EJSIT
European Journal of Science, Innovation and Technology
ISSN: 2786-4936
www.ejsit-journal.com
Volume 4 | Number 5 | 2024

Recycled Aggregate Concrete as a Layer and Its Effect on the Performance Index of Reinforced Concrete Beam

Robert Bennett Ataria and John Ayibatunimibofa TrustGod
Niger Delta University, Wilberforce Island, Bayelsa State, Nigeria

ABSTRACT

Concrete, widely used in construction, faces environmental challenges due to its reliance on natural aggregates and high carbon emissions. This study explores the potential of Recycled Aggregate Concrete (RAC) as a sustainable alternative, focusing on its use in two-layer reinforced concrete (RC) beams. By using RAC, derived from crushed concrete waste, as a layer in the beam, the study investigates how it affects the performance index, a measure that includes strength, deflection, and overall durability. The research involves twelve two-layer and six single-layer RC beams, each subjected to bending tests. Beams were divided into six groups: two single-layer beams cast with 100% recycled aggregates (RG) and 100% crushed natural aggregates (CG), and four two-layer beams (CR-50, RC-50, CR-30, and RC-30) with different ratios of recycled and natural aggregates. Key findings reveal that the CG beams, made with natural aggregates, had the highest load capacity and stiffness, while beams with recycled aggregates exhibited lower strength and stiffness but comparable deflection behavior. The study concludes that layering RAC with conventional concrete in less stressed regions can preserve structural integrity while promoting sustainability. However, using RAC alone, particularly in the tension zone, may reduce the beam's load-bearing capacity. The findings suggest that RAC, when used strategically, can enhance the environmental performance of concrete structures without severely compromising their mechanical properties.

Keywords: Aggregates, Beam, Bending Strengths, Recycled, Reinforcement, Two-Layer

INTRODUCTION

Concrete is the most extensively used material in the construction industry due to its excellent compressive strength, versatility, and affordability (Makul, 2020; Osial et al., 2022; Kryeziu et al., 2023). However, its production is resource-intensive, involving high energy consumption, significant carbon emissions, and the depletion of natural aggregates (Bleischwitzet al., 2006; Ghouleh et al., 2017). In recent years, there has been a growing push toward sustainable practices in construction (Barbhuiy et al., 2024), driven by environmental concerns and the need to reduce the ecological footprint of building materials.

One promising solution to this challenge is the use of Recycled Aggregate Concrete (RAC), which replaces natural aggregates with recycled aggregates sourced from demolition, concrete lab and construction waste. By incorporating recycled materials, RAC offers the potential to reduce the demand for virgin aggregates (Xing et al., 2022; Hasheminezhad et al., 2024), lower carbon emissions, and divert waste from landfills, making it an eco-friendly alternative to conventional concrete (Gerges et al., 2022; Shyamala et al., 2024). However, despite its environmental benefits, the use of RAC in structural applications has raised concerns regarding its mechanical properties, particularly its strength, durability, and long-term performance when compared to traditional concrete.

While several studies (Poon & Chan, 2007; Sonawane et al., 2013; Kiskuet al., 2017) have examined the use of RAC in various structural elements, two-layer reinforced concrete (RC) beams present a unique opportunity to optimize the use of recycled materials while maintaining structural integrity. In a two-layer RC beam, the concrete can be divided into two distinct layers, each with potentially different materials or properties. This layered approach allows for the strategic placement of RAC in regions of the beam where the mechanical performance requirements may not be as demanding, while conventional concrete can be used in more critical areas subjected to higher stresses.

The concept of using RAC as one of the layers in a two-layer RC beam is appealing for several reasons: By placing RAC in less stressed zones (such as the compression zone in a beam), the overall performance of the beam can be preserved while reducing the environmental impact. The use of recycled aggregates can lower material costs and reduce the need for new aggregates, leading to more economical construction (Bostanci et al., 2018; Silva et al., 2019). The integration of recycled materials into structural elements promotes the use of waste materials in construction, contributing to more sustainable building practices and supporting circular economy principles (Joensuu et al., 2020).

However, the successful application of RAC in two-layer RC beams hinges on understanding its impact on the performance index, a comprehensive metric that considers not only the strength and durability of the beam but also factors like deflection, cracking behavior, and long-term reliability. The performance index is a critical measure of how well a beam performs under load, and it is influenced by both the material properties and the overall design of the structure (Ziemian et al., 2010).

Previous research has shown that RAC tends to have lower strength and stiffness than conventional concrete (McGinnis et al., 2017), primarily due to the properties of the recycled aggregates, which often have higher water absorption, weaker bonding with cement, and greater variability in size and quality (Xiao et al., 2015). These factors can negatively affect the load-bearing capacity, durability, and overall structural performance of RAC (Sadowska-Buraczewska et al., 2020). However, when used strategically in a layered configuration, these limitations may be mitigated, provided that the RAC is confined to zones of the beam where its mechanical properties are less critical.

Despite the potential advantages of using RAC in two-layer beams, several gaps in the existing literature remain: The impact of RAC placement within the beam—whether in the top layer (compression zone) or bottom layer (tension zone)—on the beam's performance index is not well understood. Determining the most effective configuration is crucial for maximizing both structural integrity and sustainability. While individual properties of RAC, such as compressive strength and modulus of elasticity, have been studied, there is limited research on how these properties collectively affect the overall performance index when RAC is used in a two-layer RC beam.

This study seeks to address these gaps by investigating the use of recycled aggregate concrete as a layer in two-layer reinforced concrete beams, with a focus on its impact on the performance index. By evaluating the mechanical behavior, durability, and load-carrying capacity of these beams.

MATERIALS AND METHOD

Material

The two-layer reinforced concrete (RC) beams were made using Portland limestone cement, grade 42.5 N, in line with EN 197-1 (2011) standards. River sand was used as the fine aggregate, meeting the requirements of BS EN 1260:2002. For coarse aggregates, both crushed natural stone and recycled concrete from compression-tested cubes, sourced from the Niger Delta University testing laboratories, were utilized, also in compliance with BS EN 1260:2002.

Method

Twelve two-layer and six single-layer reinforced concrete (RC) beams, each measuring 900 x 75 x 112 mm, were prepared and subjected to bending tests. Each beam was reinforced with two 8 mm diameter rods at the bottom and two 6 mm diameter rebars at the top. The beams were divided into six groups as follows:

RG: A single-layer beam cast using 100% recycled aggregates derived from crushed concrete cube samples.

CG: A single-layer beam cast using 100% crushed natural aggregates.

CR-50: A two-layer beam with a 56 mm thick top layer made of crushed granite aggregates and a 56 mm thick bottom layer consisting of recycled coarse aggregates.

RC-50: A two-layer beam with a 56 mm thick top layer made of recycled coarse aggregates and a 56 mm thick bottom layer consisting of crushed natural aggregates.

CR-30: A two-layer beam with a 34 mm thick top layer made of crushed granite aggregates and a 78 mm thick bottom layer consisting of recycled coarse aggregates.

RC-30: A two-layer beam with a 34 mm thick top layer made of recycled coarse aggregates and a 78 mm thick bottom layer consisting of crushed natural aggregates.

For all two-layered beams, the first concrete layer was allowed to set before casting the second layer. Additionally, concrete cubes were produced using both crushed natural aggregates and recycled coarse aggregates to evaluate their compressive strengths. Figure 1 shows the two-layer beam considerations.

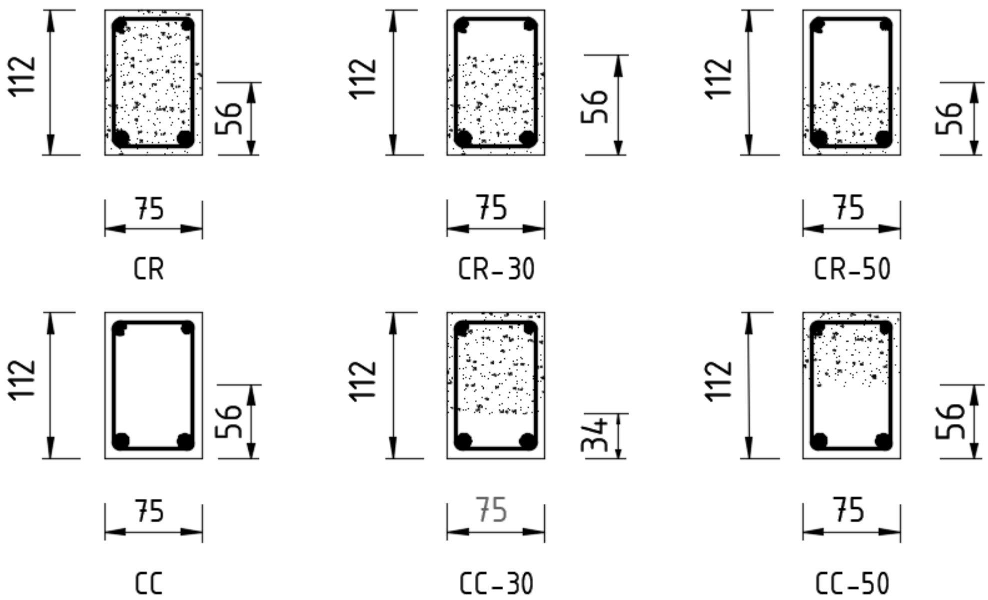

Figure 1: Beam Configuration

Instrumentation and Test Set Up

The beam samples were tested in a 50-ton loading frame, configured as simply supported beams with a one-third point load application. A dial gauge was installed on the tension flanks of each beam specimen to accurately monitor deflections. Additionally, the concrete cubes were tested after 28 days of curing using a compressive testing machine, following the guidelines of BS 1881-3:1970.

RESULTS AND DISCUSSION

Table 1 summarizes key findings from the bending tests on six groups of reinforced concrete (RC) beams, focusing on when they first cracked, how they behaved under load, and how they eventually failed.

First Crack Load

The first crack load refers to the point at which the first visible crack appeared in the beams. The difference in this load was minimal across all beams, ranging from 1.8 kN to 2.2 kN. Both the RG and CG beams (made with 100% recycled and 100% crushed natural aggregates, respectively) had the highest first crack load at 2.2 kN, suggesting stronger resistance to initial cracking. The layered beams—CR-50, RC-50, CR-30, and RC-30—showed slightly lower first crack loads, ranging between 1.8 kN and 1.95 kN.

Deflection at First Crack Load

This measures how much the beam bent when the first crack appeared. The CG beam (100% crushed natural aggregates) had the smallest deflection at first crack, just 0.15 mm, highlighting its greater stiffness and resistance to early cracking. The RC-30 beams followed closely with 0.12 mm deflection, indicating that its specific combination of aggregates also offered significant early stiffness. The other beams had slightly higher deflections: RG at 0.25 mm, CR-50 at 0.20 mm, RC-50 at 0.18 mm, and CR-30 at 0.23 mm, meaning they bent more before the first crack appeared.

Failure Load

The failure load is the maximum force the beams could handle before breaking. The CG beam outshone the others, with a failure load of 20.1 kN, likely due to the superior quality of its natural aggregates. On the other hand, the RG beam, made from 100% recycled aggregates, had the lowest failure load at 16.59 kN, reflecting the weaker nature of recycled materials. The layered beams—CR-50, RC-50, CR-30, and RC-30—all had similar failure loads, between 16.59 kN and 16.96 kN, suggesting that layering different aggregates didn't significantly boost their overall load capacity compared to the fully recycled RG beam.

Deflection at Failure Load

This reveals how much the beams could bend before breaking, offering insight into their ductility. CR-30 stood out with the largest deflection at failure, bending up to 6.3 mm, indicating that it was able to deform the most before breaking, showing the highest ductility. RC-30 also exhibited relatively high deflection at 5.79 mm. The CG beam had a moderate deflection at failure (4.5 mm), while RG bent slightly less (4.2 mm). The RC-50 beams had the smallest deflection at failure (4.1 mm), meaning it broke with less bending compared to the others.

Failure Mode

All the beams experienced a typical flexure failure, meaning they broke due to bending under the applied load. No shear failure or other types of failure were observed, indicating that the reinforcement within the beams effectively prevented such premature failures.

In simpler terms, the beams held up under the load until they cracked and bent, with differences in the strength and flexibility largely depending on the type of aggregates used. The CG beam, made from natural aggregates, was the strongest, while beams with recycled materials performed less impressively but consistently across the board.

Table 1: Measured results

Sample ID	First Crack Load (KN)	Deflection at First Crack Load (mm)	Failure Load (kN)	Deflection at Failure Load (mm)	Failure Mode
RG	2.2	0.25	16.59	4.2	Flexure
CG	2.2	0.15	20.1	4.5	Flexure
CR-50	1.9	0.20	16.76	4.74	Flexure
RC-50	1.8	0.18	16.86	4.1	Flexure
CR-30	1.95	0.23	16.96	6.3	Flexure
RC-30	1.85	0.12	16.59	5.79	Flexure

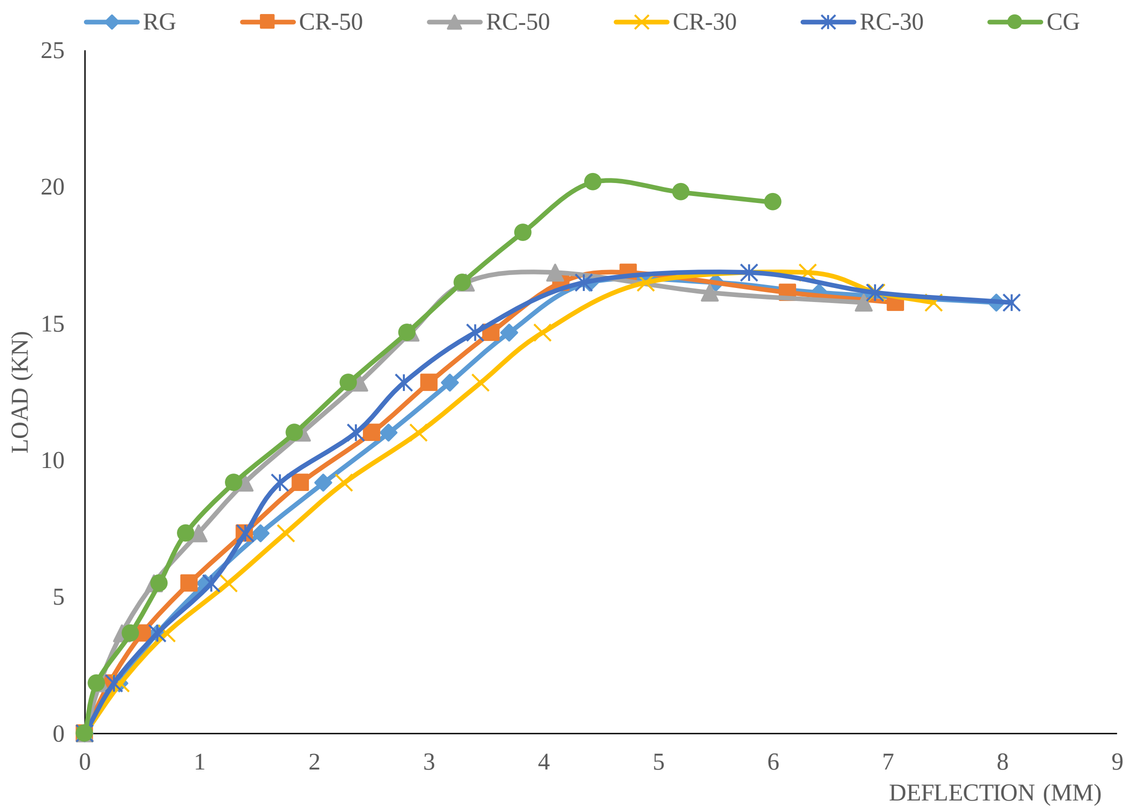

Figure 2: Load-deflection response

Load-Deflection Behavior

The graph illustrates the load-deflection behavior of six groups of reinforced concrete beams tested under bending. All beams follow a typical load-deflection pattern, starting with an initial linear phase, then gradually flattening as deflection increases, reflecting non-linear behavior as the beams near failure. Most beams reached peak loads between 15 and 20 kN.

The green curve, representing the CG beams, achieved the highest load capacity, reaching around 22 kN at about 4.5 mm deflection. This superior performance is likely due to the high-quality natural aggregates used. In contrast, the blue curve for RG beams showed a lower peak load (around 15 kN), indicating that using 100% recycled aggregates reduces the load-bearing capacity compared to CG beams.

The CR-50 and RC-50 beams, represented by orange and gray curves, performed similarly, with peak loads around 15–16 kN. The combination of 50% recycled or crushed granite in the top layer and the respective aggregates in the bottom layer led to performance comparable to the RG beams. The CR-30 and RC-30 beams (yellow and light blue curves) also exhibited nearly identical behavior, though with slightly lower peak loads than CR-50 and RC-50, reaching around 15 kN. The proportions of 30% and 70% recycled aggregates and crushed granite affected the stiffness and load capacity similarly.

The CG beams had the highest stiffness, shown by their steep rise and load-bearing capacity before failure. RG beams had the lowest stiffness, followed by the layered beams. All beams displayed similar deflection behavior after 4 mm, suggesting that once yielding occurred, the failure mechanisms were alike across the groups, despite the differences in maximum load.

CONCLUSION

Based on the experimental results and analysis of the bending tests on the six groups of two-layer reinforced concrete (RC) beams, several critical observations can be made, which lead to the following key conclusions:

i. The CG beams, made with 100% crushed natural aggregates, demonstrated the highest load capacity, reaching a failure load of 20.1 kN. In contrast, the RG beams, made with 100% recycled aggregates, had the lowest failure load at 16.59 kN. This highlights the superior strength of natural aggregates over recycled aggregates.
ii. The layered beams (CR-50, RC-50, CR-30, and RC-30) exhibited failure loads close to the RG beam (ranging from 16.59 to 16.96 kN). This indicates that layering different aggregates (recycled or crushed granite) did not significantly improve the overall load capacity compared to the single-layer beams made of 100% recycled aggregates.
iii. The deflection at first crack and failure loads varied across the groups. Beams made with natural aggregates (CG) showed less deflection at first crack (0.15 mm) compared to beams with recycled aggregates (RG at 0.25 mm). The CR-30 beams had the highest deflection at failure (6.3 mm), suggesting that certain combinations of crushed granite and recycled aggregates enhance ductility and allow for more bending before failure.
iv. The CG beams, made with natural aggregates, displayed the highest stiffness, as evidenced by their minimal deflection at first crack and relatively lower deflection at failure (4.5 mm). In contrast, the RG beams, composed of recycled aggregates, had the lowest stiffness, reflecting their reduced structural performance.
v. All beams, regardless of the aggregate type or layering configuration, failed in flexure under bending loads. This consistent mode of failure suggests that the reinforcement was adequate in preventing shear failures or other premature modes of failure, highlighting the structural adequacy of the reinforcement design across all groups.

REFERENCES

Barbhuiya, S., Kanavaris, F., Das, B. B., & Idrees, M. (2024). Decarbonising cement and concrete production: Strategies, challenges and pathways for sustainable development. *Journal of Building Engineering, 86*, 108861.

Bleischwitz, R., & Bahn-Walkowiak, B. (2006). *Sustainable Development in the European aggregates industry*. Wupp. Inst. Clim. Environ. Energy.

Bostanci, S. C., Limbachiya, M., & Kew, H. (2018). Use of recycled aggregates for low carbon and cost effective concrete construction. *Journal of Cleaner Production, 189*, 176-196.

BS EN, 12620:2002 (2008). Specification for Aggregate from Natural Sources.

BS EN, 197-1 (2011). Composition, Specification and Conformity Criteria for Common Cements.

Gerges, N. N., Issa, C. A., Sleiman, E., Aintrazi, S., Saadeddine, J., Abboud, R., & Antoun, M. (2022). Eco-friendly optimum structural concrete mix design. *Sustainability*, *14*(14), 8660.

Ghouleh, Z., Guthrie, R. I., & Shao, Y. (2017). Production of carbonate aggregates using steel slag and carbon dioxide for carbon-negative concrete. *Journal of CO2 Utilization*, *18*, 125-138.

Hasheminezhad, A., King, D., Ceylan, H., & Kim, S. (2024). Comparative life cycle assessment of natural and recycled aggregate concrete: A review. *Science of The Total Environment*, *950*, 175310.

Joensuu, T., Edelman, H., & Saari, A. (2020). Circular economy practices in the built environment. *Journal of cleaner production*, *276*, 124215.

Kisku, N., Joshi, H., Ansari, M., Panda, S. K., Nayak, S., & Dutta, S. C. (2017). A critical review and assessment for usage of recycled aggregate as sustainable construction material. *Construction and building materials*, *131*, 721-740.

Kryeziu, D., Selmani, F., Mujaj, A., & Kondi, I. (2023). Recycled concrete aggregates: a promising and sustainable option for the construction industry. *Journal of Human, Earth, and Future*, *4*(2), 166-180.

Makul, N. (2020). Advanced smart concrete-A review of current progress, benefits and challenges. *Journal of Cleaner Production*, *274*, 122899.

McGinnis, M. J., Davis, M., de la Rosa, A., Weldon, B. D., & Kurama, Y. C. (2017). Strength and stiffness of concrete with recycled concrete aggregates. *Construction and Building Materials*, *154*, 258-269.

Osial, M., Pregowska, A., Wilczewski, S., Urbańska, W., &Giersig, M. (2022). Waste management for green concrete solutions: a concise critical review. *Recycling*, *7*(3), 37.

Poon, C. S., & Chan, D. (2007). The use of recycled aggregate in concrete in Hong Kong. *Resources, conservation and recycling*, *50*(3), 293-305.

Sadowska-Buraczewska, B., Barnat-Hunek, D., & Szafraniec, M. (2020). Influence of recycled high-performance aggregate on deformation and load-carrying capacity of reinforced concrete beams. *Materials*, *13*(1), 186.

Shyamala, G., & Maruthachalam, D. (2024, June). A review of eco-friendly concrete materials: Advancements and environmental impact. In *AIP Conference Proceedings* (Vol. 3122, No. 1). AIP Publishing.

Silva, R. V., De Brito, J., & Dhir, R. K. (2019). Use of recycled aggregates arising from construction and demolition waste in new construction applications. *Journal of Cleaner Production*, *236*, 117629.

Sonawane, T. R., & Pimplikar, S. S. (2013). Use of recycled aggregate concrete. *IOSR Journal of Mechanical and Civil Engineering*, 52(59).

Xiao, J., Li, L., Shen, L., & Poon, C. S. (2015). Compressive behaviour of recycled aggregate concrete under impact loading. *Cement and Concrete Research*, *71*, 46-55.

Xing, W., Tam, V. W., Le, K. N., Hao, J. L., & Wang, J. (2022). Life cycle assessment of recycled aggregate concrete on its environmental impacts: A critical review. *Construction and Building Materials*, *317*, 125950.

Ziemian, R. D. (Ed.). (2010). *Guide to stability design criteria for metal structures*. John Wiley & Sons.