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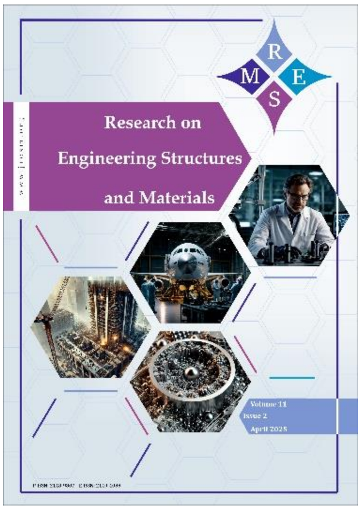

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Online Publication Date: 10 July 2025

URL: http://www.jresm.org/archive/resm2025-792me0328rs.html
DOI: http://dx.doi.org/10.17515/resm2025-792me0328rs

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article
Merie H D, Qader D N, Kamel B T, Jomaa M M. Buckling resistance of layered reinforced concrete columns: Experimental evaluation of normal and lightweight thermo-stone aggregate configurations. *Res. Eng. Struct. Mater.*, 2025; 11(6): 3187-3205.

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Research Article

Buckling resistance of layered reinforced concrete columns: Experimental evaluation of normal and lightweight thermo-stone aggregate configurations

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Article Info

Article History:

Received 28 Mar 2025
Accepted 02 July 2025

Keywords:

Buckling resistance;
Layered RC columns;
Normal concrete;
Lightweight concrete;
Thermo-stone

Abstract

Reinforced concrete (RC) columns are the vital part of building structures and play an important role in the stability and safety of the entire building under axial compression load. In this study, the buckling performance of layered RC columns made of NC, LWC and containing thermo-stone aggregate replacements was studied experimentally. Eighteen square and circular RC columns with different layer arrangements—LNN, LNL, and NNL—were tested under axial loading. Results showed that the NNL and LNN geometry performed better than the fully LWC columns in terms of axial compression and buckling. More precisely, square NNL columns with 25% thermo-stone replacement can attain an axial load capacity of 339.13kN, that represents a value 21.6% larger than the same fully LWC column (278.85kN). Similarly, layered circular columns with 50% thermo-stone replacement (CR-7 and CR-8) recorded 290.5–290.8kN, compared to 245.9kN for the fully LWC counterpart (CR-6). Deflections ranged from 3.75 mm in NC columns to 5.23 mm in layered LWC columns. Square columns consistently exhibited higher buckling resistance than circular ones due to their greater moment of inertia. The findings highlight that strategically placing NC in the middle and upper layers enhances structural performance while maintaining weight reduction.

1. Introduction

In reinforced concrete (RC) buildings, columns are important and indispensable components that deliver and provide support to the structure by withstanding axial and lateral forces. Hence, these columns are responsible for the structural response and to effectively support dominantly loads, the columns must possess good strength, durability, and ductility [1, 2]. Different reasons include the collapsing of structures and other human error factors, but the primary factor is mostly overloading and uncalculated or unconsidered additional weight put on the structures, and poor column design that is associated with poor knowledge of the properties of these columns. Particularly in tall or thin constructions where instability might result in catastrophic failure, the buckling behavior of these columns is a serious problem [3, 4].

Recently, layered columns have been used in many buildings and on a wide range as one of the new applications for lightweight columns with a high strength-to-weight ratio column, which incorporates multiple layers of concrete or reinforcement with different characteristics, have drawn interest due to their capacity to increase load-bearing capacity, ductility, and resistance to buckling [5, 6]. The behavior of these structures largely depends on the properties of concrete in each layer in addition to the type of their connection between layers. For layered columns, the

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DOI: http://dx.doi.org/10.17515/resm2025-792me0328rs

interaction between different layers of concrete and reinforcement introduces additional complexity. If the layers have different stiffnesses, strengths, and ductility, the buckling mode and critical load will also change. Moreover, it is impossible to completely ensure conformity between inter-layers, leading to inter-layer slip. If slip is sufficiently large, it has a profound effect on the mechanical behavior of the composite system. Consequentially, inter-layer slides have to be considered for the so-called partial interaction analysis of composite structures [7, 8].

In recent years, an approach to use a dual concrete column, also known as layered concrete column, has become widely studied to optimize the benefits of high-performed resistances and the physical characteristics of concrete. The authors of [9] studied the buckling behavior of layered composite columns with partial interaction between layers. Their study emphasized the challenges posed by the difference in stiffness and strength of the layers, affecting the buckling critical load and failure mode. This interlayer slip impacts the mechanical behavior of the composite system, and therefore they proposed a theoretical model taking this into account. This work highlighted the importance of inclusion of partial interaction in the response of such members. Numerical study of the buckling of axial loaded two-layer columns using finite difference method was performed by [10]. They discovered that the level of adhesion between laminates has a significant impact on the buckling strength of the column. with increasing interlayer bond defect, the slip of column will easily take place on the interlayer, which leads to decreasing of buckling resistance. These investigations show that despite the benefits of using layered columns to increase strength and decrease mass, their performance in buckling is complex should be further investigated especially with respect to material properties and layer stacks.

Lightweight concrete (LWC) has been widely used in construction for its ability to reduce the overall weight of a structure. However, the reduced stiffness of LWC compared to normal concrete (NC) raises concerns about its performance in load-bearing members. The authors of [11] conducted a review of fiber-reinforced polymer (FRP) RC columns, highlighting the potential for LWC to improve structural performance when combined with exterior FRP wraps. Their study found that LWC columns with FRP reinforcement exhibited up to 30% higher buckling resistance compared to conventional RC columns, suggesting that LWC can be a viable option when combined with appropriate reinforcement. However, there is a substantial body of literature that analyzes composite beams and beam-columns both analytically and numerically, for example, [12-19].

In continuation to the above investigations, recent studies have significantly increased our knowledge on lightweight and layered concrete columns under axial and buckling loads. The authors of [20] studied the behavior of the slender LWC-NC columns with lightweight aggregates in combination with steel confinement, showing that confined LWC-NC columns increase load capacity and ductility – observations that are pertinent to our layer-up LWC-NC configurations. In [21], the authors studied the seismic response of LWC columns under different axial forces and they found that the addition of extra transverse reinforcement is crucial for maintaining ductility, and this verifies the structural philosophy of our thermo-stone-based LWC cores. Moreover, the authors of [22] investigated the compressive axial performance of lightweight aggregate concrete (LWAC) columns confined by transverse steel confining reinforcement. They concluded that transverse confinement was effective in not only improving the compressive strength but also the ductility, because of experimental results. The work demonstrates the significant effect of steel confinement on increasing strength and deformation capacity of the LWAC for structural use. Finally, the authors of [23] investigated buckling of axially compressed, fully-encased composite columns constructed with high strength concrete (approximately 80 MPa) and ISMB 100 steel sections. Three unreinforced columns having different cross sections were tested under axial loading. It was found that larger cross sections and denser shear reinforcement enhance the buckling capacity. EC4 yielded more accurate estimates than AISC 360–10 when compared with test results. The results of tests were simulated by finite element analysis with ANSYS codes, and ANOVA demonstrated that EC4 was the most reliable model to predict the buckling resistance.

The current research addresses a gap in the understanding of the buckling behavior of layered RC columns, where limited studies have explored the influence of layering normal and LWC on structural performance, particularly under axial loading conditions. While previous research has focused on composite and lightweight columns, the specific buckling resistance of columns with various concrete layer arrangements remains underexplored. Therefore, this study aims to experimentally investigate the structural behavior of layered RC columns, utilizing normal and LWC (with different replacement ratios of thermo-stone aggregate) in varying arrangements. The research seeks to determine how these configurations impact buckling resistance, deflection, and overall structural performance.

1.1. Research Significance

This study aims to conduct an experimental investigation on the effect of different parameters on the structural behavior of layered columns combining NC and LWC, which parameters include the shape of these columns, the arrangement of layers, and the type of LWC that was manufactured by replacing different proportions of thermo-stone instead of aggregate. Thus, obtaining concrete columns with light weights that can bear external loads without any loss of their structural properties. Fig. 1 illustrates the research methodology flowchart for the current experimental investigation.

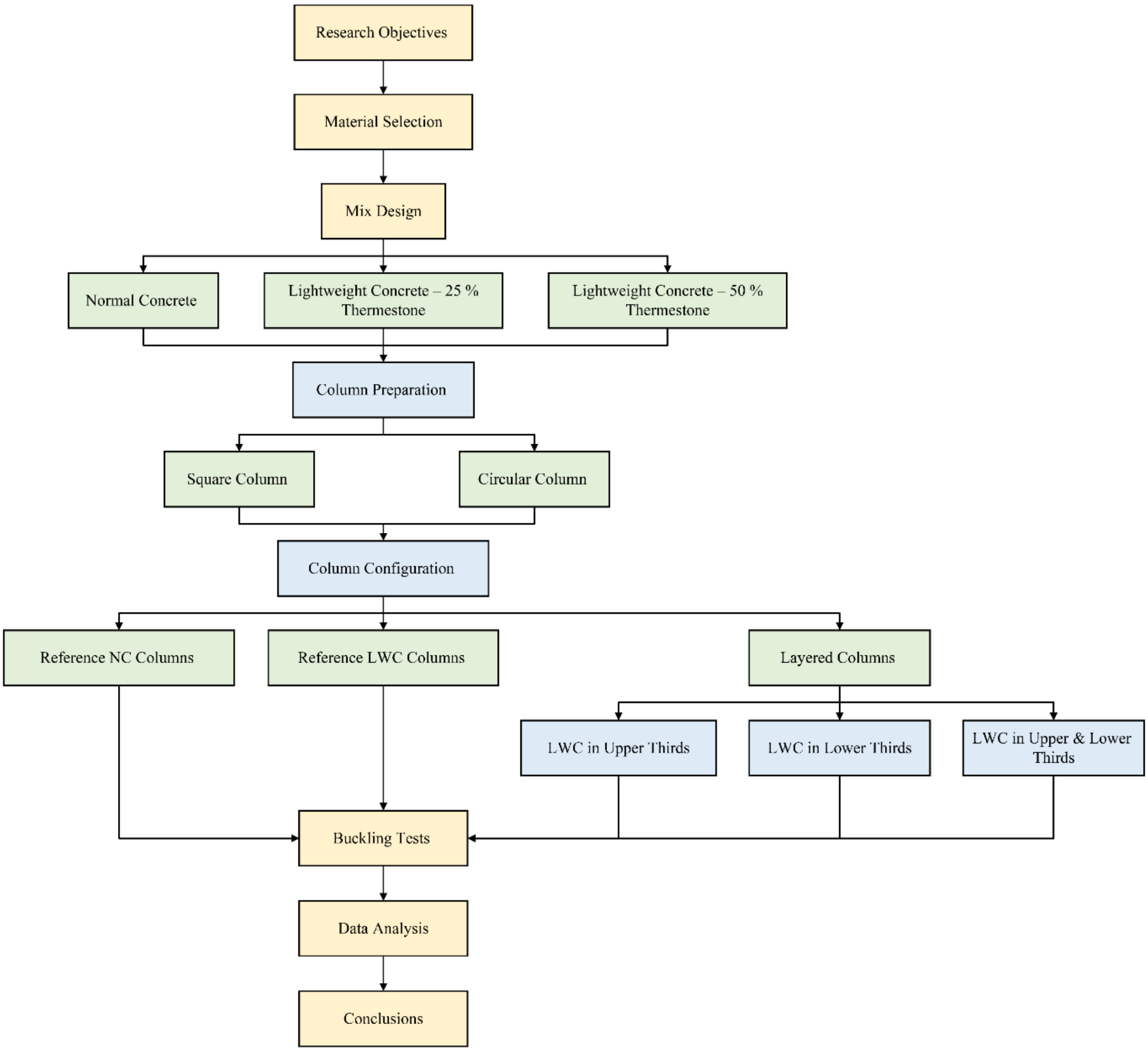

Fig. 1. Methodology flowchart for the present study

2. Experimental Program

The purpose of this experimental program is to investigate the behavior of intermediate reinforced concrete columns with square and circular cross-sections, constructed using both NC and LWC. The study includes layered configurations incorporating two thermo-stone replacement ratios for gravel (25% and 50%), as well as non-layered reference specimens for comparison. A detailed explanation of the materials used, the technique employed, and the results obtained may be found below.

2.1. Materials and Properties

2.1.1 Cement

According to Iraqi Standard (IQS) No. 5 [24], the main binding ingredient in each concrete mixture was ordinary Portland cement (OPC) type-I. Tables 1 and 2, respectively, outline the chemical and physical characteristics of the utilized cement in this study.

Table 1. Chemical characteristics of the employed cement

Properties	Composition content (%)	IQS Standard, No. 5 [24]
Oxide composition		
Alumina, Al_2O_3	4.92	
Silica, SiO_2	21.82	
Ferric Oxide, Fe_2O_3	2.98	
Lime, CaO	61.01	
Sulphatic Anhydride, SO_3	2.2	Max. 2.5
Magnesia, MgO	2.21	Max. 5
Compound composition		
C_3A	4.2	
C_2S	21.7	
C_3S	50.64	
C_4AF	7.071	
Free Lime	1.41	
Loss on ignition	1.23	Max. 4
Lime Saturation Factor (L.S.F)	0.92	0.66-1.02
Insoluble residue	0.42	1.5% max

Table 2. Physical characteristics of the utilized cement

Properties	Test result	IQS Standard, No. 5 [24]
Initial setting time, min	2hr 35 min	≥45
Final setting time, min	3hr 25 min	≤600
Specific surface area (Blaine method), m^2/kg	346	230 m^2/kg min
Compressive strength (MPa)		
at 3 days	18.32	≥ 10.0
at7 days	27.83	23 MPa min
at 28 days	35	≥ 32.5

2.1.2 Fine Aggregate

The sand employed in this investigation had maximum size of the aggregate is 4.75 mm with round-shape particles, for each mixture, dry amounts of sand were utilized. The grading of the sand was conformed to the Iraqi Standard (IQS) No. 45 [25].

2.1.3 Coarse Aggregate

Coarse aggregate, commonly found in nature as gravel, can be obtained through quarry blasting, manual crushing, or mechanical crushers. Before being used in concrete production, it must be thoroughly cleaned. Its angularity and strength influence the properties of the concrete in various ways. The gravel employed in this investigation is a river gravel with a maximum size of 12.5 mm and graded between 4.75 to 12.5 mm. It was found to conform to the Iraqi standard specifications No. 45 [25]. The gravel had a specific gravity of 2.66, and absorbed water at a rate of 0.76% as listed in Table 3.

Table 3. Characteristics of coarse aggregate employed in the current study

Properties	Specifications	Test results	Limits of specification
Specific gravity	ASTM C127 [26]	2.66	-
Absorption, %	ASTM C127 [26]	0.76%	-
Dry loose unit weight, kg/m^3	ASTM C29/C29M [27]	1341	-
Sulfate content (as SO_3), %	IQS No. 45 [25]	0.027	0.1 max

2.1.4 Water

Drinking clean water was utilized for mixing and curing the concrete samples.

2.1.5 Reinforcing Steel

A deformed reinforcing steel with nominal diameters of 10 mm (for longitudinal bars) and 6 mm (for stirrups) was used in this study. Where a reinforcing steel with a diameter of 6 mm was used in the stirrups and the reinforcing steel with a diameter of 10 mm in the longitudinal reinforcement of the specimen. The results of the laboratory test shown in Table 4 according to the reinforcing steel diameter.

Table 4. Properties of rebars

Diameter (mm)	Yield strength (MPa)		Ultimate strength (MPa)	
6	-	-	140.7	148.02
	-		147.8	
	-		155.55	
10	518.51	545.93	673.83	689.94
	568.27		713.26	
	550.99		682.75	

2.1.6 Lightweight Aggregate (Thermo-stone)

Thermo-stone is a type of block made from cellular concrete (autoclaved aerated concrete). In the original blocks it is used as an alternative over bricks in multi-story buildings to lessen the overall weight of the building and to provide thermal comfort within it. Thermo-stone is a blend of hydrated lime, sand, cement, water, and aluminum powder. The mixing process incorporates aluminum powder into the mixture, producing a gas-bubble structure in the concrete. It is happening because of a chemical reaction between aluminum powder, silica and hydrated lime. The concrete block is cured under high pressure stain at a set period of time after the primary placing. Waste from this concrete block can also be recycled to make a lightweight aggregate.

In this experimental investigation, the impact of utilizing lightweight aggregate, ranging in size from 4.75 to 12.5 mm, sourced from LWC blocks as coarse aggregate has been examined. The aggregate was obtained by crushing LWC blocks, brought from thermo-stone factory in Kirkuk city, into a similar grading to that of the natural aggregate (12.5 mm), and was used in the saturated surface dry (SSD) condition. This was then utilized to replace the coarse aggregate only with 25% and 50% as a volumetric replacing ratio. The replacement is volumetric for lightness weight of thermo-stone aggregate. Fig. 2 shows the stages of crushing thermo-stone. Table 5 lists the physical properties of thermo-stone.

Fig. 2. Stages of crushing thermo-stone

Table 5. Properties of thermo-stone aggregate

Properties	Specifications	Test results	Limits of specification
Specific gravity	ASTM C127 [26]	1.08	-
Absorption, %	ASTM C127 [26]	44.3%	-
Dry loose unit weight, kg/m^3	ASTM C29/C29M [27]	355	-
Sulfate content (as SO_3), %	IQS NO. 45 [25]	0.31	1 max

2.2. Sample Preparation and Mix Proportions

The standard compression cubes (0.15 x 0.15 x 0 .15) m and standard compression cylinders (0.15 x 0.3) m were used for testing the compressive strength of concrete. Then, the influence of using LWC on the physical properties of concrete was studied to obtain a suitable standard mixture to achieve the specifications mentioned previously. Table 6 shows the mixing ratios of the three concrete mixtures and the physical properties of each mixture with compressive strength for each mixture with a curing period of 28 days.

Table 6. Details of concrete mixtures

Trial mix	Mix type	Cement (kg/m^3)	Gravel (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	Thermo-stone kg/m^3	Superplasticizer L/100kg (cement)
1	NC	410	1035	723	179	0	0
2	LWC (25%)	410	776.5	723	198.3	54.31	1
3	LWC (50%)	410	517.62	723	205	105.62	1.1

2.2.1 Types of Specimens

In this research, two types of RC columns—square (0.15 x 0.15 m) and circular (0.15 m diameter), each measuring 0.75 m in length—were constructed using different configurations of NC and LWC with thermo-stone replacement. Table 7 provides the details for RC column specimens. The reinforcement details included 4 Ø10 longitudinal bars and Ø6 stirrups spaced at 150 mm (see Figs. 3, 4, and 5). The purpose was to assess how these variations influenced the columns' structural performance and buckling resistance. NC was used as the reference material, while LWC involved replacing either 25% or 50% of the gravel with thermo-stone aggregate to reduce the overall weight of the columns. In addition to fully NC or LWC columns, layered configurations were introduced, where the columns were divided into three layers along their length.

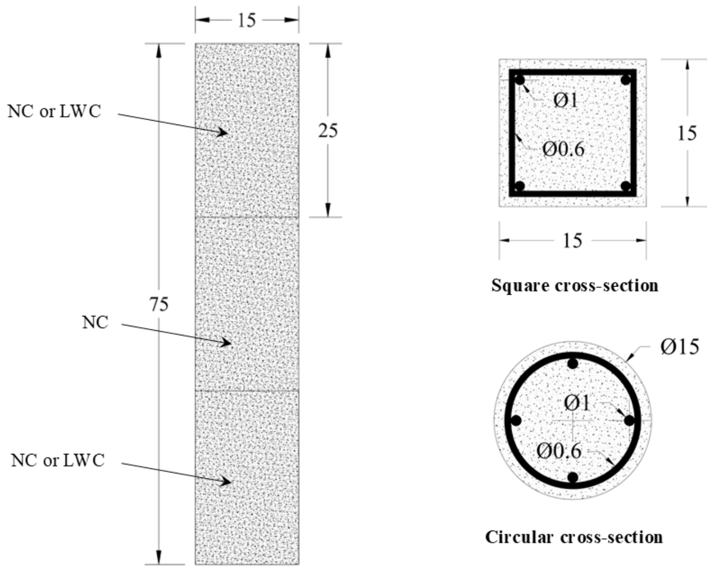

Fig. 3. Layered RC column configurations (all dimensions are in cm)

Fig. 4. Reinforcing steel cages of square and circular columns

Fig. 5. Square and circular steel molds

A total of 18 RC columns were tested, split equally into 9 square and 9 circular columns (Fig. 6), each with different concrete layer configurations. These configurations included: LNN (lower third LWC, middle third NC, upper third NC), LNL (lower third LWC, middle third NC, upper third LWC), and NNL (lower third NC, middle third NC, upper third LWC). The same layering schemes were applied to both square and circular columns to examine how the arrangement of the concrete layers influenced their buckling behavior under axial loading. The arrangement of concrete layers was modified in the upper and lower layers, while the middle layer was kept as NC to ensure strength in that region, which experiences the greatest deflection and, therefore, requires the highest strength. In the naming scheme, the first and second letters indicate the type of column, with SQ representing a square column and CR representing a circular column. The mechanical properties of fresh and hardened concrete are listed in Table 8. The RC columns were tested under axial compression using universal testing machine as shown in Fig. 7. A schematic representation of the test setup utilized in this study is illustrated in Fig. 8.

Table 7. Details of specimens

Specimen		Details of layers		
Square	Circular	Lower layer	Middle layer	Upper layer
Reference specimens (NC)				
SQ-1	CR-1		NC	
Reference specimens (LWC) (25% replacing ratio)				
SQ-2	CR-2		LWC (25%)	
Layered specimens				
SQ-3	CR-3	NC	NC	LWC (25%)
SQ-4	CR-4	LWC (25%)	NC	NC
SQ-5	CR-5	LWC (25%)	NC	LWC (25%)
Reference specimens (LWC) (50% replacing ratio)				
SQ-6	CR-6		LWC (50%)	
Layered specimens				
SQ-7	CR-7	NC	NC	LWC (50%)
SQ-8	CR-8	LWC (50%)	NC	NC
SQ-9	CR-9	LWC (50%)	NC	LWC (50%)

Fig. 6. Total RC column specimens

Table 8. Properties of concrete mixtures

Trial mix	Mix type	Density (kg/m³)	Compressive strength, f'_c (MPa)	W/C	Slump (mm)
1	NC	2364	32.7	0.436	7
2	LWC (25%)	2279.55	22.4	0.482	9
3	LWC (50%)	2201.62	23.7	0.507	8

Fig. 7. RC column specimen inside the universal testing machine

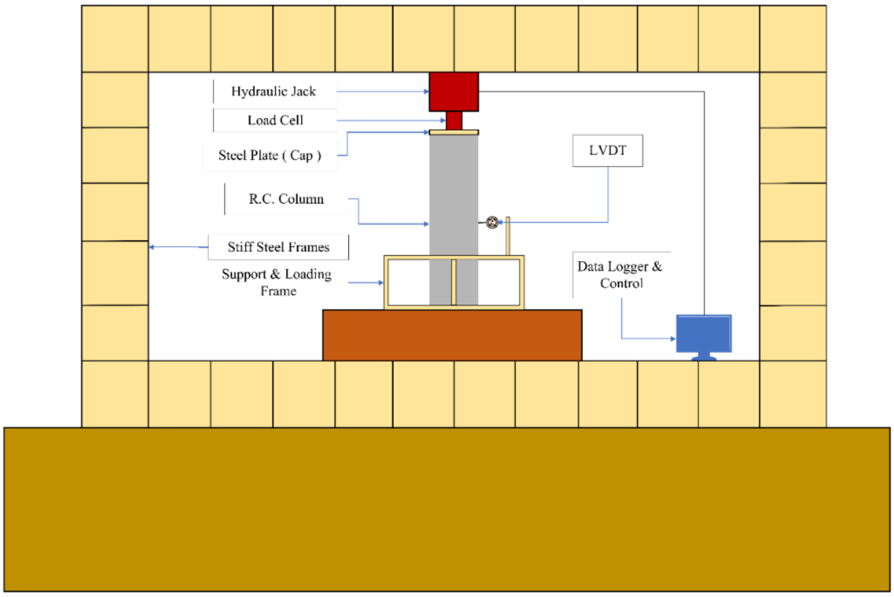

Fig. 8. An illustration of the experiment test setup used in the current study

3. Results and Discussion

This section provides a detailed analysis of the experimental results obtained from the study, comparing the performance of various layered concrete columns with different combinations of NC and LWC. The results for both square and circular column specimens are discussed, focusing on their buckling behavior, deflection characteristics, and overall structural performance.

3.1. NC Columns (Reference Specimens)

The reference specimens in this study consisted of NC columns, which provided a baseline for analyzing the buckling behavior of layered RC columns. The reference specimens used NC mixes with a compressive strength of 32.7 MPa (the density was 2364 kg/m^3), providing the necessary stiffness and mass to prevent buckling when subjected to axial loads. The major failure modes identified in the columns subjected to axial compression loading were lateral deflection followed by concrete crushing. This typical failure mode for slender columns under axial load resulted in deflection that was most pronounced in the middle third of the column height. Table 9 summarizes the properties of the specimens, including their geometry, reinforcement details, and material properties, which are essential for understanding the behavior of the reference specimens. While Table 10 provides a comparison of the results for the reference specimens, showing the critical buckling loads and deflection values.

Figs. 9 and 10 show the calculated axial load versus deflection behavior of the square and circular columns, respectively. The square column (Fig. 9) demonstrates a higher critical buckling load with lower deflection, indicating greater stiffness and resistance to buckling due to its higher moment of inertia. Its deflection curve rises gradually, reflecting slower progression toward failure. In contrast, the circular column (Fig. 10) shows a lower critical buckling load and higher deflection, indicating greater flexibility and faster approach to buckling. This comparison highlights that square column provide better buckling resistance, while circular columns exhibit more deflection under similar loading conditions.

Table 9. Properties of the square and circular column specimens

Type of specimen	Specimen code	f'_c for each layer (MPa) Upper	Middle	Lower	$f'_{c,avg}$ (MPa)	A_g (mm^2)	A_s (mm^2)	f_y (MPa)
				Square				
Reference (NC)	SQ-1	32.7	32.7	32.7	32.7	22500	314	545.93
Reference (LWC) with 25% thermo-stone	SQ-2	22.4	22.4	22.4	22.4	22500	314	545.93
Layered with 25% thermo-stone	SQ-3	22.4	32.7	32.7	32.7	22500	314	545.93
	SQ-4	32.7	32.7	22.4	25.83	22500	314	545.93
	SQ-5	22.4	32.7	22.4	25.83	22500	314	545.93
Reference (LWC) with 50% thermo-stone	SQ-6	23.7	23.7	23.7	23.7	22500	314	545.93
Layered with 50% thermo-stone	SQ-7	23.7	32.7	32.7	32.7	22500	314	545.93
	SQ-8	32.7	32.7	23.7	26.7	22500	314	545.93
	SQ-9	23.7	32.7	23.7	26.7	22500	314	545.93
				Circular				
Reference (NC)	CR-1	32.7	32.7	32.7	32.7	17662.5	314	545.93
Reference (LWC) with 25% thermo-stone	CR-2	22.4	22.4	22.4	22.4	17662.5	314	545.93
Layered with 25% thermo-stone	CR-3	22.4	32.7	32.7	32.7	17662.5	314	545.93
	CR-4	32.7	32.7	22.4	25.83	17662.5	314	545.93
	CR-5	22.4	32.7	22.4	25.83	17662.5	314	545.93
Reference (LWC) with 50% thermo-stone	CR-6	23.7	23.7	23.7	23.7	17662.5	314	545.93
Layered with 50% thermo-stone	CR-7	23.7	32.7	32.7	32.7	17662.5	314	545.93
	CR-8	32.7	32.7	23.7	26.7	17662.5	314	545.93
	CR-9	23.7	32.7	23.7	26.7	17662.5	314	545.93

Table 10. Results of RC column specimens

Type of specimen	Specimen code	Axial load (kN)	Deflection (mm)	I (mm^4)	E_{avg} (MPa)
Square					
Reference (NC)	SQ-1	374.98	3.75	42187500	21214
Reference (LWC) with 25% thermo-stone	SQ-2	278.85	4.2	42187500	14251
Layered with 25% thermo-stone	SQ-3	339.13	5.09	42187500	18893
	SQ-4	342.56	5.14	42187500	18893
	SQ-5	307.29	4.61	42187500	16572
Reference (LWC) with 50% thermo-stone	SQ-6	289.75	4.35	42187500	12312
Layered with 50% thermo-stone	SQ-7	346.06	5.19	42187500	18246.67
	SQ-8	347.21	5.21	42187500	18246.67
	SQ-9	318.85	4.78	42187500	15279.33
Circular					
Reference (NC)	CR-1	313.42	4.07	24837891	21214
Reference (LWC) with 25% thermo-stone	CR-2	238.93	4.3	24837891	14251
Layered with 25% thermo-stone	CR-3	284.9	5.17	24837891	18893
	CR-4	287.44	5.18	24837891	18893
	CR-5	262.9	4.73	24837891	16572
Reference (LWC) with 50% thermo-stone	CR-6	245.92	4.43	24837891	12312
Layered with 50% thermo-stone	CR-7	290.51	5.23	24837891	18246.67
	CR-8	290.83	5.23	24837891	18246.67
	CR-9	267.82	4.82	24837891	15279.33

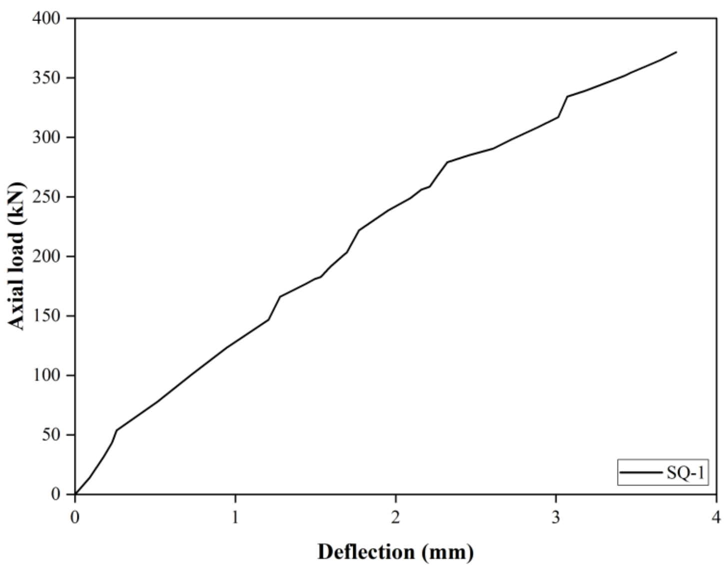

Fig. 9. Load versus deflection response for the reference square column (SQ-1)

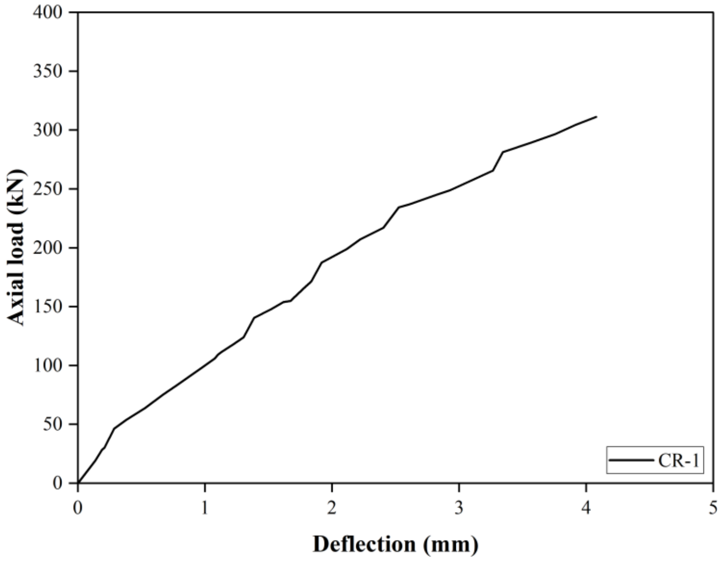

Fig. 10. Load versus deflection response for the reference circular column (CR-1)

3.2. Performance of Layered Columns: NC and LWC Configurations

The performance of layered reinforced concrete columns integrating NC and LWC was examined to determine their buckling resistance, axial load capacity, and deflection characteristics. Figs. 11 to 22 present the comparative analysis of load versus deflection behavior for square and circular column specimens with different configurations of NC and LWC. These configurations include fully NC columns, fully LWC columns with 25% and 50% replacement of thermo-stone aggregate, and layered specimens arranged in LNN, LNL, and NNL sequences.

The results indicate that fully NC columns exhibited the highest buckling resistance, as demonstrated in Figs. 10 and 11, where the NC circular column (CR-1) and NC square column (SQ-1) had significantly higher axial load capacities compared to their respective LWC counterparts (CR-2 and SQ-2). However, when LWC was used in a layered arrangement, such as the NNL configuration (CR-3 and SQ-3), an improvement in load-bearing capacity was observed compared to fully LWC columns. This suggests that placing NC in the middle and upper layers provides additional stiffness, enhancing the overall stability of the column.

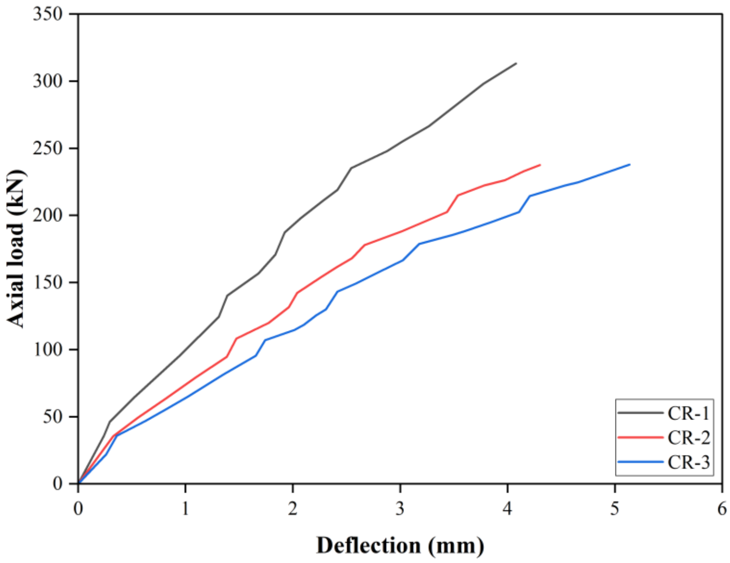

Fig. 11. Load versus deflection response between circular column NC (CR-1) and both LWC (CR-2) and layered NNL (CR-3) circular columns with 25% replacement ratio

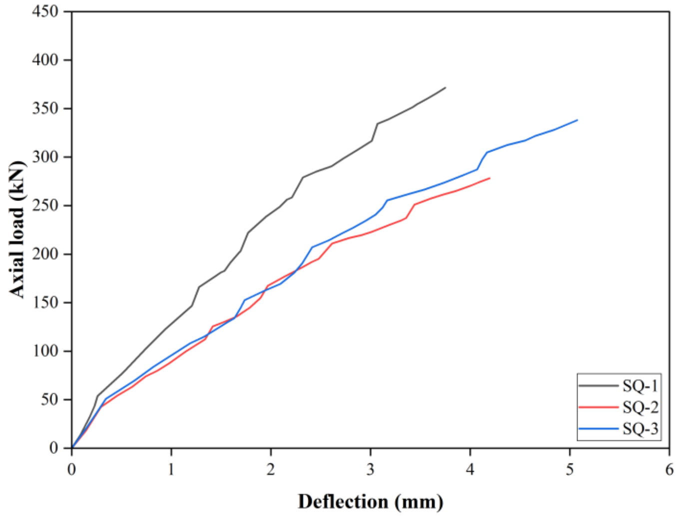

Fig. 12. Load versus deflection response between circular column NC (SQ-1) and both LWC (SQ-2) and layered NNL (SQ-3) square columns with 25% replacement ratio

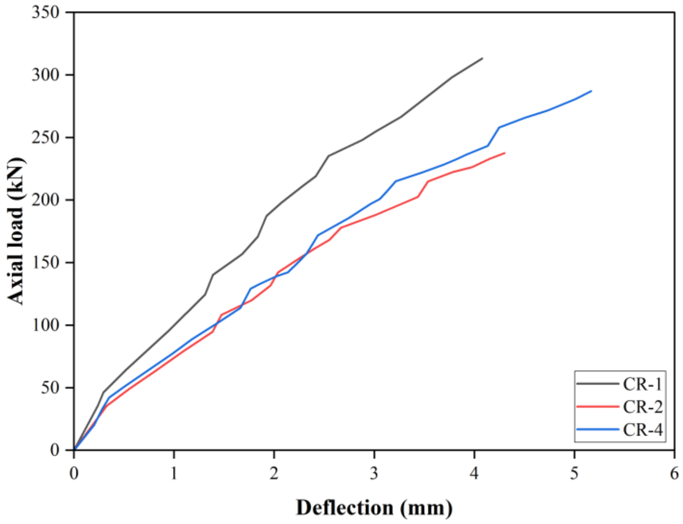

Fig. 13. Load versus deflection response between circular column NC (CR-1) and both LWC (CR-2) and layered LNN (CR-4) circular columns with 25% replacement ratio

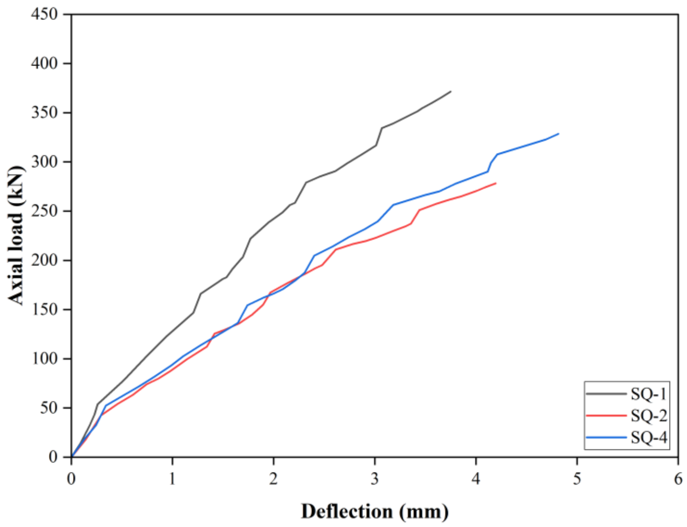

Fig. 14. Load versus deflection response between circular column NC (SQ-1) and both LWC (SQ-2) and layered LNN (SQ-4) square columns with 25% replacement ratio

Further insights into the effect of layering are shown in Figs. 12 and 13, where the LNN arrangement (CR-4 and SQ-4) is compared with fully NC and fully LWC columns. The LNN configuration, where the lower third consists of LWC, demonstrated a slight reduction in axial capacity compared to NC columns, but it significantly outperformed fully LWC columns. This trend was consistent in both circular and square columns, emphasizing the strategic advantage of maintaining NC in critical regions where maximum bending and deflection occur.

Figs. 14 and 15 illustrate the response of LNL-configured columns (CR-5 and SQ-5) in comparison to NC and LWC columns. The LNL arrangement, which incorporates LWC in both the lower and upper thirds while keeping NC in the middle, resulted in lower axial load resistance than the NNL and LNN configurations. This is attributed to the reduced stiffness in the upper and lower sections, which are essential for resisting lateral deflections under axial compression. These results suggest that the inclusion of NC in the middle layer contributes significantly to enhanced stability.

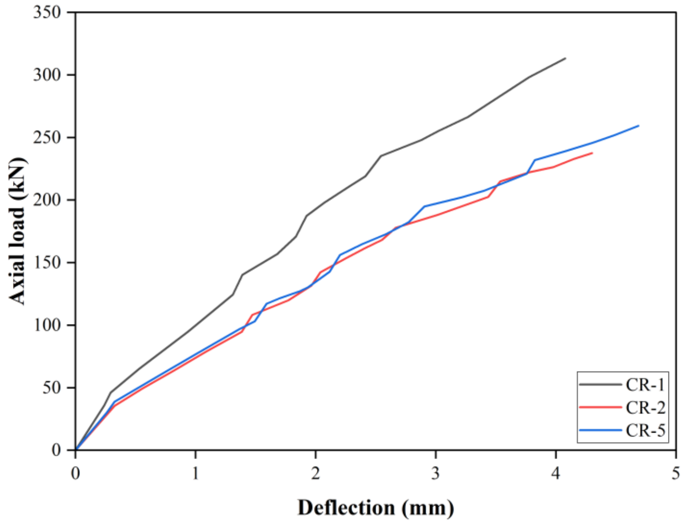

Fig. 15. Load versus deflection response between circular column NC (CR-1) and both LWC (CR-2) and layered LNL (CR-5) circular columns with 25% replacement ratio

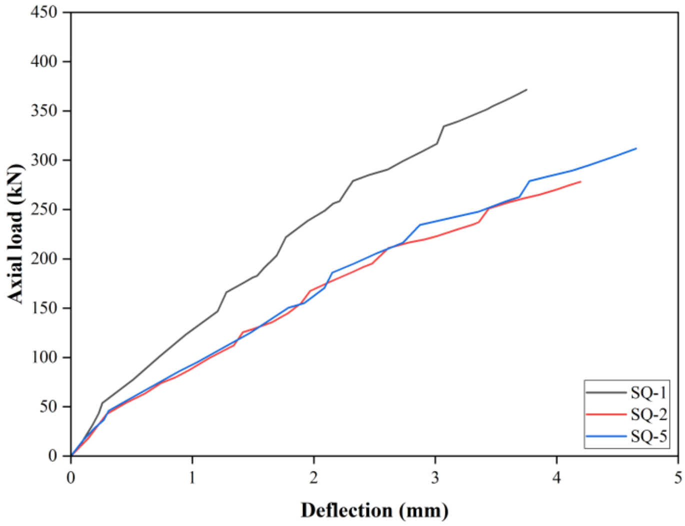

Fig. 16. Load versus deflection response between circular column NC (SQ-1) and both LWC (SQ-2) and layered LNL (SQ-5) square columns with 25% replacement ratio

A similar trend was observed for columns with 50% thermo-stone replacement, as illustrated in Figs. 16 to 21. The NC reference columns (CR-1 and SQ-1) consistently displayed superior load resistance, while the fully LWC columns with 50% replacement (CR-6 and SQ-6) exhibited reduced structural performance due to the lower stiffness of LWC. Layered specimens (CR-7, SQ-7, CR-8, SQ-8, CR-9, and SQ-9) demonstrated varying degrees of improvement over fully LWC columns, with the NNL and LNN configurations (Figs. 16-19) showing the highest performance among layered arrangements. In contrast, the LNL configuration (Figs. 20 and 21) displayed the lowest buckling resistance among the layered specimens, reinforcing the observation that LWC placement in both upper and lower thirds compromise overall stability.

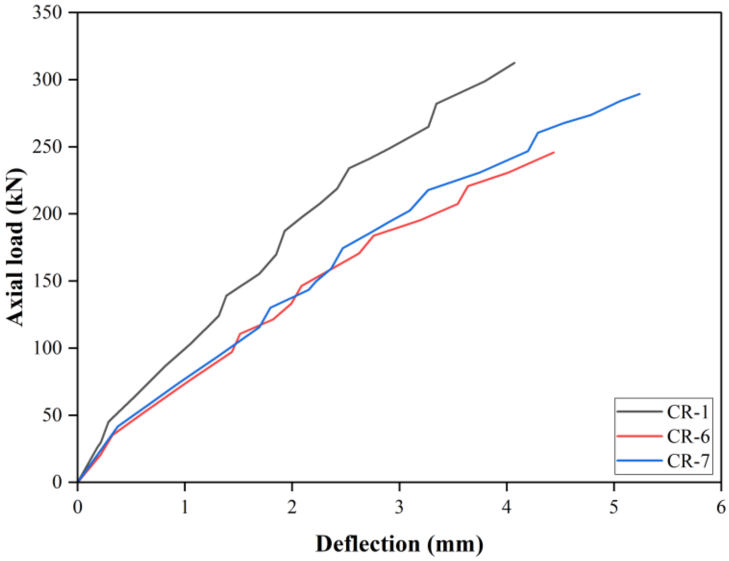

Fig. 17. Load versus deflection response between circular column NC (CR-1) and both LWC (CR-6) and layered NNL (CR-7) circular columns with 50% replacement ratio

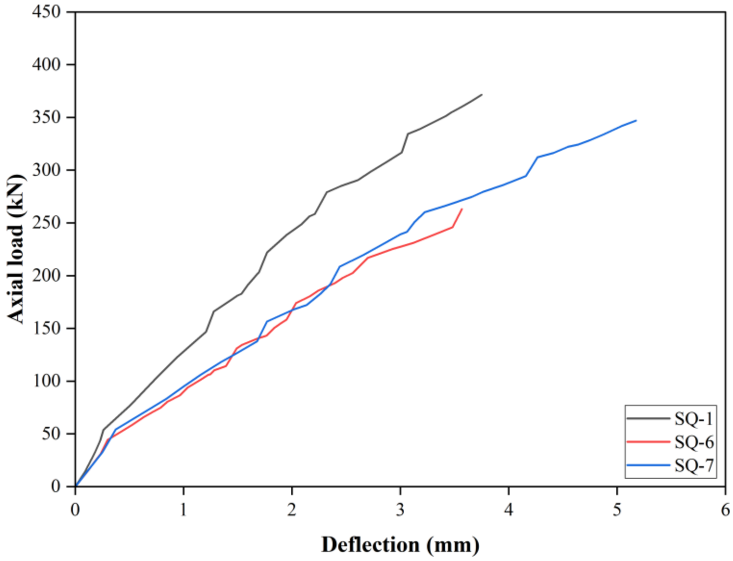

Fig. 18. Load versus deflection response between circular column NC (SQ-1) and both LWC (SQ-6) and layered NNL (SQ-7) square columns with 50% replacement ratio

The observed failure modes and structural behavior of the tested columns suggest that the internal interaction between different concrete layers plays a critical role in the buckling performance. In particular, the interface between NC and LWC in layered configurations influenced the stress distribution and deformation shape during loading. Columns with NC placed in the middle or upper segments (NNL and LNN) showed delayed initiation of lateral deflection, indicating that the stiffer NC core resisted deformation more effectively, while the adjacent LWC layers allowed for controlled flexibility. This synergy contributed to improved stability and higher buckling loads. Conversely, in LNL configurations, where LWC was used in both end regions, early buckling initiation was observed due to insufficient stiffness at the zones most susceptible to compression and tension during buckling. Furthermore, the difference in stiffness and density between NC and LWC caused differential strain behavior across the column height, which influenced the mode and location of failure. Square columns exhibited more uniform crack patterns, while circular ones showed localized buckling near the mid-height. These outcomes confirm that the interaction of layer configuration, material stiffness, and column geometry collectively govern the buckling response and failure mechanisms.

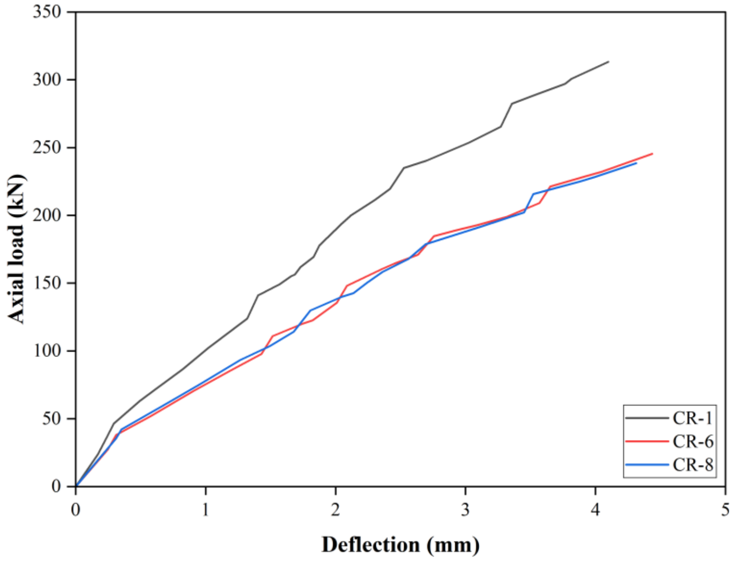

Fig. 19. Load versus deflection response between circular column NC (CR-1) and both LWC (CR-6) and layered LNN (CR-8) circular columns with 50% replacement ratio

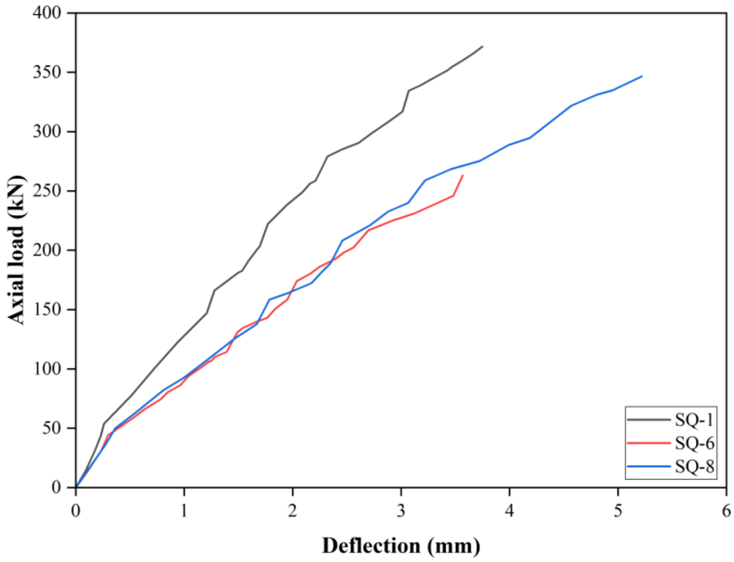

Fig. 20. Load versus deflection response between circular column NC (SQ-1) and both LWC (SQ-6) and layered LNN (SQ-8) square columns with 50% replacement ratio

According to the experimental findings, the NNL and LNN configurations demonstrated better buckling resistance than the LNL configuration. The performance benefit comes from the placement of NC in between the middle and upper sections of the part, which lends it increased stiffness and limits deflection. At all of these tested shapes, square columns showed a superior buckling resistance than circular columns. This was attributed to a higher moment of inertia leading to better stiffness response and less deflection with the same axial loading conditions. Thus, layered concrete configurations incorporating NC in critical regions can enhance stability, while square columns provide improved structural performance.

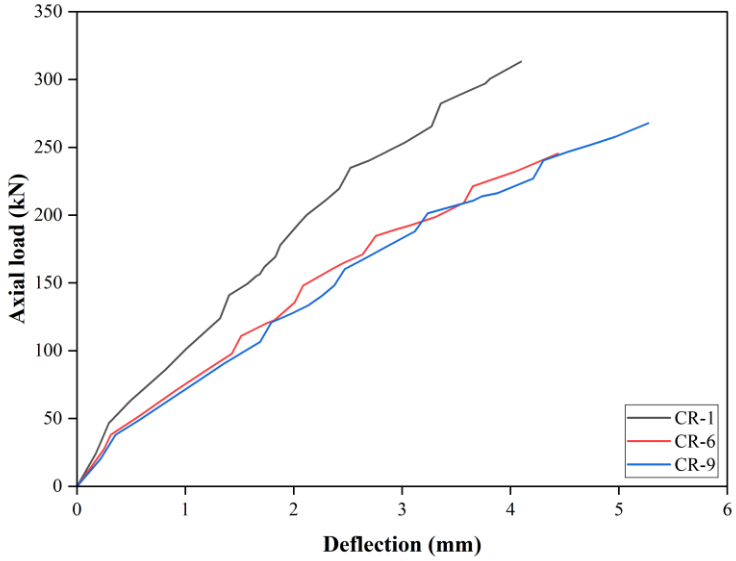

Fig. 21. Load versus deflection response between circular column NC (CR-1) and both LWC (CR-6) and layered LNL (CR-9) circular columns with 50% replacement ratio

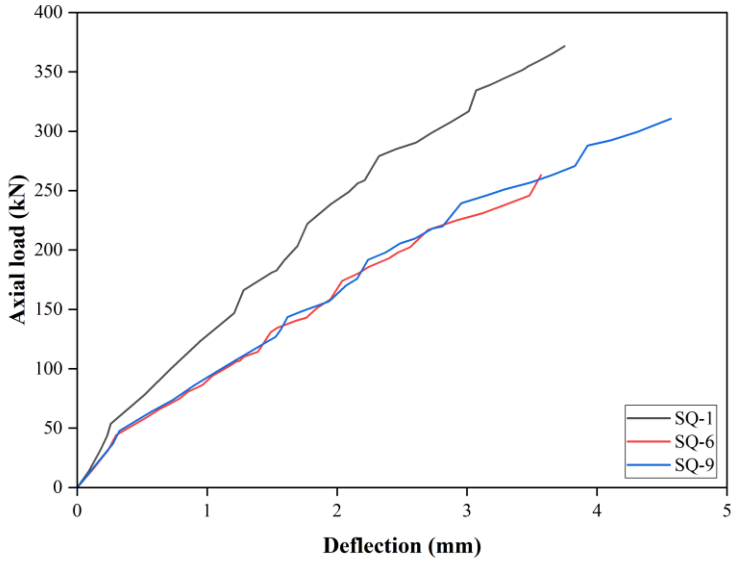

Fig. 22. Load versus deflection response between circular column NC (SQ-1) and both LWC (SQ-6) and layered LNL (SQ-9) square columns with 50% replacement ratio

The enhanced performance of the NNL and LNN configurations can be explained by the strategic placement of high-stiffness NC in the middle and/or upper zones of the columns—regions experiencing maximum compressive stress during buckling. This layered design limited lateral deflections and postponed instability onset, yielding axial load capacities up to 21% higher than fully LWC counterparts. These findings are consistent with prior studies on partial interaction and composite systems [9, 13], where stiffness contrast and bonding effectiveness between layers played a key role in structural response. Similarly, the findings align with [22], who showed that transverse reinforcement improves ductility in LWC columns; however, our results suggest that layer configuration alone can offer notable improvements even without additional confinement. Additionally, square columns exhibited higher buckling resistance than circular ones, attributed to their larger moment of inertia, aligning with classical Euler buckling theory. However, the inclusion of LWC in both top and bottom layers (LNL configuration) reduced performance, highlighting the necessity of maintaining stiffer material in tension and compression zones for buckling-critical elements.

4. Conclusions

This experimental investigation evaluated the buckling resistance of layered reinforced concrete (RC) columns constructed with combinations of normal concrete (NC) and lightweight concrete (LWC) incorporating thermo-stone aggregate. A total of 18 square and circular RC columns were tested under axial loads to assess the influence of shape, concrete layering sequence, and aggregate replacement ratio on structural behavior.

The results clearly indicate that the configuration and material composition of the layers have a significant effect on the buckling performance of RC columns. Among the various configurations, the NNL and LNN layered arrangements demonstrated the highest buckling resistance. These configurations strategically positioned the higher-stiffness NC in the middle and/or upper portions of the column, regions most vulnerable to high compressive stress and deflection. As a result, these designs enhanced overall column stability, delayed the onset of lateral buckling, and increased the ultimate axial load capacity. Notably, square NNL columns with 25% thermo-stone replacement attained axial loads up to 21.6% higher than their fully LWC counterparts, which confirms the mechanical advantage of layering concrete with appropriate stiffness profiles.

Furthermore, square columns consistently outperformed circular ones across all configurations, a trend attributed to their greater moment of inertia, which results in higher stiffness and lower lateral deflection. The study also revealed that a 25% replacement of natural aggregate with thermo-stone in LWC offered a good compromise between weight reduction and strength, while the 50% replacement ratio led to reduced performance due to lower stiffness and greater deflection.

In summary, the study confirms that layering RC columns with NC in critical regions can effectively enhance structural performance and buckling resistance without significantly increasing the overall weight. This makes such designs highly suitable for mid- and high-rise structures. Future research should explore the effects of interlayer bond quality, fatigue behavior, temperature cycling, and seismic response to further validate the practical application of layered concrete columns.

Acknowledgement

The authors extend their gratitude to the Civil Engineering Department Laboratory at the College of Engineering, Tikrit University, for its support and approval in conducting and testing the RC column specimens.

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