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AI-Based Soil Stabilization Using Recycled Concrete for Sustainable Structural Foundations

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Abstract: Weak Soils: The main drivers of foundation stability and construction performance. However, even though conventional soil stabilization has shown success, it has a negative environmental effect. Thus, sustainable materials with Recycled Concrete Aggregates (RCA), Artificial Intelligence (AI), are presented as a valid alternative. Soil samples were stabilized using different percentages of Recycled Concrete Aggregates (RCA) (0%, 10%, 20%, and 30%). In laboratory tests compaction, Unconfined Compressive Strength, California Bearing Ratio, and Atterberg limits was done. Machine learning models were also used, such as Linear Regression, Random Forest and so on to predict the soil. Results showed that by incorporating RCA, the strength and bearing ability of soils improved significantly. The most improved performance in the experiment was obtained by using 20% RCA. Of the AI models, Random Forest outperformed Linear Regression in prediction quality. All in all, the combined applications of RCA and AI techniques enable a more effective, economical, and sustainable solution to stabilize the soil with a better applicability in foundation engineering. Keywords: Soil Stabilization, Recycled Concrete, Artificial Intelligence, Machine Learning, Sustainable Foundations, Bearing Capacity.

1.Introduction

1.1 Background : Foundation safety, including soil, is largely dependent on its properties, since soil provides the foundation of any structure. Frequently these low strength and high compressibility natural soils (clayey and expansive soils) develop settlement and structure damage. Stabilization techniques primarily with cement and lime are the most widely used ways to resolve these problems. Nevertheless these methods lead to an increase in cost and also pollute the environment and contribute to high carbon footprint (Habert et al., 2020). In the last decade or so recycled materials have been used by researchers for soil stabilization. One material for this purpose is the Recycled Concrete Aggregates (RCA) derived from construction waste. Raw materials like Recycled Concrete Aggregates (RCA) can help strengthen soil, and mitigate waste disposal issues. Meanwhile, Artificial Intelligence (AI) methods are in use in the civil engineering field to predict soil properties in rapid and accurate fashion (Jagadesh et al., 2024).

1.2 Challenges in Existing Studies : There are, however, some gaps in the literature despite the considerable development done. Most studies investigate only material improvement, or strictly on prediction models, however not both in their entirety. RCA is still not fully optimized for soil stabilization, though and its response at various percentages needs to be more studied. Many AI models are also developed without sufficient experimental support, limiting the practical use of the training models (Zhang et al., 2025; Thapa & Ghani, 2025).

1.3 Motivation : Solutions to both create an effective alternative to this problem need to be found, and to be good for the environment. RCA helps manage construction waste, conserve natural resources and save construction waste. Simultaneously, AI can decrease the work and effort on testing. In this way, a more complete approach, if combined, for modern root problems. The main purposes of this study are:

1.4 The main Objectives of The Study: Objectives For the purpose of this study we aimed to investigate the effectiveness of Recycled Concrete Aggregates (RCA) on soil properties, establish the performance of highest RCA % and predict soil strength, through the use of Artificial Intelligence (AI) models, and compare the performance and accuracy of Linear Regression against Random Forest models to estimate soil behavior.

1.5 Contributions of the Paper : In this research, RCA is being investigated as a sustainable stabilizing material in strengthening weak soil. It reports precise experimental outcomes showing improvement in soil characteristics such as strength, compaction properties, surface performance and performance in stabilized soil. With this research, AI-based predictive modeling technologies predicting soil properties using machine learning (ML) has been introduced into the research environment that can aid in more rapid analysis to accelerate the work process quicker and easier on environmental impact beyond laboratory studies. Combining real-life experimentation with information-based model-guided models (like AI) approaches results are integrated into the framework, the findings of this study develop a model that provides a framework to investigate and predict soil properties by better understanding, to build trust within the practical and to be used to predict, at the least to better predict conditions are much more plausible to geotechnical engineering.

1.6 Organization of the Paper. : Section 2 discusses the literature review. Materials and methods are described in Section 3. Section 4 reports results and findings. Section 5 contains the conclusion.

2 Literature Review

Previous literature has reported different approaches to improve weak soil properties with both traditional and substitute materials. Recycled Concrete Aggregates (RCA) have been used in recent years due to their environmental and engineering benefits. Indeed, it has been reported that the addition of RCA to soil can lead to superior strength, compaction characteristics and plastic resistance.

This enhancement is attributed at least partially to the rough and angular nature of RCA particles, which leads to improved interlocking and load distribution. Several authors have observed that the best replacement rate is typically a ratio between 15% and 30% upon which the strongest improvement occurs. Fly ash, slag and other waste substances have also been used for soil stabilization besides RCA. They chemically interact with soil elements to give rise to cement-like products that are stronger and last longer than the traditional ones and also are more environmentally friendly. With an increasing emphasis on sustainable construction, construction and demolition waste reuse is increasingly being promoted as an innovative way to reduce landfill disposal and preserve natural resources. It promotes circular economy in civil engineering. However, the application of AI methodologies for geotechnical engineering is taking place. Such as Linear Regression and Random Forest are machine learning models to predict soil properties such as UCS and CBR. Of these models, Random Forest is frequently better than Linear Regression and has high accuracy since it can be able to capture complex inter-relations of dependent variables. Though many works have either investigated recycled materials or AI-based prediction, only a few combined methods were proposed. Thus, it is important to combine stabilization via RCA with AI modeling in order to achieve optimal and sustainable solutions for foundation engineering. Machine learning models (e.g., Linear Regression, Random Forest) are also effective for predicting geotechnical properties.

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Recent works have also demonstrated that advanced AI methods (e.g., neural networks and deep learning models), can be applied to closely estimate the compressive strength and soil characteristics (Jagadesh et al., 2024; Thapa & Ghani, 2025). Finally, machine learning in recycled concrete materials has enhanced the predictability and optimisation of performance that are integral in environmental sustainable construction (Zhang et al., 2025).It was further proven by more studies that the gradation and the particle size distribution of RCA can play a very important role in determining soil conditions. It has been shown that the quality of the RCA mixtures also contribute significantly to better compaction and load-bearing force compared to their ungraded counterparts.Furthermore, the residual cementitious compounds present in RCA may give rise to secondary hydration, which in increasing the strength of stabilized soil with time, can be a good reason for its stability as well. Several studies have also investigated the resilience of a range of RCA-stabilized soil conditions in different microclimate conditions.

These yields show superior resistance to wetting–drying and freeze–thaw cycle results for RCA blends and their application to pavement subgrades and embankment. However, performance in the long term is reliant on moisture variation, compaction quality, and recycled material percentage. In the last years, there has been a trend regarding the hybrid stabilization with RCA plus chemical additives, like lime or cement. These two types of composite offer mechanical and chemical stabilization and a higher strength and stiffness with the application of RCA than with RCA only. The hybrid methods work quite well in relatively plastic clays and expansive soils. Computationally, a higher level machine learning methods, like a Support Vector Machine (SVM), Gradient Boosting Machine (GBM) and an Artificial Neural Network (ANN), have been recently successfully applied for the prediction of soil stabilization results. The proposed models can adapt to nonlinearity and large datasets, and provide a much more reliable prediction compared to traditional empirical techniques. Recent developments have also highlighted the significance of dataset quality and feature choice in AI modeling. When predicting model performance, certain parameters like moisture content, curing period, RCA percentage and soil classification are also very important. To be precise, the accurate predictions can be greatly influenced upon the quality of preprocessed data which needs to be validated. Even with this progress, there are still issues of combining experimental with AI-based perspectives. Model generalization can be affected by small datasets, material property differences and absence of standard methodology. Thus, potential avenues for future studies are creation of holistic databases and hybrid modeling systems using a blend of laboratory experiments and sophisticated AI methods.

In the context of research on the potential of RCA as a sustainable soil stabilization material, existing literature shows that AI has been gaining importance in the field of geotechnical engineering. Although, there is no established paradigm, there is a rising field of incorporating machine learning and using RCA combined, which is an opportunity for innovation in sustainable foundation design.

3. Materials and Methods: The soil was a locally available clayey soil which normally has a low strength and high plasticity. These soils need improvement before construction can be done. Recycled Concrete Aggregates (RCA) were prepared by crushing waste concrete collected from demolition sites. These particles are highly rough and angular in formation, and promote bonding in soil. Clean water was consumed for mixing and maintaining the required moisture content during testing.

3.1 Experimental Program: To experimentally study the impact of RCA, soil samples used were added with different compositions of aggregates (0, 10, 20, 30%). The control sample, 0%, was collected. All the mixes were prepared for the correct blends of soil and RCA. Subsequently the samples were compacted and tested under similar conditions. The use of this approach facilitated the identification of which fraction of RCA provides the highest performance.

3.2 Tests Conducted: Numerous routine laboratory tests were performed with respect to the properties in the soil. The best moisture content and dry density were found with the use of the Standard Proctor Test. Strength of the soil was tested by conducting the Unconfined Compressive Strength (UCS). The California Bearing Ratio (CBR) Test has been done to determine if it is a good fit for a foundation and a pavement. Atterberg Limits experiments were also performed so as to identify the effect of adding RCA on the change in plasticity of the soil.

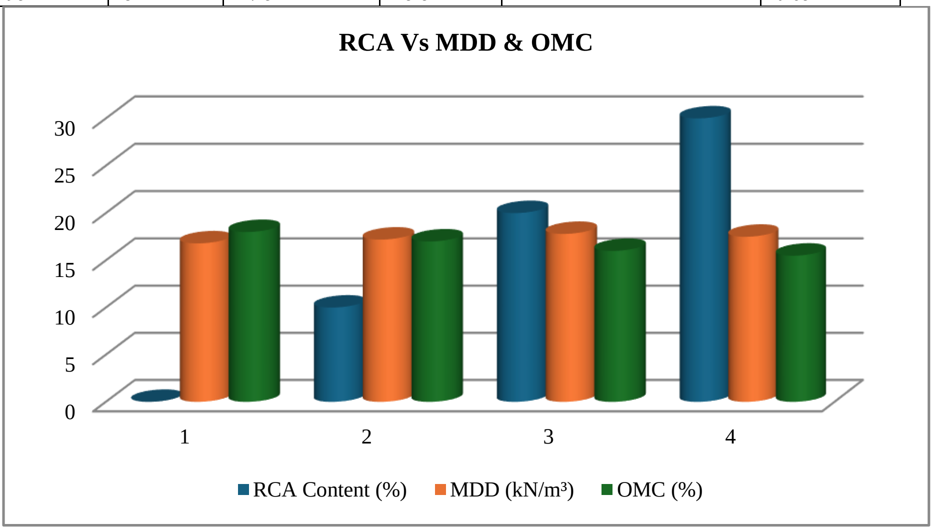
3.3 AI Model Development: The prediction of soil behaviour was achieved by incorporating machine learning models according to the experimental observations. Output UCS, CBR and bearing capacity were obtained based on RCA %, moisture content and density. Two models: Linear Regression and Random Forest were adopted to perform this study. Linear Regression assigns a simple relation to the inputs and outputs and Random Forest captures the intricate data relationships, thus obtaining a better precision. The models were constructed in Python and Excel for analysis and comparison.

4. Results and Discussion

4.1 Experimental Results

Table 1: Effect of RCA on Soil Properties

RCA Content (%)	UCS (kPa)	CBR (%)	MDD (kN/m³)	OMC (%)	Plasticity Index (%)	Void Ratio
0 (Control)	120	3.5	16.8	18	22	0.72
10	165	5.8	17.2	17	18	0.68
20	210	8.9	17.8	16	14	0.63
30	195	8.2	17.5	15.5	12	0.65



Graph1: RCA Content (%) with MDD &OMC

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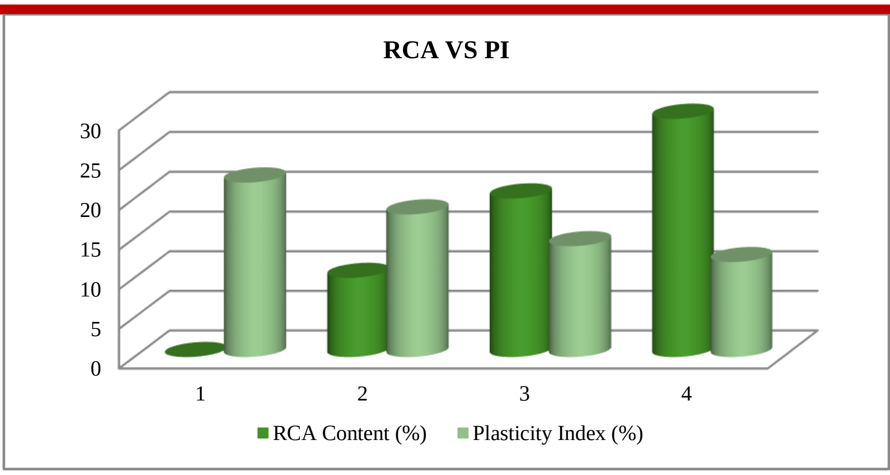

Graph2: RCA Content (%) with Plasticity Index (%)

Explanation : The results show that increasing RCA content improves soil strength and bearing capacity. The maximum UCS and CBR values are observed at 20% RCA, indicating the optimum mix. Beyond this level, a slight decrease occurs due to reduced cohesion. The plasticity index decreases steadily, showing improved soil stability.

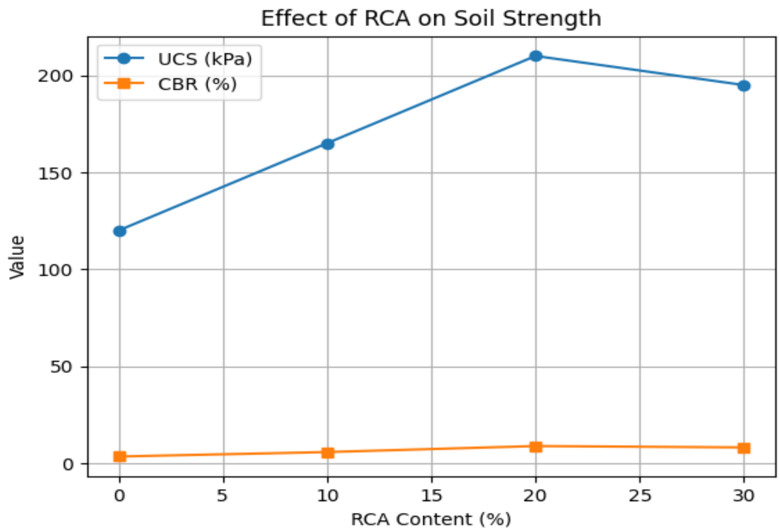

Figure 1: Variation of Unconfined Compressive Strength (UCS) with RCA Content

Explanation: The values of UCS are also plotted from 0%-20% Recycled Concrete Aggregates (RCA). This is due to the better interlocking of particles and less plasticity of the soil. The highest strength is attained at 20% of RCA in favor of best mixing. At 30% RCA, a minor reduction of UCS is observed which could be attributed to excess aggregate content damaging the soil matrix cohesion.

4.2 Compaction Behavior : Maximum Dry Density (MDD) is enhanced due to higher RCA content up to 20% - with this increasing the tendency that the compactability is improved and air voids are decreased. This is caused by better gradation and packing properties in soil-RCA mixtures. MDD: at 30% is a little less because excessive coarse particles prevent proper compaction.

4.3 Moisture Content : RCA content reduces the optimum moisture content (OMC). This is because RCA has lower water absorption than fine-grained soils, and less water has to be available for maximum density.

4.4 Plasticity Reduction : With the addition of RCA, the plasticity index significantly decreases as the swelling and shrinkage behavior is diminished. This is the improvement that lends itself well for foundation applications for higher stability in soils.

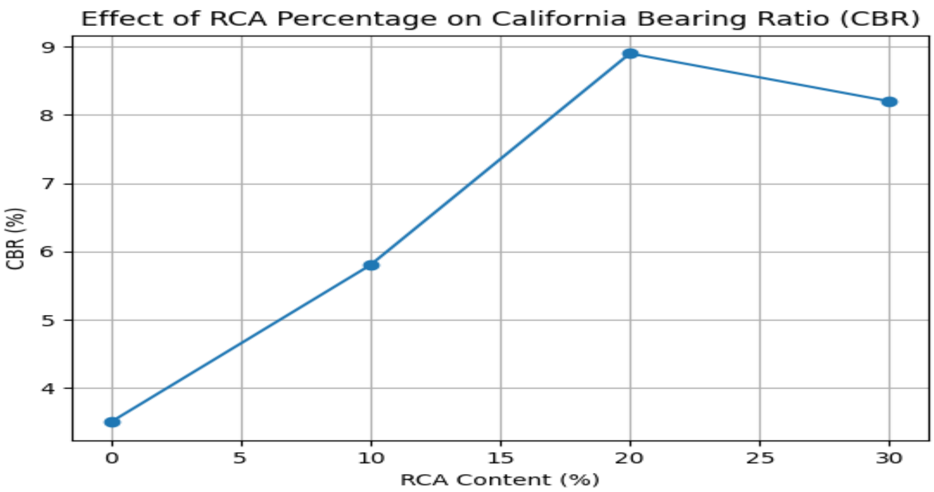

Figure 2: Effect of RCA percentage on California Bearing Ratio (CBR)

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Explanation

The graph is a visual representation of variation of California Bearing Ratio (CBR) with a rise in the level of recycled concrete aggregate (RCA) and in the load bearing capacity of soil. A high increase in CBR (CBR value) from 3.5% at 0% RCA (control sample) to 5.8% at 10% RCA shows that the load-bearing capacity of the soil is better. At 20% of the RCA as of last analysis the CBR is expected to increase sharply and the value reaches a highest value of 8.9%, indicating a suitable replacement value. This is owing to improvement in particle interlocking, better compaction and plasticity reduction of the soil. Nonetheless, the CBR value slightly decreases to 8.2% at 30% RCA, possibly due to the over abundance of coarse particles in the soil matrix that reduces the cohesiveness and bonding of the soil. Generally, the graph suggests very well when the RCA component is added, while at a certain point the soil strength decreases slightly.

4.5 AI Model Performance

Table 2: Model Accuracy

Model	R^2 Score	RMSE
Linear Regression	0.87	12.5
Random Forest	0.95	6.8

Unlike Linear Regression, Random Forest performs better for the predictions. The findings indicate an excellent fit between the predicted and measured values. Using AI helped save time and effort in repeating lab testing.

4.6 Discussion

This integrated approach of RCA along with AI can have multiple benefits. The use of recycled concrete reduces construction waste and contributes to sustainable development. Simultaneously, increased soil strength improves foundation performance and mitigates settlement challenges. AI allows speedy prediction of soil behavior, and has made it more efficient and cost-effective.

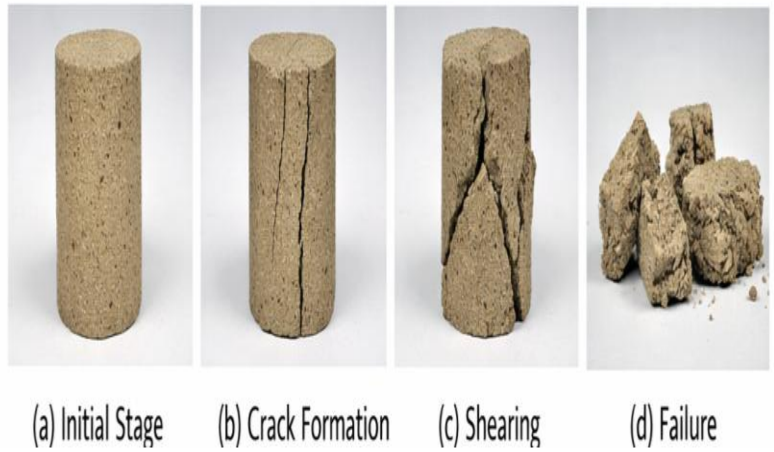

Figure 3: UCS Test Sample Failure Patterns

Explanation

Different failure stages of soil sample under experiment UCS test are depicted in Figure 3. The sample does not crack at first. Small vertical cracks start appearing with the increase of load. When loaded further, these cracks become shear planes demonstrating internal failure. Finally, the specimen fragments into pieces corresponding to complete failure. This arrangement indicates that the soil is slowly changing shape before it breaks down and the presence of RCA helps in delaying crack formation and improving strength.

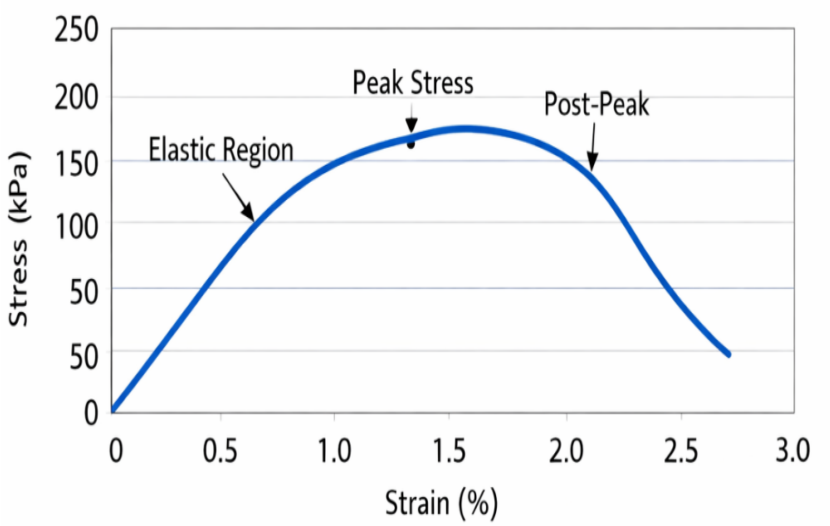

Figure 4: Stress–Strain Curve from UCS Test

Explanation

Figure 4 portrays the relationship between stress and strain during the UCS test. First, the curve shows a linear increase, the elastic region, which has the least deformation and is mostly reversible. The maximum compressive strength of the soil is then attained when a nonlinear curve is obtained, the peak of this curve occurs and continues to be plotted. The stress decreases after this peak in response to strain, indicating the sample failure. This tendency means that the soil is able to mobilize strength up to a certain limit and fails when no longer carrying a load. It shows for the first time that adding

5. Conclusion

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Recycled Concrete Aggregates (RCA) greatly improves the engineering properties of weak soils. For instance, the experimental findings show UCS and CBR increase as RCA content increases with its application and the highest performance occurs at around 20% replacement. And finally, there are numerous references to soil quality studies in this field showing that applying recycled concrete to weak soil increases its engineering properties. Slightly less strength is observed above this level due to lower cohesion and more coarse particles.
This is due to the better structure of the particles with interlocking that RCA generates. The fact of the aggregates having angular shape also improves the load transfer and helps avoid deformation. The reduction in the plasticity index and moisture content will demonstrate that on average the structure of the soils has stabilized and become less sensitive to water. This behaviour is in accordance with overall soil stabilizers that the inclusion of granular materials will provide a higher strength at the expense of compressibility.
The results of this study are in line with earlier studies that suggested higher strength and compaction results can be obtained using recycled concrete materials [3,5,11]. Similarly, the prediction of soil properties using machine learning models has also been reported in previous studies, where Random Forest models achieved superior accuracy than traditional regression approaches [1,10,17]. The Random Forest model provided a higher prediction accuracy in the current study indicating that it is a good approach to use the model in geotechnical projects.
The impact of this analysis is significant for sustainable construction. RCA minimizes construction waste and reduces the use of natural aggregates. AI-based prediction supports faster decision-making and minimizes laboratory work. The combining of these approaches will be an economical and environmentally beneficial solution for soil stabilization and foundation design. Nonetheless, limitations need to be acknowledged.
This study was based on laboratory-scale experiments and field conditions may lead to different results due to environmental variations. Because of the smaller dataset used for AI modeling, the prediction might not be as accurate within the larger scope. Only two machine learning models were considered, as more sophisticated techniques could yield better results.

Future research

can focus on validating these findings through field studies and long-term performance analysis. The use of hybrid or deep learning models may further improve prediction accuracy. It is also recommended to explore the combined use of RCA with other waste materials to enhance performance.
In summary, this study demonstrates that RCA is an effective material for soil stabilization, and AI models can successfully predict soil behavior. While some limitations exist, the overall results highlight the potential of combining sustainable materials and intelligent techniques for modern geotechnical engineering applications.

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