International Journal of Engineering and Modern Technology (IJEMT) E-ISSN 2504-8848
P-ISSN 2695-2149 Vol 11. No. 5 2025 www.iiardjournals.org online version

Experimental Investigation of the Structural Performance of Circular Reinforced Concrete Columns Under Concentric Loading at Varying Slenderness Ratios

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DOI: 10.56201/ijemt.vol.11.no5.2025.pg218.227

Abstract
This study experimentally investigates the structural performance of circular reinforced concrete (RC) columns subjected to concentric axial loading, focusing on the effect of varying slenderness ratios. A total of 54 columns were cast using three concrete grades M15, M20, and M25 and tested at six different length-to-diameter (L/D) ratios: 1, 3, 5, 7, 9, and 10. All columns were reinforced with 4Y8 longitudinal bars and tested under uniform loading conditions to evaluate axial load capacity, failure modes, and deformation characteristics. Results showed a significant reduction in axial load capacity with increasing slenderness. For M25-grade concrete, columns with an L/D ratio of 1 achieved a maximum axial load of 287.5 kN, while those with an L/D of 10 carried only 116.7 kN a 59.4% decrease. Similarly, M20 columns dropped from 266.7 kN at L/D 1 to 112.5 kN at L/D 10, reflecting a 57.8% decrease, and M15 columns decreased from 237.5 kN to 95.8 kN, a 59.7% reduction. This confirms that slender columns are more prone to buckling and instability under axial compression. Conversely, concrete grade had a positive influence on capacity. At constant L/D ratios, increasing concrete strength from M15 to M25 led to axial load capacity increases ranging from 15% to 26%, depending on the slenderness. For example, at L/D 5, the load capacity improved by 22.2% when upgrading from M15 (181.7 kN) to M25 (225.0 kN). Failure patterns further validated these results: stocky columns (L/D ≤ 3) exhibited crushing and ductile behavior, while slender columns (L/D ≥ 7) failed through buckling with minimal warning. The findings emphasize the critical role of slenderness and concrete grade in axial performance, providing practical insights for structural design and reinforcing the need for code provisions that accurately reflect slenderness effects in circular RC columns.

Keywords: *Circular, columns, axial loading, slenderness ratio, structural performance*

1. Introduction

The structural behavior of columns under concentric axial loading is significantly influenced by their slenderness ratio, which is defined as the ratio of the effective length (Le) to the diameter (D) of the column, is a decisive factor affecting axial load behavior (Mohammadi et al. 2020). This geometric parameter governs whether failure occurs primarily due to material crushing in short columns or through elastic or inelastic buckling in slender columns (Mendis et al., 2007).
Circular Reinforced concrete columns are frequently used in practice owing to their symmetrical geometry, which offers enhanced resistance to lateral loads and uniform confinement of the concrete core. These advantages make them particularly suitable for use in high-rise buildings,

bridges, and other critical infrastructure. However, the mechanical behavior of such columns becomes increasingly complex as their slenderness ratio increases. Experimental and analytical studies have shown that slender columns experience a substantial reduction in axial load-carrying capacity and exhibit more pronounced second-order effects due to P-Δ moments (Fam & Rizkalla, 2001; Lam & Teng, 2003).

Recent research highlights the critical influence of cross-sectional geometry and slenderness ratio on the structural performance of reinforced concrete (RC) columns. Studies such as those by Afefy and Fahmy (2015), Mohammadi et al. (2020), and Zhang et al. (2021) emphasize how circular columns exhibit different axial and stability behavior compared to their square or rectangular counterparts, particularly under concentric loading. While significant empirical work exists on non-circular RC columns, circular columns with varying slenderness remain underrepresented in experimental literature. Design standards like ACI 318-19 and Eurocode 2 (EN 1992-1-1) provide slenderness provisions, yet these are often generalized and may not accurately reflect the unique stress distribution in circular columns. Contemporary performance-based evaluation methods now advocate for geometry-specific experimental validation, which this study aims to contribute to.

Despite these advances, there remains a paucity of experimental data focused specifically on the behavior of circular RC columns with varying slenderness ratios under concentric axial loading. Existing design guidelines, including those outlined in ACI 318 and Eurocode 2, provide limited provisions for the accurate assessment of such columns, particularly those with high slenderness. Consequently, the need for comprehensive experimental investigations in this area is evident.

The present study seeks to address this gap by experimentally evaluating the structural performance of circular RC columns subjected to concentric axial loading across a range of slenderness ratios. The investigation focuses on key performance indicators such as ultimate load capacity, axial deformation and failure mechanisms. The outcomes of this research are expected to inform the development of improved design approaches and contribute to a more robust understanding of slender RC column behavior under axial compression.

3. Materials and Methods

3.1. Materials

The fabrication and testing of circular reinforced concrete (RC) column specimens utilized standardized materials and equipment to ensure experimental reliability. Ordinary Portland cement (ASTM C150 Type I), graded coarse and fine aggregates (ASTM C33/C33M-18), and potable water (ASTM C1602) formed the concrete mix. Columns were cast in plywood and steel formworks (ACI 347-04). A spirit level ensured alignment, while steel plates distributed axial loads uniformly. Axial deformations during testing were measured using a dial gauge calibrated to ASTM E105-20.

3.2. Specimen Design

One hundred and Eight circular RC columns were cast using normal weight concrete with an average compressive strength as shown in Table 2. All specimens had a cross-sectional diameter of 100 mm. The slenderness ratios (L/D) investigated were 1, 3, 5, 7, 9, and 10, with three specimens per group as shown in Table 1. Each column was longitudinally reinforced with 6Y8 bars with a yield strength of 400 Mpa and transverse ties spaced at 100 mm c/c to prevent premature buckling of longitudinal reinforcement.

Table 1: Experimental Configuration for Reinforced Columns for Circular Sections.

Sample ID	Specimen No	Cross section (mm)	Main reinforcement	Stirrup	Spacing (mm)	Age at loading (Days	Length (mm)
RC-C_2-25	#3	100	6Φ8	Φ6	100	28,56	1000
RC-C_2-20	#3	100	6Φ8	Φ6	100	28,56	900
RC-C_2-15	#3	100	6Φ8	Φ6	100	28,56	700
							500
							300

3.3 Material Properties

The compressive strength tests conducted on the prepared concrete cubes and cylinders, as outlined, adhered strictly to the standards and specifications of BS EN 12390-3:(2019). These results in Table 1 established a robust foundation for analyzing the structural behavior under the designed testing conditions.

Table 2: Compressive Tests Results for Control Samples

MIX ID	Average compressive strength of 150 mm x 150 mm x 150 mm concrete cubes (Mpa)		Average compressive strength of 100 mm x 100 mm concrete cylinders (Mpa)	
	28 days	**28 days**	**28 days**	**56 days**
S-M25-C1	32.37	41.37	41.37	28.03
S-M20-C1	28.96	30.34	30.34	25.5
S-M15-C1	20.59	22.02	22.02	17.01

3.3. Testing Procedure

All column specimens were subjected to a standard curing regime for 28 and 56days to ensure adequate strength development prior to testing. Following curing, the specimens were tested under concentric axial loading using a 150-ton capacity hydraulic compression machine (reactant frame), as illustrated in Figure 2. Each column was carefully aligned in a vertical position, with concentric loading applied to simulate realistic structural conditions.

To replicate pinned boundary conditions, both ends of the columns were supported in a manner that allowed rotation while preventing translation. The axial load was applied under displacement control at a constant rate until failure occurred. Throughout the test, axial deformation was monitored using precision dial gauges, which were strategically positioned at the top height of the column and near the support regions.

Figure 2: Test Setup and Compression Loading Ongoing

4. Results and Discussion

4.1 Results of Reinforced Circular Concrete Column under Concentric Loading

The experimental data were presented in Tables 3 and 4, which were analyzed to assess the compressive behavior of reinforced concrete columns with circular cross-sections. This group consists of three categories: **C-01-25**, **C-01-20**, and **C-01-15**, each representing reinforced concrete columns with varying lengths and concrete mix grades, with a reinforcement ratio (ρ) of 6.8%.

For each category, the samples were tested at curing ages of 28 and 56 days. The analysis focused on several critical parameters, including failure load, yield stress, , column length, and length-to-diameter ratio, which were systematically recorded and examined, as outlined in Tables 3 and 4.

Table 3: Compression Test Results of Reinforced Concrete Columns for Circular Sections with Varying Mix Ratio at 28 Days

Designation	**MIX Ratio**	**Length (mm)**	**Length /Depth ratio**	**Pu (kN)**	**Yield Stress (Mpa)**	**ρ (%)**
C-01-25	1: 1.67:2.7	1000	10	153.45	19.54	6.8
C-02-25	1: 1.67:2.7	900	9	165.55	21.08	6.8
C-03-25	1: 1.67:2.7	700	7	172.85	22.01	6.8
C-04-25	1: 1.67:2.7	500	5	241.67	30.77	6.8
C-05-25	1: 1.67:2.7	300	3	355.94	45.31	6.8
C-06-25	1: 1.67:2.7	100	1	552.95	70.39	6.8
C-01-20	1:1.5:3	1000	10	113.96	14.51	6.8
C-02-20	1:1.5:3	900	9	121.3	15.44	6.8
C-03-20	1:1.5:3	700	7	123.85	15.77	6.8
C-04-20	1:1.5:3	500	5	165.95	21.13	6.8

C-05-20	1:1.5:3	300	3	258.25	32.88	6.8
C-06-20	1:1.5:3	100	1	434.18	55.27	6.8
C-01-15	1: 2:4	1000	10	94.25	12.00	6.8
C-02-15	1: 2:4	900	9	98.01	12.48	6.8
C-03-15	1: 2:4	700	7	99.97	12.73	6.8
C-04-15	1: 2:4	500	5	125.65	16.00	6.8
C-05-15	1: 2:4	300	3	194.64	24.78	6.8
C-06-15	1: 2:4	100	1	344.6	43.87	6.8

Table 4: Compression Test Results of Reinforced Concrete Columns for Circular Sections with Varying Mix Ratio at 56 Days

Designation	**MIX Ratio**	**Length (mm)**	**Length /Depth ratio**	**Pu (kN)**	**Yield Stress (Mpa)**	**ρ (%)**
C-01-25	1: 1.67:2.7	1000	10	160.68	20.46	6.8
C-02-25	1: 1.67:2.7	900	9	175.77	22.38	6.8
C-03-25	1: 1.67:2.7	700	7	187.60	23.88	6.8
C-04-25	1: 1.67:2.7	500	5	264.91	33.73	6.8
C-05-25	1: 1.67:2.7	300	3	388.28	49.43	6.8
C-06-25	1: 1.67:2.7	100	1	585.94	74.59	6.8
C-01-20	1:1.5:3	1000	10	124.40	15.84	6.8
C-02-20	1:1.5:3	900	9	133.70	17.02	6.8
C-03-20	1:1.5:3	700	7	139.72	17.79	6.8
C-04-20	1:1.5:3	500	5	192.38	24.49	6.8
C-05-20	1:1.5:3	300	3	280.92	35.76	6.8
C-06-20	1:1.5:3	100	1	440.87	56.13	6.8
C-01-15	1: 2:4	1000	10	109.19	13.90	6.8
C-02-15	1: 2:4	900	9	116.06	14.78	6.8
C-03-15	1: 2:4	700	7	119.64	15.23	6.8
C-04-15	1: 2:4	500	5	161.97	20.62	6.8
C-05-15	1: 2:4	300	3	235.89	30.03	6.8
C-06-15	1: 2:4	100	1	380.03	48.38	6.8

4.1.1 Axial load versus Length-to-Depth Ratio

The effect of the length-to-depth (L/D) ratio on the axial load capacity of reinforced concrete (RC) columns is significant and well-demonstrated in both the experimental data and corresponding graphical trends as shown in Figure 2. As the L/D ratio increases from 1 to 10, there is a substantial and consistent decrease in axial load capacity across all concrete grades (M15, M20, and M25).

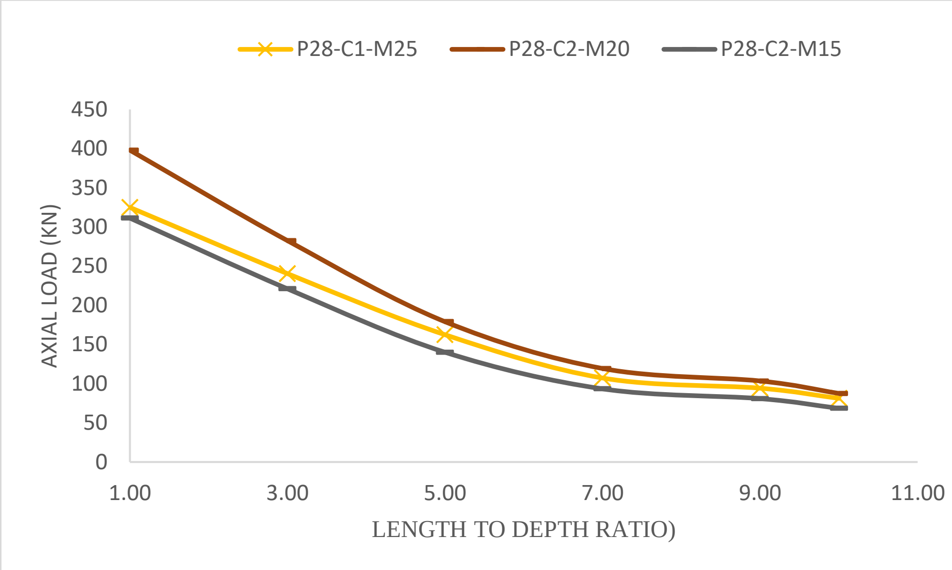

Figure 2: Trends between Axial Load and Length to depth ratio of circular Columns at Different Concrete Grades with 28-Day

For instance, in M25-grade columns, axial load capacity drops from 552.95 kN at L/D = 1 to 153.45 kN at L/D = 10 representing a 72.2% decrease. Similarly, M20-grade columns show a reduction from 434.18 kN to 113.96 kN, marking a 73.8% decline, while M15-grade columns exhibit a 72.6% decrease, falling from 344.6 kN to 94.25 kN.

This steep reduction highlights the critical role of slenderness in determining column strength. Slender columns (higher L/D ratios) are more prone to buckling under axial loads, leading to early failure modes that significantly compromise structural capacity (MacGregor & Wight, 2012; Nilson et al., 2010). In contrast, shorter columns with low L/D ratios primarily fail by crushing of concrete, which occurs at much higher loads due to their compactness and greater resistance to lateral instability (Mendis et al., 2007). The trend aligns with prior research findings, where slenderness has been established as a dominant parameter affecting stability and strength in RC column design (Acun & Sucuoglu, 2010).

Moreover, the relative reduction in strength across all concrete grades confirms that while concrete compressive strength is a critical factor, its influence is mitigated at higher L/D ratios where buckling governs the failure mechanism. These results support the recommendations in design codes (e.g., ACI 318 and Eurocode 2), which classify columns as short or slender based on L/D limits and apply buckling reduction factors accordingly

Figure 3 shows the influence of the length-to-depth (L/D) ratio on the axial load capacity for circular columns cast with three different concrete grades: M15, M20, and M25 at 56 days. As observed, there is a pronounced inverse relationship between the L/D ratio and axial load capacity. For all concrete grades, the axial load capacity significantly decreases as the L/D ratio increases from 1 to 10. Specifically, the M25-grade column shows a drop in axial load from approximately 638.85 kN at L/D = 1 to 158.35 kN at L/D = 10, marking a 75.2% reduction. Similarly, the M20-grade column decreases from 435.6 kN to 117.65 kN, a 73% drop, while the M15-grade column falls from 366.8 kN to 95.38 kN, resulting in a 74% decrease.

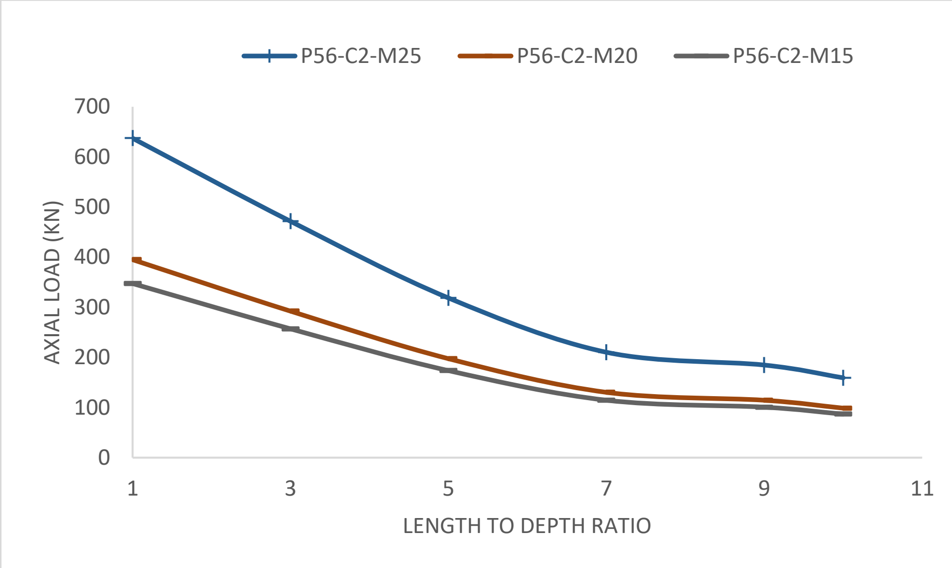

Figure 3: Trends between Axial Load and Length to depth ratio of circular Columns at Different Concrete Grades with 56-Day

This behavior reinforces the understanding that increasing slenderness leads to a dramatic reduction in axial strength due to the onset of buckling. As L/D ratio grows, columns transition from short (governed by material crushing) to slender behavior (governed by lateral instability), thereby becoming more susceptible to second-order effects such as lateral deflections and P-Δ moments (Wight & MacGregor, 2012; Kim & Kim, 2004). Even though higher concrete strength (as in M25) improves load-carrying capacity, its influence diminishes at higher L/D ratios, where geometric instability becomes the dominant factor (Sheikh & Uzumeri, 1980).
Furthermore, the consistent pattern across all concrete grades confirms the universal applicability of slenderness effects in design. Therefore, the results underscore the importance of accounting for L/D ratio during design, especially for high-rise structures and load-bearing elements in seismic zones.

4.1.2. Performance-Based on concrete grades
In Figure 2 and 3 provided illustrate the influence of concrete grade (M15, M20, and M25) on the axial load capacity of reinforced concrete columns (P28 and P56) across varying length-to-depth (L/D) ratios. In both cases, an increase in concrete grade consistently results in a higher axial load capacity, regardless of the L/D ratio. This trend confirms that concrete compressive strength plays a pivotal role in determining the load-bearing capacity of columns.
In Figure 2 At L/D = 1, the axial load for M25-grade concrete is approximately 320.5 kN, while for M20 it is 390.0 kN, and for M15 it is 300.3 kN. The M25 column exhibits a 6.7% increase over M15 and a 17.8% decrease compared to M20. As the L/D ratio increases to 10, the axial capacities drop across all grades, but the relative differences between grades become less pronounced, highlighting the growing dominance of slenderness effects over material strength. At this extreme, M25 still maintains a marginal lead, suggesting higher-grade concrete offers more resistance to axial instability.
In Figure 3, At L/D = 1, M25-grade concrete supports the highest axial load of 638.85 kN, compared to 435.6 kN for M20 and 366.8 kN for M15. This represents a 46.5% increase from M15

to M25, and a 23.4% increase from M20 to M25. At L/D = 10, M25 again outperforms with 158.35 kN, compared to 117.65 kN (M20) and 95.38 kN (M15), translating to a 66% higher capacity than M15 and a 34.5% improvement over M20. These figures underscore that higher-grade concrete significantly enhances the axial performance, especially in short and intermediate columns, where compressive strength is the dominant factor (Neville, 2011).
Finally, it is evident that while all columns lose capacity as they become more slender, the superior strength of higher concrete grades helps delay critical failure and maintain structural integrity for longer. This highlights the importance of selecting appropriate concrete grades in structural design, particularly for load-bearing and seismic-resistant applications.

4.2. Failure Modes

The failure modes of reinforced concrete columns are influenced by several interrelated factors, notably concrete strength, reinforcement ratio, curing duration, and slenderness (L/D ratio). As illustrated in Figure 4, the axial loading behavior of columns reinforced with 6.8% steel content (C) reveals critical patterns in the transition from strength-dominated to stability-dominated failure mechanisms.

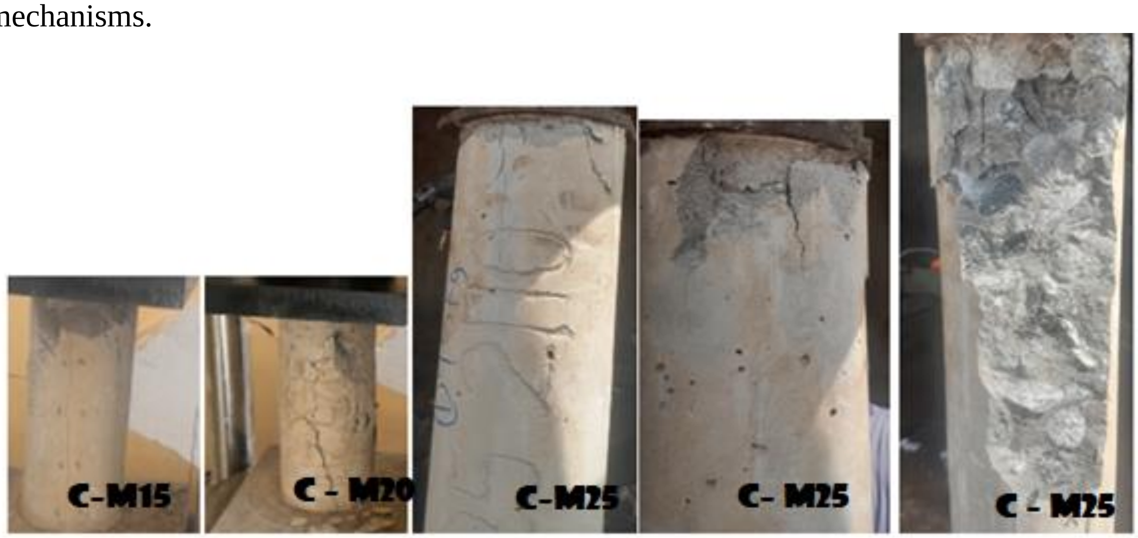

Figure 4: Failure Modes of Column Samples

Analytically, the axial load capacity of the columns shows a non-linear decline with increasing L/D ratio. For M25 concrete, axial load drops from 617.43 kN at L/D = 1 to 154.36 kN at L/D = 10, representing a 75% decrease. Similarly, for M20 and M15, capacities reduce by 78% and 78%, respectively. These reductions indicate a pronounced shift in failure mode: short columns (low L/D) primarily fail due to material crushing, while slender columns (high L/D) are susceptible to instability-induced buckling.
The inclusion of 6.8% reinforcement steel has a transformative effect on the failure mode. Whereas M15 concrete columns tend to fail abruptly and brittlely, the presence of longitudinal reinforcement in C columns promotes a ductile failure mechanism, enabling energy dissipation and improved post-yield performance. Crack propagation patterns observed in Figure 3 support this: initial vertical cracks form along the column height and progressively widen under increasing axial load, indicating gradual stiffness degradation rather than sudden collapse. This aligns with the findings of Huang et al. (2019), who emphasized that reinforcement enhances ductility by redistributing internal stresses and providing confinement to the concrete core.

At low L/D ratios, failure is governed by compressive strength, and the confined concrete core resists crushing until steel yields. As the L/D ratio increases beyond 5, however, slenderness effects become dominant, causing lateral instability (buckling) to govern the failure mode. Here, the steel reinforcement begins to yield before peak load is achieved, and concrete spalling or crushing occurs post-buckling. This dual-mode failure steel yielding combined with concrete crushing is more complex and dangerous, as it may be sudden if not properly detailed.

The failure mode evolves from compression-controlled to buckling-dominated as L/D increases, with reinforcement and concrete grade playing pivotal roles in modifying load paths and crack behavior. High-strength concrete (M25) combined with dense reinforcement (6.8%) exhibits the best performance, sustaining higher loads with more controlled failure, thus validating design principles that promote ductility and redundancy in column systems (Park & Paulay, 1975).

5. Conclusions.

The study reveals that as the length-to-depth (L/D) ratio increases from 1 to 10, the axial load capacity of reinforced concrete circular columns significantly decreases by approximately 72–78% across all concrete grades. For instance, M25-grade columns dropped from 552.95 kN to 153.45 kN at 28 days (a 72.2% decrease), and from 638.85 kN to 158.35 kN at 56 days (a 75.2% decrease). Similarly, M15-grade columns reduced from 344.6 kN to 94.25 kN (a 72.6% decrease) at 28 days and from 366.8 kN to 95.38 kN (a 74% decrease) at 56 days. These findings confirm that slenderness (higher L/D ratios) significantly compromises load capacity due to buckling. However, using higher concrete grades like M25 and reinforcing with 6.8% steel notably improves strength and ductility, delaying failure. Thus, both L/D ratio and material choice are crucial in column design to ensure structural stability and compliance with design standards.

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