Article

Behavior of Limestone Calcined Clay Cement (LC3) Columns under Axial Loading

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Abstract

The cement industry is a major contributor to global CO_2 emissions, largely due to the high clinker content of Ordinary Portland Cement (OPC). Limestone Calcined Clay Cement (LC3) has emerged as a promising low-carbon alternative, but its structural performance in reinforced concrete (RC) columns is not yet well established. This study experimentally investigates the behavior of RC columns made with LC3-50, in which 50% of the clinker is replaced by a blend of calcined clay and limestone, under axial compressive loading. Six square columns (150 × 150 × 900 mm) and companion cylindrical specimens were cast with either OPC or LC3-50 concrete and tested for 28-day compressive strength, axial load–carrying capacity, stiffness, deformation, and crack patterns. The LC3-50 concrete achieved a higher 28-day compressive strength (51.6 MPa) than OPC (44 MPa), and the LC3-50 columns exhibited an approximately 15.7% increase in ultimate axial load capacity (66.15 tons versus 57.20 tons for OPC), along with greater deformation capacity (9.65 mm versus 8.23 mm). LC3-50 columns primarily failed by material crushing, while OPC columns showed more pronounced bonding failures and earlier crack initiation. These results indicate that LC3-50 not only reduces clinker content and associated CO_2 emissions but also enhances the axial performance and ductility of RC columns, supporting its use as a sustainable alternative to conventional OPC in structural applications..

Keywords: LC3, CO2 emissions, RC columns, Axial Loading.

1. Introduction

The cement industry is widely recognized as one of the largest industrial sources of CO2 emissions, responsible for roughly 7 - 8 % of global anthropogenic CO2 output, mainly due to energy-intensive clinker production and limestone calcination [1, 2]. Ordinary Portland cement (OPC) remains the dominant binder in structural concrete, so any realistic decarbonization pathway for the built environment must address the high clinker content and associated emissions of conventional OPC systems [3].

Limestone Calcined Clay Cement (LC3) has emerged as a promising low-carbon alternative in which a substantial portion of clinker is replaced by a blend of calcined clay, limestone, and gypsum [4–6]. Compared with traditional supplementary cementitious materials (SCMs) such as fly ash and slag, calcined clays are particularly attractive because

suitable kaolinitic clays and limestone are abundant in many regions, including countries where cement demand and infrastructure growth are highest [5, 7]. This makes LC3 a technically viable and geographically scalable option for reducing the clinker factor in cement.

Experimental work and life-cycle assessment (LCA) studies consistently show that LC3 can match or exceed the mechanical and durability performance of conventional OPC concretes, while reducing energy demand by up to about 28% and total CO2 emissions by roughly 30 – 40 % per ton of cement or concrete [7–10]. These gains are primarily linked to the lower clinker content and the synergistic pozzolanic and filler effects of calcined clay and limestone, which refine the pore structure and modify the hydration products in a favorable way [8, 11]. In some scenarios, LC3 concretes have also been shown to deliver longer service life, so that CO_2 emissions per year of service life are significantly lower than for comparable OPC systems [1].

Despite these advantages, most LC3 research has focused on paste, mortar, or standard concrete specimens, emphasizing strength development, transport properties, microstructure, and durability indicators such as chloride penetration and carbonation [6, 10, 12]. There are comparatively few studies that examine LC3 at the structural element scale, especially in reinforced concrete (RC) members subjected to realistic loading conditions. This gap is critical, because in design practice engineers must rely on reliable element-level data, rather than only material level tests before specifying new binders in primary load-bearing components.

Among RC members, columns are particularly important because their axial load-carrying capacity, stiffness, deformation response, and failure modes directly govern the safety and serviceability of buildings and infrastructure. If LC3 is to move beyond "promising material" and into mainstream structural use, its performance in RC columns must be quantified and compared directly with conventional OPC systems under axial compression.

To address this gap, the present study investigates the axial behavior of RC columns cast with LC3-50 concrete, in which 50% of the clinker is replaced by calcined clay and limestone, and compares their performance with conventional OPC columns. An experimental program on six square columns (150 × 150 × 900 mm) and companion specimens was carried out to measure compressive strength, axial load capacity, stiffness, deformation characteristics, and crack patterns. The results are intended to clarify whether LC3-based concrete can be confidently used in RC columns and to provide experimental evidence supporting LC3 as a structurally viable, low-carbon alternative to OPC.
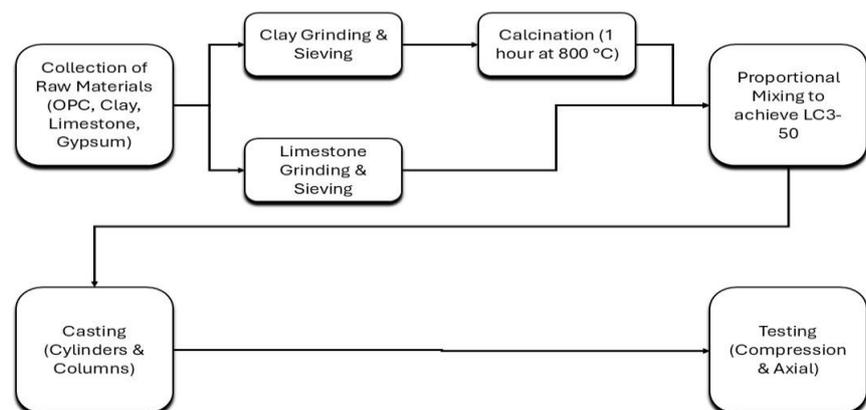
2. Experimental Work

Figure 1. Flow Chart of the Experimental Program

The experimental work consists of the collection and preparation of raw materials, casting of specimens, and testing, which was briefly described in Figure 1.

3. Materials and Methods

3.1 Materials

The OPC used in this research was a general-purpose cement with a grade of 53. The clay, which has 75% kaolinite content, which was utilized in the current study, was acquired through the natural deposits in Nagar Parkar in the district of Tar Parkar, Sindh. The procedure for determining the kaolinite content of the clay is presented in [4]. The clay is finely ground in the Los Angeles Abrasion Machine and passed through sieve #200 and then calcined at 800 °C for 1 hour in an electric furnace. Raw limestone was collected from a quarry and subsequently ground into a fine powder and passed through a #200 sieve to ensure uniformity. Gypsum is added to regulate the setting time. Well-graded coarse aggregates and fine aggregates were also collected from the local quarry. Additionally, a high-performance poly carboxylic ether-based superplasticizer (brand: Sika) was incorporated to enhance the workability of the concrete mixes. For reinforcement, Grade 60 steel rebars with a diameter of 10 mm were used for longitudinal reinforcement, while lateral reinforcement consisted of rebars with a yield strength of 450 MPa. The preparation of LC3-50 is formulated by blending various proportions of materials, as detailed in Table 1. The XRF analysis of OPC and LC3-50 is presented in Table 2.

Table 1. Proportioning of materials in LC3-50

Material	LC3-50 (%) By Clinker	LC3-50 (%) By OPC
Cement	-	52
Clinker	50	-
Limestone	15	15
Calcined Clay	30	30
Gypsum	5	3

Table 2. Chemical Composition of OPC & LC3-50

Materials	Oxides (%)								
	CaO	SiO2	Al2O3	Fe2O3	SO3	MgO	K2O	Na2O	Others
Cement	63.19	21.45	5.20	3.25	2.70	1.90	1.0	0.10	1.21
LC3-50	43.09	27.36	11.96	3.29	3.64	3.5	0.4	0.13	6.63

3.2 Mix Design and Specimen Casting

The concrete mix was designed to achieve a target compressive strength of 45 MPa at 28 days, as established through a series of mix designs. A constant water-to-binder ratio of 0.35 was maintained throughout the casting process. The fine-to-coarse aggregate ratio was 1:2. To enhance the workability of the concrete, a superplasticizer was incorporated at a dosage of 5% by weight of the total binder. The mix design is shown in Table 3.

108   All the molds are lubricated 1 day before the casting. ASTM C39 [13] Standard-size
109 cylinders (150 mm x 300 mm) and standard-size columns (150 mm x 150 mm x 900 mm)
110 with a proper 25.4 mm clear cover, shown in Figure 3, were cast from LC3-50 and OPC.
111 To remove air bubbles, a concrete vibrator is used during casting. As LC3's early strength
112 gain is slow, LC3 specimens are demolded after 3 days of casting and then placed in the
113 curing tank for 28 days. After that, all the specimens are removed from the curing tank
114 and are prepared for testing as shown in Figure 4.

115   **Table 3.** Mix Design

Con-crete	Total Binder	OPC	Cal-cined Clay	Lime-stone	Gyp-sum	Fine Ag-gre-gate	Coarse Aggre-gate	W/B	Water	SP
OPC	545	545	0	0	0	545	1090	0.35	190.75	27.25
LC3-50	545	272.5	163.5	81.75	54.5	545	1090	0.35	190.75	27.25

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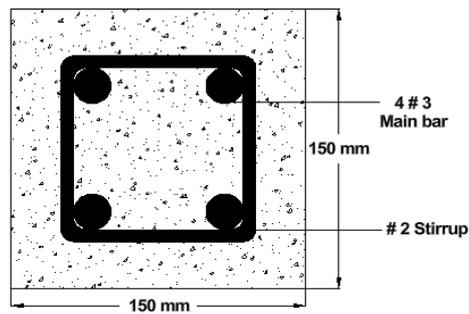
118   **Figure 2.** Column cross-section

120   **Figure 3.** Column Mold
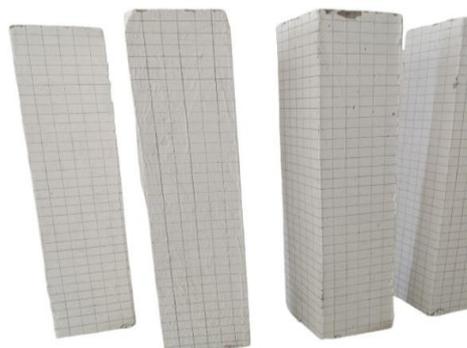

122   **Figure 4.** Column Specimen

123   *3.3   Specimen Testing*

124   Compression tests and Axial tests were performed on the OPC and LC3-50 cylinder
125   and elemental column specimens, as shown in the Figure 5. The LC3's ultimate axial load-
126   ing is compared with the OPC's ultimate axial loading, and the LC3's deformation & crack
127   pattern is compared with the OPC's, and the results were interpreted. A Load Cell of 100
128   tons and a hydraulic jack are used as shown in Figure 5. A concentrated load is applied to
129   the column using both automatic and manual compression machines.

130

131   **Figure 5**. Axial Testing Frame

132   # 4. Results & Discussion

133   *4.1. Compressive Strength:*

134   The compressive strength test was performed on cylindrical specimens, and the re-
135   sults (as presented in Table 4) reveal that LC3-50 develops higher compressive strength
136   than ordinary Portland cement (OPC) after 28 days of curing. This enhancement in
137   strength is primarily attributed to the denser microstructure achieved through the syner-
138   gistic hydration reactions in LC3. Moreover, numerous studies have demonstrated that
139   LC3 continues to gain strength beyond 28 days, owing to its sustained pozzolanic activity
140   and the gradual refinement of its pore structure over time [14].
141   Table 4: Compressive strength of OPC & LC3-50

142   **Table 4: Compressive strength of OPC & LC3-50**

143

Binder	Compressive Strength (MPa)
OPC	44
LC3-50	51.6

144   *4.2 Ultimate Axial Load & Deformation*

145   The evaluation of the ultimate axial load-bearing capacity is one of the basic require-
146   ments to measure the structural integrity and compressive behavior of a concrete column.
147   Experimental results indicate that the LC3-50 specimen had a better ultimate load capacity
148   of 66.15 tons, compared to 57.20 tons with the OPC column, representing an improvement
149   of approximately 15.7 % as shown in Figure 6. The presence of calcined clay promotes the
150   formation of C–A–S–H (calcium–alumino–silicate–hydrate) gel, which serves as the main
151   binding phase in LC3 systems. The incorporation of aluminum into the C–S–H structure

leads to a more cross-linked and compact gel, contributing to improved mechanical performance and durability. This improved performance can be attributed to the synergistic effect of calcined clay and limestone in LC3-50, which enhances pozzolanic reactions and filler effects, resulting in a denser, more refined microstructure. Under visual evaluation of both failed specimens, it was evident that material crushing was the major mode of failure in LC3-50, whilst bonding failure was the major mode of failure in the OPC column, further reinforcing that LC3-50 had higher cohesion and matrix integrity. When comparing the deformation characteristics of OPC and LC3-50. LC3-50 demonstrates notably higher deformation capacity, indicative of enhanced ductility. The LC3-50 sample achieves a deformation of 9.65 mm, surpassing OPC's deformation of 8.23 mm as shown in Figure 7, suggesting that LC3-50 not only bears greater stress but also accommodates more strain. Notably, enhancement underscores LC3-50's potential to optimize load transfer mechanisms and structural performance, while simultaneously offering significant environmental advantages through reduced clinker content and carbon emissions.
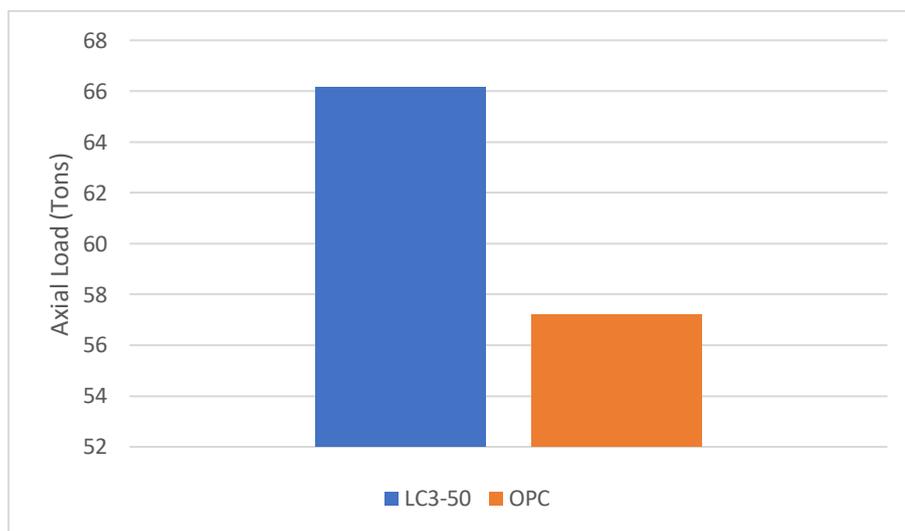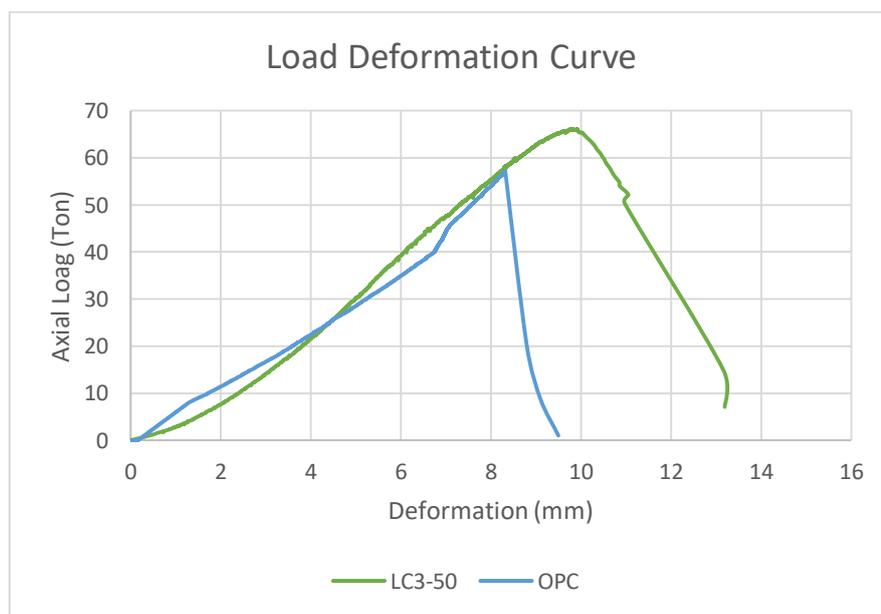

Figure 6. Ultimate Axial Load

Figure 7. Load Deformation Curve

4.3 Crack Patterns

A distinct difference in crack morphology as shown in Figure 7 was observed between the OPC and LC3-50 columns. The OPC column exhibited more cracks that started appearing on the surface at around 40 tons. Conversely, the LC3-50 specimen had fewer cracks, which started appearing on the surface around 52 tons, which are characteristic of improved strain distribution and slowed down crack propagation. The reason behind this behavior is that the addition of calcined clay and limestone in LC3-50 refined the pore structure and enhanced the interfacial transition zone (ITZ) and increased the crack resistance. Better energy absorption capacity and slower failure process are two factors that were enhanced by the better microstructural cohesion of LC3-50 concrete. On the whole, the crack pattern analysis proves that LC3-50 has a greater deformation tolerance and structural stability to axial compression than standard OPC concrete.
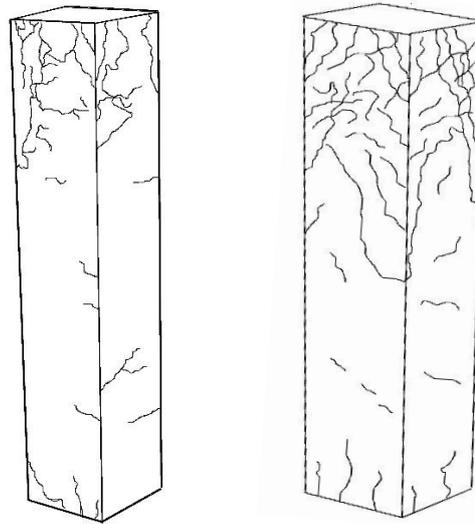

Figure 8. Crack Patterns a. LC3-50 b. OPC

Figure 9. Damaged Samples a. LC3-50 b. OPC

5. Conclusions

This study investigated the axial behavior of reinforced concrete columns made with Limestone Calcined Clay Cement (LC3-50) as a low-carbon alternative to conventional Ordinary Portland Cement (OPC). The experimental results clearly demonstrate that LC3-50 not only meets the structural performance requirements for axial loading but also surpasses OPC in several key aspects. LC3-50 concrete achieved a significantly higher 28-day compressive strength (51.6 MPa) compared to OPC (44 MPa), reflecting the beneficial synergistic hydration and microstructural refinement produced by calcined clay and limestone. At the structural element scale, LC3-50 columns exhibited an approximately 15.7% increase in ultimate axial load capacity, greater deformation capacity, and delayed crack initiation, indicating improved ductility, energy absorption, and overall stability under compressive loading.

The observed failure modes further reinforce the superior mechanical behavior of LC3-50 columns. While OPC specimens displayed earlier surface cracking and bonding-related failures, LC3-50 columns primarily failed through uniform material crushing, suggesting enhanced cohesion and a more robust interfacial transition zone. These improvements are consistent with the denser matrix and enhanced C–A–S–H gel formation associated with LC3 systems.

Overall, the findings confirm that LC3-50 is not only a viable structural substitute for OPC but a performance-enhancing alternative with substantial environmental benefits. By reducing clinker content by 50%, LC3-50 offers a practical pathway for decreasing CO_2 emissions from the construction sector without compromising, and in this case improving, structural performance. Future research should explore the long-term durability, behavior under combined loading, and full-scale implementation of LC3-based structural elements, but the present results provide strong evidence supporting the adoption of LC3 in sustainable construction practices.

6. Abbreviations

LC3	Limestone Calcined Clay Cement
OPC	Ordinary Portland Cement
CO2	Carbon dioxide
CASH	Calcium–Alumino–Silicate–Hydrate
XRF	X-ray fluorescence.

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