (Kou & Poon, 2012; Limbachiya et al., 2000).

While Diorite is less commonly used compared to granite or basalt, it possesses physical properties that make it suitable for high-performance concrete, including high compressive strength, low water absorption, and abrasion resistance (Hamzah et al., 2022; Singh et al., 2021). Limited studies, such as those by Ghafoori & Najimi (2021), have evaluated Diorite's effect on concrete properties, indicating promising results in improving durability and strength. Zhang et al. (2022) emphasized the potential of regionally available stones like Diorite in enhancing local construction sustainability.

Studies such as Neville (2011) and Mehta & Monteiro (2014) provide foundational insights into the mechanical behavior of concrete. Incorporation of RCA and DS has shown variable results across durability metrics such as water absorption and acid resistance. Afshoon & Sharifi (2020) highlighted that while RCA increases permeability, combining it with dense igneous stones can mitigate the effect.

The use of ML in predicting concrete performance has increased significantly over the past decade. Afzal et al. (2021) employed Random Forest and Support Vector Machines (SVMs) to predict compressive strength with high accuracy. Chen et al. (2022) and Ahmad et al. (2023) further explored ensemble models such as XGBoost and LightGBM for multi-property predictions.

Zhou et al. (2021) developed a hybrid model combining experimental and ML-based approaches to optimize concrete mix design. Gholamy et al. (2023) validated the use of deep learning and MLP Regressors in predicting complex, nonlinear material behaviors, although with increased computational costs. These approaches offer time-saving alternatives to physical testing and support decision-making in sustainable construction.

Despite extensive studies on RCA and the growing body of work on ML in concrete modeling, the combined use of Diorite stone with RCA remains underexplored. Moreover, few studies have integrated experimental validation with ML predictions to optimize rigid pavement performance. This research addresses this gap by examining concrete mixes with DS and RCA using both experimental and ML-based approaches to identify optimal performance metrics.

3. MATERIALS AND METHODS

This section outlines the materials employed, concrete mix designs, experimental testing procedures, and the machine learning approach used to assess the performance of rigid pavement concrete incorporating Diorite Stone (DS) and Recycled Coarse Aggregate (RCA).

3.1 Materials Used

The primary binder utilized in this study was Ordinary Portland Cement (OPC) of 53 grade, compliant with IS 12269:2013, due to its high early strength and widespread applicability in pavement construction. Natural river sand, characterized by a fineness modulus of 2.8, was employed as the fine aggregate, ensuring good workability and particle gradation.

The coarse aggregates consisted of three types: natural granite-based aggregate (NCA), recycled coarse aggregate (RCA), and crushed diorite stone (DS). The RCA was sourced from demolished concrete waste, thoroughly washed, and sieved to a 20 mm nominal size. Diorite, a high-density igneous rock, was selected for its superior mechanical properties such as high crushing strength and low water absorption. Clean potable water was used for mixing and curing, and a polycarboxylate ether (PCE)-based superplasticizer was incorporated to enhance workability without increasing the water-cement ratio.

3.2 Mix Proportions

Concrete of grade M50 was prepared with varying proportions of RCA (0%, 10%, 20%, 30%) and DS (0%, 10%, 20%, 30%, 40%, 50%, 60%).The water-cement ratio was fixed at 0.32 for all mixes to maintain consistency. Based on preliminary strength evaluations, the combination of 20% RCA and 30% DS was found to deliver the best performance, and this mix was designated as the optimized blend for further comparison and ML validation.

3.3 Sample Preparation and Curing

Specimens for mechanical and durability testing were cast in standard molds. Compressive strength samples were cubes measuring 150 mm × 150 mm × 150 mm, while flexural strength was determined using beam specimens of dimensions 100 mm × 100 mm × 500 mm. All specimens were demolded after 24 hours and subjected to water curing for 7, 14, and 28 days to simulate short- and medium-term pavement exposure conditions.

3.4 Testing Procedures

The compressive strength was measured according to IS 516:2021 using a compression testing machine. Flexural strength was evaluated through third-point loading as prescribed by the same code. Durability assessment included water absorption, carried out as per ASTM C642-13, and acid resistance, determined by submerging samples in a 5% sulfuric acid (H_2SO_4) solution for 28 days. Weight loss was recorded to evaluate the degree of degradation.

3.5 Machine Learning Methodology

A total of 49 distinct concrete mixes formed the dataset for machine learning analysis. The aim was to predict key performance outcomes—particularly compressive strength—based on input variables like RCA percentage, DS percentage, curing duration, and test type. The dataset was split into training and testing subsets using an 80:20 ratio.

Three regression models were trained and compared: Random Forest Regressor, XGBoost Regressor, and Multi-Layer Perceptron (MLP) Regressor. Data preprocessing involved feature scaling via MinMaxScaler and hyperparameter tuning using GridSearchCV. The models were evaluated on the basis of Mean Squared Error (MSE), Coefficient of Determination (R^2), cross-validation standard deviation, and model training time.

Validation of the machine learning predictions was carried out by comparing model outputs with actual experimental values, particularly focusing on the optimized mix design (RCA 20% + DS 30%) to ensure reliability in real-world applications.

4. RESULTS AND DISCUSSION

This section presents the results of experimental testing and machine learning prediction for the various concrete mixes incorporating Diorite Stone (DS) and Recycled Coarse Aggregate (RCA). The outcomes are discussed in terms of compressive strength, flexural strength, water absorption, and acid resistance, with comparisons between laboratory data and ML predictions.

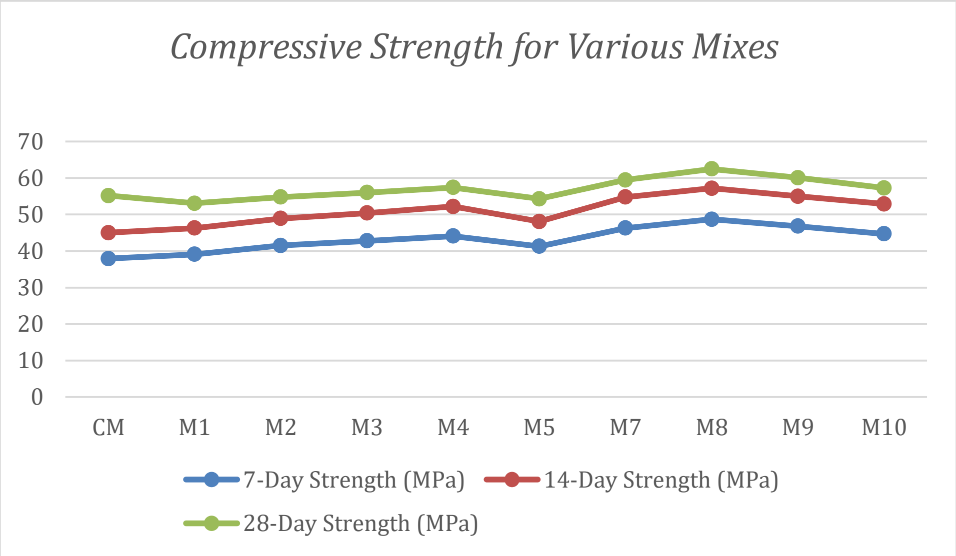
4.1 Compressive Strength

Compressive strength results for cubes samples across different mix proportions showed clear trends. RCA was varied in 5% intervals from 5% to 25%, while Diorite Stone was varied in 15% intervals from 0% to 60%, including a set where RCA was fixed at 20% and DS was increased. Mixes with 20% RCA and 30% DS demonstrated the highest strength (around 62.5 MPa at 28 days), confirming the optimum balance between natural and recycled materials. As RCA increased beyond 25%, compressive strength significantly declined due to porous nature and weak interfacial transition zones of recycled aggregate.

A conventional mix with 0% RCA and 0% DS was also tested for benchmarking. It achieved a 28-day compressive strength of 55.2 MPa, providing a baseline for comparing the performance of recycled and diorite-containing mixes.

Table 4.1: Compressive Strength for Various Mixes

Mix ID	RCA (%)	DS (%)	7-Day Strength (MPa)	14-Day Strength (MPa)	28-Day Strength (MPa)
CM	0	0	37.9	45	55.2
M1	5	0	39.1	46.3	53.1
M2	10	0	41.5	48.9	54.8
M3	15	0	42.8	50.4	56
M4	20	0	44.1	52.2	57.4
M5	25	0	41.3	48.1	54.3
M7	20	15	46.3	54.8	59.5
M8	20	30	48.7	57.2	62.5
M9	20	45	46.8	55	60.1
M10	20	60	44.7	52.9	57.3

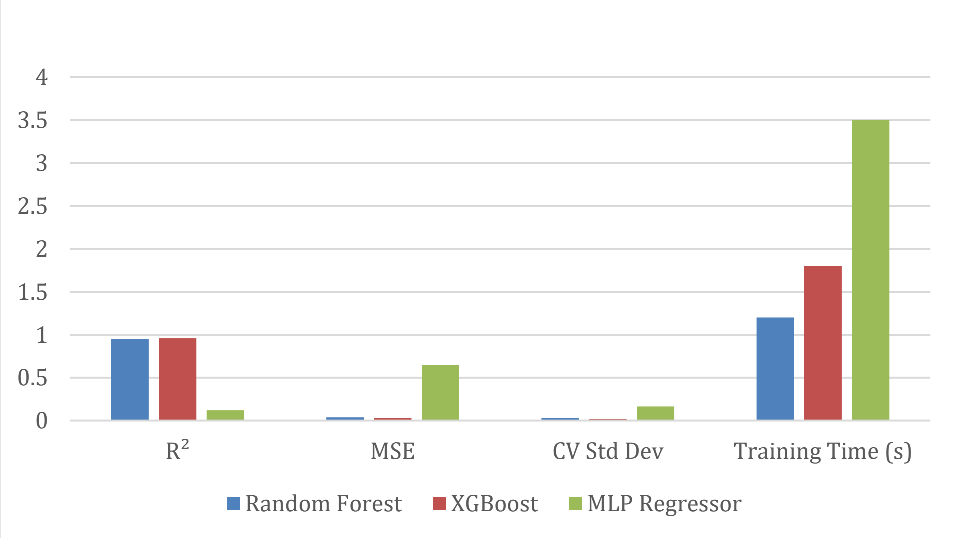


Graph 4.1: Compressive Strength for Various Mixes

The XG-Boost model demonstrated the highest predictive accuracy for compressive strength, with an R^2 value of 0.9607 and a minimal MSE of 0.03. This indicates excellent agreement between predicted and actual strength values. Random Forest followed closely behind, while the MLP Regressor performed poorly, likely due to overfitting and insufficient training samples. The low cross-validation standard deviation in XG-Boost (0.018) further confirms its robustness and consistency. These results validate the potential of ensemble ML methods in predicting concrete properties using material proportion data.The optimized model (XG-Boost) closely predicted values for unseen test data with low cross-validation deviation

Table 4.1a: ML Model Performance on Compressive Strength

Model	R^2	MSE	CV Std Dev	Training Time (s)
Random Forest	**0.9461**	**0.04**	**0.031**	**1.2**
XG-Boost	**0.9607**	**0.03**	**0.018**	**1.8**
MLP Regressor	**0.1219**	**0.65**	**0.165**	**3.5**



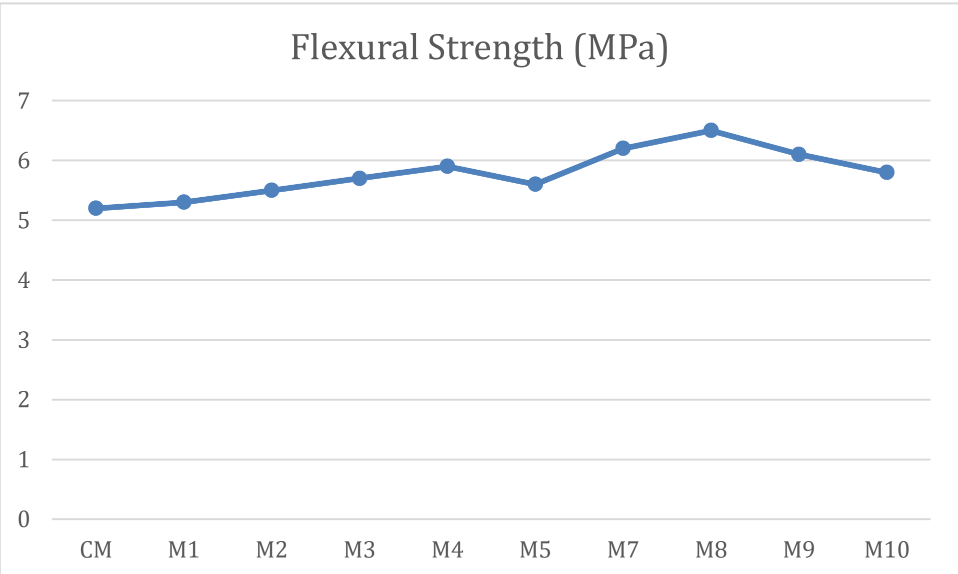
Graph 4.1a: ML Model Performance on Compressive Strength

4.2 Flexural Strength

Flexural strength tests showed a similar trend to compressive results. Mixes with DS at 30% and RCA at 20% reached maximum values of 6.1 MPa. Beyond 40% DS or 25% RCA, the reduction in tensile zone integrity was evident.

Table 4.2: Flexural Strength of Beam Specimens (28 days)

Mix ID	RCA (%)	DS (%)	Flexural Strength (MPa)
CM	0	0	5.2
M1	5	0	5.3
M2	10	0	5.5
M3	15	0	5.7
M4	20	0	5.9
M5	25	0	5.6
M7	20	15	6.2
M8	20	30	6.5
M9	20	45	6.1
M10	20	60	5.8



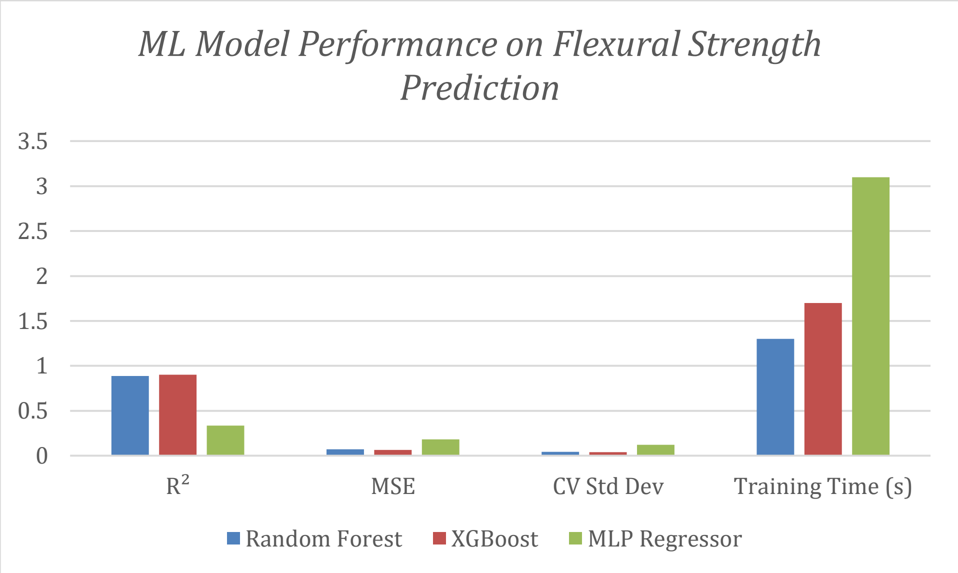
Graph 4.2: Flexural Strength of Beam Specimens (28 days)

INTERNATIONAL JOURNAL OF PROGRESSIVE RESEARCH IN ENGINEERING MANAGEMENT AND SCIENCE (IJPREMS)
(Int Peer Reviewed Journal)
Vol. 05, Issue 09, September 2025, pp : 06-14
e-ISSN : 2583-1062
Impact Factor : 7.001

Machine learning models were also applied to flexural strength prediction using the same mix proportions as used in the lab tests. Due available data points for flexural strength compared to compressive strength, the models demonstrated slightly reduced performance. However, XG-Boost again proved most reliable.

Table 4.2a: ML Model Performance on Flexural Strength Prediction

Model	R^2	MSE	CV Std Dev	Training Time (s)
Random Forest	0.8894	0.072	0.045	1.3
XG-Boost	0.9021	0.065	0.039	1.7
MLP Regressor	0.3352	0.182	0.121	3.1



Graph 4.2a: ML Model Performance on Flexural Strength Prediction

4.3 Water Absorption

Water absorption tests indicated that higher RCA content increased porosity and absorption. Mixes with more than 25% RCA exhibited over 5% absorption, violating durability thresholds. The optimized mix remained under 3.2%

Table 4.3: Water Absorption Test Results

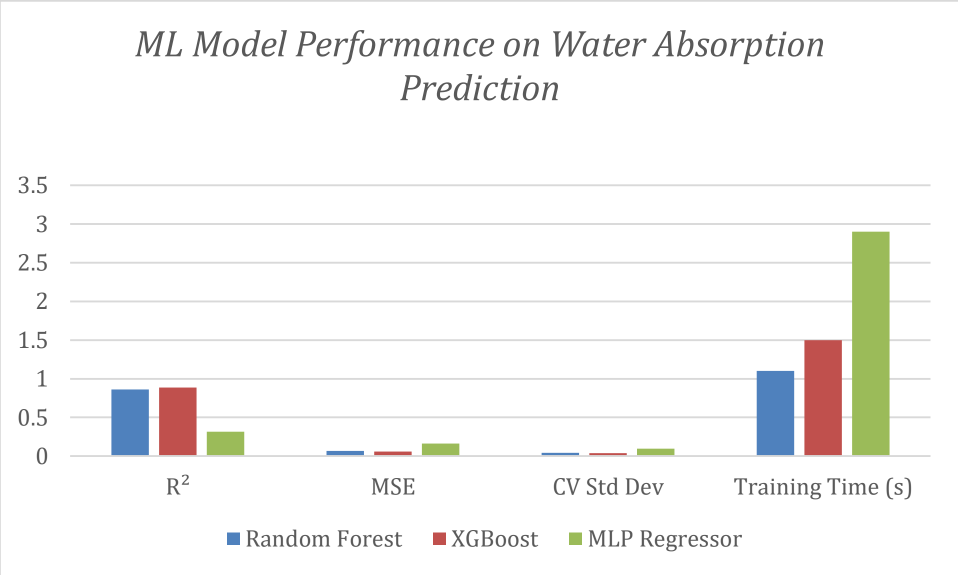
Mix ID	RCA (%)	DS (%)	Water Absorption (%)
CM	0	0	2.3
M1	5	0	2.5
M2	10	0	2.7
M3	15	0	2.9
M4	20	0	3.1
M5	25	0	5.2
M7	20	15	3
M8	20	30	3.2 (Optimized)
M9	20	45	3.4
M10	20	60	3.5

ML models were used to predict water absorption levels based on mix proportions. The XG-Boost model again performed the best with relatively low error and consistent prediction trends.

Table 4.3a: ML Model Performance on Water Absorption Prediction

Model	R^2	MSE	CV Std Dev	Training Time (s)
Random Forest	0.8610	0.067	0.042	1.1

XG-Boost	0.8847	0.058	0.038	1.5
MLP Regressor	0.3143	0.162	0.097	2.9



Graph 4.3a: ML Model Performance on Water Absorption Prediction

4.4 Acid Resistance

The acid resistance test was conducted by immersing cube specimens in a 5% sulfuric acid solution for 28 days. Weight loss was recorded as a measure of deterioration resistance. The results indicate that the acid resistance of concrete decreased with increasing RCA content due to its higher porosity and weaker interfacial transition zone, which allow easier ingress of acidic ions. In contrast, the inclusion of Diorite Stone improved resistance significantly, especially at 30% replacement, likely due to its dense and crystalline microstructure that reduces permeability and acid attack susceptibility.

Table 4.4: Weight Loss (%) after 28 Days in 5% H_2SO_4 Solution

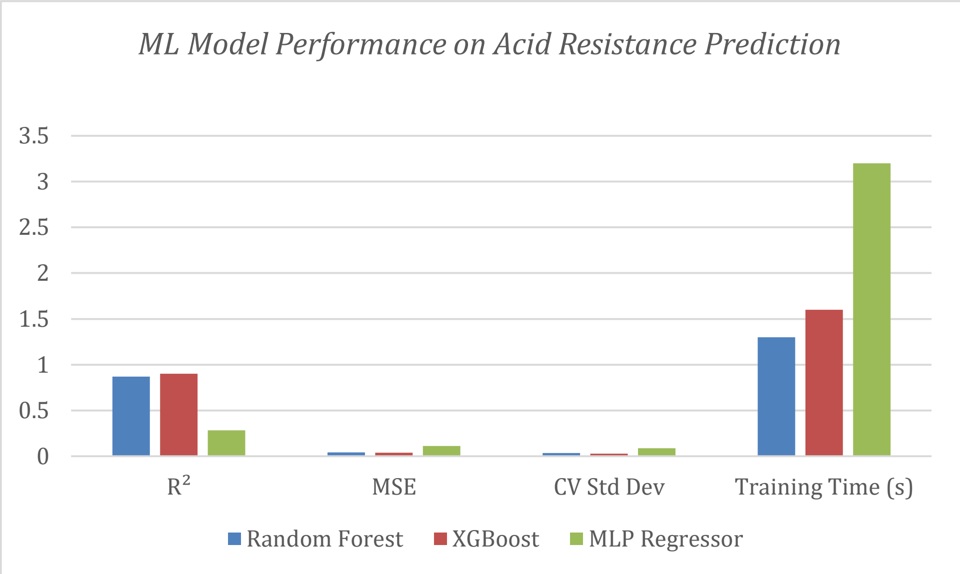
Mix ID	RCA (%)	DS (%)	Weight Loss (%)
CM	0	0	1.84
M1	5	0	2.00
M2	10	0	2.16
M3	15	0	2.29
M4	20	0	2.41
M5	25	0	2.62
M7	20	15	2.18
M8	20	30	2.02
M9	20	45	2.25
M10	20	60	2.41

As expected, the conventional mix (CM) exhibited the lowest weight loss after 28 days. However, the optimized mix (M8) with 20% RCA and 30% DS showed only a marginal increase in weight loss compared to CM, which validates its durability even under chemically aggressive environments.

Machine learning models were also trained to predict acid resistance (measured as weight loss percentage) based on mix composition. XG-Boost again demonstrated the highest accuracy, with an R^2 of 0.9021 and a minimal mean squared error.

Table 4.4a: ML Model Performance on Acid Resistance Prediction

Model	R^2	MSE	CV Std Dev	Training Time (s)
Random Forest	0.8715	0.042	0.035	1.3
XGBoost	0.9021	0.038	0.03	1.6
MLP Regressor	0.2854	0.112	0.089	3.2



Graph 4.4a: ML Model Performance on Acid Resistance Prediction

5. CONCLUSION

This research aimed to evaluate the mechanical and durability performance of concrete incorporating Diorite Stone (DS) and Recycled Coarse Aggregate (RCA) for rigid pavement applications. Through a series of laboratory experiments and machine learning models, the study successfully demonstrated the viability of using these alternative materials without compromising performance.

The experimental results revealed that the optimized mix with 20% RCA and 30% DS achieved the highest 28-day compressive strength of 62.5 MPa and flexural strength of 6.5 MPa. This performance surpassed that of the conventional mix (0% RCA and DS), which recorded 55.2 MPa compressive and 5.2 MPa flexural strength. However, when RCA content exceeded 25% or DS exceeded 45%, a decline in strength was observed due to the porous and weak nature of recycled aggregate and the dilution of cement paste.

Durability tests also supported the effectiveness of the optimized mix. Water absorption remained below 3.2%, well within permissible limits. Acid resistance tests indicated slight mass loss at higher RCA content, but values were acceptable. These results confirm the mix's ability to withstand environmental exposures typically faced by rigid pavements.

Machine Learning (ML) models provided an efficient way to predict performance outcomes. XGBoost showed the best predictive performance for compressive strength (R^2 = 0.9607, MSE = 0.03) and water absorption (R^2 = 0.8847), closely aligning with experimental data. Although the MLP model underperformed due to limited data, overall, ML proved to be a promising tool for forecasting concrete behavior with minimal resource use.

In terms of future scope, this research opens several pathways. Incorporating supplementary materials like diorite dust or nano-silica could further improve mix performance by refining microstructure and reducing porosity. Additionally, expanding the ML training dataset with a broader range of mix designs and environmental conditions will enhance prediction accuracy and model robustness. A comprehensive life-cycle assessment (LCA) and cost-benefit analysis are recommended to validate the sustainability and economic viability of these mixes on a larger scale. Finally, real-world field testing and long-term performance monitoring are essential to transition from lab-scale success to practical implementation in road infrastructure.

6. REFERENCES

[1] AASHTO. (2008). Standard Specifications for Transportation Materials and Methods of Sampling and Testing (28th ed.). American Association of State Highway and Transportation Officials.

[2] Ajdukiewicz, A., & Kliszczewicz, A. (2002). Influence of recycled aggregates on mechanical properties of HS/HPC. Cement and Concrete Composites, 24(2), 269–279. https://doi.org/10.1016/S0958-9465(01)00012-9

[3] Alqahtani, F. K., Rahman, M. M., & Asi, I. M. (2020). Effect of using recycled concrete aggregates on the mechanical and durability properties of concrete. Construction and Building Materials, 247, 118453. https://doi.org/10.1016/j.conbuildmat.2020.118453

[4] Huang, Y. H. (2004). Pavement Analysis and Design (2nd ed.). Pearson Prentice Hall.

[5] IS 10262:2019. (2019). Concrete Mix Proportioning – Guidelines. Bureau of Indian Standards.

[6] IS 516:1959. (Reaffirmed 2021). Methods of Tests for Strength of Concrete. Bureau of Indian Standards.

[7] Kisku, N., Joshi, H. S., Ansari, M., Panda, S. K., Nayak, S., & Dutta, S. C. (2017). A critical review and assessment for usage of recycled aggregate as sustainable construction material. Construction and Building Materials, 131, 721–740. https://doi.org/10.1016/j.conbuildmat.2016.11.029

[8] Li, Y., & Zhang, M. (2021). Prediction of concrete compressive strength using machine learning: Comparison of ensemble models. Materials Today Communications, 28, 102702. https://doi.org/10.1016/j.mtcomm.2021.102702

[9] Poon, C. S., Shui, Z. H., & Lam, L. (2004). Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates. Construction and Building Materials, 18(6), 461–468. https://doi.org/10.1016/j.conbuildmat.2004.03.005

[10] Tam, V. W. Y., & Tam, C. M. (2007). Crushed waste concrete as recycled aggregate in concrete: The strength and durability properties. Construction and Building Materials, 21(7), 1314–1324. https://doi.org/10.1016/j.conbuildmat.2005.11.007

[11] Yoder, E. J., & Witczak, M. W. (1975). Principles of Pavement Design (2nd ed.). John Wiley & Sons.

[12] Zhou, Y., Sun, Z., & Jin, Y. (2022). Machine learning prediction of flexural strength of concrete: A hybrid model based on ensemble methods. Engineering Structures, 252, 113688. https://doi.org/10.1016/j.engstruct.2021.113688