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Performance Evaluation of Recycled Concrete Aggregates in Seismic-Resistant Structural Design

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Abstract

The increasing demand for construction materials has led to excessive exploitation of natural aggregates, raising concerns about environmental sustainability and carbon emissions. Recycled Concrete Aggregate (RCA) has been introduced as a potential alternative to natural aggregates, but its application in seismic-resistant structures remains a challenge due to its lower mechanical properties. This study aims to evaluate the structural performance of RCA-based concrete in seismic applications by analyzing its compressive strength, tensile strength, elastic modulus, and cyclic loading resistance. An experimental approach was employed, where concrete samples with RCA proportions of 0%, 25%, 50%, 75%, and 100% were tested under standardized laboratory conditions. The results indicate that RCA can be used up to 50% without significant loss of compressive strength, which remained above 30 MPa. However, at RCA proportions above 50%, compressive strength decreased by up to 30%, and the elastic modulus dropped from 30.2 GPa (0% RCA) to 20.8 GPa (100% RCA). Cyclic loading tests further revealed a reduction in energy dissipation capacity, from 85 kJ at 0% RCA to 55 kJ at 100% RCA, and an increase in residual deformation. These findings highlight the need for mix optimization in high-RCA concrete, such as incorporating supplementary materials like fly ash, nano-silica, or fiber reinforcement to enhance mechanical performance. This study contributes to the sustainable development of construction materials by providing insights into the feasibility and limitations of RCA in seismic-resistant structures.

Keywords: *RCA, Seismic-Resistant Structures, Compressive Strength, Cyclic Loading, Sustainable Construction.*

I. INTRODUCTION

The construction industry is one of the sectors with the highest resource consumption globally, particularly in the use of natural aggregates as the primary material for concrete production. The continuous increase in demand for construction materials has led to massive exploitation of natural resources, resulting in environmental degradation and a rise in global carbon emissions. According to a report by the United Nations Environment Programme (UNEP), the construction industry accounts for approximately 39% of total global carbon emissions, with cement production being one of the primary contributors to these high emissions. In addition, construction and demolition waste also pose significant environmental challenges, with an estimated over 2 billion tons of construction waste generated annually worldwide. In recent decades, various efforts have been undertaken to mitigate the environmental impact of the construction sector, one of which is the utilization of RCA as a more sustainable material alternative. RCA is derived from crushed and processed old concrete, enabling its reuse as a building material, with the potential

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to reduce dependence on natural aggregates and decrease the volume of construction waste disposed of in landfills. In countries such as Japan and the Netherlands, construction waste recycling policies have successfully increased the use of RCA in the concrete industry. However, its application in earthquake-resistant structural design still requires further study.

Concrete with RCA has been developed as an alternative to reduce the exploitation of natural resources. However, its implementation in earthquake-resistant structures still faces various challenges. According to (Fanijo et al., 2023), the use of RCA in concrete can result in a reduction of compressive strength by up to 30% compared to concrete with natural aggregates, potentially affecting structural stability under dynamic loads. (Z. Liu et al., 2024) reported that RCA exhibits up to 50% higher porosity, which can increase water absorption and accelerate material degradation in extreme environmental conditions, including exposure to repeated seismic loading cycles. The varying mechanical properties of RCA can also lead to a reduction in the elastic modulus of concrete by up to 25%, affecting the flexibility and structural response to seismic forces. Structures incorporating RCA-based concrete tend to experience greater residual deformation after cyclic loading, which may reduce the ability of the structure to return to its original shape following an earthquake. These conditions indicate the necessity of further understanding the impact of RCA on the performance of earthquake-resistant structures, particularly in identifying strategies to enhance its performance while ensuring compliance with building safety standards.

The use of RCA in construction has been the focus of various studies aimed at reducing dependence on natural aggregates and addressing construction waste issues. According to (Muda et al., 2023), RCA exhibits different mechanical properties compared to natural aggregates, with higher porosity that may affect the compressive strength of concrete. (Xu et al., 2022) investigated the performance of RCA in structural concrete and found that the use of RCA up to 50% can still produce concrete with compressive strength that meets construction standards. (Cantero-Durango et al., 2023) examined the impact of RCA on concrete durability and reported that an increase in RCA proportion can reduce the elastic modulus, which has implications for structural stiffness. (Forero et al., 2022) demonstrated that RCA, being rougher than natural aggregates, can enhance mechanical interaction within concrete but may also increase water consumption in the concrete mix. (Tayebani et al., 2023) analyzed the impact of RCA utilization in earthquake-resistant structural design and found that the reduction in split tensile strength due to RCA usage can be compensated by the addition of supplementary binders such as fly ash or nanosilica.

Various studies have also evaluated the behavior of RCA under dynamic loading conditions, particularly in structures designed for seismic resistance. (Zhang et al., 2023) conducted cyclic tests on RCA-based concrete and reported that its energy dissipation capacity is lower than that of concrete with natural aggregates, which may affect structural response during earthquakes. (Imjai et al., 2024) compared the performance of reinforced concrete beams with different RCA proportions and found that using RCA above 50% can lead to increased residual deformation after cyclic loading. (Nikmehr & Al-Ameri, 2022) examined the effectiveness of RCA in precast concrete beams and showed that although RCA has lower compressive strength, its combination with additional materials can improve resistance to cracking under dynamic loads. (Zheng et al., 2022) investigated the relationship between RCA proportion and energy dissipation capacity in structural elements and found that increasing RCA content can reduce cyclic resistance due to microcrack accumulation. (Dong et al., 2023) evaluated the effect of RCA on reinforced concrete columns and reported that RCA usage may reduce axial load capacity, but this effect can be controlled through optimized mix design.

Although various studies have discussed the use of RCA in construction, several aspects remain insufficiently explored, particularly in the context of earthquake-resistant structures. (Yan et al., 2025) investigated the mechanical properties of RCA and found that this material has lower compressive strength compared to natural aggregates. However, no study has specifically examined how RCA affects structural resistance to repeated cyclic loading. (Liang et al., 2022) evaluated the performance of RCA in structural concrete and reported that its use can reduce the elastic modulus of concrete, but this study did not investigate its impact on energy dissipation in earthquake-resistant structural systems. (Panghal & Kumar, 2024) demonstrated that RCA can be utilized in sustainable construction with specific mix modifications. However, no study has explicitly addressed how these modifications can be applied in the design of structural elements that undergo deformation due to seismic activity. (Duan et al., 2023) examined the effect of RCA on the porosity and water absorption capacity of concrete, but their study did not relate the findings to potential changes in RCA concrete behavior under prolonged earthquake conditions. (Yang et al., 2023) tested the tensile strength of RCA concrete and found that the addition of supplementary materials can improve its performance. However, their study did not discuss how tensile strength contributes to the ductility of structures under cyclic loading.

In addition to the limited research on the impact of RCA on structural resilience, only a few studies have addressed technical standards and practical recommendations for implementing RCA in earthquake-resistant buildings. (Zhang et al., 2022) investigated the cyclic test response of RCA concrete beams and found that their energy dissipation capacity is lower than that of conventional concrete. However, this study did not explore design strategies to enhance structural resistance. (X. Liu et al., 2023) examined the performance of RCA concrete elements under dynamic loading conditions and found that residual deformation tends to increase with higher RCA proportions.

Nevertheless, this study did not discuss how this deformation could be controlled through mixing techniques or the use of specific additives. (Nor et al., 2023) investigated the effectiveness of RCA in precast structures and found that RCA concrete performs adequately under static loads. However, their study did not evaluate how the material responds to combined axial and lateral loads, which are common during earthquakes. (Revilla-Cuesta et al., 2022) analyzed the relationship between RCA substitution levels and the energy dissipation capacity of concrete, but their research was limited to laboratory testing without validation through numerical simulations or field case studies. (Huang et al., 2023) examined the use of RCA in reinforced concrete columns and found that its application can reduce axial load capacity. However, no study has explored how RCA can be combined with reinforcement techniques to enhance structural performance under seismic conditions.

The scarcity of studies systematically evaluating RCA performance in earthquake-resistant designs highlights gaps in the literature that require further investigation. (He et al., 2023) noted that most research still focuses on the mechanical properties of RCA without considering how this material can be integrated into more complex structural design systems. (Cao et al., 2023) pointed out that testing standards for RCA in earthquake-resistant design vary across countries, indicating the need for a more uniform approach to validate research findings. (Wang & Du, 2024) studied the use of RCA in modular structural systems, but their research did not address how combining RCA with other materials could improve seismic resistance. (Chang et al., 2025) demonstrated that the quality of RCA is highly dependent on its source materials. However, there is still a lack of research on strategies for improving RCA quality through advanced processing techniques. Therefore, this study aims to bridge these gaps by evaluating the performance of RCA in earthquake-resistant structural design and analyzing the effect of RCA proportions on the mechanical properties and cyclic resistance of concrete.

This study seeks to evaluate the performance of RCA in earthquake-resistant structural design through a series of laboratory tests and mechanical analyses. One of the primary aspects to be examined is how the proportion of RCA in concrete mixtures influences compressive strength, split tensile strength, elastic modulus, and resistance to cyclic loading that simulates earthquake conditions. By understanding the behavior of RCA in various structural conditions, this study aims to provide recommendations on the safe limits of RCA utilization in earthquake-resistant construction. The main research questions to be addressed include the extent to which RCA can replace natural aggregates without compromising structural performance and how concrete mix modifications can enhance RCA durability against seismic forces. The findings of this study are expected to contribute to the development of technical standards and policies related to RCA utilization in the construction industry, particularly in earthquake-prone regions. Additionally,

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Vol. 1 No. 1 March 2025
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this study aims to support sustainability efforts in the construction sector by reducing dependence on natural resources and promoting the use of concrete waste as a more environmentally friendly material.

II. RESEARCH METHOD

This study employs an experimental laboratory approach to test the mechanical properties of concrete containing RCA in various proportions. This approach enables testing under controlled conditions, ensuring that each variable can be systematically observed. The use of RCA in concrete has gained increasing research attention due to its potential to reduce construction waste and dependence on natural aggregates. In this study, various RCA mix variations are tested to understand their effects on the mechanical characteristics of concrete. The primary parameters analyzed include compressive strength, split tensile strength, elastic modulus, and cyclic resistance under seismic loading. Each test is conducted in accordance with applicable standards to ensure that the results can be accurately interpreted in the context of structural applications.

The research process consists of several key stages, including material preparation, concrete sample fabrication, mechanical testing, and data analysis. The material preparation stage involves crushing and screening concrete waste to obtain RCA with particle sizes and physical characteristics that meet technical specifications. The processed RCA is then tested for its physical and chemical properties, such as density, porosity, and water content, to ensure its suitability as a substitute for natural aggregates. Once the materials are prepared, concrete samples are produced with varying RCA proportions 0%, 25%, 50%, 75%, and 100% to evaluate changes in mechanical properties resulting from aggregate substitution. Each cast sample is tested using standardized methods to obtain data on compressive strength, split tensile strength, elastic modulus, and response to cyclic loading. The test results are systematically collected and compared with conventional concrete to identify trends in mechanical property changes due to RCA usage. After all data are obtained, statistical analysis is performed to determine the relationship between RCA proportions and concrete performance based on the measured parameters.

The RCA used in this study is sourced from demolished concrete waste, which is subsequently crushed, screened, and tested to verify its feasibility for use in concrete mixtures. The crushing and screening processes ensure that the aggregate meets the required size specifications, allowing it to be incorporated into concrete mixtures without significantly compromising quality. Additionally, Natural Aggregates (NA) are used as a control in this experiment to compare how differences in material composition affect the mechanical properties of the resulting concrete. To ensure that the concrete produced meets construction standards, the material composition is designed in accordance with ASTM C33 and SNI 7656:2015 specifications. The differences in physical characteristics between RCA and natural aggregates are presented in Table 1, which outlines variations in density, porosity, and water content for both types of aggregate. Based on this table, RCA exhibits lower density and higher porosity and water content compared to natural aggregates, which may influence the mechanical properties and long-term durability of concrete.

Table 1. Characteristics of RCA and Natural Aggregates

Parameter	RCA	Agregat Alam
Density (kg/m³)	2200-2500	2600-2800
Porosity (%)	5-10	2-5
Water Content (%)	3-7	0.5-2

In this study, concrete samples are prepared by mixing RCA and natural aggregates in various proportions, as shown in Table 2. This mixing process aims to evaluate how variations in RCA usage influence the mechanical properties of concrete, particularly in terms of strength and durability. Five mix variations are used in this study, ranging from concrete without RCA (0% RCA), which relies entirely on natural aggregates as a control, to concrete with 100% RCA, where natural aggregates are fully replaced. Each mix variation is designed to observe changes in concrete properties as the RCA percentage gradually increases in the composition. By implementing different mix compositions, this study seeks to determine the extent to which RCA can be utilized without significantly compromising the structural performance of concrete. The data obtained from these various mix proportions are analyzed to understand RCA's role in enhancing or reducing concrete strength and the implications of its application in construction.

Table 2. RCA Mix Variations in Concrete Samples

RCA Proportion (%)	Natural Aggregate Proportion (%)	Description
0 (Control)	100	Conventional concrete without RCA (only natural aggregate).
25	75	Concrete with 25% RCA and 75% natural aggregate.
50	50	Concrete with an equal composition of RCA and natural aggregate.
75	25	Concrete predominantly composed of RCA with a small amount of natural aggregate.
100	0	Concrete fully utilizing RCA without natural aggregate.

Table 2 presents the various RCA and natural aggregate mix compositions used in this study along with their descriptions. The control sample represents conventional concrete that exclusively uses natural aggregates without RCA, serving as the primary reference for performance analysis. In the 25% RCA variation, the concrete contains a small portion of recycled aggregate, while the remainder consists of natural aggregate, allowing for an initial assessment of RCA's impact on concrete strength and durability. The 50% RCA sample has a balanced composition of natural aggregate and RCA, providing insights into the transitional characteristics of concrete with an equal aggregate ratio. Meanwhile, in the 75% RCA mix, concrete is primarily composed of recycled aggregate with only a small amount of natural aggregate, offering a further understanding of the RCA utilization threshold before significant quality degradation occurs. The final sample, with 100% RCA, relies entirely on recycled aggregate without any natural aggregate, enabling an analysis of RCA's feasibility as a full replacement in structural concrete mixtures.

Compressive strength testing is conducted to assess the concrete's ability to withstand maximum compressive loads before structural failure. This evaluation is performed using a Universal Testing Machine (UTM) in accordance with ASTM C39 standards, ensuring a consistent and reliable testing procedure. The compressive strength value is calculated using the following equation (1):

$$f_c' = \frac{P}{A} \tag{1}$$

Where P represents the maximum load in Newtons (N), and A is the cross-sectional area of the concrete specimen in square millimeters (mm^2). This parameter serves as a key indicator in determining the concrete's strength and its suitability for construction applications. The results of the compressive strength test provide insights into concrete quality, particularly in the context of using RCA as a substitute for natural aggregates. By analyzing the obtained compressive strength values, the study evaluates how different RCA proportions in the concrete mix influence the structural capacity to withstand compressive loads.

Additionally, the split tensile strength of the concrete is tested to evaluate its resistance to tensile forces, which may cause cracking or structural failure. This test follows ASTM C496 standards and is conducted using cylindrical concrete samples subjected to lateral loading until reaching maximum tensile stress. The split tensile strength is calculated using the following formula (2):

$$f_t = \frac{2P}{\pi LD} \tag{2}$$

Where P is the maximum load in Newtons (N), L represents the length of the concrete cylinder in millimeters (mm), and D is the diameter of the concrete cylinder in millimeters (mm). The split tensile strength values obtained from this test play a crucial role in determining the concrete's ability to resist tensile forces within structural applications, particularly in elements subjected to bending loads. By analyzing the split tensile strength results, comparisons can be made between conventional concrete and RCA-containing concrete in terms of their ability to withstand tensile stress before cracking occurs.

In addition to compressive and split tensile strength testing, the elastic modulus is also measured to determine the stiffness of the concrete and its ability to withstand elastic deformation under applied loads. This test is performed in accordance with ASTM C469 standards, which specify the method for measuring the elastic modulus of concrete under specific loading conditions. The elastic modulus is calculated using the following equation (3):

$$E_C = 4700\sqrt{f_c'} \tag{3}$$

Where E_C is the elastic modulus in megapascals (MPa), and $f'c$ is the concrete's compressive strength in MPa. This parameter is essential for describing how concrete responds to applied loads, particularly in structural applications requiring deformation stability. By comparing the elastic modulus values of different RCA mix variations, the study provides an understanding of how recycled aggregate influences the stiffness and structural reliability of concrete. The data obtained from these tests serve as a foundation for evaluating the performance of RCA-based concrete and its potential application in construction projects requiring materials with adequate mechanical properties.

Cyclic load resistance testing was conducted to evaluate the response of concrete to repeated loading conditions similar to those experienced during an earthquake. This test aimed to measure the extent to which concrete with varying proportions of RCA could maintain its structural capacity under repeated dynamic loading. The key parameters analyzed in this test included the number of cycles until failure, energy dissipation capacity, and residual deformation, each providing insights into the durability and stability of concrete under cyclic loading conditions. The results of this test are summarized in Table 3, which indicates that concrete with a higher RCA proportion tends to exhibit a decline in energy dissipation capacity and an increase in residual deformation. A reduction in energy dissipation capacity suggests that RCA-containing concrete is more susceptible to structural performance degradation due to repeated loading, thereby diminishing its ability to absorb seismic energy. Additionally, an increase in residual deformation indicates that concrete with RCA undergoes greater permanent deformation after loading cycles, which may affect the long-term stability of structural elements. Through an analysis of these test results, a deeper understanding can be gained regarding the impact of RCA utilization on the cyclic resistance of concrete, which is a crucial factor in determining the feasibility of this material for structural applications in earthquake-prone regions.

Table 3. Cyclic Load Test Parameters for Concrete

RCA Proportion (%)	Cycles Until Failure	Energy Dissipation Capacity (kJ)	Residual Deformation (%)
0% (Control)	500	85	1.2
25%	480	80	1.5
50%	450	75	1.8
75%	420	65	2.2
100%	400	55	2.5

The data analysis in this study was conducted using statistical methods and artificial intelligence-based approaches to assess the performance of concrete incorporating recycled aggregates. One of the techniques applied was analysis of variance (ANOVA), which aimed to compare the compressive strength differences among the various RCA proportion variations in the concrete mix. Through this method, it was possible to identify whether the substitution of natural aggregates with RCA resulted in statistically significant differences in concrete performance. Furthermore, non-linear regression was employed to model the relationship between RCA proportion and the mechanical properties of concrete, including compressive strength, split tensile strength, and elastic modulus. This technique allowed researchers to understand the patterns of change in concrete characteristics as the RCA percentage increased, enabling predictions regarding the performance of concrete under different usage conditions. Meanwhile, the evaluation of cyclic resistance was conducted using a confusion matrix, which classified the level of concrete damage based on the cyclic load test data. This technique helped determine the extent to which the material could withstand repeated loading and how variations in RCA content influenced its structural stability under dynamic conditions. By integrating statistical methods with AI-based evaluation, this study provides a more comprehensive understanding of the impact of RCA on concrete performance and its feasibility for structural applications requiring high mechanical resistance.

III. RESULT

A. Results

1. Effect of RCA on Structural Performance

The compressive strength test was conducted to evaluate the impact of using RCA on the strength of structural materials. Concrete samples with varying RCA proportions, ranging from 0% to 100%, were tested to understand the extent to which the substitution of natural aggregates affects their mechanical performance. The obtained data reflect trends in compressive strength variations due to the increasing proportion of RCA in the concrete mix. The standard deviation was also measured to assess data distribution and the consistency of the compressive strength test results. By analyzing these variations, the optimal RCA utilization limit that still meets structural design requirements can be identified. The test results are systematically summarized in Table 4.

Table 4. Compressive Strength Test Results for Concrete with RCA

RCA Proportion (%)	Average Compressive Strength (MPa)	Standard Deviation (MPa)
0% (Control)	40.5	2.1
25%	38.2	2.3
50%	35.7	2.5
75%	30.8	2.7
100%	28.3	3.0

Based on the data in Table 4, it is evident that the compressive strength of concrete decreases as the RCA proportion increases. Concrete with 25% and 50% RCA still exhibits compressive strength above 30 MPa, which is generally considered to meet structural design standards. However, when the RCA proportion reaches 75% and 100%, the compressive strength declines more significantly, indicating that a high RCA content can reduce the concrete's ability to withstand compressive loads. Furthermore, the increasing standard deviation with higher RCA content suggests greater variability in test results, which may be attributed to the heterogeneous nature of RCA. Therefore, optimizing the mix design or incorporating additional materials becomes crucial to maintaining adequate mechanical performance, particularly in concrete mixes with RCA proportions exceeding 50%.

The downward trend in compressive strength is further illustrated in Figure 1, which depicts the relationship between RCA proportion and concrete compressive strength. This graph clearly demonstrates how an increase in RCA content results in a consistent decline in compressive strength. The data presented in the graph were obtained from compressive strength tests on various RCA proportions, ranging from 0% to 100%. The observed pattern indicates that a high RCA content significantly influences the mechanical performance of concrete. This visualization provides a clearer representation of how substituting natural aggregates with RCA alters the characteristics of concrete.

Civil Engineering Science and Technology (CEST)
Vol. 1 No. 1 March 2025
E-ISSN: XXXX-XXXX; P-ISSN: XXXX-XXXX, Pages 75-93

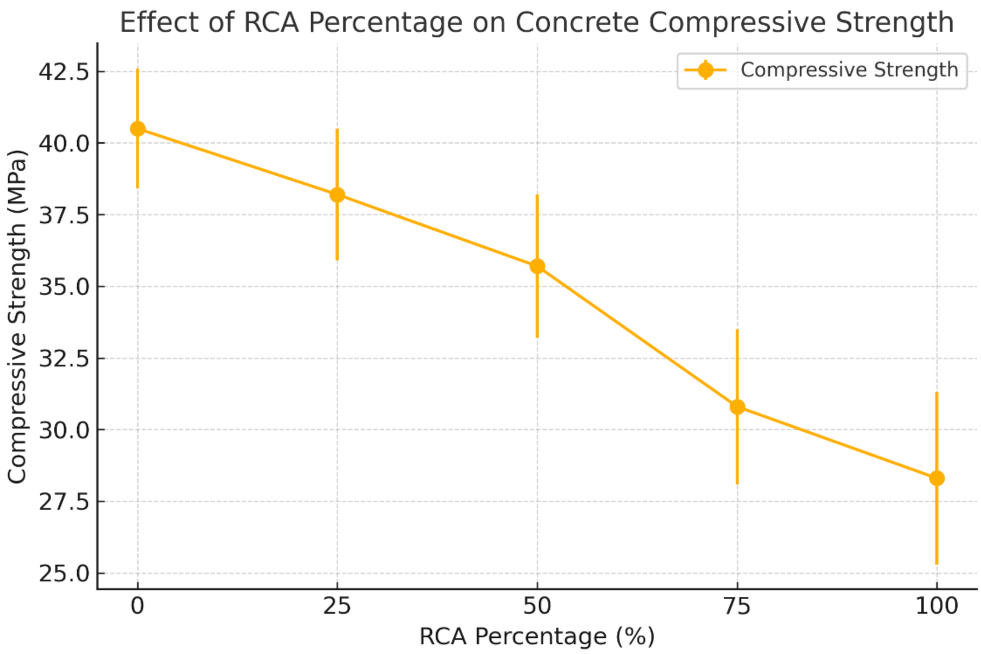

Figure 1. Relationship Between RCA Proportion and Concrete Compressive Strength

In Figure 1, it can be observed that concrete with 0% RCA exhibits the highest compressive strength, whereas concrete with 100% RCA experiences a substantial reduction in load-bearing capacity. The graph shows a relatively stable downward trend, where each increase in RCA percentage corresponds to a decline in compressive strength. The presence of error bars in the graph illustrates the variability in test results, which may be influenced by factors such as RCA quality, mix proportions, and the concrete mixing process. This pattern suggests that RCA utilization affects concrete strength characteristics, particularly at higher proportions. The large-scale use of RCA may lead to changes in the microstructure of concrete, impacting its mechanical properties. Further studies are needed to explore potential mix modifications to enhance the performance of concrete with higher RCA proportions.

The splitting tensile strength test was conducted to assess the resistance of concrete to tensile forces, which is a crucial parameter in earthquake-resistant structures. Concrete with good splitting tensile strength is more resistant to cracking and deformation caused by cyclic loading during seismic events. The test was performed on various RCA proportions 0%, 25%, 50%, 75%, and 100% to understand the impact of substituting natural aggregates on the tensile performance of concrete. The splitting tensile strength values obtained from the test can be used to evaluate the extent to which RCA-containing concrete meets structural design requirements. Variations in the test results also provide insights into the homogeneity of the mixture and the consistency of the materials used. The splitting tensile strength test results for each RCA variation are presented in Table 5.

Table 5. Splitting Tensile Strength Test Results for Concrete with RCA

RCA Proportion (%)	Splitting Tensile Strength (MPa)	Standard Deviation (MPa)
0% (Control)	3.5	0.2
25%	3.3	0.2
50%	3.0	0.3
75%	2.7	0.3
100%	2.5	0.4

The results in Table 5 indicate that the splitting tensile strength of concrete gradually decreases as the RCA proportion increases. Concrete with 0% RCA exhibits the highest splitting tensile strength, while concrete with 100% RCA shows a significant reduction. This decline can be attributed to the more porous nature of RCA and its weaker interfacial bonding compared to natural aggregates. Although concrete with up to 50% RCA still maintains relatively good splitting tensile strength, the use of RCA beyond this threshold results in a more pronounced reduction, which may affect the structural resistance to tensile loads. The increasing standard deviation at higher RCA proportions suggests that incorporating RCA tends to produce greater variations in test results. To enhance the tensile resistance of concrete with high RCA content, the use of supplementary materials such as fibers or stronger binding agents could be considered.

These variations in splitting tensile strength are illustrated in Figure 2, which shows the downward trend in tensile resistance as the RCA proportion increases. The graph indicates that a higher RCA content makes concrete more brittle under tensile forces. This decline occurs gradually, with the highest splitting tensile strength observed in concrete without RCA and the lowest in concrete with 100% RCA. The graphical representation provides a clearer understanding of the changing trends compared to tabular data alone. Additionally, the displayed standard deviation range highlights variations in test results, which may be attributed to the heterogeneity of recycled aggregates. This visualization offers valuable insight into the influence of RCA on concrete's tensile resistance, an essential aspect in earthquake-resistant structural design.

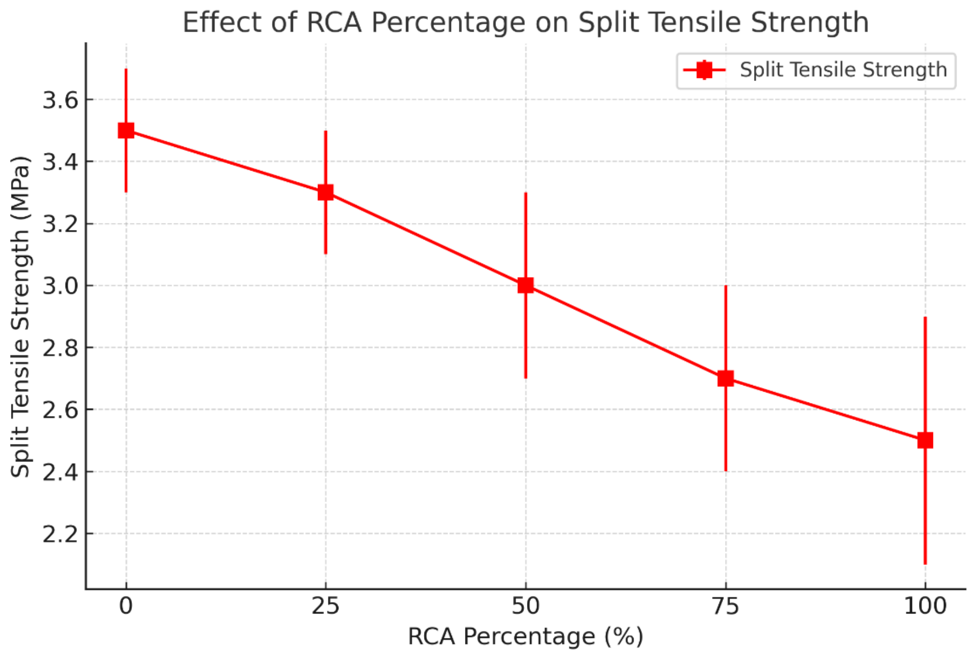

Figure 2. Relationship Between RCA Proportion and Splitting Tensile Strength of Concrete

The graph in Figure 2 illustrates the negative correlation between increasing RCA proportion and decreasing splitting tensile strength. At 0% RCA, the splitting tensile strength reaches its highest value, whereas at 100% RCA, a significant reduction is observed. This can be attributed to the more porous characteristics of RCA and its weaker interparticle bonding compared to natural aggregates. As the RCA proportion increases, the likelihood of microcracks also rises, contributing to a decline in tensile resistance. The broader standard deviation range at higher RCA proportions suggests that RCA-containing materials exhibit greater variability in test results. These findings indicate that the use of RCA in concrete should be accompanied by additional reinforcement strategies to maintain optimal tensile performance.

In addition to affecting the splitting tensile strength, an increasing proportion of RCA also impacts the elastic modulus of concrete, which is a crucial parameter in determining the structural deformation response under dynamic loads. Table 6 presents the test results for the elastic modulus of concrete with various RCA proportions. Similar to the trend observed in splitting tensile strength, the elastic modulus also decreases as the RCA content increases. This indicates that concrete with a higher RCA proportion tends to exhibit more flexible properties compared to concrete with natural aggregates. This characteristic can influence structural stiffness, particularly in the design of elements requiring high deformation resistance. Analyzing the elastic modulus is therefore a critical aspect to ensure that RCA-containing concrete maintains mechanical performance in accordance with the desired design standards.

Table 6. Elastic Modulus Test Results for Concrete with RCA

RCA Proportion (%)	Average Compressive Strength (MPa)	Standard Deviation (MPa)
0% (Control)	30.2	1.5
25%	28.5	1.7
50%	26.0	1.8
75%	23.5	2.0
100%	20.8	2.3

As shown in Table 6, the elastic modulus of concrete gradually decreases from 30.2 GPa for concrete without RCA to 20.8 GPa for concrete with 100% RCA. This decline indicates that concrete with a higher RCA proportion has a reduced ability to resist shape deformation under applied loads. The increasing standard deviation with higher RCA content suggests variability in material characteristics, which may be attributed to differences in the quality of recycled aggregates. Concrete with up to 50% RCA still exhibits a relatively high elastic modulus and falls within an acceptable range for structural applications. However, at RCA proportions exceeding 75%, a significant reduction is observed, which may affect concrete performance under dynamic loading conditions. The use of supplementary materials or optimized mix designs can be a viable strategy to maintain elasticity characteristics in accordance with structural requirements.

2. Cyclic Resistance of Concrete with RCA

The resistance of concrete to cyclic loading is a crucial factor in determining structural performance during seismic events. Table 7 presents the test results for the cyclic performance of concrete with various RCA proportions, including the number of cycles until failure, energy dissipation capacity, and residual deformation. As shown in the table, an increasing proportion of RCA affects the concrete's resistance to repeated loading cycles. Concrete with a higher RCA content tends to fail more quickly than concrete with natural aggregates. Additionally, energy dissipation capacity decreases, indicating that RCA-containing concrete is less effective in absorbing and releasing energy under dynamic loading. Evaluating these parameters is essential to ensure that concrete with RCA continues to meet safety standards for structural applications exposed to seismic loads.

Table 7. Cyclic Resistance Test Results for Concrete with RCA

RCA Proportion (%)	Cycles Until Failure	Energy Dissipation Capacity (kJ)	Residual Deformation (%)
0% (Control)	500	85	1.2
25%	480	80	1.5
50%	450	75	1.8
75%	420	65	2.2
100%	400	55	2.5

As shown in Table 7, the number of cycles until failure decreases from 500 cycles for control concrete to 400 cycles for concrete with 100% RCA, indicating that an increased RCA proportion

Civil Engineering Science and Technology (CEST)
Vol. 1 No. 1 March 2025
E-ISSN: XXXX-XXXX; P-ISSN: XXXX-XXXX, Pages 75-93

in the concrete mix affects its durability under repeated loading. Additionally, energy dissipation capacity declines from 85 kJ for control concrete to 55 kJ for concrete with 100% RCA, suggesting that RCA-containing concrete absorbs less energy before failure. Residual deformation also increases with higher RCA content, making concrete with RCA more susceptible to permanent shape changes after repeated loading cycles. At RCA proportions of 50% or higher, the increase in residual deformation becomes more significant, potentially affecting the long-term stability of the structure. To ensure that RCA-containing concrete maintains adequate resistance to cyclic loading, design strategies incorporating additional reinforcement should be considered.

The impact of this decline in cyclic resistance can be observed in Figure 3, which illustrates how RCA influences failure cycles and energy dissipation capacity under cyclic loading simulations. The graph demonstrates a negative relationship between the increasing RCA proportion and both the number of cycles until failure and energy dissipation capacity. Concrete with 0% RCA exhibits the highest number of cycles before failure, whereas concrete with 100% RCA fails more quickly. A similar trend is observed in energy dissipation capacity, which decreases as RCA content increases. This reduction is associated with the porous nature of RCA and its weaker interfacial bonding compared to natural aggregates. These factors contribute to the increased risk of early failure in concrete with a higher RCA proportion.

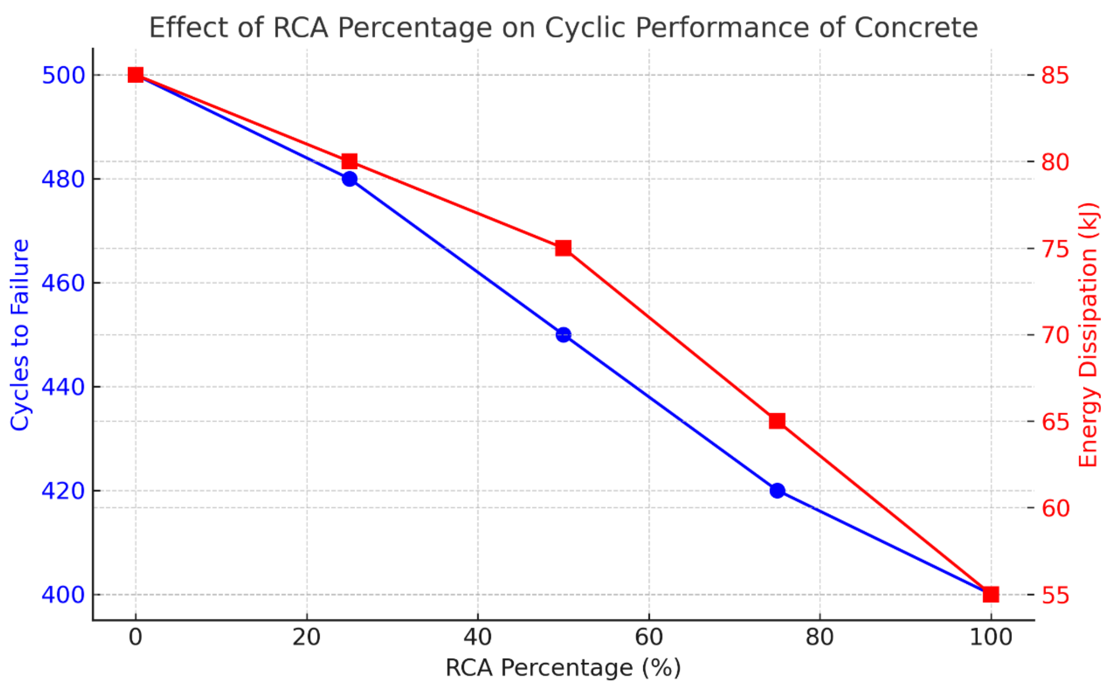

Figure 3. Relationship Between RCA Proportion and Cyclic Resistance of Concrete

Figure 3 presents two curves that illustrate changes in the number of cycles until failure (left axis) and energy dissipation capacity (right axis) as a function of RCA percentage. The blue curve represents the number of cycles until failure, which decreases linearly as RCA content increases, indicating that RCA-containing concrete fails more rapidly than control concrete. The red curve represents energy dissipation capacity, which also exhibits a similar downward trend. The reduction in energy dissipation capacity suggests that RCA-containing concrete has a lower ability to absorb energy before reaching failure. These changes indicate that the mechanical properties of RCA-containing concrete undergo modifications that affect its cyclic resistance. This aspect requires further analysis in concrete design to ensure structural resilience in accordance with the material's characteristics.

IV. DISCUSSION

Based on the findings of this study, it is evident that increasing the proportion of RCA in concrete mixtures affects various mechanical properties. These results are consistent with previous findings reported by (Z. Liu et al., 2024) and (Fanijo et al., 2023), which indicate that RCA has higher porosity and lower compressive strength compared to natural aggregates. In this study, the observed decline in compressive strength and elastic modulus suggests that using RCA in proportions exceeding 50% significantly impacts concrete performance, aligning with the findings of (Zhang et al., 2022) regarding energy dissipation in RCA-based structural elements. However, this study also demonstrates that the use of supplementary materials or mix modifications can mitigate the negative effects of RCA, as suggested by (Tayebani et al., 2023), who found that combining RCA with fly ash or nano-silica can enhance the mechanical performance of concrete. Additionally, the cyclic resistance tests indicate that concrete with higher RCA proportions experiences greater residual deformation, confirming the findings of (Zheng et al., 2022) regarding the tendency of RCA concrete to accumulate microcracks due to repeated loading cycles.

Although this study reinforces previous findings, there are some notable differences. This study found that concrete containing up to 50% RCA can still maintain relatively good mechanical properties, which contrasts with the report by (Imjai et al., 2024), stating that using more than 30% RCA significantly reduces structural performance. One possible reason for this discrepancy is the variation in RCA sources and processing techniques employed. Furthermore, this study observed a gradual decline in energy dissipation capacity with increasing RCA content, which differs slightly from the findings of (Cao et al., 2023), where an improvement in the bond strength between RCA and the cement paste was found to maintain energy dissipation at a higher level. These findings suggest that mix optimization strategies can still enhance the performance of RCA concrete. Therefore, further research is needed to explore methods for improving RCA quality and more effective mixing techniques to optimize the use of RCA concrete in seismic-resistant structures.

V. CONCLUSION AND RECOMMENDATION

The results of this study indicate that incorporating RCA in seismic-resistant structural design is feasible up to 50% without significant performance degradation. At this proportion, concrete can still maintain adequate compressive strength, elastic modulus, and cyclic loading resistance. However, when the RCA proportion exceeds 50%, a significant decline in the mechanical properties of concrete is observed, which may affect structural resilience against earthquakes. This suggests that concrete containing 75%-100% RCA still requires mix optimization to remain viable for earthquake-resistant construction. One possible strategy is the addition of supplementary materials such as fly ash, nano-silica, or fibers to enhance tensile strength and overall mechanical properties.

To further promote the use of RCA in seismic-resistant construction, future research should focus on several aspects. First, optimization of RCA concrete mixtures with supplementary materials is necessary to improve tensile strength and cyclic loading response. Second, long-term studies on RCA durability under repeated seismic loading conditions are crucial for understanding the material's stability over extended periods. Third, numerical simulation approaches, such as Finite Element Analysis (FEA), can be employed to validate experimental findings and predict the behavior of RCA concrete under various loading conditions. With further research, RCA is expected to become a more optimal and safe alternative for construction in earthquake-prone regions.

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