International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 07 , July - 2026

Study on the Properties of LC^3 Concrete*

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***Abstract*— Global warming is a threatening issue in recent times and the cement industry also contributes to CO_2 emissions. This necessitates the alternative construction materials to lessen the carbon emission, and to attain the sustainable development. One such is the LC^3 concrete, a concrete formed by blending limestone and calcined clay in the normal ordinary Portland cement. The present investigation has been carried out to study the workability, compressive strength, split tensile strength, ultrasonic pulse velocity and Sorptivity index on a concrete with different proportions of cement replaced by LC^2. The tests were carried out on M35 grade concrete with replacements of cement (by wt.) with LC^2 as 15%, 25%, 35% and 45% taking both limestone and calcined clay constant at 5% in each mix and varying calcined clay and limestone by 10% in each mix. Also, with LC^2 as 25%, 30%, 35%, 40%, 45% taking calcined clay constant at 20% and varying the limestone by 5% to 25% in each mix and again with LC^2 as 15%, 20%, 25%, 30%, 35% taking limestone constant at 10% and varying the calcined clay by 5% to 25% in each mix. With the advent of material like LC^2 in the concrete, the concrete started to change its property on further more replacements of cement with different amounts of LC^2 in an increasing order by weight. The compressive strength gave the maximum value at 35%, whereas the split tensile strength and ultrasonic pulse velocity (UPV) values kept gave maximum value at 35% and 25% LC^2 further decreases. Workability of the concrete decreases with addition of calcined clay and limestone. Sorptivity value decreases with addition of calcined clay and limestone indicates the durability of the concrete increases. From the experimental results it can be concluded that the replacement of cement by 25% and 35% LC^2 had shown better performance than the replacement of cement by limestone and calcined clay in all the mixes. With the use of LC^3 helps to protect the environment by CO_2 emissions.**

Keywords: Ultrasonic Pulse Velocity (UPV), Limestone Calcined Clay (LC^2), Carbon Dioxide (CO_2), Global Warming

1. INTRODUCTION

1.1 General

Concrete, the second most utilized material after water, relies heavily on Portland cement as its primary ingredient. However, the production of cement poses a significant threat to our planet due to global warming and environmental pollution. This is primarily attributed to the emission of CO_2 during the manufacturing process. CO_2 emissions in cement production stem from two sources: the combustion of fossil fuels to operate the rotary kiln and the chemical reactions that occur in the kiln during the production of Portland cement. As a result, the cement industry contributes approximately 5% of the total global carbon dioxide emissions. Furthermore, the extraction of raw materials such as limestone, calcined clay, and other minerals for cement manufacturing also leads to environmental degradation. The emitted CO_2 during cement production, along with the production of concrete, poses a major risk to air pollution. To address these issues, it is crucial to prioritize the use of environmentally friendly concrete. Calcined clay typically contains around 49-54% silica (SiO_2), 41-45% alumina (Al_2O_3), and 1% iron oxides (Fe_2O_3), with trace amounts of other minerals. Limestone consists primarily of 95-100% calcium carbonate ($CaCO_3$), with small amounts of silica (SiO_2), clay, and iron oxides (Fe_2O_3). The proportions can vary based on the specific source of the materials. When used together in cement, calcined clay and limestone contribute to enhanced strength and sustainability. The objective of the LC^3-Project is, through research and testing, to make LC^3 a standard and mainstream general-use cement in the global cement market for the concrete & construction applications. The limestone and calcined lay can be blended with ordinary Portland cement to produce concrete. In the present study, Ordinary Portland cement (Grade 43) was replaced by LC^2 at different percentage such as 15, 20, 25, 30, 35, 40 and 45% by weight of the cement to find out the suitable percentage of limestone and calcined clay in concrete mix with the help of compressive strength, split tensile strength, Sorptivity index, water absorption and ultrasonic pulse velocity. For the study, design mix for M35 grade of concrete has been done for which the mechanical and physical tests have been carried for cement, LC^2, fine aggregates, coarse aggregates in the laboratory. Superplasticizers (Polymer based, 1% by weight) has been also used in the concrete mix for increasing the workability at given water/cement ratio of 0.4. The concrete cubes of size 100mm×100mm×100 mm was casted and tested as per relevant IS code for their compressive strength at 7 and 28 days of maturity and concrete cylinders of size 100mm×200mm were casted and tested for the split tensile strength at 28 days. The UPV and Sorptivity index test also been performed at 28 days.

1.2 Research Significance:

LC^2 is a supplementary cementitious material (SCM) that can be used to partially replace Portland cement. LC^3 concretes can be used to produce moderate to high strength concretes. On day-to-day constructions, deriving a stronger structure within the economy is a matter of concern. The following research thus deals with the generation of a cost-effective, stronger and durable concrete. Partial use of Limestone and Calcined clay in place of cement will thus make it cost-effective though and hence we need to put a check on the strengths.

1.3 Literature Review:

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 07 , July - 2026

The literature on Limestone Calcined Clay Cement (LC^3) highlights its significant potential in enhancing both mechanical and durability properties of concrete. Abdelfattah et al. [2023][1] investigated the physico-mechanical properties of LC^3 cement using calcined clays from two Egyptian sources—Sinai and Zaafarana. The best compressive strength was observed in LC^3Z_4 (Zaafarana, 30% CC) with 52 MPa at 90 days, slightly higher than OPC (51 MPa). The highest flexural strength was also in LC^3Z_4 with 8.94 MPa, and the top indirect tensile strength was 6.60 MPa in LC^3Z_3 at 90 days, demonstrating that Zaafarana-based LC^3 exhibited superior long-term strength and durability compared to OPC and Sinai-based LC^3 mixtures. Almas et al. [2021][2] found that LC^3 performed comparably to OPC and PPC in M50 grade concrete and even exceeded them in flexural and tensile strength due to its dense microstructure and pozzolanic reactions, confirming LC^3's viability in high-performance applications. Apsa and Rao [2019][3] tested LC^3 mixes under acid and sulphate attack and concluded that mixes with higher calcined clay content showed better durability, while higher clinker content enhanced strength. Mix 3, with 50% clinker and 30% clay, offered the best balance. Bishnoi et al. [2014][4] demonstrated that LC^3 mixtures, particularly those with high-quality clay, surpass OPC in compressive strength while reducing clinker usage. LC^3 A achieved 40.8 MPa, compared to OPC's 31.0 MPa at 28 days, indicating excellent performance with a reduced environmental footprint. Dhandapani et al. [2018][5] compared LC^3 with OPC and Fly Ash blended cement in M30 and M50 grades and found that LC^3 provided superior compressive strength and better resistance to chloride penetration, thanks to its denser microstructure. Kafodya et al. [2023][6] evaluated LC^3 blends with different clinker contents and found that LC^3-50 achieved 40 MPa compressive strength with enhanced flexural strength, while LC^3-40 still met masonry requirements. Optimal clay-to-limestone ratios and low porosity were key to maximizing strength. However, higher clay contents increased water demand and porosity, requiring careful mix design. Lavanya and Rao [2019][7] confirmed LC^3's ability to reduce environmental impact while providing comparable mechanical performance. Their Mix 3 achieved slightly lower compressive strength than OPC but had higher resistance to sulphate and chloride attacks, making it a durable and eco-friendly alternative. Mishra et al. [2021][8] reported that LC^3 displayed better early-age strength, particularly in flexural and pull-out strengths, due to effective synergy among its components. The strength became comparable to OPC by 28 days, supporting its use for both early and long-term performance. Narayanan and Muniasamy [2018][9] found that a 60%-OPC, 40%-LC^3 mix improved compressive, tensile, and flexural strengths compared to conventional concrete, indicating enhanced mechanical performance and durability. Ndarowa et al. [2024][10] investigated LC^3 for 3D printing and found it improved buildability, cost-efficiency, and reduced emissions, with critical roles played by calcined clay and limestone in controlling rheology and mechanical properties. Despite challenges in flowability and extrudability, LC^3 showed strong potential for 3D printed structures, emphasizing the need for further optimization of mix designs. Overall, these studies consistently support LC^3 as a high-performance, eco-efficient cementitious material, demonstrating its mechanical reliability, superior durability, and contribution to sustainability in concrete applications. Nguyen et al. [2018][11] explored LC^2 blends in varying percentages and observed that a 15% replacement achieved a high strength of 58 MPa at 28 days, although higher replacements showed reduced strengths, emphasizing the need for optimal dosage. Reddy et al. [2021][12] emphasized LC^3's sustainability by achieving similar or superior mechanical properties while reducing CO_2 emissions by up to 30%. Improved carbonation resistance and workability further highlighted its durability and construction benefits. Scrivener et al. [2018][13] reinforced this by showing that LC^3 with 50% clinker replacement maintains compressive strength equivalent to OPC while reducing CO_2 emissions by 30%, and offers enhanced durability against chloride and sulphate attacks. Shah et al. [2020][14] focused on mortar mixes with LCCP and noted that a 15% replacement provided higher compressive strength than OPC, while up to 30% maintained or slightly enhanced strength levels, confirming the potential of partial replacements. Sharma et al. [2021][15] reviewed LC^3 development and found it capable of matching or improving upon OPC's mechanical and durability performance. The paper also discussed environmental and economic advantages, and the need for future research into admixture compatibility and large-scale feasibility. Sheikh et al. [2023][16] showed that LC^3-50 mixes outperformed OPC in compressive, tensile, and flexural strengths after 90 days due to a more compact microstructure. The results validated LC^3's superior long-term performance, making it a viable sustainable cement. Sun et al. [2024][17] studied low-clinker LC^3 cements, finding that 35% and 25% clinker contents achieved 28-day strengths of 45 MPa and 34 MPa, while 15% clinker systems required calcium hydroxide (CH) addition to reach 35 MPa. CH addition enhanced strength by boosting metakaolin reactivity and carboaluminate formation, meeting EN 197-1 standards. Despite a slight CO_2 increase from CH, it allows low-clinker cement production with good performance when environmental impacts are managed. Takhi et al. [2024][18] studied LC^3 blends with 30-40% metakaolin, finding increased water demand and setting time but good workability with more superplasticizer. After 28 days, compressive strengths ranged from 34.5 to 50 MPa, with lower drying shrinkage and thermal conductivity than OPC. LC^3 demonstrated strong potential as a sustainable cement alternative with improved durability and insulation. Upadhyaya et al. [2022][19] analysed LC^3's compressive strength using different calcined clays and showed that proper calcination significantly influenced strength. Poorly calcined clay led to lower strengths, while optimal calcination and curing achieved strengths comparable to OPC, highlighting the importance of raw material quality.

1.4 Objective of the study:

Based on the critical during literature review and research gaps identified, the following objectives are selected for the present work:

1. To investigate the mechanical properties and durability of medium grade ordinary Portland cement concrete (OPCC) and LC^3 Concrete.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 07 , July - 2026

2. To compare the mechanical properties and durability of medium grade ordinary Portland cement concrete (OPCC) and LC^3 Concrete.

2. METHODOLOGY

2.1 Materials

2.1.1 Cement

Cement is a binder, a substance used in construction that sets, hardens and adheres to other materials, binding them together. In present work Ordinary Portland Cement (OPC) Grade 43 from a single lot was used throughout the course of the investigation. Cement was carefully stored to prevent deterioration in its properties due to contact with the moisture. Cement for the project was obtained from ACC RMC plant Sirgitti, Bilaspur. The following tests on cement & results were tabulated below:

Table 2.1 Test on Cement Results

Properties	Code References	Test Result	BIS limits
Test on Ordinary Portland Cement (43 Grade)			
Fineness (%)	IS 4031 (Part 1) – 1996 (Reaff. 2005)	6	$\ngtr$10
Normal Consistency (%)	IS 4031 (Part 4) – 1988 (Reaff. 2005)	30	26-33
Initial Setting Time (min)	IS 4031 (Part 5) – 1988 (Reaff. 2005)	40	30-60
Final Setting Time (min)	IS 4031 (Part 5) – 1988 (Reaff. 2005)	435	600
Specific Gravity	IS 4031 (Part 11) –1988 (Reaff. 2005)	3.12	3.05-3.20

2.1.2 Limestone and Calcined Clay (LC^2)

Limestone is a sedimentary rock that's a common ingredient in cement, and used to improve the environmental performance of concrete. Limestone for the project was obtained from Godavari Lime Depo Bilaspur. Calcined clay is a material that can be used as a partial substitute for clinker in cement production. Calcined clay for the project was obtained from RANGSANGAM INC Hyderabad, Telangana.

Table 2.2 Chemical composition of Calcined Clay

Chemical	Chemical Composition
SiO_2	49-54
Al_2O_3	41-45
Fe_2O_3	≤1
TiO_2	≤1
MgO	≤0.5
Na_2O	≤0.2
K_2O	≤0.2

Table 2.3 Test for LC^3 Results

Properties	Code References	Test Result	BIS Limit
Fineness (%)	IS 18189:2023	4	-
Normal Consistency (%)	IS 18189:2023	37	-
Initial Setting Time (min)	IS 18189:2023	63	>30
Final Setting Time (min)	IS 18189:2023	235	<600
Specific Gravity	IS 18189:2023	2.74	-

2.1.3 Fine aggregates

The sand obtained from river beds or quarry is used as fine aggregate. The fine aggregate along with the hydrated cement paste fill the space between the coarse aggregate. The following tests on fine aggregates & results were tabulated below:

Table 2.4 Test for Fine Aggregate Results

Properties	Code References	Test Result	BIS Limit
Test on Fine Aggregates			
Fineness Modulus	IS 383 – 1970 (Reaff. 2002)	FM 3.29 Zone 1	-
Specific Gravity	IS 2386 (Part 3) – 1963 (Reaff. 2002)	2.65	2.6-3.0
Loose Bulk Density (Kg/L)	IS 2386 (Part 3) – 1963 (Reaff.2002)	1.482	1.44-1.60
Rodded Bulk Density (Kg/l)	IS 2386 (Part 3) – 1963 (Reaff. 2002)	1.625	1.60-1.76

2.1.4 Coarse aggregates

Coarse aggregate is the important constituent in concrete. The aggregate retained at 4.75 mm is considered as coarse aggregate. It can be found from original bed rocks or crushing of boulders. Coarse aggregates are available in different shape like Irregular, Rounded, Flaky, Angular. It should be free from dirt content and any organic impurities.

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ISSN: 2278-0181
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Table 2.5 Test for Coarse Aggregate Results

Properties	Code Reference	Test Result	BIS Limit
Test on Coarse Aggregates			
Fineness Modulus	IS 383 – 1970 (Reaff. 2002)	4.47	5.5-8
Specific Gravity	IS 2386 (Part 3) – 1963 (Reaff. 2002)	2.72	2.6-3.0
Loose Bulk Density (Kg/L)	IS 2386 (Part 3) – 1963 (Reaff. 2002)	1.467	1.30-1.50
Rodded Bulk Density (Kg/L)	IS 2386 (Part 3) – 1963 (Reaff. 2002)	1.596	1.54-1.74
Water Absorption	IS 2386 (Part3) – 1963 (Reaff. 2002)	0.8	<2.5
Aggregate Impact Value	IS 2386 (Part4) – 1963 (Reaff. 2002)	9.75	<20
Flakiness Index	IS 2386 (Part1) – 1963 (Reaff. 2002)	21.3	<30
Elongation Index	IS 2386 (Part1) – 1963 (Reaff. 2002)	29.8	<45

2.1.5 Superplasticizer

Superplasticizers, also known as high range water reducers, are chemical admixtures used where well-dispersed particle suspension is required. Superplasticizer for the project was obtained from India Mart.

Table 2.6 Details of Superplasticizer

Base	Polytancrete NGT
Colour	Brown Liquid
Specific Gravity	1.12
Shell Life	1 Year from date of manufacturing

2.1.6 Mix proportion

The design mix proportions for M35 grade concrete obtained as per ratio 0.4: 1: 1.65: 2.76, designed in accordance with IS:10262 – 2019 with a fix amount of superplasticizer i.e., 1% by weight of binder, for various partial replacements percentages of cement content is given below in following table:

Table 2.7 Abbreviation of Mixes

Mix	Mix Proportion
M1CC	Ordinary Portland Cement Concrete
M1LC	(85% Cement + 10% Calcined Clay + 5% Limestone)
M2LC	(75% Cement + 20% Calcined Clay + 5% Limestone)
M3LC	(65% Cement + 30% Calcined Clay + 5% Limestone)
M4LC	(55% Cement + 40% Calcined Clay + 5% Limestone)
M5LC	(85% Cement + 5% Calcined Clay + 10% Limestone)
M6LC	(75% Cement + 5% Calcined Clay + 20% Limestone)
M7LC	(65% Cement + 5% Calcined Clay + 30% Limestone)
M8LC	(55% Cement + 5% Calcined Clay + 40% Limestone)
M9LC	(70% Cement + 20% Calcined Clay + 10% Limestone)
M10LC	(65% Cement + 20% Calcined Clay + 15% Limestone)
M11LC	(60% Cement + 20% Calcined Clay + 20% Limestone)
M12LC	(55% Cement + 20% Calcined Clay + 25% Limestone)
M13LC	(80% Cement + 10% Calcined Clay + 10% Limestone)
M14LC	(75% Cement + 15% Calcined Clay + 10% Limestone)
M15LC	(65% Cement + 25% Calcined Clay + 10% Limestone)

Table 2.8 Details of Mixes

Mix	Cem (Kg/ m^3)	C.C (Kg/ m^3)	L.S (Kg/ m^3)	F.A. (Kg/ m^3)	C.A. (Kg/ m^3)	W/B	S.P. (Kg/ m^3)
M1CC	418	-	-	673.68	1128	0.4	4.18
M1LC	355.3	41.8	20.9	673.68	1128	0.4	4.18
M2LC	313.5	83.6	20.9	673.68	1128	0.4	4.18
M3LC	271.7	125.4	20.9	673.68	1128	0.4	4.18
M4LC	229.9	167.2	20.9	673.68	1128	0.4	4.18
M5LC	355.3	20.9	41.8	673.68	1128	0.4	4.18
M6LC	313.5	20.9	83.6	673.68	1128	0.4	4.18
M7LC	271.7	20.9	125.4	673.68	1128	0.4	4.18
M8LC	229.9	20.9	167.2	673.68	1128	0.4	4.18
M9LC	292.6	83.6	41.8	673.68	1128	0.4	4.18
M10LC	271.7	83.6	62.7	673.68	1128	0.4	4.18
M11LC	250.8	83.6	83.6	673.68	1128	0.4	4.18
M12LC	229.9	83.6	104.5	673.68	1128	0.4	4.18
M13LC	334.4	41.8	41.8	673.68	1128	0.4	4.18
M14LC	313.5	62.7	41.8	673.68	1128	0.4	4.18
M15LC	271.7	104.5	41.8	673.68	1128	0.4	4.18

3.1 Investigatory Tests

To investigate the strength & durability of the concrete mixes produced as per the above-mentioned proportions, following investigatory test were performed:

1. Workability (Slump Cone test)
2. Compressive strength test
3. Split tensile strength test
4. Ultrasonic Pulse Velocity test
5. Sorptivity Index test

1. Workability Test: The slump cone test is carried out in this study as per procedures mentioned in IS: 1199 – 1959.

2. Compressive strength Test: In accordance with IS: 516 – 1959, to determine the compressive ability of hardened concrete, the cubes of size 100mm X 100mm X 100mm were casted and cured for 3,7 and 28 days. Then the compression strength of the cured specimens was determined at 3,7 and 28 days. Compression testing machine was used for testing the compressive strength of concrete. At the time of testing the cube is taken out of water and is surface dried and then tested keeping the smooth faces in upper and lower part. In this study, for all mixes, i.e., for 15 to 45 % replacement of cement by LC^2 and compressive strength is determined.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 07 , July - 2026

Fig 1. Slump Cone Test **Fig 2. Cubes under CTM** **Fig 3. Cylinder under tensile load**

3. **Split Tensile strength test:** In accordance with IS: 516 – 1959, Split Tensile strength of concrete was tested on cylindrical specimens having 200mm length and 100 mm diameter at different percentage of LC^2 amount in concrete. The tensile strength of modified concrete has been tested on specimens cured for 3,7 and 28 days. After 3 and 7 days of curing, test has been conducted to check the gain in initial strength of concrete & after 28 days of curing test gives the data of final strength of concrete. Compression testing machine is used for testing the Split Tensile strength test on concrete along. At the time of testing the cylinders are taken out of water and dried and then tested. For calculating the split tensile strength (F_t) following relationship is followed:

$$F_t = \frac{2P}{\pi DL}$$

Where F_t = Split tensile strength of the concrete, P = Max. applied load, D=Diameter of the specimen, L=Length of the specimen

4. **Ultrasonic Pulse Velocity Test:** An ultrasonic pulse velocity test is a non-destructive test conducted to check the quality of the concrete matrix. In this test, the strength and quality of concrete is determined by measuring the speed of an ultrasonic pulse passing through the concrete. The test consists of passing ultrasonic wave through the core of the concrete to be tested and measuring the time taken by pulse to get through the matrix. Higher the velocities through the concrete matrix better will be the quality and homogeneity, while slower velocities indicate concrete may hold many cracks or voids. The Quality defining criteria for concrete is dependent on the velocity of ultrasonic pulse passing through it.

$$Pulse\ Velocity = \frac{Width\ of\ the\ specimen}{Time\ taken\ by\ pulse\ wave\ to\ pass\ through\ it}$$

Fig 4. Cubes under UPV **Fig 5. Cubes under capillary action**

5. **Sorptivity Index Test:** The Sorptivity test measures the rate of penetration of water into the concrete pores by capillary suction. The test was conducted at the age of 28 Days. The specimen size of 100*100*100 mm with water level not more than 5mm above the base of specimen and the flow from the peripheral surface which prevented by sealing it properly with none absorbent coating. The quantity of water absorbed in 15 minutes was measured by weighting the specimen on a top pan balance weighting up to 0.1 mg surface water on the specimen was wiped off with a dampened tissue and each weighting operation was completed within 30 seconds. Sorptivity (S) is a material property which characterizes the tendency of porous material to absorb and transmit water by capillarity. The cumulative water absorption (per unit area of inflow surface increases as the square root of elapsed time (t) $I=S.t^{1/2}$ therefore $S = I/t^{1/2}$ Where; S = Sorptivity in mm, t = elapsed time in mint. $I = \Delta W/Ad$, ΔW = change in weight = W2-W1, W1 = Oven dry weight of cylinder in grams W2 = Weight of cylinder after 30 minutes capillary suction of water in grams, A= surface area of the specimen through which water penetrated, d= density of water.

3. RESULTS AND DISCUSSIONS

The results obtained after execution of the investigatory tests are discussed as under:

3.1 Workability Test

The property of fresh concrete is indicated by the amount of useful internal work required to fully compact the concrete without bleeding or segregation in the finished product. Workability is one of the physical parameters of concrete which affects the strength and durability as well as the cost of labor and appearance of the finished product. Concrete is said to be workable when it is easily placed and compacted homogeneously i.e., without bleeding or segregation. Unworkable concrete needs more work or effort to be compacted in place, also honeycombs and or pockets may also be visible in finished concrete.

3.1.1 Slump Cone Test

Table 3.1 Slump cone test observations

Mix Designation	Mix	Total Height of Slump Cone, H (mm)	Height after removal, h (mm)	Slump Height, H – h (mm)
M1CC	Controlled Concrete	300	220	80
M1LC	(85%C+10%CC+5%LS)	300	224	76
M2LC	(75%C+20%CC+5%LS)	300	230	70
M3LC	(65%C+30%CC+5%LS)	300	232	68
M4LC	(55%C+40%CC+5%LS)	300	235	65
M5LC	(85%C+5%CC+10%LS)	300	226	74
M6LC	(75%C+5%CC+20%LS)	300	230	70
M7LC	(65%C+5%CC+30%LS)	300	232	68
M8LC	(55%C+5%CC+40%LS)	300	240	60
M9LC	(70%C+20%CC+10%LS)	300	240	60
M10LC	(65%C+20%CC+15%LS)	300	242	58
M11LC	(60%C+20%CC+20%LS)	300	245	55
M12LC	(55%C+20%CC+25%LS)	300	250	50
M13LC	(80%C+10%CC+10%LS)	300	225	75
M14LC	(75%C+15%CC+10%LS)	300	235	65
M15LC	(65%C+25%CC+10%LS)	300	240	60

From the above table represents, the Slump value decreases with increase in amount of limestone and calcined clay. As limestone and calcined clay has a finer particle size and higher surface area compared to ordinary Portland cement (OPC). This

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 07 , July - 2026

increases the water demand to coat the particles, leading to reduced workability and limestone and calcined clay particles often have higher water absorption compared to OPC. This property reduces the free water in the mix, making it stiffer and less workable. Hence the workability of M1CC(OPC) concrete mix is better than LC^3 Concrete mix.

3.2 Compressive Strength Test

Out of many tests applied to the concrete, Compressive Strength test is the utmost important which gives idea about all the characteristics of concrete. Compressive strength test was performed on all 16 mixes as per method specified by IS 516-1959 on different curing periods i.e., 7 Days and 28 Days. The average results of three samples of each mix of M35 Grade Concrete are presented in Table 3.2 and Fig 3.2

Fig 3.1 Compressive Strength Test

Table 3.2 Compressive strength observations

Mix Designation	Mix	Compressive Strength (MPa)		
		3 Days	7 Days	28 Days
M1CC	Controlled Concrete	18.36	25.98	42.97
M1LC	(85%C+10%CC+5%LS)	18	26.4	43.1
M2LC	(75%C+20%CC+5%LS)	18.24	26.78	43.3
M3LC	(65%C+30%CC+5%LS)	16.6	24.82	40.57
M4LC	(55%C+40%CC+5%LS)	16.1	24.23	40.1
M5LC	(85%C+5%CC+10%LS)	19	26.33	43.5
M6LC	(75%C+5%CC+20%LS)	18.16	25.5	40.87
M7LC	(65%C+5%CC+30%LS)	16.33	22.67	37.83
M8LC	(55%C+5%CC+40%LS)	15.67	21.33	34.5
M9LC	(70%C+20%CC+10%LS)	18.57	27.66	43.66
M10LC	(65%C+20%CC+15%LS)	20.83	28.5	44.17
M11LC	(60%C+20%CC+20%LS)	17.5	26.33	42.5
M12LC	(55%C+20%CC+25%LS)	16.33	25	38.16
M13LC	(80%C+10%CC+10%LS)	18.76	26	43.7
M14LC	(75%C+15%CC+10%LS)	19.16	27.1	44
M15LC	(65%C+25%CC+10%LS)	17.87	26.5	42.1

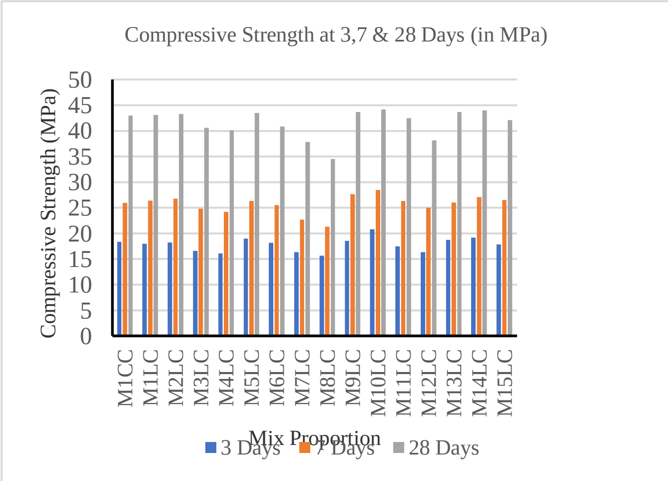

Fig 3.2 Graph for variation for compressive strength

The above graph and table represent the compressive strength at 3, 7 and 28 days of all mixes.

- We find that on increase in the amount of calcined clay in the concrete at 3 days curing, Compressive Strength of M1CC is higher than (M1LC, M2LC, M3LC, M4LC) as 18.36 MPa because calcined clay has slow the hydration of clinker phases initially, reducing early strength gains. The M4LC and M8LC have marginally lower strength as 16.1 MPa and 15.67 MPa due to of excessive calcined clay and limestone content. Similar result was observed in the paper of Vineet Shah [2020][14] when cement is replaced by LC^2 (0 - 20%).
- With addition of limestone the compressive strength increased by 10.78% in M14LC than M1CC. The highest compressive strength observed at M10LC as 20.83 MPa increased by 13.45% than OPC Concrete at 3 days of curing due to synergistic effects of calcined clay and limestone, enhancing pozzolanic reactions and forming more C-S-H gel.
- At 7 days and 28 days of curing, the highest compressive strength observed at (65%C+20%CC+15%LS) as 28.5 MPa and 44.17 MPa and 9.69% and 2.79% increased by M1CC due to synergistic effects of calcined clay and limestone, enhancing pozzolanic reactions and forming more C-S-H gel improving the later age strength. Same trend has been observed in the paper of Apsa & Rao [2019][3].
- When limestone is increasing in the (M5LC to M8LC) mix giving the highest compressive strength at (85%C+5%CC+10%LS) as 26.33 MPa at 7 days and 43.5 MPa at 28 days of curing marginally improving the strength by 1.23% than OPC due to of filler effect of the limestone and lower strength is observed at M8LC as 21.33 MPa at 7 days and 34.5 MPa at 28 days and in M12LC as 25 MPa and 38.16 MPa due to of reduction of the clinker content for the hydration and weakening the ITZ between aggregates and cement paste.
- When the calcined clay is varied taking limestone 10% Constant amount in (M13LC to M15LC) then the M14LC mix have higher strength as 44 MPa surpassing M1CC by

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2.39% and strength decreased at M15LC by 2.02% than M1CC.

- From the compressive strength test results, it is found that M10LC have higher strength without compromising at 3 and 7 days.

3.3 Split Tensile Strength Test

The Split Tensile Strength is the other important properties of concrete. The concrete is very weak in tension due to its brittleness in nature. Thus, it is necessary to determine the tensile strength of the concrete. The split tensile strength test results are presented in Table 3.3 and Fig. 3.3.

Fig 4.5 Tensile Strength Test

Table 3.3 Split tensile strength observations

Mix Designation	Mix Proportion	Tensile Strength (MPa) at 28 Days
M1CC	Controlled Concrete	3.93
M1LC	(85%C+10%CC+5%LS)	4.1
M2LC	(75%C+20%CC+5%LS)	3.85
M3LC	(65%C+30%CC+5%LS)	3.64
M4LC	(55%C+40%CC+5%LS)	3.34
M5LC	(85%C+5%CC+10%LS)	3.78
M6LC	(75%C+5%CC+20%LS)	3.4
M7LC	(65%C+5%CC+30%LS)	3.1
M8LC	(55%C+5%CC+40%LS)	2.78
M9LC	(70%C+20%CC+10%LS)	4.29
M10LC	(65%C+20%CC+15%LS)	4.06
M11LC	(60%C+20%CC+20%LS)	3.62
M12LC	(55%C+20%CC+25%LS)	3.8
M13LC	(80%C+10%CC+10%LS)	3.85
M14LC	(75%C+15%CC+10%LS)	3.97
M15LC	(65%C+25%CC+10%LS)	4.34

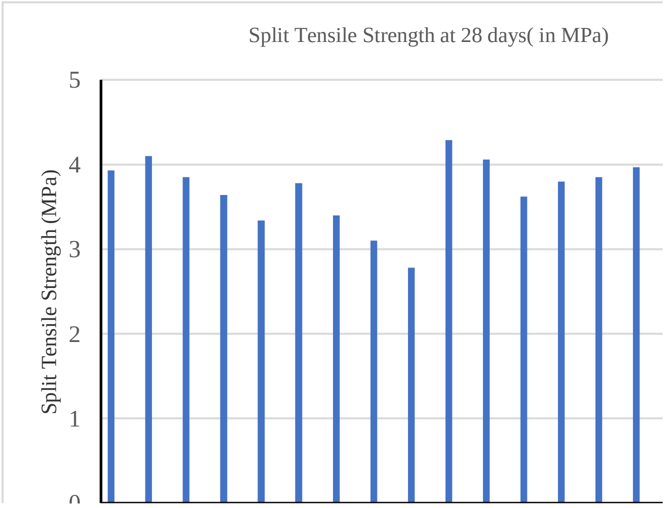

Fig 4.6 Graph for variation of Split tensile strength

The above graph and table represent the split tensile strength at 28 days of all mixes. It is found that the split tensile strength of M1CC(OPC) at 28-Days is 3.93 MPa.

- From the values obtained in table we find that on increase in the amount of calcined clay in the concrete mix (M1LC, M2LC, M3LC, M4LC, M13LC, M14LC, M15LC). Split tensile Strength increases till 15% and replacement with LC^2 for 28 days as 4.1 MPa in M1LC and also increases from (M13LC to M15LC) and highest split tensile achieved at M15LC as 4.34 MPa because of the combination of limestone and calcined clay can lead to the formation of carbo-aluminate phases, which enhance strength in M1LC and M15LC. Thereafter, the lowest value observed as 3.34 MPa for 45% replacement of LC^2 in M4LC due to excessive calcined clay can disrupt this balance, leading to reduced tensile strength due to limited carbonate reaction. Similar trend was observed in the paper of Aya R. Abdelfattah [2023][1].
- Similarly, when limestone is varied in the LC^3 concrete mix (M5LC to M12LC). The highest value is observed at (70%C+20%CC+10%LS) concrete as 4.29 MPa. Excessive limestone after 10% replacement dilutes the cementitious content, reducing cohesive strength. Limestone particles may act as weak points under tensile stress, leading to micro-cracks. Lowest tensile strength observed at (55%C+5%CC+40%LS) as 2.78 MPa.

3.4 Non-Destructive Test

Non-Destructive Test is a method of testing in existing concrete structures to assess the strength and durability of concrete structure. In the non-destructive method of testing, without loading the specimen to failure (i.e., without destructing the concrete) one can measure the quality of concrete. Now days this method has become a part of quality control process. This method of testing also helps us to investigate crack depth, micro cracks, and deterioration of concrete. There are many non-destructive testes available but the rebound hammer and ultrasonic pulse velocity (UPV) test are the most common and popular among all.

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Table 3.4 UPV Test observation table

Mix Designation	Mix Proportion	Pulse Velocity by Cross Probing (km/sec) at 28 days	Concrete Quality Grading at 28 days
M1CC	Controlled Concrete	4.11	Good
M1LC	(85%C+10%CC+5%LS)	4.29	Good
M2LC	(75%C+20%CC+5%LS)	4.24	Good
M3LC	(65%C+30%CC+5%LS)	3.8	Good
M4LC	(55%C+40%CC+5%LS)	3.68	Good
M5LC	(85%C+5%CC+10%LS)	4.42	Good
M6LC	(75%C+5%CC+20%LS)	4.97	Excellent
M7LC	(65%C+5%CC+30%LS)	3.89	Good
M8LC	(55%C+5%CC+40%LS)	3.43	Medium
M9LC	(70%C+20%C+10%LS)	4.70	Excellent
M10LC	(65%C+20%CC+15%LS)	4.31	Good
M11LC	(60%C+20%C+ 20%LS)	4.45	Good
M12LC	(55%C 20%CC+25%LS)	3.95	Good
M13LC	(80%C+10%CC+10%LS)	4.5	Good
M14LC	(75%C+15%CC+10%LS)	4.34	Good
M15LC	(65%C+25%CC+10%LS)	4.1	Good

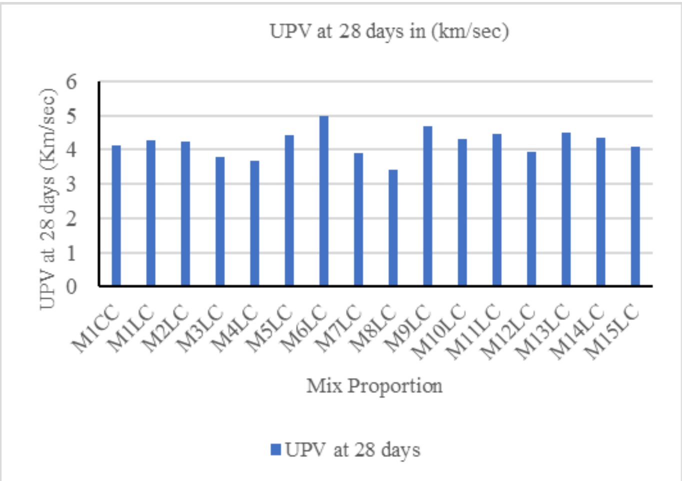

Fig 3.4 Graph for 28 Days UPV values

The above graph and table represent the compressive strength at 3, 7 and 28 days of all mixes.

- UPV Tests were performed on the cubic specimen and with the increase of amount of Calcined Clay, UPV values have reaches up to 4.29 km/sec in M1LC due to of enhances microstructure densification, improving pore structure and then further addition of calcined clay reduces the quality of the concrete. Similar trend was observed in the paper of Q.D. Nguyen [2018][11].
- When limestone is varied in then M6LC have highest pulse velocity as 4.97 km/sec and it is considered as excellent quality of concrete because of limestone filler effect enhances particle packing, reduced porosity, and denser microstructure.
- When calcined clay is varied up to 20% taking limestone constant at 10% then M9LC reaches 4.70 km/sec indicating excellent quality of the concrete. M8LC reaches 3.43 km/sec indicating medium quality of the concrete in all the above mix.

3.5 Durability Test

3.5.1 Sorptivity Index Test

Table 3.5 Sorptivity Index observations

Mix Designation	Mix Proportion	Dry Wt. (Kg)	W1 1ST 15 MIN	W2 2ND 15 MIN	W3 3RD 15 MIN	W4 4TH 15 MIN
M1CC	Controlled Concrete	2.384	2.396	2.404	2.411	2.419
M1LC	(85%C+10%CC+5%LS)	2.380	2.391	2.398	2.406	2.411
M2LC	(75%C+20%CC+5%LS)	2.378	2.386	2.394	2.399	2.403
M3LC	(65%C+30%CC+5%LS)	2.382	2.394	2.401	2.407	2.416
M4LC	(55%C+40%CC+5%LS)	2.386	2.398	2.407	2.414	2.421
M5LC	(85%C+5%CC+10%LS)	2.385	2.399	2.410	2.416	2.424
M6LC	(75%C+5%CC+20%LS)	2.378	2.390	2.400	2.405	2.409
M7LC	(65%C+5%CC+30%LS)	2.382	2.400	2.415	2.421	2.430
M8LC	(55%C+5%CC+40%LS)	2.393	2.420	2.433	2.441	2.449
M9LC	(70%C+20%CC+10%LS)	2.376	2.388	2.396	2.401	2.409
M10LC	(65%C+20%CC+15%LS)	2.380	2.390	2.399	2.406	2.412
M11LC	(60%C+20%CC+20%LS)	2.385	2.400	2.408	2.415	2.421
M12LC	(55%C+20%CC+25%LS)	2.382	2.399	2.412	2.420	2.430
M13LC	(80%C+10%CC+10%LS)	2.382	2.390	2.407	2.415	2.420
M14LC	(75%C+15%CC+10%LS)	2.387	2.400	2.414	2.420	2.423
M15LC	(65%C+25%CC+10%LS)	2.387	2.402	2.416	2.424	2.428

- The permeability is an indicator of concrete's ability to transport water more precisely with both mechanism that is controlling the uptake and transport of water and gaseous substances into cementitious material. Permeability is a measure of flow of water under pressure in a saturated porous medium while Sorptivity is materials ability to absorb and transmit water through it by capillary suction. This is a simple parameter to determine and is increasingly being used as a measure of concrete resistance to exposure in aggressive environments below figure 3.5 shows cube placed in container with water placed on it up to depth of 5 mm.

Fig 3.5 Sorptivity Index Test

Table 3.6 Results of Sorptivity value

Mix Designation	Mix Proportion	Dry Wt. Kg	Wet Wt. Kg	Sorptivity Value in mm
M1CC	Controlled Concrete	2.384	2.404	0.365

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M1LC	(85%C+10%CC+5%LS)	2.380	2.398	0.328
M2LC	(75%C+20%CC+5%LS)	2.378	2.395	0.310
M3LC	(65%C+30%CC+5%LS)	2.382	2.401	0.347
M4LC	(55%C+40%CC+5%LS)	2.386	2.407	0.383
M5LC	(85%C+5%CC+10%LS)	2.385	2.410	0.456
M6LC	(75%C+5%CC+20%LS)	2.378	2.400	0.401
M7LC	(65%C+5%CC+30%LS)	2.382	2.415	0.602
M8LC	(55%C+5%CC+40%LS)	2.393	2.433	0.730
M9LC	(70%C+20%CC+10%LS)	2.376	2.396	0.365
M10LC	(65%C+20%CC+15%LS)	2.380	2.399	0.346
M11LC	(60%C+20%CC+20%LS)	2.385	2.408	0.419
M12LC	(55%C+20%CC+25%LS)	2.382	2.412	0.547
M13LC	(80%C+10%CC+10%LS)	2.382	2.407	0.456
M14LC	(75%C+15%CC+10%LS)	2.387	2.414	0.492
M15LC	(65%C+25%CC+10%LS)	2.387	2.416	0.529

- From the table above the lower Sorptivity value is 0.310 obtained at M2LC as because the pozzolanic reaction of calcined clay produces more calcium silicate hydrate (C-S-H) gel, filling capillary pores. Similar result was observed in the paper of Vineet Shah [2020][14] and with addition of limestone the Sorptivity value decreases in M6LC and M10LC as 0.401 and 0.346 due to of the filler effect of limestone improves particle packing, further lowering Sorptivity value. Lower Sorptivity value indicates densified microstructure reduces water absorption and increases Durability.
- M7LC and M8LC have higher value of Sorptivity among all the mix indicates less durable concrete as limestone content increases reducing the clinker content. M10LC have lower Sorptivity value than M1CC(OPC) due to of synergistic effects of calcined clay and limestone, enhancing pozzolanic reactions and forming more C-S-H gel to fill the capillary pores and reducing water absorption rates.

4. CONCLUSIONS AND FUTURE SCOPES

4.1 Conclusions

The following conclusions are drawn based on experimentation:

1. The Slump value decreases with increase in amount of limestone and calcined clay as we need to add some more amount of superplasticizer to maintain the workability of the concrete.
2. At 3 days, Compressive Strength of M1CC is higher than (M1LC, M2LC, M3LC, M4LC). M4LC and M8LC have marginally lower strength. With addition of limestone the compressive strength increased by 4.35% in M14LC than M1CC. The highest compressive strength observed at M10LC increased by 13.45% than OPC Concrete.
3. At 7 Days and 28 days of curing, the highest compressive strength observed at (65%C +20%CC+15%LS) as 9.69% and 2.79% increased by M1CC. When limestone is increasing giving the highest compressive strength at (85%C+5%CC+10%LS) marginally improving the strength by 1.23% than OPC concrete at 28 days. When the calcined clay is varied taking limestone 10% Constant amount then the M14LC mix have higher strength surpassing M1CC by 2.39% and strength decreased at M15LC by 2.02% than M1CC.
4. Split tensile Strength increases till (M1LC) 15% replacement with LC^2 for 28 days and also increases from (M13LC TO M15LC) and highest tensile strength achieved at M15LC. When limestone is varied in the LC^3 concrete mix (M5LC to M12LC) then highest value is observed at (70%C+20%CC+10%LS) concrete. Lowest tensile strength observed at (M8LC) marginally by 2.92% than M1CC.
5. When limestone is varied in then M6LC (25% LC^2) have highest pulse velocity. When calcined clay is varied up to 20% taking limestone constant at 10% then M9LC indicating excellent quality of the concrete. Lowest UPV value obtained at M8LC indicating medium quality of the concrete.
6. Lower Sorptivity value is obtained at M2LC indicating high durable concrete. M6LC and M10LC Sorptivity value decreases with addition of the limestone. M7LC and M8LC have higher value of Sorptivity among all the mix indicates less durable concrete. M10LC (LC^3 Concrete) have lower Sorptivity value than M1CC(OPC) and it is also much comparable than other mix in all other criteria.

4.2 Future Scopes

The following scopes may be considered for future studies:

1. In present work, the medium grade of concrete is M35 is taken. Hence in future study, the standard grade and high-grade concrete can be considered.
2. The Present study is limited to the mechanical properties of concrete and durability. However, durability and long-term performance like acid attack, shrinkage, carbonation and creep may be considered.
3. Mechanical properties like flexural strength and modulus of elasticity may also be considered in future.
4. A variation in calcined clay and limestone % can be considered in LC^3 concrete mix in order to get target mean strength.
5. In present work, the curing is water curing. Hence in future, curing may be ambient curing or oven curing can be done for better understanding of properties of LC^3 concrete.

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