Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 9, No. 07, July, 2023

Effect of Cooling Conditions, Retrofitting on Strength of Concrete Subjected to Elevated Temperature

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Received 24 March 2023; Revised 06 June 2023; Accepted 17 June 2023; Published 01 July 2023

Abstract

Concrete has a high degree of fire resistance at moderate temperatures. High temperatures, however, cause concrete to lose its stiffness and strength. The effects of cooling techniques and retrofitting on the strength of concrete exposed to high temperatures have not been synchronized in previous studies. This experimental research aims to evaluate the effect of cooling conditions and the effectiveness of retrofitting concrete subjected to elevated temperatures. Four types of concrete: M 20 normal concrete (NC); M 20 metakaolin concrete (MC); M 40 standard concrete (SC); and M 40 self-compacting concrete (SCC) are considered in this study. A total of 864 samples consisting of cube, beam, and cylinder specimens are subjected to sustained elevated temperatures of 400°C, 600°C, and 800°C for 2 hours rating. The weight and strength of half of the heat-damaged samples are assessed following natural air cooling (NAC) and water jet cooling (WJC). The remaining 50% of samples retrofitted with carbon fiber reinforced polymer (CFRP) are tested to evaluate the upgraded strength. The experimental findings demonstrate that water jet cooling (WJC) causes more strength degradation, and CFRP proves to be effective in restoring the strength of heat-deteriorated specimens. Overall, self-compacting concrete (SCC) has shown high resistance to elevated temperatures.

Keywords: Fire Resistance; Natural Air Cooling (NAC); Water Jet Cooling (WJC); Carbon Fiber Reinforced Polymer (CFRP).

1. Introduction

Fire is one of the hazards for which structural systems often require retrofitting and rehabilitation. After devastating fire events such as the 9/11 World Trade Center [WTC] attack in New York, USA; 2011 AMRI Hospital fire in Kolkata, India, the research is focused on the evaluation of the mechanical properties of construction materials at elevated temperatures, fire-induced damages, and retrofitting techniques. Cement concrete, a widely used construction material, is considered fire-resistant as well as non-combustible material due to its low thermal conductivity [1–3]. Concrete is a heterogeneous material consisting of cement, water, fine aggregates, and coarse aggregates. When concrete is subjected to elevated temperatures, alteration of pore pressure, and an increase in porosity, thermal expansion, thermal cracking, and thermal creep take place. These physical and mechanical changes damage the micro- and mesostructure of concrete, leading to its spalling and strength degradation [4].

Research on Effect of Elevated Temperature on Properties of Normal Strength Concrete:

Researchers have studied the effects of high temperatures on the physical and mechanical characteristics of various normal-strength concrete mixes, and their findings indicate that as the temperature rises, there is a significant loss in

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http://dx.doi.org/10.28991/CEJ-2023-09-07-013

compressive and tensile strength, modulus of elasticity, and modulus of rupture [5–9]. Concrete experiences shrinkage, thermal expansion, and micro-cracking at 300°C and surface cracking followed by spalling in the temperature range of 400°C–600°C. For extended fire durations at high temperatures (often above 500°C), concrete has been found to degrade significantly in terms of strength and deformability [4–9]. Endait & Wagh [10] have recently assessed the mechanical properties of early-age concrete exposed to high temperatures using destructive as well as non-destructive methods. Researchers found that concrete samples heated for 3 days and cooled to room temperature using the air cooling method recovered at their maximal strength and pulse velocity.

Research on Effect of Elevated Temperature on Properties of High Strength and Special Concrete:

Self-consolidating concrete (SCC), fiber-reinforced concrete (FRC), high-performance concrete (HPC), high volume fly ash concrete (HVFAC), light-weight concrete (LWC), and recycled aggregate concrete (RAC) are among the high-strength and special concrete types that are tested to determine how elevated temperatures affect their mechanical and thermal properties [11–20]. For these studies, a natural cooling approach without any fire retardant coating is used. The results of these experimental studies are used to develop a mathematical modeling approach for predicting the fire resistance of concrete structures.

Research on Effect of Cooling Regime on Strength of Concrete exposed to Elevated Temperature:

According to research on the impact of high temperature and cooling regimes on the strength of concrete, rapid temperature changes (elevating or cooling) caused the onset and spread of micro-defects, which led to a greater decline in strength than in the case of gradual cooling without thermal shock [21]. Similarly, an experimental study focused on cooling methods to be adopted for concrete subjected to elevated temperatures showed that thermal shock induced by water quenching and spraying water caused more severe damage to concrete as compared to natural air cooling [22–24]. The evaluation of the drying temperature effect on the strength of concrete through experimental and data mining techniques by Kashyzadeh et al. [25] recently reported that cool wind for drying operations restores the compressive strength of ordinary concrete.

Research on Fire Coating and Retrofitting for Concrete subjected to Elevated Temperature:

The addition of steel, glass, and Polypropylene fibers [26], the use of mineral-based fire proof coating [27], and steel jacketing techniques [28, 29] are different types of fire retrofitting measures that have emerged in the recent decade. The effectiveness of carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) to enhance the post-fire capacity of reinforced concrete elements has been assessed in limited research [30–32]. According to a recent synthesis study on the repair and durability of fire-damaged prestressed concrete bridge girders by Tseng & Verma [33], the use of CFRP laminates to wrap and confine the fire-damaged or patched area effectively restores its strength.

Aims and Objectives:

In the framework of past research, comprehensive studies on the coordinated impact of cooling regimes and retrofitting techniques on the strength of concrete exposed to high temperatures have not been addressed. The present research is aimed at evaluating the simultaneous influence of cooling conditions and retrofitting on the mechanical and physical properties of four distinct types of concrete subjected to elevated temperatures. M20, a minimum grade for ordinary concrete construction [34], as well M 40 grade for infrastructure and industrial concrete construction subjected to 400 °C to 800 °C, are considered for the present study.

The detailed experimental program, consisting of details of specimens, temperature loading, cooling conditions, retrofitting details, and test procedures, is presented in Section 2. Test findings and observations for in-depth investigations of failure patterns are discussed in the subsequent section. The final section provides concluding remarks and recommendations for additional research.

2. Experimental Program

2.1. Mix Proportion

Mix designs for four distinct types of concrete: M 20 grade normal concrete (NC), M 20-grade metakaolin concrete (MC); M 40-grade standard concrete (SC), and M 40-grade self-compacting concrete (SCC) are carried out as per IS 10262 [35]. Table 1 provides the mix proportions for each type of concrete considered in this study. Basic ingredients used in these mixes are: 53-grade ordinary Portland cement (OPC) conforming to IS 12269 [36]; locally available natural sand as fine aggregate; and 20- and 10-mm-size natural rock coarse aggregate. The gradation curves for the fine and coarse aggregates, along with the recommended upper and lower bounds of IS 383 [37], are shown in Figure 1. Vertical shaft impact light weight aggregate with an average mass density = 1850 kg/m^3 and an average thermal conductivity =

0.75 W/mK is used in self-compacting concrete (SCC). In order to achieve economy in every mix, the 10% quantity of cement is replaced with fly ash as per IS 10262 [35]. Metakem® 85C an alumina silicate pozzolanic additive, is used in M 20 grade metakaolin concrete (MC). For M 40 grade standard concrete (SC) CERAPLAST 400, a high performance, low-dose superplasticizer based on melamine formaldehyde sulphonate (MFS) is used. Silica fumes at a rate of 36 kg/m^3 and Visco-Crete at a rate of 4 kg/m^3 are added to increase the workability of self-compacting concrete (SCC).

Table 1. Mix proportions for different types of concrete

Concrete	Grade	W/C	Cement (kg/m^3)	Fly Ash (kg/m^3)	Aggregate (kg/m^3)	
					Coarse	Fine
NC	M 20	0.48	320	32	550	1100
MC	M 20	0.48	320	32	550	1100
SC	M 40	0.38	440	44	675	1200
SCC	M 40	0.34	436	34	650	950

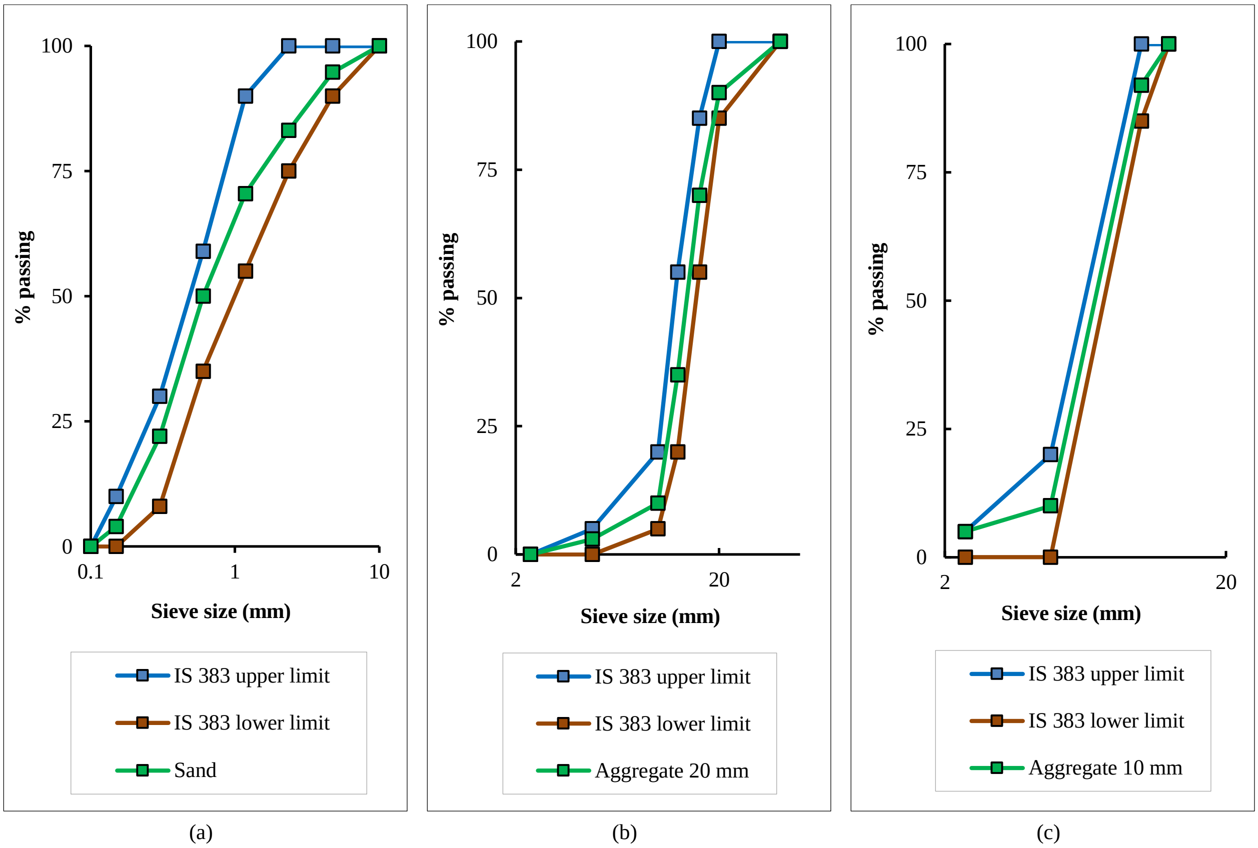


Figure 1. Gradation curves for (a) sand; (b) aggregate 20 mm; and (c) aggregate 10 mm

2.2. Details of Specimen

Three categories of specimens: i) Cube specimen (size: b =150 mm d = 150 mm h = 150 mm) for cube compressive strength; ii) Beam specimen (size: L = 750 mm; b = 150 mm; d = 150 mm) for flexural load carrying capacity; and iii) Cylinder specimen (size: d = 150 mm; h = 300 mm) for split tensile strength as per IS 516 [38] are considered in experimental program. For beam specimen, the minimum tension and shear reinforcement per IS 456 [34] are provided. Figure 2 represents details of tension and shear reinforcement in beam specimen. For four distinct types of concrete, total 1088 samples consisting 336 samples per each category of specimen are casted and cured for 1 day air curing +27 days water curing. Table 2 provides the sample distribution for cube, beam and cylinder specimens for normal, metakaolin, standard and self-compacting concrete. For each category of specimen and variety of concrete, samples tested under the room temperature (RT) are termed as control samples (CS). The effect of elevated temperature on strength of concrete is evaluated with respect to the strength of CS. Thus, for each category of specimen 144 samples are control samples (CS) and remaining 288 samples are subjected to elevated temperature of 400ºC, 600ºC, and 800ºC.

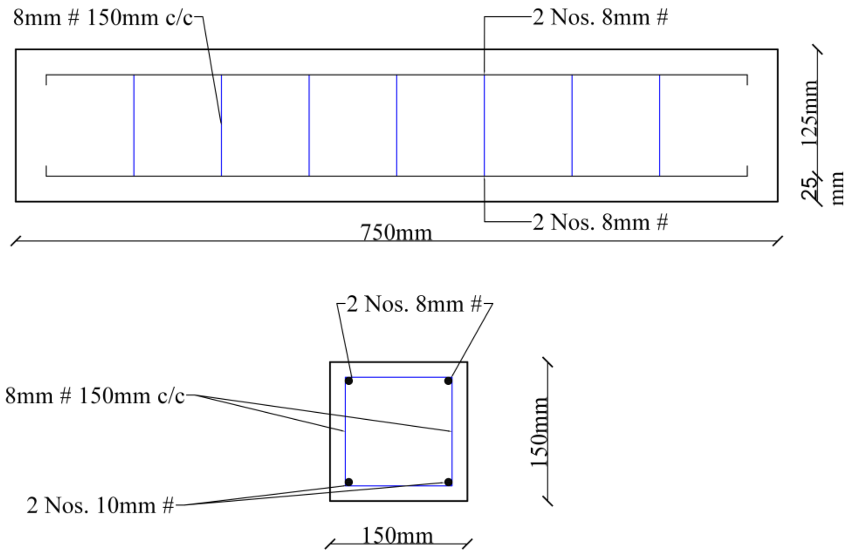


Figure 2. Details of tension and shear reinforcement in beam specimen

Table 2. Sample distribution in cube, beam, and cylinder specimens for different types of concrete

Sr. No.	Type of concrete	Grade of concrete	Specimen designation	Temp. (°C)	Cooling condition	Number of samples tested: without retrofitting: Cube	Beam	Cylinder	with CFRP retrofitting: Cube	Beam	Cylinder	Total
1	NC	M 20	NC-1 (CS)	RT =27	--	6	6	6	--	--	--	18
2			NC-2	400	NAC	6	6	6	6	6	6	36
3			NC-3	400	WJC	6	6	6	6	6	6	36
4			NC-4	600	NAC	6	6	6	6	6	6	36
5			NC-5	600	WJC	6	6	6	6	6	6	36
6			NC-6	800	NAC	6	6	6	6	6	6	36
7			NC-7	800	WJC	6	6	6	6	6	6	36
8	MC	M 20	MC-1 (CS)	RT =27	--	6	6	6	--	--	--	18
9			MC-2	400	NAC	6	6	6	6	6	6	36
10			MC-3	400	WJC	6	6	6	6	6	6	36
11			MC-4	600	NAC	6	6	6	6	6	6	36
12			MC-5	600	WJC	6	6	6	6	6	6	36
13			MC-6	800	NAC	6	6	6	6	6	6	36
14			MC-7	800	WJC	6	6	6	6	6	6	36
15	SC	M 40	SC-1 (CS)	RT =27	--	6	6	6	--	--	--	18
16			SC-2	400	NAC	6	6	6	6	6	6	36
17			SC-3	400	WJC	6	6	6	6	6	6	36
18			SC-4	600	NAC	6	6	6	6	6	6	36
19			SC-5	600	WJC	6	6	6	6	6	6	36
20			SC-6	800	NAC	6	6	6	6	6	6	36
21			SC-7	800	WJC	6	6	6	6	6	6	36
22	SCC	M 40	SCC-1 (CS)	RT =27	--	6	6	6	--	--	--	18
23			SCC-2	400	NAC	6	6	6	6	6	6	36
24			SCC-3	400	WJC	6	6	6	6	6	6	36
25			SCC-4	600	NAC	6	6	6	6	6	6	36
26			SCC-5	600	WJC	6	6	6	6	6	6	36
27			SCC-6	800	NAC	6	6	6	6	6	6	36
28			SCC-7	800	WJC	6	6	6	6	6	6	36

2.3. Temperature Loading

An underground calibrated furnace of size diameter = 1 m and height = 1.2 m with temperature capacity = 1200°C and mass capacity = 400 kg is used for temperature loading. This furnace had digital time and temperature controller with zero loss of temperature. 288 samples of each specimen are fired up to 400°C, 600°C and 800°C temperature for 120 minutes fire ratings with rate of loading of 5-7 °C/min. Figure 3 shows typical details of furnace with digital time and temperature controller.

(a)

(b)

Figure 3. (a) Details of calibrated furnace (b) digital time and temperature controller of furnace

2.4. Cooling Regimes

In order to evaluate the effect of cooling on the strength of concrete subjected to elevated temperature, two cooling regimes namely natural air cooling (NAC) and water jet cooling (WJC) are adopted in this study. The water jet cooling with working pressure of 16 kg/cm^2 for 15 min is used for 50% of heat deteriorated sample whereas for half heat deteriorated samples natural cooling method is adopted. Figure 4 shows water jet cooling of heat deteriorated samples of beam specimen.

Figure 4. Water jet cooling (WJC) of heated samples of beam specimen

2.5. Retrofitting Details

JSR strong UD400 a carbon fiber reinforced polymer (CFRP) composite laminates are used to retrofit and strengthen the 50 % of heat deteriorated samples of concrete specimens. This composite fabric possesses tensile strength of 1450 MPa and compressive strength of 800 MPa. Before retrofitting, the surfaces of heat deteriorated samples are applied with a layer of white putty and are primed with a base layer of JSR prime Resin system. The JSR prime Resin system consists of base epoxy resin and polyamide hardener in mix proportion of 2:1 by weight. The composite laminates are wrapped on the primer layer of moderately viscous JSR prime Resin system. Appropriate care is taken during mixing of resin system and warping of composite laminates to reduce the risk of exothermic reaction. A surface coat of nominal 5 mm thick cement mortar (1:6) plaster is provided to laminate warped surface of retrofitted samples. All retrofitted samples with surface coats are cured for 24 hours and dried to the room temperature (RT =27°C) before testing. The sequential process adopted for retrofitting of heat deteriorated samples is represented in Figure 5.

Application of layer of white putty to heat deteriorated specimen

Warping of JSRstrong UD400 composite laminates on the primer layer of JSRprime Resin

Cured and airdried retrofitted samples

Surface coat of nominal 5mm thick cement mortar (1:6) plaster on laminate warped surface

Figure 5. Sequential process for CFRP retrofitting of heat deteriorated samples

2.6. Test Procedure

All control as well as heat deteriorated samples of each specimen are tested in compression and flexural testing machine of (each of 1000 kN capacity) as per IS 516 [38]. The details of four-point load arrangement for flexural testing are shown in Figure 5.

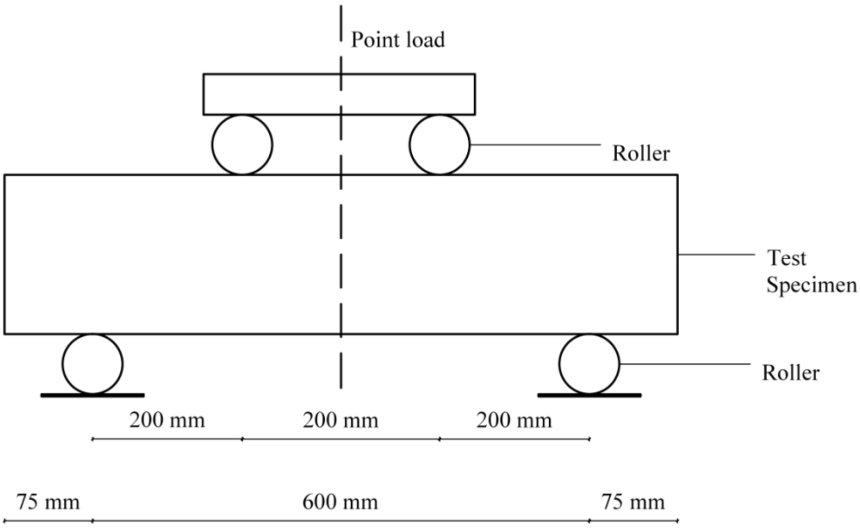


Figure 6. Four-point load arrangement for flexural test on beam specimen

Figure 7 provides detailed flow chart for sequential procedure of experimental program followed for this research.

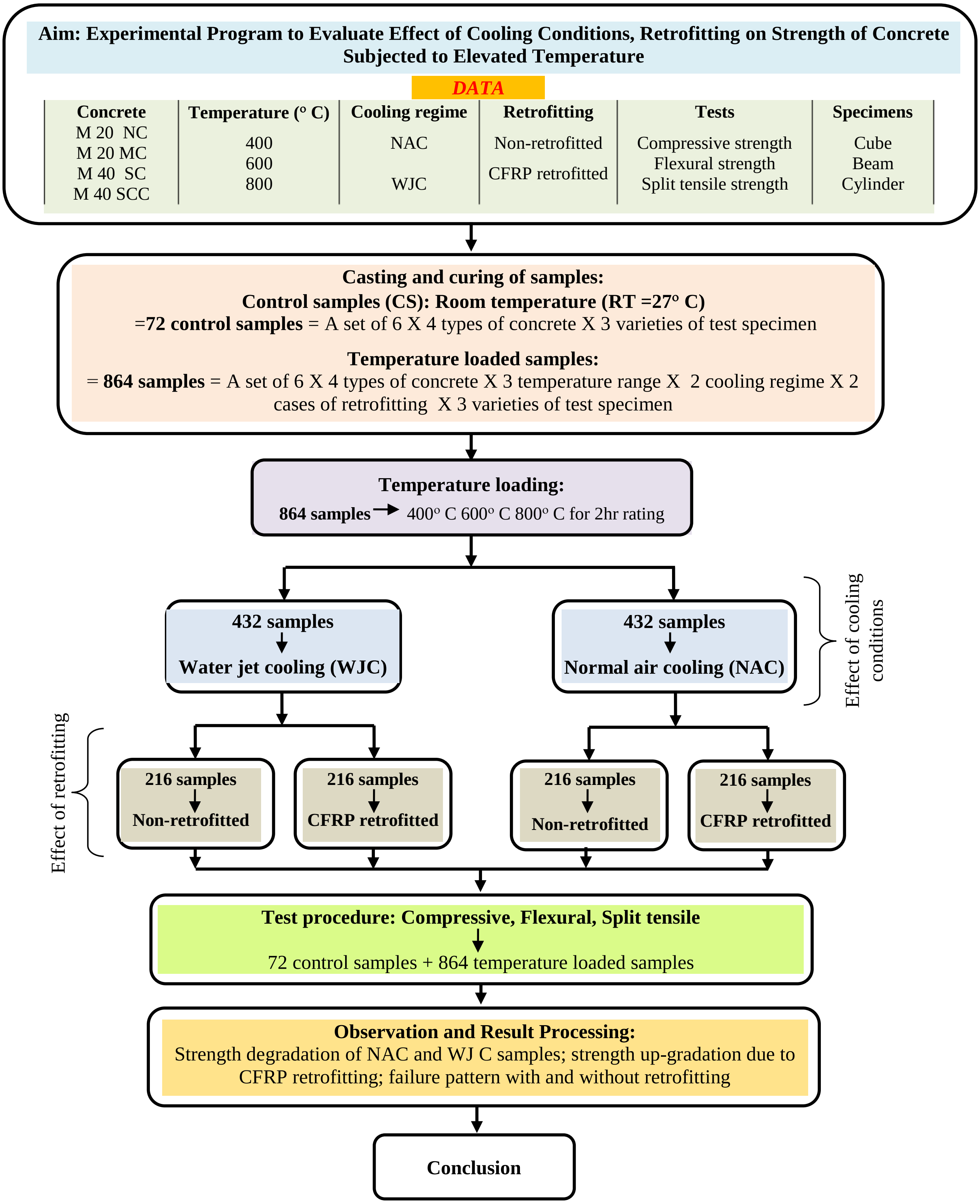


Figure 7. Flow chart for experimental program

3. Test Result and Discussion

3.1. Effect of Elevated Temperature on Cube Compressive Strength

The effect of elevated temperature on cube compressive strength is presented in Table 3. The strength values reported in table are average of six samples of cube specimen for each type of concrete, cooling regimes, non-retrofitted and retrofitted cases.

Table 3. Weight and compressive strength of cube specimens due to elevated temperature considering the effect of cooling regimes and retrofitting

Cube specimen	Temp. °C for 2 Hr	Cooling condition	Weight (kg)		Cube compressive strength (MPa)	
			Before	After	before retrofitting	after retrofitting
NC-1 (CS)	RT =27	--	8.68	8.68	26.95	--
NC-2	400	NAC	8.63	7.94	16.97	22.12
NC-3	400	WJC	8.62	7.89	17.03	22.94
NC-4	600	NAC	8.63	7.75	15.37	22.90
NC-5	600	WJC	8.66	7.70	13.43	21.86
NC-6	800	NAC	8.59	7.64	12.75	20.62
NC-7	800	WJC	8.60	7.60	10.05	17.79
MC-1 (CS)	RT =27	--	8.48	8.48	30.23	--
MC-2	400	NAC	8.52	7.83	20.48	25.33
MC-3	400	WJC	8.49	7.77	19.25	26.00
MC-4	600	NAC	8.39	7.55	19.45	27.33
MC-5	600	WJC	8.42	7.59	15.32	24.32
MC-6	800	NAC	8.50	7.53	14.86	22.83
MC-7	800	WJC	8.45	7.51	12.13	21.01
SC-1 (CS)	RT =27	--	8.45	8.45	47.85	--
SC-2	400	NAC	8.47	7.99	36.91	44.39
SC-3	400	WJC	8.45	7.95	30.79	40.03
SC-4	600	NAC	8.42	7.80	34.42	46.42
SC-5	600	WJC	8.50	7.82	28.12	41.21
SC-6	800	NAC	8.44	7.74	26.62	40.28
SC-7	800	WJC	8.48	7.71	26.05	40.19
SCC-1 (CS)	RT =27	--	8.40	8.40	48.95	--
SCC-2	400	NAC	8.45	8.05	38.08	45.73
SCC-3	400	WJC	8.48	7.97	31.62	41.11
SCC-4	600	NAC	8.43	7.84	37.13	48.06
SCC-5	600	WJC	8.49	7.83	29.76	43.17
SCC-6	800	NAC	8.50	7.83	29.07	41.60
SCC-7	800	WJC	8.46	7.70	28.66	43.04

The % weight loss and % loss in compressive strength due to elevated temperature for non-retrofitted specimens of various types of concrete for two distinct cooling conditions (NAC and WJC) are calculated with respect to the control sample (tested at room temperature). Similarly, % gain in compressive strength of CFRP retrofitted heat-deteriorated specimens is evaluated w.r.t. non-retrofitted specimens. In order to assess the rate of weight and strength loss due to elevated temperature as well as the rate of strength gain due to retrofitting, these losses for types of concrete considering two cooling regimes are presented graphically in Figure 8.

It is observed that % weight loss for samples is in the range of 7.00–10.00, with the highest loss for M 20 grade concrete in comparison with that for M 40 grade concrete. For non-retrofitted samples, the average degradation in cube compressive strength is about 45% for M 20 grade normal and metakaolin concrete and about 35% for M 40 grade standard and self-compacting concrete. The % loss in cube compressive strength for non-retrofitted samples of M 20 concrete at 800 evaluated after NAC is consistent with earlier work by Krishna et al. [9] and Sancak et al. [19]. Similarly, for M 40 grade concrete, the % weight loss and % loss in cube compressive strength agrees with past research by Arioz [5]. The non-retrofitted samples of self-compacting concrete (SCC) offered better fire resistance as the average loss in cube compressive strength = 33.84 % is least as compared to the other three types of concrete. The loss in compressive strength for samples cooled by NAC is less than that for samples cooled by WJC. This is attributed to thermal shock action [22] in water jet cooling. For both cooling regimes, the rate of loss in cube compressive strength of all four types of concrete is more acute in the range of 400°C–600°C as compared to 600°C–800°C.

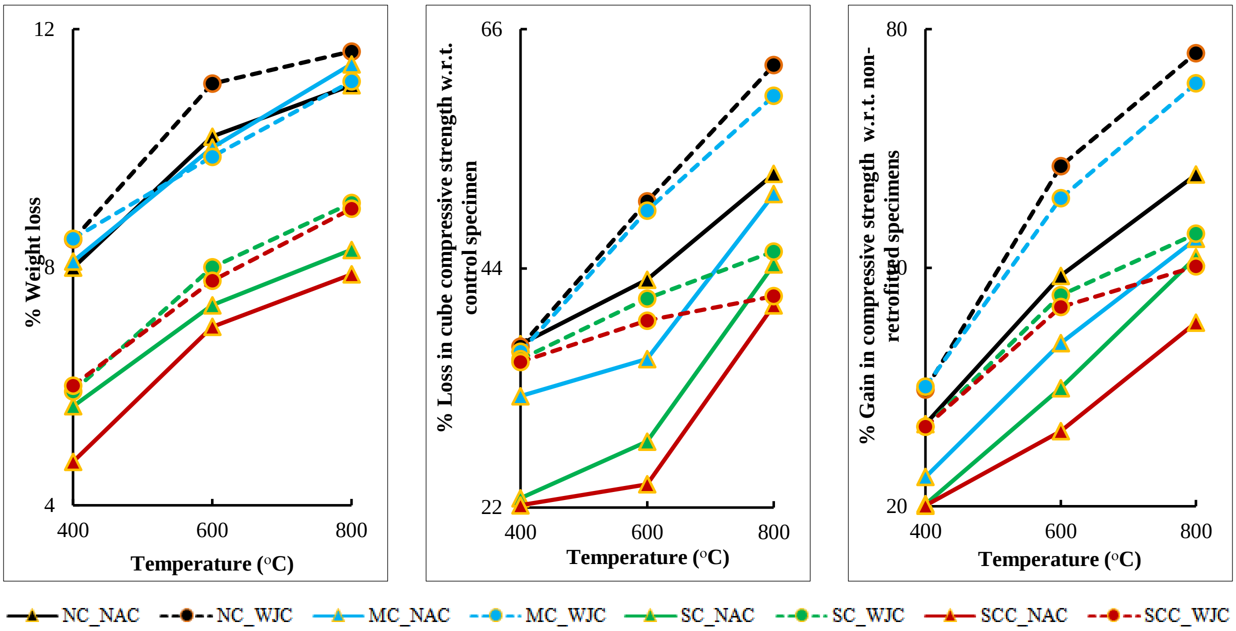


Figure 8. % weight loss; % loss in cube compressive strength due to temperature and % gain in compressive strength heat deteriorated samples after CFRP retrofitting

The CFRP retrofitting of the heat-deteriorated sample showed the maximum gain in compressive strength for M 20 grade normal concrete as compared to that for M 40 grade standard concrete (SC). The rate of strength gain due to CFRP retrofitting is higher for M 20 grade concrete samples subjected to the elevated temperature. The retrofit proved to be more effective for samples subjected to the highest temperature of 800°C.

3.1.1. Visual Inspections and Failure Pattern

Visual observations and physical examinations of cube specimens heated at high temperatures have revealed color change and micro-crack development at 400°C. The widening of cracks and spalling of concrete surfaces due to loss of aggregate bond are observed in the temperature range of 600°C–800°C. At 800°C, a noticeable deterioration in normal concrete with violent surface breaking is noticed. Similar visible symptoms of cracking and spalling are reported by Al-Radi et al. [16].

Failure patterns of heat damaged samples (at 800°C) belonging to M 20 grade NC and cooled by NAC and WJC are compared with those of control samples (tested at room temperature = 27°C) in Figure 9. It is observed that all samples damaged by heat exhibit surface cracking due to brittleness owing to the elevated temperature. Concrete spalling is more noticeable in the non-retrofitted NC-7 sample, which is cooled using the WJC method. Confinement by virtue of CFRP retrofitting to heat deteriorated samples (NC-6-800-NAC-CFRP and NC-7-800-WJC-CFRP) mitigated the severe spalling and crushing until the application of the maximum compressive load.

Control sample at 27 °C Non-retrofitted sample after 800 °C Retrofitted sample after 800 °C

Figure 9. Failure of heat deteriorated samples of cube specimens

3.2. Effect of Elevated Temperature on Beam Flexural Strength

The effect of elevated temperature on the flexural load carrying capacity of beam specimens is presented in Table 4 and Figure 10, which provide a graphical representation of the rate of loss for weight and flexural load carrying capacity due to elevated temperature as well as the rate of strength gain in CFRP retrofitted heat deteriorated specimens.

Table 4. Weight and flexural load carrying capacity of beam specimens due to elevated temperature considering the effect of cooling regimes and retrofitting

Beam specimen	Temp. °C for 2 Hr	Cooling condition	Weight (kg)		Flexural load-carrying capacity (kN)	
			Before	After	before retrofitting	after retrofitting
NC-1 (CS)	RT =27	--	42.38	42.38	100.62	--
NC-2	400	NAC	42.42	38.90	79.32	103.76
NC-3	400	WJC	42.44	38.75	76.58	103.52
NC-4	600	NAC	42.43	38.01	75.56	102.98
NC-5	600	WJC	42.30	37.64	72.84	101.24
NC-6	800	NAC	42.54	37.73	69.93	96.87
NC-7	800	WJC	42.29	37.23	67.88	95.90
MC-1 (CS)	RT =27	--	42.67	42.67	102.38	--
MC-2	400	NAC	42.56	39.21	82.54	105.31
MC-3	400	WJC	42.64	38.92	79.90	104.52
MC-4	600	NAC	42.52	38.23	78.74	103.50
MC-5	600	WJC	42.45	37.85	76.04	101.78
MC-6	800	NAC	42.72	38.03	73.21	98.02
MC-7	800	WJC	42.54	37.56	70.67	97.08
SC-1 (CS)	RT =27	--	43.21	43.21	190.33	--
SC-2	400	NAC	43.33	41.48	166.77	206.88
SC-3	400	WJC	43.23	41.08	161.55	205.45
SC-4	600	NAC	43.30	40.43	160.32	204.98
SC-5	600	WJC	43.18	39.92	154.86	201.42
SC-6	800	NAC	43.35	40.06	148.81	194.05
SC-7	800	WJC	43.24	39.73	144.60	192.36
SCC-1 (CS)	RT =27	--	43.47	43.47	194.01	--
SCC-2	400	NAC	43.54	41.75	172.64	209.56
SCC-3	400	WJC	43.41	41.37	167.98	207.36
SCC-4	600	NAC	43.69	41.13	167.05	207.83
SCC-5	600	WJC	43.33	40.20	161.27	204.90
SCC-6	800	NAC	43.39	40.44	156.49	201.67
SCC-7	800	WJC	43.36	39.93	149.52	195.23

The % loss is calculated with respect to control sample (tested under room temperature). The effect of CFRP retrofitting on heat deteriorated specimens is expressed as % gain in flexural load carrying capacity with respect to non-retrofitted heat deteriorated specimen. Similar to the cube specimens, the weight losses for beam specimen are observed to be in the range of 6 –10% which indicates the effect of temperature on weight loss is independent on shape and size of specimen. Non-retrofitted samples of beam specimen shows average 25 % reduction in flexural load carrying for M 20 grade normal and metakaolin concrete and about 20 % average reduction for M 40 grade standard and self-compacting concrete. This degradation is predominant for temperature range of 600°C–800°C. The flexural load carrying capacity of samples heated in the range of 400°C–600°C drops more rapidly as compared to those subjected to temperature range of 600°C–800°C. The rate of gain in flexural load carrying capacity is more acute for the heat deteriorated samples of M 20 grade of concrete.

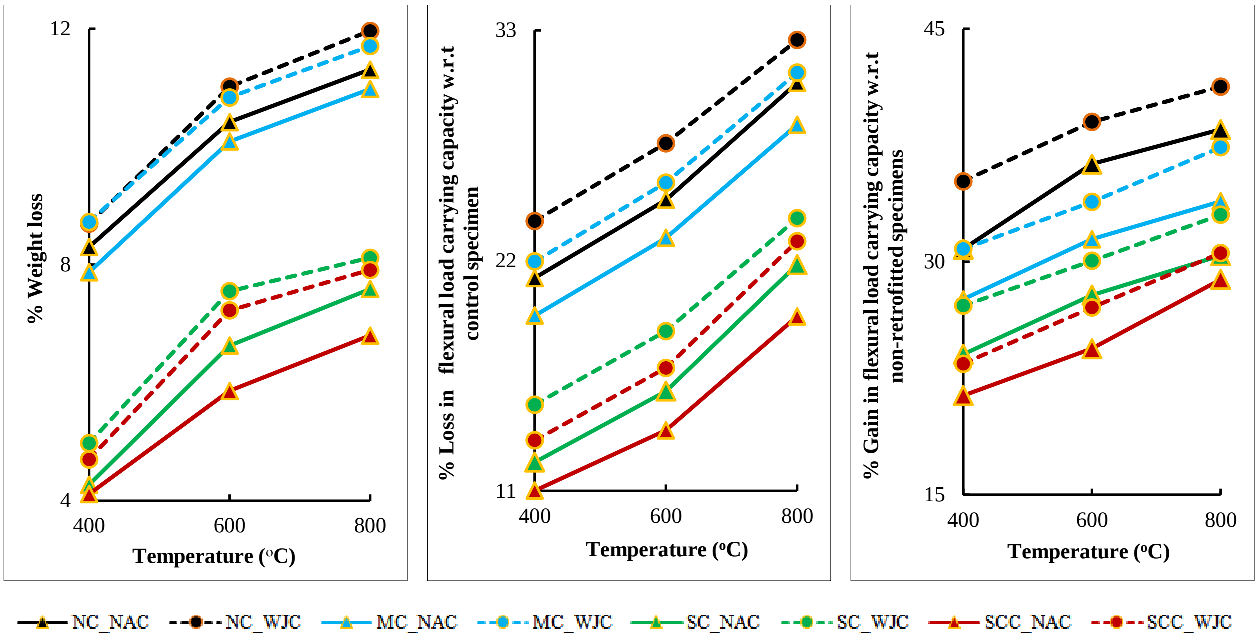


Figure 10. % weight loss; % loss in flexural load carrying capacity due to temperature and % gain in flexural load carrying capacity of heat deteriorated samples after CFRP retrofitting

3.2.1. Visual Inspections and Failure Pattern

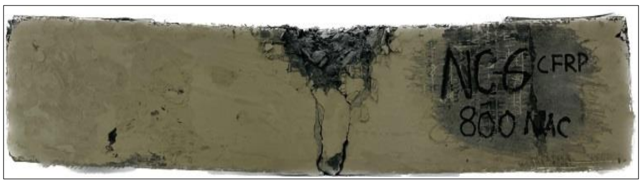
At the elevated temperature, all the beam specimen samples showed noticeable changes in surface of concrete such as change of color from grey to greyish white, distinctly visible surface cracks along the span and across the width and depth of beam cross section and spalling of concrete.

Figure 11 represents comparison of failure modes of heated samples (800°C) with control samples (27°C) where effect of cooling regime and retrofitting techniques is accounted for diagnosis. For the non-retrofitted NC-7-800 sample as cooled by WJC, severe spalling of concrete along crack propagation due to heat-induced brittleness is clearly seen in the failure mode. In contrast, for samples cooled by NAC, the spread of flexural and shear cracks as well as spalling of concrete observed to be modest. Similar to behaviour of cube samples, the confinement by CFRP laminate prove to be effective in restraining the crack propagation and thereby restoring the flexural load carrying capacity of retrofitted heat damaged samples.

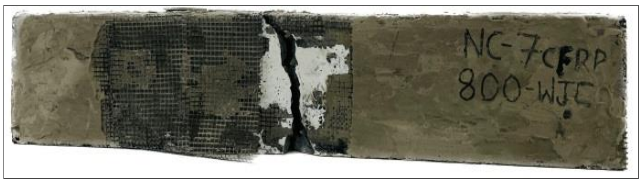
Control sample at room temperature 27°C

Non-retrofitted sample with NAC after 800 °C

Non-retrofitted sample with WJC after 800 °C



Retrofitted sample with NAC after 800 °C



Retrofitted sample with WJC after 800 °C

Figure 11. Failure pattern of heat deteriorated samples of beam specimens

3.3. Effect of Elevated Temperature on Split Tensile Strength

The effect of elevated temperature on split tensile strength of samples of various types of concrete Table 5. The rate of weight and split tensile strength loss due to elevated temperature as well as rate of strength gain due to retrofitting is plotted in Figure 12. Similar to cube and beam specimen, the weight loss due to elevated temperature observed to be in the range of 6% to 10%. For all concrete types, the rate of loss of split tensile strength is more pronounced for temperature range of 600°C – 800°C where all samples are cooled by WJC. Under elevated temperature (400°C – 800°C), maximum loss of 50% – 60% in split tensile strength is reported for M 20 grade normal concrete (NC). The M40 grade self-compacting concrete (SCC) proved to be more efficient to withstand the fire loading as loss in split tensile strength is least. The % loss in split tensile strength for SCC as reported in present study is in agreement with previous study by Sideris [11].

Table 5. Weight and split tensile strength of cylinder specimens due to elevated temperature considering the effect of cooling regimes and retrofitting

Cylinder specimen	Temp. °C for 2 Hr	Cooling condition	Weight (kg)		Split tensile strength (MPa)	
			Before	After	before retrofitting	after retrofitting
NC-1 (CS)	RT =27	--	13.37	13.37	2.58	--
NC-2	400	NAC	13.42	12.42	1.27	1.72
NC-3	400	WJC	13.45	12.22	1.23	1.75
NC-4	600	NAC	13.38	12.11	1.20	1.70
NC-5	600	WJC	13.30	11.90	1.18	1.71
NC-6	800	NAC	13.50	12.05	1.08	1.59
NC-7	800	WJC	13.40	11.83	1.04	1.55
MC-1 (CS)	RT =27	--	13.35	13.35	2.63	--
MC-2	400	NAC	13.38	12.47	1.32	1.76
MC-3	400	WJC	13.32	12.28	1.30	1.79
MC-4	600	NAC	13.39	12.18	1.26	1.74
MC-5	600	WJC	13.34	11.99	1.24	1.75
MC-6	800	NAC	13.36	12.00	1.15	1.63
MC-7	800	WJC	13.37	11.89	1.13	1.64
SC-1 (CS)	RT =27	--	13.56	13.56	3.00	--
SC-2	400	NAC	13.54	12.75	1.87	2.40
SC-3	400	WJC	13.51	12.65	1.85	2.41
SC-4	600	NAC	13.58	12.55	1.84	2.39
SC-5	600	WJC	13.49	12.33	1.80	2.36
SC-6	800	NAC	13.52	12.33	1.69	2.29
SC-7	800	WJC	13.55	12.28	1.61	2.24
SCC-1 (CS)	RT =27	--	13.47	13.47	3.06	--
SCC-2	400	NAC	13.50	12.88	1.92	2.42
SCC-3	400	WJC	13.44	12.68	1.88	2.43
SCC-4	600	NAC	13.53	12.69	1.89	2.40
SCC-5	600	WJC	13.59	12.63	1.85	2.41
SCC-6	800	NAC	13.45	12.42	1.78	2.36
SCC-7	800	WJC	13.51	12.38	1.68	2.31

The percentage loss of split tensile strength of concrete subjected to elevated temperatures is more dominant as compared to the percentage loss of cube compressive strength. Hence, the standard relationship between the compressive strength and the tensile strength changes after exposure to elevated temperatures approximating fire conditions. For all types and grades of concrete in the present study, the heat-deteriorated samples as cooled by natural air cooling (NAC) have shown better performance against elevated temperatures as the percentage loss in split tensile strength remains always less than that for samples cooled by water jet cooling (WJC). The enhancement in split tensile strength due to CFRP retrofitting is more predominant (33%–49% gain) for heat-deteriorated samples belonging to normal and metakaolin concrete of M 20 grade.

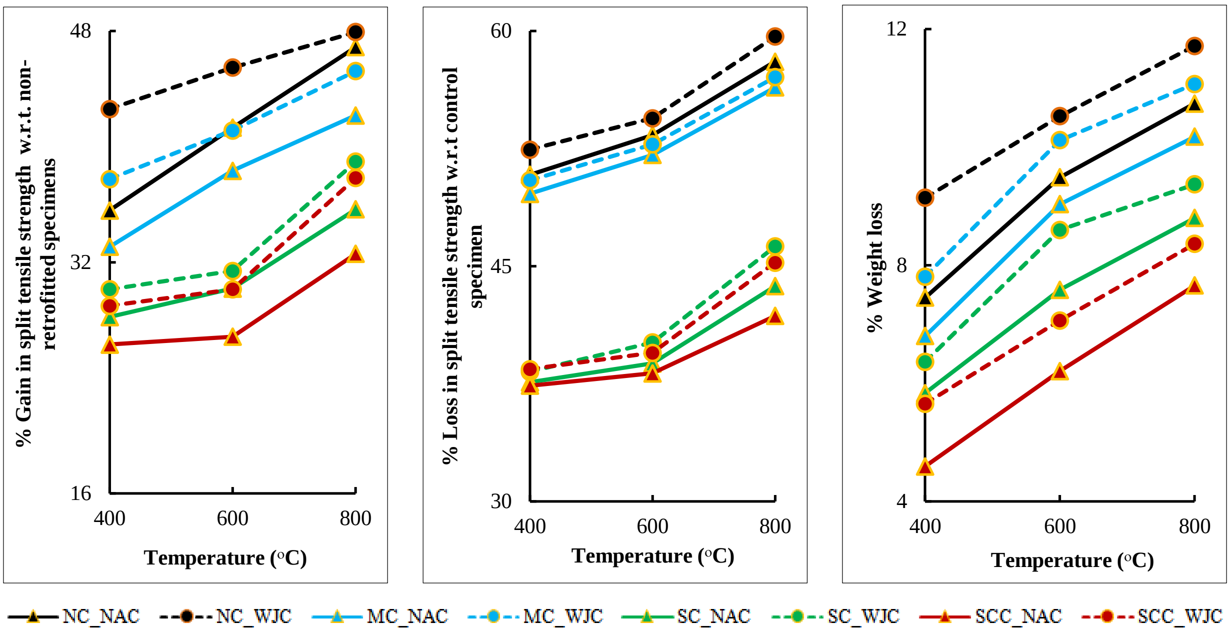


Figure 12. % weight loss; % loss in split tensile strength due to temperature and % gain in split tensile strength heat deteriorated samples after CFRP retrofitting

3.3.1. Visual Inspections and Failure Pattern

Figure 13 represents the split tensile failure pattern of non-retrofitted and retrofitted samples of M 20 grade concrete subjected to 800 °C and cooled down by the WJC method. It is clear that quick/rapid cooling by WJC causes significant brittleness, which leads to fracture in cement paste and aggregate. The usual split tensile failure seen in CFRP retrofitted samples occurs without any weakening of the bond between the cement paste and the aggregate.

Non-retrofitted after 800 °C Retrofitted after 800 °C

Figure 13. Split tensile failure of heat deteriorated sample of cylinder specimen

4. Conclusions

This experimental research investigates the synchronizing effect of cooling regimes and retrofitting techniques on the strength of concrete subjected to elevated temperatures. For four distinct types of concrete, a total of 936 samples, consisting of 72 control samples at room temperature and 864 temperature-loaded samples in the range of 400°C–800°C, were tested considering two different cooling regimes and CFRP retrofitting techniques. The findings of the experimental study led to the following concluding remarks:

- **Physical damages of concrete subjected to elevated temperature:**

  At moderate temperatures of 400°C, physical damages due to elevated temperatures, such as weight loss, a change in surface color from cement grey to powder white, thermal cracking, and spalling resulted from the loss of bond between the aggregate and cement paste, are instantly observed. These damages are severe and frequently require fire damage repairs and restorations for high temperature ranges of 600°C–800°C.

- **Effect of elevated temperature on strength of concrete:**

  Normal/low-strength concrete (NC and MC) samples subjected to elevated temperatures are more susceptible to acute strength degradation in terms of cube compressive strength, flexural load carrying capacity, and split tensile strength. For all types of concrete in this study, the loss of split tensile strength is more dominant as compared to the compressive strength of the concrete. Thus, the standard relationship between the compressive strength and the tensile strength changes after exposure to elevated temperatures. The use of light-weight aggregate with lower thermal conductivity resulted in improving the strength resistance of self-compacting concrete (SCC) against the elevated temperature. Higher residual strength offered by SCC against high temperatures is also attributed to its properties like reasonable flowability with a lower water-to-cement ratio, homogeneity of mix, and resistance against segregation.

- **Effect of cooling regime on strength of concrete exposed to elevated temperature:**

  Failure modes of all tested specimens reveal that thermal shocks from a water jet's rapid cooling produced significant fracture growth and severe spalling. In the current investigation, water jet cooling (WJC) caused higher strength degradation than normal air cooling (NAC) for all types of concrete and temperature ranges. Therefore, normal air cooling (NAC) is recommended for heat-damaged concrete in order to maintain its strength with the least amount of deterioration.

- **Effectiveness of CFRP retrofitting for concrete exposed to elevated temperature:**

  CFRP laminate retrofitting to heat-damaged samples of all concrete, irrespective of cooling regime, provided the confinement to restrain the crack propagation and sever spalling. As a result, the CFRP retrofitting technique proves to be an efficient and effective solution to restore the strength of fire-damaged concrete.

Considering the scope of current research, the study is limited to four types of concrete, three ranges of temperature, two categories of cooling regimes, and one retrofitting technique. In the future, a similar study considering high-strength concrete used in pre-stress concrete construction as well as the boarder temperature range up to 1200°C is suggested considering various cooling regimes and retrofitting techniques.

5. Declarations

5.1. Author Contributions

Conceptualization, S.B.K., P.S.S., and Y.A.K.; methodology, S.B.K, P.S.S., and Y.A.K.; experiments, S.B.K. and P.S.S.; investigation, S.B.K. and P.S.S.; data processing, S.B.K. and P.S.S.; writing—original draft preparation, S.B.K.; writing—review and editing, S.B.K., P.S.S., and Y.A.K.; supervision, S.B.K. and Y.A.K. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Acknowledgements

The authors would like to express utmost gratitude to the sponsorship and help rendered by Mr. Prakash Pol, Chairman, Industrial Heat Treaters, N-18 &W-23/B, Maharashtra Industrial Development Corporation, Ambad–422010, Nasik (India) by making available the furnace in present investigation.

5.5. Conflicts of Interest

The authors declare no conflict of interest.

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