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Effect Of Openings On Shear Strength Of Sustainable Recycled Aggregate Concrete Beams

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This study investigates the effects of openings on the shear strength of Recycled Aggregate Concrete (RAC) beams, a critical yet underexplored area in structural design. RAC is increasingly used in sustainable construction due to its environmental benefits, but its performance in complex scenarios, such as beams with openings, remains uncertain. The research involved testing three beams with varying RCA content (0%, 50%, and 100%), each subjected to four-point loading until failure. The study focused on the structural response around openings, measuring crack widths, deflection, and strain in the reinforcement. Results indicated that all beams failed in shear at the openings, exhibiting similar crack patterns but varying crack widths. Beam B1 (0% RCA) had the largest crack width, while B2 (50% RCA) showed the narrowest, suggesting complex interactions between RCA and the concrete matrix. The load-deflection and load-strain analyses revealed that increasing RCA content generally reduced the beams' load-carrying capacity, stiffness, and bond strength, particularly around the openings. These findings provide effective insights for engineers and designers, highlighting the need to carefully consider RCA content in structural applications where openings are present. The research contributes to the broader adoption of RAC in sustainable construction by addressing key challenges associated with its structural performance.

Keywords *Shear Strength – Recycled Aggregate Concrete – Sustainability – Openings.*

1. Introduction

1.1 Background

Recycled Aggregate Concrete (RAC) is a sustainable construction material that incorporates recycled aggregates from construction and demolition waste, providing an eco-friendly alternative to conventional concrete, which relies on natural aggregates from quarries[1]. These recycled aggregates typically include crushed concrete, bricks, and asphalt, offering a practical solution to the growing issue of construction waste management [2], [3]. Although RAC differs slightly in mechanical properties from traditional concrete, it can be engineered to meet various structural needs through careful mix design and the addition of supplementary materials like fly ash or slag [4], [5]. The environmental significance of RAC is substantial. It contributes to resource conservation by reducing the demand for non-renewable natural aggregates, thereby mitigating ecological impacts such as surroundings destruction and carbon emissions associated with aggregate extraction. Additionally, RAC helps reduce construction waste by recycling materials that would otherwise end up in landfills, promoting a circular economy within the building industry [6].

RAC also plays a crucial role in lowering the carbon footprint of construction projects. By reducing the need for virgin aggregates, RAC helps decrease the overall carbon emissions associated with concrete production. This is particularly important as the construction industry faces increasing pressure to meet stringent ecological regulations and sustainability targets. Economically, RAC can offer cost savings, especially in regions where natural aggregates are scarce or expensive, as recycled aggregates are often sourced locally, reducing transportation costs [7], [8]. Despite its benefits, RAC faces challenges such as variability in the quality of recycled aggregates, which can affect concrete performance, including durability and strength. However, ongoing research and technological innovations are addressing these issues, improving the reliability and performance of RAC. As standards continue to evolve, RAC is expected to become more prevalent in construction, playing a key role in reducing the ecological impact of the industry and supporting sustainable development efforts [9], [10].

1.2 Problem Statement

The use of RAC poses several challenges, particularly in terms of structural performance. A primary concern is the variability in the quality of recycled aggregates, which can negatively affect the concrete's mechanical properties, such as compressive and tensile strength. Recycled aggregates often contain impurities, like remnants of mortar or asphalt, and micro-cracks from the crushing process, leading to weaker bonding within the concrete matrix. This inconsistency can result in reduced overall strength and durability compared to conventional concrete made with natural aggregates. Shear strength is another critical issue in RAC, as the interfacial transition zone (ITZ) between the recycled aggregates and the cement paste is often weaker and more porous than in conventional concrete [11]. This weaker ITZ can diminish the shear capacity, making RAC more vulnerable to shear failure, especially in structural elements with complex load patterns. Additionally, the irregular shape and higher water absorption of recycled aggregates can lead to non-uniform stress distribution and increased porosity, further compromising shear strength.

Despite these challenges, advancements in mix design, including the use of pozzolanic materials like fly ash or silica fume, can enhance the bonding in the ITZ and improve the overall strength and durability of RAC [12], [13]. However, careful consideration of shear strength is essential when designing RAC structures, particularly in elements with critical shear demands. Ongoing research continues to optimize the use of recycled aggregates to ensure that RAC can meet the stringent requirements of modern structural design.

1.3 Objectives

The main objective of this research is to evaluate the impact of openings on the shear strength of RAC beams. Specifically, the study aims to investigate how the presence, size, and location of openings within RAC beams influence their ability to resist shear forces, comparing these effects with those observed in beams made from conventional concrete. The findings of this research are intended to provide insights that will inform the structural design and application of RAC in construction, particularly in scenarios where openings are necessary for service conduits or architectural considerations.

1.4 Significance

This paper significantly advances the understanding of how openings affect the shear strength of RAC beams, a critical but underexplored area in structural design. As the construction industry shifts towards sustainable practices, the use of RAC is increasingly important due to its environmental benefits, such as waste reduction and resource conservation. However, the structural performance of RAC, particularly in complex scenarios like beams with openings, requires further investigation. This research fills a critical gap by providing empirical data on the impact of openings on the shear strength of RAC beams.

Understanding these effects is essential for ensuring the safety, reliability, and durability of structures, as openings in beams are often necessary for services like plumbing and electrical conduits. While conventional concrete beams have established guidelines for incorporating openings, similar knowledge for RAC is lacking. This study aims to provide insights that will help engineers and designers make informed decisions when using RAC, supporting its broader adoption in sustainable construction without compromising structural integrity. Ultimately, this research contributes to more sustainable building practices by promoting the responsible use of recycled materials in construction.

2. Literature Review

2.1. Recycled Aggregate Concrete (RAC)

Recycled Aggregate Concrete (RAC) has been the subject of extensive research due to its potential to promote sustainable construction practices by utilizing construction and demolition waste. The mechanical properties of RAC, including its compressive strength, tensile strength, and modulus of elasticity, are generally lower compared to conventional concrete. This reduction is primarily due to the weaker ITZ between the recycled aggregates and the new cement paste, which is often more porous and less dense due to the presence of adhered old mortar. Despite these challenges, studies have shown that by optimizing the mix design, including the use of supplementary cementitious materials like fly-ash and silica-fume, the mechanical properties of RAC can be significantly improved, making it suitable for various structural applications [2], [14].

In terms of durability, RAC tends to have higher water absorption and permeability, which can lead to increased susceptibility to freeze-thaw cycles, chloride penetration, and carbonation. These factors can influence the long-term durability of RAC structures. However, recent advancements, such as the treatment of recycled aggregates through carbonation or coating techniques, have shown promise in enhancing the durability of RAC by reducing porosity and improving the density of the concrete. The applications of RAC have primarily been in non-structural components such as pavements and road bases, but with ongoing research and development, RAC is increasingly being considered for more demanding structural applications [15], [16].

2.2 Shear Strength in Concrete Beams

Shear strength in concrete beams is a critical aspect of structural design, ensuring that beams can resist internal shear forces that cause sliding between different parts of the structure. The shear resistance of a concrete beam is primarily provided by the concrete's tensile strength, dowel action of the reinforcement, and shear reinforcement such as stirrups. In conventional concrete beams, factors such as concrete compressive strength, size effect, shear span-to-depth ratio, reinforcement ratio, and load distribution play a significant role in determining the shear strength[17].

For RAC beams, the shear strength is influenced by the same factors but with additional considerations due to the properties of recycled aggregates. The weaker ITZ in RAC, along with the lower strength and stiffness of recycled aggregates, can reduce the shear capacity of RAC beams. The higher porosity and water absorption characteristics of RAC can further impact the material's durability and shear strength over time. Despite these challenges, research indicates that with proper mix design and reinforcement strategies, RAC beams can achieve shear strengths comparable to those of conventional concrete beams [18], [19], [20].

2.3 Effects of Openings on Concrete Beams

Openings in concrete beams, such as holes or notches, are often necessary for accommodating services like electrical conduits, plumbing, or ventilation systems. However, these openings introduce discontinuities that can significantly affect the structural behavior of the beams, particularly in terms of shear strength. Past studies have shown that the presence of openings can lead to a concentration of stress around the openings, which can reduce the shear capacity of the beam and increase the likelihood of shear failure [19], [21]. The size, shape, and location of the openings are critical factors that concern the extent of this impact. Research has demonstrated that beams with larger or improperly located openings tend to exhibit lower shear strength and higher crack propagation under load [22], [23].

For RAC beams, the effects of openings can be even more pronounced due to the inherent weaknesses associated with recycled aggregates, such as a weaker ITZ and higher porosity. However, there is limited research specifically focusing on the impact of openings on the shear strength of RAC beams. Most existing studies have focused on conventional concrete, leaving a gap in the literature regarding how these findings translate to RAC [24], [25].

2.4 Gaps in Existing Research

While there has been significant research on the mechanical properties and durability of RAC, as well as on the shear strength of beams with openings, there is a notable gap in the literature concerning the specific impact of openings on the shear strength of RAC beams. Most studies have focused on either the general performance of RAC or the effects of openings in conventional concrete beams. Few studies have combined these two aspects to examine how openings affect the shear strength of RAC beams. This gap highlights the need for further research to provide empirical data and analysis that can inform structural design practices involving RAC with openings. Addressing this gap is essential for advancing the use of RAC in more complex structural applications, thereby supporting the broader goals of sustainable construction [17], [19], [24], [25], [26]

3. Materials and Methods

3.1 Ordinary Portland Cement

In this study, Ordinary Portland Cement (OPC), specifically the CEM I 42.5 grade, is utilized. This cement is primarily produced by sintering limestone and clay into clinker, which is then finely ground with gypsum. The CEM I 42.5 grade is particularly valued for its high early strength and durability, making it appropriate for a wide range of construction applications. OPC is categorized into grades 32.5, 42.5, and 52.5, which indicate the compressive strength the cement achieves after 28 days of curing. This versatility allows OPC to be used in both general construction and more specialized projects [9], [27], [28].

3.2 Aggregates

3.2.1 Fine Aggregates

In this study, the fine aggregate (FA) used was natural sand, selected for its siliceous composition and high purity, with a fineness modulus of 2.77. The sand underwent thorough testing to ensure its suitability for construction purposes. The specific gravity was measured at 2.70, and the unit weight was recorded at 1.69. Additionally, the sand's grading complied with the Egyptian Standard Specification No. 1109/2002 [29] confirming its suitability for incorporation into concrete mixes.

3.2.2 Natural Coarse Aggregate

In this study, crushed limestone was used as the coarse aggregate, chosen for its high purity and absence of organic matter, with a maximum particle size of 19 mm. The limestone's properties were rigorously tested and found to meet the requirements of Egyptian Standard Specification No. 1109/2002 [29]. This included a specific gravity of 2.78, which is well within the acceptable range of 2.60 to 2.80, and a unit weight of 1.84. The limestone also exhibited an abrasion value of 18 and an absorption rate of 1.05%, indicating its durability and suitability for use in concrete. The fine materials content of 1.89% also complied with the standard, further confirming its appropriateness for structural applications. These characteristics underscore the limestone's conformity with the strict standards outlined in the Egyptian Specification, ensuring its reliability and effectiveness in construction projects.

3.2.3 Recycled Concrete Aggregate

Recycled coarse aggregates used in this study were sourced from waste materials and surplus from a concrete mixing plant in 6th of October City, Egypt. These materials were mechanically crushed and sorted to obtain the desired aggregate sizes [30]. The aggregates were then transported to the laboratory for further testing, with the specific gravity and absorption values documented in Table 4. It is important to note that the maximum nominal size of the recycled coarse aggregates utilized in this study was 19 mm.

Table 1 Characteristics of RCA

Test	Results
Bulk Specific Gravity	2.53
Absorption	4.62%

3.3 Water

In this study, pure, clean, potable water was used for both mixing and curing the concrete specimens. The water-to-binder ratio was meticulously maintained at 0.5 by weight to ensure that the concrete achieved the desired normal strength in the control mixes. Maintaining this consistent water-to-cement ratio (w/c) is essential for obtaining the expected mechanical properties of the concrete, as it directly influences the strength, workability, and durability of the final product.

3.4 Mix Design

In this study, the control mix was designed using the American Concrete Institute (ACI) method [31] to produce normal-strength concrete with a target compressive strength of 30 MPa. The base mix consisted of 375 kg of OPC, 713 kg of FA, and 1128 kg of NA, with a water-to-cement ratio of 0.5. Following the establishment of this foundational mix, subsequent concrete mixes were developed by substituting natural aggregates with recycled coarse aggregates (RCA) by weight, allowing for a comparative analysis of the effects of RCA on concrete performance. Additionally, concrete cubes and cylinders were cast for testing compressive strength at 7 and 28 days to assess the mechanical properties of the different mixes. The details of the material proportions used in the mix designs are provided in Table 2, while the results of the compressive strength tests for the cubes and cylinders are summarized in Table 3.

Table 2 Summary of Mixes

Mix description	Mix Name	OPS	FA	NA	RCA	Water	w/c
0% RCA	**Control mix**	375	713	1127	-	201	0.5

50% RCA	**RCA50**	375	713	564	564	201	0.5
100% RCA	**RCA100**	375	713	-	1127	201	0.5

Table 3 Compressive strength of concrete cubes and cylinders

Mix description	**Mix Name**	**f'_{cu}**	**f_{cu}**	
			7 days	**28 days**
0%RCA	**Control mix**	32.01	26.45	34.05
50% RCA	**RCA50**	31.09	24.83	32.89
100%RCA	**RCA100**	30.78	23.62	32.04

3.5 Beam specimens

The specimens used in this research consisted of three R-sections of Normal Strength Recycled Concrete beams, each with a total depth of 250 mm. The beams measured 2000 mm in length, with clear spans of 1800 mm. Openings measuring 140 x 70 mm were positioned 150 mm at the shear zone from one support on one side of each beam. The bottom longitudinal reinforcement comprised three steel bars with a 10 mm diameter and a yield strength (f_y) of 530 MPa. The top longitudinal reinforcement included two steel bars, also with a 10 mm diameter and a yield strength (f_y) of 530 MPa. Additionally, stirrups with a 6 mm diameter were spaced at 200 mm intervals, with a yield strength (f_y) of 263 MPa. The concrete dimensions and details of reinforcement of beam specimens are shown in Figure 1.

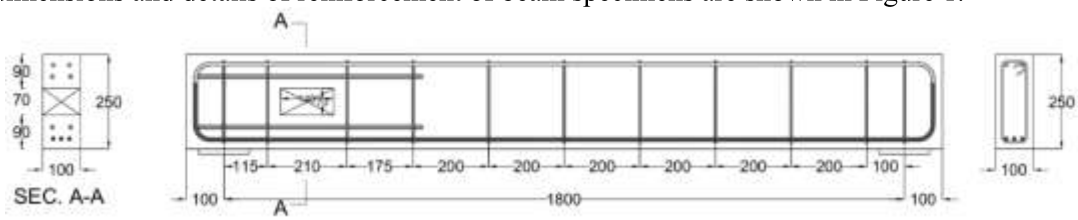

Fig. 1 Concrete dimensions, details of reinforcement and strain locations

3.6 Experimental Setup

The experimental setup in this study involved subjecting the concrete beams to a four-point loading system to evaluate their shear strength. The load was applied at two points, each located 500 mm from the nearest support. The beams were gradually loaded until failure occurred, allowing for a comprehensive assessment of their behavior under shear forces. To measure deflection, three Linear Variable Differential Transformers (LVDTs) were strategically placed on each beam. LVDT 1 and LVDT 2 were positioned directly under the load application points, while LVDT 3 was located at the mid-span of the beam. These LVDTs provided continuous deflection data, which was crucial for analyzing the deformation characteristics of the beams throughout the loading process.

In addition to deflection measurements, the setup included three steel strain gauges to monitor strain in the reinforcement. Strain gauge S1 was attached to the bottom longitudinal reinforcement, while strain gauges S2 and S3 were positioned on the stirrups around the openings in the beam. This placement allowed for precise monitoring of strain development in both the longitudinal steel and the stirrups, especially in the critical areas near the openings where shear forces are concentrated. All instrumentation, including the load cell, LVDTs, and steel strain gauges, was connected to a data acquisition system linked to a computer. This setup enabled real-time data recording throughout the testing process, providing detailed insights into the beams' structural response under loading conditions. The collected data included load-displacement curves, strain in the reinforcement, and deflection measurements, which were essential for analyzing the beams' shear performance and identifying the onset of failure. Instrumentation and test setup are presented in Figure 2.

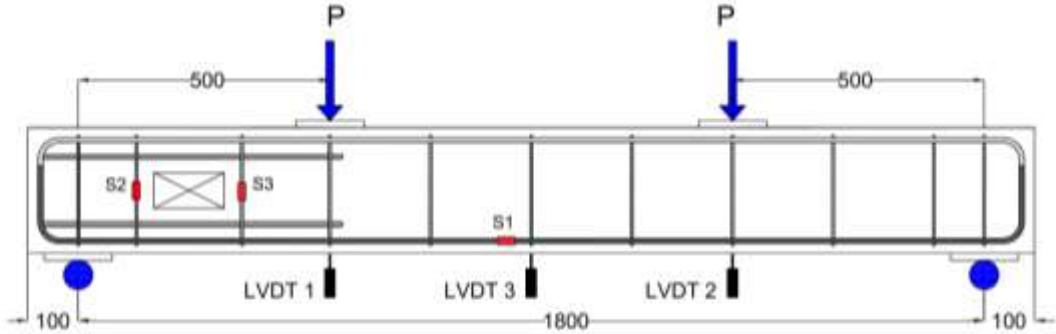

Fig. 2 Instrumentation and test setup

4. Results and Discussion

All three beams in the study experienced shear failure at the location of the openings, and they exhibited similar crack patterns. Beam B1, which contained no recycled coarse aggregate (RCA), developed the largest crack width, measuring 4.1 mm at its maximum. Beam B2, with 50% RCA, had a slightly narrower maximum crack width of 3.7 mm, suggesting that the presence of RCA might have contributed to a different crack propagation mechanism. Beam B3, despite having 100% RCA, showed a maximum crack width of 3.9 mm, which is closer to B1's crack width than B2's.

The variation in crack widths among the beams suggests that while the presence of RCA impacts the structural performance, the differences are not purely linear. The slightly narrower crack in B2 could indicate a more complex interaction between the RCA and the concrete matrix, possibly leading to better crack distribution, whereas the larger crack in B3, despite the higher RCA content, might result from the material's reduced ductility, leading to more concentrated crack formation. These crack patterns and their respective widths are detailed in Figure 3 (a, b, c) for Beams B1, B2, and B3, respectively. This analysis highlights the nuanced effects of RCA on the structural behavior of beams, especially in regions of stress concentration like openings, where shear forces are significant.

(a) Crack pattern of B1

(b) Crack pattern of B2

(c) Crack pattern of B3

Fig. 3 Crack pattern of beam specimens

The load-deflection presented in Figure 4, reveals significant differences in their structural performance under loading conditions. Beam B1, containing no RCA, exhibited the highest load-carrying capacity, reaching approximately 78 kN, and demonstrated the most ductile behavior with the greatest deflection before failure. In contrast, Beam B3, with 100% RCA, showed the lowest peak load at around 61kN and the least deflection, indicating a reduction in both strength and ductility due to the full replacement of natural aggregates with RCA. Beam B2, containing 50% RCA, displayed intermediate performance with a peak load of 70 kN, suggesting that partial replacement of NA with RCA results in a moderate reduction in structural capacity.

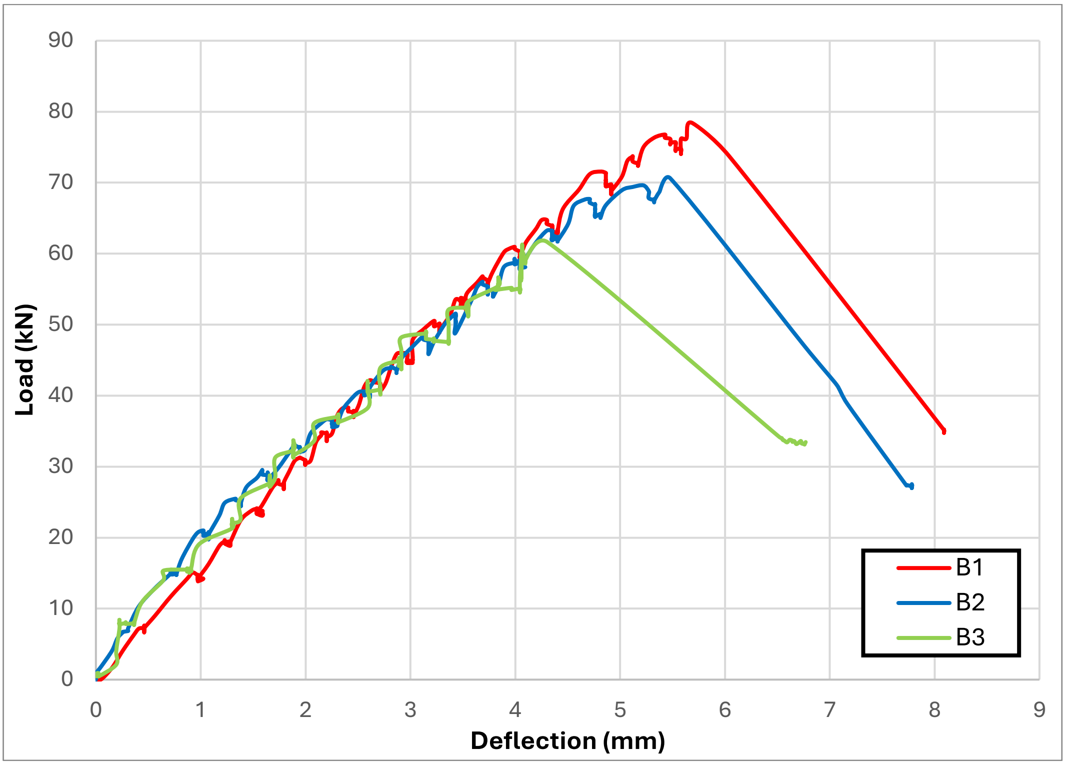

Fig. 4 Load vs mid-span deflection for beam specimens

The load-strain graph provided in Figure 5 presents key insights into the RCA on the behavior of longitudinal steel reinforcement under loading conditions. Beam B1, which contains no RCA, demonstrated the highest load capacity and the lowest steel strain, indicating a strong bond between the concrete and the reinforcement, allowing for effective load transfer and minimal deformation of the steel at higher loads. In contrast, Beam B3, which contains 100% RCA, exhibited the highest steel strain for the same loads, reflecting a weaker bond and a lower overall stiffness of the concrete, which led to earlier yielding of the reinforcement. Beam B2, with 50% RCA, showed intermediate behavior, with higher strain than B1 but lower than B3, indicating that partial RCA replacement moderately reduces the concrete's effectiveness in engaging the reinforcement.

These results suggest that as the RCA content increases, the strain in the longitudinal reinforcement also increases, reducing the beam's overall load-bearing capacity and stiffness. The higher strain in B3 implies that the reinforcement yields earlier, which, while potentially increasing ductility, compromises the beam's structural integrity.

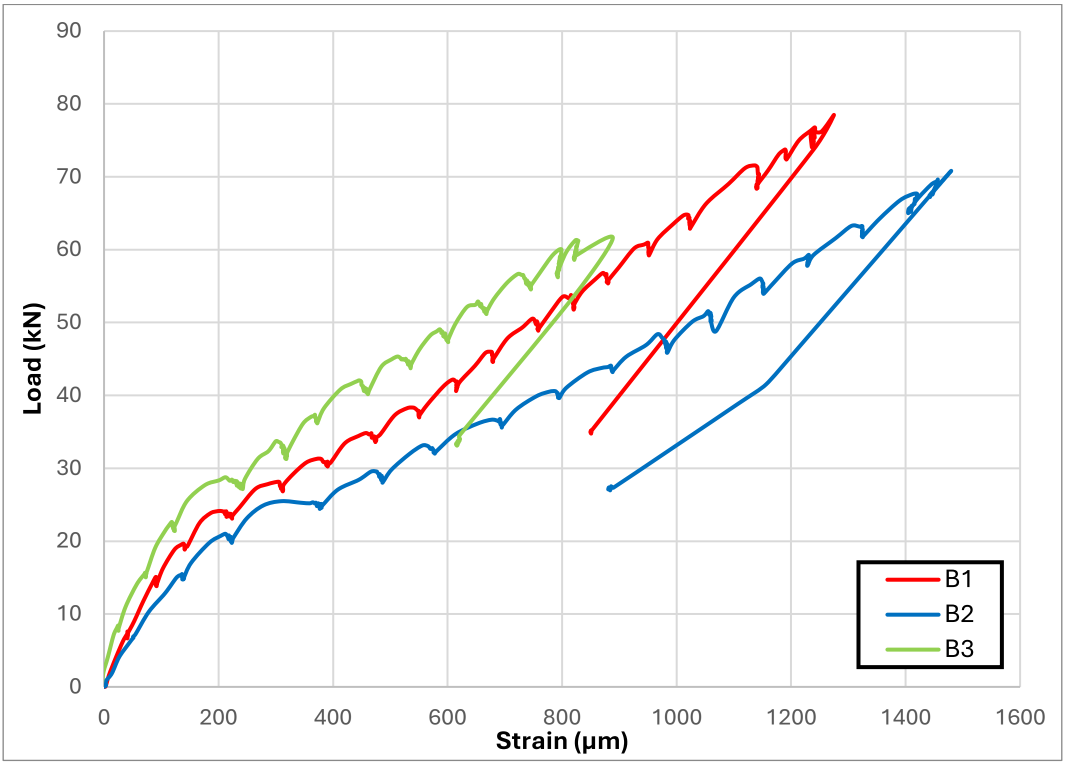

Fig. 5 Load vs longitudinal steel strain (S1) for beam specimens

Figure 6 illustrates the load-strain relationship for the strain gauge S2, which was placed on the stirrups around the opening in the beams. For Beam B1, the graph shows a consistent and gradual increase in strain as the load increases. This indicates that the stirrups in B1 effectively resist the shear forces around the opening, maintaining structural integrity up to a higher load before significant strain develops. The curve for Beam B2 shows a similar pattern to B1 but with slightly higher strains observed at lower loads. This suggests that the presence of RCA starts to compromise the beam's ability to resist shear forces, leading to earlier yielding of the stirrups. In contrast, Beam B3 exhibits the highest strain values for similar loads, indicating that the stirrups are less effective in resisting shear forces around the opening. The rapid increase in strain for B3 reflects a weaker bond between the RCA concrete and the stirrups, leading to earlier deformation and reduced overall structural performance.

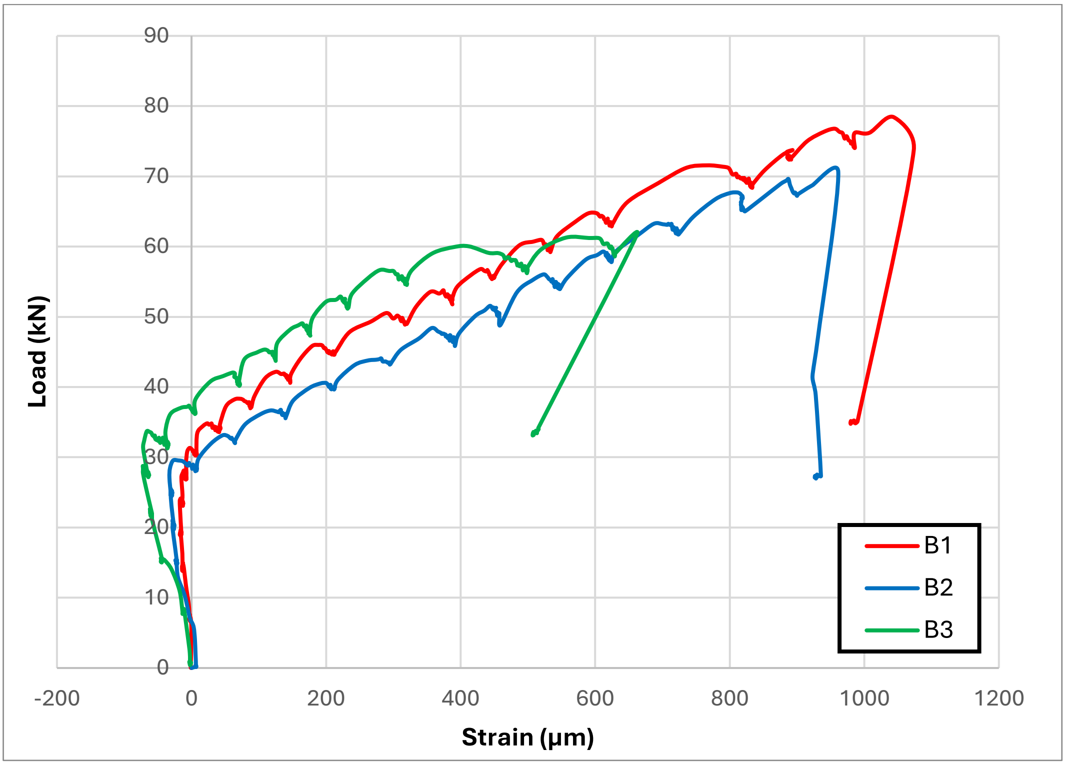

Fig. 6 Load vs stirrup strain (S2) for beam specimens

However, Figure 7 presents the load-strain behavior for strain gauge S3. Beam B1, again demonstrates the most stable load-strain relationship, with the stirrups effectively managing the shear forces as the load increases. The strain increases steadily, showing that B1 can maintain structural integrity even under higher loads. Beam B2 follows a similar trend but with higher strain values appearing at lower loads, indicating that the inclusion of RCA weakens the bond and reduces the stirrups' effectiveness. Finally, Beam B3 exhibits the highest strain levels at the lowest loads, indicating a significant reduction in the ability of the stirrups to resist shear forces. This suggests that the stirrups in B3 yield earlier and more significantly, reflecting the compromised structural performance due to the full RCA replacement. These results consistently show that increasing RCA content negatively impacts the bond between concrete and stirrups, leading to higher strains and reduced load-carrying capacity around openings.

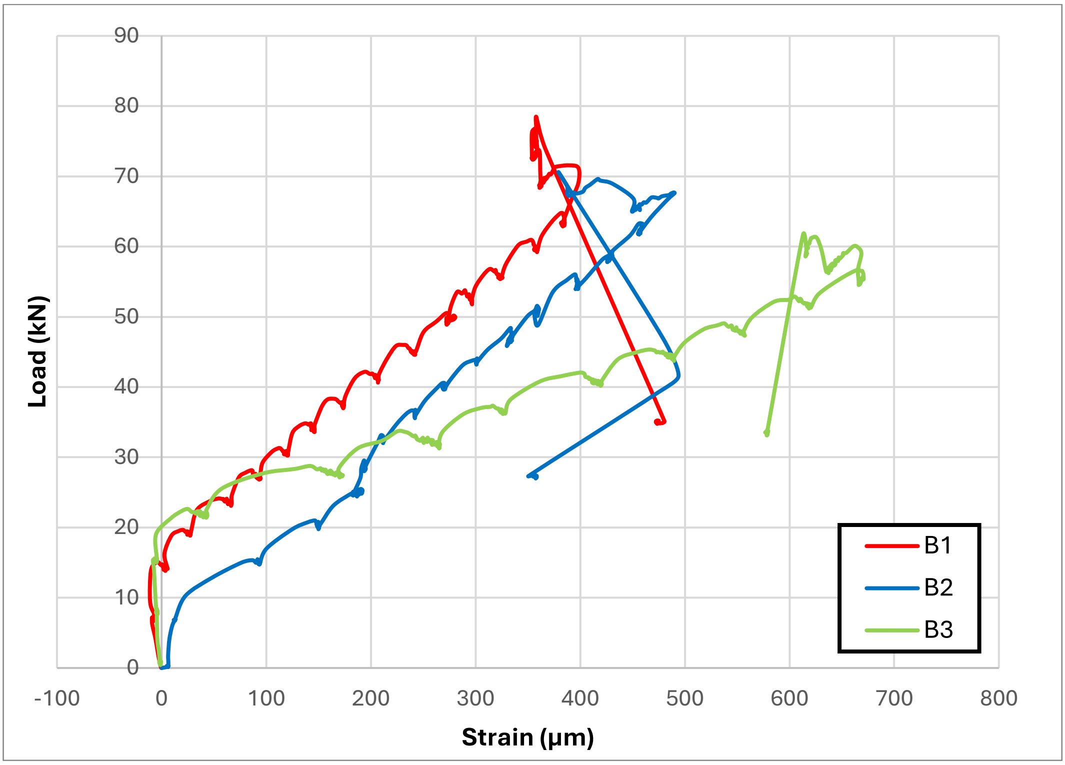

Fig. 7 Load vs stirrup strain (S3) for beam specimens

5. Conclusion

i. The study confirmed that all three beams, irrespective of the recycled coarse aggregate (RCA) content, failed in shear at the location of the openings. The similarity in crack patterns across all beams suggests that the presence of openings is a critical factor in determining the shear performance of Recycled Aggregate Concrete (RAC) beams. This finding underscores the value of addressing the impact of openings in structural design, particularly when using RAC.

ii. The maximum crack widths varied among the beams, with Beam B1 (0% RCA) exhibiting the largest crack width at 4.1 mm, followed by Beam B3 (100% RCA) at 3.9 mm, and Beam B2 (50% RCA) at 3.7 mm. The slightly narrower crack in B2 suggests that partial RCA replacement might influence crack propagation differently compared to full RCA replacement or natural aggregates, potentially due to a more complex interaction between the RCA and the concrete matrix.

iii. The load-deflection results indicated that increasing RCA content generally led to a reduction in load-carrying capacity and stiffness. Beam B1, with no RCA, achieved the highest load capacity and exhibited the most ductile behavior. In contrast, Beam B3, with full RCA replacement, showed the lowest peak load and the least deflection, highlighting the trade-offs associated with using high levels of RCA in structural applications.

iv. The load-strain analysis revealed that higher RCA content adversely affected the bond strength between the concrete and the longitudinal steel reinforcement. Beam B1 demonstrated the lowest strain in the reinforcement, indicating a stronger bond, while Beam B3 exhibited the highest strain, reflecting a weaker bond and earlier yielding of the reinforcement. This reduction in bond strength with increased RCA content emphasizes the need for careful consideration of reinforcement detailing when designing RAC structures.

v. RCA affects the deflection behavior of concrete beams primarily through its influence on the material's mechanical properties, particularly its modulus of elasticity and overall stiffness. As the RCA content increases in the concrete mix, the resulting material typically exhibits lower stiffness compared to conventional concrete made with NA. This reduction in stiffness is mainly due to the presence of old mortar attached to the recycled aggregates, which creates a weaker ITZ and increases the overall porosity of the concrete.

vi. The study also showed that the stirrups' effectiveness in resisting shear forces around the openings decreased with increasing RCA content. Strain gauges on the stirrups (S2 and S3) indicated that Beam B1 managed shear forces more effectively, with strain increasing steadily under higher loads. In contrast, Beams B2 and B3, with partial and full RCA replacement respectively, exhibited higher strain levels at lower loads, suggesting a compromised ability to resist shear forces due to the weaker bond between the RCA concrete and the stirrups.

vii. The lower stiffness of RCA concrete leads to greater deflection under the same applied load compared to natural aggregate concrete. This is because the reduced modulus of elasticity causes the concrete to deform more when subjected to stress. In the context of the beams B1, B2, and B3, as the RCA content increases from 0% in B1 to 100% in B3, the deflection observed under load also increases. Beam B1, with no RCA, shows the least deflection, while Beam B3, with 100% RCA, shows the most significant deflection, reflecting the decreased stiffness and increased deformability of the material.

viii. The incorporation of RCA in concrete can have a significant impact on the ductility of structural elements. Ductility refers to the ability of a material to undergo significant plastic deformation before failure, which is a desirable property in structural applications as it allows for energy dissipation and provides warning signs before catastrophic failure.

6. Recommendation for the Future

Future research should focus on refining the mix design of RAC by exploring various supplementary cementitious materials (SCMs) and adjusting RCA content to enhance shear strength and bond performance, particularly in beams with openings. Moreover, there is a need for long-term durability studies and investigations under dynamic loading conditions, such as seismic events, to understand the full implications of using RAC in structural applications with openings. Future work should also include advanced numerical modeling, such as finite element analysis, alongside real-world case studies to validate experimental findings and bridge the gap between laboratory results and practical construction applications

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