

Experimental Investigation on the Influence of Post-Heating Cooling Regimes on the Mechanical and Durability Characteristics of Fly Ash Concrete Subjected to Sustained Elevated Temperatures

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Abstract - Concrete is widely used in structural construction, but sustained elevated temperature can cause dehydration of cement paste, thermal incompatibility, cracking, spalling and loss of mechanical capacity. This study experimentally evaluates fly ash concrete subjected to 200°C, 400°C, 600°C, 800°C and 1000°C for four hours and subsequently cooled by gradual, intermittent or sudden water cooling. A reference mixture and 5%, 10%, 15%, 20%, 25% and 30% fly ash replacement levels were investigated using a base proportion of 1:2.5:4.0 and water-cement ratio of 0.45. Workability was measured by slump, while residual compressive, split tensile and flexural strengths were determined after 90 days of curing and thermal exposure. The 25% fly ash mixture provided the most favourable overall mechanical response. Under gradual cooling, the 25% mixture recorded 35.56, 34.00, 32.67, 9.88 and 4.00 MPa compressive strengths at 200°C, 400°C, 600°C, 800°C and 1000°C, respectively. Corresponding split tensile strengths were 4.27, 4.19, 3.93, 3.59 and 3.10 MPa, while flexural strengths were 5.60, 5.40, 5.13, 4.93 and 4.70 MPa. Gradual cooling consistently provided the highest residual performance, intermittent cooling was intermediate, and sudden cooling produced the greatest deterioration. The results demonstrate that cooling history should be considered along with maximum temperature and binder composition in post-heating assessment of concrete.

Key Words: fly ash concrete, elevated temperature, cooling regime, gradual cooling, residual strength, fire-damaged concrete.

1. INTRODUCTION

Fire and sustained elevated temperature are critical actions that can alter the physical, chemical and mechanical behaviour of concrete. Concrete response depends on exposure temperature, duration, moisture condition, aggregate type, cementitious system, porosity and stress state. After heating, the cooling path introduces an additional thermal action because different cooling rates generate different thermal gradients and residual stresses. Gradual cooling generally limits thermal gradients, whereas rapid water cooling can cause thermal shock, cracking and spalling. Fly ash is a supplementary cementitious material whose pozzolanic reaction can refine the cementitious matrix and modify the amount of calcium hydroxide available for decomposition. The present investigation therefore examines the combined influence of fly ash replacement, sustained temperature and post-heating cooling on residual concrete performance. The

study considers a reference concrete and six fly ash replacement levels, with thermal exposure at five temperatures and three cooling regimes. The measured responses are workability, compressive strength, split tensile strength and flexural strength.

2. RESEARCH BACKGROUND

Previous investigations have established that elevated temperature modifies cement paste, aggregate-paste interfaces and pore structure, resulting in strength loss and cracking. Research on post-fire assessment, thermal shock and cooling-rate effects shows that the heating-cooling history should be treated as a combined thermal exposure rather than considering maximum temperature alone [1,4,5,8,15,18,24–26,30–32,40–44]. Studies on fly ash and other mineral additions indicate that binder modification can influence cracking and high-temperature resistance [5,18,34,39,45]. The literature also shows that residual strength assessment is important for repair and reuse decisions after fire exposure [1,6,13,21,23–25]. A focused comparison of gradual, intermittent and sudden cooling for fly ash concrete across a broad temperature range therefore provides useful material-level evidence for post-heating assessment.

3. MATERIALS AND EXPERIMENTAL PROGRAMME

3.1 Materials and mix proportioning

Ordinary Portland cement of 43 grade conforming to IS 8112 was used. Zone I fine aggregate and 20 mm and down-size coarse aggregate were used, with reported specific gravities of 2.68 and 2.80, respectively. Fly ash was obtained from a thermal power plant at Shaktinagar, Raichur and had a reported specific gravity of 2.10. Glenium B233 was used as superplasticizer. The base concrete proportion was 1:2.5:4.0 with a water-cement ratio of 0.45. Cement was replaced by fly ash at 0%, 5%, 10%, 15%, 20%, 25% and 30%.

Table 1. Physical properties of constituent materials

Material	Specification / description	Specific gravity
Cement	43 grade OPC, IS 8112	3.01
Fine aggregate	Zone I sand	2.68
Coarse aggregate	20 mm and down-size	2.80

Fly ash	Thermal power plant, Shaktinagar, Raichur	2.10
Superplasticizer	Glenium B233	1.20 (reported in mix calculation)

Table 2. Concrete mix proportions

Fly ash replacement	Cement fraction	Fly ash fraction	Base proportion	w/c
0%	100%	0%	1:2.5:4.0	0.45
5%	95%	5%	1:2.5:4.0	0.45
10%	90%	10%	1:2.5:4.0	0.45
15%	85%	15%	1:2.5:4.0	0.45
20%	80%	20%	1:2.5:4.0	0.45
25%	75%	25%	1:2.5:4.0	0.45
30%	70%	30%	1:2.5:4.0	0.45

3.2 Specimens, curing and thermal exposure

Concrete was mixed, cast into moulds, compacted and demoulded after approximately 24 h before water curing. Specimens were cured for 90 days prior to thermal exposure. The test programme used 150 mm cubes for compressive strength, 150 mm diameter $\times$ 300 mm cylinders for split tensile strength and 150 mm $\times$ 150 mm $\times$ 700 mm beams for flexural strength. Specimens were exposed to 200°C, 400°C, 600°C, 800°C and 1000°C for four hours; approximately 35°C served as the room-temperature reference condition.

Table 3. Specimen dimensions and test programme

Property	Specimen	Dimension	Primary result
Workability	Fresh concrete	Slump cone	Slump spread in mm
Compressive strength	Cube	150 $\times$ 150 $\times$ 150 mm	MPa
Split tensile strength	Cylinder	150 mm diameter $\times$ 300 mm	MPa
Flexural strength	Beam	150 $\times$ 150 $\times$ 700 mm	MPa

Table 4. Curing and thermal treatment sequence

Stage	Condition	Duration
Casting	Fresh concrete in moulds	Initial setting period
Demoulding	Specimens removed from moulds	Approximately 24 h
Water curing	Curing tank	90 days
Thermal exposure	Specified maximum temperature	4 h
Post-heating cooling	Gradual / intermittent / sudden	According to regime

Table 5. Thermal exposure programme

Condition	Maximum temperature	Holding duration	Post-heating condition
Reference	35°C	Ambient	No elevated-temperature exposure
HT-200	200°C	4 h	Cooling regime assigned
HT-400	400°C	4 h	Cooling regime assigned
HT-600	600°C	4 h	Cooling regime assigned
HT-800	800°C	4 h	Cooling regime assigned
HT-1000	1000°C	4 h	Cooling regime assigned

3.3 Cooling regimes

Gradual cooling was achieved by removing heated specimens from the oven and allowing natural cooling. Intermittent cooling involved spraying a limited quantity of water at 15-minute intervals for one hour followed by natural cooling. Sudden cooling consisted of immediate water quenching for approximately 15–20 minutes followed by natural cooling.

Table 6. Post-heating cooling regimes

Cooling regime	Cooling procedure	Principal thermal effect
Gradual	Natural cooling after removal from oven	Lower thermal gradient
Intermittent	Limited water spray every 15 min for 1 h, then natural cooling	Repeated moderate thermal gradients
Sudden	Immediate water quenching for 15–20 min, then natural cooling	Severe thermal shock

3.4 Test methods and data treatment

Fresh concrete workability was evaluated using the slump test. Compressive strength was determined from 150 mm cubes using $f_c = P/A$. Split tensile strength was evaluated using 150 mm $\times$ 300 mm cylinders using $f_t = 2P/(\pi DL)$. Flexural strength was determined from 150 mm $\times$ 150 mm $\times$ 700 mm beams using the applicable flexural-strength relationship for the adopted loading arrangement. Residual strength was calculated as the heated strength divided by the corresponding room-temperature strength multiplied by 100.

Table 7. Mix-design calculation summary

Item	Calculation / reported quantity	Value
Concrete volume	Selected unit volume	1.00 m ³
Cement	$231/3.01 \times 1/1000$	0.076 m ³
Water	$130.2/1 \times 1/1000$	0.1302 m ³
Admixture	$6.6/1.2 \times 1/1000$	0.0053 m ³
All-in aggregate volume	1 (0.076+0.1302+0.0053)	0.789 m ³
Coarse aggregate	$0.789 \times 0.61 \times 2.8 \times 1000$	≈1350 kg/m ³
Fine aggregate	$0.789 \times 0.39 \times 2.68 \times 1000$	≈821.7 kg/m ³
Cementitious material	Reported mix design	330 kg/m ³
Water	Reported mix design	130.2 kg/m ³
Chemical admixture	2% in reported volume calculation	6.6 kg/m ³

4. RESULTS AND DISCUSSION

4.1 Workability

The base concrete proportion of 1:2.5:4.0 with a water-cement ratio of 0.45 produced a reported slump of 60 mm, indicating workable fresh concrete suitable for casting the laboratory specimens.

Table 8. Workability observation

Mix system	Water-cement ratio	Superplasticizer	Observed slump
Base concrete	0.45	Glenium B233	60 mm

4.2 Compressive strength

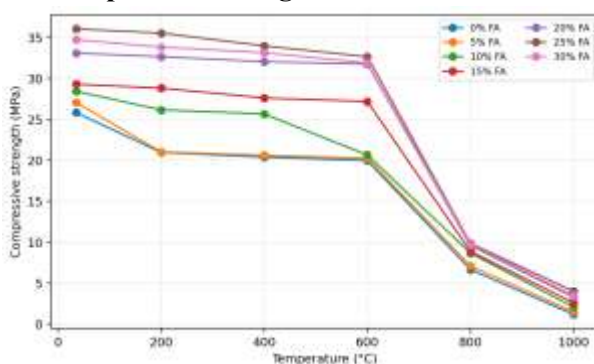


Fig. 1. Compressive strength variation with temperature—gradual cooling.

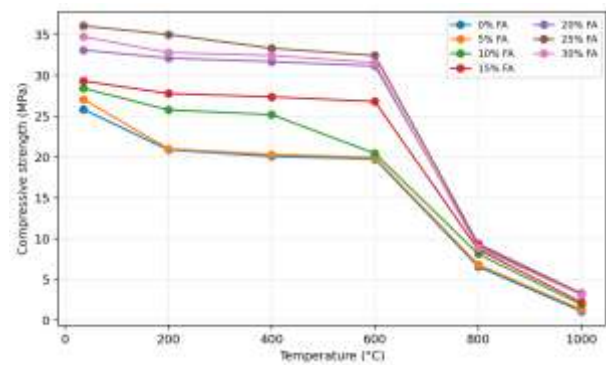


Fig. 2. Compressive strength variation with temperature—intermittent cooling.

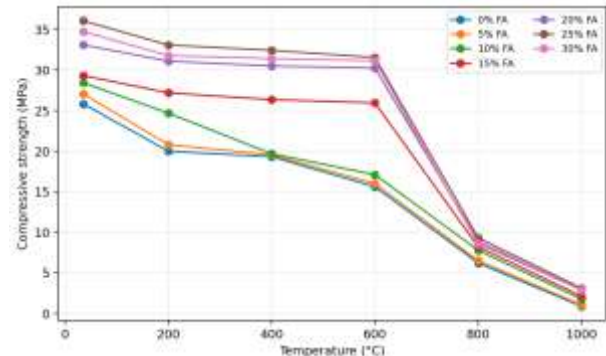


Fig. 3. Compressive strength variation with temperature—sudden cooling.

The strength curves show progressive deterioration with increasing temperature. The 25% fly ash mixture remains the most favourable composition over much of the investigated range, while sudden cooling generally gives the lowest residual values. The deterioration becomes especially pronounced between 600°C and 800°C.

4.3 Split tensile strength

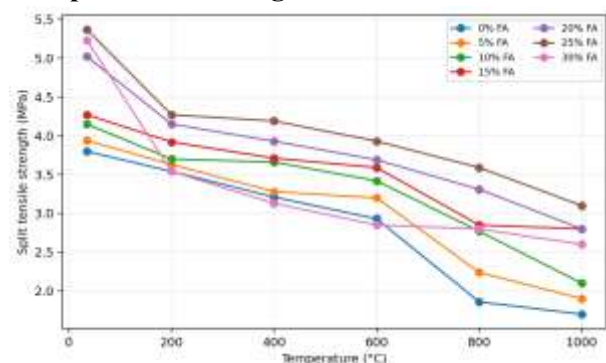


Fig. 4. Split tensile strength variation with temperature—gradual cooling.

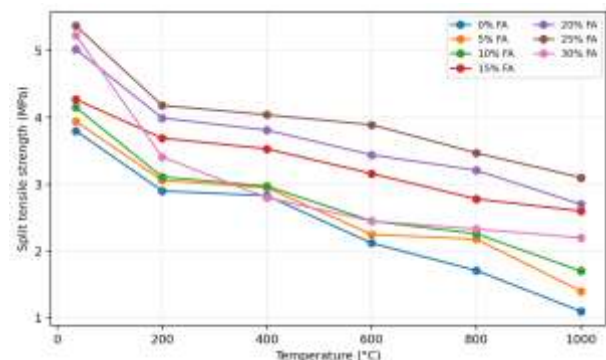


Fig. 5. Split tensile strength variation with temperature—intermittent cooling.

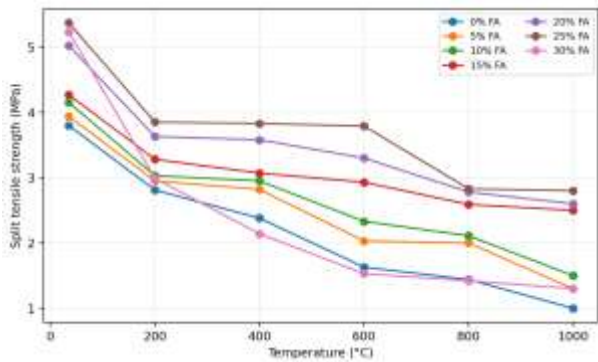


Fig. 6. Split tensile strength variation with temperature—sudden cooling.

The strength curves show progressive deterioration with increasing temperature. The 25% fly ash mixture remains the most favourable composition over much of the investigated range, while sudden cooling generally gives the lowest residual values. The deterioration becomes especially pronounced between 600°C and 800°C.

4.4 Flexural strength

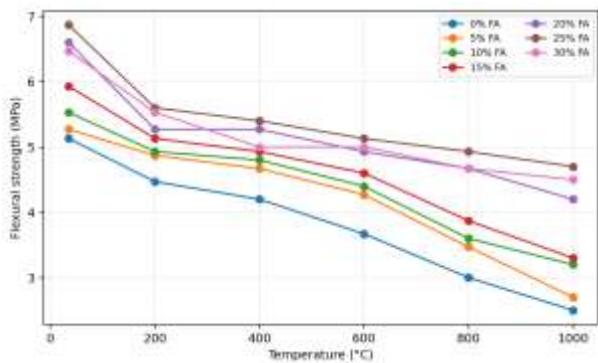


Fig. 7. Flexural strength variation with temperature—gradual cooling.

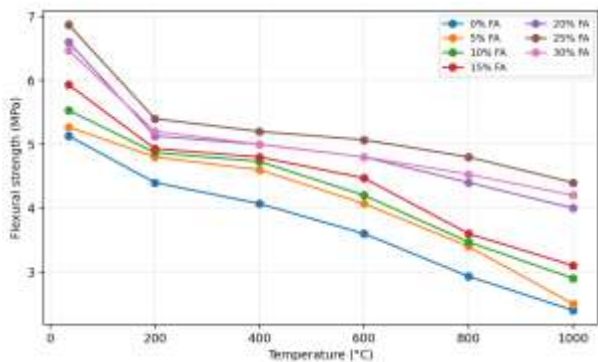


Fig. 8. Flexural strength variation with temperature—intermittent cooling.

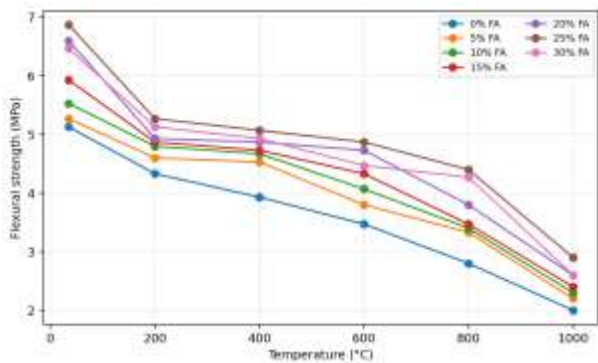


Fig. 9. Flexural strength variation with temperature—sudden cooling.

The strength curves show progressive deterioration with increasing temperature. The 25% fly ash mixture remains the most favourable composition over much of the

investigated range, while sudden cooling generally gives the lowest residual values. The deterioration becomes especially pronounced between 600°C and 800°C.

4.5 Residual performance of the 25% fly ash mixture

The 25% fly ash mixture was identified as the most favourable replacement level in the investigated series. Under gradual cooling, its compressive strength was 35.56 MPa at 200°C, 34.00 MPa at 400°C, 32.67 MPa at 600°C, 9.88 MPa at 800°C and 4.00 MPa at 1000°C, corresponding to residual strengths of 98.59%, 94.26%, 90.57%, 27.39% and 11.09%. Under intermittent cooling, the corresponding residual values were 97.09%, 92.40%, 89.94%, 25.95% and 9.12%. Under sudden cooling they were 91.77%, 89.94%, 87.50%, 25.87% and 8.62%.

Table 9. Residual compressive strength—gradual cooling

Temperature	Strength (MPa)	Residual strength (%)
200°C	35.56	98.59
400°C	34.00	94.26
600°C	32.67	90.57
800°C	9.88	27.39
1000°C	4.00	11.09

Table 10. Residual compressive strength—intermittent cooling

Temperature	Strength (MPa)	Residual strength (%)
200°C	35.02	97.09
400°C	33.33	92.40
600°C	32.44	89.94
800°C	9.36	25.95
1000°C	3.29	9.12

Table 11. Residual compressive strength—sudden cooling

Temperature	Strength (MPa)	Residual strength (%)
200°C	33.10	91.77
400°C	32.44	89.94
600°C	31.56	87.50
800°C	9.33	25.87
1000°C	3.11	8.62

Table 12. Residual split tensile strength—gradual cooling

Temperature	Strength (MPa)	Residual strength (%)
200°C	4.27	79.52
400°C	4.19	78.03
600°C	3.93	73.18
800°C	3.59	66.85
1000°C	3.10	57.73

Table 13. Residual split tensile strength—intermittent cooling

Temperature	Strength (MPa)	Residual strength (%)
200°C	4.18	77.84
400°C	4.04	75.23
600°C	3.89	72.44
800°C	3.47	64.62
1000°C	3.10	57.73

Table 14. Residual split tensile strength—sudden cooling

Temperature	Strength (MPa)	Residual strength (%)
200°C	3.85	71.69
400°C	3.83	71.32
600°C	3.79	70.58
800°C	2.83	52.70
1000°C	2.80	52.14

Table 15. Residual flexural strength—gradual cooling

Temperature	Strength (MPa)	Residual strength (%)
200°C	5.60	81.51
400°C	5.40	78.60
600°C	5.13	74.67
800°C	4.93	71.76
1000°C	4.70	68.41

Table 16. Residual flexural strength—intermittent cooling

Temperature	Strength (MPa)	Residual strength (%)
200°C	5.40	78.60
400°C	5.20	75.69
600°C	5.07	73.80
800°C	4.80	69.87
1000°C	4.40	64.05

Table 17. Residual flexural strength—sudden cooling

Temperature	Strength (MPa)	Residual strength (%)
200°C	5.27	76.71
400°C	5.07	73.80
600°C	4.87	70.89
800°C	4.40	64.05
1000°C	2.90	42.21

For split tensile strength, gradual cooling retained 79.52%, 78.03%, 73.18%, 66.85% and 57.73% at 200°C, 400°C, 600°C, 800°C and 1000°C, respectively. Sudden cooling reduced these values to 71.69%, 71.32%, 70.58%, 52.70% and 52.14%. Flexural residual strength under gradual cooling remained 81.51%, 78.60%, 74.67%, 71.76% and 68.41%, whereas sudden cooling reduced it to 76.71%, 73.80%, 70.89%, 64.05% and 42.21%.

4.6 Cooling-regime effect

The results establish a consistent cooling-regime ranking: gradual cooling produced the highest residual mechanical performance, intermittent cooling produced intermediate performance and sudden cooling produced the greatest deterioration. At 25% fly ash, the reduction relative to gradual cooling under intermittent cooling was approximately 1.52%, 2.10% and 3.57% for compressive, split tensile and flexural strength, respectively. Under sudden cooling, the corresponding reductions were approximately 6.92%, 9.83% and 5.89%. The additional deterioration is consistent with thermal shock generated by rapid surface cooling.

4.7 Thermal severity and engineering interpretation

The experimental response indicates a transition from comparatively moderate deterioration to severe deterioration between 600°C and 800°C. Up to 600°C, the 25% fly ash concrete retains a substantial proportion of its original compressive capacity under gradual cooling. At 800°C, residual compressive strength falls sharply, indicating extensive thermal damage. The consistency among compressive, split tensile and flexural responses indicates progressive matrix deterioration and cracking. Consequently, post-heating assessment should consider maximum temperature together with cooling history and material composition.

Table 18. Thermal severity classification

Temperature	Thermal severity	Residual response
200°C	Moderate	High residual mechanical capacity
400°C	Moderate-to-high	Good residual capacity
600°C	High	Pronounced deterioration begins
800°C	Very high	Severe strength loss
1000°C	Extreme	Very low residual compressive capacity

Table 19. Cooling-regime damage mechanism

Mechanism	Gradual	Intermittent	Sudden
Surface temperature change	Slow	Repeated moderate	Rapid
Thermal gradient	Low	Moderate	High
Thermal shock	Low	Moderate	High
Residual strength	Highest	Intermediate	Lowest

Table 20. Structural-material interpretation

Structural consideration	Relevant test	Interpretation
Compression capacity	Compressive strength	Residual matrix capacity
Crack resistance	Split tensile strength	Integrity of tensile path
Bending response	Flexural strength	Integrity of tensile zone
Post-fire condition	All three	Combined residual assessment

Table 21. Consolidated experimental result matrix

Property	Best replacement	Best cooling	Critical temperature range
Workability	Base mixture	Not applicable	Fresh-state
Compressive strength	25% FA	Gradual	600–800°C transition

Split tensile strength	25% FA	Gradual	600–800°C transition
Flexural strength	25% FA	Gradual	600–800°C transition

5. CONCLUSIONS

1. The base concrete proportion of 1:2.5:4.0 with a water-cement ratio of 0.45 produced a reported slump of 60 mm.
2. Fly ash replacement influenced mechanical performance at ambient and elevated temperatures, with 25% replacement providing the most favourable overall response within the investigated range.
3. Sustained elevated temperature caused progressive deterioration in compressive, split tensile and flexural strength, becoming pronounced at approximately 600°C and severe at 800°C and 1000°C.
4. The 25% fly ash mixture retained comparatively high residual compressive strength at 200°C and 400°C under gradual cooling.
5. Gradual cooling generally produced the highest residual strength, intermittent cooling produced intermediate performance and sudden cooling produced the greatest deterioration.
6. The stronger deterioration under sudden cooling is associated with thermal shock and severe thermal gradients that can induce additional cracking and spalling.
7. Post-heating cooling history should be considered during residual assessment of fire-exposed concrete; maximum temperature alone does not completely define final material condition.

6. ENGINEERING IMPLICATIONS AND FUTURE RESEARCH

The findings are relevant to structures exposed to fire, industrial heat or other sustained elevated-temperature actions. Residual compressive strength provides an important indicator of remaining compression capacity, while split tensile and flexural strengths provide complementary evidence concerning cracking and tensile-zone integrity. Cooling history should be documented during post-heating inspection whenever possible. Future studies should extend the investigation to reinforced concrete members, durability and transport properties, microstructural characterization, realistic fire curves, repeated thermal cycles, variable moisture and loading conditions, numerical thermal analysis and alternative supplementary cementitious materials.

APPENDIX A: DETAILED EXPERIMENTAL TABLES

Detailed experimental, comparative and engineering tables from the investigation are provided below for complete data traceability.

Table A1. Detailed experimental data set 1

Material	Specification / description	Specific gravity
Cement	43 grade OPC, IS 8112	3.01
Fine aggregate	Zone I sand	2.68
Coarse aggregate	20 mm and down-	2.80

	size	
Fly ash	Thermal power plant, Shaktinagar, Raichur	2.10
Superplasticizer	Glenium B233	1.20 (reported in mix calculation)

Table A2. Detailed experimental data set 2

Material	Primary function in concrete	Thermal-response relevance
OPC	Primary binder	Hydration products undergo dehydration and decomposition at elevated temperature.
Fly ash	Pozzolanic supplementary binder	Reduces clinker demand and modifies the hardened cementitious matrix.
Fine aggregate	Fills voids and contributes to skeleton	Thermal expansion and mineral characteristics influence cracking.
Coarse aggregate	Load-bearing aggregate skeleton	Aggregate expansion and phase stability affect thermal compatibility.
Superplasticizer	Improves fresh workability	Permits workable concrete at controlled water-cement ratio.

Table A3. Detailed experimental data set 3

Fly ash replacement	Cement fraction	Fly ash fraction	Base proportion	w/c
0%	100%	0%	1:2.5:4.0	0.45
5%	95%	5%	1:2.5:4.0	0.45
10%	90%	10%	1:2.5:4.0	0.45
15%	85%	15%	1:2.5:4.0	0.45
20%	80%	20%	1:2.5:4.0	0.45
25%	75%	25%	1:2.5:4.0	0.45
30%	70%	30%	1:2.5:4.0	0.45

Table A4. Detailed experimental data set 4

Item	Calculation / reported quantity	Value
Concrete volume	Selected unit volume	1.00 m ³
Cement	$231/3.01 \times 1/1000$	0.076 m ³
Water	$130.2/1 \times 1/1000$	0.1302 m ³
Admixture	$6.6/1.2 \times 1/1000$	0.0053 m ³

All-in aggregate volume	1 (0.076+0.1302+0.0053)	0.789 m ³
Coarse aggregate	0.789 × 0.61 × 2.8 × 1000	≈1350 kg/m ³
Fine aggregate	0.789 × 0.39 × 2.68 × 1000	≈821.7 kg/m ³
Cementitious material	Reported mix design	330 kg/m ³
Water	Reported mix design	130.2 kg/m ³
Chemical admixture	2% in reported volume calculation	6.6 kg/m ³

Table A5. Detailed experimental data set 5

Property	Specimen	Dimension	Primary result
Workability	Fresh concrete	Slump cone	Slump spread in mm
Compressive strength	Cube	150 × 150 × 150 mm	MPa
Split tensile strength	Cylinder	150 mm diameter × 300 mm	MPa
Flexural strength	Beam	150 × 150 × 700 mm	MPa

Table A6. Detailed experimental data set 6

Stage	Condition	Duration
Casting	Fresh concrete in moulds	Initial setting period
Demoulding	Specimens removed from moulds	Approximately 24 h
Water curing	Curing tank	90 days
Thermal exposure	Specified maximum temperature	4 h
Post-heating cooling	Gradual / intermittent / sudden	According to regime

Table A7. Detailed experimental data set 7

Condition	Maximum temperature	Holding duration	Post-heating condition
Reference	35°C	Ambient	No elevated-temperature exposure
HT-200	200°C	4 h	Cooling regime assigned
HT-400	400°C	4 h	Cooling regime assigned
HT-600	600°C	4 h	Cooling regime assigned
HT-800	800°C	4 h	Cooling

			regime assigned
HT-1000	1000°C	4 h	Cooling regime assigned

Table A8. Detailed experimental data set 8

Cooling regime	Cooling procedure	Principal thermal effect
Gradual	Natural cooling after removal from oven	Lower thermal gradient
Intermittent	Limited water spray every 15 min for 1 h, then natural cooling	Repeated moderate thermal gradients
Sudden	Immediate water quenching for 15–20 min, then natural cooling	Severe thermal shock

Table A9. Detailed experimental data set 9

Mix system	Water-cement ratio	Superplasticizer	Observed slump
Base concrete	0.45	Glenium B233	60 mm

Table A10. Detailed experimental data set 10

Fly ash (%)	35°C	200°C	400°C	600°C	800°C	1000°C
0%	25.85	20.98	20.41	20.00	6.67	1.20
5%	27.07	21.04	20.62	20.27	7.11	1.50
10%	28.44	26.18	25.67	20.67	8.67	2.10
15%	29.32	28.83	27.63	27.20	8.89	2.60
20%	33.11	32.68	32.07	31.78	9.60	3.30
25%	36.07	35.56	34.00	32.67	9.88	4.00
30%	34.74	33.85	33.16	31.91	9.78	3.50

Table A11. Detailed experimental data set 11

Fly ash (%)	35°C	200°C	400°C	600°C	800°C	1000°C
0%	25.85	20.89	20.09	19.78	6.58	1.11
5%	27.07	21.00	20.31	19.96	6.84	1.33
10%	28.44	25.78	25.20	20.44	8.13	1.91
15%	29.32	27.78	27.38	26.80	8.67	2.22
20%	33.11	32.12	31.69	31.16	9.16	3.20
25%	36.07	35.02	33.33	32.44	9.36	3.29
30%	34.74	32.80	32.44	31.56	8.89	3.11

Table A12. Detailed experimental data set 12

Fly ash (%)	35°C	200°C	400°C	600°C	800°C	1000°C
0%	25.85	20.00	19.33	15.63	6.22	0.89
5%	27.07	20.80	19.56	16.00	6.53	1.07
10%	28.44	24.70	19.69	17.11	7.78	1.78
15%	29.32	27.20	26.36	25.96	8.22	2.13

20%	33.11	31.10	30.52	30.27	8.89	2.89
25%	36.07	33.10	32.44	31.56	9.33	3.11
30%	34.74	31.80	31.42	31.16	8.58	2.89

Table A13. Detailed experimental data set 13

Temperature	Strength (MPa)	Residual strength (%)
200°C	35.56	98.59
400°C	34.00	94.26
600°C	32.67	90.57
800°C	9.88	27.39
1000°C	4.00	11.09

Table A14. Detailed experimental data set 14

Temperature	Strength (MPa)	Residual strength (%)
200°C	35.02	97.09
400°C	33.33	92.40
600°C	32.44	89.94
800°C	9.36	25.95
1000°C	3.29	9.12

Table A15. Detailed experimental data set 15

Temperature	Strength (MPa)	Residual strength (%)
200°C	33.10	91.77
400°C	32.44	89.94
600°C	31.56	87.50
800°C	9.33	25.87
1000°C	3.11	8.62

Table A16. Detailed experimental data set 16

Fly ash (%)	35°C	200°C	400°C	600°C	800°C	1000°C
0%	3.80	3.54	3.21	2.93	1.86	1.70
5%	3.94	3.63	3.28	3.20	2.24	1.90
10%	4.15	3.70	3.66	3.42	2.77	2.10
15%	4.27	3.92	3.71	3.59	2.85	2.80
20%	5.02	4.15	3.93	3.69	3.31	2.80
25%	5.37	4.27	4.19	3.93	3.59	3.10
30%	5.23	3.54	3.13	2.85	2.80	2.60

Table A17. Detailed experimental data set 17

Fly ash (%)	35°C	200°C	400°C	600°C	800°C	1000°C
0%	3.80	2.90	2.83	2.12	1.71	1.10
5%	3.94	3.06	2.95	2.25	2.18	1.40
10%	4.15	3.11	2.97	2.45	2.26	1.70
15%	4.27	3.69	3.53	3.16	2.78	2.60
20%	5.02	3.99	3.81	3.44	3.21	2.70
25%	5.37	4.18	4.04	3.89	3.47	3.10
30%	5.23	3.41	2.80	2.45	2.33	2.20

Table A18. Detailed experimental data set 18

Fly ash (%)	35°C	200°C	400°C	600°C	800°C	1000°C
0%	3.80	2.81	2.38	1.63	1.44	1.00
5%	3.94	2.95	2.82	2.03	2.00	1.30
10%	4.15	3.03	2.95	2.33	2.11	1.50
15%	4.27	3.28	3.07	2.93	2.59	2.50
20%	5.02	3.63	3.58	3.30	2.78	2.60
25%	5.37	3.85	3.83	3.79	2.83	2.80
30%	5.23	2.99	2.14	1.53	1.42	1.30

Table A19. Detailed experimental data set 19

Temperature	Strength (MPa)	Residual strength (%)
200°C	4.27	79.52
400°C	4.19	78.03
600°C	3.93	73.18
800°C	3.59	66.85
1000°C	3.10	57.73

Table A20. Detailed experimental data set 20

Temperature	Strength (MPa)	Residual strength (%)
200°C	4.18	77.84
400°C	4.04	75.23
600°C	3.89	72.44
800°C	3.47	64.62
1000°C	3.10	57.73

Table A21. Detailed experimental data set 21

Temperature	Strength (MPa)	Residual strength (%)
200°C	3.85	71.69
400°C	3.83	71.32
600°C	3.79	70.58
800°C	2.83	52.70
1000°C	2.80	52.14

Table A22. Detailed experimental data set 22

Fly ash (%)	35°C	200°C	400°C	600°C	800°C	1000°C
0%	5.13	4.47	4.20	3.67	3.00	2.50
5%	5.27	4.87	4.67	4.27	3.47	2.70
10%	5.53	4.93	4.80	4.40	3.60	3.20
15%	5.93	5.13	4.93	4.60	3.87	3.30
20%	6.60	5.27	5.27	4.93	4.67	4.20
25%	6.87	5.60	5.40	5.13	4.93	4.70
30%	6.47	5.53	5.00	5.00	4.67	4.50

Table A23. Detailed experimental data set 23

Fly ash (%)	35°C	200°C	400°C	600°C	800°C	1000°C
0%	5.13	4.40	4.07	3.60	2.93	2.40
5%	5.27	4.80	4.60	4.07	3.40	2.50
10%	5.53	4.87	4.73	4.20	3.47	2.90
15%	5.93	4.93	4.80	4.47	3.60	3.10

20%	6.60	5.13	5.00	4.80	4.40	4.00
25%	6.87	5.40	5.20	5.07	4.80	4.40
30%	6.47	5.20	5.00	4.80	4.53	4.20

Table A24. Detailed experimental data set 24

Fly ash (%)	35°C	200°C	400°C	600°C	800°C	1000°C
0%	5.13	4.33	3.93	3.47	2.80	2.00
5%	5.27	4.60	4.53	3.80	3.33	2.20
10%	5.53	4.80	4.67	4.07	3.40	2.30
15%	5.93	4.87	4.73	4.33	3.47	2.40
20%	6.60	4.93	4.87	4.73	3.80	2.60
25%	6.87	5.27	5.07	4.87	4.40	2.90
30%	6.47	5.13	4.93	4.47	4.27	2.60

Table A25. Detailed experimental data set 25

Temperature	Strength (MPa)	Residual strength (%)
200°C	5.60	81.51
400°C	5.40	78.60
600°C	5.13	74.67
800°C	4.93	71.76
1000°C	4.70	68.41

Table A26. Detailed experimental data set 26

Temperature	Strength (MPa)	Residual strength (%)
200°C	5.40	78.60
400°C	5.20	75.69
600°C	5.07	73.80
800°C	4.80	69.87
1000°C	4.40	64.05

Table A27. Detailed experimental data set 27

Temperature	Strength (MPa)	Residual strength (%)
200°C	5.27	76.71
400°C	5.07	73.80
600°C	4.87	70.89
800°C	4.40	64.05
1000°C	2.90	42.21

Table A28. Detailed experimental data set 28

Fly ash (%)	Gradual	Intermittent	Sudden
0%	20.98	20.89	20.00
5%	21.04	21.00	20.80
10%	26.18	25.78	24.70
15%	28.83	27.78	27.20
20%	32.68	32.12	31.10
25%	35.56	35.02	33.10
30%	33.85	32.80	31.80

Table A29. Detailed experimental data set 29

Fly ash (%)	Gradual	Intermittent	Sudden
0%	20.41	20.09	19.33
5%	20.62	20.31	19.56
10%	25.67	25.20	19.69
15%	27.63	27.38	26.36

20%	32.07	31.69	30.52
25%	34.00	33.33	32.44
30%	33.16	32.44	31.42

Table A30. Detailed experimental data set 30

Fly ash (%)	Gradual	Intermittent	Sudden
0%	20.00	19.78	15.63
5%	20.27	19.96	16.00
10%	20.67	20.44	17.11
15%	27.20	26.80	25.96
20%	31.78	31.16	30.27
25%	32.67	32.44	31.56
30%	31.91	31.56	31.16

Table A31. Detailed experimental data set 31

Fly ash (%)	Gradual	Intermittent	Sudden
0%	6.67	6.58	6.22
5%	7.11	6.84	6.53
10%	8.67	8.13	7.78
15%	8.89	8.67	8.22
20%	9.60	9.16	8.89
25%	9.88	9.36	9.33
30%	9.78	8.89	8.58

Table A32. Detailed experimental data set 32

Fly ash (%)	Gradual	Intermittent	Sudden
0%	1.20	1.11	0.89
5%	1.50	1.33	1.07
10%	2.10	1.91	1.78
15%	2.60	2.22	2.13
20%	3.30	3.20	2.89
25%	4.00	3.29	3.11
30%	3.50	3.11	2.89

Table A33. Detailed experimental data set 33

Fly ash (%)	Gradual	Intermittent	Sudden
0%	3.54	2.90	2.81
5%	3.63	3.06	2.95
10%	3.70	3.11	3.03
15%	3.92	3.69	3.28
20%	4.15	3.99	3.63
25%	4.27	4.18	3.85
30%	3.54	3.41	2.99

Table A34. Detailed experimental data set 34

Fly ash (%)	Gradual	Intermittent	Sudden
0%	3.21	2.83	2.38
5%	3.28	2.95	2.82
10%	3.66	2.97	2.95
15%	3.71	3.53	3.07
20%	3.93	3.81	3.58
25%	4.19	4.04	3.83
30%	3.13	2.80	2.14

Table A35. Detailed experimental data set 35

Fly ash (%)	Gradual	Intermittent	Sudden
0%	2.93	2.12	1.63
5%	3.20	2.25	2.03
10%	3.42	2.45	2.33

15%	3.59	3.16	2.93
20%	3.69	3.44	3.30
25%	3.93	3.89	3.79
30%	2.85	2.45	1.53

Table A36. Detailed experimental data set 36

Fly ash (%)	Gradual	Intermittent	Sudden
0%	1.86	1.71	1.44
5%	2.24	2.18	2.00
10%	2.77	2.26	2.11
15%	2.85	2.78	2.59
20%	3.31	3.21	2.78
25%	3.59	3.47	2.83
30%	2.80	2.33	1.42

Table A37. Detailed experimental data set 37

Fly ash (%)	Gradual	Intermittent	Sudden
0%	1.70	1.10	1.00
5%	1.90	1.40	1.30
10%	2.10	1.70	1.50
15%	2.80	2.60	2.50
20%	2.80	2.70	2.60
25%	3.10	3.10	2.80
30%	2.60	2.20	1.30

Table A38. Detailed experimental data set 38

Fly ash (%)	Gradual	Intermittent	Sudden
0%	4.47	4.40	4.33
5%	4.87	4.80	4.60
10%	4.93	4.87	4.80
15%	5.13	4.93	4.87
20%	5.27	5.13	4.93
25%	5.60	5.40	5.27
30%	5.53	5.20	5.13

Table A39. Detailed experimental data set 39

Fly ash (%)	Gradual	Intermittent	Sudden
0%	4.20	4.07	3.93
5%	4.67	4.60	4.53
10%	4.80	4.73	4.67
15%	4.93	4.80	4.73
20%	5.27	5.00	4.87
25%	5.40	5.20	5.07
30%	5.00	5.00	4.93

Table A40. Detailed experimental data set 40

Fly ash (%)	Gradual	Intermittent	Sudden
0%	3.67	3.60	3.47
5%	4.27	4.07	3.80
10%	4.40	4.20	4.07
15%	4.60	4.47	4.33
20%	4.93	4.80	4.73
25%	5.13	5.07	4.87
30%	5.00	4.80	4.47

Table A41. Detailed experimental data set 41

Fly ash (%)	Gradual	Intermittent	Sudden
0%	3.00	2.93	2.80
5%	3.47	3.40	3.33

10%	3.60	3.47	3.40
15%	3.87	3.60	3.47
20%	4.67	4.40	3.80
25%	4.93	4.80	4.40
30%	4.67	4.53	4.27

Table A42. Detailed experimental data set 42

Fly ash (%)	Gradual	Intermittent	Sudden
0%	2.50	2.40	2.00
5%	2.70	2.50	2.20
10%	3.20	2.90	2.30
15%	3.30	3.10	2.40
20%	4.20	4.00	2.60
25%	4.70	4.40	2.90
30%	4.50	4.20	2.60

Table A43. Detailed experimental data set 43

Observation	Compressive	Split tensile	Flexural
Effect of increasing temperature	Strong reduction	Strong reduction	Strong reduction
Effect of gradual cooling	Highest residual values	Highest residual values	Highest residual values
Effect of sudden cooling	Lowest residual values	Lowest residual values	Lowest residual values
Favourable replacement level	25%	25%	25%

Table A44. Detailed experimental data set 44

Replacement	General response at moderate temperature	General response at severe temperature
0%	Reference	Reference deterioration
5%	Small improvement	Limited improvement
10%	Moderate improvement	Improved retention
15%	High improvement	Improved retention
20%	High improvement	Improved retention
25%	Highest overall improvement	Highest overall retention
30%	High but below 25%	Competitive but below 25%

Table A45. Detailed experimental data set 45

Temperature	Thermal severity	Residual response
200°C	Moderate	High residual mechanical capacity
400°C	Moderate-to-high	Good residual capacity
600°C	High	Pronounced

		deterioration begins
800°C	Very high	Severe strength loss
1000°C	Extreme	Very low residual compressive capacity

Table A46. Detailed experimental data set 46

Mechanism	Gradual	Intermittent	Sudden
Surface temperature change	Slow	Repeated moderate	Rapid
Thermal gradient	Low	Moderate	High
Thermal shock	Low	Moderate	High
Residual strength	Highest	Intermediate	Lowest

Table A47. Detailed experimental data set 47

Structural consideration	Relevant test	Interpretation
Compression capacity	Compressive strength	Residual matrix capacity
Crack resistance	Split tensile strength	Integrity of tensile path
Bending response	Flexural strength	Integrity of tensile zone
Post-fire condition	All three	Combined residual assessment

Table A48. Detailed experimental data set 48

Property	Best replacement	Best cooling	Critical temperature range
Workability	Base mixture	Not applicable	Fresh-state
Compressive strength	25% FA	Gradual	600–800°C transition
Split tensile strength	25% FA	Gradual	600–800°C transition
Flexural strength	25% FA	Gradual	600–800°C transition

Table A49. Detailed experimental data set 49

Assessment parameter	Engineering significance
Residual compressive strength	Indicator of remaining compression capacity
Residual split tensile strength	Indicator of cracking and interface integrity
Residual flexural strength	Indicator of bending and tensile-zone performance
Cooling regime	Important component of post-heating history
Fly ash replacement	Material variable affecting residual performance

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