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A low carbon cement (LC_3) as a sustainable material in high strength concrete: green concrete

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ABSTRACT: Limestone Calcined Clay Cement (LC_3) Technology is a low carbon cement that combines limestone, calcined clay, and clinker, aiming to reduce CO_2 emissions by 40%-50% during production. In this study, large-scale investigations were conducted to explore LC_3 as a potential substitute for conventional cement (CC). Mechanical and durability tests were performed on LC_3, comparing results with CC and Pozzolana Cement (PC) concretes. The findings revealed that LC_3 concrete exhibited promising early-stage strength similar to CC concrete. However, at 90 days, LC_3 showcased a 10% higher strength compared to CC concrete. Additionally, LC_3 displayed a remarkable 45% increase in resistance to moisture ingress, indicating improved durability over CC concrete. These results highlight the efficacy of low carbon cement in developing ternary blended cements that offer early strength and enhanced durability, making it a viable eco-friendly alternative in the construction industry.

KEY WORDS: Sustainability; Low carbon cement; Strength; Resistivity; Sorptivity.

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RESUMEN: *Un cemento bajo en carbono (LC_3) como material sostenible en hormigón de alta resistencia: hormigón verde.* La tecnología de cemento de arcilla calcinada con piedra caliza (LC_3) es un cemento con bajo contenido de carbono que combina piedra caliza, arcilla calcinada y clínker, con el objetivo de reducir las emisiones de CO_2 en un 40 %-50 % durante la producción. En este estudio, se realizaron investigaciones a gran escala para explorar LC_3 como un posible sustituto del cemento convencional (CC). Se realizaron pruebas mecánicas y de durabilidad al LC_3, comparando resultados con los hormigones CC y Cemento con Puzolanas (PC). Los hallazgos revelaron que el hormigón LC_3 exhibió una prometedora resistencia en la etapa inicial similar al hormigón CC. Sin embargo, a los 90 días, LC_3 mostró una resistencia un 10 % mayor en comparación con el hormigón CC. Además, LC_3 mostró un aumento notable del 45 % en la resistencia a la penetración de agua, lo que indica una mayor durabilidad que el hormigón CC. Estos resultados destacan la eficacia del cemento con bajo contenido de carbono en el desarrollo de cementos mixtos ternarios que ofrecen una resistencia temprana y una mayor durabilidad, lo que lo convierte en una alternativa ecológica viable en la industria de la construcción.

PALABRAS CLAVE: Sostenibilidad; Cemento bajo en carbono; Resistencia; Resistividad; Absorción.

1. INTRODUCTION

LC_3 technology is the promising approach in reduction of CO_2 emissions. As the population growth is increasing rapidly, there is an outmost necessity of increasing the infrastructure, where cement clinker plays a pivot role in the process of construction (1, 2). An amount of about 5%-8% CO_2 emissions throughout the World was observing every year, where most of it is from the production of cement (3, 4). As of now all the developing countries were increased their infrastructure facilities, ultimately there would be more utilization of clinker and thus inviting more quantity of CO_2 emissions (5-7). There is an urgent need to decrease these emissions by adopting to sustainable technologies, where it can reduce the anthropogenic emissions to save the environment. By using various ACM's (Alternative cementitious materials) like flyash, GGBS etc.., can decrease the production of cement and global warming up to certain levels only (8-10). Hence there is a need to find out the alternative to cementitious materials which should be economical feasible, technically viable and at the same time the replacement of clinker should be more.

The utilization of ternary blended cements, which incorporate limestone and blast furnace slag in an appropriate combination, offers a promising approach to enhance the mechanical properties of concrete while maintaining its sustainability. This combination of limestone and slag exhibits a complementary effect, where limestone contributes to early-age strength, and slag enhances strength at later stages of concrete curing. Researchers have also developed models to predict the strength of concrete incorporating ternary cements, emphasizing the necessity of a minimum of 7 days of wet curing for achieving satisfactory mechanical properties (11, 12). To optimize the composition of concrete utilizing ternary composite cements, multicriteria optimization techniques have been employed. These techniques focus on jointly optimizing the absorption capacity and compressive strength of concrete produced with Portland cement, limestone, and/or granulated blast furnace slag. Through this approach, researchers aim to find the most suitable proportions of each constituent material, thereby maximizing the desired properties of the concrete.

Furthermore, studies indicate that the adoption of ternary cements can contribute to a reduction in the consumption of non-renewable resources and energy during cement production, leading to decreased CO_2 emissions. This eco-friendly approach, however, does not compromise the performance of the resulting concrete. The integration of limestone and slag in ternary blended cements offers a sustainable solution for improving concrete's mechanical properties while minimizing the environmental impact of the construction industry (13-15).

An emerging technology, known as LC_3 (Limestone, Calcined Clay, Cement), offers a promising solution to decrease CO_2 emissions in cement production by up to 40%. LC_3 is a triple blended cement that allows for the replacement of cement clinker with a percentage of 50% or more. The composition typically consists of 15% limestone (L), 30% calcined clay (CM), 5% gypsum (G), and 50% clinker. LC_3 technology utilizes abundant calcined clays, which have a higher replacement capacity compared to other alternative cementitious materials (ACMs). LC_3 is a low-carbon cementitious material aimed at reducing carbon dioxide emissions compared to traditional cement. It involves the incorporation of calcined clay as a partial replacement for clinker, the main component of cement. The manufacturing process of LC_3 entails lower temperatures compared to the production of traditional cement clinker. The calcination of the clay component in LC_3 occurs at temperatures ranging from 700 to 850 °C. In this process, appropriate proportions of limestone, clay, and gypsum (or other additives) are mixed, ground, and subjected to calcination at the aforementioned temperatures. The lower temperature requirement during calcination contributes to the reduction of the carbon footprint associated with LC_3 in comparison to traditional cement. Following calcination, the resulting material is finely ground and combined with clinker. The proportion of clinker in LC_3 can vary, but it typically amounts to around 50%. The inclusion of clinker is necessary to achieve the desired cementitious properties in LC_3 (16-18).

Based on research work done by various authors on LC_3 based mortars and concerts, it was concluded that the both mechanical as well as durability properties are performed satisfactorily when compared to other alternative binders (19, 20). As the workability of low carbon concrete is known to be less when compared to CC which can be improved by addition of superplasticizers. LC_3 has good durability aspects with respect to sulphate attack, reinforcement protection and many other factors. Besides it has numerous advantages, due to the availability of clay material in the local areas which could greatly reduce the charges of transportation and the requirements of high kiln temperatures are eliminated to a large extent, which helps to reduce the thermal energy up to 20-30%. As there are many challenges faced by common ACM's around the globe, LC_3 becomes a better alternative due its low-cost nature (21, 22). LC_3 could be a modern technology which proves to be a sustainable material, to get the optimum results and more durability than other types of alternatives to the cement. In LC_3 technology, due to the presence of reactive aluminates in calcined clay and carbonates in limestone involves in chemical reaction with the help of pozzolanic action in CM and filling effect of L creates a synergetic effect of all the constituents namely (limestone, calcined clay, and clinker) (23, 24). The pore size of $LC_{3,}$ gets reduced continuously with increase in curing period mainly due to dense binder matrix which leads to dropout in the inter connecting of pores. At early age of hydration LC_3 system attained lower pore size and reduced threshold size at microlevel, due to better hydration property and there is a shift in the narrow pore space (25).

The refinement of pore structure in LC_3 asset to create monocarboaluminate and hemicarboaluminate phases which contribute to continuous development in microstructure. Higher fineness in the calcined clay and clinker helps in the improvement of engineered properties and plays a pivot role in creating submicronic particles which reacts faster and provide surface for carboaluminate phases in the binder matrix. Further, large quantity of clinker can be replaced with $LC_{3,}$ which helps to create dense microstructure at inner binder matrix to enhance mechanical and durability properties (26). Present study was focused to identify the efficiency of LC_3 at low water-binder ratio over other types of binders in terms of hardened and durability characteristics of the resulting blending.

2. RESEARCH METHODOLOGY

Present study focuses on evaluating the performance of LC_3-based high-performance concrete with 50% clinker replacement. Previous studies have primarily explored low and medium-grade concretes using different binder mixes. From a comprehensive literature review, it has been observed that a combination of 30% calcined clay (CM), 15% limestone (L), 5% gypsum (G), and 50% clinker has shown positive outcomes in enhancing concrete properties (11). To develop high-performance concrete with 50% clinker replacement, experimental investigations on LC_3 concrete are required. The study examines the strength and durability characteristics of two concrete mixes: Mix A, a high-strength concrete with a target strength of 70 MPa, and Mix B, a standard strength concrete with a target strength of 40 MPa. The obtained results are then compared with equivalent mixes of conventional cement (CC) and pozzolana cement (PC) based concretes.

3. EXPERIMENTAL INVESTIGATION

3.1. Materials utilized

Conventional cement -OPC-53 grade (CC) satisfying to IS 269 (27) and Portland pozzolana cement (PC) satisfying to IS 269 (27) was used as binders in the present investigation and low carbon cement (LC_3) procured from TARA, New Delhi, India is used as an alternative binder to CC and PC with consists of Clinker: CM: L: G is 50:30:15:5. Physical properties of all three binders i.e., CC, PC and LC_3 are determined and tabulated in the Table 1. Gravel (CA) of 20 mm well graded satisfying the IS: 383 (28) and fine aggregate (FA) conforming to zone-II as per IS: 383 (28) was used as filling materials and the properties are shown in the Table.2. Poly carboxylic ether-based super plasticizer (SP) with brand name chryso optima-354 confirming to ASTM C494 (29) was used for better workability. Silica fume (SF) procured from apex chemicals was added in Mix A-70 MPa concrete (8 % by weight of binder) to attain required target strength at end of 28 days curing.

Table 1. Characteristics of CC, PC and $LC_{3.}$

No	TEST	CC	PC	LC_3
1	Consistency (%)	31	33	35
2	IST (min)	56	48	37
3	FST (min)	430	470	360
4	Specific gravity (SG)	3.12	2.93	2.98
5	Fineness (F)	3%	6%	5%
6	Mortar cube strength at 28 days	56.62	48.54	52.32

Table 2. Characteristics of Gravel (10 & 20 mm) and FA.

No	Material properties	Gravel (10 &20 mm)	FA
1	Bulk Density (g/cc)	1.64	1.76
2	Specific gravity (SG)	2.75	2.67
3	Fineness Modulus (FM)	7.75	2.76
4	Void ratio (V)	0.98	0.89
5	Bulk Porosity (P) % as per IS 2386-Part III	38	43

3.2. Concrete mix details

Concrete mix proportions were designed as per IS 10262 (30) and finalized based on laboratory trail tests carried on large number of specimens by considering a common binder content (370 kg/m^3 and 500 kg/m^3) and water-cement ratios (0.46 and 0.34). Further, coarse aggregates consist of 10 mm and 20 mm aggregates in the ratio of 45:55 respectively is used in the mixes to obtain good packing density and Silica fumes were added in Mix A-70 MPa grade concrete for achieving required target strength and SP was also added to bring out the target slump of about 100 mm in the trial mixes. Final mix proportions are fixed based on the 28 days compressive strength results and the details of the mixes are shown in Table 3. Nomenclature for the Mixes A and B are given as OPC-70 which indicates that Mix A with strength 70 MPa and the binder is CC similarly other mixes also named according to strength of mix and type of binder.

3.3. Tests on Matured Concrete

3.3.1. Mechanical properties

Compressive Strength (CS) of Concrete cubes of size100 mm x 100 mm were cast and tested at the end of 7 D, 14 D, 28 D, 56 D and 90 D as per IS 516 (31). Split tensile strength test (SPT) was performed on cylindrical specimens of size 75 mm radius and 300 mm length according to IS 516 (31), at the end of 28 days curing period. Flexural strength test (FST) was also conducted on prisms of size 100 mm x 100 mm x 500 mm as per IS 516 (31). All the strength tests were carried on a 3000 kN compression testing machine with adjustable loading frame.

3.3.2. Resistivity of concrete

The resistivity of concrete was determined using the Weener 4-probe resistivity meter ASTM G57 (32). This involved measuring the potential difference between two inner probes while measuring the current flow in the two outer probes. The surface of cylindrical specimens with a radius of 50 mm and a height of 200 mm was contacted under surface moisture conditions, and measurements were recorded at three different locations. The resistivity of the concrete was calculated using an empirical formula given by an Equation [1].

$$\text{Resistivity} = \frac{2\pi a \mathrm{V}}{\mathrm{I}} \qquad [1]$$

Where I=Current, V=Voltage and a= inner distance between probes in cm.

3.3.3. Defiance to chloride ion entry

The defiance to chloride entry was determined using rapid chloride permeability test (RCPT) according to ASTM C 1202 (33), to get a qualitative analysis of chloride ion ingress into concrete. An average of three specimens (size 50 mm thick and 50 mm radius) was chosen for each mix. The RCPT gives the total charge passed on a soaked concrete sample which indicates the resistance against chloride entry.

3.3.4. Accelerated corrosion permeability test (ACPT)

Accelerated corrosion test was performed to know the corrosion resistance of embedded steel in concrete under harsh environment conditions. Concrete samples of size 100 mm (ϕ) and 200 mm length by inserting 10 mm diameter steel bar were cast and tested at the required time period as per ASTM C876 (34).

3.3.5. Sorptivity test

Sorptivity is determined by calculating the rate of flow of water into the voids of concrete by capillary suction according to ASTM C1585 (35). The concrete specimens are tested after completion of required curing period and the cylindrical samples of size like RCPT were considered and samples are placed in contact with

Table 3. Mix Proportions for Mix A and Mix B are given in kg/m^3.

No	Strength of Concrete in MPa	Mix ID	Cement	FA (Zone-II)	Gravel (10 & 20 mm)	Water	SF	SP Dosage (% by weight of binder)
1	Mix A-70	OPC-70	500	575	1295	160	40	1.85
		PPC-70	500	575	1295	160	40	1.65
		LC$_3$-70	500	575	1295	160	40	2.40
2	Mix B-40	CC-40	370	729	1098	155.4	-	0.85
		PC-40	370	729	1098	155.4	-	0.70
		LC$_3$-40	370	729	1098	155.4	-	1.20

water up to a level of 5 mm from bottom. To evaluate the penetration of moisture, mass of each specimen is recorded at frequent interval of time and thesorptivity coefficient is calculated based on the Equation [2]:

$$S = \frac{i}{\sqrt{t}} \qquad [2]$$

Where, ΔW = quantity of water absorbed in (g);
i = Water absorption coefficient = $\Delta w/(A \times d)$
A = cross-section area of specimen contacts with moist (mm^2);
t = time (min); S = the sorptivity coefficient of the specimen ($mm/min^{0.5}$).

3.3.6. Porosity test

Porosity is the amount of air void between concrete medium. The porosity of concrete is defined as the ratio of the volume of void gap in a unit matter to the total volume of matter. The porosity of concrete is determined by oven drying method after 28 days of specified curing. The standard specimens of size 100mm diameter disc with a thickness of 50mm were cast and tested as per ASTM C642 (36). The porosity (Φ) of concrete is determined by using relation:

$$p = ((Wssd - Wd))/((Wssd - Ww)) \times 100\% \quad [3]$$

Where p is the porosity (mass 100%), W_{ssd} is the sample mass in soaked surface dry (SSD) condition, W_d is the sample dry mass and W_w is the mass of the soaked specimen.

4. RESULTS AND DISCUSSIONS

4.1. Strength results

4.1.1. Compressive strength results

Figure 1 in the study illustrates the compressive strength (CS) development of various concrete mixes, including Mix A-70 and Mix B-40 with LC_3, and their correlation with conventional cement (CC) and pozzolana cement (PC) concretes. The results reveal that LC_3-based concrete specimens exhibit higher compressive strength at all ages compared to CC and PC concretes in the high-strength concrete. This suggests that LC_3 has a positive impact on strength enhancement. On the other hand, PC concrete exhibits lower strength at early ages (up to 28 days) regardless of the concrete grade. However, due to its pozzolanic action, it improves its CS value at later ages (56 days and 90 days) compared to CC concrete. The presence of silica fumes in LC_3-based concrete, especially in higher grade concrete, contributes to its early-age strength development. This is a significant advantage in terms of strength achievement. Additionally, Mix B-40, the standard strength concrete, demonstrates similar behavior in strength attainment regardless of the binder used. Both LC_3 and PC-based concretes achieve better strength results at later ages (56 days and 90 days) compared to OPC (ordinary Portland cement)-based concrete. This finding highlights the potential of LC_3 and PC as alternatives to cement binders in terms of strength aspects.

The strength advancement in LC_3-based concrete, for both higher grade and standard grade, can be attributed to the presence of rich alumina in calcined clay. This alumina reacts with the calcium carbonate in limestone to form silica-carbide phases at the microlevel (18, 22). This reaction contributes to improved strength properties. In contrast, CC-based concrete exhibits lower strength results at later ages (56 days and 90 days) due to the absence of pozzolanic reactivity phases at the microlevel. The use of alternative cementitious materials (ACMs) like LC_3 can enhance the strength properties at later ages, providing a promising approach for reducing cement manufacturing. Overall, the benefits of LC_3-based concrete include higher early-age strength, better strength development in higher grade and standard grade concretes, and the potential to reduce reliance on conventional cement, thereby contributing to the reduction of carbon emissions associated with cement production.

By analyzing the error bars, a notable trend emerges, the standard deviation of strength values at 7 days is higher compared to that at 28 days. However, in the case of 40 MPa concrete, this deviation is considerably lower than in the 70 MPa concrete. Despite the deviation, both concrete mixes achieve the required strength at 28 days, regardless of the binder used. Furthermore, there is a slight deviation observed at 90 days strength due to the improved strength in LC_3-based concrete when compared to CC-based concretes. This discrepancy indicates the pozzolanic activity present in PC and LC_3-based concretes. In summary, the comparison shows that the standard deviation of strength values is higher at 7 days but decreases at 28 days. The 40 MPa concrete exhibits lower deviation than the 70 MPa concrete. At 90 days, a slight deviation is observed due to the enhanced strength of LC_3-based concrete compared to CC-based concretes. This difference signifies the presence of pozzolanic activity in PC and LC_3-based concretes.

4.1.2. Split tensile strength and flexural strength results

Figure 2 and 3 shows the results of SPT and FST for Mix A-70 and Mix B-40 with various types of binders. From SPT values, it was plainly noticed that all types of concrete are attain similar results irrespective type of binder and strength of mix. However, LC_3 based concretes contribute higher SPT value that that of CC and PC concretes, only marginal differences are observed at end of 28 days testing. Figure 3 de-

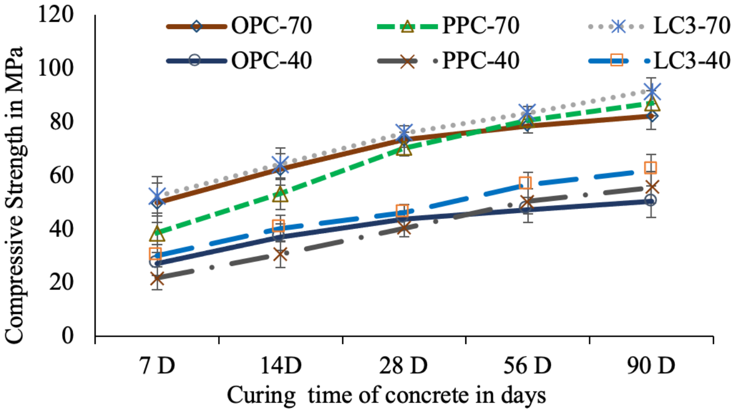


Figure 1. Compressive Strength Test results for Mix A-70 and Mix B-40 with different binders.

picts the results for FS for Mix A-70 and Mix B-40 with different binder. From results it was observed that in case of FS, LC_3 concrete shown better result than that of CC and PC concretes. Further studies should be carried to known efficiency of LC_3 binder at later ages in terms of improvement in SPT and FS results. The attribution of strength in LC_3 concrete is due to the formation of carboaluminate phases at inter facial transition zone, which allows for the alternative binary reactions in blended cements (10).

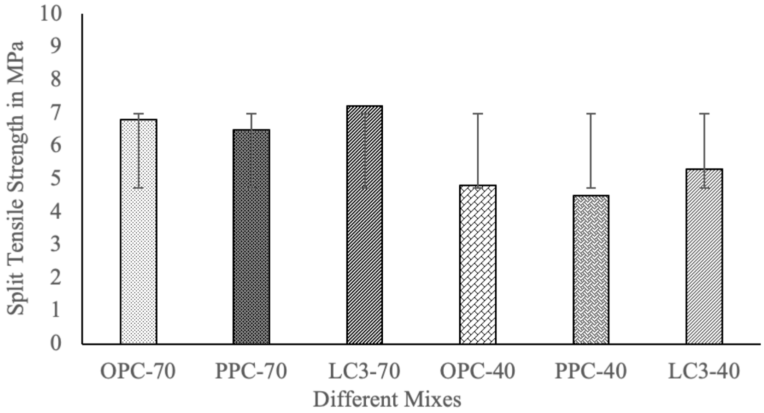


Figure 2. SPT results for Mix A-70 and Mix B-40 with different binders.

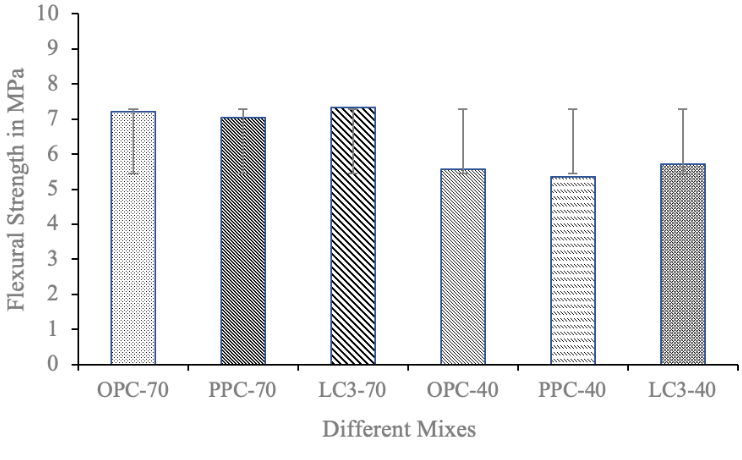


Figure 3. FST results for Mix A-70 MPa and Mix B-40 MPa with different binders.

4.2. Durability results

4.2.1. Surface resistivity test results

Surface resistivity provides valuable insights into the interconnectedness of pores within the concrete medium and serves as an immediate indicator of concrete quality in terms of its resistance to ionic ingress. Table 4 illustrates the corrosion rate corresponding to different electrical resistivity values. Figure 4 and 5 present the electrical resistivity of Mix A-70 and Mix B-40 concrete specimens with various binders at different curing ages (7 days, 14 days, and 28 days).

The results indicate that Mix A-70 MPa concrete exhibits higher resistance compared to the 40 MPa concrete. This is attributed to the lower water-binder ratio and the incorporation of silica fumes, which contribute to improved resistivity. Conversely, LC$_3$ concrete consistently demonstrates higher resistivity values throughout the curing stages, regardless of the concrete strength. The increase in resistivity during the early stages of low carbon concrete is attributed to the refinement of pore structure within the concrete system. In contrast, PC-based concretes exhibit low corrosion rates during later stages, particularly after 14 days of curing, and show enhanced resistivity at 28 days due to extended pozzolanic reaction with prolonged curing time. CC-based concretes, however, exhibit moderate susceptibility to corrosion during the initial curing stages and demonstrate minimal changes in resistivity with extended curing time. Notably, in Mix A-70, CC-based concrete with silica fumes displays better resistivity at 28 days of curing compared to Mix B-40. Overall, LC$_3$-based concrete demonstrates higher surface resistance primarily due to the development of a dense microstructure within the binder matrix. Additionally, PPC-based concretes exhibit significant improvements in resistivity with prolonged curing periods (20).

Table 4. Corrosion Rate as per (ASTMG57-06).

Corrosion Rate as per (ASTM G57-06)	Very High	High	Moderate	Low
Electrical Resistivity (kΩ-cm)	< 5	05 to 10	10 to 20	>20

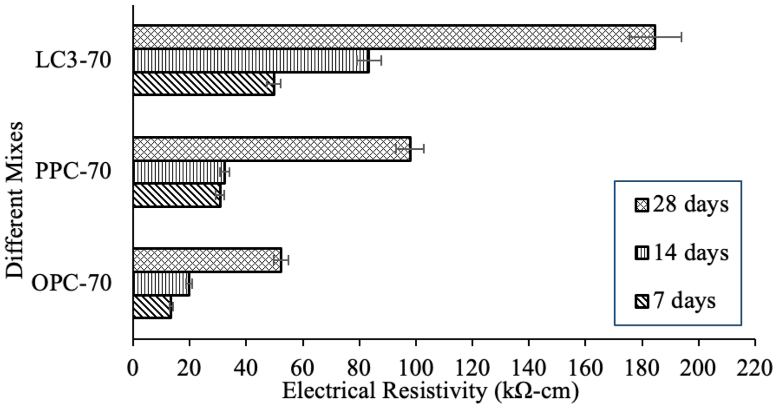


Figure 4. Surface resistivity of concrete for Mix A-70 with different binders.

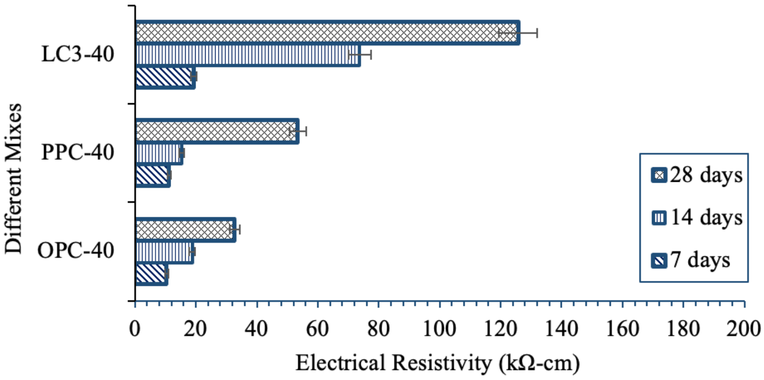


Figure 5. Surface resistivity of concrete for Mix B-40 with different binders.

4.2.2. Defiance to chloride ion entry

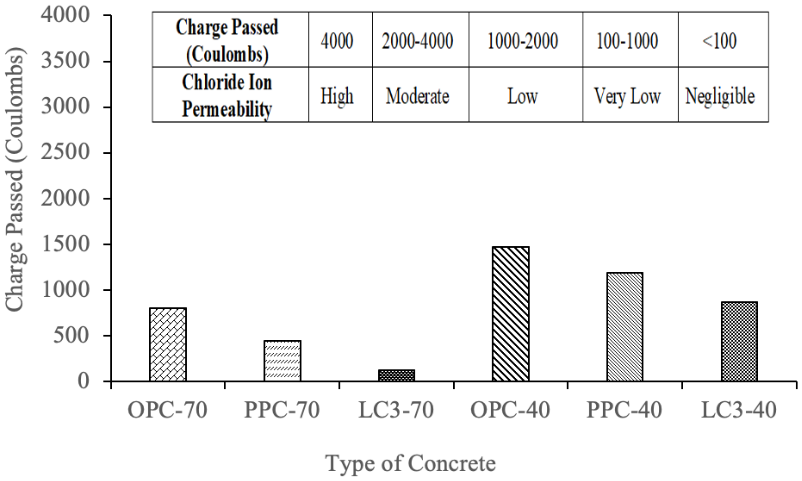
RCPT (Rapid Chloride Permeability Test) measures the quantity of chloride ion penetration into the concrete structure by determining the amount of charge passed in coulombs. Lower charge passed indicates higher resistance to chloride ion ingress. Figure 6 illustrates the experimental results of RCPT for Mix A-70 and Mix B-40 with different binders after a 28-day curing period.

The results indicate that LC_3-based specimens exhibit a lower amount of total charge passed, indicating a significant contribution to resistance against chloride ingress in the concrete, particularly during the early stages of curing, regardless of the concrete grade. Moreover, PC-based specimens show improved performance compared to CC-based specimens. Fly ash-based concretes demonstrate enhanced quality only after 28 days of curing, whereas LC_3 concrete exhibits better resistance to chloride ingress during the early stages, which is a positive outcome for the utilization of alternative binders in terms of enhancing durability at an early age of the concrete. Furthermore, CC-based Mix A-70 concrete with the addition of silica fume displays very low chloride ion permeability. Similarly, LC_3 concrete in the same mix exhibits negligible chloride ion ingress. The primary reason for this resistance is the faster reactivity potential of calcined clay, which aids in the creation of a refined pore structure and a dense cement matrix at the microlevel. This, in turn, prevents the entry of fluid medium into the concrete, contributing to improved resistance to chloride ingress (21).

4.2.3. Accelerated corrosion permeability test results

Impressed voltage technique was used to identify the susceptibility of concrete to corrosion environment. Resistance of concrete will be higher, when less amount of current is passed through a specimen and the post depassivation cracking time should be higher for the same specimen. Table 5 & Figure 7 shows the final critical corrosion current (CCR) in mA and post depassivation cracking time (PDCT) in hrs, results for Mix A-70 and Mix B-40 with different binders. From results it is found that the lower corrosion current (mA) was recorded for LC_3 based concrete specimens when corelated to CC and PC based concrete specimens. On the other hand, the post depassivation cracking time is also higher for LC_3 based concrete specimen, which indicates the strong resistance towards corrosion in harsh environments. Whereas PC based specimens are competitive and on par with LC_3 specimens, this could be because of pozzolanic reaction at inner phases of concrete. However, CC based specimens reported higher critical corrosion current (mA) value irrespective of strength concrete and the cracking period is less, which indicates that the resistance to corrosion was not significant when corelated to LC_3 and PC based concretes.

High strength concrete i.e., Mix A-70 specimens has shown improved resistance to corrosion when compared to standard concrete i.e., Mix B-40 irrespective of type of binder, which is mainly due to the lower water-binder ratio which creates dense pore structure at inter facial transition zone of concrete phases and effect of silica fume helps in evolution of secondary C-S-H gel. However, the post depassivation cracking time was less in CC based concrete specimens, this indicates early failure after the process of initial crack. Better resistance to failure due to lower corrosion rate and delay in the initial crack was observed in LC_3 based concrete, which is a positive indication for attaining better durability. LC_3 is one of the best alternatives for replacing cement up to maximum extent without compromising the strength and durability aspects, because clinker phases in OPC will



Charge Passed (Coulombs)	4000	2000-4000	1000-2000	100-1000	<100
Chloride Ion Permeability	High	Moderate	Low	Very Low	Negligible

Figure 6. RCPT results for Mix A-70 and Mix B-40 with different binders.

undergo maximum reaction at early stages whereas, LC$_3$ develop sifted pore structure at starting stage of hydration process. In addition to this due to the availability of rich aluminates in calcined clay's helps to create more binding at inner transition zone when compared to other types of binders (2, 4).

4.2.4. Sorptivity test results

Absorption rate in concrete is determined based on the moisture ingress through capillary action which is termed as sorptivity. The sorptivity coefficient was determined from the descend of the linear relation between cumulative water absorption (i) and square root of time (√t). Higher the sorptivity values, higher was the porosity which represents lower durability. Figure 8 depict the plots of cumulative water absorption (i) vs time$^{0.5}$ (√t) and Figure 9 shows the sorptivity coefficient values for different mixes. From Figure 8, it is clearly observed the absorption of water is more in case of Mix B-40 specimens when compared to Mix A-70 specimens. However, CC based concrete reported high water absorption in both mixes when compared to the PC and LC$_3$ based concretes. Due to supplement of ACM's the binary pozzolanic and high packing density attains lower water absorption rate in PPC and LC$_3$ based concretes. From Figure 9, it can be concluded that LC$_3$ based concrete attains lower sorptivity coefficient value when relates to other binders. However, PC based concrete reported minimal and on par with the LC$_3$ based concrete, as the supplementary cementitious materials act as pore refinement in the inner phases of concrete which will form binder matrix at capillary pores. Although CC based concrete performed well in case of Mix A-70 but not up to level of LC$_3$ based concrete. The main reason for having improved performance, in terms of strength, low permeability, high electrical resistivity, high resistance towards chloride ingress, low critical current and prolonged cracking period in LC$_3$ based concrete is due to the presence of fibrillar-like pore structure which further helps in reducing threshold size and critical pore size at the microlevel (18, 20).

4.2.5. Porosity test results

The porosity (mass %) was determined based on oven drying method for Mix A-70 and Mix B-40 with three binders. Form Table 6 it is clearly identified that Mix A-70, LC$_3$ based concrete undergone less porosity (mass %) when corelated to CC and PC concretes. However, PC based specimens exhibit similar trend that of LC$_3$ based specimens, this is mainly due to the ternary action of binders which creates a dense cement matrix at inner phases of concrete. On other hand CC based concrete reported higher porosity value in Mix A-70, but in case of Mix B-40 CC based

Table 5. ACPT values for Mix A-70 and Mix B-40 with different binders.

Type of Binder	Mix A-70		Mix B-40	
	CCR (mA)	PDCT (hrs)	CCR (mA)	PDCT (hrs)
OPC	16.8	282	30.4	218
PPC	13.7	334	25.6	243
LC$_3$	10.8	368	22.4	268

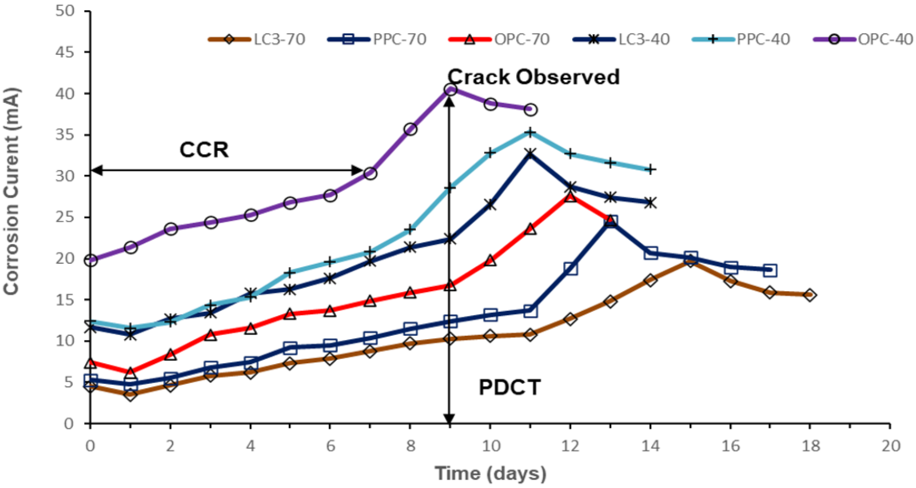


Figure 7. Corrosion current (mA) vs Time (days) for Mix A-70 and Mix B-40 with different binders.

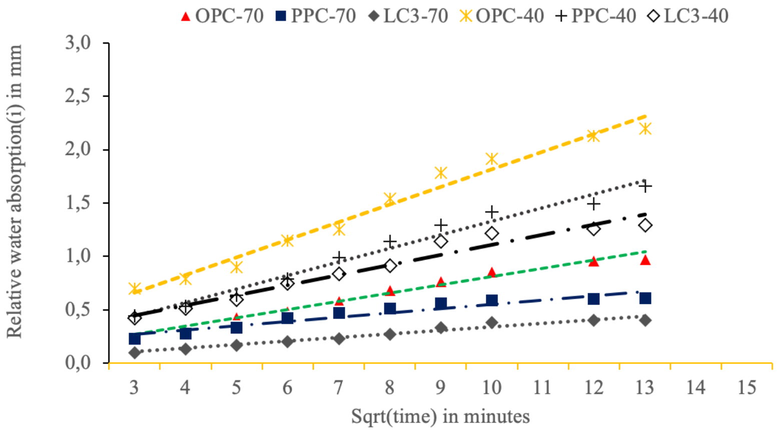


Figure 8. Cumulative water absorption *Vs* Sqrt (time) for Mix A-70 and Mix B-40 with different binders.

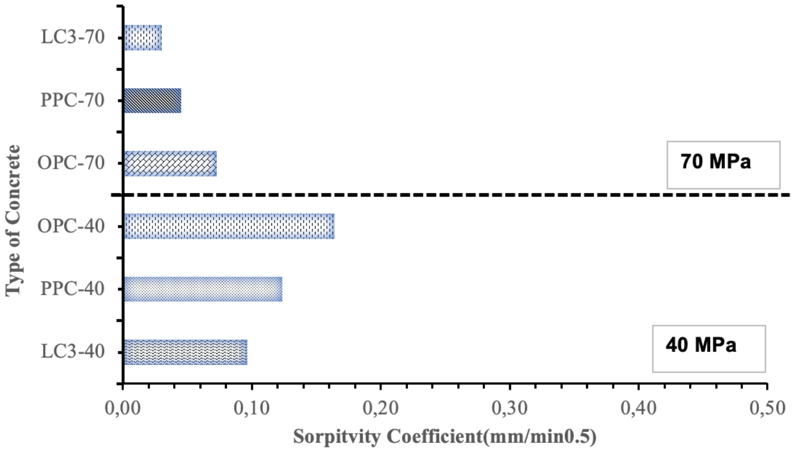


Figure 9. Sorptivity Coefficient results for Mix A-70 and Mix B-40 with different binders.

Table 6. Porosity (mass %) for Mix A -70 and Mix B-40 with different binders.

Type of binder	Porosity (mass %)	
	Mix A-70	**Mix B-40**
OPC	6.61 ± 0.3	8.81 ± 0.2
PPC	4.98 ± 0.2	8.26 ± 0.4
LC_3	4.27 ± 0.4	8.15 ± 0.5

concrete has shown similar porosity (mass %) when compared to PC and LC_3 based concretes.

Figure 10 shows the strength verses porosity relationship for different mixes with the 28D-compressive strength values and 28D-Porosity values for the two mixes of different binders. The strength vs porosity relationship obtained from experimental investigation was compared with the various models in the literature on cement-based materials (37) and this experimentally obtained strength-porosity values are compared with models of Balshin (38), Ryskovitch (39), Hasselman (40) and Schiller (41). The values of the parameters σ_0 in models of Hasselman, Balshin and Ryskovitch correlate to the strength of non-pervious material and are extrapolated to the strength of samples at zero porosity. The proposed strength at zero porosity (σ_0) from Balshin, Ryskovitch and Hasselman are 87.40, 90.19 and 83.28 MPa. It was clearly observed that the experimental data fitted well linearly with all equations. Based on porosity results it is found that the samples with more porosity values exhibits low CS value and lower porosity values exhibit high CS value. The main reason that LC_3 based concrete performed well in all aspects of durability

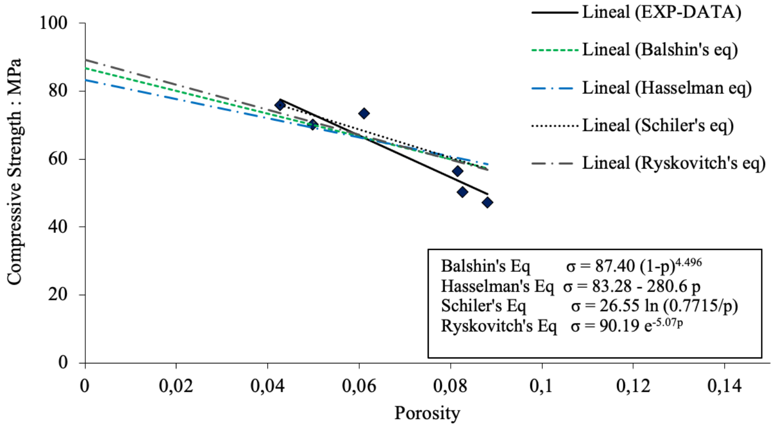


FIGURE 10. Experimental data on Strength-porosity dependence for Mix A-70 and Mix B-40 with different binders.

properties is due to the early reduction of inter connecting pore space by the mechanism of ternary binding system. The resistivity of LC_3 based concrete was significantly higher than that of CC and PC concretes which is mainly due to refinement of pore structure (pore space reduces) and also presence of highly reactive aluminate phases in calcined clay, which allows to develop dense microstructure (6, 18).

5. CONCLUSIONS

Based on experimental studies carried on two mixes (70 MPa and 40 MPa) with various types of binders (i.e., LC_3, CC and PC), the following conclusions can be drawn:

- LC_3 concrete exhibited superior early-stage strength development compared to CC and PC concrete. However, at 90 days of curing, LC_3 concrete (Mix A-70) achieved a 10% higher compressive strength (CS) value compared to CC concrete, while Mix B-40 specimens showed an 18% higher CS value.
- In terms of resistivity, LC_3 concrete specimens demonstrated 70% higher resistivity values at all curing stages, regardless of the concrete strength, when compared to CC concrete specimens. On the other hand, CC-based concretes exhibited moderate susceptibility to corrosion during the initial stages of curing and showed minimal changes in resistivity with extended curing time.
- LC_3-based specimens (Mix A-70) exhibited excellent resistance against chloride ion ingress during the early stages of curing, irrespective of the type of binder and concrete strength. Additionally, Mix B-40 specimens displayed a 40% higher resistance compared to CC specimens.
- In conclusion, LC_3-based concrete has demonstrated enhanced durability compared to normal concrete. The inclusion of LC_3 has resulted in several beneficial outcomes. Concrete (Mix A-70) with LC_3 exhibited a 55% higher resistance to moisture ingress compared to CC concrete. Similarly, Mix B-40 displayed a 40% increase in resistance and achieved lower porosity values when compared to CC and PC concretes.
- The comprehensive studies conducted indicate that LC_3 concrete exhibits superior performance in terms of hardened and durability aspects. It has shown high strength, low permeability, high electrical resistivity, increased resistance to chloride ingress, and a low critical current. These findings highlight the favorable attributes of LC_3 concrete, suggesting its potential as a viable alternative to CC and PC concretes.
- Overall, the incorporation of LC_3 in concrete formulations holds promise for improving the performance and durability of concrete structures.

AUTHOR CONTRIBUTIONS:

Conceptualization: S. Bhavani, M.L.V. Prasad. Research: S. Bhavani, M.L.V. Prasad. Methodology: S. Bhavani, M.L.V. Prasad. Supervision: M.L.V. Prasad. Writing - original draft: S. Bhavani. Writing - review & editing: S. Bhavani, M.L.V. Prasad.

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