Study on the Behavioral Response of Concrete to Prolonged Exposure to Elevated Temperatures

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Abstract - This study investigates the residual strength of High Strength Concrete (HSC) made with Ordinary Portland Cement (OPC) and Portland Pozzolana Cement (PPC) when subjected to elevated temperatures, ranging from 50°C to 250°C for durations of 1, 2, and 3 hours. Concrete, extensively used in high-rise buildings, industrial facilities, and critical infrastructure, is vulnerable to cracking, spalling, and structural damage when exposed to high temperatures, leading to significant financial losses. This research focuses on understanding how HSC, which includes additives like micro silica and pulverized fuel ash, performs under thermal stress, particularly in environments like nuclear reactors and petrochemical tanks. The study explores the effects of temperature exposure on compressive, split tensile, and flexural strength, comparing the properties of concrete exposed to heat with those of room-temperature concrete. One major challenge in high-temperature exposure is the thermal mismatch between concrete’s surface and core, leading to internal stress and cracking. The dehydration of calcium silicate hydrate (C-SH) gel in the cement paste results in shrinkage, reduced binding strength, and eventual failure. The findings provide critical insights into the thermal durability of HSC, offering guidelines for its use in high-temperature environments and ensuring structural integrity under extreme conditions.

Key Words: Cement paste shrinkage, Compressive strength, Elevated temperatures, Fire resistance, Flexural strength, High Strength Concrete (HSC), Micro silica, Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC), Pulverized fuel ash, Residual strength.

1.INTRODUCTION

High Strength Concrete (HSC) plays a pivotal role in infrastructure, especially in applications exposed to extreme thermal conditions, such as in nuclear reactors, industrial plants, and aerospace structures. However, the performance of concrete under high-temperature exposure is a critical concern, as elevated temperatures can significantly degrade its mechanical properties. Ordinary Portland Cement (OPC) and fly ash-based Portland Pozzolana Cement (PPC) are two types of binders used in High Strength Concrete, each exhibiting distinct behavior under thermal stress. This study aims to investigate the impact of elevated temperatures on the compressive strength, split tensile strength, and flexural strength (modulus of rupture) of both OPC and PPC-based High Strength Concrete. Specimens subjected to temperatures of 50°C, 100°C, 150°C, 200°C, and 250°C for durations of 1, 2, and 3 hours are tested to evaluate their performance under both thermal and mechanical loading. Understanding how these concretes react under varying conditions will help optimize their use in high-temperature applications. Previous research has highlighted that exposure to temperatures above 100°C can lead to significant strength loss in concrete due to microcracking, dehydration, and thermal incompatibilities (Rathore et al., 2016). By comparing OPC and PPC concretes, this research aims to provide insights into the better performing material for heat-resistant applications..

1.1 SCOPE OF THE STUDY

This study focuses on the behavior of High Strength Concrete (HSC) exposed to elevated temperatures, particularly in applications such as jet take-off areas, rocket pads, nuclear reactors, and industrial plants. The research investigates the thermal effects on concrete, including micro-cracking, dehydration, and thermal incompatibility, which cause strength reduction. Additionally, the study examines the performance of M60-grade HSC using both OPC and PPC under unstressed conditions, evaluating their response to temperatures up to 250°Cover a duration of 10,000 seconds, to enhance the understanding of their behavior in high-temperature environments.

1.2 OBJECTIVES

1.To investigate the effect of elevated temperatures on the compressive strength of High Strength Concrete (HSC) made with OPC and PPC, subjected to different durations of exposure.

2.To examine the changes in split tensile strength of High Strength Concrete (HSC) made with OPC and PPC when exposed to elevated temperatures for varying durations.

3.To analyze the variation in flexural strength of High Strength Concrete (HSC) made with OPC and PPC under elevated temperature conditions for different exposure times.

4.To establish a comprehensive understanding of the strength behavior of High Strength Concrete (HSC) under elevated temperature conditions

2.Material used in the study

2.1 Properties of Materials

Cement

Two types of cement were used in this study: Ordinary Portland Cement (OPC) Grade 53 and Portland Pozzolana Cement (PPC) Grade 53. The key properties include chemical composition, fineness (OPC: 328 m²/kg, PPC: 374 m²/kg), and compressive strength (OPC: 58.6 N/mm² at 28 days, PPC: 58.8 N/mm² at 28 days).

Fine Aggregate

River sand (Zone II, IS: 383-1970) was sourced locally, with a fineness modulus of 2.3 and a specific gravity of 2.60. The sand was air-dried to prevent bulking before use.

Coarse Aggregate

Locally sourced hard blue granite with a maximum size of 12.5 mm was used, having a fineness modulus of 6.57 and a specific gravity of 2.63.

Water

Potable water with a pH of 7.65, conforming to IS: 3025, was used for mixing.

Admixture

Pozzolana Portland Cement (20% pozzolana) was utilized, along with Complast SP 430 superplasticizer (IS: 9103) to enhance workability

2.2 Mix proportions

Table.1 mix proporations

Cement	Fine aggregate	Coarse aggregate	Water
1	(1 x 3.6) / (1.43+1)	(1.43 x 3.6) / 2.43	0.324
1	1.48	2.12	0.324

2.3 Testing of Specimen

This study investigates the effects of elevated temperatures on the compressive, split tensile, and flexural strengths of High Strength Concrete (HSC) made with OPC and PPC. Specimens were exposed to temperatures ranging from 50°C to 250°C for durations of 1, 2, and 3 hours. Compressive strength tests were conducted on 100mm cubes, which were removed from the oven and tested while still hot. The specimens were aligned in the compression testing machine, and the load was gradually applied until failure. The maximum load at failure was used to calculate the compressive strength.

For split tensile strength, 150mm diameter and 300mm long cylinders were tested in the hot condition after exposure. The specimens were placed in the compression machine with plywood strips and aligned for proper loading. The split tensile strength was calculated using the formula: σ=2Pπld\sigma = where P is the maximum load, l is the length, and d is the diameter.

Flexural strength was tested using 100mm x 100mm x 500mm beams placed in a universal testing machine under a two-point load. The load was increased until failure, and the flexural strength was calculated using the appropriate formula. In all tests, three specimens were used for each condition, and results with variations exceeding 15% from the average were excluded.

3.EXPERIMENTALPROGRAME

Age (Days)	Exposed temp(C) Times of Exposure (hours) 50 C			Exposed temp(C) Times of Exposure (hours) 100C			Exposed temp(C) Times of Exposure (hours) 150C			Exposed temp(C) Times of Exposure (hours) 200C			Exposed temp(C) Times of Exposure (hours) 250C		
	1h	2h	3h	1h	2h	3h	1h	2h	3h	1h	2h	3h	1h	2h	3h
1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
7	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
28	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
56	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
91	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Total															270

Table.2 experimental programme

4. RESULTS AND DISCUSSIONS

This study investigates the effect of elevated temperatures on the residual compressive strength of concrete made with Ordinary Portland Cement (OPC) and Portland Pozzolana Cement (PPC). Elevated temperatures cause physical changes in concrete, such as moisture loss, thermal dilations, and microstructural changes, which lead to a reduction in strength. The extent of strength loss is influenced by the amount of moisture lost, temperature, and exposure duration. At lower temperatures, moisture loss varies, but beyond 150°C, most moisture is lost, and strength decreases significantly.

The results show that both OPC and PPC concretes exhibit similar behavior at elevated temperatures, with an increase in residual compressive strength up to 150°C. For OPC, the strength at 1 day of age increases by up to 33% at 200°C, while PPC shows up to 41% improvement under the same conditions. However, beyond 150°C, strength begins to decline due to thermal stresses and chemical changes in the concrete. At later ages (7, 28, 56, and 91 days), both OPC and PPC experience a

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decrease in strength as the temperature increases, with PPC showing a more gradual loss.

The study also indicates that exposure duration plays a role, with longer exposure leading to more significant strength reductions, especially at higher temperatures. PPC concrete outperforms OPC in retaining strength, particularly at higher temperatures and longer exposure durations. This is attributed to the presence of pozzolana in PPC, which enhances durability and thermal stability by reducing micro-cracking compared to OPC.

4.1 Residual Compressive Strength

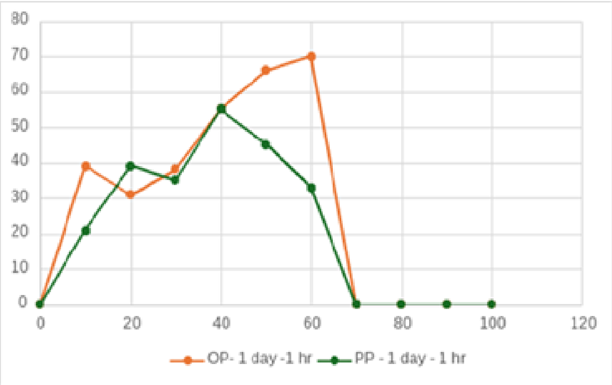

Fig.1.Variation of compressive strength with temperature for OPC and PPC concretes of 1

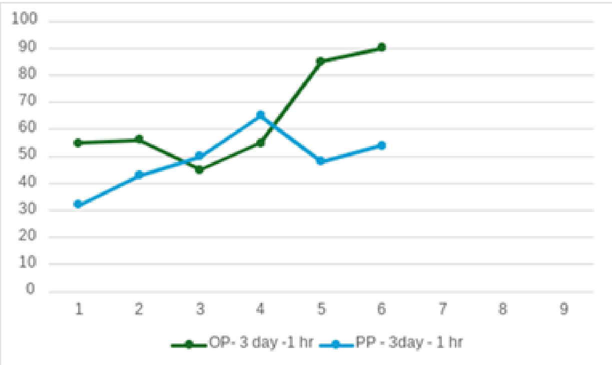

Fig.2.Variation of compressive strength with temperature for OPC and PPC concretes of 3days age for 1 hour exposure

Exposure to elevated temperatures causes moisture loss, microcracking, and chemical changes in concrete, reducing strength. Residual compressive strength is expressed as a percentage of 28-day unheated OPC concrete strength. Both OPC and PPC concretes show an increase in strength up to 150°C due to accelerated hydration, followed by a decline at higher temperatures from thermal decomposition. At 1-day age and 3-hour exposure, OPC and PPC concretes showed peak strength gains of 33% and 41% at 200°C, respectively, but experienced strength loss beyond 150°C.

With increasing age, residual compressive strength generally improved across all temperatures, with PPC outperforming OPC due to better thermal stability from pozzolanic materials. At 56 and 91 days, PPC retained higher strength than OPC, particularly at 250°C, where PPC showed only a 7.5% decrease versus 36.5% for OPC. PPC's superior durability and resistance to thermal degradation align with its enhanced mechanical and microstructural properties.

4.2 Residual Split Tensile Strength

Split tensile strength variations were examined for OPC and PPC concretes at different ages (1, 3, 7, 28, 56, and 91 days) exposed to elevated temperatures for 1, 2, and 3 hours. The legend in figures indicates the cement type (OP or PP), concrete age (nd), and exposure duration (nh). PPC's behavior closely mirrored OPC's across all conditions, with the most significant strength reductions observed after 3-hour exposures. At 1-day age, residual tensile strength for OPC at 3 hours ranged from -9.9% to 22.6% at 50°C to 200°C, peaking at 150°C, and declining thereafter. At 3 days, changes ranged from -5.5% to 6%, with similar trends in PPC. Up to 150°C, tensile strength increased due to accelerated hydration. Beyond 150°C, strength declined, driven by thermal decomposition and hydrate instability. The findings align with prior studies, confirming temperature and exposure duration as critical factors influencing tensile strength.

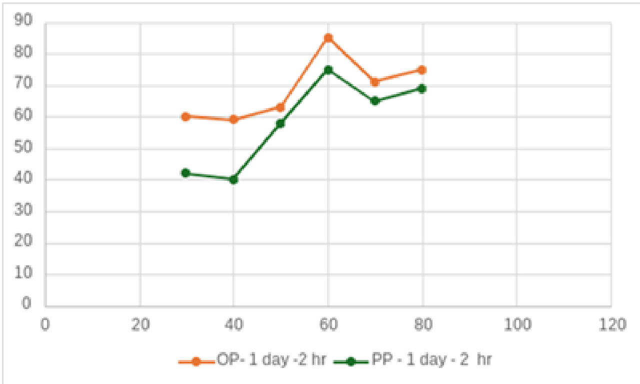

Fig.3 Variation of split tensile strength with temperature for OPC and PPC concretes of 1 day age for 2 hours exposure

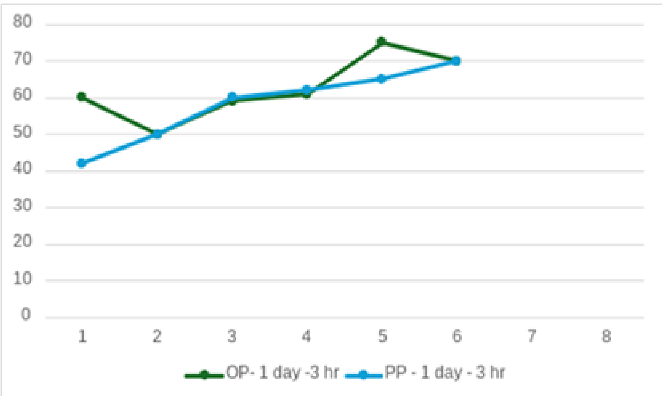

Fig.4 Variation of split tensile strength with temperature for OPC and PPC concretes of 1 day age for 3 hours exposure

4.3 Residual Flexural Strength

The residual flexural strength of High Strength Concrete (HSC) under elevated temperatures depends on factors like concrete age, temperature, exposure duration, and cement type. Residual strengths are expressed as percentages of unheated 28-day OPC concrete. Results show that both OPC and PPC concretes exhibit increased flexural strength up to 150°C due to accelerated hydration, followed by a decline at higher temperatures due to thermal decomposition.

At 1-day age and 3 hours exposure, OPC retained 0.5% to 4.5% higher strength at 50°C–200°C but declined by -2.7% at 250°C. PPC showed consistent improvement of 5.2% to 13% up to 200°C. At higher ages (3–91 days), OPC and PPC strengths generally decreased as temperatures and exposure durations increased.

PPC exhibited slower initial strength gain but outperformed OPC at later ages due to higher residual compressive strength, making PPC more resilient under prolonged exposure to elevated temperatures

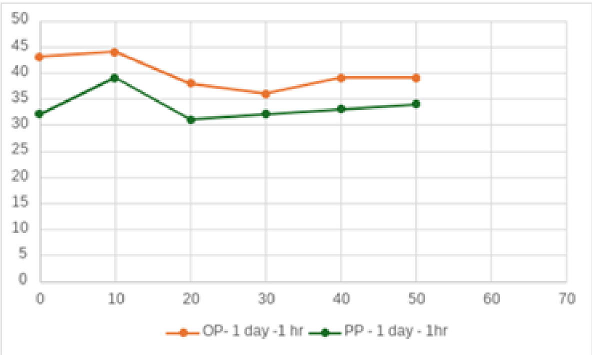

Fig.5 Variation of flexural strength with temperature for OPC and PPC concretes of 1 day age for 1 hour exposure

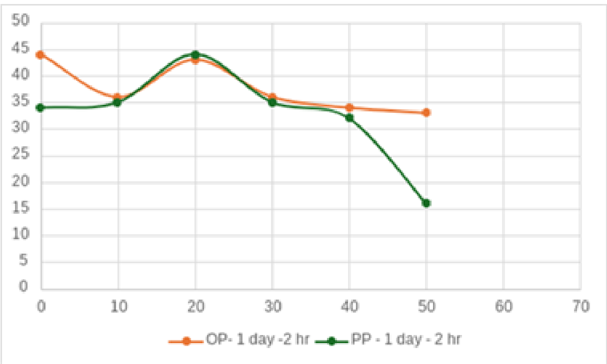

Fig.6 Variation of flexural strength with temperature for OPC and PPC concretes of 1 day age for 2 hours exposure

5.Conclusion

The study highlights the optimization and behavior of High Strength Concrete (HSC) and its performance under different conditions. Superplasticizer dosage significantly influences compressive strength, with 400ml/50kg cement emerging as the optimal amount. A compaction period of 40 seconds proved most effective in achieving target strength. HSC demonstrated behavior similar to Normal Strength Concrete (NSC), with rapid early strength development that stabilized beyond 56 days. Smaller specimens exhibited higher strengths, and HSC showed superior flexural performance with a higher modulus of rupture compared to theoretical values.

Under elevated temperatures, both Ordinary Portland Cement (OPC) and Portland Pozzolana Cement (PPC) concretes displayed strength gains up to 150°C, attributed to accelerated hydration. Beyond this temperature, strength degradation occurred due to thermal stresses. OPC performed better at early ages, while PPC outperformed OPC at later stages due to its enhanced thermal stability. These findings underscore the potential of PPC in high-temperature applications and confirm HSC's suitability for advanced construction needs.

5.1 Scope of the study

1. Assessing the impact of elevated temperatures on HSC under mechanical stress.
2. Investigating how cooling methods like air cooling and water quenching affect residual strength.
3. Studying the influence of heating rates on HSC residual strength.
4. Analyzing the effect of different aggregates on HSC performance at high temperatures.
5. Evaluating the combined use of admixtures to enhance thermal resistance.
6. Testing HSC behavior under extreme temperatures, up to 1000°C.
7. Examining the effects of extended exposure durations, up to 1 day, on HSC strength retention.

These studies will enhance understanding of HSC's durability, paving the way for advanced applications in high-temperature environments.

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