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A Comprehensive Review of the Formation, Properties, and Applications of Limestone Calcined Clay Cement (LC^3)

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Abstract

Limestone Calcined Clay Cement (LC^3) has emerged as a promising alternative to conventional Portland cement due to its reduced carbon footprint and improved performance characteristics. This comprehensive review explores the formation, properties, and applications of LC^3, aiming to provide a detailed understanding of its potential in sustainable construction practices. The review begins with an overview of the raw materials involved in LC^3 production, highlighting the synergistic effects of limestone and calcined clay in enhancing cementitious properties and reducing clinker content. Structural and chemical transformations during the calcination and hydration processes are discussed, emphasizing the role of supplementary cementitious materials in optimizing cement performance. The mechanical, durability, and environmental attributes of LC^3 are critically examined, showcasing its superior strength development, resistance to chloride ingress, and lower energy consumption compared to traditional cements. Applications of LC^3 in various construction sectors, including residential, commercial, and infrastructure projects, are elucidated, demonstrating its versatility and potential for global adoption. Furthermore, challenges such as standardization, scalability, and economic feasibility are addressed alongside future research directions aimed at advancing LC^3 technology. This review consolidates recent advancements and establishes LC^3 as a viable solution for sustainable cement production, offering insights into its transformative impact on the construction industry and environmental sustainability.

Keywords: Cement clinker reduction, Durability enhancement, Environmental impact, Limestone Calcined Clay Cement (LC^3), Sustainable cement

1. Introduction

The building and infrastructure industries have long been recognized as the primary predictors of economic expansion and prosperity in a nation [1]. Cement production can greatly cut carbon emissions and the use of scarce resources by substituting supplemental cementitious materials (SCMs) [2-5] for traditional materials [6]. This is especially true for poor nations. The introduction of ecological material is one of engineering's most exciting and sought-after research areas. Concrete is in significant as a building and construction material in civil engineering and related fields. For every ton of regular Portland cement (OPC), we may detect the generation of almost one ton of CO_2 [7-10]. Relatively 7% of global CO_2 release are imputed to cement sector, making it among the most significant source to greenhouse gas release [11-15]. The slag, fly ash, or limestone make up over 80% of the SCMs applied to lower the clinker aspect in cement. 2014 saw the production of 4.3 billion tons of cement. Approximately, 3.5 billion tonnes are coming from China, India, CIS, and Asia. Practically 0.4 billion tons, or 9% of the world's cement manufacture, were produced by industrialized nations (Japan, the USA, and Europe). When calcined clays are coupled with limestone (LC^3 technology), there is an enormous amount of opportunity to improve usage of supplemental cementitious materials as a partial substitution of clinker in cement as well as concrete [16].

A novel ternary blended cement called as Limestone Calcinated Clay Cement (LC^3) was created through recent joint research between Switzerland and Cuba. By utilizing calcinated clay as well as limestone, LC^3 have 50% clinker. Research indicates LC^3 provide comparable or superior contribution to OPC as well as PPC for numerous areas. Previous research has also described the chemistry and optimal content of LC^3. Since the first LC^3 pilot project was produced in India, it also be said that clays having extremely low kaolinitic composition produce cement with good performance [17-19], It has been discovered that the kaolinite clay that is present in India possesses pozzolanic qualities; when heated to 800C, it dihydroxylates and becomes reactive pozzolana [20]. When limestone is incorporated in blended cements, mono carboaluminates are found to be a moistening component that is much more sustainable than mono sulphoaluminate [21].

The development of environmentally sustainable solutions that improve concrete performance is essential for the continuous application of concrete as a building material. This is especially true since cement, which makes up the majority of the binding ingredient, accounts for approximately 5% of all anthropogenic CO_2 releases globally [22]. The consistent need for housing and infrastructure in India and other growing nations is expected to drive up cement consumption in the next decades. Thus, any enhancement concerning the viability of the concrete has a noteworthy effect When industrial co-products or residues-like fly ash [23-27] as well as slag, in another word supplementary cementitious materials (SCMs)-are used as cement substitutes, concrete performance improves, including prolonged strength as well as decreased infiltration of external chemical species. This has extended the functioning durability of reinforced concrete structures. Even so, changes in power generation sources as well as steel processing methods are likely to limit the common accessibility of fly ash as well as slag during the next few decades. According to recent research, the clinker replacement level can be raised to over 50% with mixing of limestone together with calcinated clay [28-31].

One workable method to minimize the cement industry's carbon footprint is to substitute supplementary cementitious material (SCM) for the clinker in Portland cement when mixing concrete. However, the supply of conventional SCMs like fly ash and slag is anticipated to decline because the demand for steel and coal is rising more slowly than that of cement. Limestone calcinated clay cement (LC^3) is a new kind of low-carbon cement that has been available recently. It is made of cement that has up to 60% less clinker by using both calcinated clay as well as limestone as SCM. Because clay as well as limestone were readily available everywhere in the world. LC^3 is inexpensive and has a low embodied CO_2 content (30% less than Portland cement). Additionally, after three days of hydration, the strength and durability of this new type of cement have proven to be exceptional, matching or surpassing those of regular Portland cement materials.

When compared to Portland cement materials, LC^3's finer microstructure has been linked to the majority of its improved characteristics. As a ternary binder system, LC^3's microstructural growth and pore structure can be altered by a variety of variables, including chemical and physical ones. Shearing action, dilution, and the filling effect of calcined clay particles are examples of potential physical impacts. In terms of the chemical impacts, the Portland cement reaction can be accelerated and extra nucleation sites for the synthesis of hydration products can be provided by the SCMs in LC^3. Furthermore, the hydration process is influenced by the cement phase assemblage because of the pozzolanic reaction of calcinated clay as well as the synergistic impacts of calcinated clay as well as limestone particles. The improved qualities could also be attributed to a decrease in porosity connection. Though crucial to the better macro-level performance of LC^3-based materials, the pore structure properties and evolution of LC^3 from early to late ages remain mostly unknown.

This study evaluates limestone-caleined clay-based concrete for its compatibility in structural implementation using the performance-based methodology. Examined are the several limestones along with calcined clay contents, usefulness, mechanical functionality, mass density, pulse velocity as well as drying compression of both fresh and hardened concrete. Additionally, a number of characteristics linked to durability, including pH, pore solution compositions, porosity, and surface resistivity, were carefully evaluated. Finally, the generated crystalline structure was found with X-ray diffraction. The reference GP cement concrete's performance is contrasted with that of the limestone-calcined clay-based concrete.

2. Theoretical Background

Nearly 5% to 7% of overall artificial CO_2 release was attributed to Portland cement production, of which 40% come from fuel combustion and 50% are the result of chemical reactions [32, 33]. One practical way to minimize the overall carbon footprint in construction sites is to employ supplementary cementitious materials (SCMs) like fly as well as Ground Granulated Blast Furnace Slag (GGBFS) to minimize the amount of Portland cement needed for concrete [34-38]. Because they are widely available, calcined clays have drawn a lot of interest recently as one of the most promising SCMs. Seventy-four percent of the earth's crust is made up of alumina-silicate minerals and sheets of silica. This structure is known as clay structure. Clay can be found practically anywhere [39], whereas classic SCMs (fly ash or GGBFS) are only found in certain parts of the planet. By using calcined clay, pozzolanic interactions between AS2 ($Al_2O_3.2SiO_2$) and CH can eventually increase the pore structure of concrete [40-44]. Nevertheless, calcinated clay have major effect on the primary age strength improvement of mortar as well as concrete, much like fly ash and GGBFS do. Because of this, Portland cement concrete that contains SMCs typically exhibits a decrease in strength as it ages and a rise in strength as it ages [2, 45]. Limestone addition to ternary mixed cement is one potential solution to this issue [45, 46-48].

The filler effect of limestone powder is to improve surface area facilitates the nucleation of hydration products and speed up processes. Isothermal calorimetry and compressive strength testing were used in earlier research to demonstrate the beneficial "filler effect" of finely ground limestone at varying particle sizes as well as OPC replacement rates [49-51]. In addition to its physical filling function, limestone hastens the moisturizing of alite, which enhances material's primary strength. Furthermore, ettringite can stabilize and the overall volume of hydration products can rise because of interactions between calcium carbonates of limestone powder and aluminate hydrates. Anhydrous clinkers' low aluminate content may restrict this process. However, the low dissolution rate of limestone restricts the synthesis of carbonate-AFm even in cases where the system is supplied with adequate and highly reactive alumina, such as hydratable alumina [52, 53]. Furthermore, it has been observed that carbonate salts that are extremely soluble (Na_2CO_3) do not promote the production of carboaluminate phases in hydration products. This suggests that calcium has a crucial part in the production of carboaluminate phases [54]. On the other hand, if a substantial amount of limestone is blended with SCMs having a high alumina content, a considerable amount of carboaluminate phases may be produced [55, 56]. Combining SCMs with limestone in ternary mixed cement produces mixture having enough strength advancement after all SCMs provides prolong strength when limestone filler regulates primary strength. Many analyses have analysed ternary mixed cements that contains limestone.

According to Mounanga [57], with a constant cement replacement rate, the mechanical endurance of the ternary binder (OPC, fly ash as well as limestone) is greater on comparing with binary binder. It has been discovered that limestone can substitute 5% of OPC or fly ash in concrete without compromising its compressive and tensile properties. Almost all findings showed that the inclusion of limestone powder stop the primary age strength of concrete containing SCMs from decreasing. In ternary blended cement, complementary effects of calcined clays and limestone powder have also been taken into account. According to their findings [28], metakaolin and limestone powder in a 2:1 ratio had superior mechanical qualities around 7 as well as 28 days on comparing 100% OPC concrete with OPC displacement rates as high as 45%. Ettringite was stabilized and additional AFm phases (hemicarboaluminate) were generated because of the process between calcium carbonates and aluminates [56, 58- 59]. The outcomes also showed that, in contrast to a binary blend of calcinated clay together with OPC, ternary systems involving calcinated clay along with limestone interacted more effectively. A different study [60] looked at OPC replacement rates as high as 40% using 3.1 ratio of calcinated kaolin clay to limestone filler. Quantity of coarse pores in the matrix is significantly reduced as a result of the limestone filler's facilitation of pozzolanic reactions, especially at primary age, as per the results. Another author [61] looked at how resistant calcined clay as well as limestone mortars were to carbonation, chloride diffusion along with sulphate assault.

In comparison to the reference OPC mortar, metakaolin-limestone [28, 62-64] mortars demonstrated a strong resistance against sulphate and chioride assault, but a weak performance against carbonation. The OPC reference mortars displayed maximum refusal to carbonation, when the binary blend containing metakaolin as well as the ternary blend containing metakaolin along with limestone both showed decreased refusal. The max susceptible material to carbonation was limestone mortar [65, 66]. According to a recent publication [67], restrainment of stratlingite along with different aspects including monosulfate, hemicarbonate and monocarbonate occurs when metakaolin is mixed with limestone. DTG analysis supported the observation made by another author [68] that pozzolanic reactions as well as its resulting production of carboaluminate hydrates caused a decrease in Portlandite content. As a result, reducing CO_2 emissions must be accomplished without raising manufacturing costs, and even low-skilled personnel should be able to prepare concrete easily. A recently produced cement that satisfies these parameters is limestone calcinated clay cement (LC^3), which utilizes calcinated clay as well as limestone as SCMs. By replacing 50% of the clinker with LC^3, PC emissions can be lowered by up to 40%.

A relatively new and promising low embodied carbon and environmentally favorable cement is limestone calcinated clay cement (LC^3). Before industry adopts LC^3 concrete, number of its engineering properties need to be evaluated. In this study, General Purpose (GP) cement is a combination of limestone with calcinated clay in a 2:1 ratio [69-73]. The 15%, 30% as well as 45% GP cement displacement rates were taken into consideration. In Australia, a blend of limestone as well as calcined clay was applied in place of GP cement for concrete mixes, without any adjustments made to the blended cement's sulfate concentration or alkalinity. About 50% of the low grade calcined clay was amorphous. In fact, research on high grade kaolinite clays ignores the possible uses for widespread accessibility to low-grade [74-76].

Numerous investigations have looked into the mechanical characteristics, age, hydration, permeability, longevity, and environmental effects of limestone concrete. The qualities of the mortar or concrete having limestone filler are comparable to control mix when replacement amounts are up to 10% [77]. According to recent studies, the global warming potential of cement-based materials can be reduced by concrete including limestone filler in a manner that may be advantageous to SCM. This provided an explanation of the geochemical properties of S-rT's CPB (cemented paste backfill) (Sulfuride rich tailings). The study studied the effects of vigorous tank strain on cemented paste restock by 365 days. Cemented paste backfills containing Alkaline Industrial by Products (AIPs) creates much less SO42-, Ec along with acidity [78] in comparison to the control. Based on these results, the study concluded that groundwater quality is significantly impacted by an appropriate cemented paste restocking layout that controls HMs (hydraulic modulus). Additionally, [79] reported the outcome of theoretical as well as experimental analysis about impact of particle size on the rheology of self-consolidating concrete containing limestone filler in a novel condition. The experimental analysis about impact of particle size on SCC rheology of limestone filler in a novel form was presented in the first section. The study's second section created a straightforward theoretical design for figuring the filler dosage while taking particle size into account.

Through practical tests on several SCCs (self-consolidating concrete) combined with diverse amounts of filler, study verified the theoretical model. The outcome shows the rheology and compressive strength of all concrete are comparable. Similar to this, [80] used anti- corrosion chemicals to systematically evaluate deterioration effects in slag derived from fiber concrete. Chiorides are thought to be the most aggressive element that degrades steel in reinforced concrete, according to observations made in [81]. Furthermore, it is demonstrated that inclusion of limestone powder improved the particle size, enhancing the concrete's absorptivity to chloride ions. It has been suggested that total of limestone powder in concrete will increase and diffusion coefficient of chloride would decrease when grain size of limestone is smaller when compare to cement. Similarly, sulfate is considered as a vigorous component of cement concrete. To evaluate the refusal to sulfate deterioration, a study examined the decline in concrete strength. These investigations have shown that the resistance to sulfate deterioration is much increased while a portion of the cement is substituted to limestone powder.

It also analysed effects of soil respiration on soil pH when recycled concrete aggregate were utilized as the foundation for roads. Furthermore, in order to validate the use of very alkaline pH from recycled concrete aggregate in severe soil circumstances, an analysis disassembled as well as evaluated the columns for soil pH along with base. Similar to that, it looked at creative, ecological as well as sustainable concrete by using different types of seawater. Furthermore, SWSSC (Seawater Sea sand concrete) had a very high volume of incursion capillary pores, which were responsible for the concrete's macroscopic strength [82- 85]. Lastly, it claimed that adding seawater or sea sand to plain concrete and reinforcing clear of deterioration is a promising method of producing concrete that is free of harmful substances without harming the environment.

3. LC^3 Materials

The four main ingredients that go into making the LC^3 blend were gypsum, limestone, calcined clay as well as clinker. Figure 1 shows the schematic diagram for components present in LC^3.

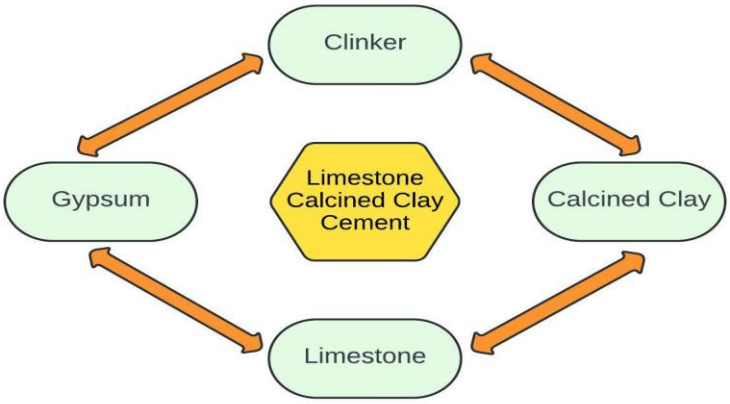


Figure 1. Components of LC^3 [86].

3.1 Clinker

Aluminous and calcareous materials are heated to 1400 degrees Celsius to generate clinker. During this process, 60-62 percent of the carbon dioxide is released. Following heating, the clinker will take on the lumpy appearance seen in Figure 2.

Figure 2. Form of lumps from clinker [87].

Because the clinker content in LC^3 is lowered to 50%, CO_2 emissions are 30% minimum in OPC and 11% minimum in PPC [5]. In this investigation, clinker content was utilized in varied proportions: 40%, 50% as well as 60%.

3.2 Calcined clay

For LC^3, clay with a kaolin material content of over 40% is appropriate. Conventional kiln at rotary, units of calcination flash, shuttle kilns, hearth kilns roller, and muffle furnaces can all be used to calcine clay [6]. Calcining clay containing kaolin produces metakaolin, it includes aluminosilicate and interacts with calcium hydroxide like regular pozzolana to produce aluminum hydrate and CSH (Calcium silicate hydrate) gel. Moreover, the alumina and limestone might react to form carboalumination hydrates.

3.3 Limestone

LC^3 prolong mine duration with decreasing raw material waste. Limestone with low calcite content that contains foams like quartz and dolomite would be utilized in LC^3, as can limestone that is unsuitable for clinker manufacturing. Portland cement, calcined clay as well as limestone have been combined with low-grade overburden material-clay and limestone which are high in dolomite and usually considered trash in standard manufacturing-to form a unique ternary blended cement. Firing is considered while applying temperature equivalent to half of clinkerization temperature. Due to no calcination, the limestone does not raise CO_2 emissions. India carried out several laboratories and three industrial trial batches of limestone-calcinated clay cement between 2014 to 2017. Calcinated clay at different temperatures is seen in Figure 3 [88].

Figure 3. Calcinated clay at various temperatures [87].

Additional interactions between the extra alumina supplied form calcinated clay and calcium carbonate that limestone supplies to system will generate alumina phases. The substance stays in the firing chamber for about 60 minutes, and a respectably high level of reactivity is attained [89, 90]. Specialized flash calciners are used for flash calcination. The initial clay-like substance needs to be dried and processed into a powder beforehand. After that. it is put into a stream of hot gas that has a brief residence period and a temperature of about 800-900°C. The method allows for the deployment of various heat recovery cycles, which increases efficiency capability. The power consumption pace of 2211 MJ/t of metakaolin flash is indicative of this [91]. Few writers compared the LC^3 and OPC along with PPC.

3.4 Mixture proportioning

Figure 4 shows the schematic comparison diagram for components needed for LC^3 and Portland cement whereas figure 5 shows the schematic diagram about the production of both LC^3 as well as Portland cement. The cement used was normal Portland Cement (53 grade), which complies with IS 12269 [92]. Portland Pozzolana Cement (PPC) was made in a lab setting using siliceous fly ash at Ennore, Chennai. The PPC were given the designation FA30 and had a 30% substitution level (i.e. 70% OPC along with 30% fly ash). LC^3 was taken from an industrial manufacturing test conducted in Gujarat, India. LC^3 blend utilized in the analysis, the ratio of clinker to calcinated clay, limestone, and gypsum were 50:31:15:4. A notable importance is that clinker utilized in LC^3 differs from that used in OPC. Table 1 also includes information on chemical makeup of clinker utilized in LC^3. The cement functionality from the industrial LC^3 manufacturing have been elucidated by Arun et al. [1]. In this system, the gypsum was tuned so that, as shown by isothermal calorimetry, process of the aluminates (derived from calcinated clay) is driven past the primary calcium silicate process. Table 1 displays chemical makeup of materials employed in investigation. By dissolving the powder in isopropanol, the laser diffraction data showed the particle size distribution. It is evident that compared to regular Portland cement, fly ash utilized in this investigation had more coarse particles. Because of calcinated clay and limestone powder, LC^3 has more finer particles. The physical functionality of the blends as well as compressive strength of cement mortar at a w/b proportion of 0.42 are also shown in Table 2. A combo of 10 mm as well as 20 mm crushed granite were utilized for coarse aggregate in concrete, whilst graded river sand having supposed max aggregate size of 4.75 mm were utilized for thin aggregate. To gain desired slump of 80- 120 mm, a superplasticizer (SP) based on polycarboxylic ether (PCE) with a 34% solid content was employed.

Table 1: Chemical composition of materials

Oxides		**LC^3**	
	Clinker	**Clay at Calcined**	**Limestone**
CaO	63.81	0.09	48.54
SiO_2	21.12	58.43	10.07
Al_2O_3	5.24	24.95	1.74
Fe_2O_3	3.41	5.08	1.62
MgO	3.06	0.19	0.467
K_2O	0.19	0.21	0.13
TiO_2	0.1	1.41	0.206

Table 2: Characterization of physical condition of LC^3

Characteristics	**LC^3**
Specific gravity	3.01
Consistency (%)	33
Starting time setting (min)	101
Ending time setting (min)	165
Blaine's fineness (m2/kg)	520
Soundness (mm)	0.1
Compressive strength of mortar (MPa)	43.7

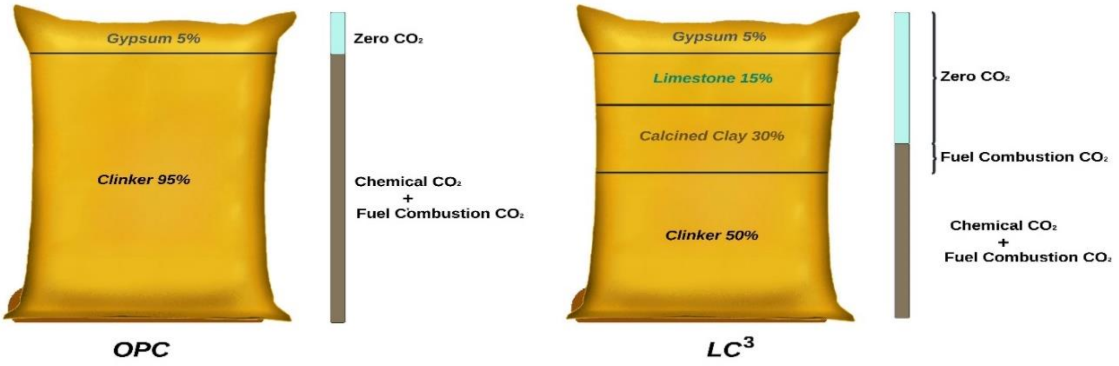


Figure 4. Cement manufacturing processes

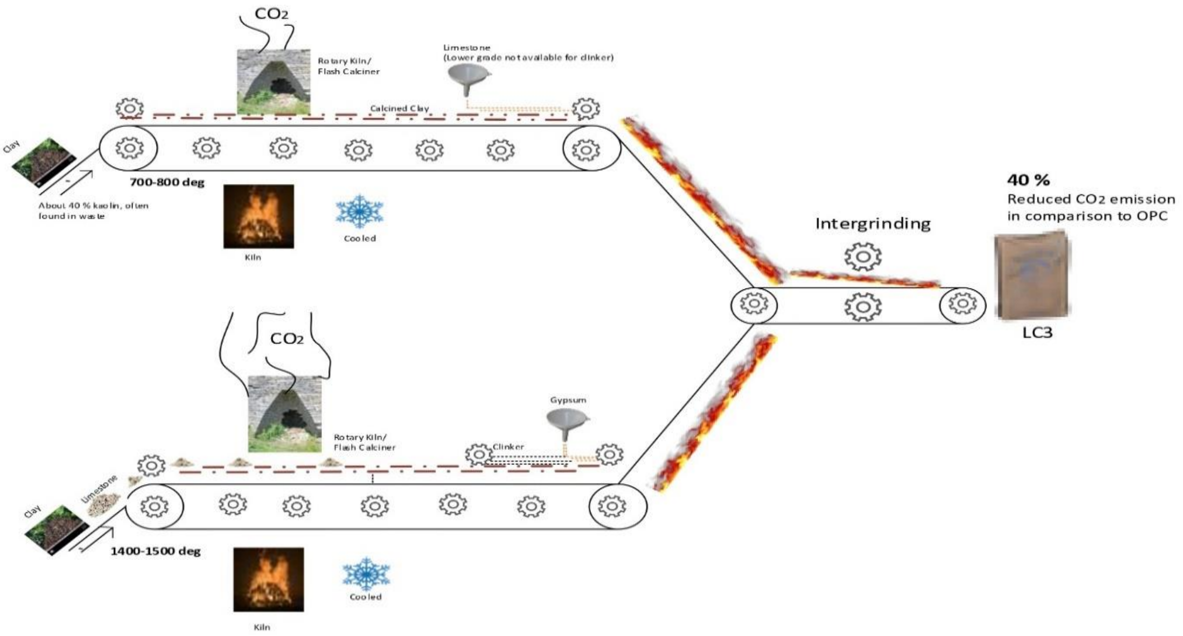


Figure 5. Production of LC^3 cement at lower temperatures (top line) than Portland cement (lower line) Drawing Courtesy LC^3 Project

4. FUNCTIONALITIES OF LC^3

4.1 Physical and chemical functionalities

Due to the source of collection, there is a lot of uncertainty in the physical functionality of calcinated, and only a few writers have described the LC^3 properties composition. Both OPC and PPC were used in the comparison [93].

4.2 Cement Mortar

After conducting numerous experiments on LC^3 mortars, the researchers resolved that the material's compressive strength is nearly identical to that of OPC 43 grade cement. A crucial importance to note the w/c proportion of the LC^3 system which is greater due to consistency because w/c is fixed using consistency standard measurement. When calcined bentonite was mixed with cement mortar, workability was reported to be lower [94-97].

4.3 Cement concrete

In the lab, a number of concrete combinations were created utilizing all of the LC^3, OPC, and PPC blends. The best flow with LC^3 blends was observed when a chemical admixture based on polycarbonxvlate ether was utilized to attain a decline within the range of 75-100 mm. Out of OPC and PPC, LC^3 demonstrated superior strength qualities [98]. Although there was significant batch-to-batch variance in the concrete's strengths, it was usually noted that LC^3 performed better and was nearly equal to PPC for a given water to cement ratio. This fluctuation may have been caused by the clays' uneven calcination. When calcined kaolinite was used instead of cement in the mortar, the strength increased significantly after 7 days when contrasted with control mortar. This increase is attributed to calcinated clay's pozzolanic nature, which mixes CH to produce more C-S-H, filling enough space as well as enhancing the mechanical characteristics.

4.4 Carbonation of concrete

The phenolphthalein indicator test results, in conjunction with the scattering exposed to 1% CO_2 for eight weeks and following thirty weeks of spontaneous carbonation, were used to calculate the carbonation depths [99-102]. When exposed to 1% CO_2, OPC-50 specimens failed to exhibit a distinct carbonation front. For OPC-50, no carbonation front could be reported. Overall, the results show that LC^3 concrete's resistance to carbonation declines with increasing substitution of OPC. It indicates that in terms of concrete carbonation resistance, the LC^3 fared better than the PPC and OPC.

4.5 Porosity

A few tests were performed with prism measuring 40 mm x 40 mm x 160 mm, the size of the specimens being determined by analysis [98]. The increased porosity that resulted from adding LC^3 to the concrete was noted.

4.6 Alkali silica reaction

In 2018, an alkali-silica reaction test was carried out by M. S. H. Khan and associates, Calcined kaolinite makes up 40% of the clay that was investigated in LC^3-65 and LC^3-50. The mortar bars were moistened in 0.32 M NaOH solutions at 38°C after a 28-day fog cure [103]. The alkali-silica reaction in concrete is often proficiently prevented with the application of more cementing materials because of minimal alkalinity as well as the availability of Al in the pore solution [103].

4.7 Compressive Strength

For a period of 28 days, the M30 as well as M50 concrete mixes' compressive strength progression were akin to OPC as well as LC^3 concrete mixtures. This shows that LC^3 binder systems have better strength potential even though the LC^3 M50 required less binder to attain the same strength goal, FA30 concrete mixes have lower primary age strength characteristics. This was because the mix's water content was lowered to achieve a comparable 28-day strength. The FA30 and LC^3 mixes demonstrated a huge improvement in compressive strength at larger ages (28 - 365 days) in comparison to the OPC system. Furthermore, compared to M50 concretes, the M30 [104-108] mixture of FA30 as well as LC^3 demonstrated somewhat greater improvement in compressive strength. This development is facilitated by the prolonged pozzolanic response [109].

As for common mixture, or mixture with the same binder concentration as well as w/b, it was discovered that the strength of concrete with LC^3 binder was stronger at all ages. This demonstrates how the improved hydration qualities of the LC^3 binder technology impact the concrete's mechanical attributes. The findings show that LC^3 binder, as opposed to OPC and FA30, can yield better compressive strength evolution in concretes with equal mixture proportions.

4.8 Shrinkage

Autogenous and drying shrinkage have an effect on concrete structure cracking as the binder stages continues to distort in presence of restrictions given by the hardened concrete's aggregates. Dried shrinkage is caused by the concrete losing moisture as a result of drying, whereas autogenous compression was regulated with the variation in internal relative humidity (RH) of system as a result of self-desiccation at a minimal water-binder ratio. According to Bissonnette et al. [110], the paste volume, size of the specimen, relative humidity as well as water-binder ratio were the contributing factors impacting the shrinkage measurement. In [111], the specific shrinkage factor is explained.

4.9 Strength and Durability

Since permeability and pore structure have a significant impact on concrete durability: the mean pore diameter, porosity as well as fractal pore dimension were measured using ultrasonic waveform analysis and mercury intrusion porosimetry to further grasp the microscopic mechanism. Several cement systems were examined in order to comprehend concrete governed by plastic as well as drying settings. Inclusion of 30% limestone caused a considerable decrease in mean pore diameter as well as porosity of the concrete [112]. The outcomes demonstrated that LC^3 had superior degree of hydration, shrinkage, and setting time. The strength, resilience along with capability of composite Portland cement mixed with fly ash were further illustrated in [113]. Their effectiveness has been contrasted with concrete combinations using Portland cement, slag cement, and regular PLC.

When compared to other combinations, the observed results showed a decrease in the composite PLC blends' penetrating capabilities. Chloride conductivity, oxygen permeability and water sorptivity were all taken into account in this analysis. Comparing compressive strengths of PLC mixture having FA as well as GGBS, this study discovered that PLC mixtures as well as FA have lower values. The experimental ramifications of employing a blended PLC concrete mixture were also covered in this research. The effects of ground limestone's organic carbon on PLC concrete's characteristics and behavior in both normal and aggressive media were also examined. These findings highlighted the important role that limestone clay concrete plays in both normal and hostile conditions, especially at large cement to limestone ratios. Limited research used calcinated limestone powder as well as Hwangtoh clay in many experimental investigations to analyse the durability, hydration as well as strength functionality of binary or ternary composites. Information gathered as a consequence of the experiment's findings is as follows. 15% replacement in ternary composites is thought to be the most optimal, and 30% replacement could serve as a cutoff point to reach plain concrete strength.

For all mixtures aged between 3 and 270 days, there is a linear relationship between the total water as well as strength. Electrical resistivity and carbonation have grown significantly because ternary composite has been used more often in place of limestone. The combined water is a more reliable predictor of the blended concrete's carbonation resistance than strength. Recent studies show that concrete can be made with less carbon dioxide throughout the manufacturing process and with greater strength and durability when limestone fines (LF) are substituted for an equivalent amount of cement paste. However, there are a number of advantages to using limestone fines in place of cement paste. It looked into how adding limestone fines affected the packing density of the concrete mixture and WTF (water film thickness). Additionally, by comparing the strength to-void ratio and durability, the study looked at the functions of WFT and packing density.

It was suggested, based on the results, that substituting limestone fines for cement paste would greatly increase strength and durability by reducing WFT and boosting packing distribution. By including three different waterproofing solutions, such as X, P, and K, it also shed light on how to increase the durability and microstructural characteristics of cement composites. To verify permeability/durability results, these combinations were examined. Concrete strength and hydration qualities have been studied using XRD, isothermal calorimetry, mercury intrusion porosimetry techniques, setting periods as well as compressive strength in relation to substitution as well as fitness of limestone powder. Findings demonstrated the effects of addition of limestone via nucleation sites on strength and moisturization. According to the research that is currently available, [114] examined the durability of crushed limestone used in place of siliceous sand in mortar and concrete. According to these carbonation results, powdered limestone is more suitable replacement for siliceous sand. Nonetheless, thorough research has to be done to elucidate the process.

Furthermore, the influence of limestone powder (LP)-containing generated sand on the hydration products as well as microstructure of concrete with 100% recycled coarse aggregates were analysed. Outcome of the analysis showed that the majority of limestone powders were inert along with only a minimal percentage of limestone powder had actually taken part in the hydration reaction. Additionally, the DIP method was used to examine the grain shape parameters of natural sand as well as sand made from limestone [115-118]. The results showed that the artificial sand was thin, flat, and harsh, while the natural sands were considerably finer as well as more spherical shaped. In a similar vein, a thorough investigation covering most essential durability features of concrete which was composed of blended cement with calcined clay was conducted. These findings demonstrated that during the observation of pozzolanic activity, the calcinated clays has no possibility of getting digested in the concrete. Study also noted that there are significant differences in the freeze-thaw resilience of different calcined clay quality. To further validate the acceptability of mixes, extra testing ought to be done.The durability and degradation resistance of MKLF (Metakaolin Limestone) concrete were investigated experimentally using the simulated solution. According to the electrochemical experiments, adding Metakaolin Limestone improves resistance to degradation and delays its commencement.

4.10 Impact

There are a number of environmental effects of limestone cement concrete, including the need to look at the properties of limestone cement with different replacement levels. Based on the research, the study found that 0% to 25% of limestone powder was applied in limestone cement concrete to substitute some of the cement. Furthermore, that was seen. Limestone powder was used with silica fume to refine the features of concrete. The study also measured compressive strength, splitting tensile strength as well as elasticity modulus. It has been analyzed how long limestone cement concrete will last among different C3A (tricalcium aluminate) levels. Using an accelerated test, the study determined the weight loss, length change as well as compressive strength loss of the concrete attack. Additionally, the study used steel reinforcement weight loss, cracking breadth, and first cracking time to determine corrosion resistance using accelerated corrosion analysis. Consequently, using 10% limestone won't affect the characteristics of concrete in the long or short term [119-121]. Whereas using limestone cement, having 25% limestone content have negligible effects on deterioration before cracking. Using blended limestone cement in a sulfate attack is not advised.

5. APPLICATIONS OF LC^3

Construction supplies like solid concrete bricks, RCC door and window frames, paving blocks, as well as Autoclaved Acrated Concrete (AAC) blocks were manufactured using LC^3 which is shown in figure 6. Without making any alterations to the customary mixing designs and production procedures, it was discovered that the building materials satisfied the requirements of the applicable standard. Most notably, it was discovered that when regular Portland or pozzolanic cements were substituted with LC^3 throughout these processes, neither worker retraining nor equipment recalibration was necessary. In central India, a two-story structure with both reinforced and plain concrete components was constructed entirely with LC^3.Once more, it was discovered that producing concretes similar to those typically used in such building did not require significant adjustments to combination designs or retraining of the personnel to utilize the cements [122]. These findings are crucial in proving that LC^3 can be used in place of OPC or PPC in general-purpose applications. To further confirm the cement's suitability for automated manufacturing techniques, concrete paver blocks as well as autoclaved aerated concrete (AAC) [123-126] blocks were manufactured in fully automated plants. Again with a few adjustments in combination plan was necessary for manufacturing as well as final goods yet complied with regulations. AAC blocks were utilized in the wall construction process.

A new low-carbon blended cement called Limestone Calcinated Clay Cement (LC^3) enables cement producers to lower their production-related CO_2 emissions. The LC^3 technology was brought from the lab to large-scale commercial manufacturing with the assistance of funding from the Swiss Agency for Development and Cooperation (SDC). SDC is pushing for the implementation of LC^3 standards and backing international outreach. It also funded the creation of the scientific foundation for LC^3 and the testing of production.

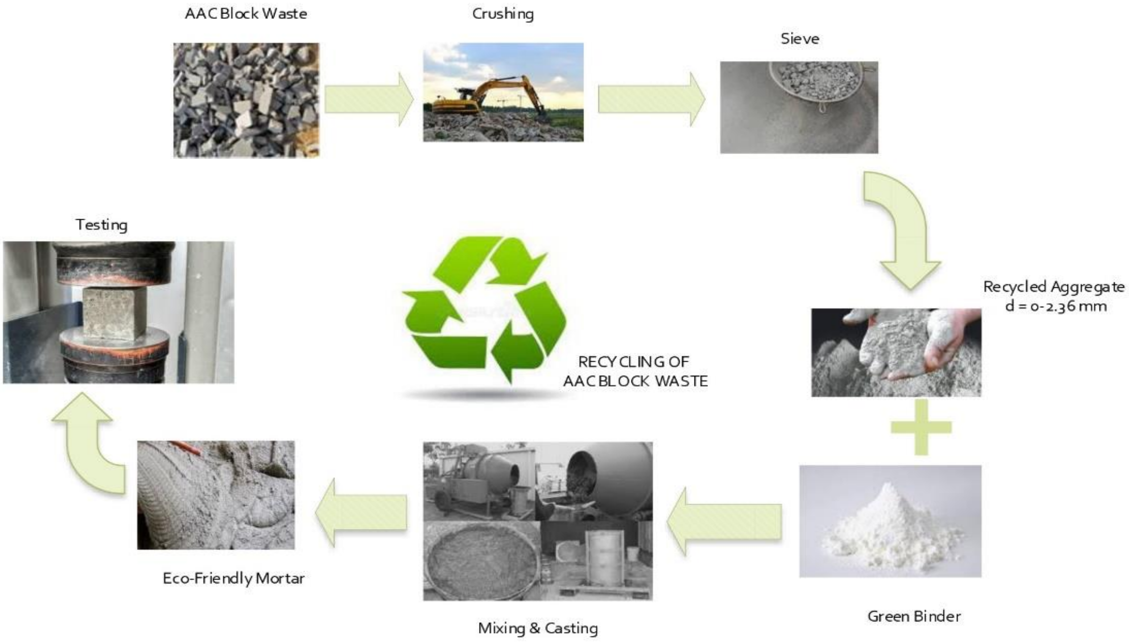
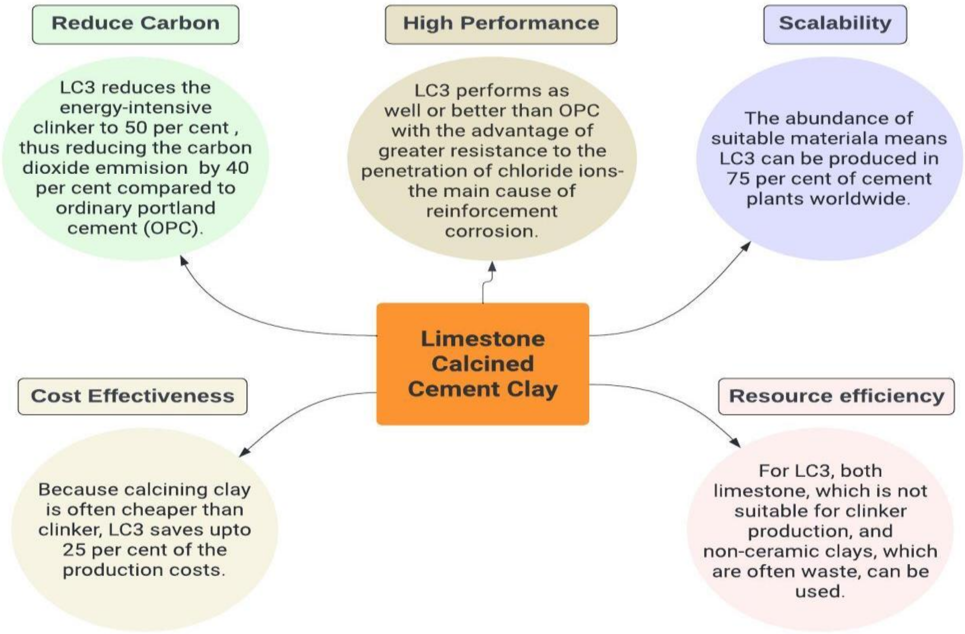


Figure.6 Graphical representation for the AACW aggregate preparation and application in LC^3 motor [127]



LC3 reduces the energy-intensive clinker to 50 per cent , thus reducing the carbon dioxide emmision by 40 per cent compared to ordinary portland cement (OPC).

LC3 performs as well or better than OPC with the advantage of greater resistance to the penetration of chloride ions- the main cause of reinforcement corrosion.

The abundance of suitable materiala means LC3 can be produced in 75 per cent of cement plants worldwide.

Because calcining clay is often cheaper than clinker, LC3 saves upto 25 per cent of the production costs.

For LC3, both limestone, which is not suitable for clinker production, and non-ceramic clays, which are often waste, can be used.

Figure.7 Adopting the LC^3

6. Energy and Materials Reduction

Lime and carbon dioxide are produced by heating limestone to a high temperature in the cement-making process. An intermediary product called clinker is created by heating the lime further, and it is combined with other ingredients to create Portland cement. The advantages attained by adopting LC^3 is shown in figure 7. Concrete is a common building material that is made by combining cement, crucial binding agent, along with aggregate as well as water.

- Enlightening efficiency of energy.
- Improving efficiency of material.
- Using alternative materials of binding source.
- Shifting to alternative fuels from traditional fuels.
- Applying decarbonized, alternative raw materials as well as feedstocks.
- Applying electrochemical process for production.
- Application of carbon capture as well as storage.

With significant reductions in new carbon emissions possible, calcined clays represent one of the best material efficiency approaches for the industry. This is especially true when mixed with other decarbonization strategies such as electrification and improved energy efficiency. Calcinated clays are applied as SCM in concrete replacing Portland cement, or they can be mixed with limestone to create blended cement. Calcined clays are already well-liked in the standards community and can be produced using existing machinery, such as rotary kilns, which lowers capital costs. Schematic diagram about the energy consumed during cement manufacturing process when applying limestone in shown in figure 8.

With current technological advancements, limestone calcinated dlay cement is a low- carbon substitute for Portland cement that cuts CO_2 release to 40%. It underwent extensive analysis to prove its potential on par with Portland cement, but at a 25% lower cost of production because of reduced energy and material usage. It is suitable for a range of structural implementations, such as pavements, highways, residential commercial buildings as well as other infrastructure, because it also has sufficient mechanical attributes like durability.

Given that India's yearly per capita consumption of cement is nearly equivalent to that of food, CO_2 release from the cement industry must be reduced as the nation's cement demand rises. India has made a commitment to sustainable development along with fulfilling its Intended Nationally Determined Contribution (INDC) to the Paris Climate Agreement, which requires reducing the emissions from the cement industry. LC^3 was gaining popularity as an environmentally friendly alternative to traditional Portland cement (OPC). It is a cement blend consisting of clinker, calcinated clay, and limestone along with gypsum which may usually reduce release by 40%.

The Bureau of Indian Standards (BIS) has published an Indian Standard (IS) number (IS 18189: 2023) for LC^3 in India, which is a noteworthy milestone. The code offers thorough instructions and requirements for the manufacture, examination, and application of LC^3 in concrete. By implementing this rule, LC^3 is expected to become more widely accepted and used in India's construction sector, opening the door for the expansion of low-carbon cement blends. We explore the specifics of LC^3, its benefits for the environment, and the ramifications of the new IS code in this blog post. These points point to a revolutionary change in the direction of cleaner infrastructure and the decarbonization of the cement sector.

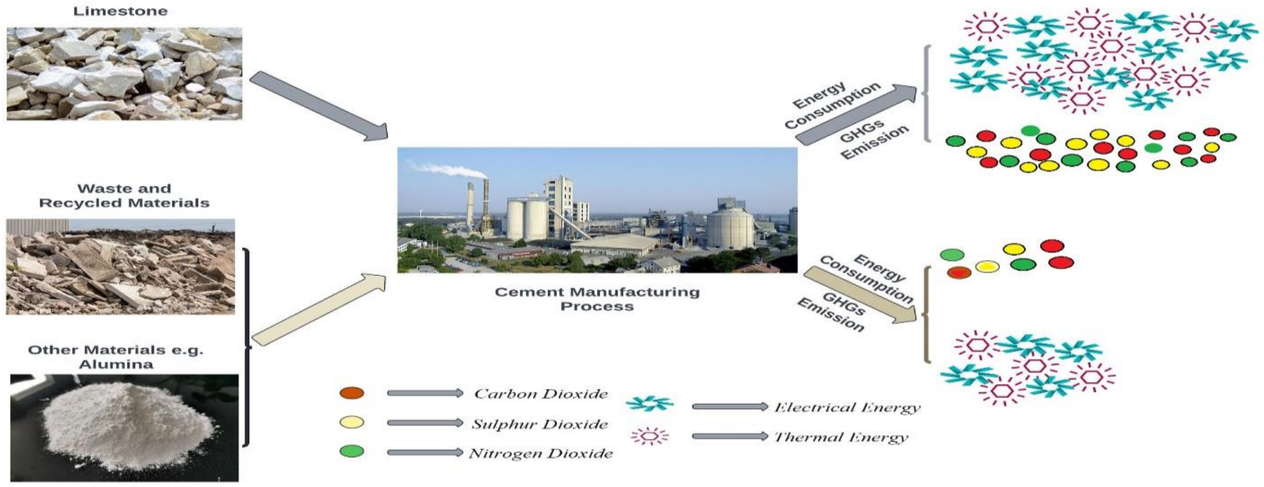


Figure 8. Energy consumption using limestone [128].

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6.1 LC^3 as a replacement for conventional cement

The Swiss Agency for Development and Cooperation (SDC) and the Ecole Polytechnique Fédérale de Lausanne (EPFL) collaborated to create LC^3, a low-carbon substitute for regular Portland cement (OPC). An ideal LC^3-50 cement blend combo is composed of 50% clinker, 15% limestone, 5% gypsum along with 30% calcinated clay. This combination reduces overall costs by up to 25% and reduces carbon emissions by about 40% when compared to standard OPC. Figure 9 represent the changes that occurs when LC^3 is substituted with conventional cement. A significant issue with the production and performance of LC^3 is the accessibility of clays and their corresponding kaolinitic content.

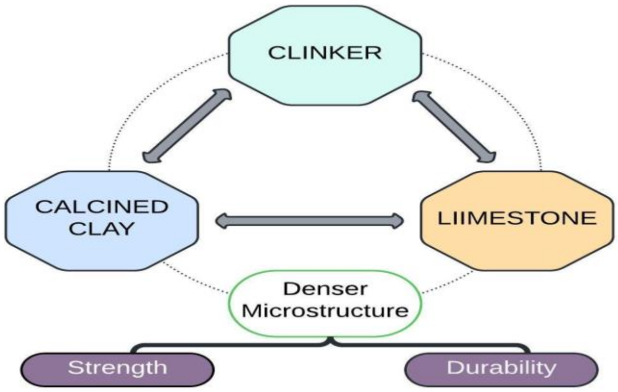

Figure 9. Replacement of conventional cement.

After nearly ten years of study at the Indian Institute of Technology Delhi, Indian Institute of Technology Madras as well as Society for Technology and Action for Rural Advancement (TARA), it was discovered that LC^3 has better durability qualities, which makes this cement blend appropriate for a range of building uses. It is a great option for buildings near the shore due to its enhanced resistance to sulfate assault and chloride penetration. Furthermore. LC^3 contains less alkali, which reduces the possibility of alkali-silica interactions and lengthens the life span of concrete constructions.

In response to the need for sustainable building methods and the growing awareness of climate change, academics and business experts decided to create a national standard for LC^3.

6.2 LC^3 production and deployment in India

Since its introduction in 2014, LC^3 has been applied in over 25 pilot projects at various scales and in various countries. One noteworthy work is the Jhansi model house in India, which was built with LC^3 in 98% of the structural components. At their Jhaijhar facility, JK Lakshmi and IIT Delhi collaborated to carry out the first-ever full-scale LC^3 plant experiment in 2017. With possible reductions in CO_2 release to 30% together with energy consumption in cement manufacturing of 20%, the trial's results are encouraging.

Furthermore, LC^3 prefab materials were applied in the construction of the offices of the Swiss Agency for Development and Cooperation, which are housed at Delhi premises of the Swiss Embassy.

In order to produce LC^3, JK Lakshmi Cement partnered with TARA in 2022 to integrate calcinated clay technology into its operations. There is movement in the nation for more cement companies to start producing LC^3.

6.3 Environmental Performance of SCM

Researchers have highlighted problems like how different processing of metakaolin vary its environmental impact and how the overall environmental load of the blended cement is affecting the environmental, social, and economic implications of the material at the industrial scale. A thorough analysis of greenhouse gas footprint along with calcination of clays is necessary to address these and other issues. It can better comprehend the capability of cement, limestone, and metakaolin-based concrete binder when contrast with commercially available Pozzolan-Portland-Cement (PPC) concretes and traditional Portland cement concrete by assessing their environmental impact. To examine cement with metakaolin's environmental performance, a life-cycle assessment (LCA) must be performed which is shown in figure 10.

Before anything else, it is crucial to determine the environmental benefits of using metakaolin in place of some of the cement when making concrete. The emission factors that MK currently uses are approximations derived from the manufacturing processes of cement. Their reported emissions from fuel-derived emissions and raw material extraction are 175 kg CO_2/tonne-MK. Regretfully, Gartner does not provide information about how this value was calculated. Furthermore, it indicates that this value is backed by private information derived from an environmental impact assessment and provides this emission factor afterward. According to premise where 1.16 kg of kaolin is needed in order to produce 1 kilogram of metakaolin after calcination, it noted as 423 g CO_2-eq/kg of metakaolin. Furthermore, the energy consumption of 2.5 MJ/kg of metakaolin utilizing natural gas as energy source for clay calcination was the basis for calculating this value. According to private correspondence with material suppliers, the cradle-to-gate analysis calculate as 330 g CO_2-eq/kg of metakaolin derived from 400 kWh/t of embodied energy. A highlight how the kind of fuel used in MK's calcination process contributes to its considerable variability in embodied energy. The utilization of alternate heat sources, such as biomass, may result in lower levels of the global warming potential (GWP) of MK.

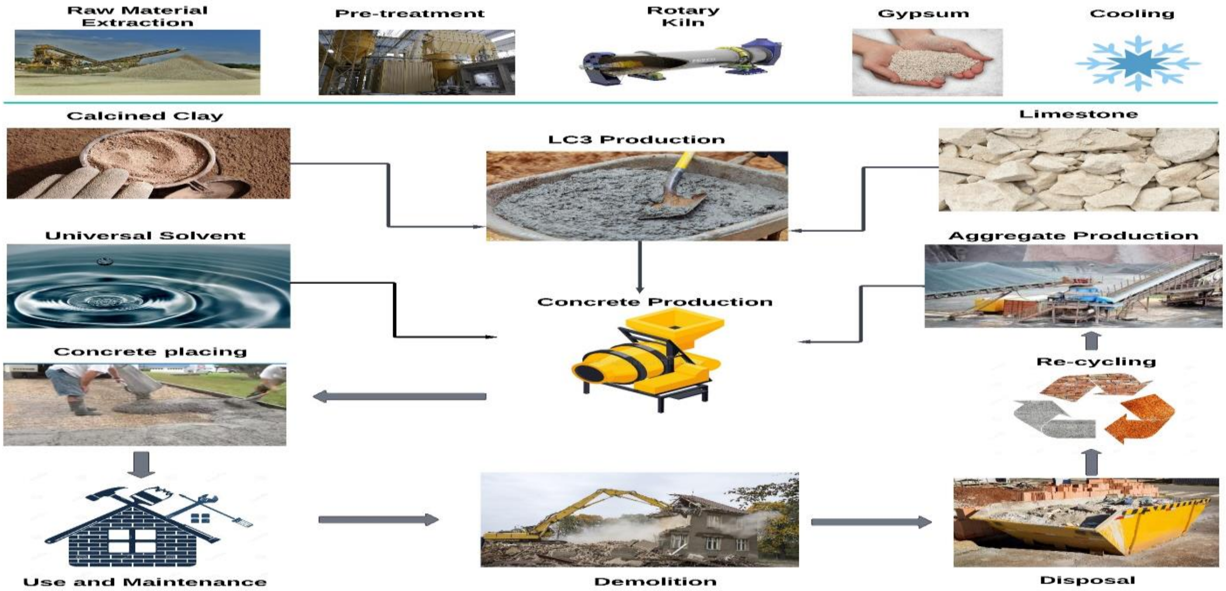

Figure 10. Life cycle assessment of LC^3 Concrete [129].

Upon using biogas (agricultural waste) as energy source for calcination process, these authors stated 92.4 g CO_2-eq/kg of MK; these releases are around 5 times minimum from the above analysis. Based on estimations from cement industry specialists along with calculations of specific heat as well as calcination energy from thermogravimetric study of many clay samples, the suggested value of 2.6 MJ/kg of clay needed for calcination. An LCA was carried out for their study, taking into account typical values for India, to contrast the environmental profile of over 30 mix proportions of different concretes.

The environmental profile of cement is impacted more by the use of metakaolin as an SCM than by the use of well-known (by)products like slag and fly ash, according to these researchers. Energy from fuel combustion during calcination is needed to activate these clays and create a reactive substance (metakaolin). Metakaolin is widely and readily available. making it an excellent displacement for other commercially available SCMs (e.g. fly ash, slag) even if its production needs energy input for its calcination Additionally, because fly ash together with slag are byproducts of the steel as well as energy industries, majority of life cycle assessments (LCAs) of blended cements that use these ingredients do not account for the processing-related consequences in their evaluations Since the slag as well as fly ash are regarded as residue of these industrial facilities, they ought to bear some of the environmental weight. When these effects are taken into account, the overall environmental impact of concretes created with these SCMs may rise and may even surpass that of concretes combined with metakaoli [130].

6.4 Future of LC^3

LC^3 offers a viable option for low-carbon building, as India intends to lower 45 percent of its release intensity by 2030 as part of its NDC under the Paris Agreement. The reduction process of carbon emission made by LC^3 is shown in figure 11.

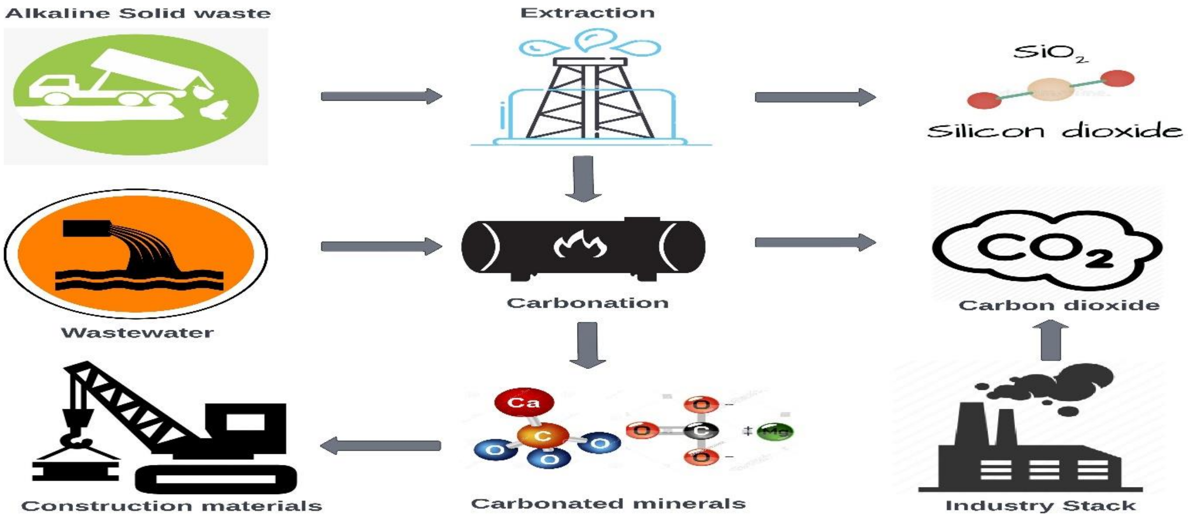

Figure 11. Reducing global carbon emission with LC^3 [131].

The importance of concentrating on minimal embodied carbon plan together with elevation along with minimised carbon material manufacturing as well as selection is emphasized in recent paper by NIUA and RMI. Although LC^3 offers a viable way to build low- carbon buildings, obstacles still stand in the way of its broad implementation. They consist of educating specialists in the construction industry, guaranteeing regular quality control, providing specialized training, supplying source materials, incorporating LC^3 into current supply chains as well as being approved by regulators along with builders.

Although this move might cause some problems for established cement producers, it also marks a fresh beginning for the nation's low-carbon cement industry and offers an opportunity. "Lodha Net Zero Urban Accelerator, in partnership with RMI, plans to launch a pilot on LC^3 with a goal to generating proof as well as confidence about its impact for the greater ecosystem of developers, contractors, industry supply chain as well as policymakers," said Aun Abdullah, head of ESG at Lodha Group, in an interview with RMI India.

Because of its lower carbon footprint, increased durability along with financial advantages, LC^3 has ability to revolutionize nation's building as well as infrastructure construction practices. With numerous adequate case studies attesting to its efficacy, publication of LC^3 IS code represents paradigm shift in the field of sustainable construction. The release of the code is expected to hasten the adoption of LC^3 throughout the nation and establish guidelines for other nations considering incorporating LC^3 into their own codes. India's pursuit of sustainable growth will surely influence the construction industry going forward, thanks to LC^3.

7. CONCLUSION

Various analyses were performed to analyze the characteristics of both concrete and LC^3 mortar. Their reported findings served as the foundation for the conclusions that followed. This study has shown that, in this constrained environment, LC^3 constitutes a solid option. Three types of cement that can be manufactured in Cuba have been assessed from an environmental and economic perspective in this study. The LC^3 technique comprised 50% clinker, 15% unburned limestone, 30% calcinated clay along with 5% gypsum. It's an energy- saving as well as cost-effective process. There were considerable savings in production as well as investment expenses coupled with greenhouse gas release. The results that are shown are robust and account for several factors. Therefore, LC^3 has a tremendous deal of potential to offer a workable way to meet the growing demand for cement with little money invested and little carbon released. The LC^3 blends had production problems, but even with below 40% calcinated kaolinite composition in calcinated clay applied in blends, which is observed as the blends made with higher-quality clays compatibly produced mortars, concretes, and construction products with superior strengths than OPC.

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