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Investigation on Key Influencing Factors Affecting Temperature Distribution in Concrete

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Abstract

Concrete is an unavoidable composite material used in buildings and structures. The behavior of concrete under the effect of fire is always critical, causing more structural damage. This research proposes experimental investigation on various factors that affect temperature distribution in concrete when exposed to fire. Water cement ratio, grade of concrete, curing period, type of admixtures, and fibers are the factors taken into consideration. The test was carried out in the temperature range of 100 °C to 600 °C. The temperature was measured at various depths of the specimen and then compared. Results from experiments show that grade of concrete, water-cement ratio, curing period and admixture type significantly influences the temperature distribution in concrete whereas contribution of fiber type is negligible. Comparison of temperature distribution at 25 mm from the bottom of specimen at 600 °C for M20 grade with 0.5 and 0.4 water cement ratio was done. It is found that temperature distribution in concrete goes higher as water cement ratio goes higher. There is an increase of 22.6% of temperature distribution for 0.5 water cement ratio than 0.4. Concrete samples which were cured for 14 days, and 28 days were tested, temperature distribution in concrete cured for 14 days is higher than that cured for 28 days. It is because of the curing time of calcium silicate hydrate (CSH) gel, and it was not fully matured and there was no moisture to finish the hydration process of cement.

Keywords

concrete, temperature distribution, fire, admixture, fibers

1 Introduction

Concrete is a composite material which is used for construction purposes in almost all of the geographical regions. Concretes performance under compressive stress and fire load is very impressive compared to other materials. Availability of materials, ease of handling, molding to desired shapes and size, durability, rigidity, and economical compared to steel, makes the concrete more likeable. But it has its own flaws like poor tensile strength, low ductility, occurrence of cracks, creep and shrinkage, requirement of long curing time and form work. Performance of concrete in fire is pretty good, it doesn't burn or melt.

Concrete reinforced with steel, leads to a material with both compressive and tensile strength, having large fields of application. Capacity of a structural member depends upon various factors like quality of raw materials, water-cement ratio, aggregate volume fraction, age of concrete, compaction of concrete, curing of concrete, and percentage of reinforcement. Concrete structures perform better than steel under fire. Concrete structures have to be designed to sustain fire accidents, since fire may have adverse effects on the structures, such as reduction in strength, spalling, deterioration in the properties of constituents of concrete and reinforcements etc., depending upon temperature and duration of fire. Though concrete's major intrinsic benefit is its performance to fire, but exposure to long hours can cause serious damage to the structure. When concrete is left unprotected to elevated temperatures, around 300 °C, the free water present in capillary pores of the concrete, the water in calcium

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silicate hydrate (CSH) gel and chemical bond, and water in CSH and sulphoaluminate evaporates, which causes concrete to shrink [1]. When there is a fire, the reinforcement is exposed to hot gases due to the shrinkage due to the water loss and steam pressure that forms in the concrete [2].

The system of pore in concrete gets dried up above 400 °C and the cement paste undergoes series of reactions. Following this, the hydration products are disengaged, and CSH gels break into piece [3]. On further temperature increase, around 530 °C, hydrate lime is formed from transformation of $Ca(OH)_2$, so that the concrete splits up into various pieces, and surface of concrete turns to white. The pressure generated by evaporation of the water within the concrete, changes in the chemical structure of cement paste and aggregate, and the thermal incompatibility between cement paste and aggregate during heating are the key factors influencing the structural integrity under elevated temperatures [2]. The yield strength and tensile strength of the reinforcing steel specimens with cover remained consistent with those of the reinforcing steels not exposed to high temperatures up to 500 °C. However, once this temperature threshold is surpassed, the reinforcing steel with cover experiences a loss in its strength capabilities [2].

Therefore, studying the behavior of concrete structural members is vital in designing structures which are subjected to high temperature to deliver fire-resistant design.

Studies were carried out to understand the fire load and its effects and the influencing factors in the past. Shi et al. [4] investigated fire load on flexural members to study the outcome of cover thickness on resistance of members. Cover provided was between 10 mm to 30 mm. From the studies it was clear that the bottom concrete cover had a good influence on ultimate loading capacity of the specimens, but this influence decreased as concrete cover thickness was increased [2]. Investigated the effect of concrete cover on reinforced concrete bars exposed to elevated temperatures and found the best cover which gives optimum results in fire resistance [5, 6]. Studied about effects of fibers in temperature in concrete and bars [7]. Investigated outcome of high temperature on the properties of the reinforcement bars which are kept between at a distance of 3.5 to 5.5 cm covers inside samples. From results, it is clear that steel bars get more resistance in high temperature with bigger covers.

Poon et al. [8] evaluated the performance of concrete with metakaolin (MK) at elevated temperatures up to 800 °C. They made 8 high strength and 8 normal strength concrete mixes containing 20%, 10%, 5% and 0% MK and then found out the residual compressive strength, chloride-ion penetration, porosity and average pore sizes. It was noted that the MK concrete witnessed higher loss of compressive strength and permeability related durability than the corresponding silica fume (SF), fly ash (FA) and ordinary Portland cement (OPC) concretes at higher temperatures.

Poon et al. [9] studied outcomes of high temperatures on the compressive strength, stiffness, and toughness of concrete. MK and SF were used as cement replacements and concrete mixes were reinforced with either or both steel fibers and polypropylene (PP) fibers.

After being exposed to the high temperatures, the MK concrete showed quicker losses in compressive strength, elastic modulus, and energy absorption capacity. When concrete was exposed to high temperatures, steel fibers effectively reduced the concrete’s loss in compressive strength. By comparing, using PP fibers reduced the energy absorption capacity of the concrete after exposure to 800 °C, despite the fact that it only slightly improved the concrete's ability to absorb energy before heating. References [3, 10, 11] have done similar studies on concrete with the addition of fibers.

Kodur and Khaliq [12] studied various outcomes of temperature on thermal properties of various types of high strength concrete (HSC). It was concluded from the results that temperature has very important influence on thermal properties of HSC, self-compacting concrete (SCC) and fly ash concrete (FAC).

Demirboğa and Gül [13] determined the effects of SF and FA on thermal conductivity of lightweight aggregate concrete. SF and FA were added for cement by reducing the cement weights in the ratio of 10%, 20% and 30% by weight. Thermal conductivity decreased as SF and FA content is increased. The reduction due to FA is higher compared to SF. Kim et al. [14] studied about the influencing factors on thermal conductivity of concrete, mortar and cement paste. Age of concrete, water cement (w/c) ratio, type of admixture, aggregate volume fraction, fine aggregate faction, temperature and humidity condition of specimen are the influencing parameters considered for the experimental investigation. Shen et al. [15] have done similar numerical and experimental study of thermal conductivity of cracked concrete. Reference [16] evaluated the performance of concrete beams with various fiber reinforced polymer and steel bars exposed to elevated temperature. From the study it was found that the beams with carbon fiber (CF) reinforced polymer have more load carrying capacity compared to other types of beams. This finding underscores the effectiveness of CFRP in enhancing the thermal performance and structural integrity of concrete beams under fire conditions. The study's results suggest that CFRP not only improves load-bearing capabilities but also potentially offers better resistance to the thermal stresses encountered during a fire.

Whereas [17] investigated the effect of elevated temperature on compressive strength of concrete made of various types of aggregate and found that the type of aggregate has a great effect on compressive strength and thermal resistance of concrete. Concrete which was andesite showed highest residual strength after exposing to elevated temperature. This finding suggests that the choice of aggregate can substantially impact the thermal performance of concrete. Andesite's superior performance in retaining strength highlights its potential as a preferred aggregate for improving the fire-resistance of concrete structures.

Influence of different types of OPC on hardened cement paste exposed to high temperatures was studied by [18] and concluded that changes in water cement ratio have no impact on relative strength. This insight is valuable for understanding how OPC behaves under thermal stress and for designing concrete mixtures that can maintain structural integrity at elevated temperatures.

From above literatures it can be concluded that reinforced concrete members subjected to high temperatures, loses its compressive strength and modulus of elasticity. In addition to that yield strength, tensile strength, modulus of elasticity and ductility of reinforcing steel bars also decreases. Cover provided for structural members delays direct exposure of fire to reinforcing steel. RCC members with greater cover thickness performed better than that with lesser cover to reinforcing steel when exposed to temperatures above 500 °C. Since concrete is a composite material, thermal conductivity of cement paste and mortar is completely different from aggregates. Conductivity of cement paste and mortar changes with water-cement ratio and admixture type. Moisture condition and aggregate volume fraction influences the thermal conductivity of concrete. This paper presents influence of constituents of concrete and curing period on temperature distribution in concrete. There are rare research works reported in the temperature distribution in concrete under various key parameters affecting it when exposed to fire.

2 Materials and methodology

General ingredients used for making concrete in this study are cement, coarse and fine aggregate, water, admixtures, and fiber. For the investigation OPC conforming to IS 12269:2013 [19] were used. The specific gravity of the cement was 3.15. Sand conforming to Zone-II of IS 383:1970 [20] was used as fine aggregate. Locally available aggregate of 10 mm was used as coarse aggregate. The specific gravity of cement, fine aggregate and coarse aggregate were 3.15, 2.65 and 2.85 respectively. Potable water was used for mixing and curing. Mineral admixtures such as SF, MK, FA and fibers such as C, basalt (B), glass (G), and PP were used for the investigation. Table 1 shows chemical properties of admixtures used in concrete. Table 2 depicts properties of various fibers used for this study.

2.1 Mix design

Concrete mix was designed as per Indian Standard [21]. To study the effects of different grades, M20, M30, M40 and M50 grades of concrete were selected as shown in Table 3. Fine aggregate and coarse aggregate are denoted as FA and

Table 1 Chemical properties of admixtures used in concrete

Admixtures	FA	SF	MK
Specific gravity	2.45	2.33	2.79
Silica (SiO_2)%	59.55	92.5	61.90
Iron oxide (Fe_2O_3)%	3.87	0.74	1.84
Alumina (Al_2O_3)%	29.29	0.8	33.15
Calcium oxide (CaO)%	2.72	0.2	0.08
Magnesium oxide (MgO)%	0.46	0.47	0.23
Sodium oxide (Na_2O)%	0.73	0.54	0.27
Potassium oxide (K_2O)%	1.72	1.82	2.42
Sulphur (SO_3)%	0.05	–	–
Color	Light grey	Gray	White
Surface area (m^2/kg)	500–900	12070	9100
Particle size (μm)	45–100	0.15	0.7

Table 2 Properties of fibers used in concrete

Fiber	Length (mm)	Density (g/cm^3)	Melting point (°C)	Young's modulus (GPa)
BF	11	2.95	1300–1450	120–150
CF	11	1.91	1250–1350	250–300
GF	11	3.12	600–750	80–110
PP	11	0.89	170–260	60–80

Table 3 Mix design

Specimen	Cement (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	Water (kg/m^3)
M20	324.76	1070.34	872.54	191.47
M30	383.21	1075.54	819.63	167.40
M40	414.30	804.32	1156.43	153.23
M50	450.21	771.43	1144.57	133.20

CA respectively. To investigate the effect of water cement ratio, 0.4 and 0.5 ratios are selected with M20 grade concrete. To study the effect of admixtures in temperature distribution in concrete, 10% of cement volume was replaced with proportionate quantities of admixture in M20 grade of concrete. For the case of fibers, a constant addition of 0.1% has been used as a replacement of cement.

2.2 Heating of specimens

An electric furnace with an open top was used to heat the samples as shown in Fig. 1. Dimensions of the furnace used is 300 mm × 300 mm × 300 mm. Side of the furnace is blanketed with ceramic wool and the furnace is designed in such a way that only one flat face of the specimen can be exposed to heat. The concrete cylinders of 100 mm diameter and 200 mm height were cast and cured in water at temperature of 27 ± 2 °C for 28 days as per IS 516 [22]. Cured cylinders were dried using air at a temperature of 26 ± 2 °C prior to drilling holes of 12 mm diameter and 50 mm depth in the cylinder to facilitate the installation of thermocouples. It is to measure the temperature across its height while the bottom of the specimen gets exposed to a high temperature regime which is from 100 °C to 600 °C in steps of 100 °C in a furnace for a retention period of 45 min. Holes were drilled at 25, 50, 75, and 100 mm from the bottom of concrete cylinder. During the heating process temperature was noted at these 4 observation points starting from 100 °C till 600 °C at the bottom of the specimen at every interval of 100 °C.

Fig. 2 shows specimen inside furnace and Fig. 3 shows overall methodology for this study. Various parameters selected for studying its influence on temperature distribution in concrete are grade, water cement ratio, admixtures, fibers and curing period.

Fig. 1 Digital controlled electric furnace

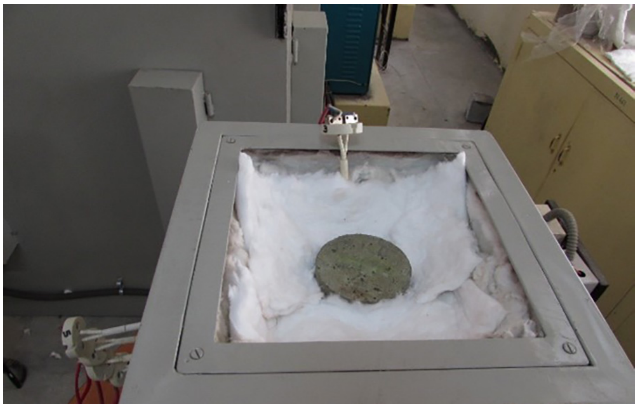


Fig. 2 Methodology

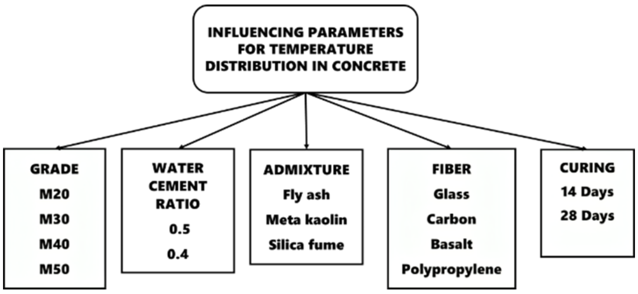


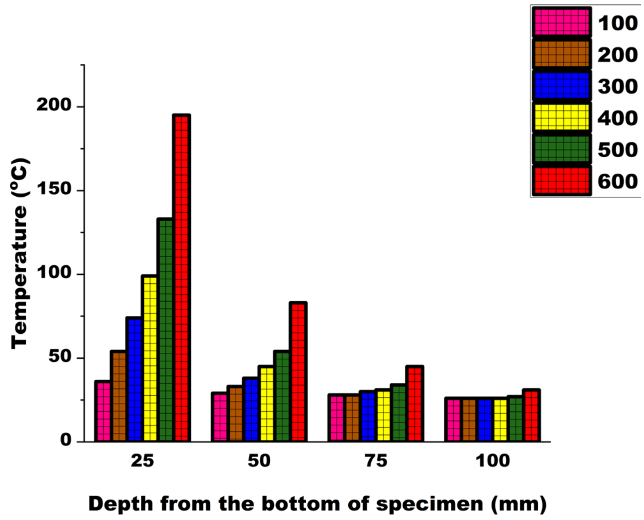
Fig. 3 Methodology

3 Experimental investigation

3.1 Influence of water-cement ratio on temperature distribution in concrete

w/c ratio is simply the ratio of weight of water to weight of cement. The weight ratio between water and cement is the most important mix design variable and it greatly influences the strength and durability of concrete when it is cured properly. Any excess water excluding water required for hydration creates pores, but air-filled pores do not contribute to strength of concrete. Low water cement ratio on the other hand causes poor workability. Volume of pores in concrete may influence heat transfer in concrete and thereby the residual properties of fire exposed concrete. A higher w/c ratio increases the volume of capillary pores, which can store more moisture. During fire exposure, this moisture evaporates, creating internal steam pressure and contributing to a higher temperature distribution within the concrete.

To study the impact of water cement ratio on temperature distribution in concrete two samples with water cement ratio of 0.5 and 0.4 and with same aggregate volume fraction was used. Fig. 4 depict temperature distribution measured in M20 concrete with w-c ratio of 0.5 and 0.4 respectively. References [23–25] have investigated the effect of water curing in strength development in concrete under various conditions. From these studies it's clear that proper



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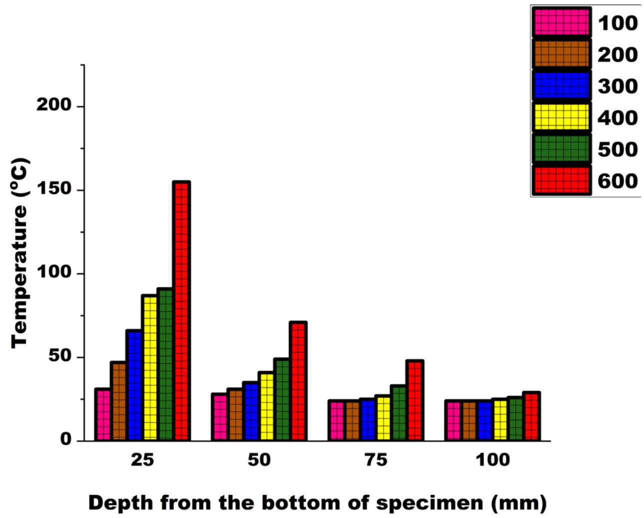


(b)

Fig. 4 Measured temperature distribution in M20 concrete with w/c ratio; (a) 0.5; (b) 0.4

water curing is vital to attain full strength and capacity of concrete. Fig. 5 shows comparison of temperature distribution at 25 mm from the bottom of specimen at 600 °C for M20 with different water cement ratio. From figures and data, it is clear that with 0.5 and 0.4 water cement ratio there is a change in thermal conductivity. Concretes conductivity goes higher as water cement goes higher. There is an increase of 22.6% of heat distribution in specimen with water cement ratio of 0.5 than 0.4 at 25mm depth of the specimen from bottom at 600 °C for M20 concrete.

3.2 Influence of curing period on temperature distribution in concrete

Concretes curing is done to keep moisture content in newly placed concrete. To achieve impermeable, crack-free, and long-lasting concrete, it is essential to carefully control the

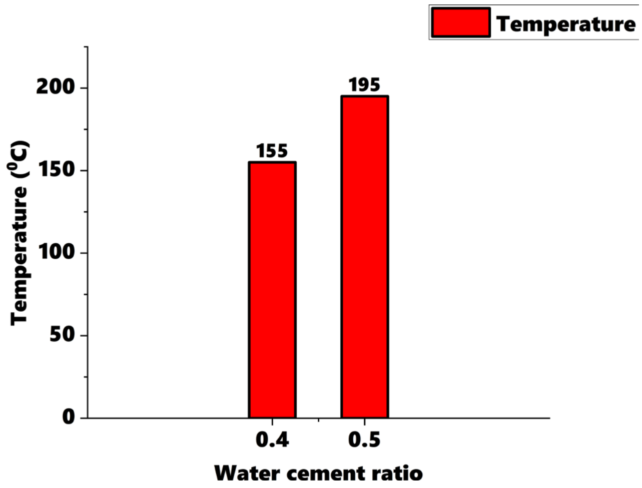
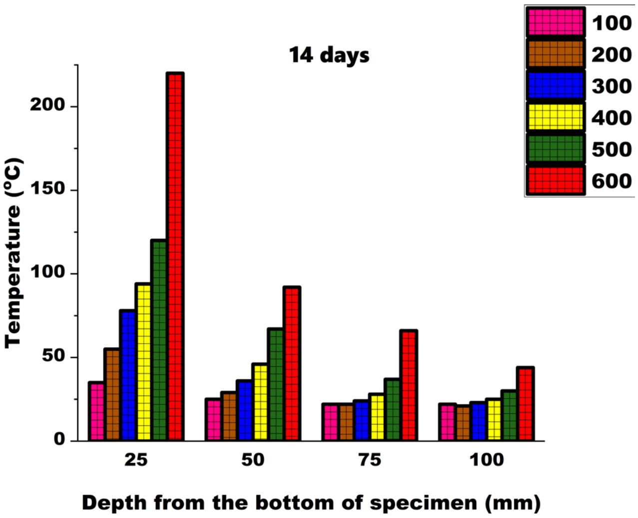


Fig. 5 Temperature distribution at 25 mm for concrete with different w/c ratio

temperature and moisture conditions during the hydration process. So that the concrete will develop hardened properties over a period of time. Curing period affects the development of CSH gel, which is crucial for the strength and durability of concrete. Proper curing ensures sufficient hydration, reducing the presence of unhydrated cement and residual capillary water. Concrete achieves its strength after 28 days of curing, on this course the maturity of cement paste varies, therefore when exposed to fire during such conditions the heat transfer in concrete also varies. Concrete samples cured for 14 days and 28 days are used to study impact of curing period on temperature distribution in concrete. References [26–28] have investigated extensively about effect of curing under different conditions to concrete and its properties. From this analysis, it's evident that curing plays a major role in concretes strength gain. Fig. 6 shows temperature distribution measured in M20 concrete cured for 14 and 28 days. Temperature distribution in concrete cured for 14 days is higher when compared with concrete cured for 28 days. Because, during the curing period the CSH gel is not fully matured and there is a moisture content in the concrete available to finish hydration of cement, this moisture content may elevate the thermal conductivity in concrete. Fig. 7 depicts a omparison between specimens with different curing period of its temperature distribution measurement at 25 mm. There is an increase of 16.85% in temperature for 14 days curing than 28 days curing at 25 mm depth of specimen from the bottom at 600 °C for M20 concrete.

3.3 Influence of grade on temperature distribution in concrete

The grade of concrete, such as M20, indicates its compressive strength and composition. Higher-grade concretes typically have lower porosity and higher density, which can influence their thermal properties. The characteristic compressive strength of concrete is dependent on factors such as water cement ratio, volume fraction of aggregate, grading and shape of aggregate. Therefore, to study the influence of grade of concrete on temperature distribution in concrete four different grades were used (M20, M30, M40 and M50). Fig. 8 illustrate measured temperature distribution in concrete samples. Fig. 9 shows a comparison of temperature distribution at 25 mm from bottom of specimen at 600 °C for different grades of concrete. References [14, 29, 30] have done experimental studies in thermal distribution of concrete. The experimental findings suggest that higher-grade concretes tend to have a more uniform temperature distribution under fire conditions due to their lower permeability and better-integrated structure.



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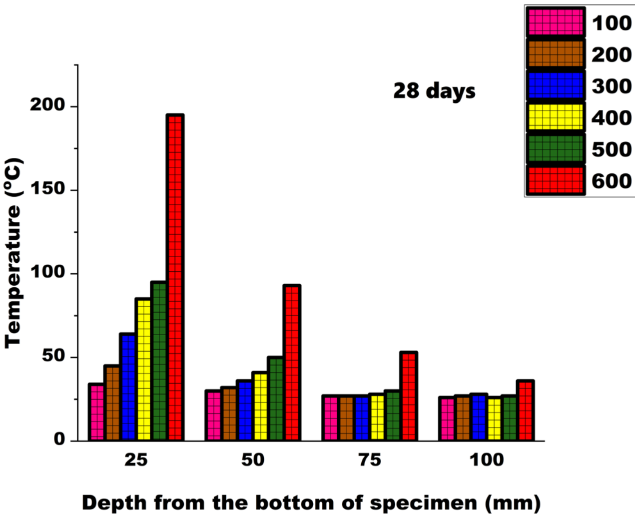


(b)

Fig. 6 Measured temperature distribution in M20 concrete cure for (a) 14; (b) 28 days

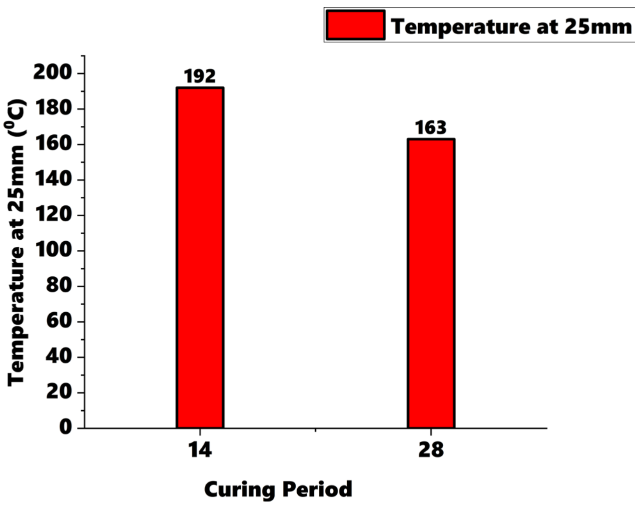
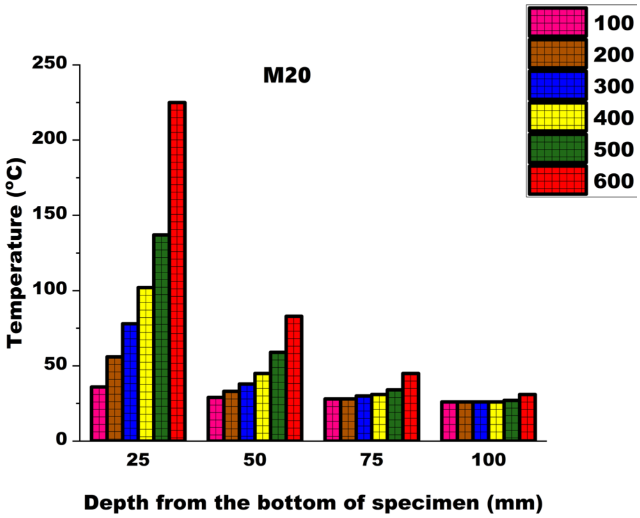


Fig. 7 Temperature distribution at 25 mm for M20 grade with different curing periods



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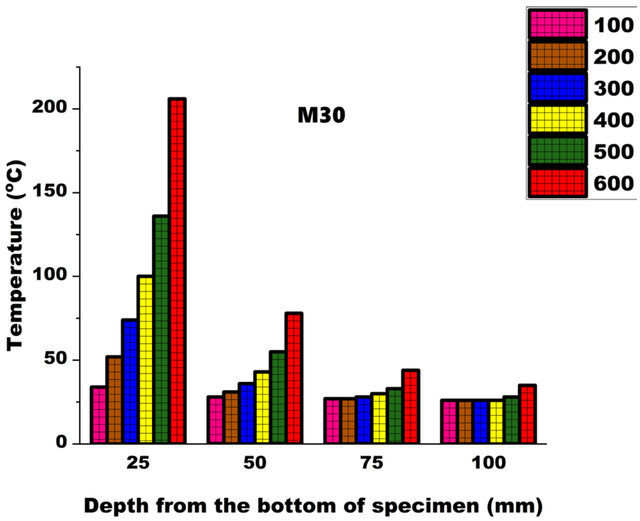


(b)

Fig. 8 Measured temperature distribution in (a) M20; (b) M30; (c) M40 and (d) M50 grade concrete

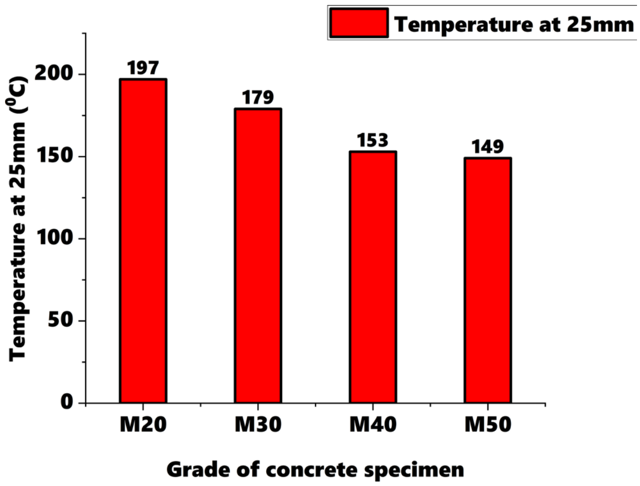
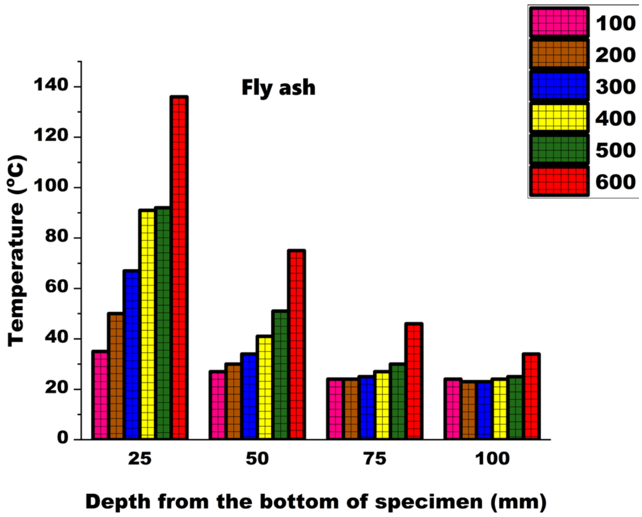


Fig. 9 Temperature distribution at 25 mm for different grades of concrete

Temperature distribution in concrete follows a decreasing gradient from the face at which it is exposed to temperature to high depths. As grade of concrete goes higher the temperature distribution decreases because the cement content increases with grade, lower cement content with higher water content has higher conductivity. The difference in temperature distribution in M20 and M50 grade concrete specimen at 25 mm depth from bottom at 600 °C is 25.8%.

3.4 Influence of admixture type on temperature distribution in concrete

Admixtures are chemical substances added to concrete to improve various properties [31]. To attain the requirements of complexity of structures, mineral admixtures like FA, Mk and SF are added to the concrete mix. It is to attain the concrete with better properties like compressive strength, workability, and durability. These admixtures can alter the thermal behavior of concrete by affecting its microstructure, density, and moisture content. These admixtures are very fine-grained inorganic materials that have pozzolanic properties. To study the outcome of admixtures on temperature distribution in concrete, three samples were used in which mineral admixture were used as 10% replacement of cement volume. Fig. 10 shows measured temperature distribution in M20 concrete with various admixtures. References [8, 13, 32, 33] have studied the outcome of different admixtures in concrete and its strength under elevated temperature. The study's results indicate that the type of admixture significantly influences temperature distribution, highlighting the importance of selecting appropriate admixtures for fire-resistant concrete. MK



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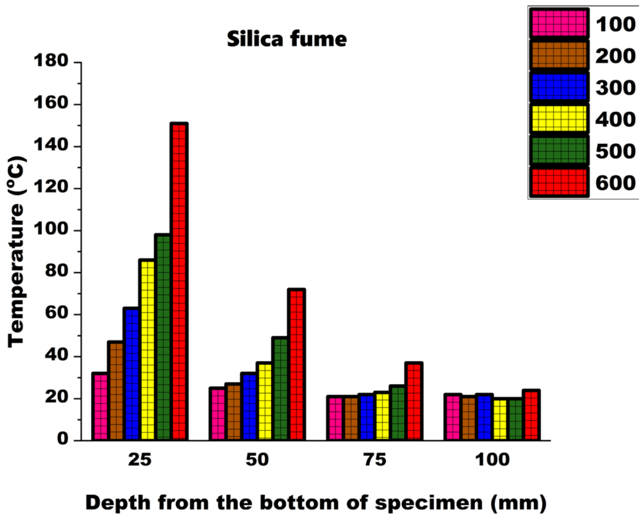

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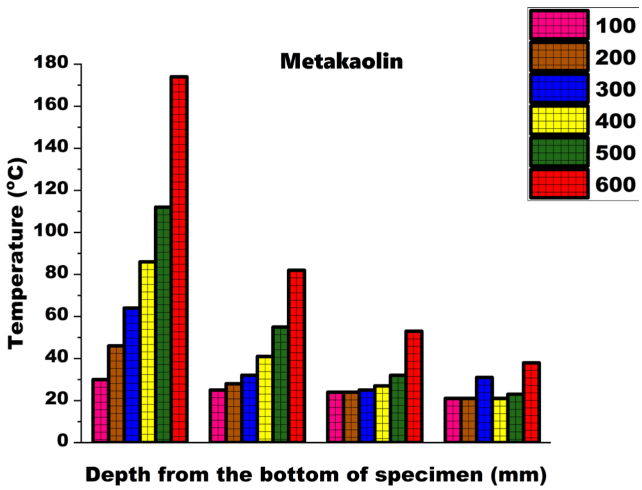

(c)

Fig. 10 Measured temperature distribution in M20 concrete with (a) FA; (b) SF; (c) MK and SF is denser than FA, when these added in concrete as a replacement of cement, MK and SF fills well leaving less pores in concrete when compared with FA. Therefore, the temperature distribution in concrete with MK and concrete with SF is higher than the one with FA. There is an increase of 30% temperature distribution in sample with MK than FA at 25 mm depth from bottom at 600 °C for M20 concrete as seen in Fig. 11.

3.5 Influence of fiber type on temperature distribution in concrete

Fibers made from glass, steel, organic polymers can be used to improve crack-related properties of concrete. Natural vegetable fibers like jute and sisal are also popular. Fibers are often added to concrete to improve its tensile strength and ductility. There are so many different advantages to using fibers in concrete like increased strength, reduced cracks and crack width, improved fire and impact resistance. Plastic shrinkage cracking can be reduced to a great extent by using synthetic fibers at a very small amount. To improve flexural strength and toughness and to control crack width in concrete metal fibers are used. The amount of fibers to be used based up on type and size of fibers and requirement. By adding fibers, workability of concrete will reduce, and it needs longer mixing times. Fibers are generally in concrete to advance crack related properties and for increasing strength and fire resistance. In both plastic and hardened stage OPC concrete is brittle and is susceptible to cracks. As concrete hardens the water present in the pores evaporate, this

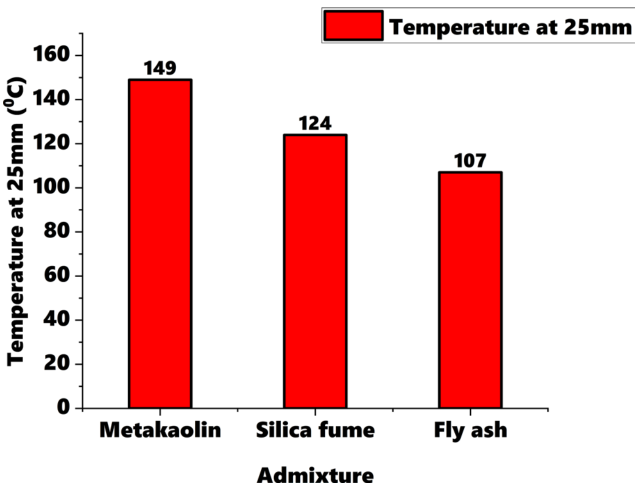

Fig. 11 Temperature distribution at 25 mm for M20 concrete with different admixture

volume change causes the concrete to make crack. This, in turn, can lead to a negative perception of quality, durability, and serviceability. The incorporation of fibers aids in altering the properties of concrete during both its plastic and hardened stages, thereby enhancing its durability. Thermal and shrinkage cracks can be reduced by incorporating synthetic fibers. Addition of steel fibers elevates ductility performance, post-crack tensile strength, fatigue strength and impact strength of concrete structures. To study the outcome of fibers on temperature distribution in concrete four different fibers were used such as BF, CF, GF and PP. Fig. 12 depicts measured temperature distribution in M20 concrete with various fibers in M20 concrete and Fig. 13 shows comparison of temperature distribution at 25 mm from the bottom of specimen at 600 °C for M20 grade with different fibers. Li et al. [6] have studied about BF reinforced polymer in the past. Horak et al. [34] gave insights into the behavior of fiber reinforced polymer during fire exposure. Akbarzadeh Bengar et al. [35] have studied about other fibers and its influences. Influence of fiber type on temperature distribution in concrete is minimal. This could be due to the dominant influence of other factors such as w/c ratio and curing period. There is no significant change in temperature distribution in concrete samples at 25 mm from the bottom of specimen at 600 °C for M20 grade.

4 Conclusion

Various factors affecting the temperature distribution in concrete is investigated through several tests. Grade of concrete, water cement ratio, curing period, admixture type and fiber type are the factors analyzed. The tests were carried out at a certain temperature range. A cylinder with size 100 mm × 200 mm was used as specimen. The influence of temperature affects the performance of concrete under mechanical loading. The increase in water content has an effect on increasing heat distribution, due to the higher rate of evaporation. It is evident from the results of w/c ratio and curing age. It is found that, grade of concrete is inversely proportional to temperature distribution and lower cement content has higher conductivity. MK and SF are denser than FA and when these are added to concrete leaves fewer pores compared to FA, so the temperature distribution with MK and SF are higher than with FA in concrete. From investigation it is found that influence of fiber type on temperature distribution in concrete is minimal.

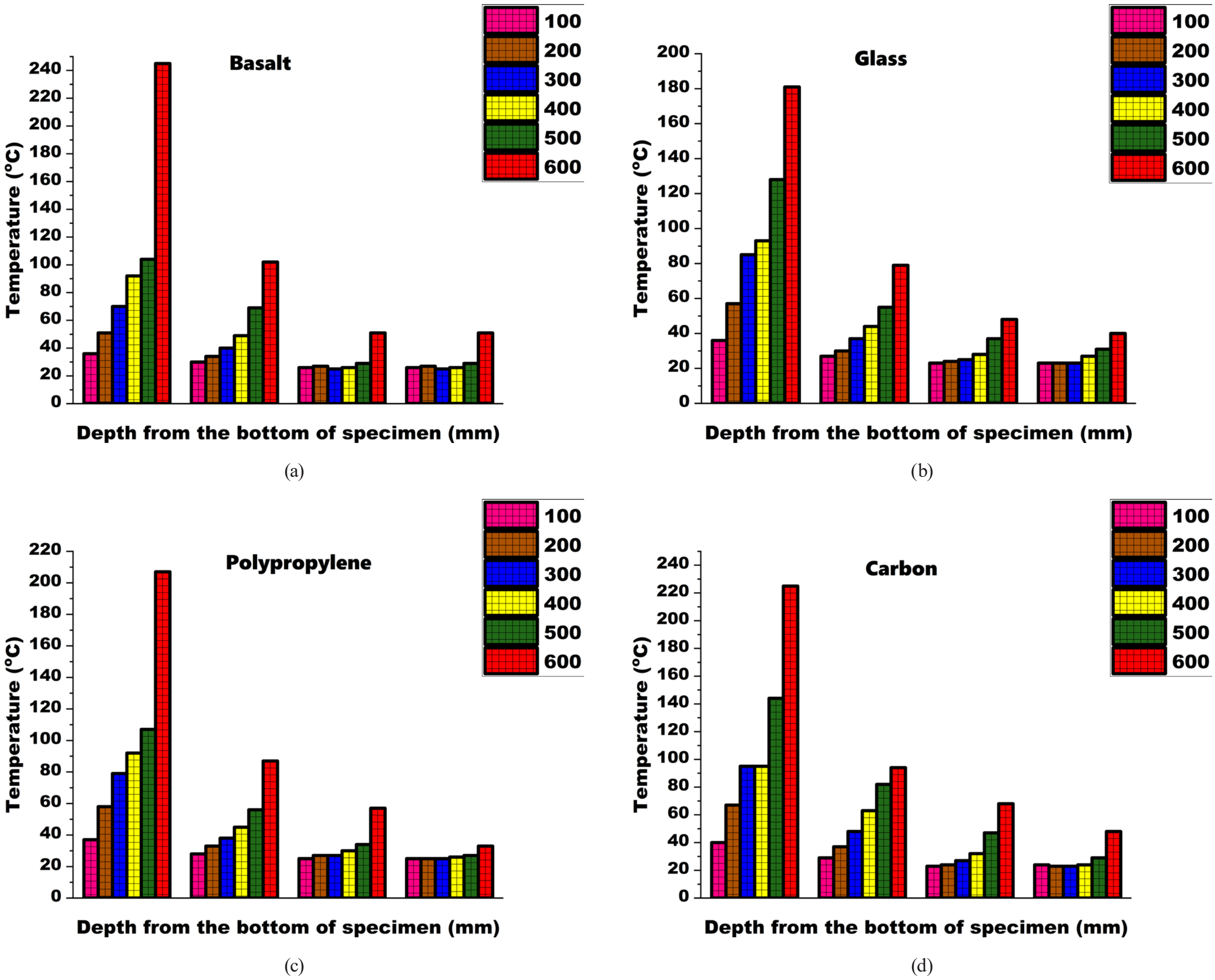

Fig. 12 Measured temperature distribution in M20 concrete with (a) Basalt filter, (b) Glass fiber; (c) Polypropylene fiber; (d) Carbon fiber

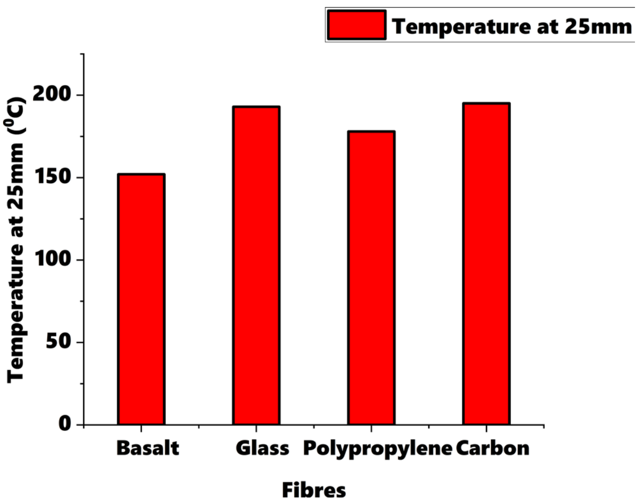

Fig. 13 Comparison of temperature distribution for M20 grade with various fibers

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