# Structural Performance of An Limestone Calcined Clay Cement ($LC^3$) Concrete


*Submitted by*

**Khawar Tufail**

MS Structural Engineering (Fall 2018)

00000275934

*Supervisor*

**Dr. Hammad Anis Khan**

**NUST Institute of Civil Engineering (NICE)**

**School of Civil and Environmental Engineering (SCEE),**

**National University of Sciences and Technology (NUST), Islamabad**


**Aug 2022**

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A thesis submitted to the NUST Institute of Civil Engineering in partial fulfillment of the

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**MASTER OF SCIENCE**

in

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Thesis Supervisor:

**Dr. Hammad Anis Khan**

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Thesis Supervisor's Signature

Department of Structural Engineering

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School of Civil and Environmental Engineering (SCEE),

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By

**Khawar Tufail**

This is to certify that we have examined the above MS thesis and found that it is complete and satisfactory in all respects.

| | |
|---|---|
| Dr. Hammad Anis Khan | Dr. Fawad Ahmed Najam |
| Assistant Professor | Assistant Professor |

| | |
|---|---|
| Dr. Azam Khan | Dr. Junaid Ahmad |
| Assistant Professor | Assistant Professor |

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I certify that final copy of MS thesis written by Mr. Khawar Tufail (Registration No.00000275934) of NICE (SCEE) has been verified by undersigned, found complete in all respects as per NUST Statutes/Regulations, is free of plagiarism, errors and mistakes and is accepted as partial fulfillment for award of MS degree.

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**Supervisor:** Dr. H ammad Anis Khan

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# Declaration

I certify that this research work titled "*Structural Performance of An Limestone Calcined Clay Cement (LC3) Concrete*" is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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**Khawar Tufail**

**00000275934**

# Copyright Statement

# Acknowledgements

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# Abstract

This thesis is on a breakthrough technology to reduce $CO_2$ emissions from cementitious material that is limestone calcined clay cement ($LC^3$). The use of SCMs to replace the part of clinker in cement is the most successful strategy to reduce $CO_2$ emissions in global cement industry. The only type of material available in the quantities needed to meet the demand is clay containing kaolinite, which can be calcined to produce an effective SCM. As discussion proceeds workability, hydration and chemistry of $LC^3$ is discussed followed by its durability properties. At the end suggestions for further research.$LC^3$ is family of cement in which clinker content is replaced by calcined clay and lime stone with some proportion of CC : LS (2:1). In this paper kaolinite content of different clays were investigated and more than 40% kaolinitic clay were chosen in replacement of OPC along with Limestone. After that Kaolinite clay were grinded, passed from #200 sieve and heated at a temperature of 850 $C^0$ for 1 hour. Hardened properties such as compressive strength, split tensile strength, flexural strength, modulus of elasticity of concrete using Limestone calcined cement were investigated by taking W/B ratio 0.5 constant. The experimental program were deal with mechanical properties of $LC^3$ concrete with the following combination of $LC^3$-30, $LC^3$-50, $LC^3$-65, and LC3-80 along with normal OPC. Based on the experimental results it was noted that replacement less than or equal to 50% with conventional cement we can get the ultimate strength approximately equal to OPC.After that best mechanical properties showing sample were taken into structural level testing like four point bending test along with expermimental results FEA were also carried out on same beams having OPC , $LC^3$-50 , $LC^3$-65 , $LC^3$-80 beams. Load vs deflection , comparison of peak loads ,comparison of ultimate deflection both experimentally and FEA deflection , crack width , number of cracks , minimum spacing of cracks , maximum spacing of cracks , average spacing of crakcs these were the testes carried out on each beam and lastly comparison of carbon footprint were also carried out in a form of percentage differnce of $CO_2$ emmision with respect to normal ordinary portland cement and percentage difference of energy consumed with respect to normal ordinary portland cement (OPC).

**Keywords:** $LC^3$ (Lime stone calcined clay cement) , SCM's (Supplementary cementitious material , Kaolinite clay , FEA(Finite element analysis) , CO2 emission , ordinary Portland cement (OPC).

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# List of Abbreviations

| | |
|---|---|
| ASTM | American Society of Testing and Materials |
| fc' | Compressive Strength |
| SCM | Supplementary Cementitious Materials |
| $LC^3$ | Limestone Calcined Clay Cement |
| OPC | Ordinary Portland Cement |
| XRF | X-ray fluorescence |
| XRD | X-ray diffraction |
| TGA | Thermogravimetric Analysis |
| SEM | Scanning Electron Microscope |
| EDX | Energy Dispersive X-Ray |
| FEA | Finite Element Analysis |

# CHAPTER 1: **INTRODUCTION**

## 1.1 Problem Statement

Climate change is one of the most pressing issues confronting humanity today. This climate change involves global warming induced by greenhouse gases (most notably carbon dioxide) emitted by human-made sources, which has resulted in weather pattern shifts. This shift in the weather pattern has disrupted life on the only life-bearing planet Earth, and it must be addressed right away. According to current estimates, the cement sector contributes roughly 5% of global man-made CO2 emissions, making it one of the world's two largest polluters.

There is expected to be a rise in cement consumption as the population grows. There is a trend in the rise of industries for rising and emerging economies like China, India, Pakistan, Brazil, Mexico, Russia, South Africa, and Chile, and so these are hot areas for future mass infrastructure growth. Cement demand will rise because of this economic expansion, which will be fueled by increased personal income, GDP, and infrastructure spending. By 2023, demand will have increased by 1% each year to 4.1 billion metric tons. As a result, those countries may have a significant challenge in meeting the increased demand for cement. Given the present increase in cement demand, traditional Portland cements with a greater clinker-to-cement ratio will not be able to meet these requirements. As a result, solutions must be found that are cost-effective, long-term, environmentally benign, and align with global concerns about reducing carbon dioxide emissions.

## 1.2 A possible remedy-SCMs

The use of supplementary cementitious materials as a CO2 reduction solution is not new, but it has been thoroughly researched. There are a range of supplemental cementitious materials with varied pozzolanic qualities on the market, but they are not a practical alternative for mass production due to their varying availability around the world, and the product can be even more expensive than ordinary OPC. Furthermore, there is a limit to how useful their incorporation is in the cement system. Geopolymers, in addition to SCMs, are being examined as an alternative. However, their application is expected to be on a medium to large scale.

Limestone calcined clay cements (LC3) are yet another low-carbon cement option that has been developed for mass manufacture. Limestone calcined clay cement (also known as LC3) is a new technology in the cement business that addresses the demand for a sustainable, cost-effective, and low-carbon cement system that can be employed on a large scale.

This thesis looks at the introduction of LC3 technology in Pakistan, its viability in the local building industry, and the best mix design that delivers OPC-like strength and study its mechanical properties as compared to OPC. LC3 isn't just one type of cement; it's a family of cements made up of ingredients with varying substitute-to-clinker ratios. As the name implies, it uses high-temperature calcined clay as an additional cementitious ingredient. Because of the combination of limestone and calcined clay, LC3 is compatible with OPC while minimizing CO2 emissions and thereby conserving natural resources. Clay and limestone are already utilized as SCMs, but the breakthrough is in combining these two readily available materials without compromising cement strength or other mechanical qualities.

## 1.3 Objectives

The main objectives of this research are the comparison of the following behaviors' of LC3 concrete blends to OPC:

- Load Controlled stress-strain behavior
- Compressive strength
- Split tensile strength
- Toughness
- Mineralogical properties
- Flexural strength
- Four point bending test on beams
- FEA (Finite Element Analysis) on each beam

# CHAPTER 2: LITERATURE REVIEW

## 2.1 Cement

Cement, also known as binder, is a widely used building substance that binds other materials by setting, hardening, and sticking to them. After water, it is the world's second most consumed resource.

Portland cement is a common form of cement used all over the world. In a rotating kiln, clay and limestone are heated together at 1,500°C. The resulting hard product, known as clinker, is then mixed into a powder with a small amount of gypsum to create OPC (Ordinary Portland cement). Portland cement is used to make concrete, mortar, and most non-specialty grouts. Portland cement is most used in the production of concrete, which is a composite material made up of aggregate, cement, and water.

Because clinker is responsible for 60% of CO2 emissions, reducing the amount of clinker used and substituting it with a supplemental cementitious material will considerably reduce the amount of CO2 emitted, lowering the environmental effect.[1]

One of the most successful and effective strategies for reducing CO2 emissions in the worldwide cement industry is to include supplemental cementitious materials (SCMs) in the binder system.[2]

## 2.2 Clay

Throughout history, clays have been widely employed as pozzolanic materials. Despite the presence of many other competing resources, such as industrial wastes, clays remain a viable alternative as a supplemental cementitious ingredient.

### 2.2.1 Clay as supplementary cementitious material

The use of metakaolin-rich clay to replace clinker, resulting in a lower clinker/cement ratio, is thought to be an efficient technique to reduce CO2 emissions.[3] One of the main advantages of employing calcined clay for this purpose is that it does not reduce the binder's compressive strength; in fact, substitutions of up to 45 percent produce superior mechanical results than conventional Portland cement.[4]

### 2.2.2 Calcination of clay

Clay must be calcined in order for its pozzolanic properties to be activated. Calcination is the process of heating clay in the presence of oxygen. It causes dihydroxylation of clay minerals, which increases the compressive strength of the clay. If the calcination temperature is carefully managed, the performance of the clay can be improved to that of normal OPC. In the instance of kaolin, calcination at 550C results in a compressive strength of 113 percent of OPC.[5] This temperature can reach 950 degrees Celsius. As a result, a calcination temperature of 550 C is commonly employed for cost-effectiveness.

## 2.3 Pozzolanic Reaction

The sum of SiO2 + AI2O3 + Fe2O3 should be larger than 70%, according to ASTM C-618 (ASTM C618-91, 2019), and clays have a sufficient percentage of this sum (Changling Hea, 1995). Thermal activation of clay (around 600 oC-900 oC) causes the structure of clay to break down due to dehydroxylation, resulting in the formation of a new phase with higher reactivity. In kaolinite clays, this phase includes metakaolin (AI2O3.2 SiO2) or AS2. The fundamental pozzolanic reaction consists of the following steps:

CH + metakaolin (AI2O3.2 SiO2) + H → C-S-H + C-A-H[6]

CSH gel, as well as other crystalline products such as calcium aluminate hydrates and alumino-silicate hydrates, are formed as a result. The temperature of the reaction and the ratio of metakaolin to CH determine the crystalline products.[7]

## 2.4 Limestone

The addition of limestone to the LC3 blend improves the rheological qualities of the concrete by lowering the flow resistance.[8]

In comparison to pure cement concrete, limestone cement concretes have a poorer resilience to freezing and thawing. The best protection against rebar corrosion is found in Portland limestone cement, which contains 20% limestone. Carbonation depth (the average distance from the surface of concrete or mortar where carbon dioxide has reduced the alkalinity of the hydrated cement) and overall porosity of the mortar are both reduced by the limestone additions.[9]

## 2.5 Water Content

To manufacture the cement paste, you'll need water. The amount of water required can have a significant impact on the LC3 blend's mechanical qualities.

### 2.5.1 Effect of Water/cement Ratio

Increases in the w/b ratio increase porosity, lowering the compressive strength value. A decrease in the w/c ratio, on the other hand, increases compressive strength while decreasing workability. The fracture behaviour of a mortar with a low w/c ratio is similarly more brittle than that of a mortar with a high w/c ratio, according to a report.[10]

The compressive strength of concrete varies inversely with the water/cement ratio, according to Abrams' generalisation law. The interfacial transition zone between concrete paste and aggregate, which determines the strength of concrete, is affected by the water–cement ratio (W/C). The increased water requirement caused by the high fineness (induced by the sheet-like structure) and narrow particle size distribution is one of the concerns with the use of calcined clays.

## 2.6 Curing

Curing is critical for cement mortar and concrete specimens, since it affects their strength and longevity. The effect of curing temperature ranging from 20 to 30 degrees Celsius on the characteristics of LC3 has already been investigated. The hydration of clinker and the pozzolanic process are aided by increasing temperature, resulting in a rise in LC3 strength development at a young age. The samples cured at 30 °C for 28 days have a coarser threshold pore diameter, but this has no effect on the LC3 strength. However, the majority of the earlier studies were carried out at a lower temperature (20 °C) than the average operating temperature in tropical nations.[11]

## 2.7 Fresh properties of $LC^3$

### 2.7.1 Viscosity

The metakaolin content is a crucial determinant of the LC3 system's fresh properties as well as strength development.[12] The main reason for this is that MK (metakaolin) is a water-absorbing substance that raises the system's viscosity [13]. To balance the inherent static charges present on the surface of clay, clays have a tendency to exchange cations with other additional material. As a result, when admixtures are injected, the clay particles quickly exchange cations with the organic matter already present in the admixture. As a result, there is less dispersion and thus less absorption of the admixture on the surface, necessitating a higher admixture dosage. This larger dose may result in a cost rise, a setting time increment, and a strength development delay.[14]

### 2.7.2 Slump

The water content, super plasticizer employed, and, most importantly, the metakaolin content in the mix all affect the slump values of the LC3 system. The morphology of the metakaolin in the mix determines the slump values. The slump increases as the particle shape becomes more spherical and less rough. The slump is shown to lessen as the surface roughness increases.[15]

### 2.7.3 Adhesion and Cohesion

The combined impact of limestone and calcined clay results in a cohesiveness enhancement (the ability to stick with the same substance). The cohesion of the mix increases as the SCM content increases, but the addition of limestone diminishes the mix's cohesion. The mix's adhesion (ability to attach to other surfaces) improves as the amount of calcined clay increases.[16]

## 2.8 Mechanical Properties of LC3

### 2.8.1 Compressive Strength

Compression testing with a compression testing machine is commonly used to determine a specimen's compressive strength. The specimen with the greatest amount of clinker has the greatest compressive strength in the LC3 system. The compressive strength of clinker increases as the amount of clinker increases.[17]

### 2.8.2 Flexure Strength

On days 7 and 28, the flexural strength of the LC3 specimen is greater than that of the OPC. It shows that adding calcined clay increases the ductility of the mixture. The calcium hydroxide of the hydration product and calcium alumina silicate hydrates C-A-S-H are generated during the pozzolanic activity of clay. The flexural strength of C-A-S-H products and crystalline calcium aluminates is increasing due to the increased formation of C-A-S-H products and crystalline calcium aluminates.[18]

## 2.9 Hydration of LC3

### 2.9.1 Phase Assemblage

X-ray diffraction can be used to investigate the different stages of hydration of LC3. A peak of hemicarboaluminates is found in the LC3 system after 24 hours of hydration (2 = 10.8o)[19]. A slight rise of monocarbonaluminates (2 = 11.7o) is detected at 28 and 90 days, but the entire conversion of hemicarboaluminates to monocarbonaluminates is not observed. After 24 hours of hydration, only residues of portlandite are visible. This could be due to the calcined clay in the mix reacting quickly. [26]

EDM/SEM (Scanning Electron Microscopy / Energy Dispersive X-Ray Spectroscopy) is employed to characterize the C-A-S-H gel because it cannot be investigated using XRD due to its amorphous nature. Calcined clay contains alumina, which alters the structure and shape of the calcium silicate hydrate while also incorporating alumina into the gel. [33] Many factors influence alumina uptake, including alkali content, clay grade, and the Ca/Si ratio, among others. At 28 days of hydration, the average C-A-S-H composition is C1.61A0.115SHX, indicating that LC3 has a higher alumina absorption than conventional OPC.[20]

### 2.9.2 Alite and Belite Hydration

The degree of hydration of alite and belite in the LC3 system is determined using quantitative rietveld analysis. Later phases appear to have a reduced level of hydration. The hydration was found to be 15% lower when compared to OPC. At 90 days, the degree of hydration of belite in a limestone-calcined clay system was determined to be 35%[35]. When calcined clay and limestone are joined in a system, the low hydration becomes more apparent. This is owing to the pore refinement that occurs when calcined clay is present. The hydration steps are slowed as a result of the pore refining. The LC3 system's mercury intrusion test demonstrates that the limiting critical pore diameter is reached in 7 days. There is no drop in pore size after that.[19] [46] [50]

### 2.9.3 Reaction Kinetics

Isothermal calorimetry is used to investigate the early hydration kinetics.In the calorimetry of the LC3 system, there were two peaks. The first peak represents silicate hydration, while the second peak represents aluminate hydration. Because of its filler character and the existence of additional nucleation sites, calcined clay speeds hydration. As a result, the LC3 system generates the initial hydration peak earlier than the OPC system. In the LC3 system, there is a distinct second peak. The depletion of sulphate occurs about 9.5 hours after the injection of water, near the commencement of this peak.[40] [44] [45]

### 2.9.4 Strength Development

Within the first 28 days, the LC3 system achieves the majority of its compressive strength. The major factor for the formation of early strength is calcined clay. Between 28 and 90 days, there is very little strength increase. The hydration of

C2S and C3S explains this. Pore refinement is the LC3 system's key limiting factor for hydration and thus strength growth.[21] [42] [43]

## 2.10 Microstructure Of LC3

Clay is a high-quality substance. When used as a clinker substitute, it has a significant impact on the matrix's microstructure. [41]

### 2.10.1 Pore Size Distribution

Initially, the porosity values of the calcined clay system with varying clay percentage are 49-50 percent.[22] This value continuously declines until the 28th day of hydration. The porosity remains constant after 28 days. When compared to OPC, calcined clay blends have a total increase of 16 percent in porosity. [39] [40]

There is no significant difference in the first 7 days for capillary pores (5-0.01 m). The difference between the OPC and LC3 systems becomes more noticeable after 14 days. At this point, there has been a 10% rise in capillary porosity. However, the capillary pores of systems with 15-25 percent calcined clay for prolonged periods of hydration show little variation.[23] [38]

The pore size of the mix becomes finer with the addition of calcined clay. At 7 and 90 days, there is a noticeable shift in pore size, indicating the start and conclusion of clay's pozzolanic activity. The pore size shrinks dramatically on the first day of hydration. [37] This decline occurs in normal OPC after 1 to 56 days of hydration. This pore size decrease takes 28 days with a 10% metakaolin system. After 14 days, pore size reduction in mixes containing more than 10% stops. The average pore size of mixes containing 10% or more metakaolin is very similar.[22]

### 2.10.2 Production of calcium hydroxide with time

It is necessary to know the amount of calcium hydroxide in the mix to determine the degree of hydration of metakaolin. During the early phases of hydration, the amount of calcium hydroxide increases[35]. With the passage of time, this amount decreases. At 56 and 90 days of hydration, this decline is noticeable. [27]

The first increase can be explained by OPC hydration, which diminishes as metakaolin's pozzolanic activity rises. The pozzolanic activity of the clay is demonstrated by the inflexion points at 56 and 90 days. [28]

### 2.10.3 Degree Of hydration

The degree of hydration of the LC3 system can be determined using a variety of ways.

Because of the entire absence of the pozzolanic reaction inside the system, the degree of hydration is below 100% for up to 14 days[23]. Until now, the whole reaction has taken place between water and clinker particles. [34] This hydration value is above 100% of typical OPC from 14 to 90 days, indicating that the pozzolanic process and cement hydration overlap. After 90 days, the hydration value remains steady, with a little drop for mixes containing more than 20% metakaolin.[24]

For mixes with low metakaolin content, the value of degree of hydration decreases after 90 days. The pozzolanic reaction is now complete. [33]

### 2.10.4 Relationship Between porosity and degree of hydration

When both porosity and hydration are studied over time, a definite relationship can be established. [31] Total, capillary, and gel pores all had R2 values of 0.71, 0.81, and 0.88, respectively, when correlated with degree of moisture. [32] Gel pores had the best correlation, followed by capillary pores, and finally total pores. This suggests that pore refinement is mostly connected to values of degree of hydration exceeding 100 percent. The rise in hydrated phases during the pozzolanic reaction is the reason for this.[22] [29] [30]

# CHAPTER 3: MATERIALS AND METHODOLOGY

## 3.1 Materials

The next section discusses the materials utilised in the production of $LC^3$ blends as well as their characterization, followed by a detailed experimental technique.

### 3.1.1 Coarse aggregate

Natural coarse aggregates, which were utilized in concrete, are available locally, and the source is in Margalla. The coarse aggregate had a maximum aggregate size of 19 mm. Before casting concrete, all materials were thoroughly cleaned. All of the materials utilised in the concrete casting process were SSD (Surface Saturated Dry). The curvature of the Coarse Aggregate Gradation Curve is similar to a "S," indicating that the aggregates are well graded. Figure 1 depicts the coarse aggregate gradation curve.

**Figure 3.1 Coarse Aggregate**

**Table 3.1 Properties of Coarse Aggregate**

| | | | |
|---|---|---|---|
| Dry Weight | A | 3011 g | |
| Super Saturated Dry Weight | B | 3029 g | |
| Submerged Weight | C | 1897 g | |
| Specific Gravity | A/(B-C) | 2.66 | ASTM C127 |
| Absorption | (B-A)/A | 0.6 % | ASTM C127 |
| Dry Rodded Density | | 1631 $kg/m^3$ | ASTM C29 |

**Table 3.2 Sieve Analysis of coarse Aggregate ASTM C136**

| Sieve # | Amount Retained (grams) | | | Amount retained in Percentage (%) | Cumulative Percentage (%) | Percentage Passing (%) |
|---|---|---|---|---|---|---|
| | Trial 1 | Trial 2 | Trail 3 | | | |
| 1 in | 6 | 7 | 11 | 0.41 | 0.41 | 99.59 |
| ¾ in | 10 | 4 | 13 | 0.46 | 0.87 | 99.13 |
| ½ in | 1451 | 1445 | 1457 | 74.52 | 75.39 | 24.61 |
| 3/8 in | 475 | 480 | 470 | 24.4 | 99.79 | 0.21 |
| Pan | 3 | 4 | 5 | 0.21 | 100 | 0 |

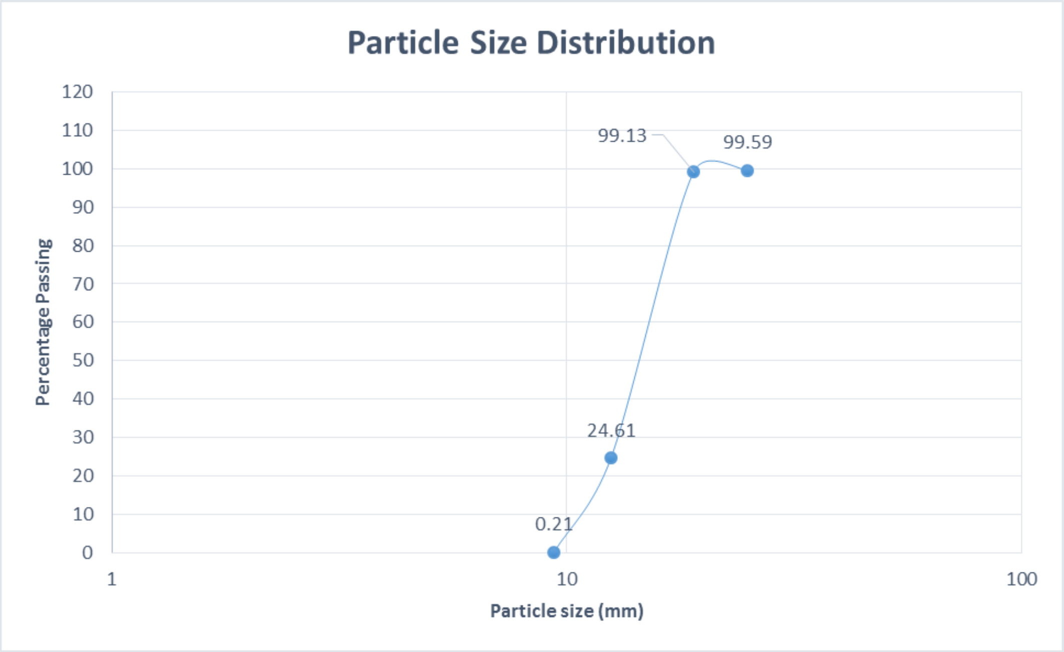


**Figure 3.2 Particle Size Distribution of coarse Aggregate ASTM C136**

### 3.1.2 Fine Aggregate

Concrete sand is readily available in the area. Lawrence Pur is where the sand comes from. We selected sand that was smaller than 4.75 mm in size. The sand was sieved before being used in concrete casting. The sieve used for sieving was the No. 4 Sieve. Sand fineness modulus was in the middle of the range indicated by ASTM Standard.

**Figure 3.3 Sand**

**Table 3.3 Fineness Modulus of Sand ASTM C136**

| Sieve # | Amount Retained (grams) | | | Amount retained in Percentage (%) | Cumulative Percentage (%) | Percentage Passing (%) |
|---|---|---|---|---|---|---|
| | Trail 1 | Trail 2 | Trail 3 | | | |
| #4 | 32.1 | 28.5 | 30.3 | 5.05 | 5.05 | 94.95 |
| #8 | 52.4 | 54.8 | 53.6 | 8.93 | 13.98 | 86.02 |
| #16 | 68.2 | 60.08 | 54.1 | 10.68 | 24.66 | 75.34 |
| #30 | 207.9 | 212.7 | 210.3 | 35.05 | 59.71 | 40.29 |
| #50 | 104 | 103.2 | 103.6 | 17.27 | 76.98 | 23.02 |
| #100 | 88 | 97 | 92.5 | 15.42 | 92.4 | 7.06 |
| #200 | 38 | 42 | 40 | 6.67 | 99.07 | 0.93 |
| Pan | 5.7 | 5.5 | 5.6 | 0.93 | 100 | 0 |
| Fineness modulus (FM) | | | | 2.73 | | |

**Table 3.4 Properties of Fine Aggregate ASTM C128**

| | | | | |
|---|---|---|---|---|
| Mass of Flask | W1 | 12 | 12 | 12 |
| Mass of Flask + Dry Sand | W2 | 61.5 | 63 | 60 |
| Mass of Flask + Dry Sand + Water | W3 | 73 | 74 | 71 |
| Mass of Flask + Water | W4 | 42 | 42 | 42 |
| K | | 1 | 1 | 1 |
| Specific Gravity | S.G | 2.68 | 2.68 | 2.53 |
| Average Specific Gravity | 2.63 | | | |
| Moisture Content | 0.9 % ASTM C566 | | | |

### 3.1.3 Cementitious Materials

Ordinary Portland Cement (OPC Type I) was utilised in the production of concrete and is still widely used today. Fauji Cement Company Limited is the cement's maker. Fauji cement is commonly utilised in Pakistani construction.

Clay which i used in replacement of ordinary portland cement was the clay having kaolinite content were 79% because literature and past studies says clay used in LC3 comppsition should have kaolinite content more than 40% in order to achieve performance similar to OPC.

Calcined clay was used in place of cement in concrete. Calcined clay is made from naturally occurring white china clay. Clay was found in the neighbourhood. The colour is grey white.

Calcined clay initially this clay was in the form of larger form of aggregates so in order to convert these boulders type aggregates into clay having size equal to cement firstly these boulders were decomposed into samll pieces after that two to three times grinding process were carried out in different machines and with the help of labours as well.After grinding process this clay has to pass different sieves so that all impurities should be removed before final passing of sieve number #200.

After clay prepartion this clay than put into different boxes in order to calcined at $850^0$ in firnace.

**Figure 3.4 Calcined Clay**

**Figure 3.5 Cement**

**Table 3.5 Specific Gravity of Cement and Calcined Clay ASTM C 188**

| No. | Cement | Calcined clay |
|---|---|---|
| Weight of sample | 64 g | 64 g |
| Initial reading | 0.42 ml | 0.41 ml |
| Final reading | 20.76 ml | 24.1 ml |
| Total volume displaced | 20.34 ml | 23.69 |
| Density (g/ml) | 3.147 | 2.702 |
| Water density (At 4$^{o}$ C) | 1 g/ml | 1 g/ml |
| Specific Gravity | 3.147 | 2.702 |

**Table 3.6 Properties of Cement and Calcined Clay**

| No. | Cement | Calcined clay |
|---|---|---|
| Colour | Grey | White |
| Fineness | 95 % ASTM C184 | Total passed by No. 200 sieve |

**Methodology**

The study's major goal is to replace cement with recycled concrete aggregate as coarse aggregate, fly ash, and glass powder. Concrete tests were performed to accomplish the study's objectives of fresh concrete qualities, mechanical properties, and durability attributes. To begin, several aggregate tests were conducted for the concrete mix design. Specific gravity, fineness modulus, moisture content, absorption, and oven dry rodded density were all determined during these testing. All of the tests were conducted in accordance with ASTM standards.

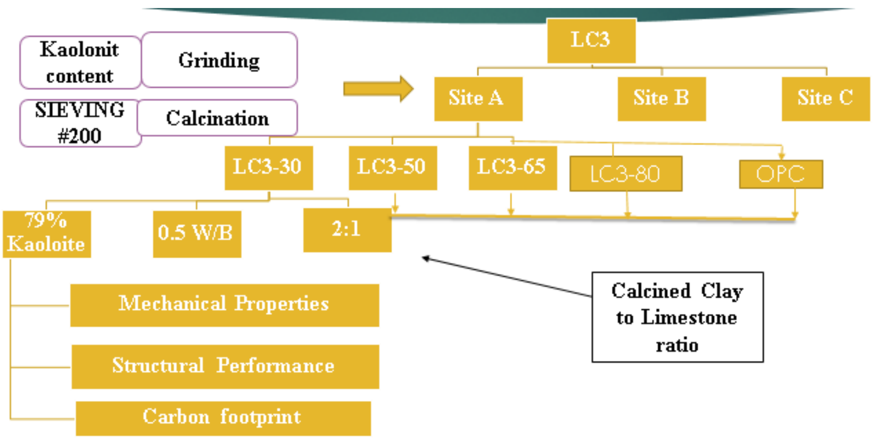


**Figure 3.6 Methodology**

### 3.1.4 Mix Design

After performing test on aggregate and getting values, we made mix design according to standard ACI (American Concrete Institute) code for Control Mix (M1). The ACI Standard ACI 211.1-91 used for selecting proportions for concrete.

**Target Strength**

Compressive Strength = 27.58 MPa

**Target Slump**

75-100 mm

**Maximum Aggregate Size**

19 mm

**Estimation of Mixing Water and Air Content**

From Table given in ACI 211.1, weight of water for slump (75-100mm) and Maximum Aggregate size (19mm) is:

Weight of water = 205 kg/$m^3$

Air Content (Given in Table) = 1.5%

**Selection of Water/Cement Ratio**

Water/Cement ratio and Compressive strength relationship table shows that the w/c for 27.58 MPa is

Water/Cement = 0.54

**Calculation of Cement Content**

Weight of Cement = Weight of water/ (w/c) = 205/0.54

Weight of Cement =380kg/$m^3$

**Estimation of Coarse Aggregate content**

FM of sand = 2.7

Dry Rodded Volume of Coarse Aggregate =1631 kg/$m^3$

On a Dry Rodded basis, table given in ACI 211.1 indicates that 0.63 $m^3$ of coarse aggregate used in each cubic meter of concrete. So

Weight of Coarse Aggregate = 0.63 * 1631 = 1028kg

**Estimation of Fine Aggregate content**

Volume of each material calculated:

Volume of water = 205/1000 = 0.205 $m^3$

Volume of cement = 380/ (3.15x1000) = 0.121 $m^3$

Volume of coarse aggregate = 1028/ (2.66x1000) = 0.386 $m^3$

Volume of entrapped air = 2% of 1$m^3$ = 0.02 x 1.00 = 0.020 $m^3$

Total volume of Materials except Fine Aggregate

= 0.205+0.121+0.386+0.02 = 0.732 $m^3$

Volume of Fine Aggregate = 1 – 0.732 = 0.0.268 $m^3$

Weight of Fine Aggregate = 0.268 x 2.63 x 1000 = 705 kg

### 3.1.5 Trial Mix

After the Mix Design was completed, a trail batch of concrete was made to modify slump, eliminate segregation, and increase strength. The compressive strength of the trial batch was measured after seven days. There were two trail batches created (Control mix and M8 (Maximum Replacement Mix)). The slump cone test was used to determine slump for the experimental batch. The samples were cured for seven days before being put through a compression test to assess compressive strength.

### 3.1.6 Casting and Curing

We created 16 cylinders (100mm X 200mm) and 1 beam for each blend (100mm X 100mm X 500mm). There were a total of 80 cylinders and 5 beams cast.

The samples for each mix were cast after the mix design and trial mix were completed successfully. Making and curing test specimens were done according to ASTM C192 (Cylinders and Beams). To begin with, all of the materials were batched. The components were then placed in a mixer for dry mixing for 3 minutes. After that, water was added to the dry mix, and the mixer was turned on for three minutes. The tests were carried out on new concrete to establish its qualities. The concrete was then poured into moulds. After drying for 24 hours, the moulds were demolded. Samples were demolded and then cured in a water pond. After 28 days of curing, samples were tested to establish their mechanical and durability properties.

# CHAPTER 4: EXPERIMENTAL PROCEDURE

## 4.1 Fresh Concrete

### 4.1.1 Workability

Workability of concrete is defined as ease of placement of concrete According to the ASTM C143, this test method is used to determine slump of fresh concrete. The slump cone test was done to determine slump of fresh concrete. The dimension of slump cone mold has height of 300 mm, top diameter 100 mm and base diameter 200 mm. For performing test, placed the mold on rigid, flat, free of vibration surface and level surface. Hold mold firmly in place and by using scoop, poured the concrete in three layers. The volume of each layer is 1/3 of mold volume. Rod the layer 25 times with tamping rod by using gentle hand. Top surface of concrete was strike off by temping rod in screeding and rolling motion. Removed the mold by raising mold in a steady and vertical direction. Measured the slump by taking distance from top of mold to top of displaced surface of concrete.

**Figure 4.1 Control Mix Slump**

**Figure 4.2 Mix  Slump**

### 4.1.2 Fresh Concrete Density

ASTM C138 test method is used to determine fresh density of concrete and this standard provide formulas to determine yield, air content and cement content of concrete. For determining fresh concrete unit weight, first of all, measured the volume of mold and then determined the mass of mold. Poured the concrete into mold in 3 direction and each layer rodded 25 times. After pouring, finishing was done by using flat strike-off plate. Measured the weight of mold with concrete. The density is determined by formula given below.

Density: $D = (M_c - M_m)/V_m$

Where $M_c$ is mass of measure with concrete, $M_m$ is mass of measure and $V_m$ of measure. The unit of density is equal to $kg/m^3$.


**Figure 4.3 Fresh Concrete Density**

## 4.2 Mechanical Properties

### 4.2.1 Hardened Concrete Density

According to ASTM C642-13, the density of concrete is determined by dividing the weight of specimen by specimen volume.

ρ= M/V

Where m is mass of specimen and V is volume of specimen.

### 4.2.2 Compression Test

The compression test is performed according to ASTM C39 and it is performed to determine characteristic compressive strength of concrete. Compressive strength is defined as ability of concrete specimen to resist load before failure. It is very important test because this test  gives picture about characteristics of concrete.

UTM machine is used for performing test. The size of specimen, cylinders are 100 mm X 200 mm. From each mix 6 numbers of specimens were tested for compression. For one day , 3 days,7 days , 14 days and 28 days specimens were test with 2 specimens for each mix design. For compression test, the specimens were removed from curing tank after complete curing time. For 24 hours, the specimens were placed in lab for dry in air. Afterward, the specimen were placed between plates of UTM machine. The load was applied on cylindrical specimen. The load was applied in controlled manner so that loading rate was same during whole test. The loading rate, which applied on cylinders specimen was 0.25 MPa/sec.

**Figure 4.4 Specimen placement in UTM for Compression Test**

### 4.2.3 Split Tensile Test

According to ASTM C496, split tensile test is performed on concrete cylinder having size of 100 mm X 200 mm to determine split tensile strength of cylinder specimen. Split tensile strength is maximum stress on tension face side. It is determined by splitting of specimen along vertical diameter. For split tensile test, test specimens were removed from curing tank after completing curing period. After 24 hours of removal from curing tank, the specimen was placed in assembly shown in figure. The assembly was placed between plates of UTM machine. The load was applied on the assembly continuously and without shock

**Figure 4.5 Universal Testing Machine**

**Figure 4.6 Assembly for Split Tensile Test**

### 4.2.4 Flexure Test

This test is determined ability of beam to resist the failure in bending. The flexural test is performed on beam (100 X 100 X 500 $mm^3$). This test is performed according to ASTM C78 to determine flexural strength of beam. The flexural strength of concrete is also known as modulus of rupture. It is indirect measurement of tensile strength of concrete. UTM machine is used for this test. Third point loading method was used for this test. For test, the lines were drawn as just shown in figure. Placed the beam between plates of UTM machine. The beam was placed on supports (Roller Supports). The steel rod was placed on beam at midpoint and loading was started. Load was applied on rod and transfer to the beam as point load. During testing, it is necessary that loading is applied at uniform rate to the breaking point and load was applied continuous and without shock

**Figure 4.7 Flexural test of Beam**

### 4.2.5. Stress-Strain curve and modulous of elasticity of concrete

This test is performed to determined the stress strain behaviour of Control sample and LC3-30 , LC3-50 , LC3-65 and LC3-80 in UTM machine .After ploting stress-strain curve modulous of elasticity is calculated by measuring of slope of every curve .After ploting stress-strain curve of control sample and LC3 variations of each sample toughnes index was measured by calculating aread under each curve.

### 4.2.6. Beams details with materials properties

Four beams were casted one was made from normal ordinary Portland cement concrete & other three beams were made with LC3 concrete (LC3-50,LC3-65,LC3-80) with respect to calcined clay and limestone replacement with ordinary Portland cement.These beams were taken on the base of compressive strength which were already performed during mehanical properties of ordinary portland ement concrete and LC3 Concrete .Beams length was 3.15m with the cross section of 127mm x 203mm.

Reinforcement detail were as top two compression bar was 10mm dia and two bras of bottom tensile reinforcement were having dia 12mm and stirrups dia were 6mm @5”C/C .

5’’x8’’x 10.5’ Long RC Beams

- Total 4 beams were casted.
- 1 simply reinforced concrete beams
- 2 reinforced with same bars & LC3- 50 Concrete
- 3 reinforced with same bars but concrete was LC3-65
- reinforced with same bars but concrete was LC3-80

**Figure 4.8 Casting of RCC Beams**

Calculation of materials like coarse aggragte , fine aggregate , water, limestone and calcined clay for each beam as shown in below table .Along with concrete material data next table is showing the reinforcement data like reinforcement diameter , steel yielding strength and modulous of elasticity of steel reinforcement .

Depending upon the results discussed, LC3 50 65 and 80 was chosen in ordr to find Structural performance on RCC Beams four point bending test.

**Table 4.1 Calculation of materials for RCC Beams**

| Calculation of materials | | | | | | |
|---|---|---|---|---|---|---|
| **Specimen ID** | **Weight of Clay (kg/m3)** | **Weight of cement (kg/m3)** | **Weight of fine Agg(kg/m3)** | **Weight of coarse Agg (kg/m3)** | **Amount of water (lit/m3)** | **Weight of Limestone (kg/m3)** |
| **OPC** | 0.00 | 32.01 | 64.03 | 96.04 | 16.01 | 0.00 |
| **LC3-50** | 10.67 | 16.01 | 64.03 | 95.04 | 16.01 | 5.34 |
| **LC3-65** | 7.47 | 20.8 | 64.03 | 96.04 | 16.01 | 3.73 |
| **LC3-80** | 4.27 | 25.61 | 64.03 | 95.04 | 16.01 | 2.13 |

**Table 4.2 Reinforcement Details**

| **Bar** | **Diametre (mm)** | **Fy(Mpa)** | **Es (Gpa)** |
|---|---|---|---|
| **Plain bars** | 6 | 393.65 | 208.400 |
| **Type-A** | 10 | 505.77 | 148.758 |
| **Type-B** | 12 | 491.37 | 185.425 |

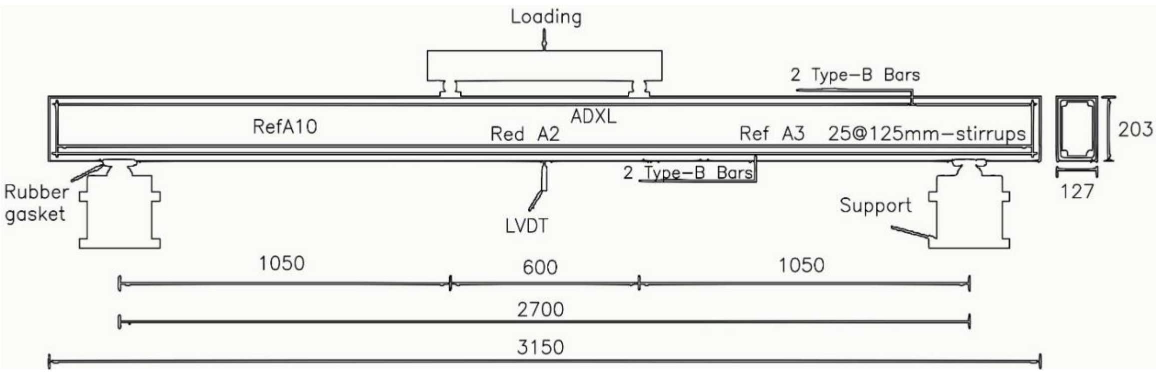


**Figure 4.9 Beam test setup (all dimensions are in mm,15mm cover provided to reinforcement)**

## 4.3. Experimental details with test setup

A four point bending test were conducted on each beam in order to check structural flexural performance of each beam and results were also verified through fem analysis as well.

Two roller support were kept on each left and right support having dia 75 mm and one assembly were kept above exactly at the center of beam having distance were apart as loading point were 2 feet. the ultimate beam loadind capacity was 22KN and loading rate was 0.49KN/s upto failure of each beams. A gasket of thicknes 6mm was used to certify the uniform transfer of load from the beam to the support pedestal during a static loading.. Two LVDT's were placed one at exactly at mid span of beam and one were exactly at the loading point of beam in order to find deflection of beam during loading .

Microscope were used to find the cracks pattern, crack width and roller were used to find the crack height and crack spacing on beams during the crack propagation when load were applied.

**Figure 4.10 Experimental setup of RCC Beams**

Cracks were measured using a microscope and with the help of flashlight to make the crack appear more clear and easier to be measured.

Least count (1 unit) on the microscope represents 0.002mm of length.

**Figure 4.11 Microscope to fined out crack width**

## 4.4. FAE ANALYSIS

Finite element analysis were also carried of these beams with the help of CDP (Concrete demage plasticity model) for both compression and as well as tension demage by using abaquas software.

From stress strain data ,elastic modulus, yield stress and with the help of CDP models we calculated the inelastic strain and demage papameter for compression and for tension cracking strain and demage parameter were also meaured by using CDP model as shown in figure.

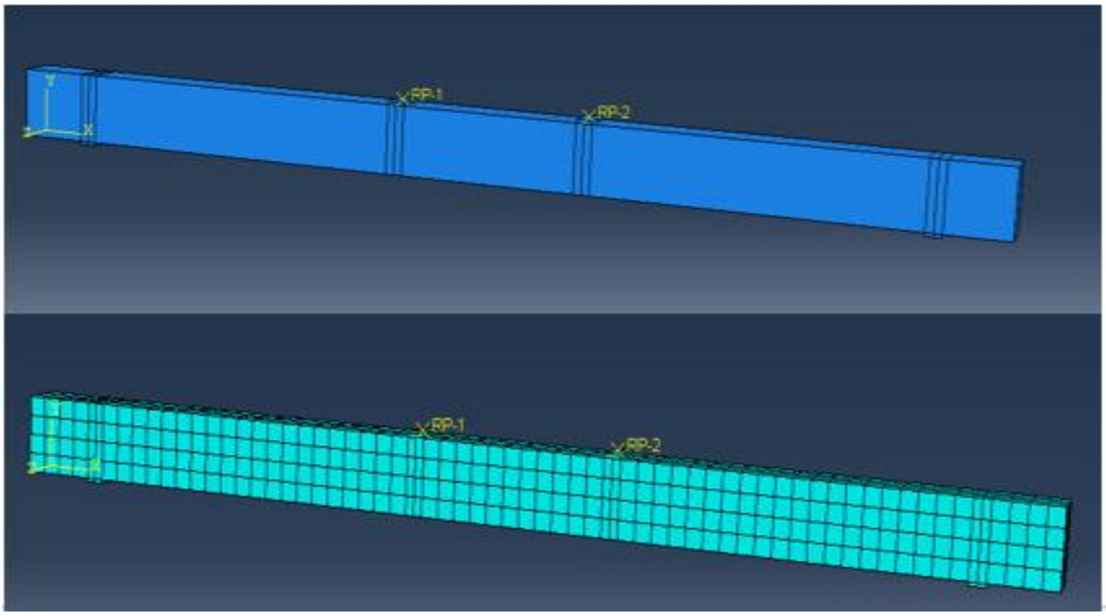


**Figure 4.12 Abaquas modeling sketch**

# CHAPTER 5: RESULTS AND DISCUSSION

## 5.1 Global Warming

Carbon dioxide ($CO_2$) is a byproduct of a chemical conversion process limestone ($CaCO_3$) is converted to lime (CaO) to produce clinker, causing global warming .

As of 2018 roughly 4 billion tons of cement was produced annually. This accounts for nearly 8% of total global $CO_2$ emissions.

### 5.1.1 Substitute

A percentage of cement clinker should be replaced by some other cementitious material to lower $CO_2$ emissions for example Fly ash, Silica Fumes, and Slag.

The sources of these SCMs may be compromised in near future. like the world is moving toward renewable energy production so coal power stations are being replaced by environment-friendly processes.

Clay :

Clay, containing the alumina-silicate minerals, represents 74% of the Earth's crust .

There are over thirty types of clay, Major clay include kaolinite, bentonite .

Kaolinite is Clay Mineral, having the chemical formula $Al_2Si_2O_5(OH)_4$.

## 5.2 Clay Selection

There are three type of clay in terms of its minearlogical composition first one is kalonitic clay second one is montmorolinite clay and third one is illite clay in order to make LC3 cement we used kaolonitic clay because we had seen thermal decomposition of the different clay type and have decomposition in different ranges. They represent the heat which is absorb by the loss of hydro oxide from the structure which is called dehydrooxidation. Here we had seen different clay types have dehydro oxidation in different temperature. The dehydro oxidation for kaolinite is in 400 to 600 degree c this represents that how much kaolinite is present in a clay.Kaolonitic clay has given us pozzolanic reaction in which portlandite is consumed and converted into CSH gel so more strength were come with in LC3 variations.After calcination this kaolonite converted into metakaoloine.Kaolonitic clay should have kaolonitic content more than 40%

### 5.2.1 Kaolonite content

To determine the kaolinite content, a basic oven and clay sample was used. The clay was heated at different temperatures of 200C, 400C, 600C and 800C for 1 hour each and weighted to see the loss in mass. The following equation is used to find the kaolinite content

$$wt(\%\ kaolinite) = \frac{wt_{400C} - wt_{600C}}{wt_{200C} - wt_i} \times 7.17 \times 100.$$

Literature states that 40% kaolinite content is required for comparable strength gain and our test procedure gave 79.94% kaolinite content in our sample clay.

**Table 5.1 Kaolonite determination procedure**

| **Description** | **Crucible (gms)** | **Crucible (gms)** | **Crucible (gms)** |
|---|---|---|---|
| Weight of empty Crucible after heating at 800 C for 1 Hour ( $wt_i$ ) | 51.8897 | 51.9062 | 49.2723 |
| Sample weight | 10.0017 | 10.0022 | 10.0016 |
| Weight of Crucible after heating at 200 C for 1 Hour ( $_{wt200\ c}$ ) | 61.7904 | 61.8016 | 59.1731 |
| Weight of Crucible after heating at 400 C for 1 Hour ( $_{wt400\ c}$ ) | 61.7387 | 61.8016 | 59.1731 |
| Weight of Crucible after heating at 600 C for 1 Hour ( $_{wt600\ c}$ ) | 60.5961 | 60.7719 | 57.9739 |
| $Wt\%_{kaolinite}$ | 82.74 | 71.87 | 83.77 |
| Average $Wt\%_{kaolinite}$ = 79.94% | | | |

### 5.2.2 Calcination

Most important is the calcination must be high enough to completely remove the waste and hydroxyls from the structure and this create structural disorder which enhances its reactivity but if we go too high then we get decrease in reactivity by the loss of surface and then crystallization so this is what is shown here u can see the dihydroxylation takes place between 500 and 650 then we have this window during which we have moved this product before crystallization but infact we find that if we stop at 600 this does is very optimal terms of reactivity the optimal range is about 700 to 800 and we can understand this if we make more sophisticated analysis with Al NMR so what Al NMR shows is the local environment around the aluminium ions and particularly the presence of this 5 Al NMR is the one that gives this extra activity now we can see the amount of this by increases between 600 and 800 so we can also see the importance of correct fire window her so her we see in blue the medium diameter of the particles of clay and in the red the surface area.

**Figure 5.1 Calcination of clay**

**Figure 5.2 Limestone output**

**Figure 5.3 Clay output**

This kaolonitic clay and limestone should be purvarazied , grinded and than mutt pass through sieve number #200 so that their particle size should match with the particle size of the ordinary portland cement .more finer will be the particle more reaction would take place during hydrtion process.

## 5.3 Mechanical Properties of Concrete

The mechanical properties of concrete had been calculating using UTM machine.

### 5.3.1 Compressive Strength

Target compressive strength of concrete (Control Mix) was 27 MPa. We have achieved 26.2 Mpa strength at 28 days after taking average of 2 samples which were tested after 28 days of curing. Compression test for OPC were carried out at 1 day ,3 days , 7 days , 14 days and 28 days respectively . A clear trend of strength development is showing in below table and bar graph where at one day OPC strength was 4.192 MPa , at 3 days strength was 10.48 MPa , at 7 days strength was 17.03 MPa , at 14 days strength was 23.58 MPa and at 28 days strength was 26.2 MPa.

Similarly Compression test for $LC^3$-30 were carried out at 1 day ,3 days , 7 days , 14 days and 28 days respectively . A clear trend of strength development is showing in below table and bar graph where at one day $LC^3$-30 strength was 3.35 MPa , at 3 days strength was 8.384 MPa , at 7 days strength was 13.624 MPa , at 14 days strength was 18.864 MPa and at 28 days strength was 20.96 MPa.

Similarly Compression test for $LC^3$-50 were carried out at 1 day ,3 days , 7 days , 14 days and 28 days respectively . A clear trend of strength development is showing in below table and bar graph where at one day $LC^3$-50 strength was 3.94 MPa , at 3 days strength was 9.8512 MPa , at 7 days strength was 16.0082 MPa , at 14 days strength was 22.1652 MPa and at 28 days strength was 24.628 MPa.

Similarly Compression test for $LC^3$-65 were carried out at 1 day ,3 days , 7 days , 14 days and 28 days respectively . A clear trend of strength development is showing in below table and bar graph where at one day $LC^3$-65 strength was 3.98 MPa , at 3 days strength was 9.956 MPa , at 7 days strength was 16.1785 MPa , at 14 days strength was 22.401 MPa and at 28 days strength was 24.89 MPa.

Similarly Compression test for $LC^3$-80 were carried out at 1 day ,3 days , 7 days , 14 days and 28 days respectively . A clear trend of strength development is showing in below table and bar graph where at one day $LC^3$-80 strength was 4.066 MPa , at 3 days strength was 10.1656 MPa , at 7 days strength was 16.51911 MPa , at 14 days strength was 22.8726 MPa and at 28 days strength was 25.414 MPa.

**Table 5.2 Compressive strength at different days**

| **MIX Design** | **CompStrength at 1 Day** | **Comp Strength at 3 Days** | **Comp Strength at 7 Days** | **Comp Strength at 14 Days** | **Comp Strength at 28 Days** |
|---|---|---|---|---|---|
| **OPC** | 4.192 | 10.48 | 17.03 | 23.58 | 26.2 |
| **LC3-30** | 3.35 | 8.384 | 13.624 | 18.864 | 20.96 |
| **LC3-50** | 3.94 | 9.8512 | 16.0082 | 22.1652 | 24.628 |
| **LC3-65** | 3.98 | 9.956 | 16.1785 | 22.401 | 24.89 |
| **LC3-80** | 4.06624 | 10.1656 | 16.51911 | 22.8726 | 25.414 |

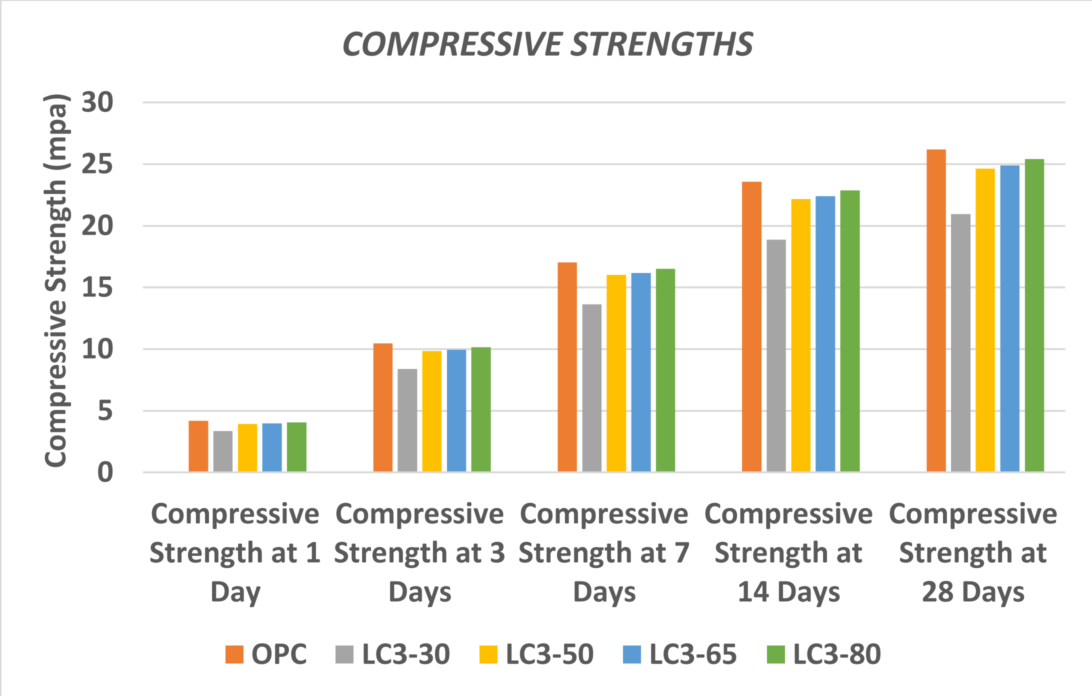


**Figure 5.4 Bar graph of compressive strength at different days**

I had performed compression test on cylinders of 4 by 8 inch size LC3-30 , LC3-50 , LC3-65 , LC3-80 along with control OPC samples.

These are the results of 1 day , 3 days , 7 days ,14 days and 28 days testing.

- We can see a clear trend of strength development right from one day to 28 days control sample of normal OPC get the higher strength as compared to others all samples.
- After OPC , $LC^3$-80 get the second higher strength , in which I replaced 20% cement with calcined clay and limestone.
- After $LC^3$-80 , $LC^3$-65 get the third higher strength , in which I replaced 35% cement with calcined clay and limestone.
- After $LC^3$-65 , $LC^3$-50 get the fourth higher strength , in which I replaced 50% cement with calcined clay and limestone.

- And lastly $LC^3$-50 , $LC^3$-30 get the strength , in which I replaced 70% cement with calcined clay and limestone.
- These ultimate strength indicates that replacement less than or equal to 50% with cement , we can get the compressive strength nearly equal to OPC ,with come percentages of less or more than OPC strength.
- Within the $LC^3$ system, the specimen having highest Calcined clay and limestone amount exhibits lowest compressive strength

When comparing with OPC, Clay being more water absorbing material results in less excess water pores hence even at a high water content (0.5) $LC^3$ yields better results

### 5.3.2 Split tensile Strength

I had performed split tensile test on cylinders of 4 by 8 inch size LC3-30 , LC3-50 , LC3-65 , LC3-80 along with control OPC samples.

These are the results of 28 days testing.

- At 28 days control sample of normal OPC get the higher strength as compared to others all samples.
- After OPC , $LC^3$-80 get the second higher strength , in which I replaced 20% cement with calcined clay and limestone.
- After $LC^3$-80 , $LC^3$-65 get the third higher strength , in which I replaced 35% cement with calcined clay and limestone.
- After $LC^3$-65 , $LC^3$-50 get the fourth higher strength , in which I replaced 50% cement with calcined clay and limestone.

- And lastly $LC^3$-50 , $LC^3$-30 get the strength , in which I replaced 70% cement with calcined clay and limestone.
- These ultimate strength indicates that replacement less than or equal to 50% with cement , we can get the compressive strength nearly equal to OPC ,with come percentages of less or more than OPC strength.
- Within the $LC^3$ system, the specimen having highest Calcined clay and limestone amount exhibits lowest compressive strength

When comparing with OPC, Clay being more water absorbing material results in less excess water pores hence even at a high water content (0.5) $LC^3$ yields better results.

**Table 5.3 Split tensile test results at 28 days**

| Mix Design | Tensile Strength at 28 Days (Mpa) |
|---|---|
| OPC | 2.88 |
| LC3-30 | 1.75 |
| LC3-50 | 2.39 |
| LC3-65 | 2.42 |
| LC3-80 | 2.66 |

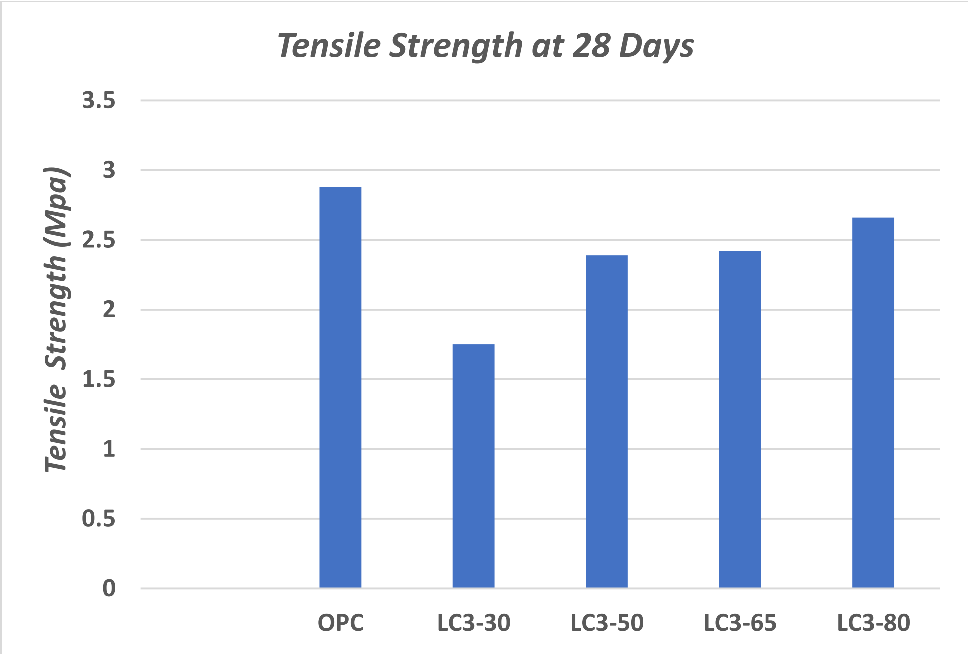


**Figure 5.5 Bar graph of split tensile results**

### 5.3.3 Flexural Strength

I had performed Flexural test on beams of 100mm by 200mm into 500mm size $LC^3$-30 , $LC^3$-50 , $LC^3$-65 , $LC^3$-80 along with control OPC samples.

These are the results of 28 days testing.

- At 28 days control sample of normal OPC get the higher strength as compared to others all samples.
- After OPC , $LC^3$-80 get the second higher strength , in which I replaced 20% cement with calcined clay and limestone.
- After $LC^3$-80 , $LC^3$-65 get the third higher strength , in which I replaced 35% cement with calcined clay and limestone.
- After $LC^3$-65 , $LC^3$-50 get the fourth higher strength , in which I replaced 50% cement with calcined clay and limestone.

- And lastly $LC^3$-50 , $LC^3$-30 get the strength , in which I replaced 70% cement with calcined clay and limestone.
- These ultimate strength indicates that replacement less than or equal to 50% with cement , we can get the compressive strength nearly equal to OPC ,with come percentages of less or more than OPC strength.

Within the LC3 system, the specimen having highest Calcined clay and limestone amount exhibits lowest compressive strength

When comparing with OPC, Clay being more water absorbing material results in less excess water pores hence even at a high water content (0.5) $LC^3$ yields better results.

**Table 5.4 Flexural strength at 28 days**

| **Mix Design** | **Flexural Strength at 28 Days** |
|---|---|
| OPC | 5.6604 |
| LC3-30 | 3.6546 |
| LC3-50 | 4.7556 |
| LC3-65 | 4.9554 |
| LC3-80 | 5.0364 |

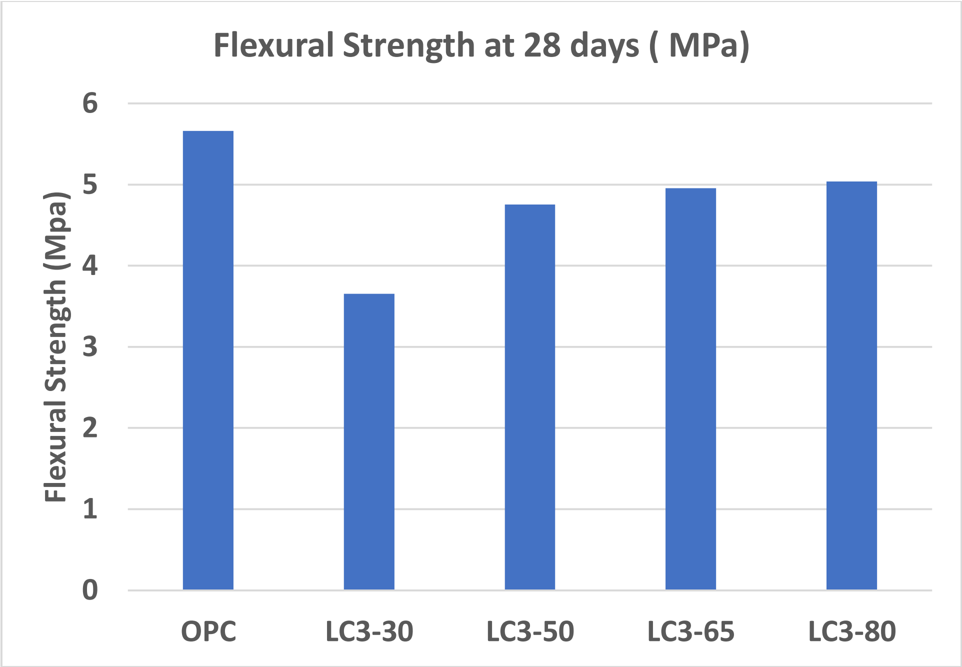


**Figure 5.6 Bar graph of Flexural strengths**

- Beams were casted for each formulation and tested at 28 days
- The flexural strength of LC3 specimen is more than OPC.
- It shows that with addition of calcined clay, the ductility of the mix increases.

Stress-Strain curve

I had performed stress- strain test on cylinders of 4 by 8 inch size LC3-30 , LC3-50 , LC3-65 , LC3-80 along with control OPC samples.

These are the results of 28 days testing.

- At 28 days control sample of normal OPC get the higher strength as compared to others all samples.

- After OPC , $LC^3$-80 get the second higher strength , in which I replaced 20% cement with calcined clay and limestone.
- After $LC^3$-80 , $LC^3$-65 get the third higher strength , in which I replaced 35% cement with calcined clay and limestone.
- After $LC^3$-65 , $LC^3$-50 get the fourth higher strength , in which I replaced 50% cement with calcined clay and limestone.
- And lastly $LC^3$-50 , $LC^3$-30 get the strength , in which I replaced 70% cement with calcined clay and limestone.
- These ultimate strength indicates that replacement less than or equal to 50% with cement , we can get the compressive strength nearly equal to OPC ,with come percentages of less or more than OPC strength.
- Within the LC3 system, the specimen having highest Calcined clay and limestone amount exhibits lowest compressive strength

When comparing with OPC, Clay being more water absorbing material results in less excess water pores hence even at a high water content (0.5) LC3 yields better results.

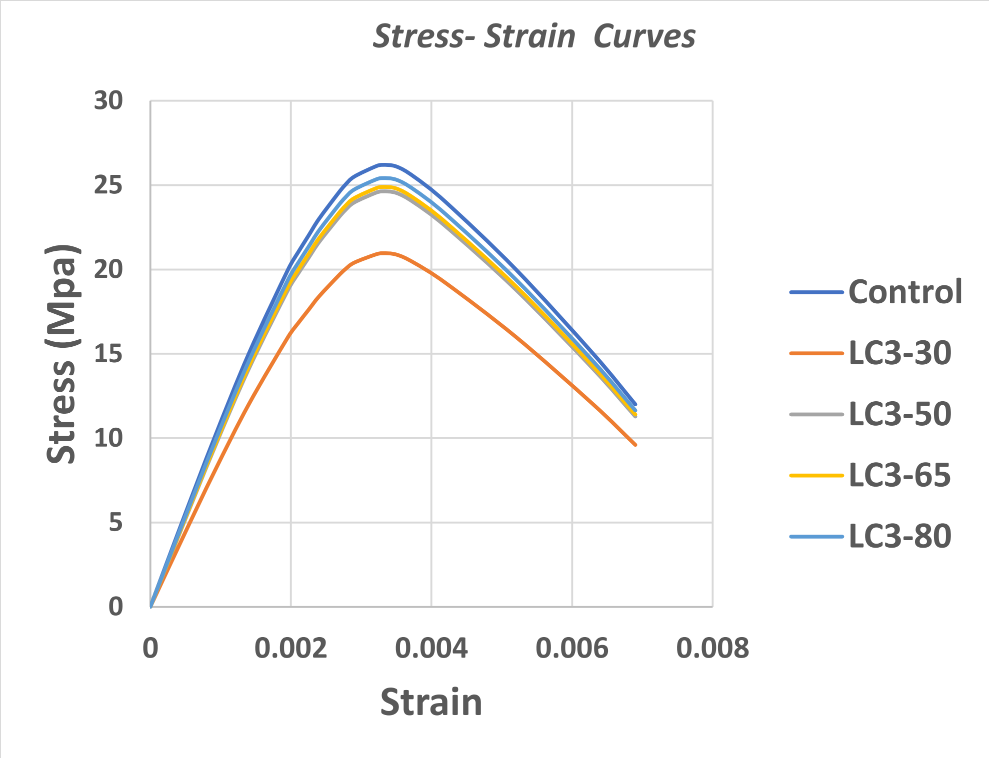


**Figure 5.7 Stress-Strain curves**

Stress-Strain curves of LC3 Concerte shows exactly same trend as normal ordinary portland cement concrete.LC3 Concrete is showing ductiltiy and modulus of elasticity at material level testing same as ordinary portland cement concrete . The Stress-Strain of LC3 is comparable to OPC despite reductions in the amount of cement. The addition of calcined clay to the mixture appears to increase its ductilityas well. Replacement in a form of Calcined Clay and Lime stone within LC3 variation's strength is going to be increased as shown in Graph .

### 5.3.4 Toughness

I had performed stress- strain test on cylinders of 4 by 8 inch size LC3-30 , LC3-50 , LC3-65 , LC3-80 along with control OPC samples.

These are the results of 28 days testing and from each curve of stress strain i calculated the area under these curves in order to find the toughness of each samples.

- At 28 days control sample of normal OPC get the higher toughness as compared to others all samples.
- After OPC , $LC^3$-80 get the second higher toughness , in which I replaced 20% cement with calcined clay and limestone.
- After $LC^3$-80 , $LC^3$-65 get the third higher toughness , in which I replaced 35% cement with calcined clay and limestone.
- After $LC^3$-65 , $LC^3$-50 get the fourth higher toughness , in which I replaced 50% cement with calcined clay and limestone.
- And lastly $LC^3$-50 , $LC^3$-30 get the toughness , in which I replaced 70% cement with calcined clay and limestone.
- These ultimate toughness indicates that replacement less than or equal to 50% with cement , we can get the toughness nearly equal to OPC ,with come percentages of less or more than OPC strength.
- Within the LC3 system, the specimen having highest Calcined clay and limestone amount exhibits lowest toughness.

When comparing with OPC, Clay being more water absorbing material results in less excess water pores hence even at a high water content (0.5) LC3 yields better results.

**Table 5.5 Toughness index**

| Mix ID | Toughness |
|---|---|
| OPC | 124.95 |
| LC3-30 | 99.95 |
| LC3-50 | 117.45 |
| LC3-65 | 118.7 |
| LC3-80 | 121.2 |

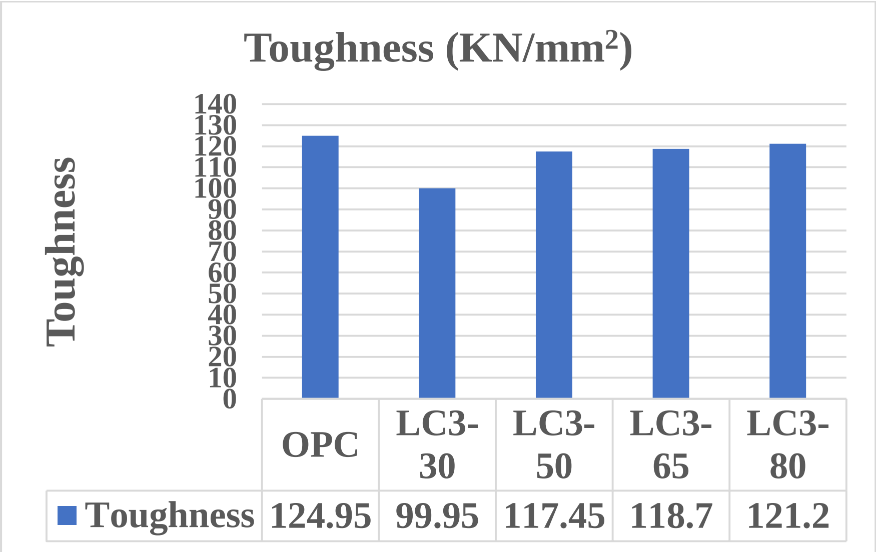


**Figure 5.8 Bar graph of Toughness index**

## 5.4 Conclusion

PHASE-2

The following result were drawn from the above experimental results

- 1: it was found from the above results that replacement of calcined clay and lime stone (2:1) enhance mechanical performance in OPC .
- 2: From the test outcomes on compressive strength of concrete LC3-80 gives resutls nearly equal to OPC concrete but replacement of calcined clay and limestone less than or equal to 50% gives results nearly equal to OPC concrete.
- 3: From the test outcomes on split strength of concrete LC3-80 gives resutls nearly equal to OPC concrete but replacement of calcined clay and limestone less than or equal to 50% gives results nearly equal to OPC concrete.
- 4: From the test outcomes on flexure strength of concrete LC3-80 gives resutls nearly equal to OPC concrete but replacement of calcined clay and limestone less than or equal to 50% gives results nearly equal to OPC concrete.
- 5: From stress-strain data we can conclude that concrete LC3-80 gives resutls nearly equal to OPC concrete but replacement of calcined clay and limestone less than or equal to 50% gives results nearly equal to OPC concrete.

Depending upon the results discussed, LC3-50 , LC3-65 and LC3-80 was chosen in order to find Structural performance on RCC Beams four point bending test.

PHASE-3

The following result were drawn from the above experimental results of beams having four point bending test.

## 5.5 Results and discussions

Four beams were tested process as already been discussed above using four point bending test results

## 5.6 Load-Deflection Relationship

When load were applied on beams mid span deflection were measured at the exact centre of beam and simultaneously at the centre of two applied loading point during four point bending test.initially when load were applied all beams were uncracked and stiff when further load is applied first crack appeared approximatly at the centre span of beam as flexure cracks.

**Table 5.6 Structural Failure Mode**

| **Specimen ID** | **First crack load (KN)** | **Ultimate load (KN)** | **First Crack deflection (mm)** | **Ultimate deflection (mm)** |
|---|---|---|---|---|
| OPC | 1.962 | 19.62 | 5.04 | 15 |
| LC3-50 | 1.52 | 17.658 | 5.25 | 16.96 |
| LC3-65 | 1.49 | 18.54 | 5.22 | 16.5 |
| LC3-80 | 1.55 | 18.83 | 5.19 | 16.17 |

### 5.6.1 OPC Beam

OPC Beam under four point loading test the initial crack was developed at 1.962KN with the initial deflection of 5.04mm at the mid span of beam .The ultimate failure load on OPC beam was 19.62KN with the ultimate mid span deflection of 15mm.Cracks were developed at the centre of beam initially than these cracks propogates in the upper direction of beam and when load were continously increasing more crack were genertated both at the right hand side and left hand side ,these cracks were also propogates during the load increment time.The number of cracks occurs in OPC beam were 17 with average spacing of 12.7cm.

### 5.6.2 LC$^3$-50

LC3-50 Beam under four point loading test the initial crack was developed at 1.52KN with the initial deflection of 5.24mm at the mid span of beam .The ultimate failure load on LC3-50 beam was 17.65KN with the ultimate mid span deflection of 16.96mm.Cracks were developed at the centre of beam initially than these cracks propogates in the upper direction of beam and when load were continously increasing more crack were genertated both at the right hand side and left hand side ,these cracks were also propogates during the load increment time.The number of cracks occurs in LC3-50 beam were 17 with average spacing of 13.175cm.

### 5.6.3 LC$^3$-65

LC3-65 under four point loading test the initial crack was developed at 1.49KN with the initial deflection of 5.22mm at the mid span of beam .The ultimate failure load on OPC beam was 18.54KN with the ultimate mid span deflection of 16.5mm.Cracks were developed at the centre of beam initially than these cracks propogates in the upper direction of beam and when load were continously increasing more crack were genertated both at the right hand side and left hand side ,these cracks were also propogates during the load increment time.The number of cracks occurs in LC3-65 beam were 18 with average spacing of 13.18cm.

### 5.6.4 LC$^3$-80

LC3-80 Beam under four point loading test the initial crack was developed at 1.55KN with the initial deflection of 5.19mm at the mid span of beam .The ultimate failure load on OPC beam was 18.83KN with  the ultimate mid span deflection of 16.17mm.Cracks were developed at the centre of beam initially than these cracks propogates in the upper direction of beam and when load were continously increasing more crack were genertated both at the right hand side and left hand side ,these cracks were also propogates during the load increment time.The number of cracks occurs in LC3-80 beam were 18 with average spacing of 12.7cm.

## 5.7 FAE Analysis

The computational data and experimental model showed great agreement as a result of load deflection, as shown in Figure

This means that the static curve experiment of beam agrees great with the curve of beam model up to initial cracking of loads; After that loading, the stiffness of the beam model decreases as compared to the experimental curve, that can be related to the uniform crack propagation in the beam model. However, the beam model becomes stiffer after the 9th damage level towards failure than the experimental beam curve. Maybe lack of incorporation of the bond modelling between concrete and rebar were caused by these variations.

**Table 5.7 Comparison of EXP & FAE Deflectons**

| Beam ID | Mid-span Deflection (mm) | | Error % | Error % |
|---|---|---|---|---|
| | Experimental | FEA | | |
| OPC | 15 | 12.68 | 0.1546667 | 15.466667 |
| LC3-50 | 16.96 | 13.78 | 0.1875 | 18.75 |
| LC3-65 | 16.5 | 13.44 | 0.1854545 | 18.545455 |
| LC3-80 | 16.17 | 13.14 | 0.187384 | 18.738404 |

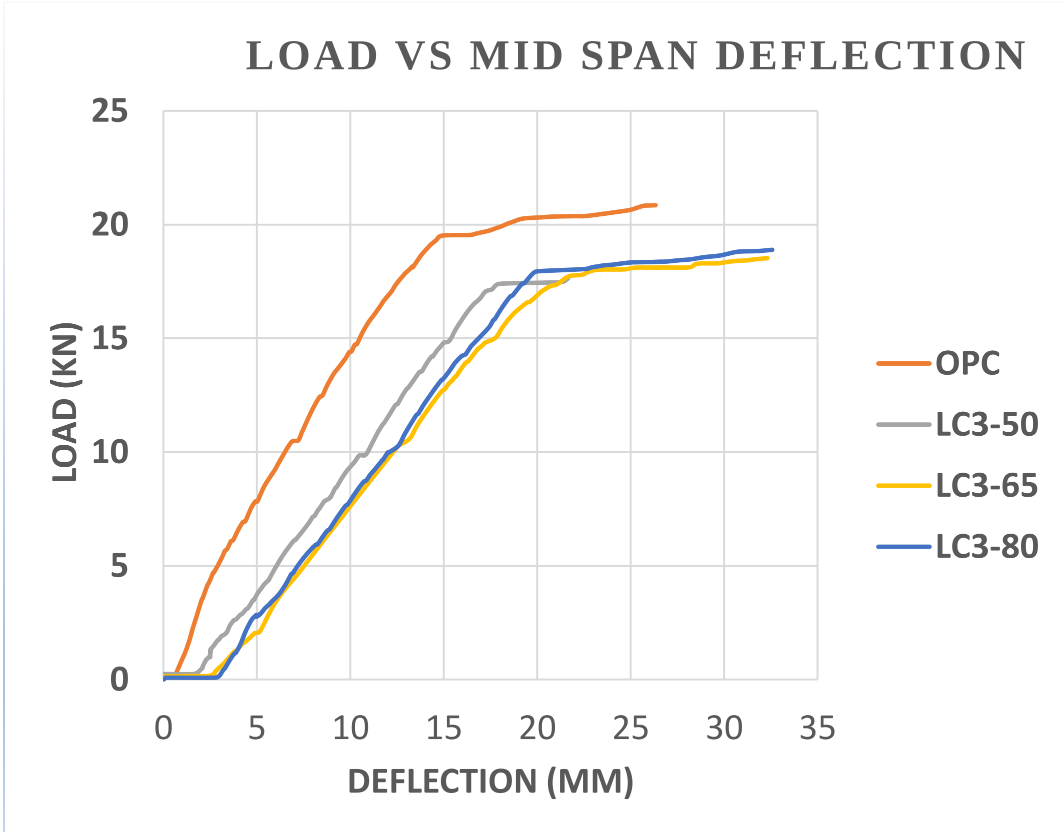


**Figure 5.9 Experimental curves of RCC Beams**

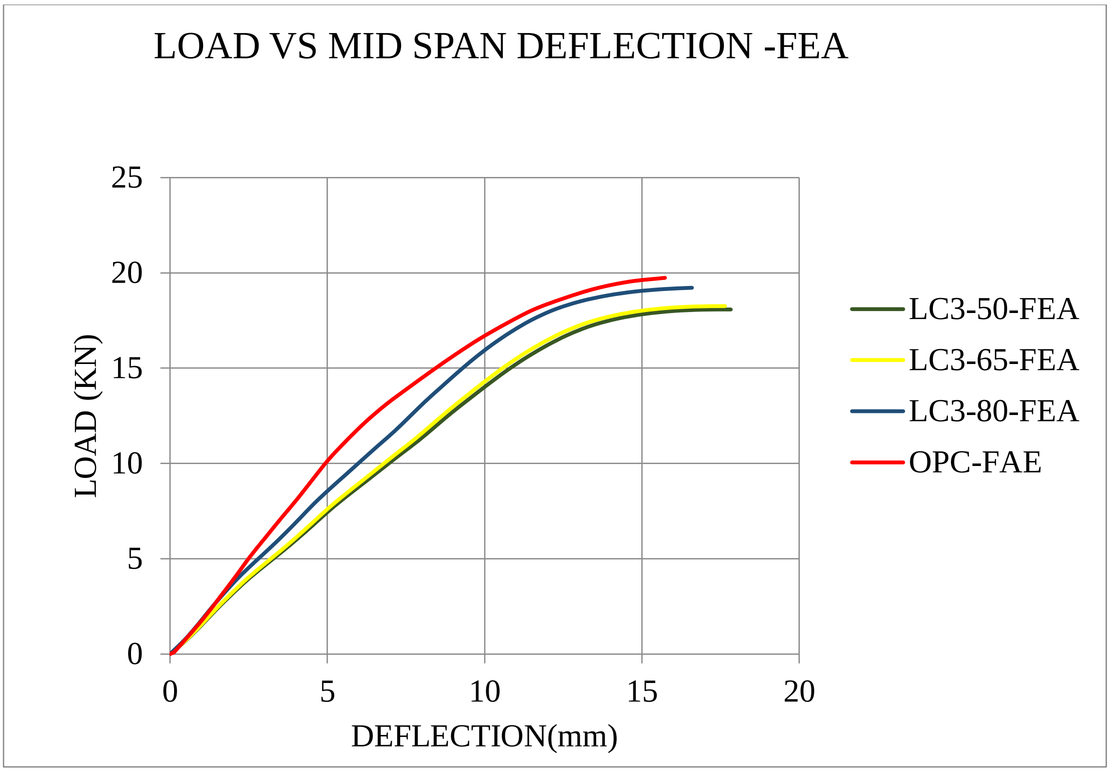


**Figure 5.10 FEA Curves of all RCC Beams**

## 5.8 Comparison of peak loads

- When we compare peak loads of all beam samples than control sample of beam which is made up of ordinay portland cement shows higher peak load as compared to others samples.
- After OPC , $LC^3$-80 get the second higher prak load , in which i replaced 20% cement with calcined clay and limestone.
- After $LC^3$-80 , $LC^3$-65 get the third higher peak load , in which i replaced 35% cement with calcined clay and limestone.
- After $LC^3$-65 , $LC^3$-50 get the fourth higher peak load , in which i replaced 50% cement with calcined clay and limestone.

- These ultimate peak loads  indicates that replacement less than or equal to 50% with cement , we can get the peak loads nearly equal to OPC ,with come percentages of less or more than OPC strength.

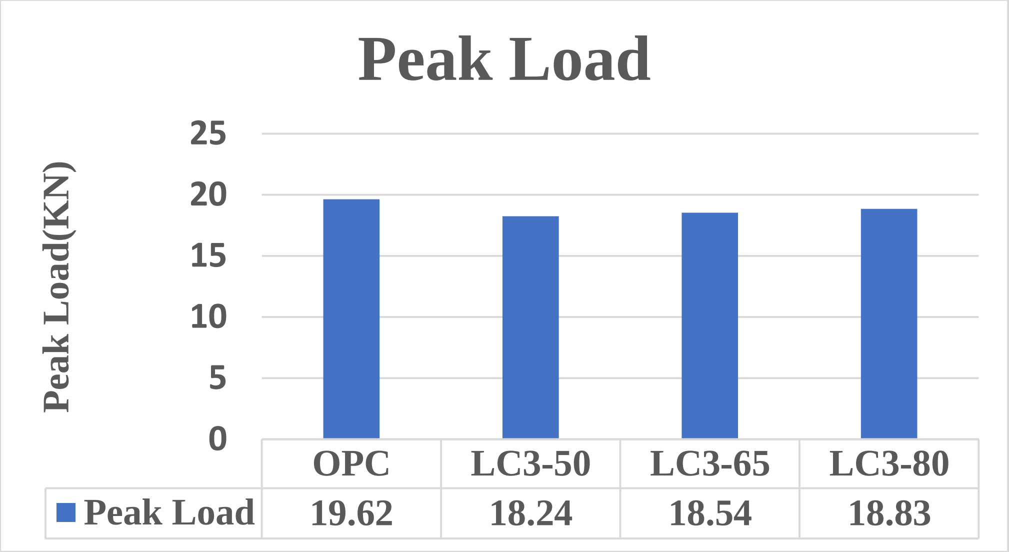


**Figure 5.11 Comparison of Peak loads**

## 5.9 Comparison of ultimate deflections

- When we compare ultimate deflections of all beam samples than control sample of beam which is made up of ordinay portland cement shows lower deflection as compared to others samples.
- After OPC ,  $LC^3$-80 get the second lower ultimate deflection , in which i replaced 20% cement with calcined clay and limestone.
- After $LC^3$-80 ,  $LC^3$-65 get the third lower ultimate deflection , in which i replaced 35% cement with calcined clay and limestone.

- After $LC^3$-65 , $LC^3$-50 get the fourth lower ultimate deflection , in which i replaced 50% cement with calcined clay and limestone.
- These ultimate defections indicates that replacement less than or equal to 50% with cement , we can get the ultimate deflections nearly equal to OPC ,with come percentages of less or more than OPC strength.

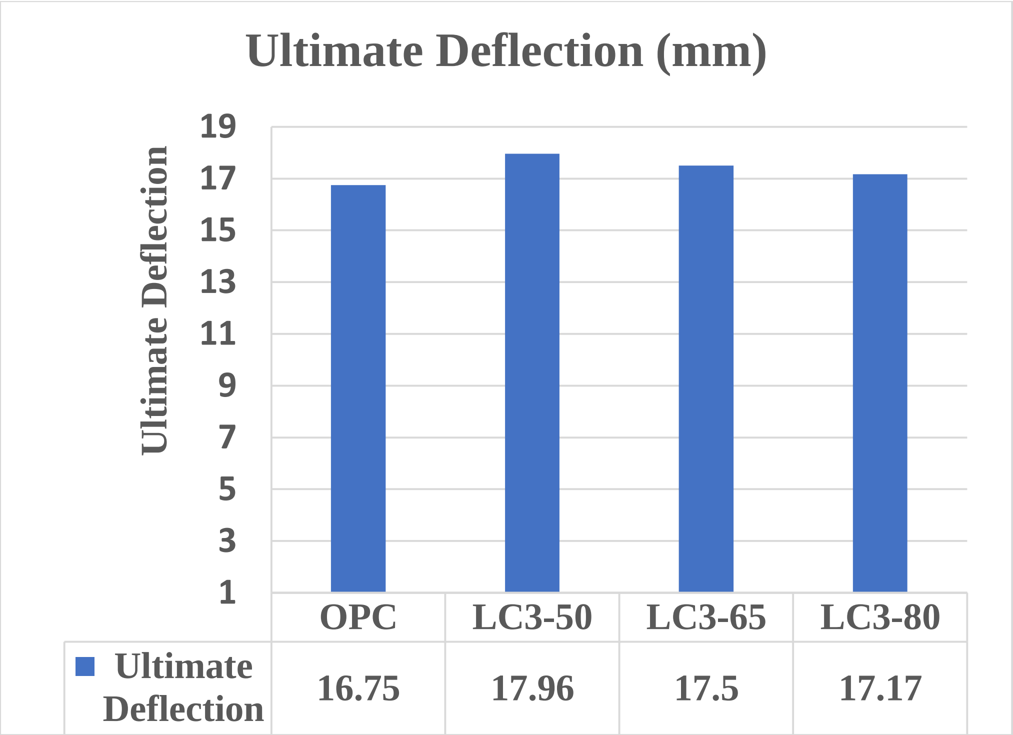


**Figure 5.12 Comparison of ultimate deflections**

## 5.10 Comparison of crack width at peak loads

- When we compare crack width at peak loads of all beam samples than control sample of beam which is made up of ordinay portland cement shows lower crack width as compared to others samples.

- After OPC , LC$^3$-80 get the second lower crack width at peak loads , in which i replaced 20% cement with calcined clay and limestone.
- After LC$^3$-80 , LC$^3$-65 get the third lower cracks width at peak loads , in which i replaced 35% cement with calcined clay and limestone.
- After LC$^3$-65 , LC$^3$-50 get the fourth lower crack width at peak loads , in which i replaced 50% cement with calcined clay and limestone.
- These crack width at peak loads indicates that replacement less than or equal to 50% with cement , we can get the cracks width at peak load nearly equal to OPC ,with come percentages of less or more than OPC strength.

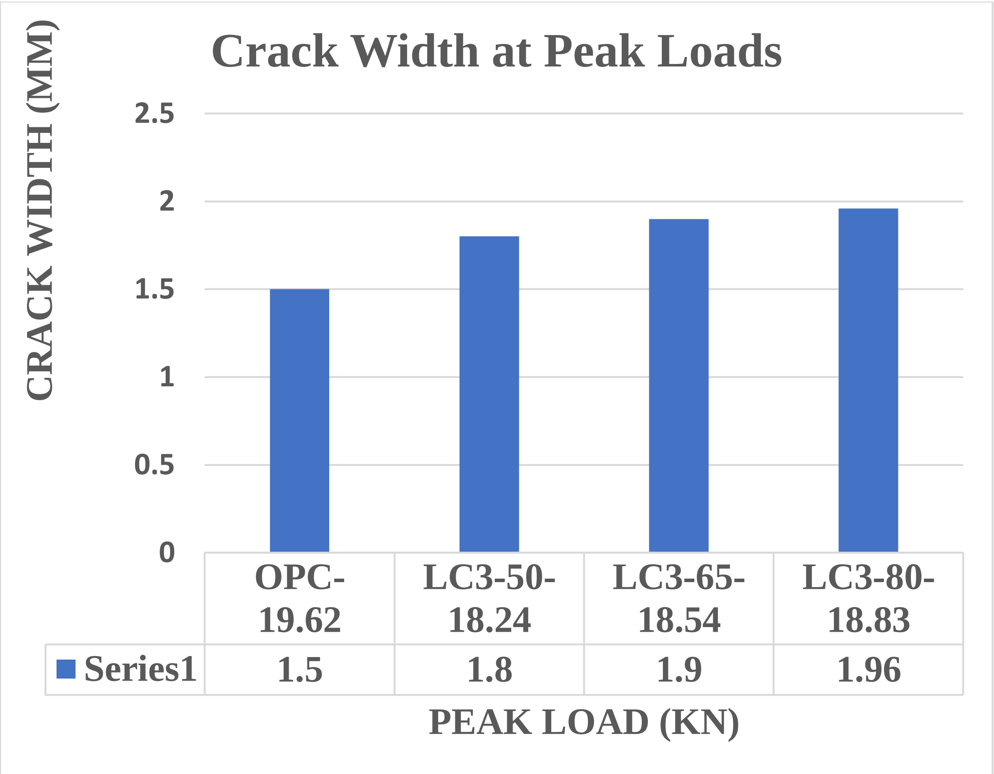


**Figure 5.13 Graph of Crack width at Peak loads**

## 5.11 Results of cracks and spacing

- When we compare results of cracks and spacing of all beam samples than control sample of beam which is made up of ordinay portland cement shows better results as compared to others samples as shown in below table.
- After OPC , $LC^3$-80 shows better results as shown in below table , in which i replaced 20% cement with calcined clay and limestone.
- After $LC^3$-80 , $LC^3$-65 shows better results as shown in below table, in which i replaced 35% cement with calcined clay and limestone.
- After $LC^3$-65 , $LC^3$-50 shows better results as shown in below table , in which i replaced 50% cement with calcined clay and limestone.
- These results indicates that replacement less than or equal to 50% with cement , we can get the results nearly equal to OPC ,with come percentages of less or more than OPC strength.

**Table 5.8 Results of cracks and spacing**

| **Mix id** | **No of cracks** | **Ave length of crack (cm)** | **Minimum spacing of crack (cm) $S_{min}$** | **Maximum spacing of crack (cm) $S_{max}$** | **Avg spacing of crack $S_{avg}$** | **S min / S avg** | **S max / S avg** |
|---|---|---|---|---|---|---|---|
| OPC | 17 | 9.75 | 10.16 | 15.24 | 12.7 | 0.8 | 1.2 |
| LC3-50 | 17 | 12.5 | 8.10 | 18.25 | 13.175 | 0.61 | 1.38 |
| LC3-65 | 18 | 11.5 | 8.25 | 18.75 | 13.18 | 0.62 | 1.42 |
| LC3-80 | 18 | 11.2 | 8.89 | 17.78 | 13.33 | 0.66 | 1.33 |

## 5.12 Result of ductility index, stiffness index and modulus of elasticity

- When we ductility index , stiffness index and modulu of elasticity of all beam samples than control sample of beam which is made up of ordinay portland cement shows higher results as compared to others samples as shown in below table.
- After OPC , $LC^3$-80 get the second higher results as shown in below table values , in which I replaced 20% cement with calcined clay and limestone.
- After $LC^3$-80 , $LC^3$-65 get the third higher results as values are shown below in table , in which I replaced 35% cement with calcined clay and limestone.

- After $LC^3$-65 , $LC^3$-50 get the fourth higher results as values are shown below in table , in which I replaced 50% cement with calcined clay and limestone.
- These results indicates that replacement less than or equal to 50% with cement , we can get the all results nearly equal to OPC ,with come percentages of less or more than OPC strength.

**Table 5.9 Result of Ductility index , Stiffness index and modulous of elasticity**

| Mix id | Ductility index (u) | Stiffness (KN/mm) | Modulus of Elasticity (N/mm2) |
|---|---|---|---|
| OPC | 3.32 | 1.171 | 22022 |
| LC3-50 | 3.42 | 0.98 | 21015 |
| LC3-65 | 3.54 | 1.00 | 21075 |
| LC3-80 | 3.50 | 1.036 | 21098 |

## 5.13 Carbon foot print and energy consumptions

- As ordinary portland cement is producing CO2 in numerous amount and also use lot of energy consumptions for OPC , so in order to reduce carbondioxide and energy consumptions we use SCM's (supplementary cementious material like limestone calcined cement in which we replace cement with calcined clay and limstone .
- As we are replacing cement with calcined clay and limestone so more would be the replacement more would be carbondioxide emission reduced.

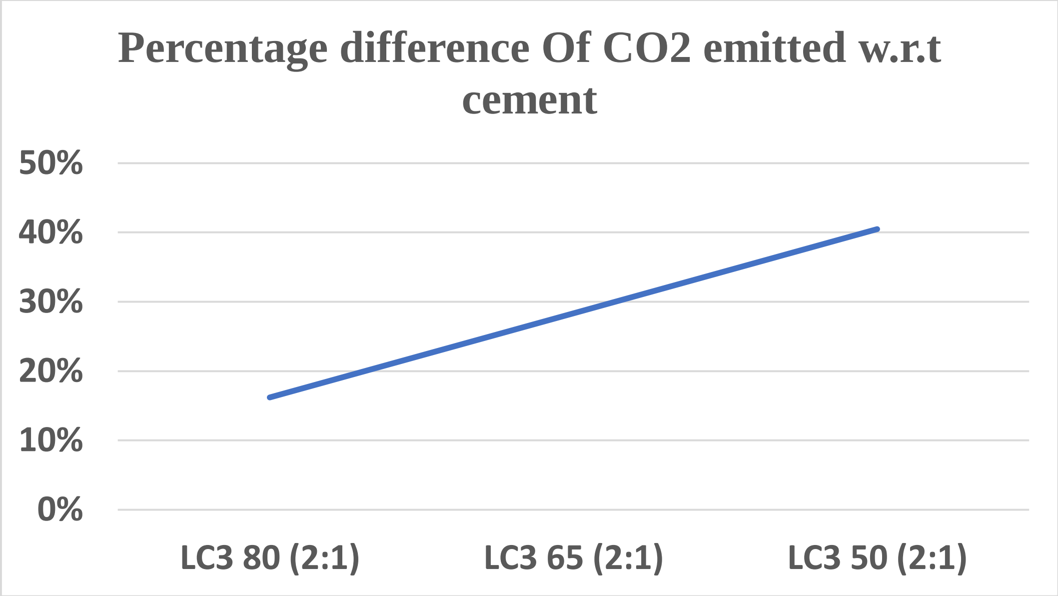


**Figure 5.14 Percenatage difference of C02 emisssions w.r.t cement**

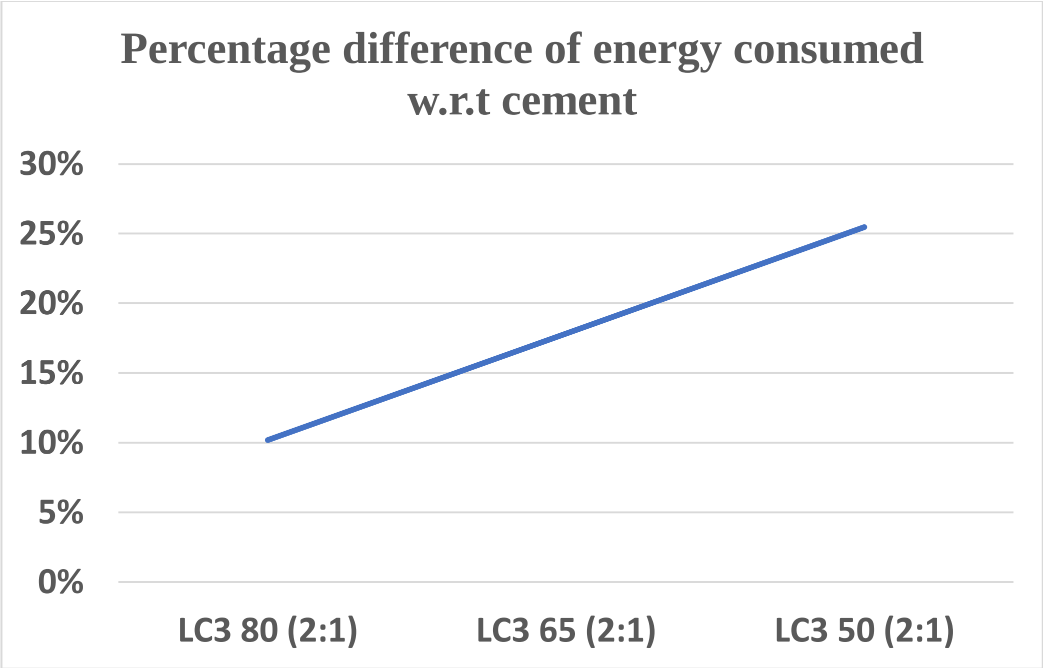


**Figure 5.15 Percentage difference of energy consumed w.r.t cement**

Results in above graph shows that LC3-50 is giving us more percentage differnce of CO2 emitted with respect to cement and percentage difference of energy consumed with respect to cement because in $LC^3$-50 we replace larger amount of cement with calcined clay and limestone.

## *5.14* Conclusions

Beams with replacment 80% 65% and 50% with OPC were given stiffness index , toughness index nearly equal to OPC beam.

Number of cracks ,cracks propogation ,minimum spacing of crack ,maximum spacing of crack were also nearly equal to 100% OPC beam.

Load deflection curve of all beam shows similar behaviour as control beam were showing during experimentally and FEA .

Percenatage difference of CO2 emmision w.r.t OPC and Percentage difference of energy consumed w.r.t OPC comes out to be lower in $LC^3$-50 cement.

## 5.15. Industrial Feasibility and Future Iinvestment

$LC^3$ binders hold a strong future in cement industry because

- Refurbished cement manufacturing machinery
- Low grade clay - abundantly available
- Economical – energy saver since
    - clinker manufacturing kiln requires 1450°C, and
    - calcined clay preparation requires 850°C

## 5.16. Recommendations

1. Comparative study between low- grade and high-grade Clays

2. effect of different types of limestones on the blend
3. utilization of super plasticizers in $LC^3$ blends
4. effect of different w/b ratios on $LC^3$ mix
5. durability assessment of different blends of LC

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