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UHPC Jacketing with Local Aggregates for Axial Strengthening of RC Columns

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Abstract: This study investigates the axial load performance of reinforced concrete (RC) columns strengthened with ultra-high-performance concrete (UHPC) jacketing incorporating locally sourced coarse aggregate. Four column specimens were tested, with variations in core concrete strength (20 MPa and 35 MPa) and jacketing material (normal concrete and UHPC). Monotonic axial compression tests were performed to evaluate load-bearing capacity, stiffness, ductility, energy absorption, and toughness. At 90 days, compressive strengths were 24.32 MPa for the 20 MPa concrete, 46.95 MPa for the 35 MPa concrete, and 80.06 MPa for the UHPC. Results demonstrate that UHPC jacketing significantly improved axial performance compared to normal concrete, particularly in terms of maximum load, stiffness, and toughness. However, higher-strength cores exhibited slightly reduced ductility. The findings underscore the potential of UHPC with coarse aggregate as a cost-effective strengthening material for existing RC columns, offering practical guidance for retrofitting strategies in developing countries.

Keywords: *Axial compression; coarse aggregate; jacketing; RC column; strengthening; UHPC.*

1. Introduction

Ultra-high-performance concrete (UHPC) is an advanced cementitious composite known for its high compressive strength, dense microstructure, and superior durability compared to conventional concrete [1], [2]. Over the past two decades, UHPC has gained increasing attention in both new construction and rehabilitation of deteriorated reinforced concrete (RC) structures[3], [4]. Research has focused on optimizing UHPC mix design, classification, and standardization to enable broader application in structural engineering practice [5].

Among various strengthening techniques, concrete jacketing remains a practical and effective approach to improving the axial load capacity, stiffness, and ductility of RC columns [6]. The use of UHPC as a jacketing material has demonstrated significant benefits due to its superior mechanical properties, particularly when combined with steel fibers for enhanced confinement [7], [8]. Recent studies have confirmed that UHPC-based retrofitting strategies, whether in ultra-high-performance fiber-reinforced concrete (UHPFRC) or locally adapted UHPC. UHPC can provide exceptional axial strength, energy absorption, and toughness [9], [10], [11], [12], [13], [14].

However, much of the existing research focuses on UHPC formulated with fine powders and nanoscale materials, achieving compressive strengths exceeding 120 MPa. Limited studies have explored UHPC incorporating coarse aggregates sourced locally, particularly in the context of cost-effective strengthening solutions for developing countries. The use of coarse aggregate (≤4.75 mm) in UHPC offers advantages in reducing material costs and simplifying production, making UHPC more practical for large-scale retrofitting projects.

In practice, the condition of existing RC columns varies widely, with compressive strengths often ranging from low to medium-grade concrete. Understanding how UHPC jacketing interacts with different core concrete strengths is critical for reliable strengthening design, especially for aging structures in developing countries. Additionally, selecting the jacketing material type is a key decision in retrofit projects, where cost, constructability, and performance must be balanced. This study therefore focuses on these two variables (core concrete strength and jacketing type) to provide practical, data-driven insights for optimizing UHPC retrofitting strategies in real-world applications.

2. Methods

2.1. Materials Preparation

Two types of concrete were used in this study: normal concrete (NC) for the column core and ultra-high-performance concrete (UHPC) with coarse aggregate for the jacketing layer. The target compressive strengths for the column core concrete were set at 20 MPa and 35 MPa to represent typical existing conditions in Indonesia. A strength of approximately 20 MPa reflects older or deteriorated structures, while 35 MPa represents relatively newer construction or higher-quality concrete commonly used in practice. By including both strength levels, the experimental program aimed to capture the influence of core concrete quality on the effectiveness of UHPC jacketing.

The NC was produced using locally sourced materials, while the UHPC mix was designed to achieve approximately 80 MPa compressive strength, with enhanced durability and low permeability, incorporating coarse aggregate (≤4.75 mm) to improve cost efficiency and local applicability. All materials were prepared under controlled laboratory conditions to ensure consistency and quality.

2.2. UHPC Mix Proportion

The UHPC mixture consisted of Portland slag cement (PSC), natural sand, crushed stone, silica fume, a high-range water-reducing admixture, and steel fibers. PSC was chosen due to its wide availability in Indonesia and its supplementary cementitious material (SCM) content, which improves durability, reduces the heat of hydration, and lowers the environmental impact of concrete production. This selection supports the development of a cost-effective and sustainable UHPC mix adapted to local resources.

Steel fibers (Dramix 3D, PT Bekaert) were incorporated at 2% by volume, with a length of 30 mm, diameter of 0.38 mm, tensile strength of 3070 MPa, and a modulus of elasticity of 210,000 MPa. A fiber volume of approximately 2% was selected based on previous research, which shows that this dosage achieves an optimal balance between crack-bridging ability and workability, providing effective confinement without excessive segregation or mixing challenges. [8], [11].

The water-to-binder (w/b) ratio was fixed at 0.20 to achieve the dense microstructure and low porosity typical of UHPC, ensuring high compressive strength while maintaining adequate workability through the use of a high-range water-reducing admixture. This w/b ratio was also selected to accommodate the inclusion of coarse aggregate without compromising mechanical performance.

The final mix design followed Oesman et al. (2022), with partial replacement of fine powders by coarse aggregate (≤4.75 mm) to improve cost efficiency and simplify large-scale production. Table 1 presents the UHPC mix proportions.

Table 1. Composition of UHPC mix.

Materials	Quantity (kg/m3)
PSC cement	750.40
Natural sand	454.95
Crushed stone	556.05
Silica fume	321.60
Superplasticizer	10.72
Water	203.68

2.3. Specimen Preparation

All column specimens had a square cross-section of 150 × 150 mm and a total height of 750 mm. Each column was reinforced with four longitudinal Ø10 mm bars placed at the corners and Ø8 mm stirrups spaced at 100 mm along the height. For strengthened specimens, a 15 mm-thick jacketing layer of either NC or UHPC was cast monolithically around the column core. The jacket thickness of 15 mm was selected to represent a thin, efficient strengthening layer for laboratory-scale testing while maintaining proportionate confinement effects similar to those used in field applications (typically 25–40 mm). This approach minimizes material use and highlights the efficiency of UHPC in thin retrofitting configurations.

Prior to jacketing, the surface of the existing core was mechanically roughened by chipping and brushing to achieve adequate surface roughness and remove loose materials. An epoxy-based bonding agent was then applied to the prepared surface to enhance the bond between the old concrete and the new jacketing material. A tight wooden formwork was assembled around the core, and the jacketing layer was cast in a single pour, with careful vibration to ensure proper compaction and minimize voids.

After casting, all specimens were initially covered with plastic sheets for 24 hours to prevent early moisture loss. They were then placed in a water-curing tank and subjected to moist curing at room temperature (25 ± 2°C) for 28 days. Following this stage, specimens were removed from the tank and stored under laboratory air-dry conditions until reaching 90 days of age, when axial compression tests were performed.

Due to limitations in testing facilities, material availability, and the scope of this experimental program, only one specimen was prepared and tested for each variable combination. The objective of this study was to provide exploratory and comparative insights into the effects of UHPC jacketing and core concrete strength on axial performance. While these results are indicative rather than statistically generalized, they offer valuable preliminary data for guiding future large-scale investigations.

Table 2 summarizes their configuration., while Table 2 summarizes their configuration, while Figure 1 illustrates the specimen cross-section and reinforcement details.

Table 2. Test specimens of composite columns.

Specimen	Jacketing Thickness	Core Concrete Strength (MPa)	Jacketing Type	Dimensions (mm)
CC-35	-	35	-	150 × 150 × 750
CR-35	15 mm	35	Normal	180 × 180 × 750
C35-UHPC	15 mm	35	UHPC	180 × 180 × 750
C20-UHPC	15 mm	20	UHPC	180 × 180 × 750

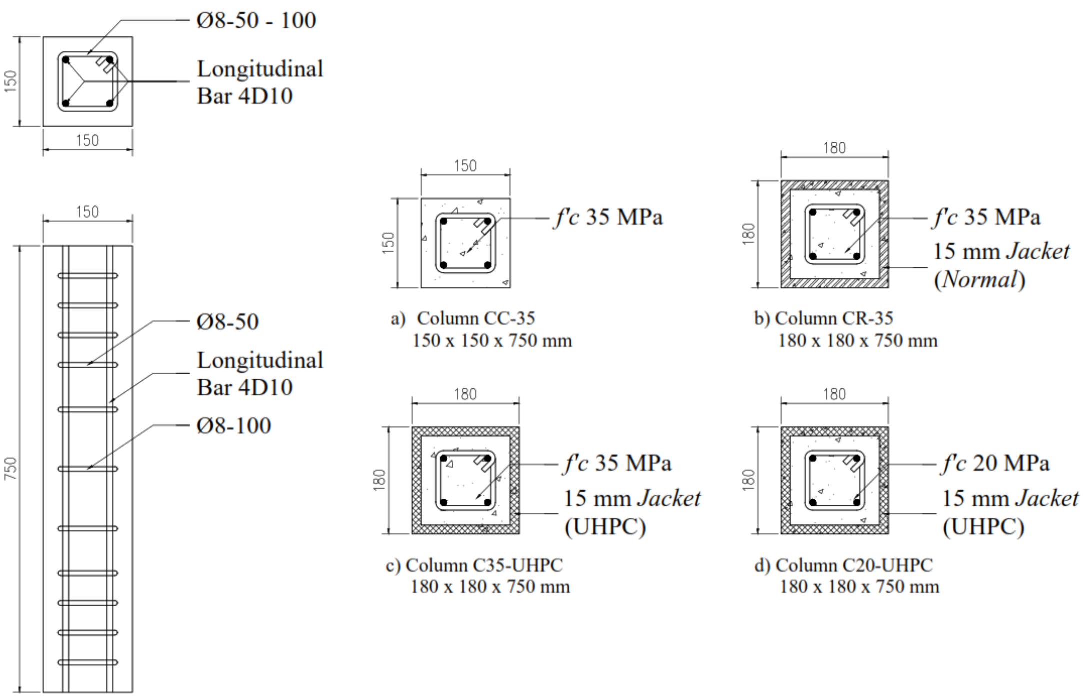

Fig. 1. Cross-section and details of column specimen.

2.4. Test Setup and Instrumentation

Axial compression tests were conducted using a 2000 kN Universal Testing Machine (UTM) under displacement-controlled loading. Each specimen was capped with steel plates to ensure uniform load distribution. The primary measurement of vertical deformation was obtained through the UTM's built-in displacement transducer, which recorded axial shortening throughout the test.

Fig. 2. Curing of test specimens: compressive strength test specimens and composite columns specimen.

To capture the confinement effect and monitor deformation patterns, four Linear Variable Differential Transformers (LVDTs) were installed on orthogonal faces of each specimen. Two LVDTs were mounted on the front face and two on the side face, positioned at one-third and two-thirds of the specimen height, to record lateral displacements. This arrangement allowed for the evaluation of both axial and lateral deformation responses, providing insight into column behavior and jacket confinement performance under axial loading (Figure 3).

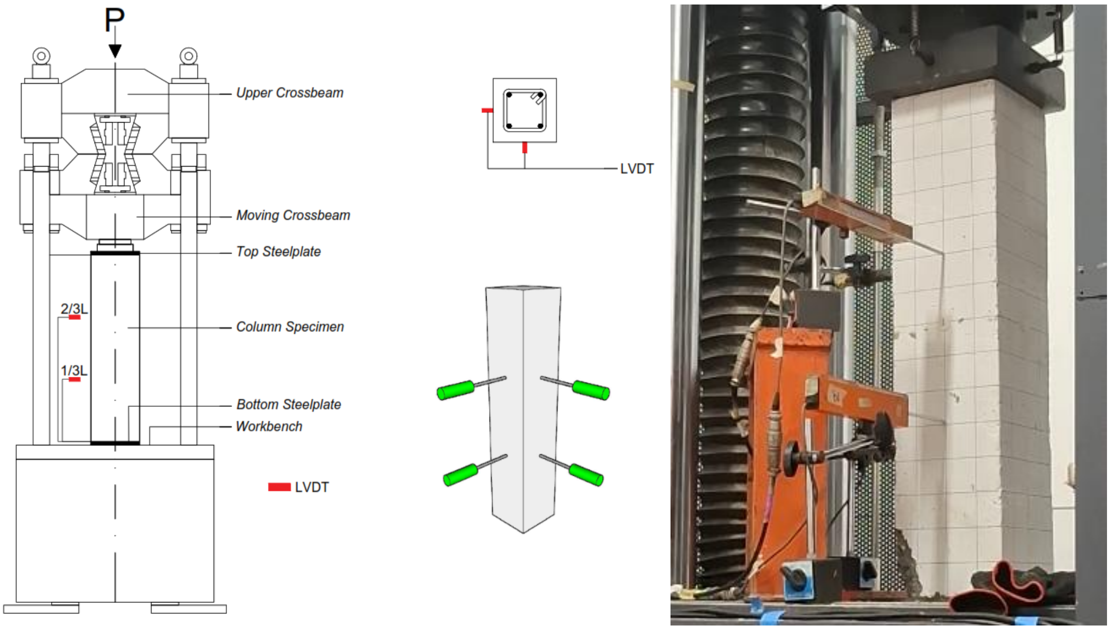

Fig. 3. Test setup and instrumentation

3. Results and Discussion

3.1. Compressive Strength of Materials

Compressive strength tests were conducted on all concrete types at 90 days (Table 3 and Figure 4). The average compressive strengths were 24.32 MPa for the normal concrete with a target of 20 MPa, 46.95 MPa for the concrete with a target of 35 MPa, and 80.06 MPa for the UHPC mix. These results confirm that the locally developed UHPC achieved approximately 80 MPa strength using coarse aggregate and PSC, demonstrating its suitability as a high-performance jacketing material.

Table 3. Compressive strength at 90 days.

Grade	Compressive Strength 90 Days (MPa)		
20 MPa	24.10	25.88	22.97
35 MPa	53.17	40.47	47.22
UHPC	81.03	88.45	70.68

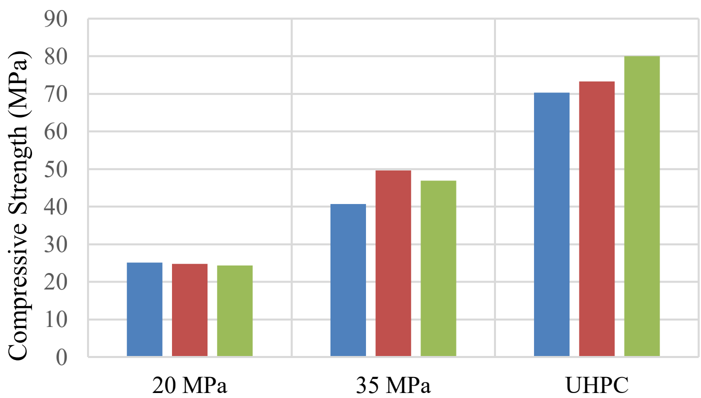

Fig. 4. Compressive Strength at 90 days

3.2. Axial Load Capacity and Structural Response

The experimental results demonstrate that UHPC jacketing substantially enhances the axial performance of RC columns, particularly in terms of maximum load, yield load, stiffness, and toughness. The C35-UHPC specimen achieved a maximum load of 1621.43 kN, representing a 46.8% increase compared to the unstrengthened control (CC-35), whereas NC jacketing (CR-35) failed to improve performance, instead showing a 16.3% reduction in maximum load. This confirms that thin UHPC jackets, even at only 15 mm thickness, can significantly increase axial load-bearing capacity, while conventional concrete jacketing may not provide effective confinement or strength enhancement.

Columns with higher-strength cores (C35-UHPC) exhibited superior load capacity and initial stiffness compared to those with lower-strength cores (C20-UHPC), consistent with the understanding that core concrete properties directly influence composite section performance. However, these benefits were accompanied by more brittle post-peak behavior, as reflected in lower ultimate load and reduced ductility. Conversely, C20-UHPC exhibited more stable post-peak response, emphasizing the trade-off between peak strength and deformation capacity.

3.3. Influence of Strengthening Layer Type on RC Column Behavior

Figure 5 compares the load–vertical deformation responses of the control column (CC-35), the column jacketed with normal concrete (CR-35), and the column jacketed with UHPC (C35-UHPC). Table 4 summarizes the corresponding axial performance parameters.

Normal concrete jacketing (CR-35) failed to improve performance, resulting in a 16.3% reduction in maximum load compared to the unstrengthened specimen (CC-35). Yield load also decreased by 20.1%, and toughness dropped by 39.3%, indicating insufficient confinement and ineffective composite action. The ultimate load of CR-35 (295.22 kN) was substantially lower than that of the control (1065.36 kN), reflecting premature jacket debonding and brittle failure.

In contrast, UHPC jacketing (C35-UHPC) produced a 46.8% increase in maximum load and a 47.2% increase in yield load compared to CC-35. Initial stiffness improved by 31.5%, while ductility increased modestly from 1.27 to 1.50. Energy absorption and toughness rose dramatically, reaching 5459.88 kNmm and 7150.22 kNmm, respectively. Lateral displacement measurements confirmed that UHPC jacketing provided superior confinement, leading to delayed cracking, improved load transfer, and a stiffer composite response.

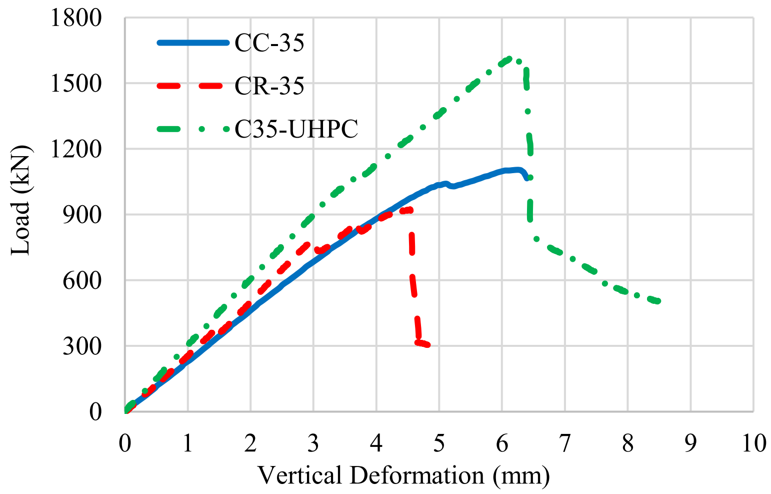

Fig. 5. Load-vertical deformation curve of layer type on RC column

These results highlight the clear advantage of UHPC over conventional concrete for thin jacketing applications. Even at a thickness of only 15 mm, UHPC was able to substantially enhance axial performance, validating its effectiveness as a retrofitting solution for strength-critical structural elements.

Table 4. Summary of the axial performance of different jacketing type.

Parameter	CC-35	CR-35	C35-UHPC
Maximum load (kN)	1104.45	924.06	1621.43
Ultimate load (kN)	1065.36	295.22	498.1
Yield load (kN)	1037.17	828.84	1527.06
Initial stiffness (kN/mm)	231.01	253.05	303.78
Ductility (μ)	1.27	1.3	1.5
Energy absorption (kNmm)	4122.94	2436.01	5459.88
Energy dissipation (kNmm)	151.78	160.39	1690.34
Toughness (kNmm)	4274.73	2596.4	7150.22

Initial stiffness increased by 31.5% with UHPC jacketing, whereas NC jacketing offered only a modest 9.5% improvement. Ductility improved slightly with both jacketing types, with UHPC achieving 1.50 compared to 1.27 for the control. The toughness of C35-UHPC reached 7150.22 kN·mm, a 67.3% increase over CC-35, demonstrating UHPC's ability to enhance energy absorption and confinement.

3.4. Influence of Core Concrete Strength

Figure 6 compares the axial responses of two UHPC-jacketed specimens with different core concrete strengths: C35-UHPC (35 MPa core) and C20-UHPC (20 MPa core). Table 5 summarizes their performance indicators.

The specimen with a 35 MPa core (C35-UHPC) achieved a maximum load of 1621.43 kN, representing a 60.8% increase compared to C20-UHPC (1008.10 kN). Similarly, the yield load increased by 60.3%, and initial stiffness improved by 27.4%, confirming that the quality of the core concrete has a substantial influence on the overall performance of UHPC-jacketed columns.

However, the ultimate load of C35-UHPC was lower (498.10 kN vs. 640.67 kN for C20-UHPC), indicating a more brittle post-peak response typical of high-strength concrete. This is consistent with the slightly lower ductility of C35-UHPC (1.50) compared to 1.57 for C20-UHPC, suggesting that while higher-strength cores enhance peak capacity, they also reduce deformation capacity.

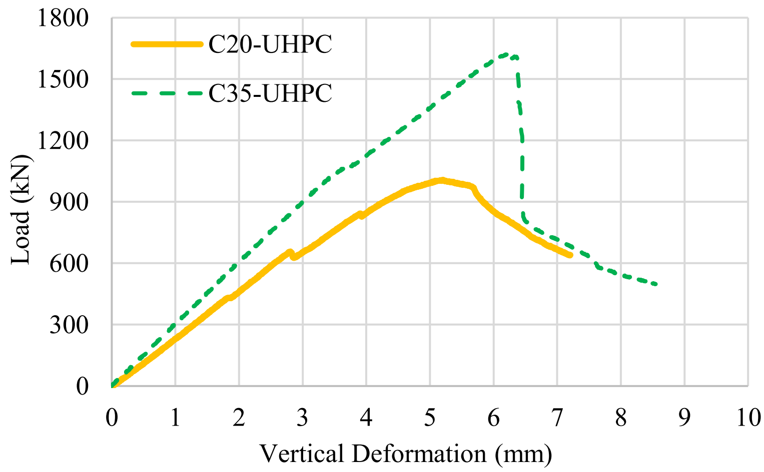

Fig. 6. Load-vertical deformation curve of existing RC column

The total toughness of C35-UHPC reached 7150.22 kNmm, which is 50.2% higher than that of C20-UHPC (4586.60 kNmm). Energy absorption and dissipation metrics show that the high-strength core improves energy storage but may compromise post-peak stability. These results emphasize the strength–ductility trade-off in retrofit design: higher-strength cores combined with UHPC jacketing provide maximum strength and stiffness, whereas lower-strength cores offer improved ductility and more stable post-peak performance, which could be advantageous in seismic or deformation-critical applications.

Table 5. Summary of the axial performance of existing RC column.

Parameter	C35-UHPC	C20-UHPC
Maximum load (kN)	1621.43	1008.1
Ultimate load (kN)	498.1	640.67
Yield load (kN)	1527.06	952.38
Initial stiffness (kN/mm)	303.78	238.38
Ductility (μ)	1.5	1.57
Energy absorption (kNmm)	5459.88	2931.82
Energy dissipation (kNmm)	1690.34	1654.77
Toughness (kNmm)	7150.22	4586.6

This integrated analysis demonstrates that UHPC layers significantly enhance reinforced concrete column performance, while the strength of existing concrete remains a critical factor influencing maximum load, initial stiffness, and energy absorption, although with trade-offs in ductility and ultimate load.

3.5. Energy Absorption and Confinement Effect

Analysis of toughness and energy dissipation metrics highlights the effectiveness of UHPC jacketing in improving overall structural resilience. The C35-UHPC specimen demonstrated the highest toughness (7150.22 kNmm) and energy absorption capacity (5459.88 kNmm), significantly surpassing both the control and NC-jacketed specimens. Lateral displacement measurements from LVDTs confirmed that UHPC jacketing effectively confined the core, limiting lateral expansion and enhancing stiffness under compression.

These findings align with previous studies [11], [13], [14], which have reported similar confinement benefits from UHPC jackets. The present study further demonstrates that even a thin UHPC jacket with coarse aggregate can provide substantial improvements, suggesting that UHPC can be adapted for cost-efficient, field-applicable retrofitting solutions.

3.6. Performance-Based Design Implications

The results highlight important considerations for performance-based retrofitting:

1. strength cores with UHPC jackets deliver maximum axial capacity and stiffness but are prone to brittle post-peak failure.
2. Lower-strength cores with UHPC jackets provide greater ductility and residual strength, which may be advantageous in seismic regions or applications where deformation capacity is critical.
3. NC jacketing showed poor performance and delamination, indicating that traditional jacketing materials may not be effective for strength-critical retrofits.

These observations underscore the potential of locally sourced UHPC as a reliable strengthening material and the importance of selecting retrofitting strategies based on the desired performance objectives (strength vs. ductility).

3.7. Limitations and Future Work

This study is exploratory in nature, with one specimen per test configuration due to resource limitations. While the results are consistent with literature and provide valuable comparative insights, statistical generalization requires larger sample sizes. Additionally, this research focused only on short-term monotonic axial loading; cyclic and seismic performance, long-term durability, and field-scale constructability were not evaluated.

Future studies should include:
1. Larger-scale testing with multiple replicates per configuration.
2. Detailed microstructural and interface bond analysis.
3. Cyclic and seismic load testing to assess ductility and energy dissipation under realistic conditions.
4. Optimization of UHPC mix design with coarse aggregates for scalability.

4. Conclusion

This study evaluated the axial performance of RC columns retrofitted with thin (15 mm) UHPC jackets using coarse aggregate. The main findings are:
1. Effectiveness of UHPC Jacketing: UHPC jackets substantially enhanced maximum load, stiffness, energy absorption, and toughness. Even with minimal thickness, a 46.8% increase in load capacity and a 67.3% improvement in toughness were achieved.
2. Limitations of Normal Concrete Jacketing: Conventional concrete jacketing demonstrated poor confinement and premature debonding, reducing both load capacity and toughness.
3. Influence of Core Strength: Higher-strength cores improved axial capacity and stiffness but resulted in more brittle post-peak behavior. Lower-strength cores provided better ductility and residual strength, which may be preferable in seismic applications.
4. Practical Relevance: Locally sourced UHPC with coarse aggregate provides a cost-effective retrofitting solution, balancing performance and constructability for developing countries.

Although exploratory with limited specimens, these results provide essential comparative data for optimizing UHPC-based retrofitting. Future research should address cyclic/seismic behavior, microstructural bond characteristics, and large-scale implementation.

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