Properties, Compatibility, Environmental Benefits and Future Directions of Limestone Calcined Clay Cement (LC3) Concrete: A Review

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Abstract:

This review paper provides a comprehensive analysis of the production, properties and applications of Limestone Calcined Clay Cement (LC3). The paper begins with an introduction to LC3 and its importance in reducing carbon emissions in the cement industry. It then discusses the raw materials used in the production of LC3 and the properties of the material, including its hydration process and thermal and X-ray diffraction analysis. The properties of LC3 concrete, including fresh, mechanical and durability properties, are also examined. The compatibility of chemical admixtures with LC3 is explored, followed by a discussion on the environmental benefits of using LC3. The paper then assesses the economic feasibility and social acceptance of LC3 in the construction industry, along with its potential impact on local communities. Case studies are provided on LC3 concrete projects. The review concludes with a discussion of future directions and research needs, including recommendations for further innovation in production and scaling up LC3 production. The findings of this review paper suggest that LC3 has significant potential for reducing the carbon footprint of the cement industry while providing an economically viable and sustainable alternative to traditional cement materials.

Keywords: Limestone Calcined Clay Cement (LC3), Carbon Emissions, Concrete Properties, Environmental Sustainability, Economic Feasibility

1. Introduction

The cement industry is a significant contributor to global greenhouse gas emissions, accounting for 5-8% of total emissions. Each tonne of cement produced emits about the same amount of carbon dioxide, which has a harmful impact on the environment. According to the International Energy Agency (IEA), global cement production exceeds 4000 million tonnes per year, and it is expected to grow by 12-23% by 2050. Therefore, there is an urgent need to take quick action to reduce carbon emissions and mitigate climate change. As a result, many studies have been conducted to find ways to reduce the use of cement in construction projects while maintaining the necessary strength and durability of the concrete. One approach that has gained attention is the use of Supplementary Cementitious Materials (SCMs), which are materials that can replace a portion of the cement used in concrete. SCMs such as Pulverised Fuel Ash (PFA), Ground Granulated Blast Furnace Slags (GGBS), and Silica Fume (SF) have been utilised often in concrete (Yang et al. 2022; Wang et al. 2021b).

Currently, SCMs are found in nearly every type of cement. However, the quality and quantity of SCMs available for a global cement replacement strategy remain limited. PFA has lower reactivity, and hence only a limited portion of clinker can be replaced by it. GGBS, on the other hand, despite having the possibility of higher replacement levels, is only available in limited amounts. According to Fig. 1, the amount of slag available in the world accounts for only 5–10% of total cement output. Moreover, iron production and hence slag production is concentrated in only a few nations, making supply in the countries with the largest cement demand severely limited. Steel consumption is growing at a slower rate than cement demand, and more steel is being recycled due to environmental concerns, which makes it unlikely that the supply of GGBS will increase significantly in the near future.

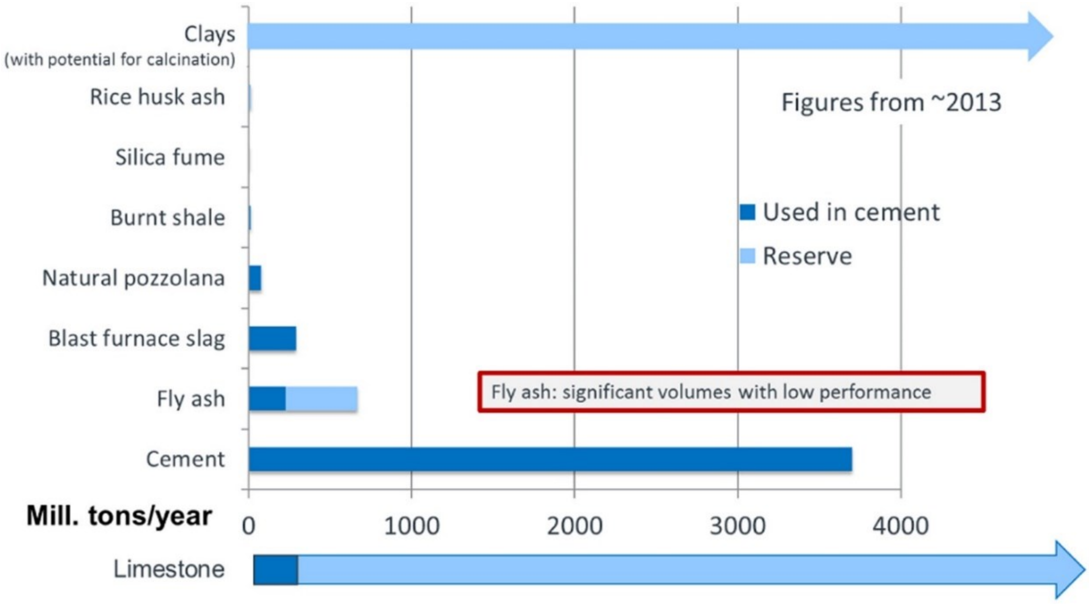

Fig. 1: Availability of common supplementary cementitious materials (Scrivener et al. 2018)

Limestone calcined clay cement (LC3) is a promising alternative to traditional cement as it can significantly reduce carbon emissions in the cement industry. LC3 is a low-carbon cement that is made by blending limestone and calcined clay, which is a type of clay that has been fired at high temperatures. The alumina from the calcined clay reacts with the carbonate from the limestone to form a carboaluminate phase, which provides the cement with its strength and durability (Scrivener et al., 2018). Compared to other supplementary cementitious materials like fly ash, limestone is more abundant and readily available. Fly ash, while more abundant than cement, is highly variable in quality, with only about a third of it being suitable for use in cement mixing (Snellings, 2016). Furthermore, with increasing pressure to reduce environmental emissions, the use of coal to generate energy is being questioned in numerous countries, which puts fly ash's long-term availability in doubt.

While limestone is abundant, adding more than 10% of it to cement increases porosity and degrades characteristics (Matschei et al., 2007). However, calcined clay has been proven to be a good alternative to cement. It is widely available and has been extensively researched for its use in the production of low-carbon cement (Alujas et al., 2015; Avet and Scrivener, 2018; Fernandez et al., 2011; Sabir et al., 2001; Scrivener, 2014; Siddique and Klaus, 2009). The use of calcined clay in LC3 has several advantages. Firstly, clays and limestone are abundantly available all over the world, making it a practical and sustainable choice for producing low-carbon cement (Bishnoi et al., 2014; Emmanuel et al., 2016). Secondly, LC3 can be produced using widely available and well-known methods in the cement industry, which means it does not require any specific training to use (Bishnoi et al., 2014; Emmanuel et al., 2016). Finally, LC3 does not require any specific handling, making it easier to incorporate into existing cement production processes (Scrivener et al., 2018).

In the lab, LC3 blends containing 40% clinker have been produced, indicating that LC3 can replace a significant proportion of clinker in cement production (Antoni et al., 2012). The use of LC3 can significantly reduce carbon emissions in the cement industry and has been identified as a promising solution for meeting carbon emission targets. However, further research is needed to better understand the properties and performance of LC3 and to identify areas where improvements can be made (Krishnan et al., 2018a; Krishnan et al., 2018b; Dixit et al., 2021; Huang et al., 2020; Lin et al., 2021).

XRD (X-ray diffraction) and TG (Thermogravimetric) analysis are commonly used techniques to investigate the phase composition and thermal behaviour of LC3. XRD helps to identify the crystalline phases present in LC3 samples and to monitor the formation of new phases during hydration. TG, on the other hand, measures the weight loss of a sample as it is heated, providing information on the evolution of water and other volatile species during heating. By combining these two techniques, researchers can gain insights into the complex chemical reactions and phase transformations occurring during the hydration of LC3, which is essential for optimising the material's properties and performance.

The aim of this review paper is to provide a comprehensive analysis of the current state of knowledge on the use of LC3 in concrete. The paper covers a wide range of topics related to LC3, including its fresh, mechanical and durability properties, environmental benefits, challenges and opportunities and real-world applications. The paper draws on a range of sources, including peer-reviewed research papers, conference proceedings and technical reports. The review focuses on the most recent and relevant studies, with a particular emphasis on papers published in the last decade. However, there are some limitations to the scope of this review. Firstly, the focus of the paper is on LC3, and other alternative cements are not covered in detail. Secondly, due to the broad scope of the review, it is not possible to cover every aspect of LC3 in depth. Finally, the review primarily focuses on the technical and engineering aspects of LC3, and social, economic and political factors influencing its adoption are not explored in detail.

2. Production of LC3

The process of calcination involves heating a material to a high temperature in order to bring about a chemical change. In the case of clay, calcination involves heating it to around 700-850°C. This process is important in the production of LC3, which is made by co-grinding or mixing limestone and calcined clay together into a homogenous blend. LC3 is a type of cement that has gained attention in recent years due to its potential to reduce carbon emissions. The majority of research on LC3 has been done on clays with kaolinite as the primary component. However, other clays such as illite and montmorillonite have also been investigated. It has been observed that the reactivity of illite and montmorillonite is lower than that of kaolinite (Fernandez et al. 2011).

Preliminary studies on LC3 have also revealed that increasing the amount of kaolinite content in clays above 60% provides little to no further benefit in terms of compressive strength (Fig. 2). However, it has been noted that the use of clays with higher kaolinite content can lower the hydration of clinker phases, notably C_2S content (Avet et al. 2016; Bishnoi et al. 2020; Cardinaud et al. 2011). The enhanced reactivity of kaolinitic clays relative to illite and montmorillonite has been linked to their faster elimination of water molecules in the microstructure. As water is removed, the clay's crystalline structure breaks down, allowing it to dissolve in alkaline conditions. Several physical and chemical activation strategies have been discovered to improve the reactivity of clays. Heat is commonly used to extract the water from the clay, which is typically done at temperatures above 700°C. However, there is some debate about the temperature required for complete calcination. It is generally agreed that heating a solid at a temperature more than 900°C can lower its reactivity by a process called sintering, which results in recrystallisation into spinel, mullite and cristobalite.

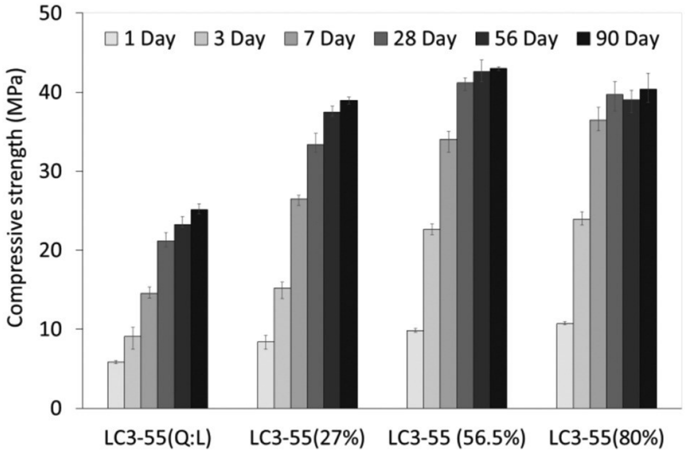

Fig. 2: Influence of Kaolinite content on the compressive strength of LC3 (Fernandez et al. 2011)

The process of clay calcination has been proven to be effective in producing calcined clay using both rotary kilns and flash calciners. A study by Canut et al. (2020) investigated the use of flash calcination for clay calcination and found that higher calcination temperatures can be tolerated. Additionally, Nguyen et al. (2020) showed that flash calcination results in a lower amorphous content compared to rotary kiln calcination. However, it is important to note that most clay research has focused on clays with hematite and quartz as the primary impurities. Therefore, the influence of additional clay phases on cement characteristics is still poorly understood (Krishnan et al. 2019; Vizcaíno et al. 2015; Yu et al. 2021).

Zunino et al. (2020) demonstrated that when a calcium-rich phase is formed on metakaolin particles, clays with calcite impurities are less reactive, resulting in reduced reactivity and specific surface area. Lowering the calcination temperature and lengthening the residence duration may help to reduce this effect. The reactivity of calcined clay is also determined by the kaolinite content. Martirena et al. (2020) found that the colour of calcined clay is determined by the quantity of iron in the raw clay. The reddish hue of LC3 is due to the presence of iron in the raw clay, while the cement itself is a dark-coloured powder. Initially, the acceptance of LC3 was limited due to its colour. However, later research revealed that when clays are calcined in reducing conditions with iron as an impurity, magnetite forms instead of hematite, resulting in a grey colour for the clay and cement as can be seen in Fig. 3 (Chotoli et al. 2017). It is important to note that the compressive strength of LC3 appears to be unaffected by clay colour, but more research is needed to fully understand the effect of clay colour on the hydration, mechanical and durability properties of LC3.

Fig. 3: Images of clay: (a) raw clay; (b) calcined clay; (c) calcined clay with colour control (Chotoli et al. 2017).

Avet et al. (2016) conducted a study on 46 various clays from around the world to investigate the effect of calcined kaolinite content on the strength of LC3 mortar (Fig. 4). The study found that when clays with 40% or more kaolinite are used, the strengths of LC3-50 are comparable to OPC concrete after 7 days. LC3-50 is made up of 50% ground clinker, 30% calcined clay, 15% limestone, and 5% gypsum. Additionally, these clays, which are one of the raw materials needed in cement production, are widely distributed and can be found in existing cement plant quarries. Finally, the particle size distribution of OPC, flash calcined clay and limestone, as determined by laser diffraction, is depicted in Figure 5 of Nguyen et al. (2020), while Figure 6 shows the XRD patterns of flash calcined clay and limestone. The only crystalline phases detected in both flash calcined clay and limestone were quartz and calcite.

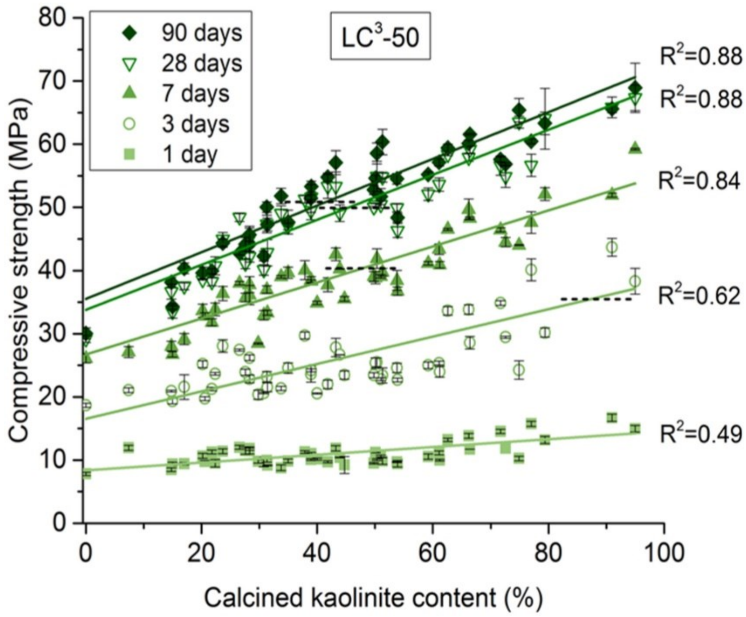

Fig. 4: Influence of calcined kaolinite content on mortar strength of LC^3 (Avet et al. 2016)

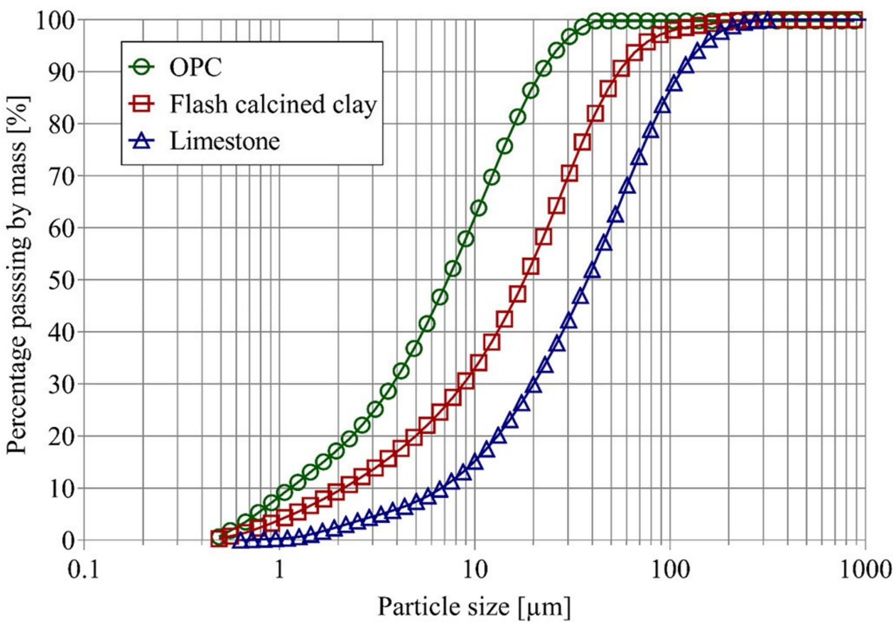

Fig. 5: Particle size distribution of OPC, calcined clay and limestone (Nguyen et al. 2020)

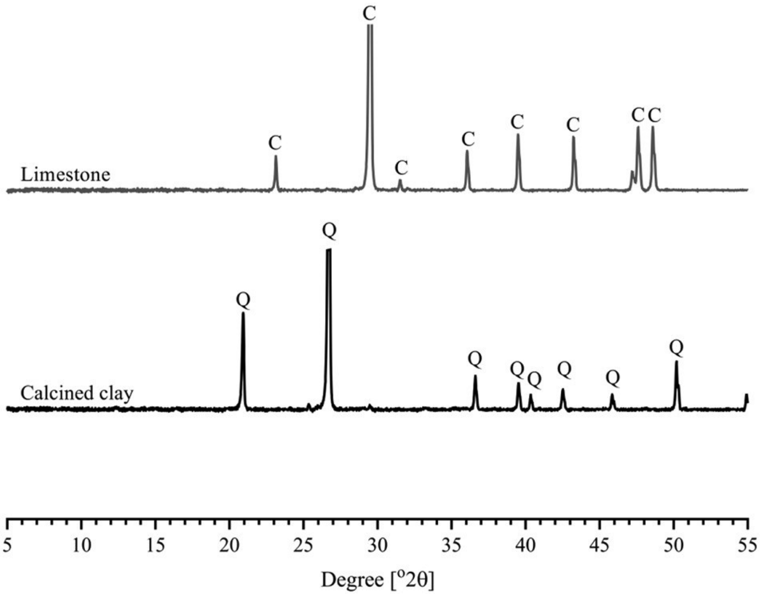

Fig. 6: XRD patterns of calcined clay and the limestone (Nguyen et al. 2020)

The process of calcination, involving the heating of clay to temperatures ranging from 700 to 850°C, is a pivotal step in the production of LC3. LC3, a promising alternative to traditional Portland cement, has garnered attention for its potential to significantly reduce carbon emissions. Most research on LC3 has primarily focused on clays rich in kaolinite, with limited exploration of other clay types like illite and montmorillonite, which exhibit lower reactivity.

Notably, studies have revealed that increasing the kaolinite content in clays beyond 60% does not substantially enhance compressive strength. However, clays with higher kaolinite content can influence the hydration of specific clinker phases, particularly affecting C2S content. The reactivity of these clays is attributed to their ability to rapidly eliminate water molecules, which breaks down their crystalline structure, facilitating dissolution in alkaline conditions. Various physical and chemical activation strategies have been explored to enhance clay reactivity, including heat treatment. However, there is ongoing debate about the optimal calcination temperature, with temperatures exceeding 900°C potentially leading to reduced reactivity through sintering.

While clay calcination processes can be carried out using rotary kilns or flash calciners, much of the research has centred on clays with hematite and quartz as primary impurities. The influence of additional clay phases on cement properties remains poorly understood. Impurities in clays, such as calcite and iron, can significantly impact reactivity and colour. Iron content affects the colour of calcined clay, with early concerns about LC3's colour being addressed through research. It appears that clay colour has limited impact on compressive strength, but further investigation is needed. Research has demonstrated that clays with 40% or more kaolinite content can yield LC3 strengths comparable to ordinary Portland cement (OPC) concrete after 7 days. These clays are widely distributed, making them readily available for cement production. In conclusion, these findings highlight the complexity of LC3 production and the need for a deeper understanding of clay composition, calcination parameters, and impurities to harness LC3's potential as an eco-friendly cement alternative.

3. Properties of LC3

3.1 Hydration

The hydration of LC3, a low-carbon cement consisting of clinker, calcined clay, and limestone, involves the reaction of these components with water to form various mineral phases. The ideal ratio of calcined clay and limestone is determined by the physical properties and chemical composition of the clinker, and the amount of calcined kaolinite accessible for reaction is proportional to the amount of C3S and C2S in the clinker. The hydration of LC3 results in the formation of calcium-alumino-silicate-hydrate (C-A-S-H), carboaluminate phase, and ettringite. These mineral phases help reduce the porosity of the cement matrix, making it more durable. The rate of hydration of LC3 is influenced by various factors, including the availability of alkalis and sulphates.

Sharma et al. (2021) provided a comparison of the compositions of OPC (OPC) and LC3 as shown in Fig. 7. LC3 utilises calcined clay and limestone to replace some of the clinker, as illustrated in Fig. 7. The concept of combining calcined clays and limestone to replace more clinker was first proposed by Antoni et al. (2012), although calcined clays and limestone have long been used as pozzolanic materials and cement fillers (Cao et al. 2021; John et al. 2018). The key innovation of LC3 is the use of commonly available kaolinite clay, particularly the low-grade ones blended with an additional 15% of limestone, which has a synergistic effect and achieves comparable performance OPC. The calcination of kaolinite-containing clay produces metakaolin, which is an amorphous alumino silicate that reacts with calcium hydroxide to form C-A-S-H and aluminate hydrates. When alumina reacts with limestone, hard and crystalline carboaluminate phases are formed, contributing to the microstructural growth of the cement matrix. The significant increase in the synthesis of carboaluminate phases is the primary reason for LC3's comparable performance to that of OPC.

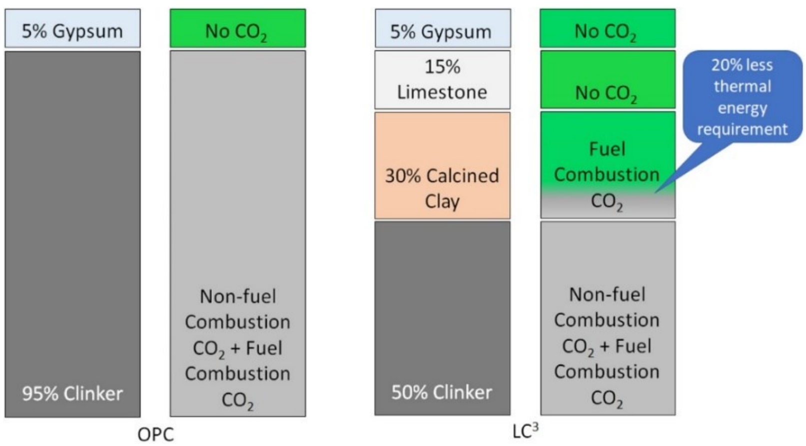

Fig. 7: A comparison of the composition of OPC and LC^3 (Sharma et al. 2021)

Figure 8 in Sharma et al. (2021) compares the heat of hydration of LC3 and OPC produced with the same clinker over the first 24 hours. The results show that the acceleration of LC3 is faster following the induction phase, and after the initial peak, another peak arises that is identical to C3A in OPC. The initial peak is due to the silicate phases, while the second peak is caused by alumina derived from clinker or calcined clay (Vance et al. 2012; Zunino and Scrivener, 2019). According to Zunino and Scrivener (2019), the second peak is produced by the hydration of aluminate phases in clinker.

Similar peaks have also been observed in studies on lime-calcined clay-gypsum systems without any aluminate phases. The amount of gypsum and kaolinite in the clay affects the position of the second peak, as shown in Fig. 9. Furthermore, another peak after the aluminate peak at 24 hours is associated with carboaluminate synthesis. To avoid poor long-term strength development caused by the aluminate peak too soon after the silicate phases, the amount of sulphate should be controlled to ensure that the aluminate peak occurs at least 1 hour after the silicate phases (Scrivener et al. 2018). In summary, the heat of hydration results suggest that LC3 has faster early strength development due to the alumina derived from calcined clay. However, to achieve good long-term strength development, the amount of sulphate in the mix needs to be controlled to avoid the aluminate peak occurring too soon after the silicate phases.

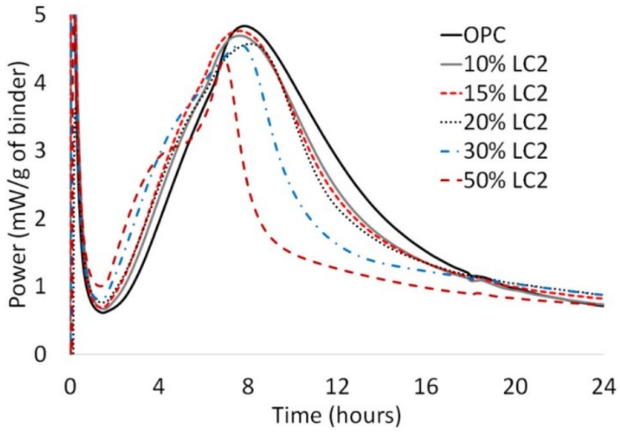

Fig. 8: Isothermal calorimetry curve of OPC and LC[3] at different level of LC2 (Shah et al. 2020)

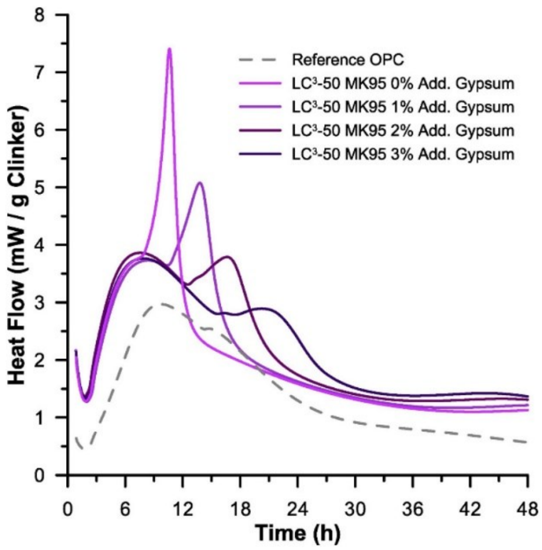

Fig. 9: Isothermal calorimetry curve of OPC and LC3 with different amounts of gypsum (Zunino and Scrivener, 2019)

Most of the research on LC3 is based on a mix of clinker, calcined clay, and limestone in a 1:1:0.5 ratio by mass (Bonavetti et al. 2011). However, the ideal proportion of calcined clay and limestone depends on the properties and composition of the clinker used (Krishnan and Bishnoi, 2020). The amount of calcined kaolinite available for reaction is related to the C_3S and C_2S content of the clinker (Andres et al. 2015). The carboaluminate phase forms when limestone reacts with the alumina phase of the cement and calcined clay, but its development is delayed until sulphates have dissolved in the pore solution (Dhandapani and Santhanam, 2017; Bonavetti et al. 2001). The rate of hydration of LC3 is also affected by the availability of alkalis (Avet et al. 2019; Krishnan et al. 2021).

A significant portion of the limestone in the LC3 system acts as an unreacted filler. The reaction between calcium hydroxide and the silicate phases of calcined clay results in the formation of C-A-S-H, which is responsible for much of the strength development in LC3 cement (Bonavetti et al. 2011). The composition of C-A-S-H is influenced by the proportion of kaolinite in the calcined clay and the hydration temperature (Bonavetti et al. 2011). Sulphate added to LC3 is adsorbed on the surface of C-A-S-H at high curing temperatures, which controls the availability of aluminate phases for carboaluminate phase formation (Dhandapani and Santhanam, 2017). According to published studies, the carboaluminate and ettringite phases together make up approximately 25% of the total volume of the hydrated cement paste in LC3, while C-A-S-H accounts for roughly 50% of the overall volume (Mishra et al. 2019).

LC3 is a low-carbon cement that uses calcined clay and limestone to replace some of the clinker. Its hydration involves the formation of various mineral phases, such as calcium-alumino-silicate-hydrate (C-A-S-H), carboaluminate phase, and ettringite, which contribute to the reduction of porosity and increased durability of the cement matrix. LC3 has comparable performance to OPC due to the significant increase in the synthesis of carboaluminate phases, which is the primary reason for its comparable performance to that of OPC. However, to achieve good long-term strength development, the amount of sulphate in the mix needs to be controlled to avoid the aluminate peak occurring too soon after the silicate phases. The ideal proportion of calcined clay and limestone depends on the properties and composition of the clinker used, and the carboaluminate phase forms when limestone reacts with the alumina phase of the cement and calcined clay. The rate of hydration of LC3 is also affected by the availability of alkalis.

The hydration process of LC3 is a multifaceted chemical transformation involving clinker, calcined clay, and limestone. LC3, designed to reduce carbon emissions in the construction industry, forms essential mineral phases during hydration, including calcium-alumino-silicate-hydrate (C-A-S-H), carboaluminate phase, and ettringite. These phases work in concert to decrease the porosity of the cement matrix, enhancing its durability and long-term performance. Sharma et al. (2021) offer a compelling comparison between LC3 and Ordinary Portland Cement (OPC) compositions, highlighting LC3's innovative use of calcined clay and limestone as partial clinker replacements. LC3's key innovation lies in its utilization of readily available kaolinite clay, often of lower grade, combined with limestone, yielding performance similar to OPC. The calcination of kaolinite clay results in metakaolin, which reacts with calcium hydroxide to form C-A-S-H and aluminate hydrates. Simultaneously, alumina from clinker or calcined clay reacts with limestone, forming robust carboaluminate phases that contribute to the microstructure's growth. The heat of hydration comparison demonstrates LC3's accelerated early strength development, attributed to the presence of alumina from calcined clay. However, controlling sulphate levels in the mix is imperative to prevent premature aluminate peak formation, which can compromise long-term strength. The hydration rate of LC3 is influenced by various factors, including alkali and sulphate availability.

3.2 TG and XRD Analysis

In a study conducted by Parashar and Bishnoi in 2021, the authors used differential thermogravimetric (DTG) analysis to investigate the hydration behaviour of limestone calcined clay cement (LC3) at different ages. As shown in Figure 10, the DTG plot of the LC3 mix indicated that the breakdown peak of calcium-silicate hydrate (C-S-H), Al2O3-Fe2O3-mono (AFm) and tri (AFt) phases, and carboaluminate phases was observed in the range of 50°C to 200°C, suggesting that the LC3 mix was rapidly hydrated. The researchers also found that CH was present in the hydrated LC3 mix after three days but was absent in the 7, 28, and 90-day hydrated samples, as confirmed by the DTG plot. The rapid consumption of CH was attributed to the pozzolanic reaction and carboaluminate production in the LC3 mix. Moreover, the presence of carboaluminates was observed to have minimal growth with increasing age.

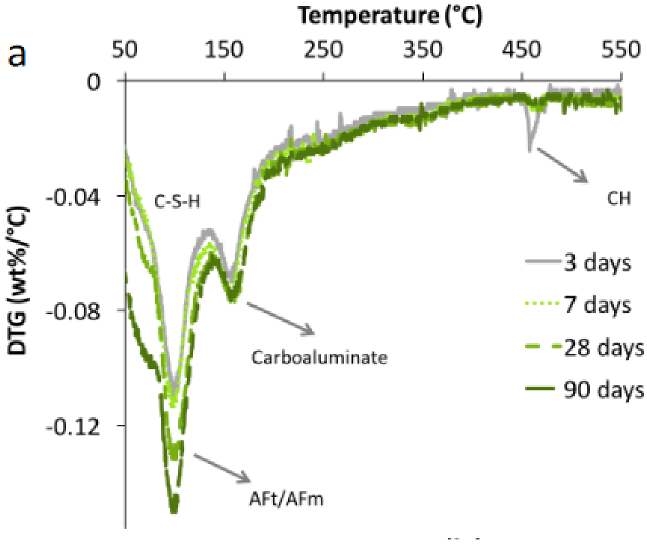

Fig. 10: Differential thermogravimetric (DTG) plot of LC3 (Parashar and Bishnoi, 2021)

Krishnan and Bishnoi (2020) employed XRD to examine the development of hydration products of OPC and LC3 and slag-limestone cement (SLSC) (Fig. 11). These samples were hydrated for a period of 90 days, and the resulting products were analysed using XRD. The researchers found that in both LC3 and SLSC mixes, carboaluminate phases (Hc and Mc) were formed during the hydration process. Furthermore, they observed that the AFt phase remained stable after 90 days. Interestingly, while the conversion of Hc to Mc phase was visible in the SLSC mix after 90 days, only a small quantity of Hc was transformed to Mc in the LC3 mix. Additionally, the XRD data obtained in this study confirmed that calcium hydroxide (CH) was not present in LC3. This is an important finding because CH is a by-product of the hydration process in OPC and is known to contribute to the carbonation of concrete over time, leading to decreased durability.

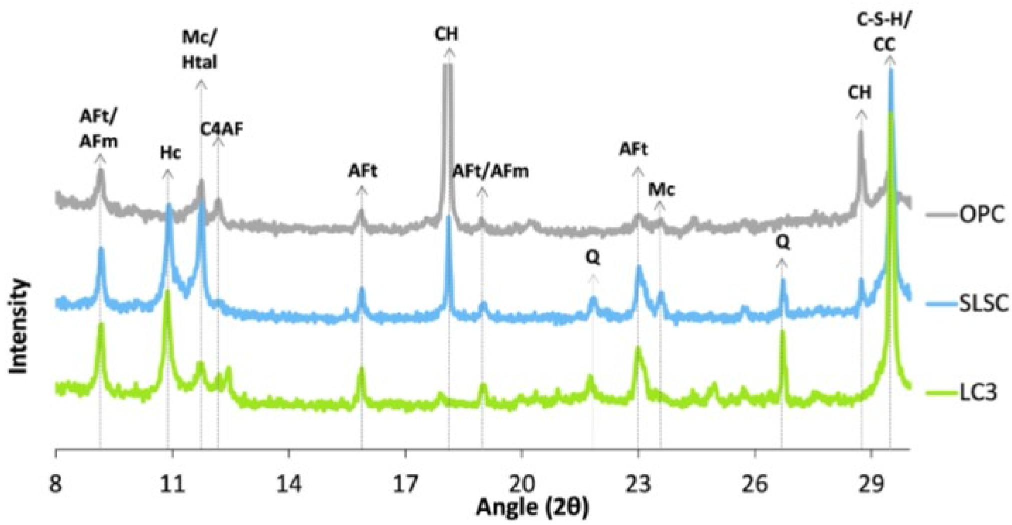

Fig. 11: X-ray diffractograms of OPC, LC3 and SLSC mixes (Krishnan and Bishnoi (2020)

Nguyen et al. (2020) analyzed the XRD patterns of OPC, LC3-20, and LC3-30 pastes after 28 days of water curing, as shown in Figure 12. In the LC3 system, the magnitude of the Portlandite peak was reduced, and it had the smallest magnitude in the LC3-30 paste. This reduction in the Portlandite peak can be attributed to the pozzolanic reaction between the calcined clay and the limestone, which consumes the $Ca(OH)_2$, the source of Portlandite. In LC3 pastes, quartz and calcite peaks were also visible. The sharp peaks of calcite after 28 days of cure demonstrate the presence of unreacted limestone in the LC3 system. The C-S-H peaks appear to coincide with several of the peaks in the LC2-20 and LC-30 pastes, indicating the formation of C-S-H in the LC3 system, as well as in the other cement systems. The usual peaks of ettringite in OPC paste were found at 9.0°. Figure 12 further shows that the LC3 paste had a larger monocarboaluminate peak intensity than the LC3-20 pastes, indicating that the LC3-30 paste had a higher degree of carboaluminate formation, which can be attributed to the higher amount of limestone in the mix.

On the other hand, LC3 has a larger specific surface area compared to other cements due to the fineness of calcined clay particles (Emmanuel et al. 2016). LC3 has a Blaine fineness that is double that of conventional cements, which means that it has a larger surface area per unit of weight. The amount of water required to achieve a standard consistency in LC3 is, however, comparable to that required in other cements. The Blaine fineness of LC3 is roughly 600 m2/kg, while OPC is around 300 m2/kg. The W/C required for standard consistency in LC3 is 0.28, while it is 0.31 in OPC (Emmanuel et al. 2016). However, it is worth noting that Blaine fineness may not be a good fit for LC3 because the range of fineness exceeds 600 m2/kg (Arvaniti et al. 2015). The high fineness of LC3 makes it more reactive and helps to increase its strength and durability.

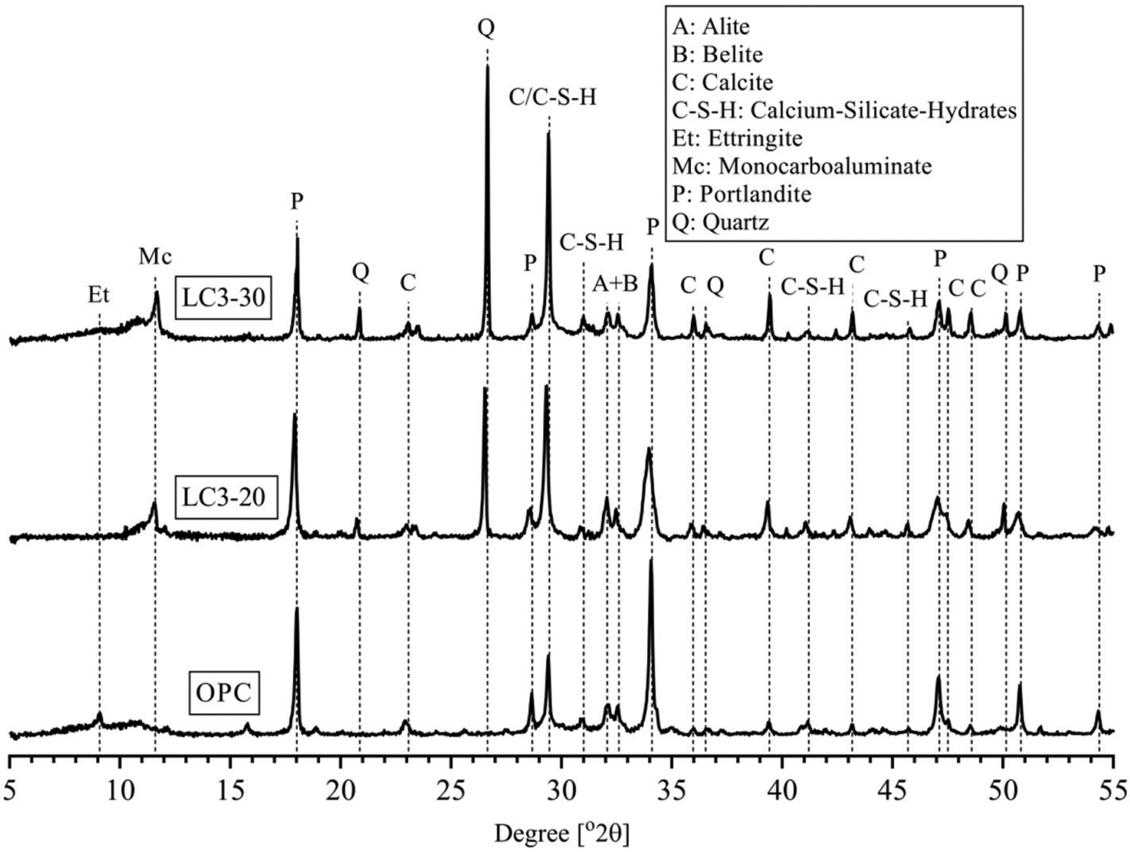

Fig. 12: X-ray patters of OPC and LC3 pastes (Nguyen et al. 2020)

Cements and LC3 (Limestone Calcined Clay Cement) both serve as construction materials used in various applications. The advantages and disadvantages of both cements are summarised in Table 1. It is important to note that LC3 is a relatively new and evolving technology, and its performance and availability may vary by region. Additionally, the choice between conventional cements and LC3 may depend on local factors, sustainability goals, and project-specific requirements. Therefore, a thorough evaluation should be conducted before selecting a cement type for a particular application.

Table 1: Advantages and disadvantages of conventional cement and LC3

Aspect	**Conventional Cements**	**LC3**
Advantages		
Sustainability	- High early strength	- Reduced carbon emissions
	- Widely available	- Incorporates abundant raw materials
	- Familiar technology	- Potential for local sourcing
	- Proven performance	- Improved durability
		- Reduced energy consumption
		- Lower clinker content
		- Utilises waste materials
Durability	- Good durability	- Enhanced durability
	- Long-lasting	- Reduced alkali-silica reaction
	- Suitable for most apps	- Lower permeability
		- Resistant to sulphate attack
Environmental Impact	- High carbon footprint	- Lower carbon footprint
	- Resource-intensive	- Reduced resource consumption
	- High CO_2 emissions	- Lower CO_2 emissions
	- Quarrying impacts	- Reduced quarrying
	- Limited use of waste	- Utilises industrial waste
Cost	- Relatively inexpensive	- Cost-competitive in some regions
	- Established supply chain	- May require process adjustments
Disadvantages		
Sustainability	- High carbon emissions	- May require new infrastructure
	- Depleting resources	- Limited availability in some areas
	- Environmental impact	- Variable performance in some cases
	- Quarry rehabilitation	
Durability	- Vulnerable to alkali-silica reaction	- Limited long-term data
	- High permeability	- May require quality control
Environmental Impact	- High energy consumption	- Limited research and adoption
	- Land degradation	
	- Dust and noise pollution	

Cost	- Fluctuating prices	- Initial setup costs may be high
	- Transportation costs	- Limited availability in some areas

4. Properties of LC3 Concrete

4.1 Fresh Properties

The workability of LC3 concrete depends on various factors such as the water-cement ratio, the use of superplasticizers and the proportion of constituents such as calcined clay and limestone. LC3 concrete typically has good workability due to its high fines content and the presence of calcined clay, which acts as a natural pozzolan and enhances the fluidity of the mix. The use of LC3 in concrete and mortar may lead to some changes in the fresh properties of the resulting mix. Chen et al. (2020) observed that LC3 concrete has a higher water demand than traditional concrete due to the enhanced water absorption and specific surface area of LC3. This has also been attributed to the flocculation of finer clay particles and the retention of water between the flocs and between the clay sheets (Muzenda et al. 2020; Hou et al. 2021). In a study by Yu et al. (2021), it was reported that ultra-high volume LC3 mixes exhibited fast slump loss and high thixotropy. Thixotropy refers to the property of a material to show a decrease in viscosity under the influence of shear and time, which is a desirable property for concrete during transportation and placement. Hou et al. (2021) conducted a detailed study of the mechanisms behind the dominating thixotropy of LC3 concrete and attributed it to the flocculation of clay particles in the LC3 system.

A slump test is a common method for evaluating the workability of fresh concrete. A typical slump test result for LC3-70 concrete is shown in Figure 13, where the slump value and slump flow were 235 mm and 415 mm, respectively, after 10 minutes of mixing. However, the slump value decreased to only 100 mm after 25 minutes of mixing (Beigh et al. 2020). The rapid slump loss has been attributed to the adsorption of superplasticizer molecules by calcined clay particles, which reduces the water-reducing effectiveness of polycarboxylate-based superplasticizers over time (Ng and Plank, 2012).

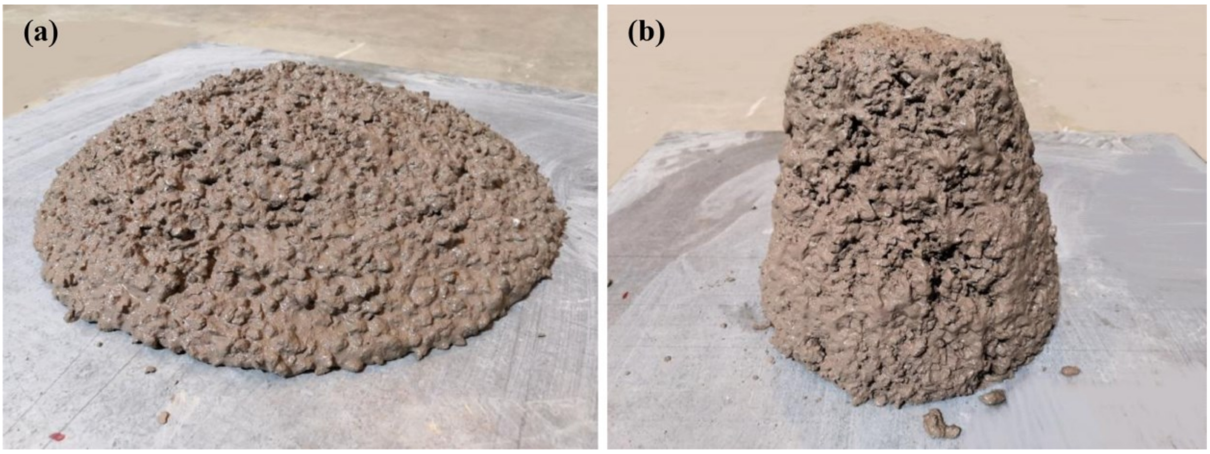

Fig. 13: Slump of LC^3-70 concrete (a) 10 minutes after mixing: slump = 235 mm; (b) 25 minutes after mixing: slump = 100 mm (Yu et al. 2021)

Conflicting results have been reported regarding the bleeding and segregation resistance of LC3 concrete. While Nair et al. (2020) found that LC3 mixes had a lot of bleeding, Bishnoi et al. (2020) reported that the concrete was more stable and did not have any bleeding or segregation even in blends with greater superplasticiser dosages and in self-compacting concrete (SCC). Therefore, further research is required to determine the effects of LC3 on the bleeding and segregation resistance of concrete.

In their study, Shah et al. (2020) investigated the effects of using limestone and calcined clay as partial replacements for OPC in cement paste on the setting time (Table 2). They used a range of substitution levels, including 10%, 15%, 20%, 30%, and 50%, and evaluated the initial setting time and standard consistency of the resulting mixes. The standard consistency of the mixes increased with the amount of OPC substitution, indicating that the blended mix required more water to achieve the same workability as the OPC mix. The authors observed that the setting time of the limestone-calcined clay blends increased slightly compared to that of the OPC at lower replacement levels, but blends with higher quantities of limestone and calcined clay set faster. Setting time results for blends containing 30% and 50% were obtained from isothermal calorimetry, which showed that these blends had a shorter induction period and accelerated faster. This is in contrast to the qualities of cement substituted with the most regularly used supplementary cementitious materials (SCMs), which usually take longer to set.

The increased reactivity of calcined clays could explain why mixes with higher replacement levels have a faster setting time. Due to the structure and fineness of calcined clay, limestone-calcined clay blends require more water to achieve the same flow as OPC. However, the limestone particles in LC3 can help to reduce the need for additional water to some extent. The authors concluded that the use of limestone and calcined clay as partial replacements for OPC in cement paste has the potential to improve the setting time and other properties of the resulting mix, although further research is needed to investigate the effects of different substitution levels on the performance of concrete.

Table 2: Standard consistency and initial setting time (Shah et al. 2020)

Mix	Stannard consistency (%)	Initial Setting time (min)
OPC	31	140
LC^3-10	34	145
LC^3-15	36	155
LC^3-20	37	145
LC^3-30	38	125
LC^3-50	43	120

4.2 Mechanical Properties

Compressive strength is a critical parameter for concrete as it measures the ability of concrete to resist external loads and stresses. Several factors can influence the compressive strength of LC3 concrete. The calcined clay content is one of the most significant factors, with higher calcined clay content generally resulting in lower compressive strength. Curing conditions such as temperature and humidity can also influence the strength development of LC3 concrete. In addition, the water-cement ratio plays a critical role in determining the compressive strength of LC3 concrete.

In the study conducted by Nguyen et al. in 2020, the compressive strength of mortar samples was investigated to evaluate the mechanical performance of LC3. The mortar samples were tested for compressive strength at various ages of 1, 7, 14, 21, and 28 days. The results of the study are presented in Figure 14. In the study, two different types of LC3 mortar were used, LC3-20 and LC3-30. The LC3-20 mortar had 20% of the OPC replaced with a 2:1 mass ratio of calcined clay and limestone, while LC3-30 had 30% OPC substitute. The control sample used in the study was an OPC mortar. The results of the study showed that the OPC control sample had the highest compressive strength at all ages. However, the LC3 mortar, including both LC3-20 and LC3-30, had comparable (or slightly lower) strengths to the OPC mortar. The LC3-30 mortar had slightly lower strength after 21 and 28 days. Overall, the compressive strength of the LC3 mortar was found to be approximately 12% lower than that of the OPC mortar. These results suggest that LC3 has promising mechanical properties and can be used as a sustainable alternative to OPC, particularly in low to medium-strength applications.

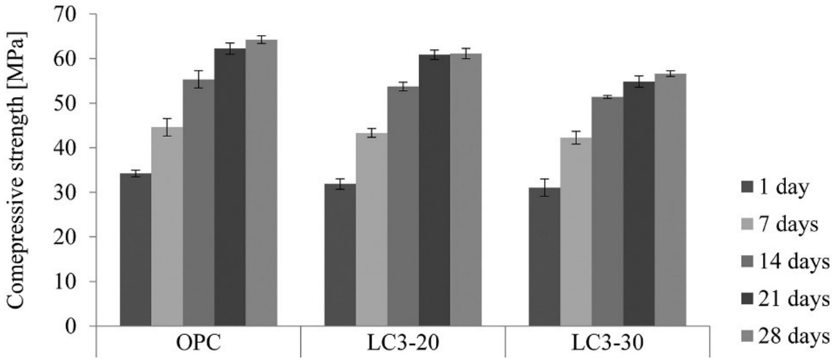

Fig. 14: Compressive strength of mortar (Nguyen et al. in 2020)

In their study, Dixit et al. (2021) explored the compressive strength of LC3 mortar produced from clays sourced from five distinct regions in Singapore. The researchers graphically represented the variation in strength across the mixes for the first 91 days, as illustrated in Figure 15. The substitution of OPC with calcined clay and limestone resulted in a 20% reduction in strength after 28 days, which aligns with similar findings from previous research conducted by Avet and Scrivener (2018), Krishnan et al. (2019), Dhandapani and Santhanam (2017), and Du and Pang (2018). The primary cause for this reduction is pore refining, which slows down the formation of carboaluminate, clinker hydration, and the generation of AFm phases. On the other hand, the control mix, which had 100% OPC, continued to gain strength for up to 91 days. However, the strength development of blended mixes was minimal. The study's findings highlight that while LC3 has the potential to reduce carbon emissions, the reduction in strength when substituting OPC with calcined clay and limestone may limit its applicability in construction projects that require high-strength concrete. Nonetheless, further research could explore other factors that may impact the strength development of LC3 mixes, such as curing conditions, aggregate type, and particle size distribution.

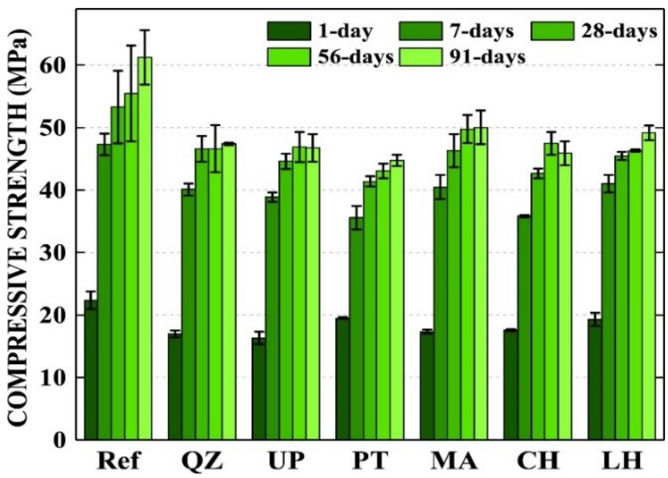

Fig. 15: Compressive strength of mortar with clays from 5 different sources in Singapore (Dixit et al. 2021)

In the study conducted by Yu et al. (2021a), the researchers investigated the compressive strength of mortar mixes that were made using ultrahigh-volume limestone calcined clay (UHV-LCC) at different LCC-binder and water-binder ratios. The compressive strength of the mortar after seven and twenty-eight days was shown in Figures 16 and 17, respectively. The results showed a linear drop in compressive strength as the LCC-binder ratio increased, while the water-binder ratio remained constant. The study also compared the compressive strength of Mortar-L80 series (LCC mix with 80% LCC) and Mortar-L50 series (LCC mix with 50% LCC) at the same age and with the same water-binder ratio. The results indicated that the Mortar-L80 series had nearly half the compressive strength of Mortar-L50 series. The researchers attributed this reduction in strength to the dilution effect of LCC. As more OPC is replaced by LCC, less calcium hydroxide becomes available for the pozzolanic process. Similar findings were reported by Yu et al. (2021b), which further supports the conclusion that the dilution effect of LCC has a negative impact on the compressive strength of mortar. Overall, these findings provide insights into the effects of using UHV-LCC and the importance of carefully considering the LCC-binder and water-binder ratios when designing mortar mixes.

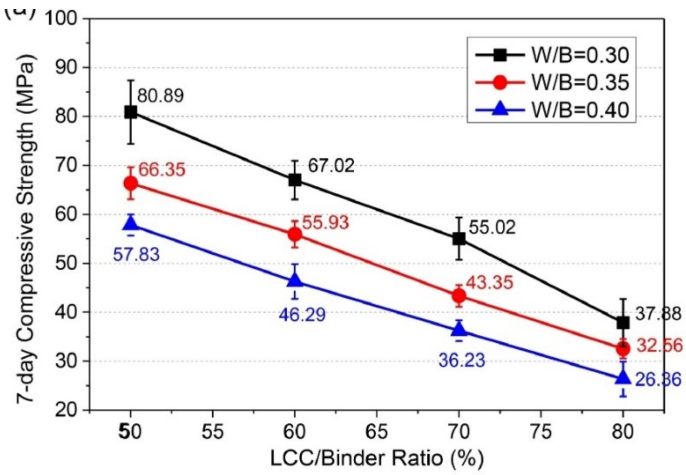

Fig. 16: Compressive strength of UHV-LCC mortar at 7 days Yu et al. (2021a)

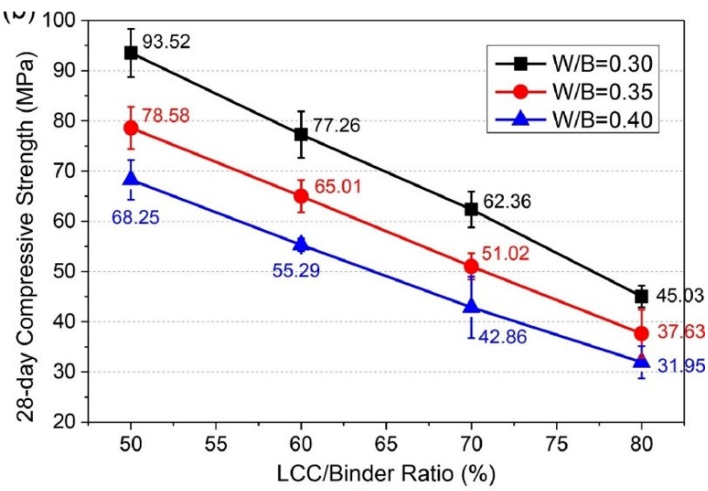

Fig. 17: Compressive strength of UHV-LCC mortar at 28 days Yu et al. (2021a)

In the study conducted by Dhandapani et al. (2018), the compressive strength development of LC3 was compared to that of OPC and fly ash-based concrete. Three types of concrete mixes were investigated: two aimed at obtaining equal strength classes (M30 and M50 concrete grades) with each binder, and a third had the same binder content and water binder ratio. The compressive strength of various concrete mixes was shown in Figure 18. The results showed that after 28 days, the compressive strength of M30 and M50 concrete mixes was similar to that of OPC and LC3 concrete. However, FA30 combinations had lower early strength than reference concrete (100 percent OPC). Interestingly, FA30 and LC3 mixes exhibited a greater improvement in strength from 28 to 365 days compared to OPC concrete. Furthermore, the FA30 and LC3 concrete mixes in M30 concrete exhibited slightly higher compressive strength than the FA30 and LC3 mixes in M50 concretes. This was attributed to the extended pozzolanic reaction. The study found that concrete with an LC3 binder was stronger at all ages than ordinary mixes (i.e., mixes with the same binder content and w/b). The higher hydration attributes of the LC3 binder system had an impact on the mechanical properties of concrete, as seen in the diagram. Overall, the findings suggest that when the same proportions of OPC and FA30 are used, the LC3 binder can provide a higher compressive strength evolution in concrete than OPC and FA30. These results could have important implications for the use of LC3 in structural concrete applications.

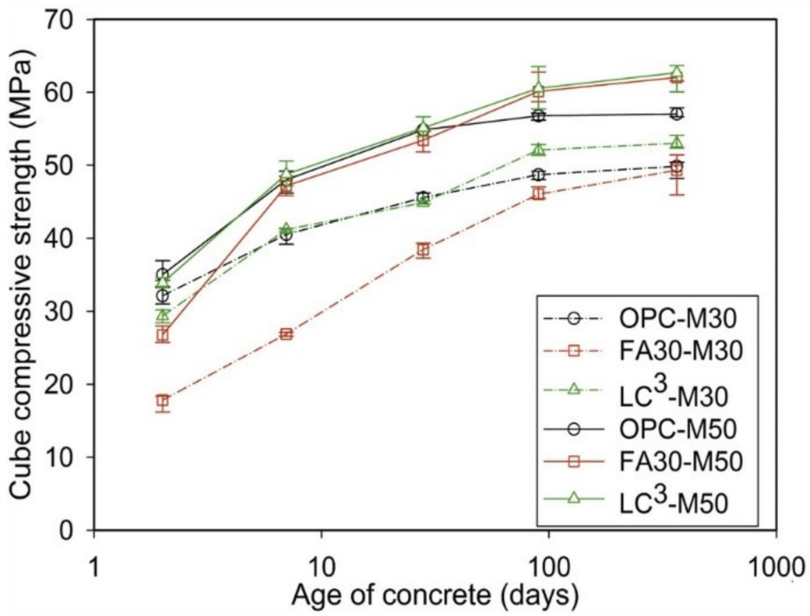

Fig. 18: Compressive strength development of LC^3 concrete Dhandapani et al. (2018)

Although there is available information about the compressive strengths of LC3 concrete in literature, there is a lack of data on other mechanical properties. To fill this gap, Dhandapani et al. (2018) conducted an investigation on the static modulus of various LC3 concrete mixes. The results of this study are presented in Figure 19, which shows that the elastic modulus of LC3 concrete is comparable to that of FA30 and reference OPC concrete. These findings suggest that in structural applications, LC3 concrete can provide mechanical performance that is similar to OPC concrete. Additionally, Figure 20 displays the relationship between elastic modulus and compressive strength, with an R2 value of 0.89 indicating a linear trend regardless of the concrete's binder content. The predicted moduli from Indian Standards: IS 456: 2000 and Federation Internationale du Beton, 2010 are also included for comparison.

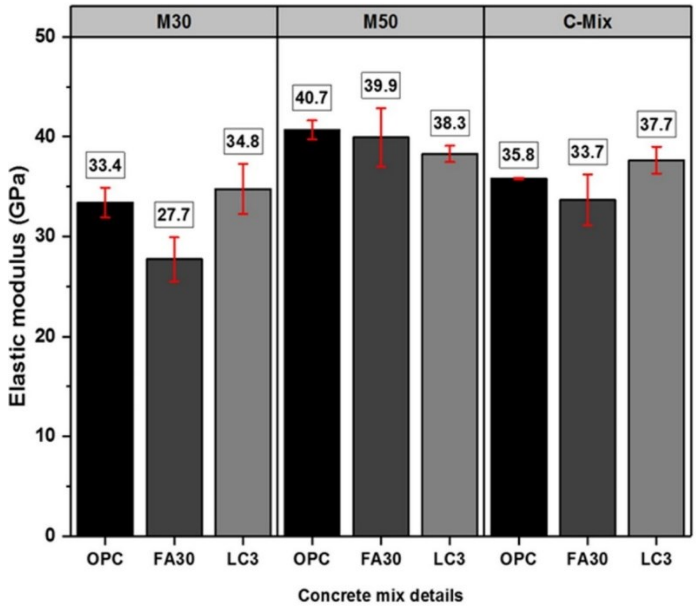

Fig. 19: Elastic moduli of concrete made with us of OPC, FA30 and LC3 (Dhandapani et al. 2018)

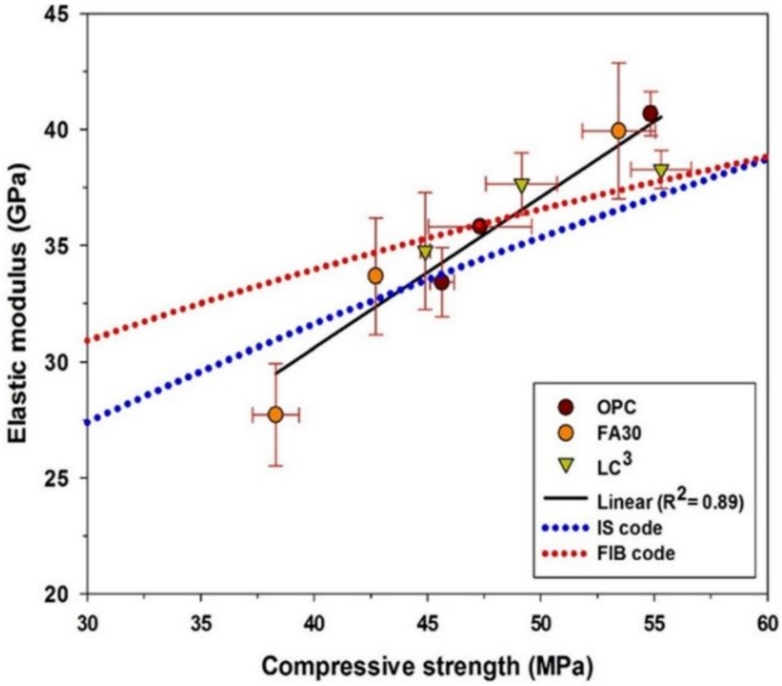

Fig. 20: Correlation between elastic modulus and compressive strength (Dhandapani et al. 2018)

The use of LC3 as a replacement for ordinary Portland cement (OPC) has been shown to improve the strain capacity and reduce crack width in Engineering cementitious composites (ECC) (Wang et al. 2021a). However, there is still a lack of research on the tensile and flexural behaviour of unreinforced LC3 concrete, which requires further investigation. One study found that LC3-ECC with a clinker proportion as low as 20% had a tensile strength of 5MPa (Yu et al. 2020). Additionally, the fineness of the limestone used in LC3 can affect the crack width (Zhang et al. 2020).

Compared to OPC concrete, LC3 concrete has been found to have a higher flexural strength due to the presence of higher quantities of crystalline aluminates and C-A-S-H (Qinfei et al. 2019; Wang et al. 2021a). LC3 concrete has also been shown to have a similar autogenous shrinkage to OPC and fly ash blended cement concrete (Dhandapani et al. 2018). Furthermore, LC3 concrete has been demonstrated to have reduced creep when compared to conventional OPC concrete (Ston et al. 2018). This reduction in creep may be attributed to the intermixing of clay particles with the C-S-H gel, which may also affect the viscosity behaviour of C-S-H. It has been reported that LC3 with higher calcined kaolinite content will have less creep, making it particularly advantageous in prestressed applications. Additionally, the use of LC3 can enhance the bond between polyethylene fibres and the cement matrix, further demonstrating the potential benefits of LC3 in improving the mechanical properties of concrete (Wang et al. 2021a).

4.3 Durability Properties

Studies have shown that although LC3 cement contains a high amount of alumina, its chloride binding capacity is not very high compared to high alumina cement (Maraghechi et al. 2018). The conversion of monocarboaluminate and stratlingite to Friedel's salt is reported to result in greater chemical binding rather than physical binding of chlorides (Sui et al. 2019a; Sui et al. 2019b). The clay purity significantly affects the resistance of LC3 to chloride ion movement (Maraghechi et al. 2018). LC3 has a slightly lower pH (around 13.2) than OPC (around 13.8), which may result in the initiation of corrosion at lower chloride concentrations. However, LC3 concrete has a slower moisture migration rate and higher resistivity, which may result in a slower rate of corrosion even after initiation. Preliminary tests suggest an increase in the service life of LC3 concrete compared to OPC, but further research is required to establish this claim.

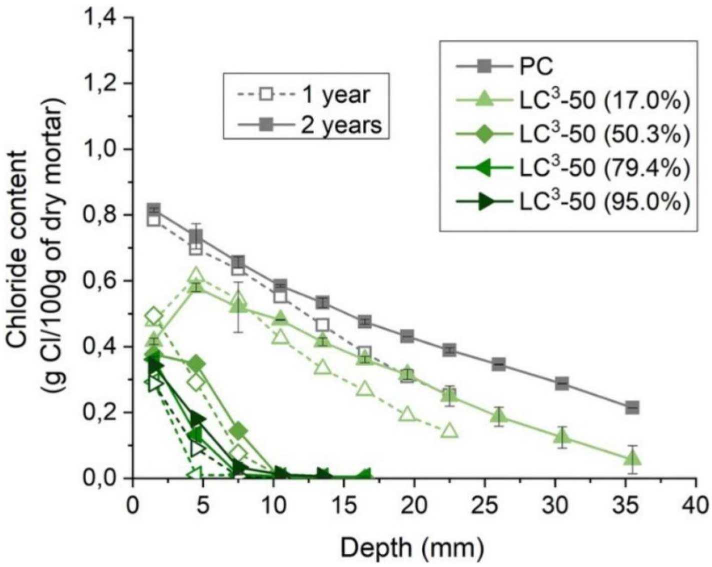

Fig. 21: Chloride profile of OPC and LC^3 mixes at different kaolinite content (Maraghechi et al. 2018)

The chloride profiles generated from bulk diffusion studies on seven different concrete mixes are depicted in Figures 22a and 22b (Dhandapani et al. 2018b). Figure 22a shows the profile of M35 concrete, while Figure 22b shows that of M50 concrete. It is evident from both figures that OPC concrete exhibits higher rates of chloride ingress. This can be attributed to the fact that PFA and LC3 concrete possess a less porous microstructure. Additionally, the binder phases in these mixes have a high ionic resistance (Dhandapani et al., 2018a; Dhandapani and Santhanam, 2017). The concentration of surface chloride is mainly determined by the near-surface porosity of the concrete. Despite having the same exposure, LC3 and PFA-1 concrete displayed lower porosity and smaller pore diameter (Dhandapani et al., 2018b), leading to a decreased concentration of surface chloride. Moreover, because the OPC systems have a lower slope, chloride transport is mostly diffusion-driven and dependent on concentration gradient. LC3-1P had a mix proportions comparable to PFA-1 in Fig. 22a, whereas LC3-1S had a lower binder concentration and a higher water-binder ratio. Both LC3-1P and LC3-1S had low chloride concentrations. Similarly, among M50 concrete (see Fig. 22b), OPC-2 experienced more chloride infiltration than PFA-2 and LC3-2, despite appearing to have identical chloride resistance.

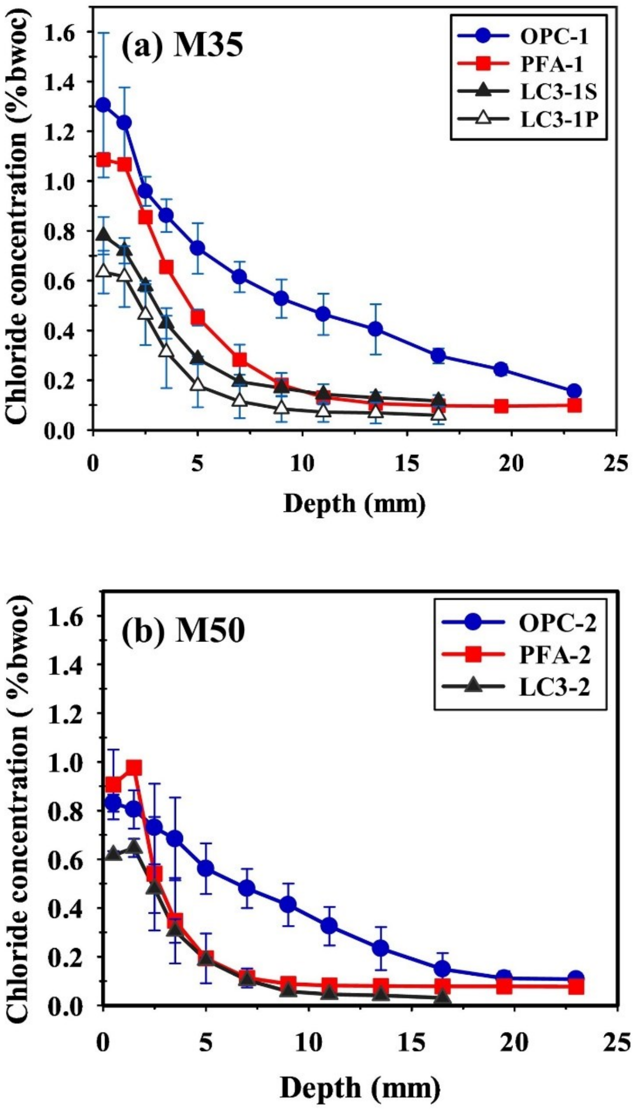

Fig. 22: Chloride profiles in concrete mixes after 56 days of exposure to chloride solution (Dhandapani et al. 2018b)

The study conducted by Dixit et al. (2021) investigated the chloride penetration of an LC3 mortar made from clays originating from five distinct sources in Singapore. The researchers analyzed the results of chloride penetration tests performed on 28-day and 91-day old samples and presented their findings in Figure 23. The graph was divided into three categories based on the extent of chloride penetration: low, moderate, and high. The researchers observed that both the sample with quartz filler QZ and the control sample showed 'strong' chloride ion conduction. This was because the QZ mix had less binder than the reference sample, leading to fewer hydration products being produced to fill in the pores. The blended samples, on the other hand, exhibited significant improvement and were classified as having low to moderate penetration. The researchers explained that the pore structure of blended cements became more refined due to the presence of longer C-A-S-H gel chains and more hydration products such as carboaluminates. As a result, the pore connectivity decreased, and the pore network became more tortuous, leading to an increased barrier to chloride penetration. Overall, the study demonstrated that the use of blended cements can be an effective strategy for reducing chloride penetration in concrete.

The "low" penetration classification was given to both specimens since their RCPT values were equal. A remarkable finding was observed in the blended samples, with an approximate 20% drop in RCPT coulombs from 28 to 91 days, despite the compressive strength remaining constant. As the critical pore radius decreases, preventing additional hydration product precipitation, the microstructure and capillary porosity densify. This results in a more complex pore network, as reported in a recent study on comparable blended systems (Suma and Santhanam, 2015).

The resistivity measurements were conducted on 28-day and 91-day aged samples in a study by Dixit et al. (2021). The results are presented in Figure 24. The resistivity measurements produced similar outcomes to the RCPT tests. The blended mixes showed a substantial increase in resistivity compared to the reference mix, with clays MA and LH displaying up to a 200% increase. Despite the variation in kaolinite content, the clays MA and LH demonstrated similar resistivity readings. The increase in resistivity observed in the blended samples between 28 and 91 days is significant and correlates with the RCPT data. The study's findings can be utilized to draw two main conclusions when comparing the reference mix to blended mixes. Firstly, the additional hydration products created a tortuous network of pores without improving the mortar's strength. Secondly, the hydration products formed between 28 and 91 days did not affect the compressive strength of the mortar but had a significant impact on pore interconnectivity convolution because of their lower stiffness. These findings are critical in understanding the relationship between the microstructure and the performance of blended cements, which can assist in the development of new and improved construction materials.

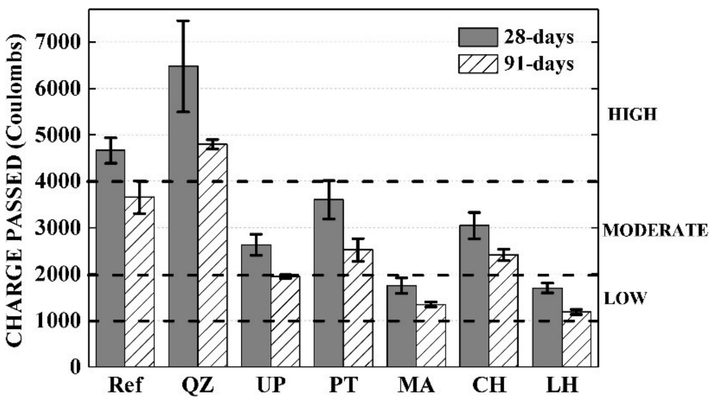

Fig. 23: RCPT results of 28 days and 91 days sample (Dixit et al. 2021)

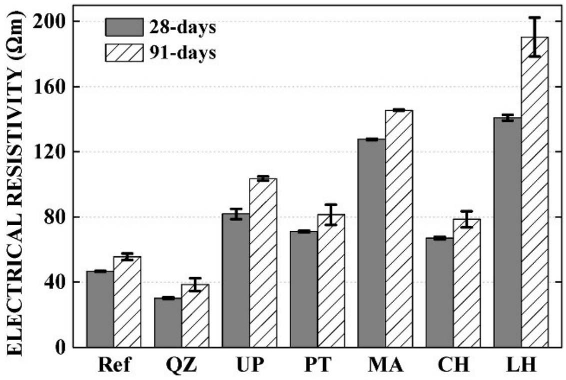

Fig. 24: Electrical resistivity results of 28 days and 91 days sample (Dixit et al. 2021)

The pore size distribution of different types of pastes is compared in Figure 25 (Dhandapani and Santhanam, 2017) using the mercury intrusion porosimetry (MIP) technique. The results show that the pore structure of LC3 paste is finer than that of OPC or fly ash-based pastes. This suggests that the pore refinement in LC3 paste is due to a more homogeneous dispersion of hydration products, which may have precipitated on the calcined clay and limestone's extremely high surface area. Additionally, the finer porosity observed in LC3 paste can be attributed to a higher volume fraction of low-density crystalline phases such as ettringite and carboaluminates. These phases are known to contribute to the formation of a more refined pore structure, thereby reducing the permeability of the paste. Overall, the pore refinement observed in LC3 paste compared to OPC or fly ash-based pastes is likely to improve its durability and resistance to ingress of harmful substances such as chloride ions.

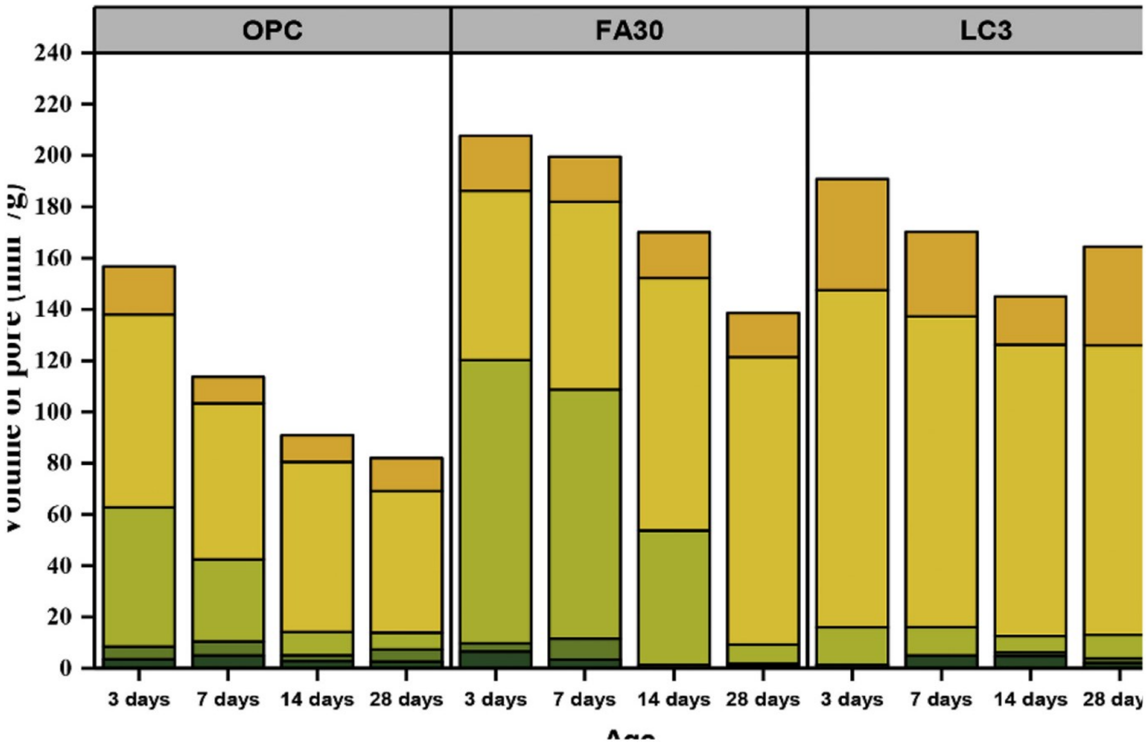

Fig. 25: Pore size distribution OPC paste, Fly-ash blended paste and LC3 paste (Dhandapani and Santhanam, 2017)

The study conducted by Nguyen et al. (2020) evaluated the resistance of LC3 mortar to alkali silica reaction (ASR) through tests on the expansions of mortar bars submerged in alkaline solution. The results, shown in Figure 26, demonstrated that the average expansion of OPC mortar bars increased over time, reaching 0.22% and 0.40% after 10 and 21 days, respectively. These findings were consistent with those reported in a previous study by Mahanama et al. (2019) that used the same reactive aggregate. Interestingly, as the amount of calcined clay and limestone in the mix increased, the expansions of mortar bars decreased significantly. Specifically, the expansion of LC3 mortar bars containing a 20% mix of calcined clay and limestone was reduced by 33% when compared to the reference mortar bars. Similarly, the expansion of LC3 mortar bars containing a 30% mix of calcined clay and limestone was reduced by 56%. These results suggest that the incorporation of calcined clay and limestone in LC3 mortar can effectively reduce the risk of ASR, which is a significant durability concern in concrete structures.

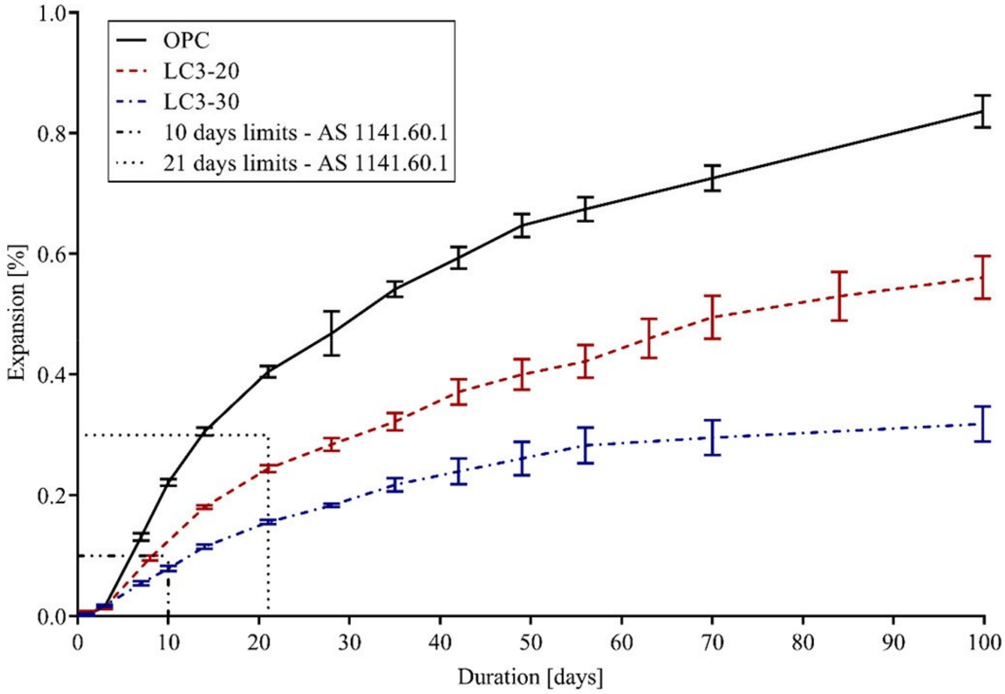

Fig. 26: ASR expansion of mortar bars (Nguyen et al. 2020)

Studies have found that LC3 cement shows improved resistance to expansion and cracking when exposed to sodium sulphate, as compared to other cements (Avet and Scrivener, 2018; Shi et al. 2019; Suma and Santhanam, 2015). The resistance to sulphates increases as the percentage of clinker replaced with limestone and calcined clay increases. While carboaluminates to ettringite conversion may be a less harmful process, further research is needed to understand the mechanism behind the improved resistance. Although accelerated tests with magnesium sulphate have shown to be harsher than practical settings, more research is required to determine the impact of magnesium sulphate on LC3. The behaviour of LC3 concrete in fire or at high temperatures has not been extensively studied. A study by Lin et al. (2021) has reported that LC3 concrete has comparable residual compressive strength ratios to OPC concrete when exposed to varied elevated temperatures ranging from 300°C to 900°C. However, as the amount of calcined clay and limestone increases, the residual compressive strength of LC3 decreases. The effect of repeated freezing and thawing on LC3 concrete has not been studied extensively. Due to its finer and less interconnected pores, LC3 is expected to have higher resistance to freeze-thaw cycles as compared to OPC.

LC3 concrete has demonstrated improved resistance to sulphate attack, making it suitable for environments with higher sulphate concentrations. The use of calcined clay as a key ingredient in LC3 contributes to this enhanced sulphate resistance. Some research indicates that LC3 concrete exhibits improved freeze-thaw resistance due to its composition, making it suitable for cold climates or areas with frequent freeze-thaw cycles. LC3 concrete has been found to possess good abrasion resistance, making it suitable for applications in high-traffic areas, industrial floors, and pavements. Research has shown that LC3 concrete can have lower permeability, reducing the ingress of water and aggressive substances. This property helps protect embedded reinforcement and increases the concrete's durability. While specific findings may vary, LC3 concrete generally exhibits creep behaviour similar to or better than traditional concrete, which is important for assessing its long-term durability under sustained loads. Research on LC3 concrete's resistance to biogenic corrosion in settings like wastewater treatment facilities is ongoing. Early findings suggest that LC3 may offer advantages in such environments.

5. Compatibility of Chemical Admixtures with LC3

LC3 is a promising low-carbon alternative to traditional OPC-based concrete due to its reduced CO_2 emissions and lower energy consumption during production. However, as with any new material, there are still many challenges that need to be addressed before it can be widely adopted in the construction industry. One of these challenges is the compatibility of chemical admixtures with LC3.

Chemical admixtures are commonly used in concrete to improve its performance and workability. They can reduce the amount of water needed to achieve a certain level of workability, increase strength and durability, and control setting time. However, the use of chemical admixtures in LC3 concrete is still not well understood, and there is a lack of research in this area. One of the main reasons for this is that clay particles in LC3 have a distinct form and surface charge compared to clinker, which can impact the efficacy of chemical admixtures. In most admixtures, the particle surface is the most important determinant of adsorption and function, and the mechanisms on which water-reducing and air entraining admixtures work are based on electrostatic forces. The presence of clay particles is likely to have an impact on these mechanisms.

Some research has been conducted on the compatibility of chemical admixtures with LC3. For example, Nair et al. (2020) found that LC3 is more compatible with polycarboxylate ether-containing admixtures than with sulphonated naphthalene formaldehyde-containing admixtures. However, the saturation dosage is higher than OPC, and the use of polycarboxylate ether-based superplasticisers can reduce slump retention (Lorentz et al. 2020; Huenger and Sander 2020). The proportion of kaolinite in the clay also has a big impact on admixture performance (Lorentz et al. 2020). Given the massive internal and external surface areas of calcined kaolinite, it is not surprising that the proportion of kaolinite affects the performance of admixtures in LC3 concrete. Therefore, it is important to optimize the kaolinite content in the clays to improve the performance of LC3.

Despite these challenges, LC3 has some unique properties that make it attractive for certain applications. For example, clay particles interact with high-range water reducing admixtures in LC3 concrete, resulting in structural build-up and yield stress, which makes it a good option for 3D printable concrete (Nair et al. 2020; Vance et al. 2013). Additionally, it has been demonstrated that properly planned concrete mixes can result in pumpable and sprayable cement composites, even with the different rheology of LC3 compared to OPC (Zhu et al. 2021). Furthermore, the addition of silica fume to the particle packing of LC3 has been shown to improve its structural recovery, dynamic and static yield stress, and yield stress for 3D-printable concrete (Long et al. 2021).

6. Environmental Benefits of LC3

LC3 is a promising alternative to traditional cement production, offering significant environmental benefits. LC3 is a blend of clinker, calcined clay, limestone, and gypsum, which reduces carbon emissions in the cement production process by up to 40%. The increased use of LC3 in the construction industry could play a vital role in reducing greenhouse gas emissions and mitigating the impacts of climate change.

One of the primary environmental benefits of LC3 is its lower carbon footprint. According to Malacarne et al. (2021) LC3 production reduces carbon emissions by up to 40% compared to traditional cement production. This is due to the use of calcined clay and limestone as a substitute for traditional clinker in the production process. Calcined clay and limestone are less carbon-intensive than traditional clinker, which is produced by heating limestone and clay to high temperatures in a kiln. The lower carbon footprint of LC3 production helps to reduce the amount of carbon dioxide released into the atmosphere, which is a significant contributor to climate change.

Another significant environmental benefit of LC3 is its reduced energy consumption. The production of traditional cement is an energy-intensive process that requires large amounts of fossil fuels. In contrast, the production of LC3 requires less energy due to the use of calcined clay and limestone as a substitute for traditional clinker. This not only reduces carbon emissions but also reduces the demand for fossil fuels and helps to conserve natural resources.

In addition to its lower carbon footprint and reduced energy consumption, LC3 also offers other environmental benefits. For example, the use of LC3 can help to reduce waste by using industrial by-products as raw materials. The production of calcined clay, for example, uses waste materials from the production of alumina, which would otherwise be discarded. This not only reduces waste but also helps to conserve natural resources by using industrial by-products that would otherwise be disposed of in landfills.

Furthermore, LC3 can help to reduce the environmental impact of concrete production by reducing the amount of water needed in the production process. The use of calcined clay and limestone in LC3 production increases the workability of the concrete, allowing for a reduction in the amount of water required. This reduces the environmental impact of concrete production by reducing the amount of water needed and reducing the amount of wastewater produced.
Lastly, LC3 has the potential to promote sustainable development by providing economic benefits to local communities. The use of local materials, such as clay and limestone, can help to create jobs and stimulate local economies. This, in turn, can help to reduce poverty and promote sustainable development.

In summary, the environmental benefits of LC3 are significant and promising. Its lower carbon footprint, reduced energy consumption, reduced waste, reduced water consumption, and potential for sustainable development make it an attractive alternative to traditional cement production. By increasing the use of LC3 in the construction industry, we can help to reduce greenhouse gas emissions, conserve natural resources, and mitigate the impacts of climate change. However, further research and development are needed to increase the adoption of LC3 and overcome the challenges associated with its production and use.

7. Examples of LC3 Concrete Projects

LC3 concrete is a promising material that has been used in various construction projects around the world, demonstrating its potential as a sustainable alternative to traditional Portland cement concrete. In India, for example, LC3 has been used in several projects, including the construction of a low-cost housing project, the offices of the Swiss Agency for Development and Cooperation, roads, pavements and a check dam.

One notable project in India is the model house in Jhansi, which is made almost entirely of LC3 concrete. The house used 26.6 tons of industrial waste (192 kg/sqm) and saved 15.5 tons of CO_2 (114 kg/sqm), which is equivalent to the emissions of 10 passengers traveling by plane from Switzerland to South Africa. The model house in Jhansi serves as an excellent example of how LC3 can be used to build sustainable and affordable housing for low-income families. In addition to the model house in Jhansi, LC3 has also been used in the construction of the offices of the Swiss Agency for Development and Cooperation in Delhi. The offices were built using LC3-prefab materials, which allowed for faster and more efficient construction. LC3 has also been used in the construction of roads, pavements, and a check dam in India, demonstrating its versatility as a construction material.

LC3 concrete has also been used in various projects in Latin America, particularly in Cuba. These projects include a LC3-house, testing sites in the sea, art sculptures, and pavements. The LC3-house in Santa Clara, Cuba, is an excellent example of how LC3 can be used to build sustainable housing. The house was built using a concrete mix that contained 50% LC3, resulting in a 30% reduction in CO_2 emissions compared to traditional concrete. Overall, the use of LC3 concrete in construction projects around the world has demonstrated its potential as a sustainable and cost-effective alternative to traditional Portland cement concrete. As more research is conducted and more projects are initiated, LC3 is expected to become more widely used in the construction industry.

These examples demonstrate the potential of LC3 concrete as a sustainable alternative to traditional Portland cement-based concrete. These projects have shown that LC3 concrete can meet the same performance and durability requirements as traditional concrete while significantly reducing carbon dioxide emissions and lowering costs. As such, LC3 concrete is becoming an increasingly popular choice for construction projects that prioritize sustainability and environmental impact reduction.

8. Economic Feasibility and Social Acceptance

8.1 Economic Feasibility of LC3 in Concrete Production

LC3 has shown potential as a sustainable alternative to traditional Portland cement concrete due to its lower carbon footprint. However, the economic feasibility of LC3 in concrete production remains a critical factor in determining its widespread adoption. One significant advantage of LC3 is its lower production cost compared to Portland cement concrete. LC3 utilises limestone and clay, which are widely available and cheaper than the raw materials used in Portland cement production. Moreover, the calcination process required to produce the calcined clay used in LC3 requires lower temperatures than the production of Portland cement, reducing energy costs.

A study (Hanein et al. 2022) conducted by the Swiss Federal Institute of Technology in Lausanne (EPFL) estimated that the production cost of LC3 is around 10-20% lower than that of Portland cement. The study also found that the cost of LC3 could be further reduced by optimizing the calcination process and using industrial waste materials as alternative sources of clay. Another factor contributing to the economic feasibility of LC3 is its potential for carbon credit trading. Carbon credits are a financial instrument that allows companies to offset their greenhouse gas emissions by funding projects that reduce emissions elsewhere. The use of LC3 in concrete production could enable companies to earn carbon credits due to its lower carbon footprint compared to Portland cement concrete. In addition to production cost savings and carbon credit trading, LC3's potential for long-term cost savings due to its durability is another economic advantage. LC3 concrete has shown better resistance to chemical and physical degradation, reducing maintenance costs and increasing the lifespan of structures.

Despite these advantages, there are still some challenges to the economic feasibility of LC3 in concrete production. One issue is the lack of established supply chains and infrastructure for the production and distribution of LC3 materials. This may result in higher transportation costs and supply chain disruptions, which could increase the cost of LC3. Moreover, the adoption of LC3 may require new investments in technology and training for construction professionals. This may result in higher upfront costs and may deter some stakeholders from adopting LC3. Furthermore, the cost of LC3 may vary depending on the location and availability of raw materials. For example, countries with limited access to limestone and clay may find LC3 less economically feasible due to higher transportation costs and a lack of local supply chains.

In summary, the economic feasibility of LC3 in concrete production depends on several factors, including the cost of raw materials, production processes, infrastructure, and supply chain efficiency. However, LC3 has shown potential for cost savings due to lower production costs, carbon credit trading, and long-term durability. As the demand for sustainable building materials continues to grow, further research and investment in LC3 could lead to increased adoption and reduced costs.

8.2 Social Acceptance of LC3 as Building Materials

Social acceptance of building materials is an important factor in the construction industry, as it affects the willingness of communities to accept new construction materials and technologies. LC3 is a relatively new building material that has been developed to address the environmental and economic challenges associated with traditional Portland cement. The acceptance of LC3 by society can play a significant role in its adoption as a mainstream construction material.

One of the main advantages of LC3 is its sustainability. LC3 is made by blending limestone, calcined clay, and other additives, which results in a lower carbon footprint compared to traditional Portland cement. The production of LC3 requires lower temperatures, resulting in lower energy consumption and less greenhouse gas emissions. The use of LC3 in construction can also reduce the amount of waste produced from traditional cement production, as well as conserve natural resources. Another advantage of LC3 is its cost-effectiveness. The raw materials used in the production of LC3 are widely available, making it a viable option for regions with limited resources. LC3 can also be produced using existing cement production facilities with minor modifications, reducing the need for new infrastructure and increasing the economic feasibility of its adoption.

However, the social acceptance of LC3 can be a barrier to its widespread adoption. Some potential concerns include the perceived quality of LC3, the familiarity of contractors and builders with the material, and the willingness of customers to accept it. To address these concerns, it is important to increase awareness and education about the benefits and properties of LC3. One strategy to increase social acceptance is to showcase successful LC3 projects in various regions. For example, the affordable housing project in Colombia, which used LC3 to build houses for low-income families, can serve as a model for other similar projects in the region. The use of LC3 in the construction of bridges, highways, and other public infrastructure can also demonstrate its durability and strength, increasing public trust in the material. Another approach is to involve local communities in the adoption of LC3. By engaging with stakeholders and providing them with information about the properties and benefits of LC3, it is possible to build trust and encourage local adoption. Community-based construction projects, such as schools or community centres, can provide opportunities for local residents to learn about LC3 and become familiar with its properties. Finally, the availability of LC3 in the market and the cost of the material can also affect social acceptance. The cost of LC3 is generally lower than traditional Portland cement, but its availability can still be limited in some regions. Increased production and distribution of LC3 can address this issue, making it more accessible to builders and contractors.

It is true that cement has a long history of use in construction, and there is a substantial body of data on its long-term performance in various environments. LC3, being a relatively new material, does require more extensive testing and data collection to fully understand its performance and durability in different conditions. This is a reasonable concern, as long-term performance data are crucial for gaining trust in any new construction material. Recommending a progressive approach to LC3 adoption, starting with non-critical structures like storage buildings and road pavements, is a prudent strategy. This allows for the assessment of its performance in less critical applications before moving on to more important and safety-critical structures like residential buildings and bridges. It is worth noting that the widespread acceptance of Portland cement in construction didn't happen overnight. It took time, research, and practical experience to gain confidence in its performance. Similarly, LC3 may follow a similar trajectory, where acceptance grows as more data on its long-term performance becomes available.

8.3 Potential Impact of LC3 on the Construction Industry and Local Communities

LC3 has the potential to make a significant impact on the construction industry and local communities. Here are some potential impacts of LC3:

1. Environmental Impact: The use of LC3 in concrete production has the potential to reduce CO_2 emissions by up to 40% compared to traditional Portland cement. This can help mitigate the impact of construction on the environment, especially in regions where construction is a significant contributor to greenhouse gas emissions. Additionally, the use of locally available materials such as clay and limestone in LC3 can reduce transportation-related emissions and support local economies.

2. Economic Impact: LC3 can be produced using locally available materials, which can significantly reduce production costs compared to traditional Portland cement. This can make LC3 an attractive alternative for construction projects with limited budgets, such as low-income housing projects. Additionally, the use of LC3 can create job opportunities in local communities for the extraction and processing of raw materials.

3. Social Impact: The use of LC3 in construction projects can have a positive impact on local communities by providing affordable housing solutions and infrastructure development. For example, the use of LC3 in low-income housing projects can provide durable and affordable housing for people who may otherwise be living in substandard conditions. Additionally, LC3 can be used to construct infrastructure such as bridges, roads, and dams, which can improve access to essential services and promote economic growth.

4. Technical Impact: LC3 has similar technical properties to traditional Portland cement, making it a viable alternative in most construction applications. However, it may require some adjustments to the manufacturing process and mix design. The use of LC3 also requires a higher water-cement ratio than Portland cement, which can affect the workability and strength of the concrete. As such, further research and development are needed to optimize the use of LC3 in different construction applications.

5. Regulatory Impact: The use of LC3 in construction projects may require regulatory approvals and certifications. For example, in some countries, LC3 may not be covered

by existing building codes and standards. As such, it may be necessary to develop new standards and regulations that take into account the unique properties of LC3.

6. Market Impact: The increasing demand for sustainable construction materials can create opportunities for LC3 in the global construction market. The use of LC3 can provide a competitive advantage for construction companies that prioritize sustainable building practices. Additionally, the use of LC3 can create opportunities for businesses involved in the production and supply of raw materials, as well as the manufacture of LC3-based products.

In summary, the potential impact of LC3 on the construction industry and local communities is significant. The use of LC3 can help mitigate the environmental impact of construction, reduce production costs, provide affordable housing solutions, and promote economic growth. However, the use of LC3 requires further research and development to optimize its use in different construction applications. Additionally, regulatory approvals and certifications may be required, and new building codes and standards may need to be developed to ensure the safe and effective use of LC3. Nonetheless, the increasing demand for sustainable construction materials creates opportunities for LC3 in the global construction market, making it a promising alternative to traditional Portland cement.

8.4 Comparison with Other Alternative Cements

Environmental Impacts:

- **LC3**: LC3 significantly reduces carbon emissions compared to traditional Portland cement due to the incorporation of calcined clay and limestone. It involves a lower clinker-to-cement ratio, which reduces the energy requirements for production. LC3's environmental advantages lie in its potential to mitigate climate change by lowering the carbon footprint of construction materials.

- **Other Alternative Cements**: Various alternative cements, such as calcium sulfoaluminate cements, geopolymers, or magnesium-based cements, have their own sustainability benefits. Geopolymers, for example, can be synthesized using industrial by-products, contributing to waste reduction. A comprehensive life cycle analysis is necessary to understand how each alternative stacks up in terms of reducing greenhouse gas emissions, energy use, and resource consumption.

Mechanical Properties:

- **LC3**: LC3 aims to maintain robust mechanical properties, including compressive strength. It should be compared with other alternative cements to assess its competitiveness in terms of strength, stiffness, and durability. Strength is a critical factor for ensuring structural integrity and load-bearing capacity.

- **Other Alternative Cements**: Alternative cements can have varying mechanical properties based on their composition and curing conditions. Some, like calcium sulfoaluminate cements, may offer rapid strength development, making them suitable for certain applications. Magnesium-based cements may excel in terms of fire resistance. Evaluating these properties is vital for determining the most suitable material for a specific project.

Cost Considerations:

- **LC3**: LC3's cost-effectiveness depends on local factors, including the availability of raw materials and production facilities. A thorough analysis should assess how LC3's costs compare to traditional Portland cement and other alternative cements. Cost factors include material acquisition, processing, transportation, and construction costs.

- **Other Alternative Cements**: The economics of alternative cements can vary widely by region. Factors like material availability, energy costs, and market demand influence their cost competitiveness. Understanding the cost implications of using alternative cements informs budget decisions for construction projects.

Long-Term Durability:

- **LC3**: LC3's long-term durability in different exposure conditions is a vital consideration. It should be evaluated for resistance to sulphate attack, freeze-thaw cycles, and chemical exposure, and compared to other alternative cements. Durability directly impacts the longevity and maintenance requirements of structures.

- **Other Alternative Cements**: Durability performance differs among alternative cements based on their composition. Calcium sulfoaluminate cements, for instance, exhibit rapid strength development but may require additional measures to mitigate sulphate attack. Robust durability testing helps identify strengths and weaknesses in various environmental scenarios.

Why Prefer LC3:

Society might prefer LC3 over other alternative cements for several reasons:

- **Significant Carbon Reduction**: LC3's ability to substantially reduce carbon emissions aligns with global efforts to combat climate change. This makes it an appealing choice for environmentally conscious construction projects.
- **Availability of Raw Materials**: LC3's raw materials, clay and limestone, are abundant and accessible in many regions, contributing to its feasibility for widespread adoption.
- **Balanced Performance**: LC3 maintains competitive mechanical properties while reducing its environmental impact, striking a balance between sustainability and practicality. This makes it a practical choice for builders and architects aiming to construct sustainable structures.

Performance in Alternate Wet-Dry Conditions:

- LC3's performance in alternate wet-dry conditions should be thoroughly investigated through experiments and tests. Such conditions, where moisture levels fluctuate cyclically, can potentially lead to issues like surface deterioration, cracking, and increased permeability.
- The pozzolanic properties of LC3, including the presence of clay and limestone, may contribute to its ability to resist damage from alternating moisture exposure. Researchers should assess how LC3 maintains its integrity under such conditions.
- Comparative studies with other alternative cements can provide insights into whether LC3 is more or less susceptible to moisture-induced deterioration compared to its counterparts.

In conclusion, the comparison between LC3 and other alternative cements is a multifaceted process that considers environmental impact, mechanical properties, cost-effectiveness, and long-term durability. Society's preference for LC3 is influenced by its potential to significantly reduce carbon emissions, the availability of raw materials, and its balanced performance. Evaluating LC3's behaviour in alternate wet-dry conditions is essential for understanding its suitability for various environmental contexts. Comprehensive research and empirical data are essential for informed decision-making in the construction industry's transition to more sustainable materials.

9. Future Directions and Research Needs

9.1 Recommendations for Future Research

Despite the promising results of LC3 research and its potential as a sustainable alternative to traditional Portland cement concrete, there is still a need for further research in various areas. Here are some recommendations for future research:

1. Long-term durability: While LC3 has demonstrated good short-term durability, more research is needed to assess its long-term durability and resistance to environmental factors such as freeze-thaw cycles, alkali-silica reactions, and chemical attack. Long-term studies of LC3 concrete in real-world conditions can help to improve understanding of its long-term durability.

2. Performance under different conditions: LC3 concrete has been tested and used in various regions around the world, but more research is needed to assess its performance under different environmental and climatic conditions. For example, LC3 concrete may behave differently in regions with high humidity or extreme temperatures. Testing under different conditions can help to ensure that LC3 is a viable option for construction in diverse regions.

3. Optimisation of production process: The production process of LC3 concrete requires the use of calcined clay, which is energy-intensive. More research is needed to optimize the production process and reduce the energy required for calcination. This can help to reduce the carbon footprint of the LC3 production process and make it even more sustainable.

4. Life-cycle assessment: While LC3 concrete has demonstrated significant reductions in CO_2 emissions during its production, there is a need for more comprehensive life-cycle assessments to understand the overall environmental impact of LC3 compared to traditional concrete. This includes assessing the environmental impact of the production, transportation, and disposal of LC3 concrete.

5. Social acceptance and user feedback: While LC3 has demonstrated potential as a sustainable alternative to traditional concrete, it is important to understand the social acceptance of LC3 by different stakeholders such as contractors, engineers, architects, and end-users. Research on user feedback and acceptance can help to identify potential barriers to the adoption of LC3 and develop strategies to address them.

6. Economic feasibility: While LC3 has demonstrated potential to reduce production costs compared to traditional concrete, more research is needed to understand the economic feasibility of large-scale production and adoption of LC3. This includes assessing the cost-effectiveness of LC3 production, transportation, and implementation compared to traditional concrete.

7. Standardisation and certification: Standardization and certification of LC3 concrete can help to ensure its quality, safety, and consistency. More research is needed to develop

standards and certification processes for LC3 concrete to promote its widespread adoption in the construction industry.

In conclusion, LC3 concrete has demonstrated great potential as a sustainable alternative to traditional Portland cement concrete. However, more research is needed in various areas to optimize its production, assess its long-term durability, understand its environmental impact, and promote its social acceptance and economic feasibility. With continued research and development, LC3 can become a widely adopted building material that can help to reduce the environmental impact of the construction industry and contribute to sustainable development.

9.2 Potential for Further Innovation in the Production and Application of LC3

LC3 has already demonstrated its potential as a sustainable alternative to traditional Portland cement in terms of reducing CO_2 emissions and production costs. However, there is still room for further innovation in the production and application of LC3, which could lead to even greater benefits for the construction industry and the environment. One potential area for innovation is the optimization of the production process. Currently, the production of LC3 involves a two-stage process: calcination of clay and limestone at a lower temperature than traditional cement production, and blending of the calcined materials with clinker and gypsum to form the final cement product. Researchers have already identified some ways to optimize this process, such as using a higher proportion of clay in the initial mix to reduce the amount of limestone required, or using alternative fuels such as biomass to reduce the carbon footprint of the production process. However, there is still scope for further research to refine these methods and identify additional strategies for optimising LC3 production.

Another area for innovation is the development of new applications for LC3 in construction. While LC3 has already been used successfully in a range of projects, including low-cost housing in Colombia and office buildings in India, there may be other potential applications that have not yet been explored. For example, LC3 could be used to produce precast concrete elements such as beams and columns, which could reduce the need for on-site concrete mixing and improve the quality and consistency of the finished product. Alternatively, LC3 could be used in the production of masonry units such as blocks and bricks, which are commonly used in low-rise construction and could benefit from the reduced environmental impact of LC3.

Another area for potential innovation is the development of new materials that incorporate LC3. For example, researchers have already developed a type of lightweight concrete made from LC3 and expanded polystyrene beads, which could be used in applications such as insulation and soundproofing. Additionally, LC3 could be used as a binder in the production of alternative building materials such as rammed earth and compressed earth blocks, which are becoming increasingly popular in sustainable construction. Finally, there is also potential for innovation in the marketing and promotion of LC3 as a sustainable building material. While LC3 has already gained some traction in the construction industry, there may be opportunities to increase its uptake through targeted marketing campaigns and educational initiatives. For example, architects and engineers could be educated on the benefits of LC3 and how to design structures that incorporate it, while builders and contractors could be trained in the proper handling and use of LC3-based products.

9.3 Challenges and Opportunities for Scaling up LC3 Production

One of the main challenges for scaling up LC3 production is the availability and consistency of raw materials. The production of LC3 requires a specific type of clay, known as kaolinite, which is not readily available in all regions. The availability of limestone, another key component, may also be limited in some areas. Furthermore, the quality and consistency of these raw materials can vary, affecting the properties of the final product. Therefore, efforts should be made to identify new sources of raw materials and improve the quality control of existing sources. Another challenge is the adoption of LC3 by the construction industry and local communities. Although LC3 has shown promising results in laboratory and pilot projects, its successful adoption at a larger scale depends on its acceptance by end-users. This requires a comprehensive understanding of the technical, economic, and social factors that affect the use of LC3. Education and awareness-raising campaigns can also play a crucial role in promoting the benefits of LC3 and addressing any misconceptions or doubts about its performance.

Additionally, the production of LC3 involves a more complex process than traditional cement production, which may require additional equipment and expertise. This can lead to higher production costs, particularly in the initial stages of scaling up. Therefore, further research and development are needed to optimize the production process and reduce costs. Despite these challenges, the scaling up of LC3 production also presents significant opportunities. The lower carbon footprint of LC3 can contribute to mitigating climate change and reducing greenhouse gas emissions. This can also help countries meet their commitments under the Paris Agreement and other international agreements. Moreover, LC3 has the potential to create new economic opportunities and jobs in the raw material extraction, processing, and construction industries.

To scale up LC3 production successfully, it is essential to adopt a holistic approach that addresses the technical, economic, and social aspects of its production and use. This requires collaboration and coordination between different stakeholders, including researchers, industry players, policymakers, and local communities. Governments and international organizations can also play a vital role in providing incentives and support for LC3 production and adoption. In terms of future innovations in the production and application of LC3, there is still much room for further research and development. For example, the use of alternative raw materials, such as volcanic ash or waste materials, could expand the availability and reduce the cost of LC3 production. Additionally, further improvements in the production process, such as the use of renewable energy sources, can reduce the carbon footprint of LC3 even further. In terms of applications, LC3 can be used in a wide range of construction projects, from low-cost housing to high-rise buildings. However, there is still room for further research and development to optimize the use of LC3 in different types of structures and environments. For example, the performance of LC3 in extreme weather conditions or high-traffic areas needs to be further investigated.

10. Conclusions

10.1 Summary of the Key Findings and Implications for the Use of LC3

Limestone calcined clay cement (LC3) is a promising alternative to traditional cement, offering significant environmental benefits, lower costs, and improved durability. Over the past few years, extensive research has been conducted to investigate the potential of LC3 as a sustainable building material. The key findings from these studies have significant implications for the use of LC3 in the construction industry.

One of the most significant findings is that LC3 can significantly reduce CO_2 emissions compared to traditional cement. Studies have shown that LC3 can reduce CO_2 emissions by up to 40%, due to its lower clinker content and the use of calcined clay. This is an essential factor in addressing the environmental impact of the construction industry, which accounts for a significant proportion of global CO_2 emissions.

Another key finding is that LC3 has similar strength and durability characteristics to traditional cement, making it a viable alternative for most construction applications. The use of LC3 in construction has also been found to increase the durability and resilience of concrete structures, which can have significant economic benefits over the life of the building. LC3 has also been found to have a lower production cost compared to traditional cement, as it requires less energy during production and can be made using local raw materials. This makes it a more affordable option for construction projects, particularly in low-income countries and regions.

However, several challenges need to be addressed to scale up the production and use of LC3. One of the key challenges is the limited availability of suitable clays for calcination, which can affect the quality and consistency of the cement produced. This highlights the need for further research and development in identifying and sourcing suitable raw materials. Another challenge is the lack of awareness and understanding of LC3 among stakeholders in the construction industry, which can hinder its adoption and implementation. This highlights the need for education and awareness-raising campaigns to promote the benefits of LC3 and encourage its use in construction projects.

Overall, the findings from studies on LC3 have significant implications for the use of sustainable building materials in the construction industry. LC3 offers a viable and cost-effective alternative to traditional cement, with the potential to significantly reduce CO_2 emissions and improve the durability and resilience of concrete structures. However, further research and development are needed to address the challenges in scaling up its production and use and to promote its adoption and implementation among stakeholders in the construction industry.

10.2 Final Thoughts and Potential Impact of LC3 on the Construction Industry

In conclusion, limestone calcined clay cement (LC3) offers a promising alternative to traditional Portland cement, with significant environmental, economic, and social benefits. The use of LC3 can result in reduced CO_2 emissions, lower production costs, and improved durability and strength of the concrete produced.

The key findings suggest that LC3 has the potential to replace up to 50% of the cement content in concrete without compromising the strength and durability of the material. This, in turn, could lead to a significant reduction in CO_2 emissions from the construction industry, which is one of the largest contributors to greenhouse gas emissions globally. The implications of LC3 on the construction industry are immense. With the potential to reduce production costs and improve the quality of concrete, LC3 could lead to the development of more affordable and sustainable housing for low-income communities. The use of LC3 in infrastructure projects, such as roads and bridges, could also result in improved durability and longer service life of these structures, resulting in reduced maintenance costs over time.

Moreover, LC3 production can also provide a solution to the problem of industrial waste, as the clay and limestone used in the production process are by-products of other industries. This not only reduces the environmental impact of these industries but also creates new opportunities for the production of building materials. However, scaling up LC3 production and application poses several challenges. One major challenge is the lack of awareness and acceptance of LC3 among stakeholders in the construction industry. Addressing this challenge requires more extensive research and outreach efforts to educate industry professionals and the general public about the benefits of LC3.

Another challenge is the limited availability of the raw materials required for LC3 production. While clay and limestone are abundant in many parts of the world, their quality and characteristics can vary, making it challenging to produce consistent and high-quality LC3. Furthermore, the production process for LC3 is still relatively new and requires further optimization and standardization to ensure consistency and scalability. The development of new technologies and processes, such as pre-calcination of the clay, could also improve the efficiency and quality of LC3 production.

11. Outlook

The outlook for Limestone Calcined Clay Cement (LC3) is undoubtedly promising, but realizing its full potential in the construction industry will require concerted efforts and strategic actions. Here are some future directions and recommendations to foster the adoption of LC3:

1. **Research and Development**: Continued research and development efforts are vital to refine LC3 production processes, enhance material consistency, and explore alternative raw materials. Collaborations between academic institutions, industry players, and governmental bodies can drive innovation.

2. **Raw Material Sourcing**: Identify and secure reliable sources of high-quality clays and limestone suitable for LC3 production. Regional assessments of available resources can help ensure a consistent supply chain.

3. **Awareness and Education**: Launch comprehensive awareness campaigns targeting construction professionals, policymakers, and the general public. These campaigns should include real-world case studies, technical guidelines, and training programs to promote understanding and acceptance of LC3.

4. **Standards and Regulations**: Develop clear standards and regulations for LC3 production and application to boost its acceptance and integration into the construction industry. Collaboration between regulatory bodies and experts is essential in this regard.

5. **Industry Adoption**: Encourage construction companies to adopt LC3 through incentives, tax breaks, or green building certifications. Public and private partnerships can facilitate its integration into real-world projects.

6. **Collaboration**: Foster international collaboration to share knowledge, best practices, and experiences related to LC3 production and usage. This can accelerate its global adoption and reduce regional disparities.

7. **Innovation**: Continue to innovate in LC3 technology by exploring alternative raw materials and production techniques. Such innovations can further enhance its sustainability and cost-effectiveness.

8. **Lifecycle Assessment**: Conduct comprehensive lifecycle assessments comparing LC3 to traditional cement to provide a more accurate understanding of its environmental benefits throughout the construction process.

9. **Government Support**: Governments can play a pivotal role by incentivizing LC3 research and development, offering grants for pilot projects, and incorporating LC3 into public infrastructure initiatives.

10. **Market Development**: Encourage the development of LC3-based construction materials beyond cement, such as precast concrete elements and masonry blocks. This can create a broader market for LC3-based products.

In conclusion, LC3 holds immense promise as a sustainable and cost-effective alternative to traditional cement in the construction industry. Its potential to reduce carbon emissions, lower production costs, and improve the quality of concrete makes it a compelling choice for future construction projects. However, addressing challenges and driving its adoption will require a collaborative effort involving researchers, policymakers, industry stakeholders, and the public. LC3 has the potential to reshape the construction industry into a more sustainable and economically viable sector, but its realization depends on sustained commitment and cooperation across various sectors.

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