B. TECH. PROJECT REPORT

On

EXPERIMENTAL EVALUATION OF MECHANICAL BEHAVIOUR OF LIMESTONE CALCINED CLAY CEMENT (LC3) CONCRETE SUBJECTED TO ELEVATED TEMPERATURE

BY

DHEERENDRA SINGH

(160004012)

DISCIPLINE OF CIVIL ENGINEERING

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EXPERIMENTAL EVALUATION OF MECHANICAL BEHAVIOUR OF LIMESTONE CALCINED CLAY CEMENT (LC3) CONCRETE SUBJECTED TO ELEVATED TEMPERATURE

A PROJECT REPORT

Submitted in partial fulfillment of the

requirements for the award of the degrees

of

BACHELOR OF TECHNOLOGY

in

CIVIL ENGINEERING

Submitted by:

Dheerendra Singh

Guided by:

Prof. Sandeep Chaudhary

Discipline of Civil Engineering (IIT Indore)

INDIAN INSTITUTE OF TECHNOLOGY INDORE

November 2019

CANDIDATE'S DECLARATION

I hereby declare that the project entitled **"Experimental evaluation of mechanical behaviour of limestone calcined clay cement (LC3) concrete subjected to elevated temperature"** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in 'civil engineering' completed under the supervision of **Dr. Sandeep Chaudhary, Professor, civil engineering,** IIT Indore is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

Dheerendra Singh

(Roll No. 160004012)

Signature and name of the student(s) with date

CERTIFICATE by BTP Guide(s)

It is certified that the above statement made by the students is correct to the best of my knowledge.

Signature of BTP Guide(s) with dates and their designation

Preface

This report on "Experimental evaluation of mechanical behavior of limestone calcined clay cement (LC3) concrete subjected to elevated temperature" is prepared under the guidance of Prof. Sandeep Chaudhary.

I have tried to the best of my abilities and knowledge to explain the content in a lucid manner. I have also added tables and figures to make it more illustrative.

Dheerendra Singh

Roll No. 160004012

B.Tech. IV Year

Discipline of civil engineering

IIT Indore

Acknowledgements

I wish to thank Prof. Sandeep Chaudhary for his kind support and valuable guidance. I would also like to acknowledge the support extended by my colleagues. It is their help and support, due to which we became able to complete the design and technical report.

The financial support provided by Indian Institute of Technology is gratefully acknowledged.

Finally, I offer my sincere thanks to all other persons who knowingly or unknowingly helped me in completing this project.

Without their support this report would not have been possible.

Dheerendra Singh

Roll no. 160004012

B.Tech. IV Year

Discipline of civil engineering

IIT Indore

Abstract

Cement concrete is widely used as a structural material in building construction. A thrust towards sustainability has resulted in the development of several new and alternate construction materials. These sustainable construction materials need to be assessed for their influence on the properties of concrete prior to their industrial application. An important design consideration for building safety is fire resistance of the concrete structure. Concrete, at elevated temperatures, undergoes significant physicochemical changes and has a damaging effect on the micro-structure and meso-structure of concrete. Exposure to elevated temperature results in a generalized decay in the mechanical properties of the concrete, which can lead to detrimental effects at the structural level. Therefore, it becomes necessary to assess the performance of new and alternate sustainable construction materials at elevated temperatures for fire safety considerations.

Limestone Calcined Clay Cement (LC3) is a recently developed sustainable alternative to conventionally used binders like OPC and PPC. For its application in the construction industry, LC3 is evaluated and compared with conventionally used binders (OPC and PPC) after exposure to elevated temperatures. The fire response of the concrete structural members is assessed from the residual properties of concrete after exposure to elevated temperatures. Concretes made from LC3, OPC and PPC using similar design were exposed to elevated temperatures of 200, 400, 600, 800, and 1000°C, in a previously heated electric test furnace for different time durations of 0.5, 1, 2, and 4 h. The residual mechanical properties (compressive strength, mass loss, volume change, UPV, and TGA of these concretes after natural cooling was assessed, and the influence of exposure to elevated temperature on these concretes was compared.

Experimental results indicate that the general performance of LC3 after exposure to elevated temperatures was slightly poor when compared to OPC and PPC, and thus use of safer design values from standards is suggested during the industrial application of LC3.

Table of Contents

List of Figures

List of Tables

1 Introduction:

In the modern world, we have a population of 7.7 billion people, and it is getting crowded. According to a report of the United Nations, the community will reach up to 10 billion in 2050. More infrastructure needs to be built for these people. More concrete will be required; therefore, more cement needs to be produced. But it is well known that the production of cement produces a lot of carbon dioxide (CO2), which a greenhouse gas. It harms the environment by trapping the heat in the atmosphere; as a result, it gives rise to a global increase in temperature. Also, cement production accounts for nearly 5-8% of total anthropogenic CO2 emissions, and cement is the second largest used product after water. Therefore, as a concern, we need to decrease its use as well as its production for a healthy environment. As a substitution to this, we need to use Supplementary Cementitious Materials (SCMs) like silica fumes, limestone, fly ash, etc. we have maintained sustainability in every aspect of working [1-2]. These SCMs are the by-products or waste, which are a sustainable alternative as compared to cement. A recently developed sustainable form of blended cement using SCMs is limestone calcined clay cement or LC3. It has tremendous potential to replace the clinker in cement and concrete [3].

As concrete does not burn, this can't be set on fire and doesn't emit any toxic products when setting on fire. It acts as a fire shield between adjacent spaces. Concrete is known for its capacity to tolerate a high degree of temperatures and fires [4]. This specialty is because of its low thermal conductivity (heat transfer) and high specific heat capacity. But, from this it should not be assumed that fire or high temperatures don't affect the concrete at all in any aspects rather most of the mechanical properties are affected such as its color changes, and compressive strength, density of concrete, modulus of elasticity and the looks of its surface considerably affected by high temperatures. Hence, to study these properties of concrete at high temperatures, some of the researchers have been currently taking an interest in the possibility of increasing the fire resistance of this material (concrete). According to some research and study, the fire resistance of concrete can be made better in many ways. The replacement of cement with slag or fly ash, for example, is a very efficient way. Because the thermal properties of concrete are mainly correlated with the type of aggregate used, An important focus has been put on the possibility of using slag as a concrete aggregate, which would not only be a great contribution to fire engineering, but also to waste material handling.

Also, we can use LC3 as an SCM because the LC3 cement produces around 30% savings in CO_2 emissions as compared to ordinary Portland cement (OPC) and nearly 10% as compared to Portland pozzolana cement (PPC). With having the same mechanical properties and improvements in some areas of durability when clinker is substituted to nearly 50% by LC3. Many mechanical properties of LC3 have been studied at room temperature till now by many researchers.

But in this study, we were going to investigate some properties like compressive strength (C.S), volumetric change, mass loss (Δm), Ultrasonic Pulse Velocity (UPV) value and Thermogravimetric Analysis (TGA) of concrete when incorporated with LC3, when concrete is subjected to elevated temperature and also compared to the room temperature results. Also, a comparative study of these properties with the concrete made up of LC3, OPC and PPC at elevated temperature has been done such that we can find out which type of concrete can have more resistance to fire and have fewer effects on mechanical properties of concrete in fire-prone areas. Through this research, we can also suggest some modifications in the code of fire resistance.

In our study, we have taken the temperature ranges of 20 °C, 200 °C, 400 °C, 600 °C, 800 °C, and 1000 °C. And in each temperature ranges, four/three samples are subjected to put in the oven, which has temperature variation up to 1200 °C for the time duration of 0.5 h, 1 h, 2 h, and 4 h at standard condition.

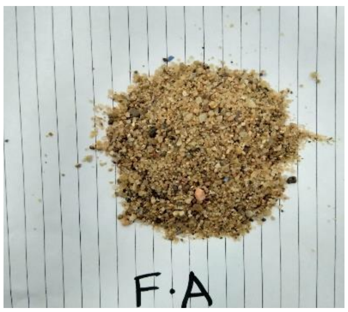
The tested results can be useful for many considerations and will be the basis for further research work.

2 Experimental Work:

The experimental methodology consists of mix proportioning, casting of specimens, exposing the specimens to elevated temperature and testing. The method had been briefly explained below. In this project, the mechanical properties of different types of cement (OPC, PPC, and LC3) had been compared at elevated temperatures.

2.1 Materials:

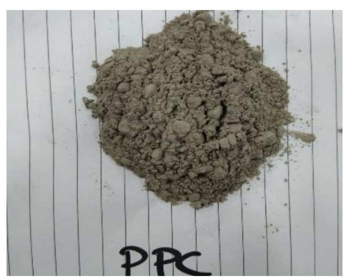
For the mixture preparation, Ordinary Portland Cement (OPC 43grade), Portland Pozzolana Cement (PPC fly ash based) and Limestone Calcined Clay Cement (LC3-50) cement, made using LC2 as supplied by TARA has been used, with a specific gravity of 3.15, 2.75 and 2.88 respectively, according to Indian Standards IS:8112-1989 (OPC) and IS:1489 (PPC). There is no code for LC3 till now. The coarse aggregates of size 10mm and 20mm have been used in 50:50 in the mixture. Natural river sand of Zone-II has been used as fine aggregates. The sieve analysis for coarse aggregate, and fine aggregate was carried out. The first one conforms to Table 2 in IS: 383-1970, and the latter conforms to Table3 of IS 383.



a. Fine aggregate (natural river sand)

b. Coarse aggregate (10mm and 20mm)

c. OPC



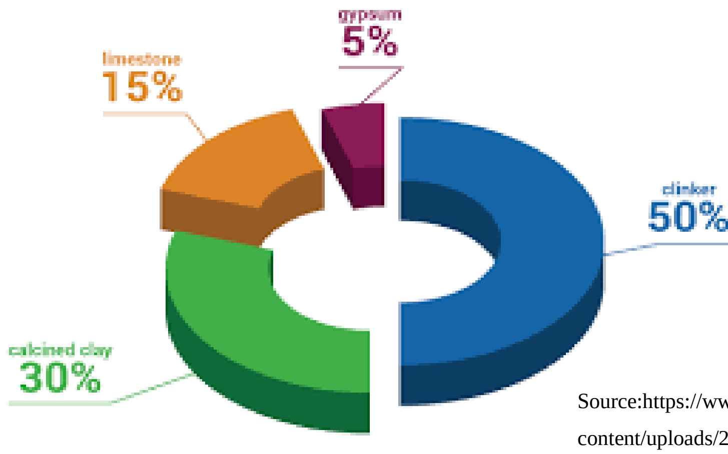
d. PPC

e. LC3

Fig.1. Materials used in mix proportions

2.2 Composition of LC3-50:

In normally blended cement, the limit on pozzolan addition is 35%. But if the ratio calcined clay/limestone is kept at 2:1, this could provide further substitution of 15% of the clinker. i.e. LC3-50 (50% ground clinker, 30% calcined clay, 15% limestone, 5% gypsum)[5].



Source:https://www.lc3.ch/wp-content/uploads/2014/09/Pie_1_2-011.jpg

Fig 2. Composition of LC3-50

Table 1. Physical properties of aggregates used:

Properties	Natural River sand	10mm aggregate	20mm aggregate
Water absorption (%)	0.83	1.51	1.6
Specific gravity	2.64	2.90	2.91

2.3 Mix Proportions and Sample Preparation:

The mixtures were prepared with the constant cement content (400 kg/m^3) and with the constant water to cement ratio (w/c=0.35). The mix design for M40 grade of concrete was carried out according to IS 10262-2009, exposed to very severe conditions and with a specific characteristic compressive strength of 40 MPa and a target mean strength of 48.25 MPa. The final mix proportions obtained for three types of the mixture containing three different type of cement (OPC, PPC, and LC3) is listed in Table 2.

Table 2. Mix design/proportion for 1 m^3 of concrete:

Materials (in Kg)		OPC	PPC	LC3
Cement		400.00	400.00	400.00
Water		166.73	166.06	166.25
Fine Aggregate		671.73	654.81	659.69
Coarse Aggregate	10mm	680.59	663.44	668.39
	20mm	679.99	662.85	667.80
w/c ratio		0.35	0.35	0.35

The specimens of measurements 10×10×10 cm were casted. For each case of different cement (OPC, PPC, and LC3), three mixes had been prepared for the casting of required samples. Now for each case, we have five different temperature exposures (200, 400, 600, 800, and 1000 °C) and for each temperature we had exposed the samples for four different time duration (0.5, 1, 2, and 4 h) and in every case we had taken four samples for average values and there were also two cases at room temperature for 7 and 28 days testing, therefore total number of samples casted for three types of cement were, 3×[(5×4×4) + (4+4)] = 264.

After 24 h of casting, samples then demolded and placed in a water tank and kept there at room temperature of about 20±2 °C until they were tested. The specimens were cured for 28 days. Then removed from the water tank and placed in the air for 24 h under the fan to remove extra moisture. Then initial measurements had been taken before the samples had put in the furnace at elevated temperatures.

2.4 Exposure to Elevated Temperature:

All the experiments were carried out using an electric heating furnace/oven of 42 kWh power with a maximum temperature of 1200 °C. The temperature change in the oven was according to the fire curve, as shown in fig.4 for the available oven.

Fig.3.a. Electric Furnace (oven).

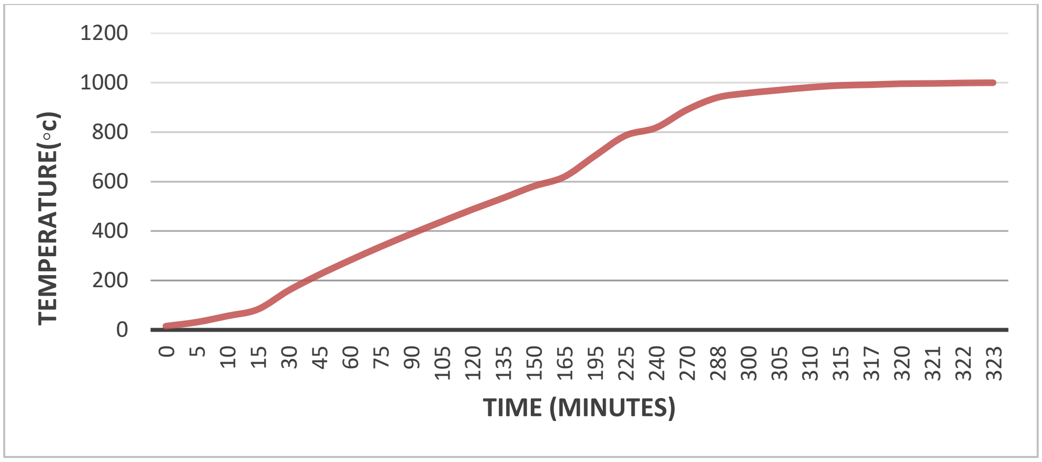


Fig.3.b. Fire curve for electric furnace.

After 28 days of normal curing, samples had been taken out of the tank and then air dried in the laboratory for 24 hr before they were exposed to elevated temperatures. The specimens had been put into a test furnace (or oven) that was preheated to certain temperatures of 200, 400, 600, 800 and 1000 °C. Then a set of four sample were placed inside the furnace at a certain temperature for different time duration of 0.5, 1, 2 and 4 h each. After that the samples were taken out and left to cool down at room temperature till their temperatures reaches to room temperature. Initially non-destructive test were performed (like measurements of weight, dimensions, and UPV test) then finally compressive strength test had been done as destructive test.

2.5 Samples Preparation for TGA:

Three different types of cubes using cement pastes of ordinary Portland cement, Portland pozzolana cement and limestone calcined clay cement having constant w/c ratio of 0.35 had been casted. After 28 days curing the specimen were grinded to fine particles passing 90 micron sieve, which were then used for TGA analysis.

2.6 Tests:

After that, the samples had been cooled down to the room temperature, then their compressive strengths had been tested. Before this testing we have to take measurements like weight, dimensions, Ultrasonic Pulse Velocity (UPV) value, and surface photos before and after the samples are subjected to elevated temperatures. Thermogravimetric Analysis (TGA) had been also done on cement pastes of OPC, PPC, and LC3 having constant w/c ratio as we had for mix proportions. Compressive strength was tested on the cubes according to Indian standards [IS: 516-1959].

2.6.1 Mass Loss (in %):

In this study, % loss in mass has been observed with respect to their 28d mass, each for OPC, PPC, and LC3 concrete.

2.6.2 Volume Change (%ΔV):

There can two possible reasons for the increased volume of samples. First one, as moisture is present in the samples and on subjecting it to elevated temperatures, so, as moisture try to come out in the form of vapours/steam it produced a pressure which push the molecules of the samples outward resulting in increased volume. Secondly, we know that the materials can be thermally expanded due to increase in its temperature, so there had been increase in volume of the concrete samples even very small at lower temperatures, but measurable increase in volume at higher temperatures.

2.6.3 Compressive Strength:

The compressive strength of concrete at an elevated temperature is of primary interest in fire resistance design. The variation of compressive strength with temperature for three different types of concrete (containing cement OPC, PPC, LC3) had been studied. Compressive strength tests had been done according to Indian standard code, IS 516-1959 [7]. Test had been done after samples subjected to elevated temperatures and then put on the compression testing machine between upper and lower plate

Figure 4. The sample placed between the upper and lower plate of UTM

2.6.4 Ultrasonic Pulse Velocity (UPV):

Test have been done by using UPV machine having a transmitter and receiver. Then the sample have been put between those two ends, a value will be shown on the screen, it will be pulse velocities. We have taken the pulse velocity before and after the exposure of samples to elevated temperature.

The principle behind this method is to assess the quality of concrete, if we get comparatively higher velocities then the quality of concrete in terms of density, homogeneity, and uniformity is good. But In the case of poorer quality, we will get lower velocities. If there is a crack, void, or flaw inside the concrete, which comes in the way of transmission of the pulses, the pulse strength is attenuated, and it passes around the discontinuity, thereby making the path length longer. Consequently, lower velocities are obtained.

Fig.5. UPV setup.

2.6.5 Thermogravimetric Analysis (TGA):

Thermogravimetric analysis (TGA) is mainly employed in research and testing to determine the characteristics of materials, rate of degradation, absorbed moisture content of the materials, or the kinetics of a reaction based on their changes in weight.

TGA provides a quantitative analysis of mass change in the materials associated with the thermal degradations. These curves (Thermogravimetric) are given for specific materials and chemical compounds due to its unique pattern from physicochemical reactions happening over specific temperature ranges and at heating rates.

There can three different kinds of reaction:

1. Till 300°C --the water is removed from the hydrated products, likely to include most of the cement phases, and most of the C-S-H gel. Many minor processes are commonly occurred in this region, attributed to capillary pore water, interlayer water, and adsorbed water. because of the dynamic heating process, the corresponding peaks overlap each other
2. Between 400°C–500°C - Dehydroxylation.
3. Greater than 600 °C - Decarbonation.

3 Test Results and Discussions:

3.1 Mass Loss (%):

Mass loss was calculated by the difference between the average mass at 28 days at room temperature to average mass at elevated temperatures. We have measured the mass before and after samples subjected to elevated temperatures.

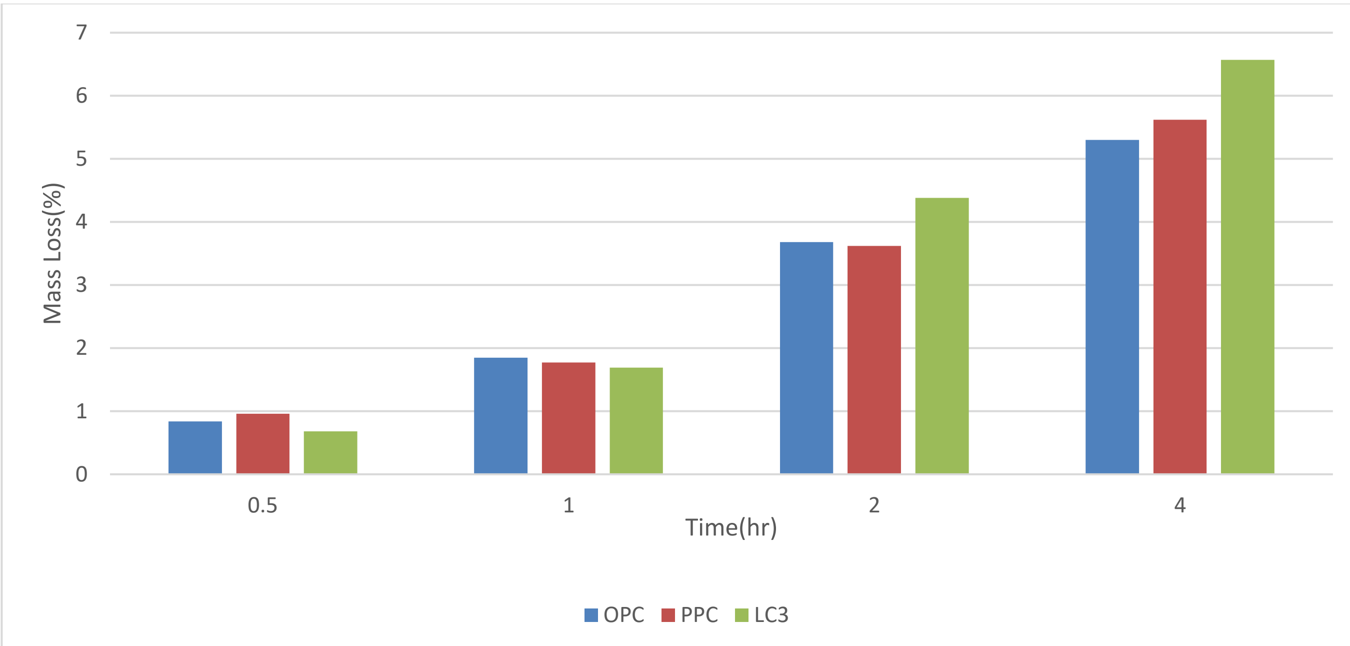


Fig.6.Average mass loss in % for OPC, PPC and LC3 concrete at a temperature of 200 °C for different time durations.

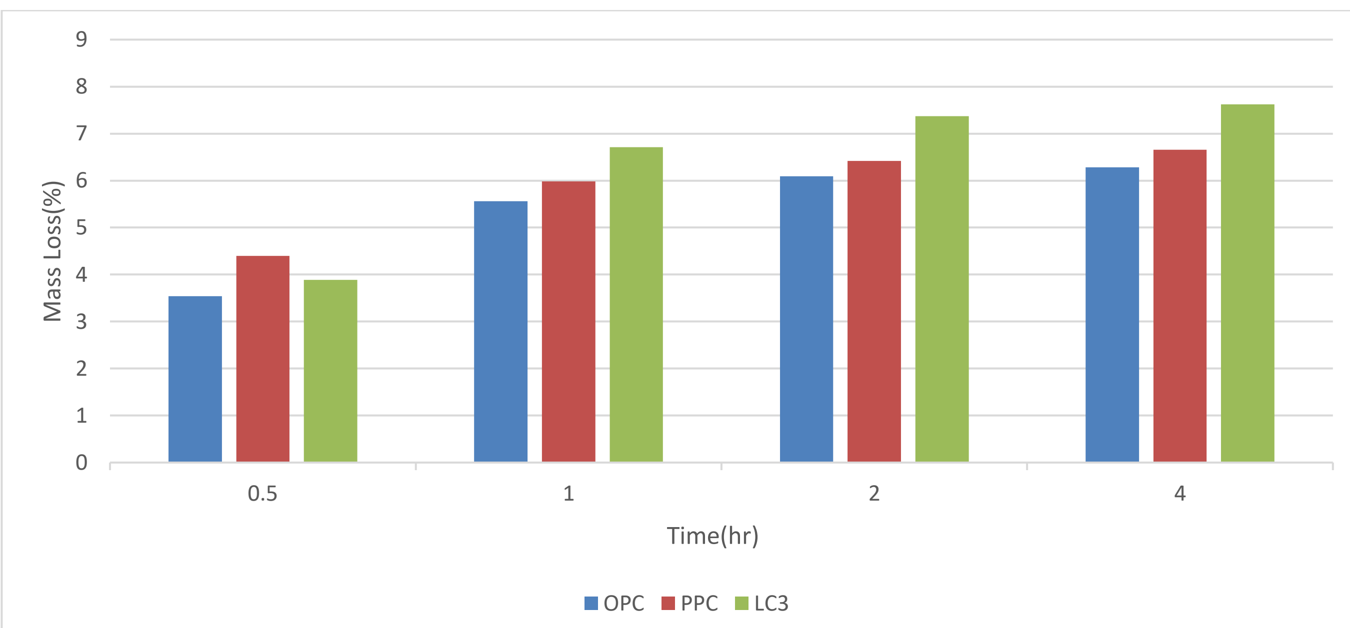


Fig.7. Average mass loss in % for OPC, PPC and LC3 concrete at a temperature of 400 °C for different time durations.

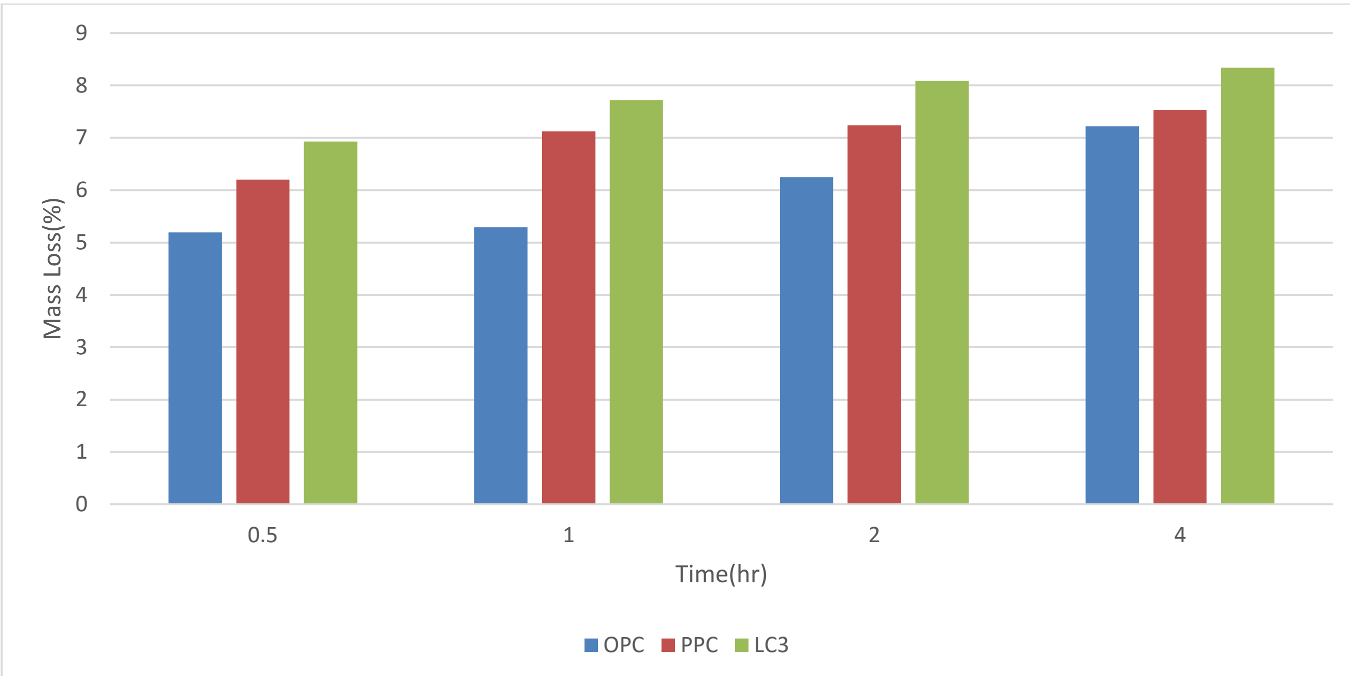


Fig.8. Average mass loss in % for OPC, PPC and LC3 concrete at a temperature of 600 °C for different time durations.

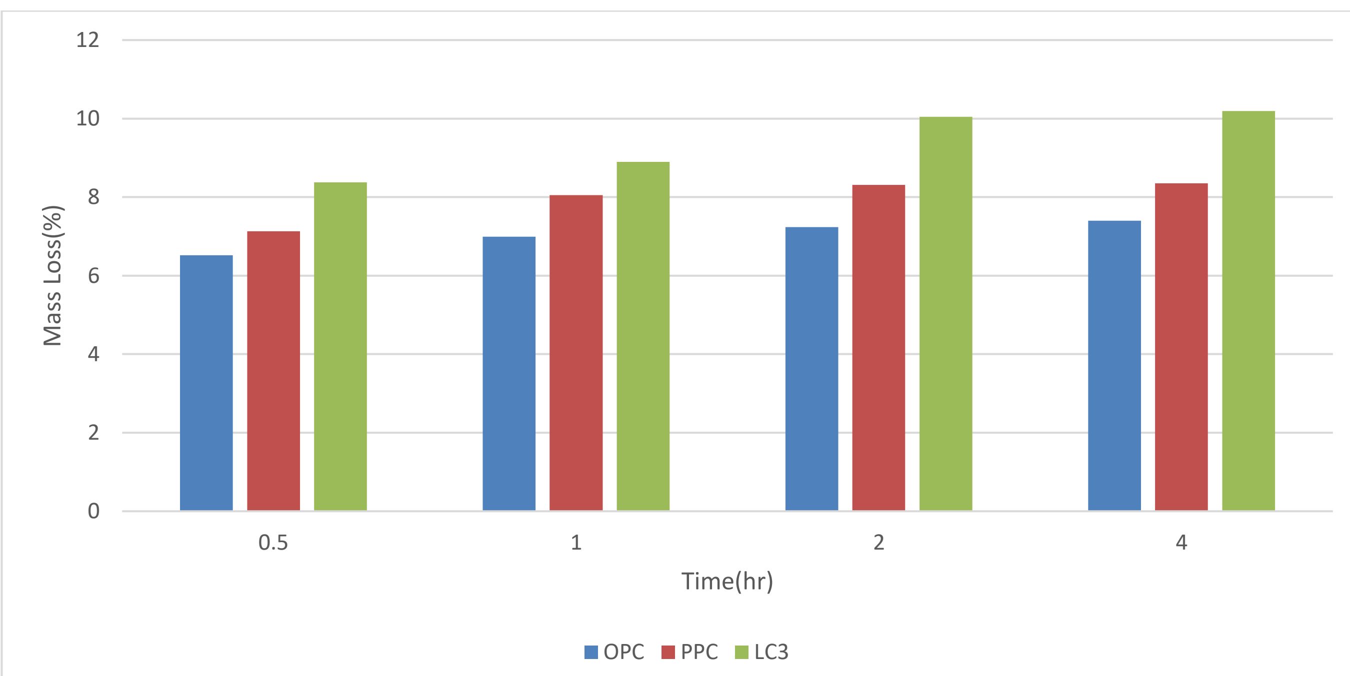


Fig.9. Average mass loss in % for OPC, PPC and LC3 concrete at a temperature of 800 °C for different time durations.

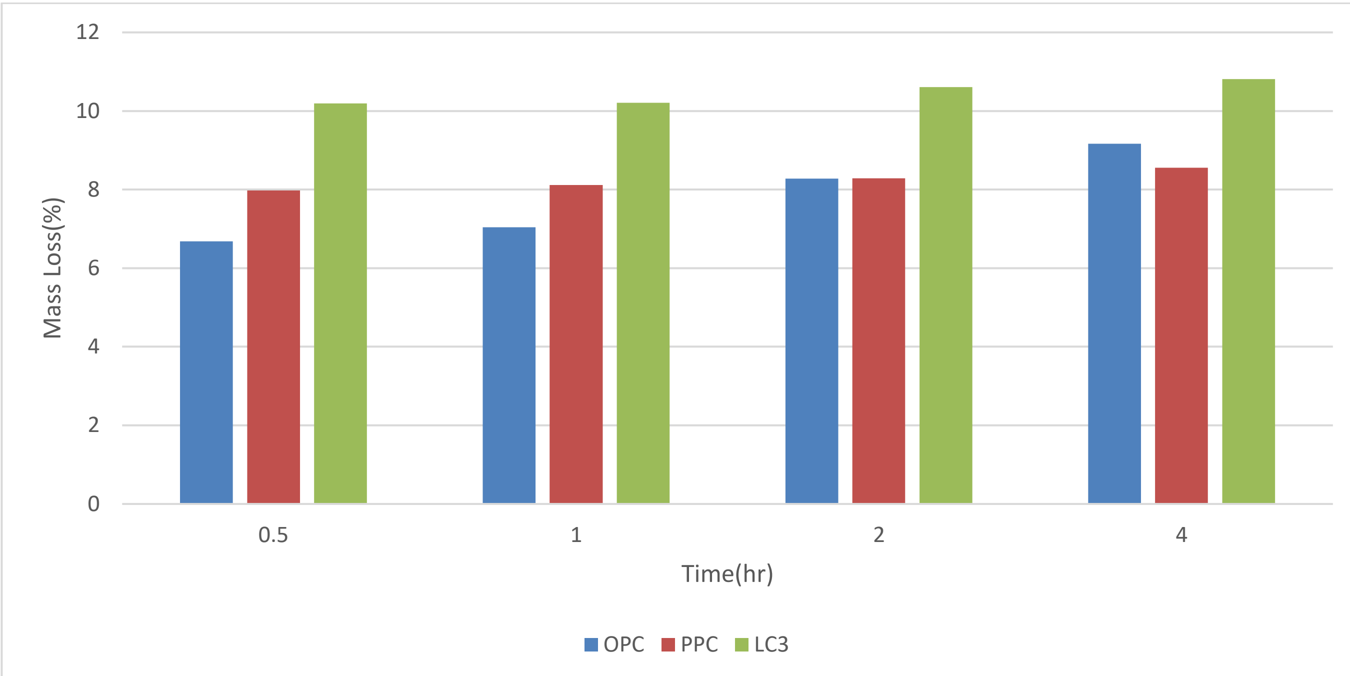


Fig.10. Average mass loss in % for OPC, PPC and LC3 concrete at a temperature of 1000 °C for different time durations.

From the above figures of mass loss, it has been observed that mass loss gradually increases with the increase in temperature (200 to 1000 °C) and time duration (0.5 h to 4 h) for all three types of cement.

From Fig.6, For OPC, PPC and LC3 concrete mass loss increases from 0.84 to 5.30%, 0.96 to 5.62%, 0.68 to 6.57% respectively at 200 °C from 0.5 h to 4 h. Least mass loss in LC3 concrete was observed at 0.5 and 1hr time duration, however for a longer duration (2h and 4h), LC3 had more mass loss as compared to the other two concrete types. But relatively, for short duration like 0.5h PPC concrete has more % of mass loss as compared to the concrete of OPC and LC3 with respect to their 28 d mass. Also, OPC has the least mass loss for a longer time duration (2 and 4 h). Further, their mass loss % is comparable at lower time duration as compared to 2 and 4hr.

At a temperature 400 °C, for 1, 2, and 4 h time duration, LC3 has more mass loss, then PPC and least for OPC concrete for each time interval. However for 0.5 h, PPC concrete has more mass loss than the other two, which have a comparable loss (Fig.7).

At temperatures of 600, 800, and 1000 °C, as shown in Fig.8 to Fig.10, there was nearly very less effect of time duration on % loss in mass. Unlike low temperatures % loss in mass showed a clear comparison between OPC, PPC and LC3 concrete. Therefore, Mass loss was observed from 5.19 to 9.17%, 6.20 to 8.56%, and 6.93

to 10.81% for OPC, PPC, and LC3 concrete, respectively, from temperature 600 to 1000 °C. It has been observed that LC3 concrete has more mass loss, and OPC concrete has the least. But at 1000°C, for 4 h time duration, PPC concrete has less mass loss than OPC concrete. Thus, it can be said in general LC3 concrete had higher mass loss as compared to conventional concrete.

3.2 Volume Change (% ΔV):

Dimensions have been measured before and after exposure of samples at elevated temperatures. The average difference in these volumes before and after expose to elevated temperatures divided by its initial average volume is called percentage volume change. Measurements have been taken for different temperatures and for different time durations as shown in Figure 11 to Figure 15.

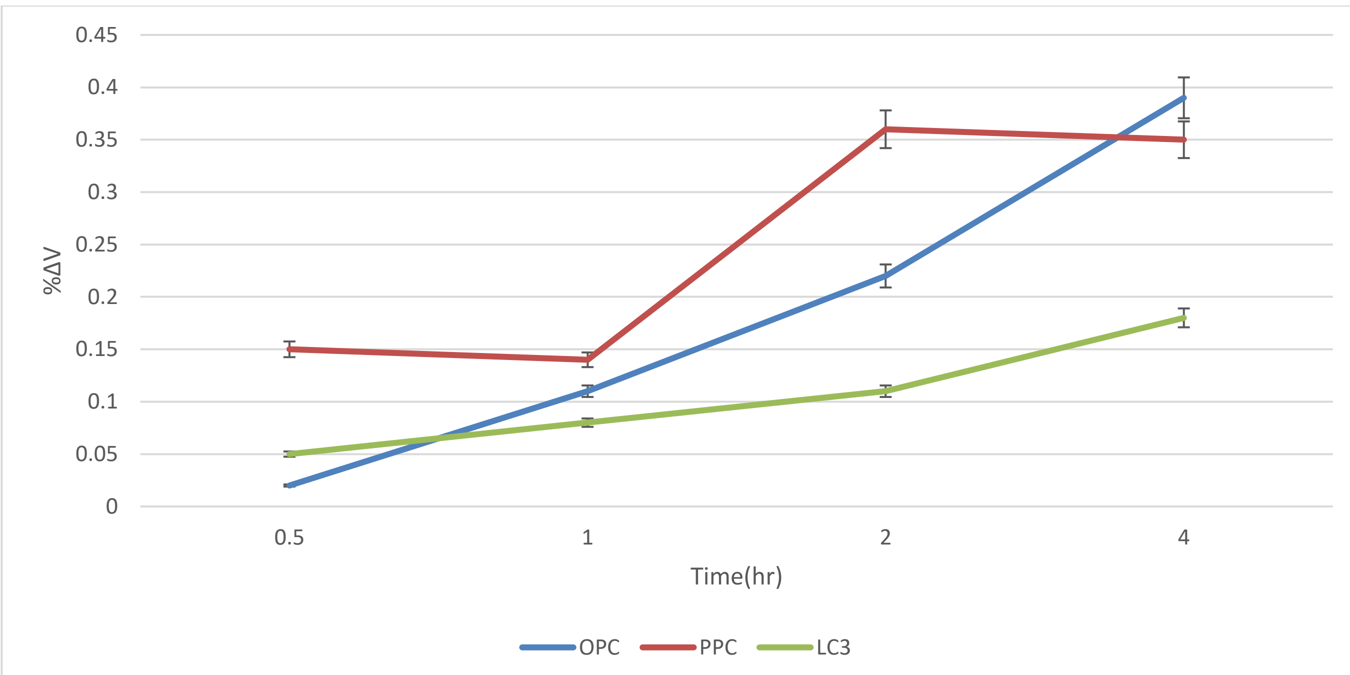


Fig.11. Average change in volume (in %) of OPC, PPC and LC3 concrete at a temperature of 200 °C for different time interval.

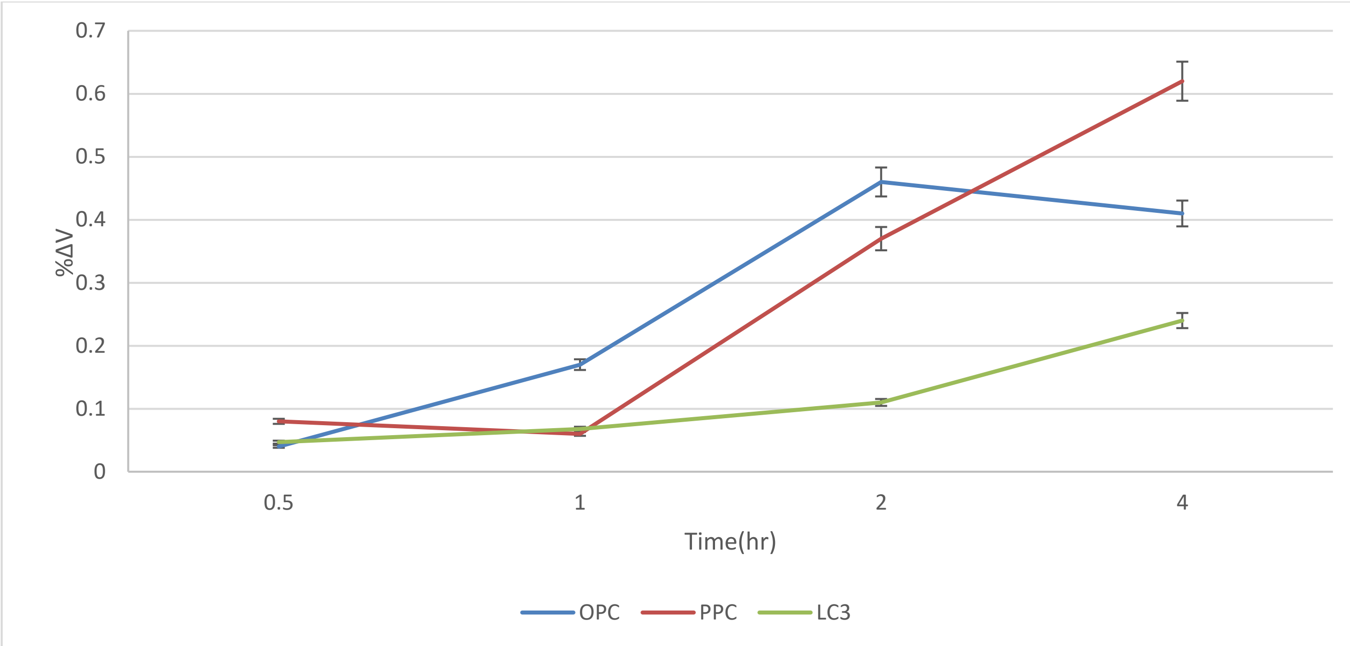


Fig.12. Average change in volume (in %) of OPC, PPC and LC3 concrete at a temperature of 400 °C for different time interval.

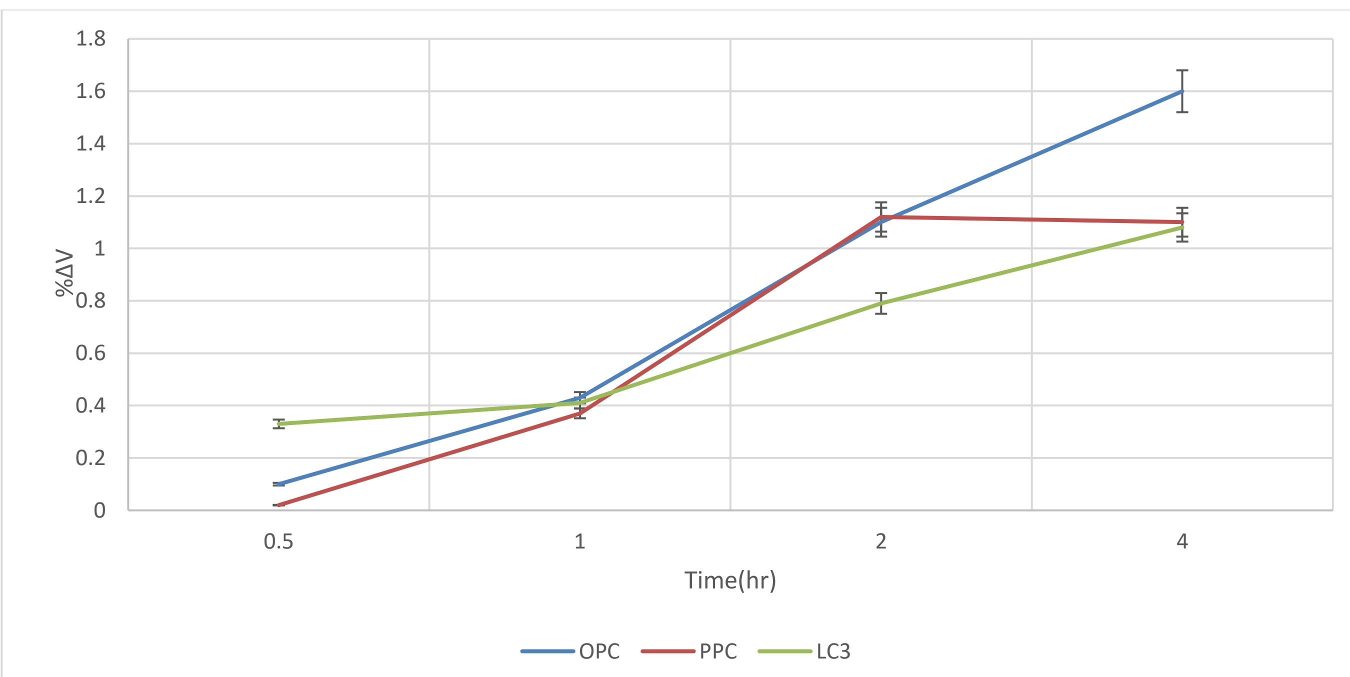


Fig.13. Average change in volume (in %) of OPC, PPC and LC3 concrete at a temperature of 600 °C for different time interval.

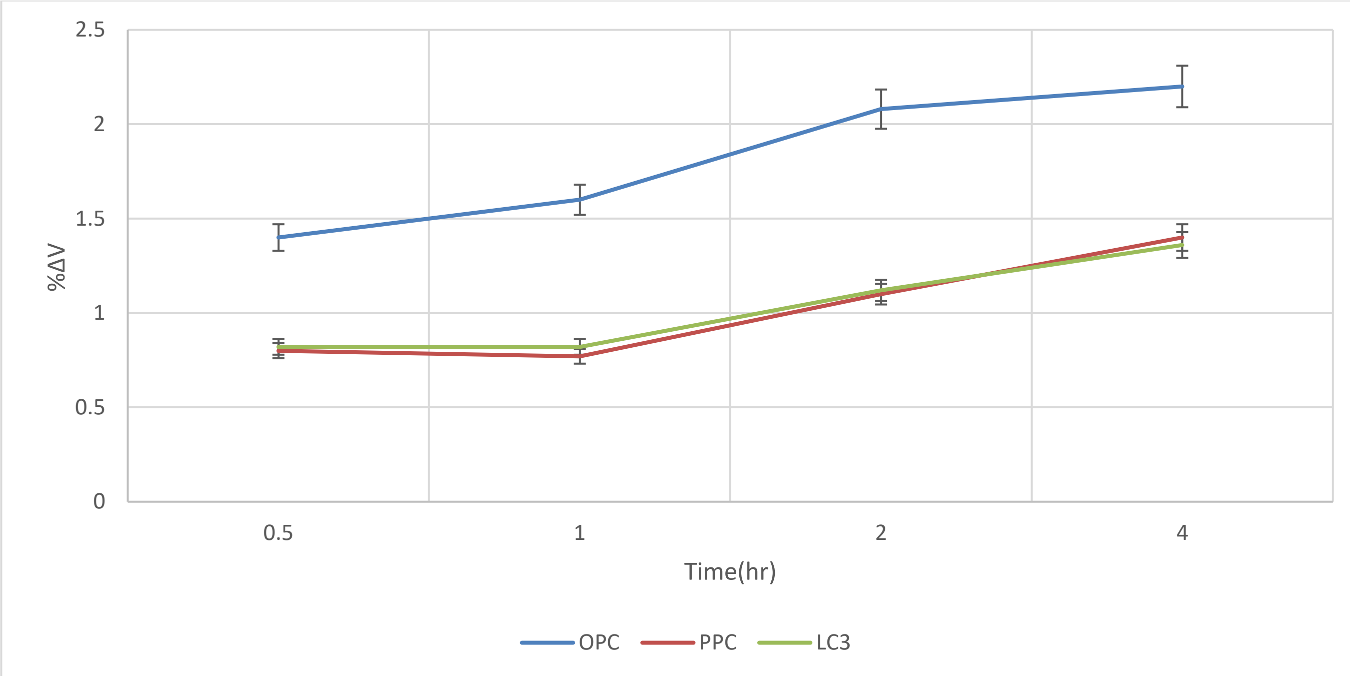


Fig.14. Average change in volume (in %) of OPC, PPC and LC3 concrete at a temperature of 800 °C for different time interval.

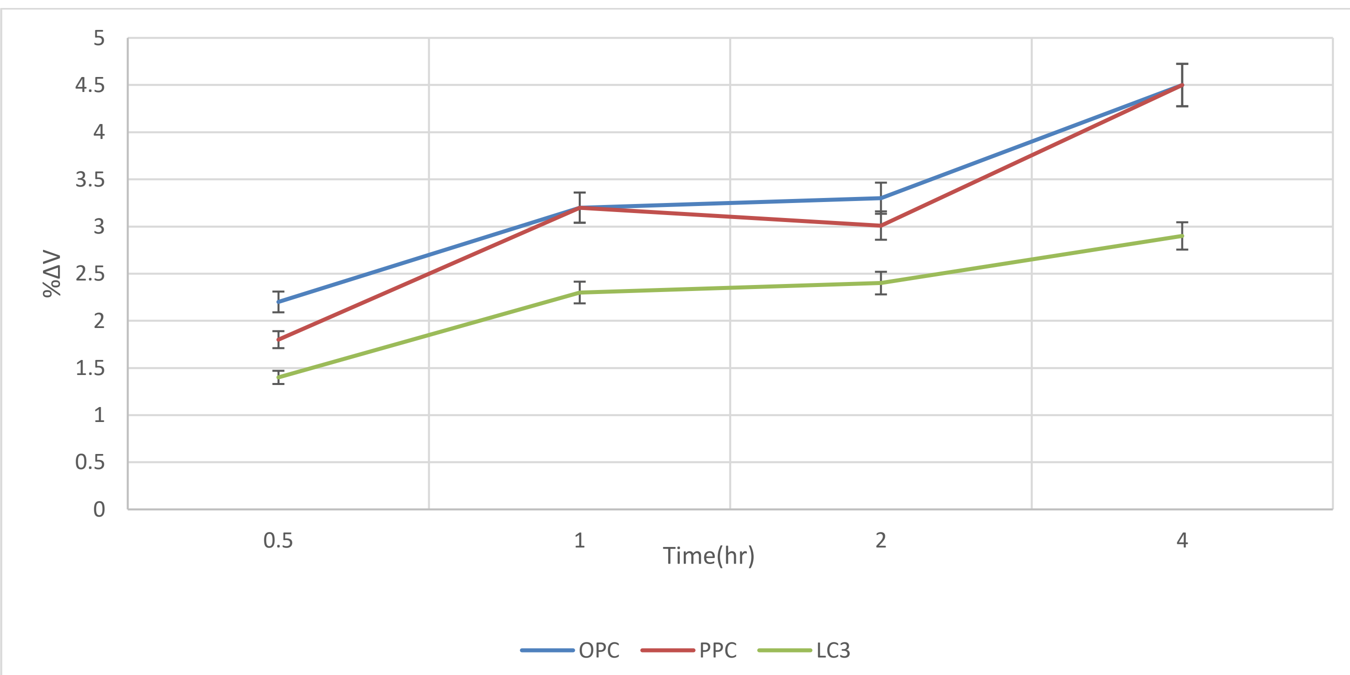


Fig.15. Average change in volume (in %) of OPC, PPC and LC3 concrete at a temperature of 1000 °C for different time interval.

A general trend has been observed from Fig.11 to Fig.15, that LC3 had least % increase in volume for all given temperature ranges and time durations, except for 0.5 h, at 200 °C it had more expansion than OPC concrete but less than PPC concrete and at 600 °C for 0.5 and 1 h, it had more expansion than OPC and PPC concrete. Also, at 200 °C, PPC concrete had more percentage increase in volume than the other two concrete (Fig.11).

At 800 °C, both PPC and LC3 concrete had a similar % increase in volume (Fig.14). At T=1000 °C, PPC and OPC concrete had a comparable percentage increase in volume (Fig.15). The % increase in the volume of OPC and PPC concrete was 0.02 to 4.50% each, and for LC3 concrete, 0.47 to 2.90% for temperature ranges from 200 to 1000°C.

Therefore, it can be said that despite higher mass loss in LC3 concrete, volume change was still lower as compared to conventional concretes. This can have a better impact on fire resistance of structure as thermal strain-based stresses will be lower in the concrete, which will require further experimental design.

3.3 Compressive Strength:

The average value of compressive strength before and after exposure to elevated temperatures have been recorded for all temperature ranges 200, 400, 600, 800, and 1000 °C, and at each temperature, for different time duration like 0.5, 1, 2, and 4 h ,for each types of concrete (OPC, PPC, and LC3).

The variation of average compressive strength (in %) at elevated temperature with respect to room temperature compressive strength has been shown in fig.17 to fig.21.

Table 3: Compressive strength and average weight of samples at 7 and 28 day at room temperature.

Type of cement	7day C.S (MPa)	28day C.S (MPa)	Average weight (gm) at 28 day.
OPC	35.26	61.52	2615.37
PPC	21.42	50.62	2561.97
LC3	27.37	42.44	2570.62

a. Electric furnace at 1000 °C b. Sample after subjecting to 1000 °C for 4 h.

Fig.16. Experimental work on exposure of test specimen to elevated temperature

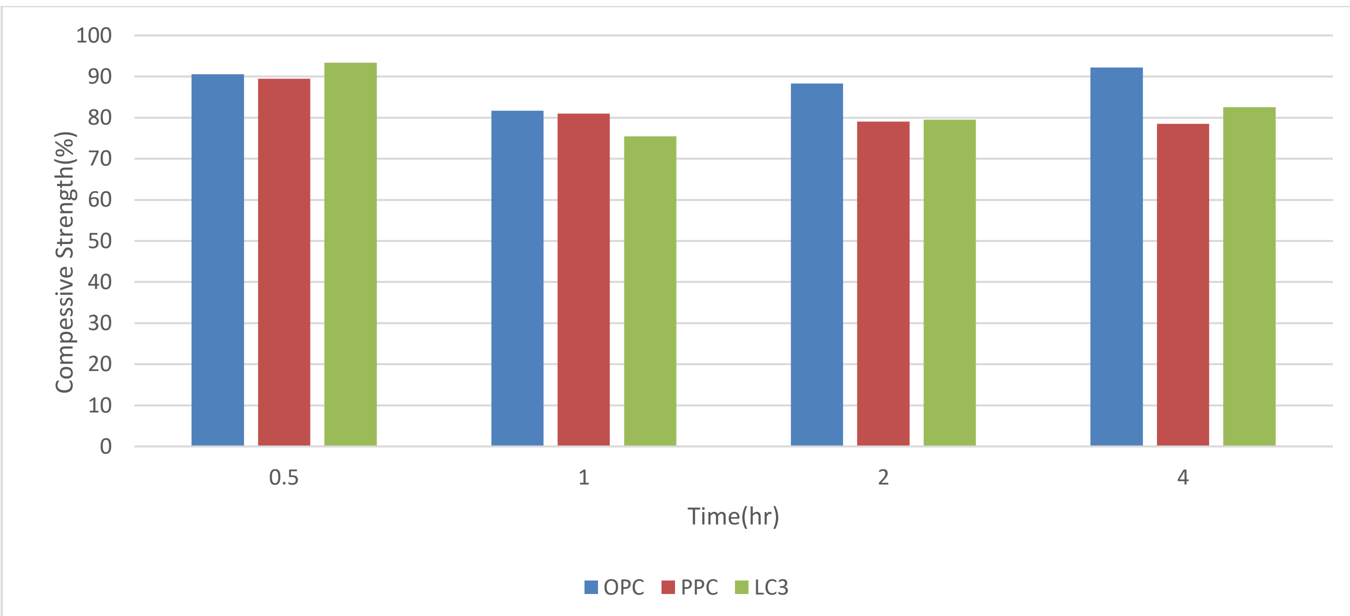


Fig.17. Average compressive strength (in %) for OPC, PPC, and LC3 concrete at a temperature of 200 °C for different time durations with reference to concrete at room temperature.

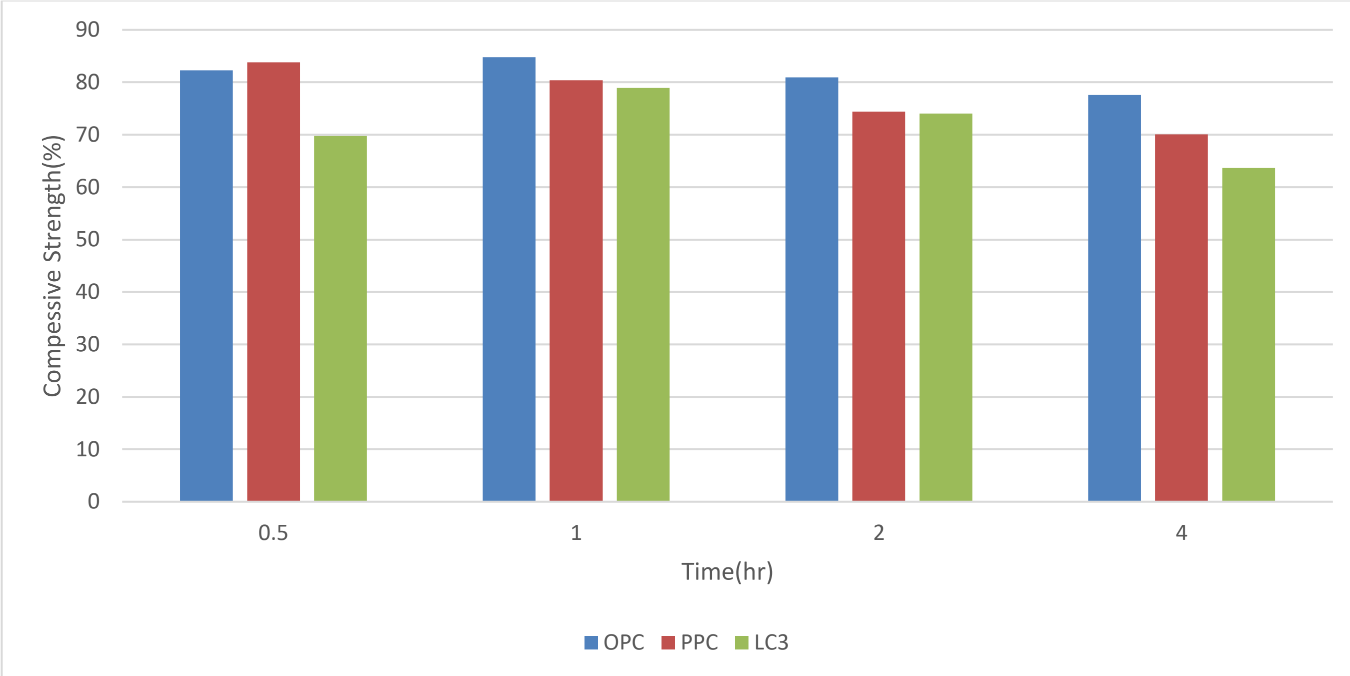


Fig.18. Average compressive strength (in %) for OPC, PPC, and LC3 concrete at a temperature of 400 °C for different time durations with reference to concrete at room temperature.

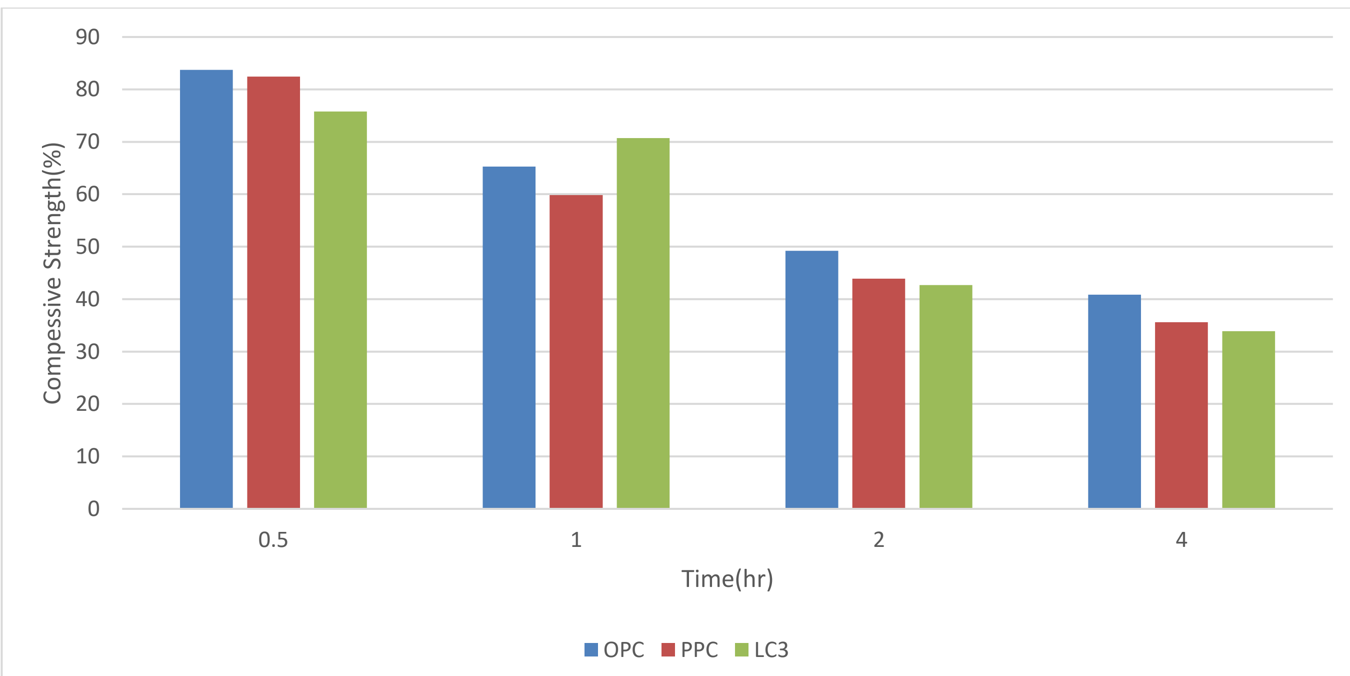


Fig.19. Average compressive strength (in %) for OPC, PPC, and LC3 concrete at a temperature of 600 °C for different time durations with reference to concrete at room temperature.

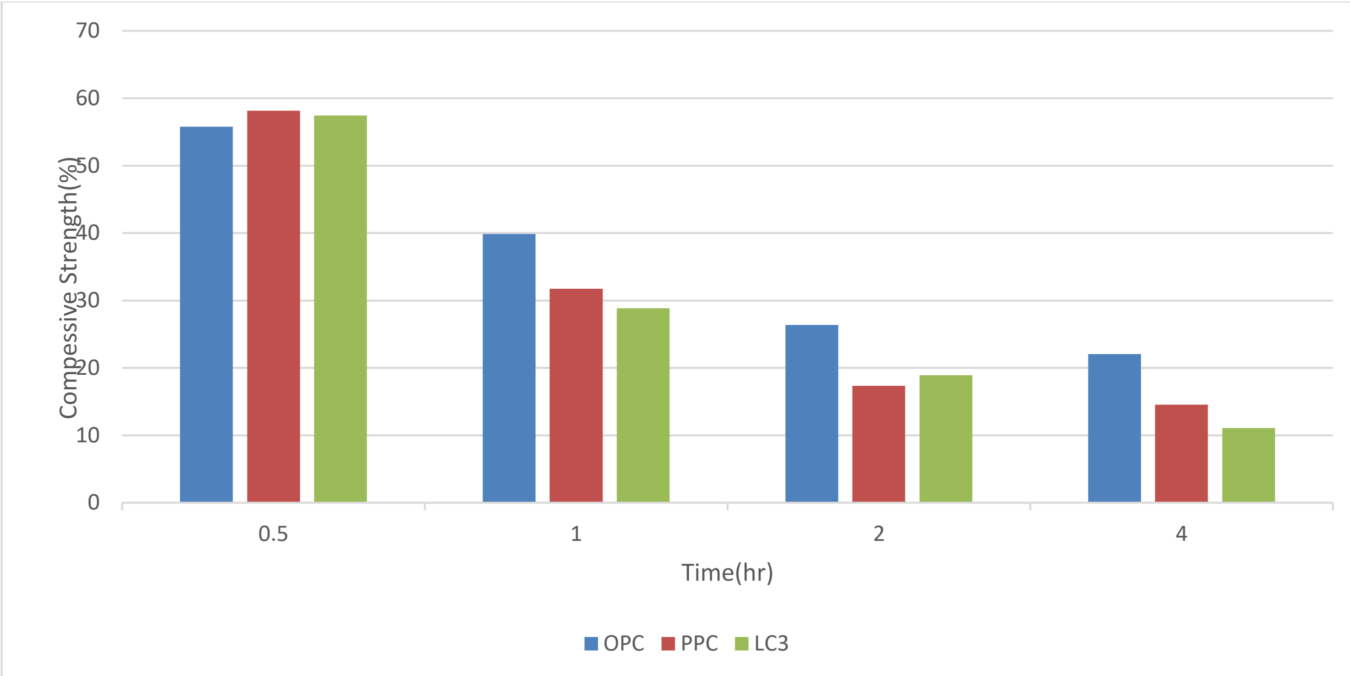


Fig.20. Average compressive strength (in %) for OPC, PPC, and LC3 concrete at a temperature of 800 °C for different time durations with reference to concrete at room temperature.

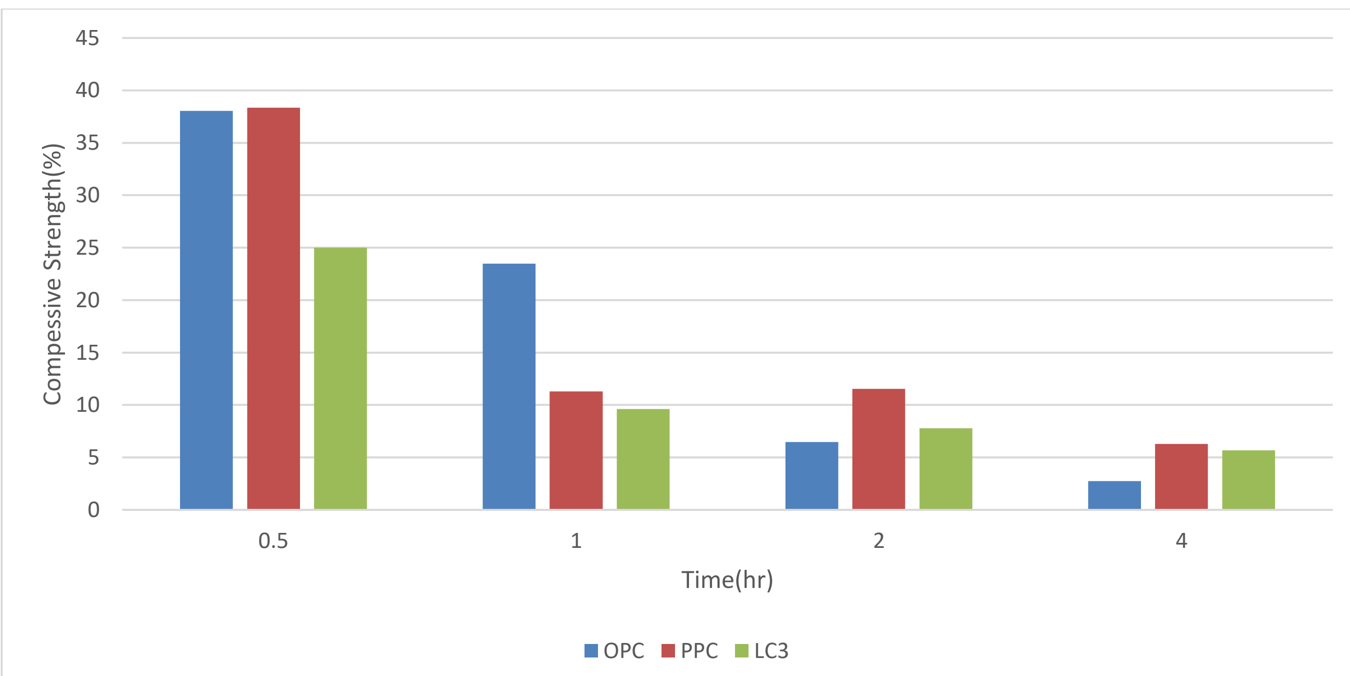


Fig.21. Average compressive strength (in %) for OPC, PPC, and LC3 concrete at a temperature of 1000 °C for different time durations with reference to concrete at room temperature.

For temperature 200 °C, as shown in Fig.17, there is a slightly higher reduction in compressive strength for PPC and LC3 concrete, than of OPC concrete but for all different time durations (0.5 to 4 h), their percentage compressive strength with respect to their 28 day compressive strength is comparable to each other.

At 400°C, small reduction in compressive strength had been observed, at 0.5 and 1h time duration, OPC and PPC had comparable % compressive strength and for longer durations (2 and 4hr) PPC concrete had less C.S than OPC concrete. But LC3 concrete had less compressive strength than other two, in all time durations. The strength varies from 84.77 to 77.60%, 83.83 to 70.09%, and 78.95 to 65.00% for OPC, PPC, and LC3 concrete Fig.18.

Now, from temperature 600 to 1000 °C (Fig.19 to Fig.21) there was a general trend of gradual decrease in compressive strength with the increasing temperature and increasing time durations. For temperature 600 and 800 °C OPC concrete mainly had greater strength than other two concrete and LC3 had lowest at each time duration. But at 1000 °C, for longer duration (2 and 4 h), LC3 concrete had greater compressive strength than OPC concrete but less than PPC concrete.

Overall, LC3 concrete shows a slightly lower strength characteristics as compared to conventional concretes.

3.4 Ultrasonic Pulse Velocity (UPV):

The variation of average UPV value (in %) at elevated temperature with respect to room temperature average UPV value has been shown in Fig.22 to Fig.26.

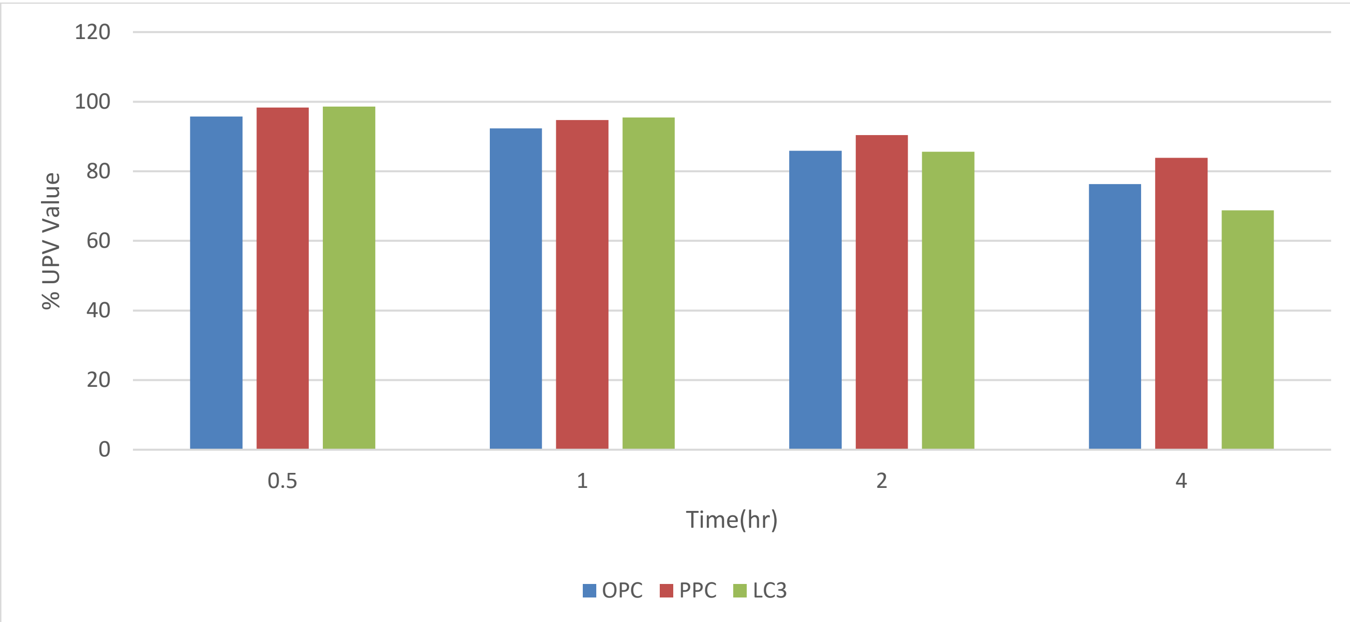


Fig.22. Average UPV value (in %) for OPC, PPC, and LC3 concrete at a temperature of 200 °C for different time durations.

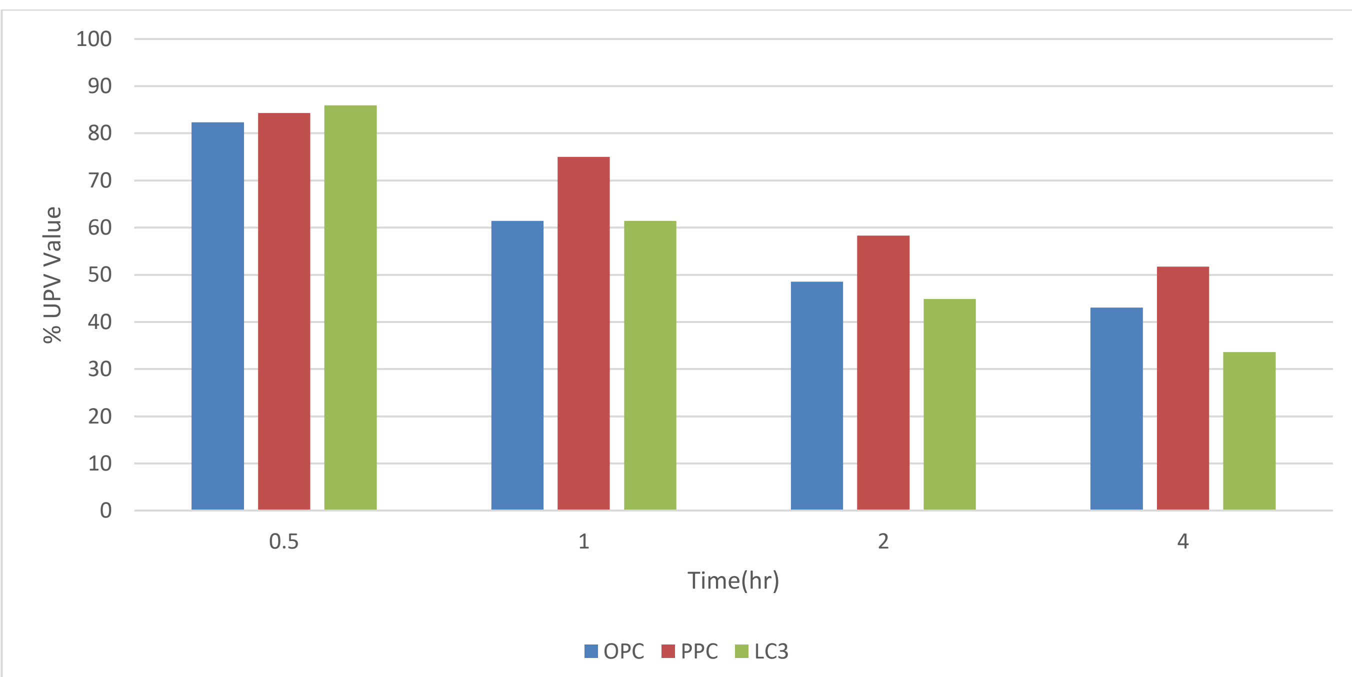


Fig.23. Average UPV value (in %) for OPC, PPC, and LC3 concrete at a temperature of 400 °C for different time durations.

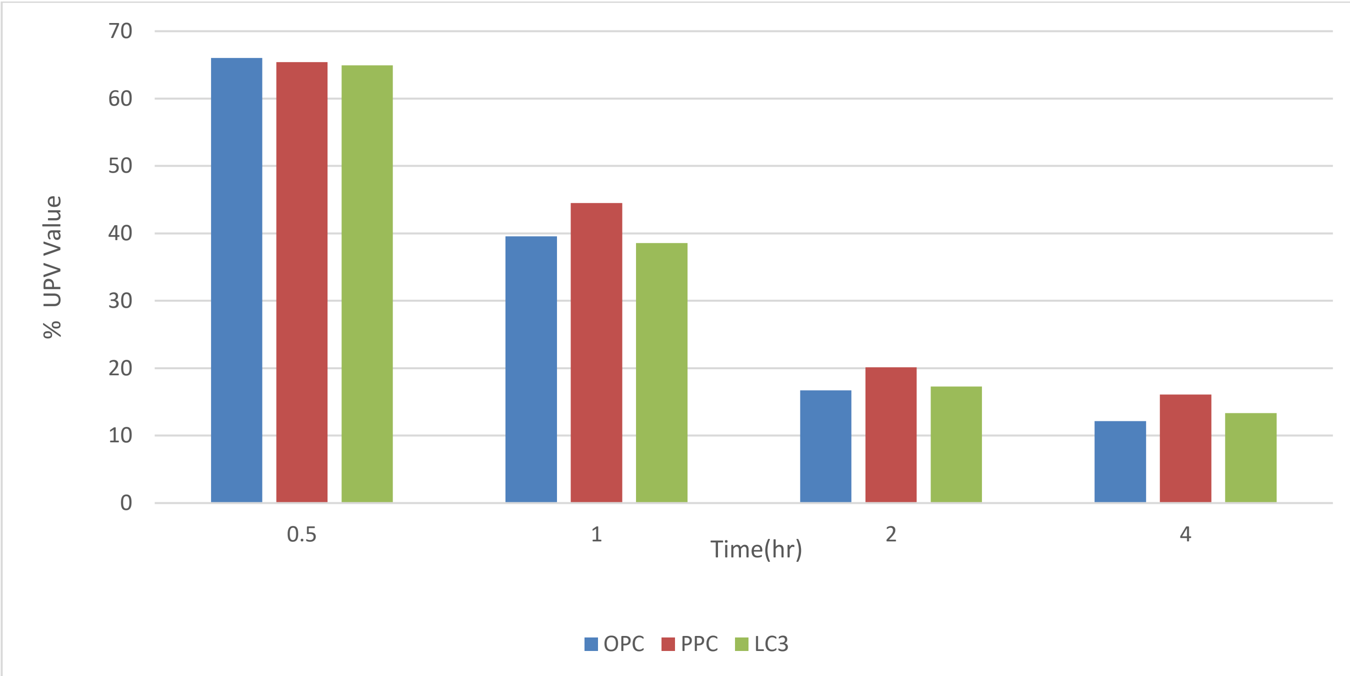


Fig.24. Average UPV value (in %) for OPC, PPC, and LC3 concrete at a temperature of 600 °C for different time durations.

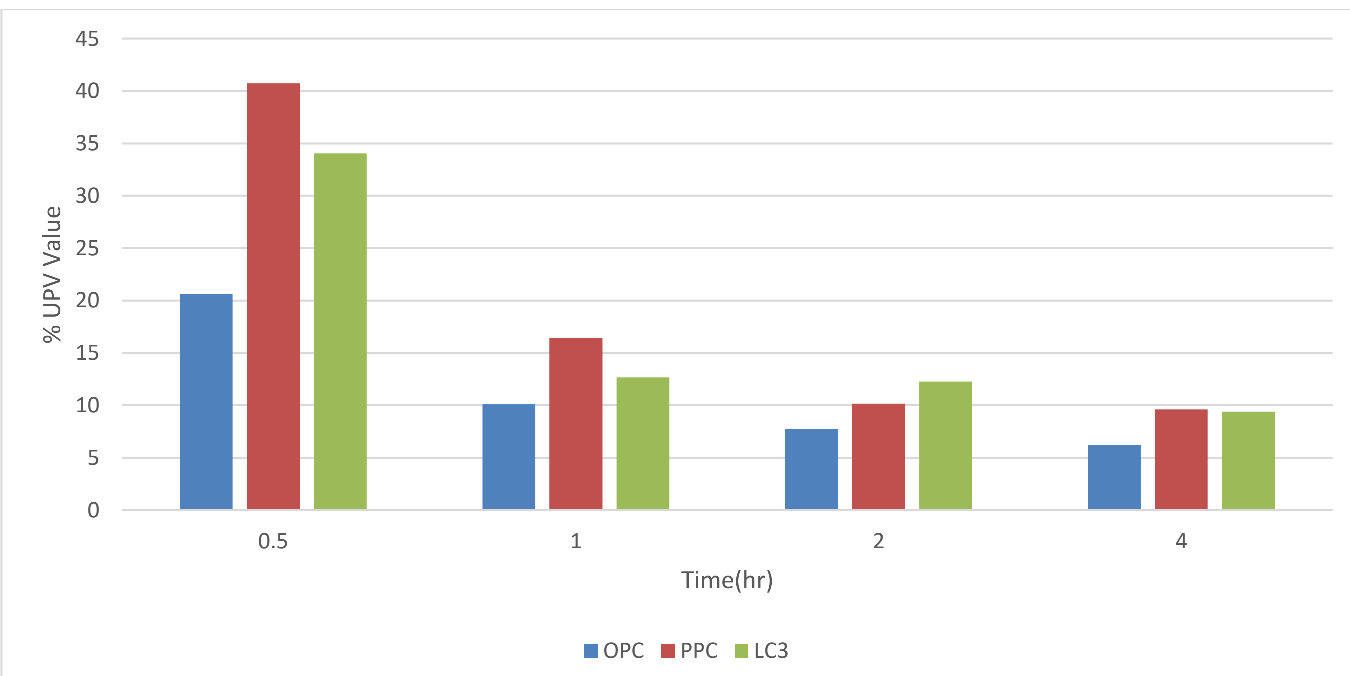


Fig.25. Average UPV value (in %) for OPC, PPC, and LC3 concrete at a temperature of 800 °C for different time durations.

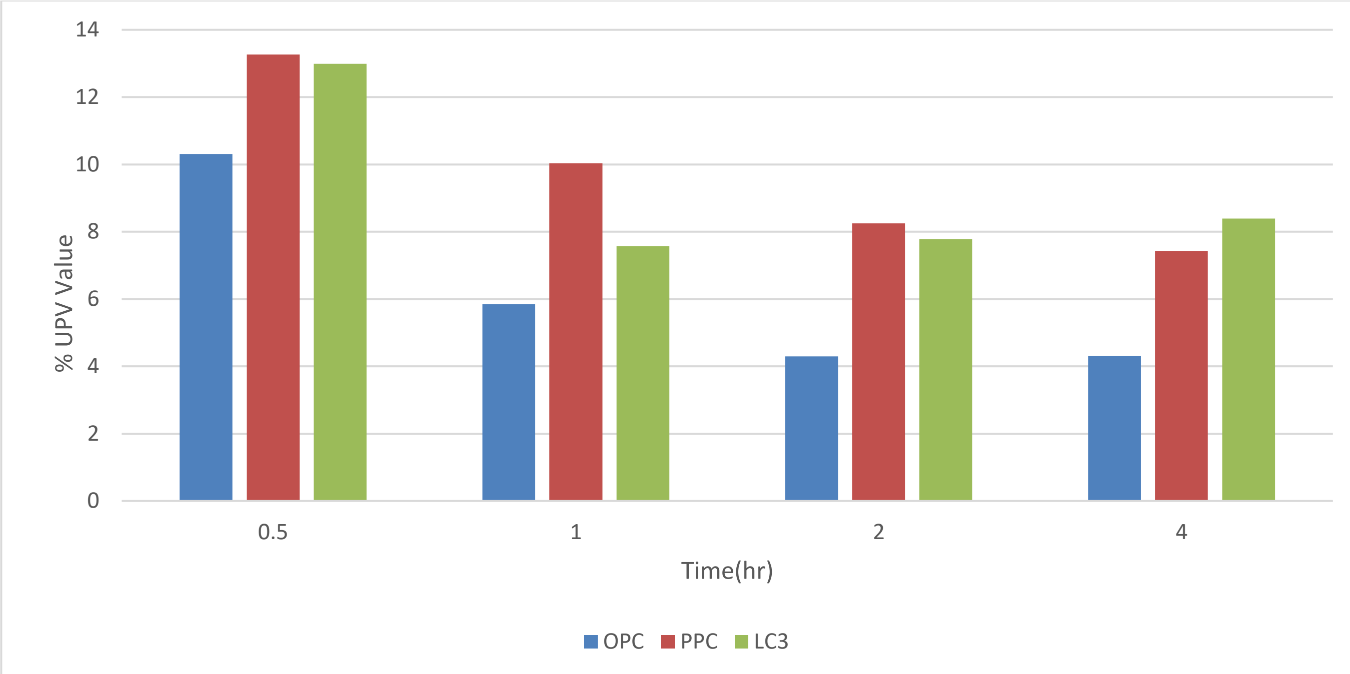


Fig.26. Average UPV value (in %) for OPC, PPC, and LC3 concrete at a temperature of 1000 °C for different time durations.

The main motive to use the UPV test is for the determination of concrete uniformity, cracks, or voids' presence, changes in properties with temperature.

From Fig.22, i.e., at temperature 200 °C, the UPV values are comparable, at each time durations and very less difference in values, still gradual decrease in value as time duration increases. However, for a shorter duration (0.5 and 1 h), LC3 concrete had slightly greater UPV value than the other two concrete. And for 2 h and 4 h duration, PPC concrete had a slight upper hand in UPV value. So, it can be interpreted that very fewer cracks had been developed mainly due to steam pressure, as the temperature is higher than the boiling point of water.

At 400 and 600 °C temperature, the difference in UPV values increases as temperature and time durations increase, and in both case trend is similar where, PPC concrete has greater UPV values as compared to OPC and LC3 concrete at each time duration, whereas LC3 and OPC concrete has similar UPV values at both temperatures with respect to their individual time durations Fig.23 and Fig.24.

Interestingly, at 800 and 1000 °C, there is much higher loss in UPV values for OPC concrete as compared to PPC and LC3 concrete. However in both cases, PPC concrete has higher UPV values among three types of cement concrete. Also, LC3 concrete has higher UPV values than OPC concrete which means fewer cracks/voids as compared to OPC concrete.

3.5 Thermogravimetric Analysis (TGA):

The results as obtained by TGA machine are reported in the form of graphs from Fig.27 to Fig.29.

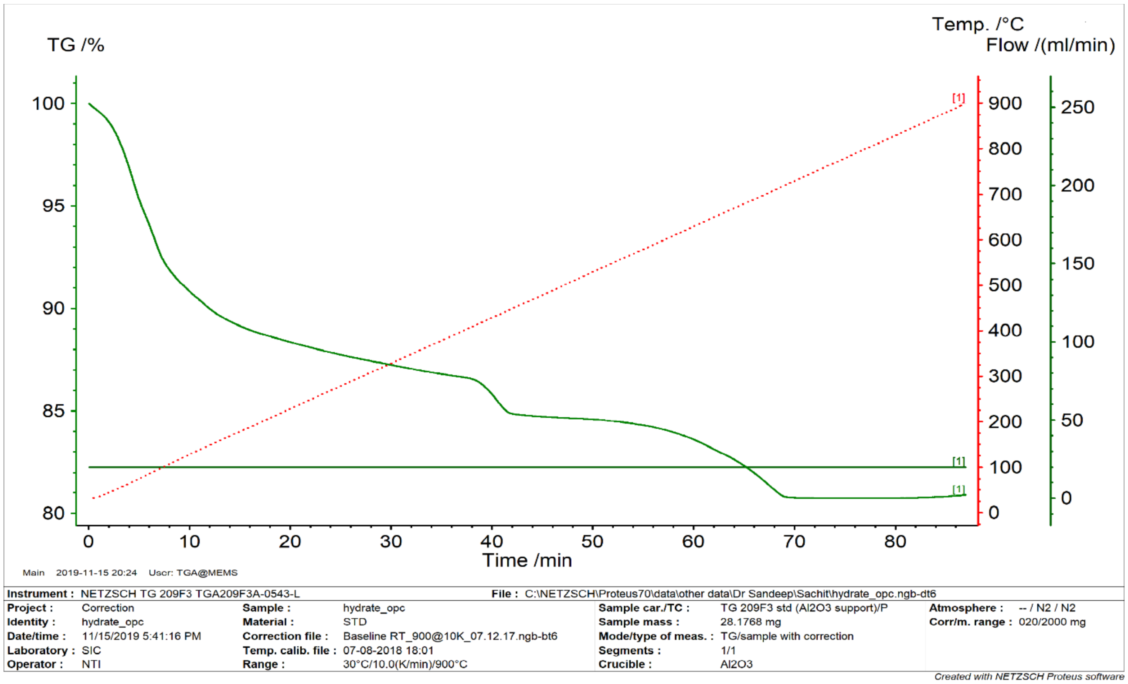


Fig.27. TGA graph for Ordinary Portland cement (OPC).

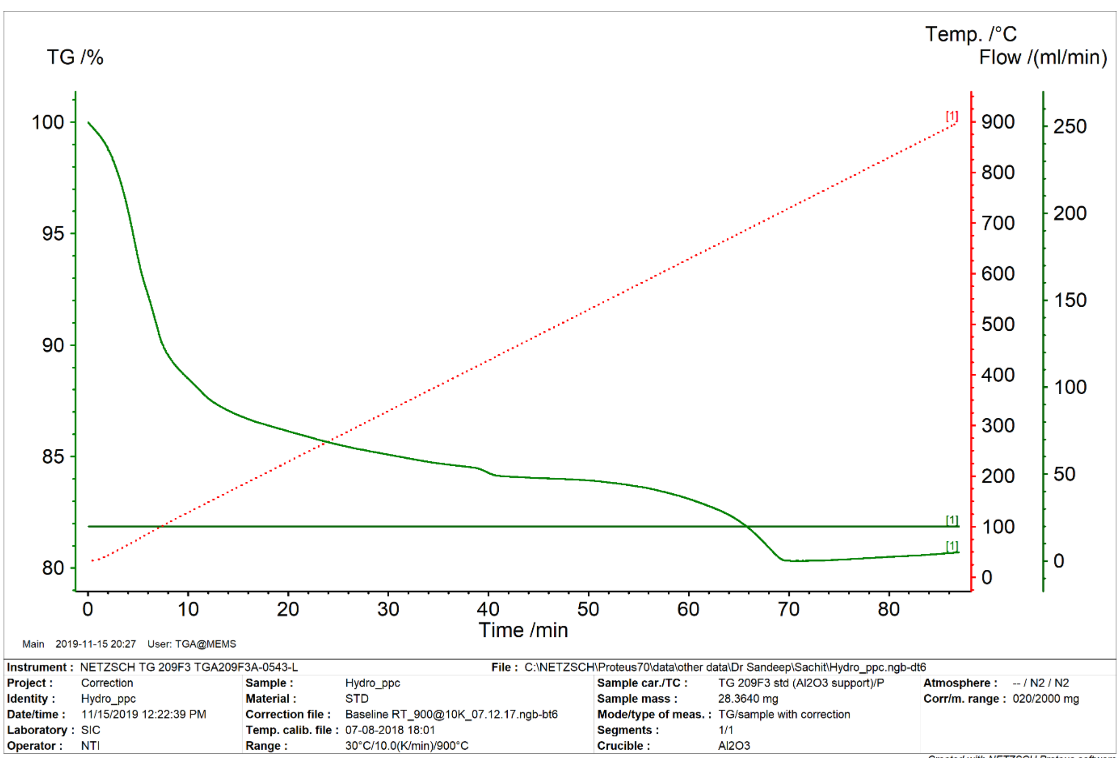


Fig.28.TGA graph for Portland pozzolana cement (PPC).

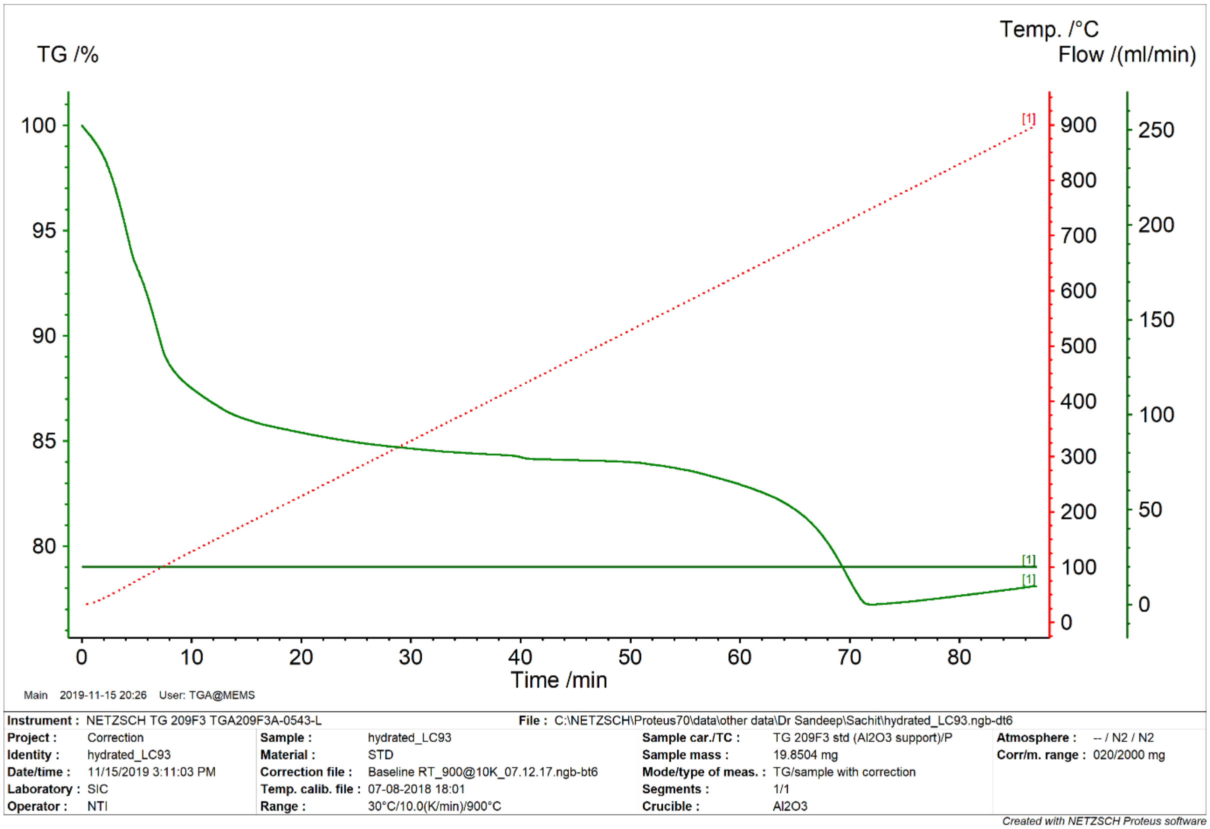


Fig.29. TGA graph for Limestone Calcined Clay cement (LC3).

Table 4: Temperature v/s mass (%) for OPC, PPC and LC3.

Temperature(°C)	Mass(%) for OPC	Mass(%) for PPC	Mass(%) for LC3
32	99.98	99.99	99.99
100	92.41	90.19	89.38
200	88.76	86.51	85.71
300	87.52	85.32	84.79
400	86.64	84.58	84.37
500	84.67	84	84.06
600	84.09	83.46	83.37
700	81.53	81.34	80.76
800	80.74	80.43	77.46
900	80.88	80.71	78.11

The machine has a rate of increase in temperature of 10 °C/min. and the temperature ranges from 30 to 900 °C in the TGA machine.

The TGA has been done for hydrated cement paste of OPC, PPC, and LC3 after 28 day of curing in the water tank. From the above Table.4 and Fig.27 to Fig.29, it can be observed that there is nearly equal mass loss at each temperature for OPC and PPC pastes but slightly more mass loss in LC3 paste at any given temperature. Since, there is comparable mass loss at any temperature for all the three cement pastes, which means we can use more sustainable cement (LC3) in place of OPC and PPC which are not much environment friendly with some safety measures. However, due to higher mass loss in LC3 a slightly higher factor of safety can be adopted during design.

Also, there is slight increase in the mass of all three cement pastes at very high temperature, which could be happened due to formations of new product (physicochemical changes) within cement pastes after reacting with air (oxygen, carbon dioxide , Sulphur etc.) at higher temperature. In this case the temperature is around 900 °C where this change occurred.

4 Conclusions:

This report presents a case study on the mechanical behavior of limestone calcined clay cement (LC3) concrete at elevated temperatures with the aim to determine the mechanical properties of the material. Concrete at elevated temperatures, undergoes significant physical and chemical changes. These changes cause properties to deteriorate at elevated temperatures and introduce additional complexities. The results are intended to provide information for developing specific fire performance criteria for the actual behavior of LC3 concrete structures exposed to high temperatures. The experimental tests are conducted on the three types of concrete containing OPC, PPC, and LC3 at constant w/c ratio and constant amount of cement. Within the scope of work, the compressive test, mass loss, volume change, UPV values, and TGA were conducted at elevated temperatures 200, 400, 600, 800, and 1000 °C for a duration of 0.5, 1, 2 and 4 h. Based on the obtained data following conclusions are made:

1. Generally, mass loss is slightly higher in case of LC3 concrete as compared to OPC and PPC concrete at elevated temperatures like 200 and 400 °C for different time durations (0.5, 1, 2, and 4 h), but at higher temperatures (600, 800, and 1000 °C) mass losses are nearly comparable to each other and independent of time duration.
2. LC3 concrete volume increases with the increase in temperatures and with time durations and the expansion is less than the conventionally used concrete.
3. Compressive strength strengths are comparable for all three types of concrete, however LC3 had a slightly lower compressive strength in general.
4. UPV values represent cracks/voids. In this case, mostly UPV values are higher LC3 concrete than OPC concrete at any temperature and time durations, i.e., fewer cracks/voids as compared to OPC concrete.
5. The TGA analysis of cement pastes of OPC, PPC, and LC3, showed the relatively comparable mass loss but slightly higher mass loss for LC3 at any given temperature.

Overall LC3 performed comparable to OPC and PPC after exposure to elevated temperature. LC3 had lower volumetric changes leading to lesser cracks but had comparatively higher mass loss and strength loss. This can mean that structure made using LC3 based concrete may have slightly lower thermal strain based stresses under exposure to elevated temperature but based on current observations performs slightly poor as compared to OPC and PPC in terms of strength performance.

Thus, we can conclude that with the slight precautions, LC3 cement can also be used in place of OPC and PPC cement at elevated temperatures by using a safety factor of the higher time duration from existing standards [9], by adopting slightly thicker sections.

Further investigation are required on thermal strain based stresses for better evaluation and identification of advantages of using LC3 if any under elevated temperature conditions.

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