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MULTISCALE ANALYSIS OF STRUCTURAL PERFORMANCE AND FAILURE MECHANISMS IN LAYERED REINFORCED CONCRETE BEAMS WITH RIVER GRAVEL AND CRUSHED COARSE AGGREGATE INTERFACES

BY

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Abstract

The structural performance and failure mechanisms of layered reinforced concrete (RC) beams incorporating river gravel and crushed coarse aggregates were investigated through a multiscale analysis. The experimental program involved testing six small-scale reinforced concrete (RC) beams (0.9 × 0.075 × 0.112 m) were tested for bending strength, including two monolithic (NA, RV) and four layered configurations (50RVT, 50RVB, 30RVT, 70RVB). Monolithic beams used uniform aggregates: crushed natural aggregates (NA) or river gravel (RV). Layered beams combined materials: 50RVT and 50RVB had equal 56 mm layers with varying aggregate placement, while 30RVT and 70RVB had unequal layer thicknesses. All beams were reinforced with 2Y8 bars at the bottom and 2R6 bars at the top, with a tensile reinforcement ratio of 0.013. These variations explored material placement and thickness effects on performance. Beams were subjected to third-point loading to evaluate load-carrying capacity, ductility, stiffness, and cracking behavior. Results demonstrated that the NA beam achieved the highest stiffness and load-carrying capacity due to uniform crushed aggregates, though at the expense of ductility. The 50RVB configuration achieved the highest ductility index (2.85), balancing strength and deformability by placing crushed aggregates in the compression zone and river gravel in the tensile zone. Unequal layer thicknesses, as in 30RVT and 70RVB, reduced structural efficiency due to limited stress distribution. This study concludes that strategically layering crushed aggregates and river gravel optimizes RC beam performance. Placing crushed aggregates in the compression zone and river gravel in the tensile zone provides an effective balance between strength and ductility, contributing to sustainable and resilient RC beam designs.

Keywords: *Bending, Crushed aggregates, Ductility, layered beam, Load, River gravels,*

INTRODUCTION

The use of layered reinforced concrete (RC) beams, which combine different aggregate types within a single beam, offers potential for enhanced material performance and sustainability (Anike et al., 2022; Sbahieh et al., 2022). This approach involves integrating layers with varying aggregate compositions—such as natural river gravel and crushed coarse aggregates—which could optimize structural properties while reducing reliance on virgin materials. River gravel, known for its rounded shape and smooth texture, offers ease of workability and often higher resistance to weathering (Sulymon, 2025; Nwafor, 2022), while crushed aggregates, typically more angular, may exhibit superior bonding with cementitious material due to their rougher texture (Ouyang, 2020; Wembe, 2023). The inclusion of these distinct materials in layers within RC beams introduces unique interactions, influencing the overall mechanical performance, durability, and failure mechanisms of the beams.

Multiscale analysis, which examines structural performance from the micro- to the macro-scale, provides a detailed framework for understanding these complex interactions and their effects on RC beam behavior (Barbhuiya et al., 2023; Long et al., 2024). On a microscale, the bonding quality between cement paste and aggregate particles in each layer determines the composite's local strength and crack propagation behavior (Daneshvar et al., 2022; Hlobil et al., 2022). At the mesoscale, the interface between layers of different aggregates becomes a focal point, with stress concentrations and potential for debonding, which could significantly influence the beam's load-carrying capacity

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(Zhang, 2022; Yu et al., 2024). Finally, on a macroscale, the layered RC beam's flexural, shear, and torsional resistance, alongside its long-term durability, reflect the cumulative impact of these micro- and meso-level interactions.

The study of failure mechanisms in layered RC beams with river gravel and crushed aggregates is particularly important, as differences in aggregate properties can lead to various modes of failure under different loading conditions. Possible failure modes include delamination or debonding at the layer interface, flexural cracking, shear cracking, or crushing in compression (Opelt 2018; Zimmermann & Wang, 2020). These modes are influenced by aggregate interlock, interface bond strength, and layer arrangement (Moslemian et al., 2013; Mansourinik & Taheri-Behrooz, 2020) and are best understood through multiscale approaches that consider each structural level's unique contributions. By using river gravel as a layer, engineers can reduce the environmental impact of construction while maintaining structural integrity. In this context, multiscale analysis offers a critical perspective for designing layered RC beams that meet both performance and sustainability criteria, providing relevant information into achieving balance between durability, resource efficiency, and structural safety.

Although research highlights the environmental benefits of using river or local aggregates, studies have yet to fully quantify how layering river gravel and crushed aggregates affects the structural performance while optimizing sustainability. Furthermore, there is limited guidance on balancing resource efficiency with performance to create durable, safe RC beams using locally available materials in a layered design. This research seeks to address these gaps by providing a detailed, multiscale analysis of layered RC beams with river gravel and crushed aggregate interfaces, advancing the understanding of interlayer bonding, failure mechanisms, and the implications of aggregate choice on sustainability and structural integrity.

The study intends to investigate the effects of combining river gravel and crushed coarse aggregates in layered RC beams and to understand the multiscale interactions that impact the beams' structural performance and failure modes. This research will contribute to sustainable engineering by providing guidelines for the use of local and river gravel aggregates in layered RC beams. The findings will advance knowledge of multiscale structural behavior in layered beams, enabling engineers to design structures that balance sustainability with high structural integrity. Additionally, by clarifying failure mechanisms, this study will support safer and more resilient structural designs.

MATERIAL AND METHOD

2.1 Material

The layered reinforced concrete (RC) beams were constructed using grade 42.5 N Portland limestone cement, conforming to EN 197-1 (2011) standards. Fine aggregates were composed of river sand, adhering to BS EN 1260:2002 specifications, while the coarse aggregates consisted of crushed natural stone and river gravel, in full compliance with BS EN 1260:2002 criteria. Marine plywood formwork was employed during the casting process to ensure structural integrity and uniformity.

2.2 Method

Four (4) double-layer and two (2) single-layer small scale reinforced concrete (RC) beams of 0.9 x 0.075 x 0.112 m were designed and tested for bending strength. The NA configuration is a monolithic beam with a single, uniform layer made entirely of crushed natural aggregates. Since the beam is homogenous, there is no separate bottom layer. The RV configuration is a monolithic beam with a single, uniform layer made entirely of river gravel. Being homogenous, it has no distinct top or bottom layer. The 50RVT configuration is a two-layer beam with equal 56 mm layers, consisting of river gravel in the top layer and crushed aggregate in the bottom, with a tensile reinforcement ratio of 0.013. The 50RVB configuration is a two-layer beam with 56 mm layers, consisting of crushed aggregate in the top and river gravel in the bottom layer; the 30RVT configuration has two layers (34 mm top and 78 mm bottom) with river gravel in the top and crushed aggregate in the bottom layer; and the 70RVB configuration has two layers (78 mm bottom and 34 mm top) with crushed aggregate in the top and river gravel in the bottom, each with a tensile reinforcement ratio of 0.013. The beam samples were reinforced with 2Y8 and 2R6 at the bottom and top, respectively. Various beam types are presented in Table 1.

Table 1: beam types

Sample	Beam parameters			Top layer (mm)	Bottom layer (mm)	Tensile Reinf. ratio	Top Layer Agg. type	Bottom Layer Agg. type
	L (m)	D (m)	B (m)					
NA	0.9	0.112	0.075	112	-	0.013	Crushed Agg	-
RV	0.9	0.112	0.075	112	-	0.013	River gravel	-
50RVT	0.9	0.112	0.075	56	56	0.013	River gravel	Crushed Agg
50RVB	0.9	0.112	0.075	56	56	0.013	Crushed Agg	River gravel
30RVT	0.9	0.112	0.075	34	78	0.013	River gravel	Crushed

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								Agg
70RVB	0.9	0.112	0.075	34	78	0.013	Crushed Agg	River gravel

2.3 Test Setup

The beam samples were tested using a 50-ton loading frame, configured as simple-supported beams with a load applied at one-third of the span, illustrated in Figure 1. A dial gauge was positioned on the beam's tension side to track deflection, while steel rollers at each end acted as supports. A hydraulic jack was used to apply the load, which was recorded via a load cell. At each loading step, we documented the load applied and the corresponding deflection shown on the dial gauge.

RESULTS AND DISCUSSION

Load Carrying capacity

The Table 2 summarizes experimental results for six reinforced concrete beam configurations, varying in aggregate composition and layer arrangement. The key parameters recorded include yield load, failure load, ductility index, and failure mode, which are significant to this study. As indicated in **Figure 1 and Table 2**, beam NA achieves the highest yield load (18.59 kN) and failure load (20.41 kN) among all specimens. However, it exhibits the lowest ductility index (1.16). This behavior can be attributed to the uniform distribution of crushed aggregates, characterized by their higher strength and density compared to river gravel. These properties enhance the beam's resistance to compressive stresses, contributing to its superior load-carrying capacity (Qian & Li, 2009). Nevertheless, the inherent brittleness of crushed aggregates significantly limits the material's ability to deform plastically, resulting in a rapid failure mechanism with minimal energy absorption.

The RV beam configuration demonstrates a substantially lower yield load (5.55 kN) and failure load (14.92 kN) compared to the NA configuration. However, it exhibits a higher ductility index (1.59), indicating greater deformation capacity prior to failure. This behavior is primarily influenced by the properties of river gravel, which is characterized by lower intrinsic strength and a smooth surface texture. These factors reduce the aggregate's bond strength with the surrounding cement matrix, thereby diminishing the overall structural performance (Omoding, 2022). Nonetheless, the rounded geometry of river gravel contributes to enhanced ductility by facilitating micro-cracking and accommodating deformation under loading conditions, thereby delaying failure.

The performance of layered beam configurations 50RVT, 50RVB, 30RVT, and 70RVB demonstrates the influence of material placement and layer thickness on structural behavior, as summarized below:

50RVT configuration exhibits a moderate yield load of 7.58 kN, a failure load of 14.92 kN, and a significantly enhanced ductility index of 2.65. The improved ductility is attributed to the structural arrangement, where the top layer of river gravel, despite its lower strength, resists compressive forces with higher deformability. Simultaneously, the bottom layer of crushed aggregates enhances tensile resistance, facilitating substantial energy absorption and delaying failure. This interaction results in superior ductility compared to monolithic configurations.

This 50RVB beam achieves an improved yield load of 9.42 kN, the second-highest failure load of 18.59 kN, and the highest ductility index of 2.85 among all configurations. The enhanced performance arises from the placement of crushed aggregates in the top layer, which efficiently resists compressive stresses, while the river gravel bottom layer accommodates tensile stresses with greater deformability. The complementary interaction between these materials maximizes both strength and ductility, offering an optimal balance for structural performance.

Beam 30RVT had the same yield load as the 50RVB configuration (9.42 kN), this beam shows a reduced failure load of 14.92 kN and a lower ductility index of 1.83. The reduced performance is attributed to the thinner top layer of river gravel, which limits the beam's compressive resistance, while the thicker crushed aggregate bottom improves tensile resistance. However, the imbalance in layer thickness hinders efficient load transfer and stress distribution, resulting in reduced strength and ductility compared to configurations with equal layer thickness.

Beam 70RVB configuration matches the yield load of 9.42 kN and achieves a higher failure load of 16.75 kN with an intermediate ductility index of 2.26. The thicker top layer of crushed aggregates effectively handles compressive stresses, contributing to higher load resistance. Meanwhile, the thinner river gravel bottom provides moderate tensile capacity but limits the beam's ability to deform plastically. This arrangement enhances strength but slightly compromises ductility due to reduced tensile deformation capacity.

Table 2: Test results

Sample ID	Yield Load (KN)	Deflection at Yield (mm)	Failure Load P (kN)	Deflection at Failure (mm)	Bending capacity M=PL/4 (kNm)	Ductility Index	Failure Mode
NA	18.59	3.82	20.41	4.43	4.59	1.16	Flexure
RV	5.55	2.34	14.92	3.28	3.73	1.59	Flexure
50RVT	7.58	1.42	14.92	3.76	3.73	2.65	Flexure

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50RVB	9.42	1.63	18.59	3.82	4.65	2.85	Flexure
30RVT	9.42	2.29	14.92	4.2	3.73	1.83	Flexure
70RVB	9.42	2.1	16.75	4.75	4.19	2.26	Flexure

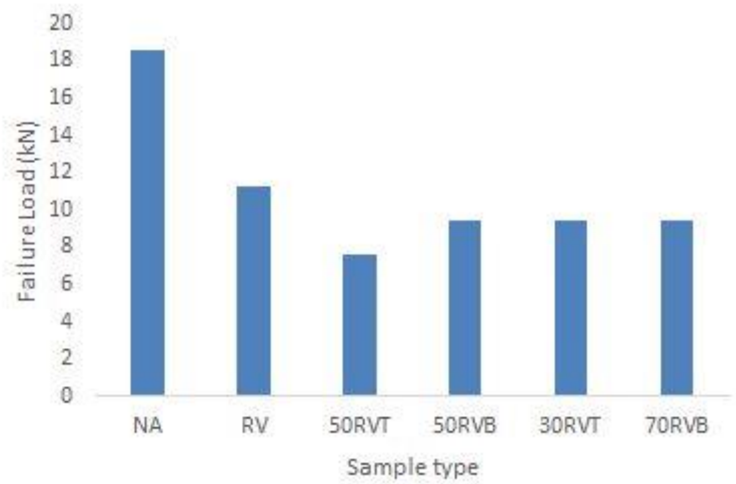

Figure 1: Variation of load capacity

Load-deflection behaviour
The load-deflection graph as shown in **Figure 2** reveals the stiffness characteristics of the six beam configurations, as indicated by the slopes of their initial linear regions. The NA configuration shows the steepest initial slope, signifying the highest stiffness, attributed to its uniform crushed natural aggregate composition, which provides superior compressive resistance. Studies have shown that crushed aggregates, due to their angular shape and rough texture, form a strong bond with the surrounding cement matrix, enhancing stiffness (Neville, 2011; Mehta & Monteiro, 2017). Conversely, the RV beam displays the lowest initial slope, indicating reduced stiffness due to the lower strength and smooth texture of river gravel, which weakens the bond with the matrix, as also reported by Siddique (2013).

Among the layered configurations, 50RVB and 70RVB exhibit relatively high initial slopes, reflecting their effective handling of compressive forces due to the presence of crushed aggregates in the top layers. This behavior aligns with findings by Rao et al. (2010), who emphasized the importance of placing stronger aggregates in compression zones for improved stiffness. The 50RVT beam shows moderate stiffness, slightly lower than 50RVB, as river gravel in the top layer reduces the compressive resistance. The 30RVT configuration demonstrates reduced stiffness compared to the equal-thickness configurations (50RVB and 50RVT), likely due to the thinner crushed aggregate layer, which diminishes load transfer efficiency.

The stiffness of the beams is directly influenced by the distribution and properties of the aggregates, with configurations utilizing crushed aggregates in compression zones exhibiting higher stiffness compared to those with river gravel or uneven layer thickness, corroborating the work of Neville (2011) and other researchers in aggregate mechanics.

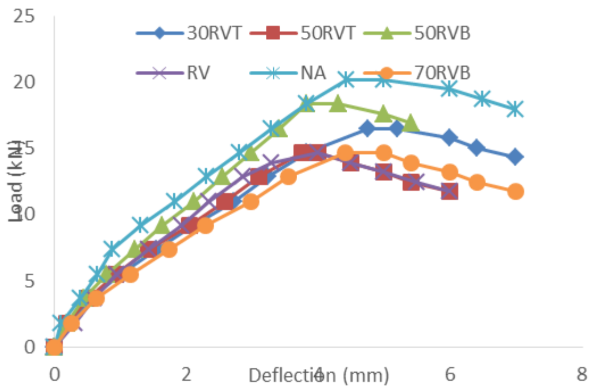

Figure 2: Load-deflection response

Cracking Capacity
The cracking capacity of reinforced concrete beams, as indicated by their load-deflection behavior, varies based on aggregate configurations. Beams with crushed natural aggregates (NA) demonstrate the highest cracking capacity due to their stiffness and strong bond strength. In contrast, beams with river gravel (RV) show the lowest capacity, attributed to weaker bonds and lower tensile strength. Layered configurations offer intermediate performance: 50RVT (river gravel top, crushed aggregate bottom) achieves moderate cracking capacity, balancing the weaker top layer with a stronger bottom layer. 50RVB (crushed aggregate top, river gravel bottom) shows high capacity, benefiting from improved compressive resistance and effective stress distribution. Configurations with thinner layers, such as 30RVT (thinner river gravel top), have reduced cracking capacity, while 70RVB (thicker crushed aggregate top)

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provides moderate to high capacity, leveraging the stronger top layer despite the thinner bottom layer's limitations.

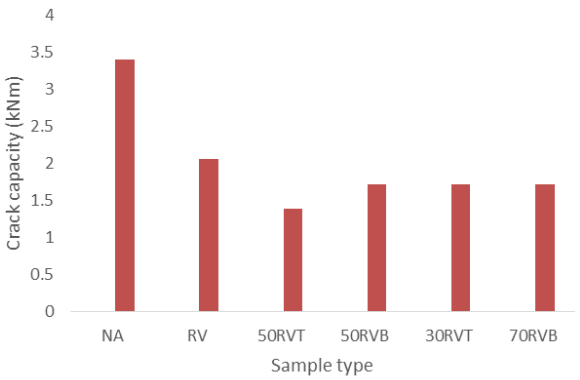

Figure 3: Variation of cracking capacity

Findings of the study

The structural performance of layered reinforced concrete beams is significantly influenced by material placement and layering. Configurations with crushed aggregates in the top layer (e.g., 50RVB and 70RVB) offer higher strength and stiffness due to higher compressive resistance, while those with river gravel in the top layer (e.g., 50RVT and 30RVT) enhance ductility but have lower strength. Uniform beams with crushed aggregates (NA) achieve the highest strength but suffer from reduced ductility, highlighting a trade-off between rigidity and deformation capacity. Layered configurations like 50RVB achieve an optimal balance of strength and ductility, effectively distributing loads and resisting cracking by placing crushed aggregates in compression zones and river gravel in tension zones.

CONCLUSIONS

The conclusions derived from the multiscale analysis of structural performance and failure mechanisms in layered reinforced concrete beams with interfaces of river gravel and crushed coarse aggregates are as follows:

1. Beams constructed with crushed natural aggregates (NA) consistently demonstrated the highest stiffness, cracking capacity, and load-carrying capacity due to their superior bond strength and compressive resistance. In contrast, river gravel beams (RV) exhibited lower performance metrics, attributed to weaker bonding and reduced aggregate strength.
2. Layered beams, particularly 50RVB (crushed aggregate top, river gravel bottom), achieved the highest ductility index. This result highlights the effectiveness of combining stronger aggregates in the compressive zone with more ductile aggregates in the tensile zone for improved energy absorption and delayed failure.
3. Unequal layer thicknesses, as in 30RVT and 70RVB, resulted in reduced structural efficiency compared to equal-layer configurations (50RVT and 50RVB). Thicker crushed aggregate layers provided better stiffness and strength, while thinner layers of river gravel limited tensile and ductile performance.
4. The strategic placement of crushed aggregates in the top layer (compression zone) and river gravel in the bottom layer (tensile zone), as in 50RVB, enhanced both strength and ductility. This configuration achieved the second-highest failure load and the highest ductility index, making it the most balanced design.
5. Beams with crushed aggregates in the compression zone exhibited higher cracking capacities due to their better bonding and resistance to tensile stresses. Configurations with river gravel in the top layer or thinner crushed aggregate layers (e.g., 30RVT) showed reduced cracking capacity, emphasizing the importance of material placement in resisting early failure mechanisms.

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