Thermal Behaviour of Different Types of Concrete Subjected to Elevated Temperature

Nawal Kishor Banjara[1,2](https://orcid.org/0000-0002-7433-9379), Ajay Chourasia[1,2] , R Pradeep Kumar[1,2] (https://orcid.org/0000-0003-4120-2058)

[1,2]CSIR-Cenral Building Research Institute, Roorkee, India

[1,2]Academy of Scientific and Innovative Research (AcSIR), Ghaziabad

nawalkishor@cbri.res.in

Abstract. The escalating growth in science, technology, and global population has led to the rapid growth of high-rise buildings. Recent years have witnessed numerous building fire accidents worldwide, resulting in profound human losses. The investigation of building resistance under fire events is crucial for mitigating such risks. For assessing structural fire behaviour, it is very much important to understand the concrete behaviour, when it is exposed to higher temperature. Construction materials such as concrete with higher grades, high-performance concrete (HPC) and 3D printed concrete (3DCP) are gaining prominence in high-rise buildings. Understanding the thermal and fire behavior of these different types of concrete is imperative for ensuring the safety and resilience of modern structures. Hence, in this paper, thermal behaviour (thermal conductivity, thermal diffusivity, and heat capacity) and fire behaviour of plain concrete (PC), HPC and 3D printed concrete which is subjected to elevated temperature are studied. It is performed on furnace exposed for a temperature range of 100ºC to 800ºC. The temperature monitoring was carried out for the time taken to reach the desired temperature at the core of the concrete specimens. Non-destructive testing (NDT) methods are used for determining the changes in concrete strength of exposed specimens. This study also focused on to develop a relationship between thermal behavior with mechanical properties of different types of concrete. This research intention is to contribute the useful insights to the field of fire safety in buildings.

Keywords: Plain concrete; 3D printed concrete; High performance concrete; Thermal properties; Elevated temperature

1 Introduction

Fire accidents can cause lot of loss in terms of life and economy. Due to fire event, concrete structures losses its strength and it can be one of the most unfavourable factors that affects the strength and stability of concrete structures. Concrete is broadly known as a fire-resistant non-combustible material which is widely used in the construction industry. Fire is one of the most severe environmental conditions a building can experience in its lifespan [1]. The chances of fire occurrence are greater than earthquakes in the lifespan of a building [2], [3]. Precautionary measures can easily prevent loss of properties and lives under such catastrophic scenarios, proper architectural planning [4], avoiding the use of flammable materials, using proper control devices and ventilation, etc., and personal precautions by the occupants [5]; sometimes fire can be the result of unforeseen and uncontrollable events, like fire following earthquakes [6], [7], fire due to electrical faults, fire due to explosions [8], [9], etc. As the fire suppression system becomes unusable, the worst-case scenario is a structural system weakens which leads to a total collapse of a building. Because when concrete is exposed to fire, it undergoes many changes such as thermos-mechanical and thermo-chemical changes in its original composition and mechanical properties [10]. Thus, providing safe material and appropriate design safety measures against fire is necessary.

Fire is one of the divesting hazards which produces rise in the temperatures, which can severely damage the buildings or building components. At higher temperature, in the concrete structure, it develops pore water pressure which increases in the porosity, thermal expansion, cracking and creep occurs. Due to these reasons, damages in the micro- and meso-structure of concrete starts which leads to its mechanical decay and spalling of the concrete. The vaporization due to increase in temperature, produces temperature difference, which induces high vapour pressure during heating, and it results in developing tensile stresses in the concrete that plays primary reason for cracking in the concrete.

The most important aspect after a structure is subjected to fire is to evaluate its structural safety [11]. It is well known and all are aware of the damage that causes due to fire accidents. It causes in terms of loss of human lives, homes, livelihoods and environmental effects. However, the assessment of fire-damaged structures begins with visual inspection as a preliminary evaluation [12-13], followed by subsequent detailed assessments using various tests such as material tests, non-destructive tests (NDT) etc. Ultrasonic pulse velocity (UPV) is one of the attractive subjects in the area of non-destructive testing (NDT) of concrete, when it is used for assessing properties of fire exposed concrete. This study includes a number of tests which were performed to evaluate the changes occurs in the wave pulse velocity of the concrete when it is exposed to higher temperatures.

Also, at the same time, another NDT method which is Schmidt Rebound Hammer (RH) was used to measure the toughness of the concrete, when it is exposed to higher temperature conditions. In addition to the tests such as UPV, the RH test is an alternative simple and economical NDT method to determine the residual strength of concrete. The RH test is based on the relationship between the concrete compressive strength and the surface hardness of the concrete surface measured as the rebound number acquired from the test. [14]. The rebound value of the mass displayed gives the measure of the surface hardness of the material. [15]. The RH test can be used to estimate the compressive strength of unheated concrete or concrete under normal conditions at ambient temperatures and heated concrete at higher temperatures. [16-17].

1.1 Thermal Properties of Concrete

The thermal properties of concrete are essential factors that influence its performance in various applications, including its behaviour under fire conditions. Here are the key thermal properties of concrete:

1.1.1. Thermal Conductivity (k)

This property measures how well concrete conducts heat. Concrete typically has a low thermal conductivity, which means it does not transfer heat quickly. The thermal conductivity of concrete varies depending on factors such as its composition, density, and moisture content. Typical values range from about 0.8 to 1.7 W/m·K (watts per meter-kelvin).

1.1.2. Specific Heat Capacity (C)

It refers to an amount of heat is needed to increase the temperature of a unit mass of concrete by one-degree Kelvin (or Celsius). Concrete has a moderate specific heat capacity, typically ranging from 0.7 to 1.0 kJ/kg·K (kilojoules per kilogram per Kelvin). This property influences concrete's ability to absorb and retain heat.

1.1.3. Thermal Diffusivity (h)

Thermal diffusivity measures how quickly heat spreads through a material. It is the ratio of thermal conductivity to the specific heat capacity and density. Concrete's thermal diffusivity is influenced by its composition and density, affecting how it responds to changes in temperature. It is directly related to the conductivity through the equation.

$$Diffusivity = \frac{Conductivity}{C\rho} \tag{1}$$

1.1.4. Relation between Important Thermal Properties

Relationship between thermal conductivity, specific heat, thermal diffusivity and density as given below.

$$h^2 = \frac{k}{\rho c} \tag{2}$$

Where, k = Thermal conductivity

C = Specific Heat

h = Thermal Diffusivity

ρ = Density

Understanding these thermal properties is essential for engineers and architects in designing energy-efficient buildings, assessing fire safety, and optimizing the performance of concrete structures in various environmental conditions.

1.2 Fire Resistance Heating Curve

Fire resistance tests can be performed on various sizes and scales of materials, elements, and structures to find the temperature at different layers of concrete elements with respect to time. It accomplishes the heating of the element similar to the heating during a fire scenario. Different fire scenarios, testing methods, conditions, and criteria are given in international and national standards like EN 1992-1-2 (2004) [18], IS 3809 (1979) [19], ISO 834 (1999) [20], ASTM E119 [21], and ASTM E1529 [22] for standard fire, natural fire, hydrocarbon-I, modified hydrocarbon-II, external fire, and realistic fire, load, time-temperature curves, respectively as shown in Figure 1. The Indian standard (IS 3809) has adopted the ISO 834 standard fire test curve for testing the fire resistance of building elements. The criteria of tests mainly include resistance, integrity, and insulation (REI), according to En 1992-1-2 [18].

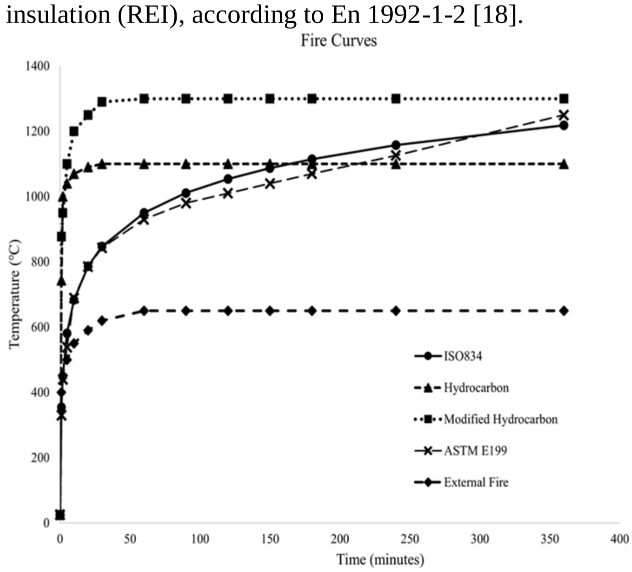


Fig. 1. Comparison of various time-temperature heating curves for fire resistance testing [18-22]

1.3 Effect of Concrete under Fire

Concrete undergoes several effects when exposed to fire, which can impact its structural integrity and overall performance. Understanding these effects is crucial for designing fire-resistant structures and ensuring safety in buildings. The primary effects of fire on concrete are loss of strength, cracking and spalling, change in physical properties, chemical changes, loss of bond strength, thermal stress, and insulation performance.

1.4 Post-Fire Assessment

After a fire event, it is essential to assess the extent of damage to concrete structures thoroughly. Non-destructive testing methods, such as ultrasound, rebound hammer and thermal imaging, can help evaluate the integrity of concrete elements and determine whether repair or replacement is necessary. To mitigate these effects and enhance the fire resistance of concrete structures, engineers use various strategies such as incorporating fire-resistant additives, applying protective coatings, designing adequate fire barriers and insulation, and implementing proper structural detailing and reinforcement practices.

2 Experimental Details

2.1 Material Used

Specimens used here for experiments are concrete cubes and cylinders. Materials required for casting concrete cubes which include cement, fine aggregate (FA), coarse aggregate (CA) and water. Portland grade 43 cement was used for this study.

2.2 Experimental Specimens

For fire resistance test and thermal properties of concrete, different type and grades of concrete specimens are considered in this study. For fire resistance test, cube specimens of size 150×150 ×150 mm and cylindrical specimens of size 150 × 300 mm were cast. For evaluating thermal properties, cube samples of size 50×50 ×50 mm were cast. Specimens were cast in steel moulds and were demoulded after a set time of 24 hours of casting. Specimens are water cured for 28 days as shown in Figure 2. For 3D printed concrete, cylindrical specimens were taken out from printed bed (shown in Figure 2). Specimens were then furnace exposed for a temperature range of 100 to 800º C. Specimens were placed in the furnace and standard fire temperature and duration was set. Specimens were thus heated gradually and the temperature was recorded at the centre of the specimens by means of the K -type of thermocouple. The thermocouple is further connected to a data taker for recording the readings.

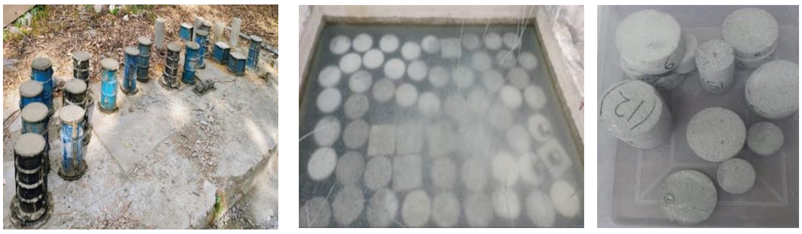


Fig. 2. Casting and curing of specimens

3 Thermal Properties

Cube size of 50×50 ×50 mm was used for evaluating thermal properties of concrete used. For 3DCP, cylindrical specimen of diameter 50 mm with 35 mm height are considered. Transient Plane Source (TPS) method, which is based on the procedure of a transiently heated plane sensor, is most known as the hot disc thermal constants analyzer as shown in Figure 3(a). Two same size specimens are placed one over the other and in between sensor is kept as shown in Figure 3(b).

(a) (b)

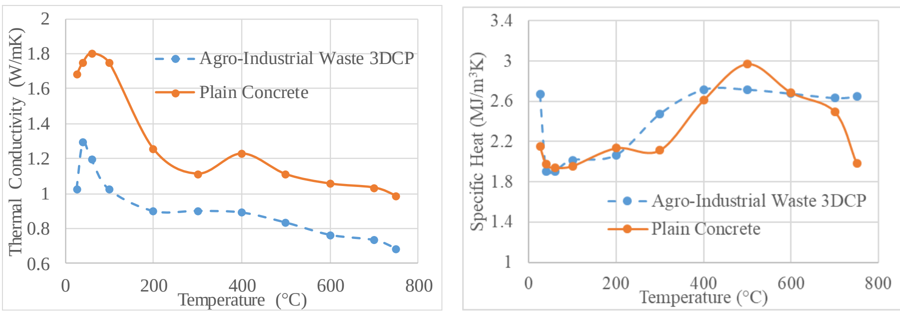
Fig. 3. TPS hot disk setup for evaluating thermal property of concrete

Based on the study, test is performed for 20 seconds time and heating power is kept as 120 mW. The following results of M30, M40, M50 and M60 grade of concrete, 3D printed mortar specimen, 3DCP plain concrete and 3DCP agro-industrial waste concrete specimens are obtained as given in Table 1.

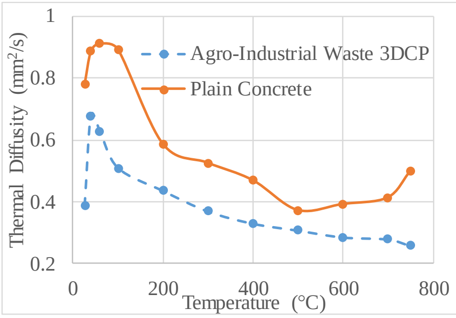
Table 1. Thermal behaviour of concrete

Grade of Concrete	Thermal Property (W/mK)	Thermal Diffusivity (mm2/s)	Specific Heat (MJ/m3K)
M30	0.865	0.640	2.153
M40	0.830	0.215	1.803
M50	1.495	0.129	1.562
M60	1.746	0.012	1.046
3DCP mortar	0.755	0.478	1.578
3DCP	0.157	0.014	3.190
3DCP Agro-Inds.	0.244	0.041	6.087

Further, thermal properties of plain concrete and agro-industrial waste 3D printed concrete (Cement, Bagasse, fly ash, M-sand) were also assessed at ambient and higher temperature as shown in Figure 4.



(a) (b)



(c)

Fig. 4. Thermal properties of plain and 3DCP

4 Fire Resistance Behaviour

The process of exposing the specimens to heat in a furnace and studying its behaviour is referred to as thermal behaviour. An electrical muffle furnace was used for exposing the concrete specimens at particular temperatures of 100 ºC to 800 ºC with an interval of 100 ºC respectively. Concrete specimens were then placed in the furnace and the duration of exposure to the desired temperature was set. K-type thermocouple was used (placed on the centre of concrete specimens during cast of specimens) to measure the temperature at the centre of the specimen. The entire process of heating was monitored. The process was performed for temperatures of 100 ºC, 200 ºC and upto 800 ºC for all the concrete specimens. Figure 5, shows the exposure of specimens in the furnace.

Fig. 5. Fire exposure of specimens in muffle furnace

Fire resistance and cracking patterns of concrete at different temperature are given below in Table 2.

Table 2. Observation of fire exposed concrete at different temperature

Temp. (°C)	Crack Formation	Color Significance	Implication
Low Temperature (100 – 300)	Concrete generally experiences minimal damage. Cracks that do form are often fine and surface-level due to minor thermal expansion and contraction.	Cracks are typically white or light gray, indicating surface thermal cracking with minimal structural impact.	Concrete remains largely intact, with only superficial effects visible.
Medium Temperature (400 – 600)	More significant cracking occurs due to higher thermal stresses. The concrete may start to spall, especially at the surface where the thermal gradients are most intense.	Cracks may appear yellow or orange due to oxidation of iron compounds within the concrete.	The concrete may lose some of its load-bearing capacity and require repair or reinforcement.
High Temperatures (700 – 800)	Extensive damage is observed, including severe spalling and substantial cracking. The concrete may experience significant degradation and start to disintegrate.	Cracks are typically red, brown, or black, reflecting severe oxidation, chemical reactions, and breakdown of the concrete matrix.	Concrete loses much of its structural integrity and load-bearing capacity. Immediate assessment and potentially full replacement or remediation are necessary.

5 Non-Destructive Testing (NDT) Methods

5.1 Ultrasonic Pulse Velocity (UPV) Test

UPV test is an in-situ, NDT test to assess the quality of the concrete as shown in Figure 6. The in-situ quality of concrete is evaluated by determining the wave velocity of an ultrasonic wave pulse crossing through the concrete structure. It measures the time taken by the ultrasonic wave to pass through the one surface to other of the structure. Higher wave velocities show a good quality of concrete and continuity of the material used, while lower velocities may indicate the bad quality of concrete and which may have many cracks or voids. The qualitative grading of concrete based on UPV data as per IS 13311-Part I is given in Table 3.

$$Pulse\ Velocity\ (v) = \frac{Width\ of\ structure\ (L)}{Time\ taken\ by\ pulse\ to\ go\ through\ (t)} \tag{3}$$

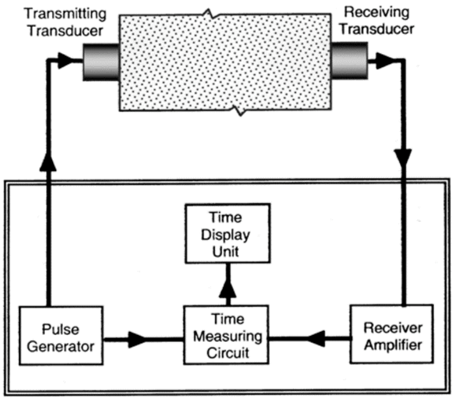


Fig. 6. Method of propagating and receiving pulses

Table 3. Concrete quality grading as per IS 13311 (Part I)

UPV Value km/sec (V)	Concrete Quality Grading
< 4.50	Excellent
3.50 - 4.50	Good
3.00 - 3.50	Medium
> 3.00	Doubtful

In the experiment performed transmitter and receiver were placed on opposite sides of the concrete specimens as shown in Figure 7. The wave generated through sending end was propagated to the receiving end. Time taken for the travel of wave and its velocity was noted. This entire process was repeated for exposed specimens of 100 º C to 800 ºC. The travel time of the pulse wave and pulse velocity are measured. It is observed that pulse velocity decreased with increasing temperatures.

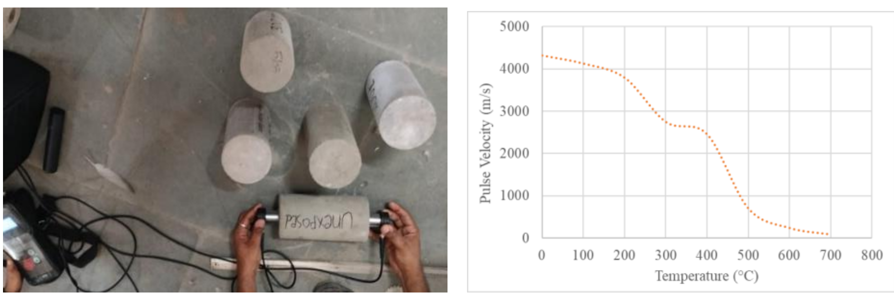


Fig. 7. UPV tests performed on exposed concrete specimens

5.2 Rebound Hammer (RH)

RH test is performed to obtain the surface hardness of a concrete surface by using Schmidt RH as per IS: 13311 (Part 2) -1992. Table 4 gives qualitative information on the quality of concrete based on the rebound hammer number. In order to assess the quality in terms of surface hardness of a concrete specimens, RH tests were performed at the same place where UPV readings were taken.

Table 4. Average Rebound number and quality of concrete

Average Rebound Number	Quality of Concrete
>40	Very good hard layer
30 to 40	Good layer
20 to 30	Fair
<20	Poor concrete
0	Delaminated

The purpose of evaluating the rebound number in a hammer test is associated with determining concrete toughness. The main objective of this study is to evaluate the robustness of RH reading data in fire exposed conditions of concrete specimens as shown in Figure 8.

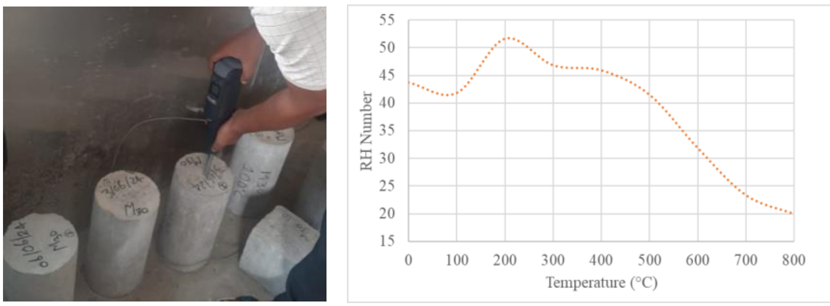


Fig. 8. Rebound Hammer performed on exposed concrete specimen

6 Conclusions

In this study, thermal and fire behaviour of different grades of normal strength of concrete with 3D printed concrete was discussed. Experimental studies were carried out for evaluating thermal and fire resistance properties. For assessing thermal properties of different grade of concrete and 3DCP specimens, at ambient temperature and at higher temperature, studied were performed. The thermal properties of concrete, such as specific heat, thermal expansion, thermal diffusivity, and thermal conductivity, were comprehensively examined. The research emphasises the complexities of concrete's thermal properties, which are influenced by composition, aggregate type, moisture content, and temperature. It was found that with increase in strength of concrete, thermal conductivity increase and vice versa. Similarly, specific head reduces. For fire performance, exposure of material was carried out upto 800 °C. It emphasises the relevance of understanding these qualities when designing and building concrete buildings subject to significant thermal loads or temperature variations. Further NDT tests were also performed on unexposed and exposed specimens. With increase in exposure temperature, reducing in RH and UPV were observed. Hence, fire exposure to concrete specimens have direct effect on the mechanical properties. The results of the study will be very much use full for carrying out structural fire audit after the fire events.

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Conflict of Interest

The author states that there is no conflict of interest

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