Strength Characteristics of Concrete Exposed to Elevated Temperatures and Cooled Under Different Regimes

Subhash C. Yaragal[1], K S Babu Narayan[2] and Adari S[3]
[1,2]Professors, [3]Post Graduate Student, Department of Civil Engineering, National Institute of Technology, Karnataka, Surathkal, PO Srinivasnagar – 575025, Karnataka State, INDIA. email: subhashyaragal@yahoo.com

ABSTRACT
Concrete loses strength in the event of accidental fires. The residual strength of normal strength concrete is of vital importance for ascertaining serviceability of buildings after the event of fires. Strength loss in concrete is dependent on the temperature of exposure, its duration and the way it gets cooled. In this study concrete cubes of size 100 mm have been cast for M25 grade of concrete, 28 days water cured. The specimens were subjected to elevated temperatures of 150°C, 250°C, 350°C, 450°C and 550°C with a retention period of 1 hour. After 1 hour of exposure, specimens were allowed to cool under different cooling regimes to ambient temperature. Later their appearance, colour and cracks were observed and also weight losses were determined. Further, destructive tests were conducted to estimate residual compressive and split tensile strengths. Important performance changes have been presented and discussed. Split tensile strengths are related to compressive strengths for all the cases of cooling regimes.

Keywords: Concrete, Fire, Elevated temperatures, Compressive strength, Cooling regimes

1. INTRODUCTION
Concrete at elevated temperatures is sensitive to the temperature level, heating rate, thermal cycling and temperature duration (as long as chemical and physical transformations occur). Its mechanical properties such as strength, modulus of elasticity decrease remarkably and this results in structural quality deterioration of concrete. Unless large temperature differentials develop (as in rapid heating), the compressive strength of concrete at elevated temperatures is usually maintained up to 300°C. However, above this temperature, significant decrease in strength can be anticipated. The magnitudes of the decrease depends on the nature of the aggregate and the initial moisture content of the specimen. The changes in strength have been attributed to a combination of decomposition of the hydrated pastes, deterioration of the aggregates and the thermal incompatibilities between paste and aggregate leading to stress concentrations and micro cracking.

When exposed to high temperature, the chemical composition and physical structure of the concrete change considerably. The dehydration, such as the release of chemically bound water from the calcium silicate hydrate (CSH), becomes significant above about 110°C. The dehydration of the hydrated calcium silicate and the thermal expansion of the aggregate increase internal stresses and from 300°C micro cracks are induced through the material, Hertz K D (2005). [$Ca(OH)_2$], which is one of the most important compounds in cement paste, dissociates at around 530°C resulting in the shrinkage of concrete, Ivan Janotka et al. (2005).

Unravelling the heating history of concrete and different cooling regimes is important to forensic research or to determine whether a fire-exposed concrete structure and its components are still structurally sound or not. There are many ways to extinguish fire. Fire is generally extinguished by water and CaO turns into $Ca(OH)_2$ causing cracking and crumbling of concrete. Therefore, the effects of high temperatures are generally visible in the form of surface cracking and spalling. Some changes in colour may also occur during the exposure. The alterations produced by high temperatures are more evident when the temperature surpasses 500°C. Most changes experienced by concrete at this temperature level are considered irreversible. CSH gel, which is the strength giving compound of cement paste, decomposes further above 600°C. As a result, severe micro structural changes are induced and concrete loses its strength and durability.

Shrinkage may also start due to the decomposition of $CaCo_3$ into Co_2 and CaO with volume changes causing destructions. Consequently, elevated temperatures and fire may cause aesthetic and functional deteriorations to the buildings. Aesthetic damage is generally easy to repair while functional impairments are more profound and may require partial or total repair or replacement, depending on their severity.

A.F. Bingol and R. Gul (1998) have reported the compressive strength of normal strength concrete at elevated temperatures up to 700°C and the effect of cooling regimes were investigated and compared. Thus, two different mixture groups with initial strengths of 20 MPa and 35 MPa were produced by using river sand, normal aggregate and Portland cement. Thirteen different temperature values were chosen from 50 to 700°C. The specimens were heated for 3 hours at each temperature. After heating, concretes were cooled to room temperature either in water rapidly or in laboratory conditions gradually. After 400°C, both type of concrete lost their strength rapidly and the strength loss was more in water-cooled specimen when compared to air cooled.

Xin Luo and Wein Sun (2000) have reported that high performance concrete is worse when compared with normal strength concrete after being subjected to different high temperatures of 800°C and 1100°C and subjected to cooling regimes of gradual and rapid cooling. Deterioration of compressive strength of the concrete was measured. The results obtained showed that the strength of both the HPC and NSC reduced sharply after their exposure to high temperatures. Thermal shock due to rapid cooling caused a bit more deterioration in strength than in the case of gradual cooling without thermal shock. A. M. K. Abdelalim and G. E. Abdel (2009) reported that CO_2 powder cooling regime provided the least damage to the concrete after exposure to fire while water cooling regime was the worst of the studied cooling regimes.

In this paper, the performance of concrete when subjected to elevated temperatures and when cooled under various regimes is analyzed and discussed.

2. MATERIALS AND TEST FACILITY

Economical mix proportions have been obtained from trial mixes to obtain slump value in the range of 75–100 mm. The properties of Ordinary Portland Cement, fine and coarse aggregates are detailed below.

Ordinary Portland Cement 43 grade was used for preparing the concrete specimens. The chemical composition of the cement is given in table 1. The mix proportion is given in table 2. River sand conforming to zone 3 (I.S 383-1970 grading requirements) with specific gravity 2.65 was used. Coarse aggregates with specific gravity 2.77 satisfying I.S 383-1970 grading requirements for graded aggregates was used.

Table 1. Chemical composition of cement

Soluble silica (%)	21.6
Alumina (%)	5
Iron oxide (%)	3.7
LIME (%)	63.1
Magnesium (%)	0.8
Insoluble residue (%)	1.8
Sulphur (sulphur trioxide) (%)	2.1
Loss on ignition (%)	2
Chloride content (%)	0.01

Table 2. Mix proportion

Water	Cement	Fine aggregate	Coarse aggregate	
0.45	1	1.198	2.923	
			30% 10 mm = 0.877	70% 20 mm = 2.046

The concrete was mixed in a concrete mixer and poured into moulds of size 100 mm ∞ 100 mm ∞ 100 mm. After 24 hours the concrete cubes were demoulded and cured for 28 days under water. Later the cubes were removed from the curing tank and kept exposed to atmosphere until the day of testing. The measured slump of fresh concrete is 95 mm.

2.1. Electric Furnace Temperature Build-up Curve

Figure 1 shows the furnace temperature build up curve. From Figure 1, it is observed that the temperature build up till 400°C is at a faster rate of 20°C/minute compared to temperature built up above 400°C. Temperature build-up is gradual above 400°C and is at the rate of 7°C/minute.

3. METHODOLOGY

The specimens were subjected to sustained elevated temperatures from 150°C to 550°C in increments of 100°C and in each case retention time was 1 hour. After subjecting to elevated temperature, the cubes were allowed to cool under different cooling regimes. Physical observation of appearance, colour and cracks, were noted before the weight loss of specimen was recorded for assessing percentage loss in water absorption. The destructive tests were performed for ascertaining residual compressive and split tensile strength evaluation.

3.1. Specimens Cooling

The six different cooling regimes studied include furnace cooling, sand bath, air cooling, sprinkling water for 5 minutes, sprinkling water for 10 minutes and sudden cooling.

In the furnace cooling, after exposing the cubes to the designated temperature they were allowed to cool in the furnace itself till the room temperature was reached. In the sand bath cooling regime, after exposing the cubes to the required temperature, they were removed from the furnace and placed in a box with sand at the bottom. The box was immediately filled with sand. For air curing, cubes after exposure were removed and were kept exposed to the ambient atmosphere till the room temperature is

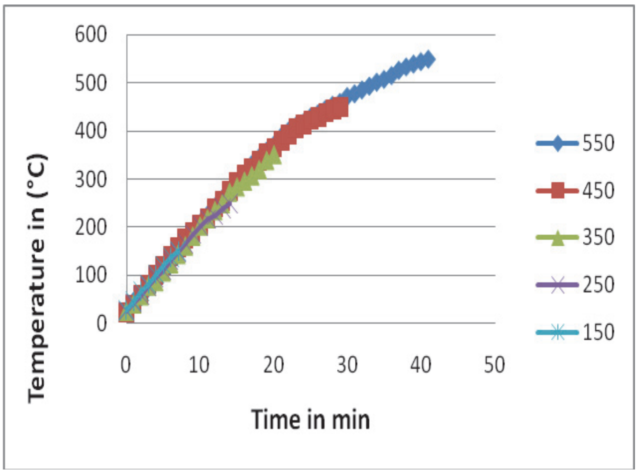

Figure 1. Time temperature build-up curve for the furnace.

reached. Cooling by sprinkling water involved a constant continuous discharge using jet spray water for either 5 minutes or 10 minutes. For sudden cooling in water, after exposing the cubes to the required temperature, they were removed from the furnace and were placed in the tub of water which was allowed to cool till room temperature.

4. RESULTS AND DISCUSSION

The specimens were closely examined for their physical properties like dimensions, spalling and colour before and after exposure and cooling. Important results relating to loss in weight and loss in strength for various cooling regimes is presented and discussed.

4.1. Physical Properties of Specimen

4.1.1. General

Physical observations were conducted before subjecting the specimen for destructive testing such as change in colour, surface cracking, and amount of spalled surface and presence of surface voids. This will provide some reference for structure in real time. Therefore by combining changes in rules of strength, colour, and temperature during an accidental fire, the residual compressive strength and splitting strengths can be assessed with fair degree of accuracy.

4.1.2. Dimensions of the specimen

Before exposing to elevated temperatures the dimensions of, all the specimen were found to be within the tolerance limits specified in the relevant IS codes (IS: 516-1959, IS: 5816-1999). The specimen revealed excellent physical appearance without honeycombing or any defect before exposure. After exposure to elevated temperatures there was no significant distortion of the specimen, is observed but however for the specimen which were kept at 550°C, a small amount of deterioration of concrete at the edges and corners was observed (smudged corners and edges).

4.1.3. Spalling and surface colour

The change of concrete colour can be attributed to the change in texture and composition, expansion and crystal destruction during a fire. The variation of the colours under rising temperature can be identified under two main categories. At 150°C, the concrete colour doesn't change noticeably. When temperatures are increased up to 450°C–550°C concrete colour slightly changed to dust colour or brownish/ yellowish grey.

4.2. Loss in Weight of Specimen

Initial specimen weights were taken after 28 days of water curing. After exposure to various elevated temperatures and cooled under different cooling regimes. They were then dried and later, the weights of the specimen were recorded to determine the percentage loss in weight. Table 3 presents the results for all the cases.

Table 3. Variation in percentage loss in weight for exposure and different cooling regimes

Temperature (°C)	Furnace cooling	Sand bath cooling	Air cooling	Sprinkling water for 5 minutes	Sprinkling water for 10 minutes	Sudden cooling in water
150	5.3	5.1	4.9	4.5	4.4	4.3
250	5.8	5.4	5.3	4.9	4.8	4.7
350	7.2	6.3	6.1	5.7	5.4	5.3
450	7.4	6.8	6.7	6.3	5.9	5.8
550	7.7	7.4	7.0	6.9	6.7	6.6

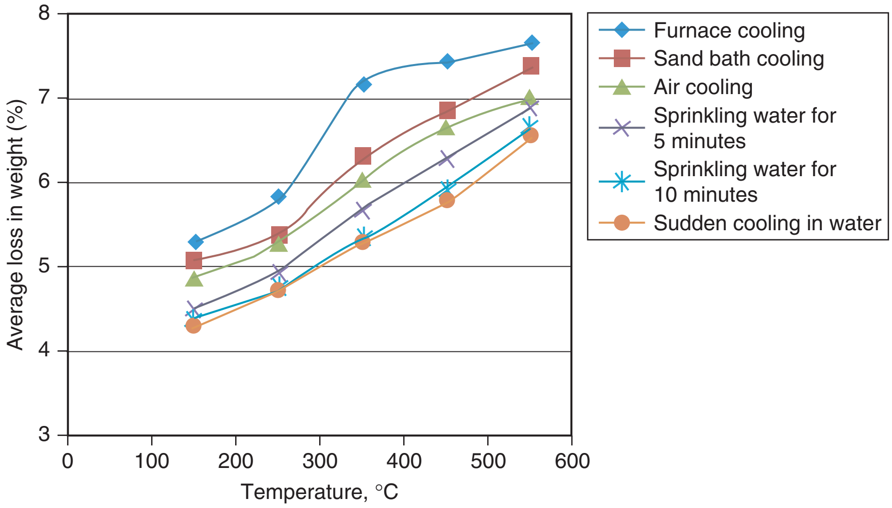

Figure 2. Variation in percentage loss in weight for exposure and cooled under various regimes, with temperature.

From Table 3 and Figure 2, for furnace cooling, it is observed that 69.1% of total weight loss occurs when exposed to 150°C. The remaining 30.9% weight is lost, as 7%, 17.6%, 3.4% and 2.9% for temperature changes of 150°C to 250°C, 250°C to 350°C, 350°C to 450°C and 450°C to 550°C respectively.

For sand bath cooling, it is observed that 68.8% of the total weight loss occurs when exposed to 150°C. The remaining 31.2% weight is lost, as 4.2%, 12.4%, 7.3% and 7.3% for temperature changes of 150°C to 250°C, 250°C to 350°C, 350°C to 450°C and 450°C to 550°C respectively.

For air cooling, it is observed that 69.3% of the total weight loss occurs when exposed to 150°C. The remaining 30.7% weight is lost, as 5.6%, 11.2%, 8.6% and 5.3% for temperature changes of 150°C to 250°C, 250°C to 350°C, 350°C to 450°C and 450°C to 550°C respectively.

For cooling by sprinkling water for 5 minutes, it is observed that 65.0% of the total weight loss occurs when exposed to 150°C. The remaining 35.0% weight is lost, as 6.4%, 10.8%, 8.8% and 9.0% for temperature changes of 150°C to 250°C, 250°C to 350°C, 350°C to 450°C and 450°C to 550°C respectively.

For cooling by sprinkling water for 10 minutes, it is observed that 65.8% of the total weight loss occurs when exposed to 150°C. The remaining 34.2% weight is lost, as 5.6%, 8.8%, 8.7% and 11.1% for temperature changes of 150°C to 250°C, 250°C to 350°C, 350°C to 450°C and 450°C to 550°C respectively.

For the case of sudden cooling, it is observed that 65.9% of total weight loss occurs when exposed to 150°C. The remaining 34.1% weight is lost, as 6.3%, 8.6%, 7.4% and 11.8% for temperature changes of 150°C to 250°C, 250°C to 350°C, 350°C to 450°C and 450°C to 550°C respectively.

It is seen that 4.0% to 8.0% of total weight loss occurs when exposed to 150°C to 550°C under different cooling regimes. The maximum weight loss is observed in the case of furnace cooling and minimum weight loss is observed for the case of sudden cooling.

4.3. Residual Compressive Strength

Following Table 4 shows the consolidated relative residual compressive strength of concrete cubes after exposure and subsequent cooling under various regimes.

From Table 4 and Figure 3, it is observed that the residual coefficient of compressive strength of cubes exposed to 150°C is slightly higher by about 8% than, that of cubes tested at normal room temperature. This is mainly because, at earlier elevated temperatures the moisture content in the cubes

Table 4. Relative residual compressive strength of NSC cubes after exposure to elevated temperatures and cooled under different regimes

Temperature (°C)	Furnace cooling	Sand bath cooling	Air cooling	Sprinkling water for 5 minutes	Sprinkling water for 10 minutes	Sudden cooling in water
Room	1.00	1.00	1.00	1.00	1.00	1.00
150	1.08	1.05	0.96	0.95	0.94	0.91
250	0.94	0.91	0.90	0.86	0.83	0.77
350	0.91	0.87	0.82	0.80	0.78	0.71
450	0.80	0.76	0.71	0.70	0.65	0.59
550	0.64	0.62	0.60	0.56	0.50	0.45

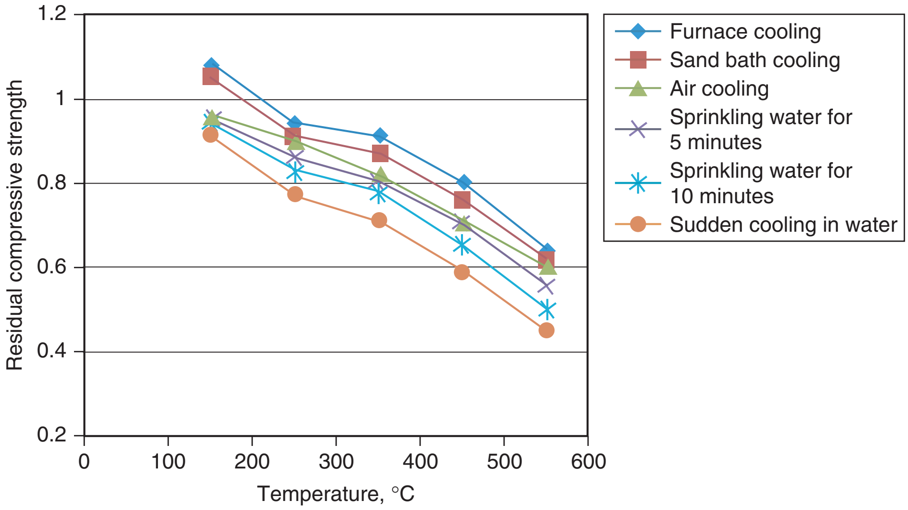

Figure 3. Variation in relative residual compressive strength for different cooling regimes, with temperature.

gets converted to vapour pressure (steam), which contributed to the additional compressive strength than that of strength at room temperature as observed by Saava et al. (2005), Metin Husem (2005), Y Xu et al. (2003), Emre sancak (2008). This effect is called as autoclaving effect.

On further increase of temperature there is loss in compressive strength gradually, as compared to strength at room temperature due to loss of moisture content and disintegration of hydrated cement paste. At 250°C the residual coefficient of compressive strength is 0.94, and drops gradually to 0.91, 0.80 and 0.64 at elevated temperatures of 350°C, 450°C and 550°C respectively for the furnace cooling which is gradual.

Further, for the case of sudden cooling, it is observed that the residual coefficient of compressive strength of cubes exposed to 150°C is 0.91 and drops gradually to 0.77, 0.71, 0.59 and 0.45 at elevated temperatures of 150°C, 250°C, 350°C, 450°C and 550°C respectively.

The percentage differences between the two cooling regimes are 17, 17, 20, 21 and 19 respectively for 150°C, 250°C, 350°C, 450°C and 550°C. On an average 20% change is reported for temperatures of 350°C and above.

The results of other four intermediate cooling regimes, show that the intensity of thermal shock is in order and hence strength loss is in order of furnace cooling, sand bath, air, sprinkling water for 5 minutes, sprinkling water for 10 minutes and sudden cooling conditions.

4.4. Residual Split Tensile Strength

Following Table 5 shows the consolidated relative residual split tensile strength of concrete cubes after exposure and subsequent cooling under various regimes.

From Table 5 and Figure 4, it is observed that the residual coefficient of split tensile strength of cubes exposed to 150°C is 0.92 and drops gradually to 0.83, 0.75, 0.65 and 0.52 at elevated temperatures of 250°C, 350°C, 450°C and 550°C for the case of furnace cooling where the thermal shock is gradual.

Further, for the case of sudden cooling, it is observed that the residual coefficient of split tensile strength of cubes exposed to 150°C is 0.43 and drops gradually to 0.37, 0.31, 0.27 and 0.24 at elevated temperatures of 250°C, 350°C, 450°C and 550°C, for this case thermal shock is sudden.

The percentage difference between the two extreme cooling regimes are 49, 46, 44, 38 and 28 respectively for 150°C, 250°C, 350°C, 450°C and 550°C. There is a decreasing variation from 50% to nearly 30% for temperature change of 150°C to 550°C.

4.5. Relationship Between Compressive Strength and Split Tensile Strength

Figures 5 (a) to (f) presents a graph between residual split tensile strength to residual compressive strength of concrete for all the cooling regimes reported. The prediction equation for each case is also presented.

The error in prediction of split tensile strength from compressive strength by the proposed equation is presented for the case of furnace cooling in Table 6 below. The observed maximum error in prediction is found to be 4.3%.

Table 5. Relative residual split tensile strength coefficient of NSC cubes after exposure to elevated temperatures and cooled under different regimes

Temperature (°C)	Furnace cooling	Sand bath cooling	Air cooling	Sprinkling water for 5 minutes	Sprinkling water for 10 minutes	Sudden cooling in water
Room	1.00	1.00	1.00	1.00	1.00	1.00
150	0.92	0.84	0.72	0.63	0.56	0.43
250	0.83	0.75	0.67	0.57	0.54	0.37
350	0.75	0.61	0.57	0.46	0.39	0.31
450	0.65	0.59	0.45	0.39	0.35	0.27
550	0.52	0.46	0.37	0.33	0.29	0.24

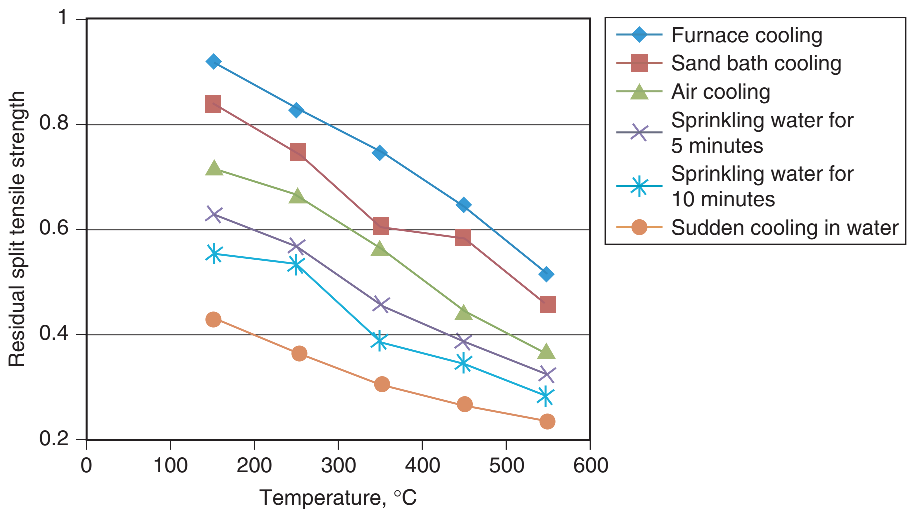

Figure 4. Variation in relative residual split tensile strength for different cooling regimes, with temperature.

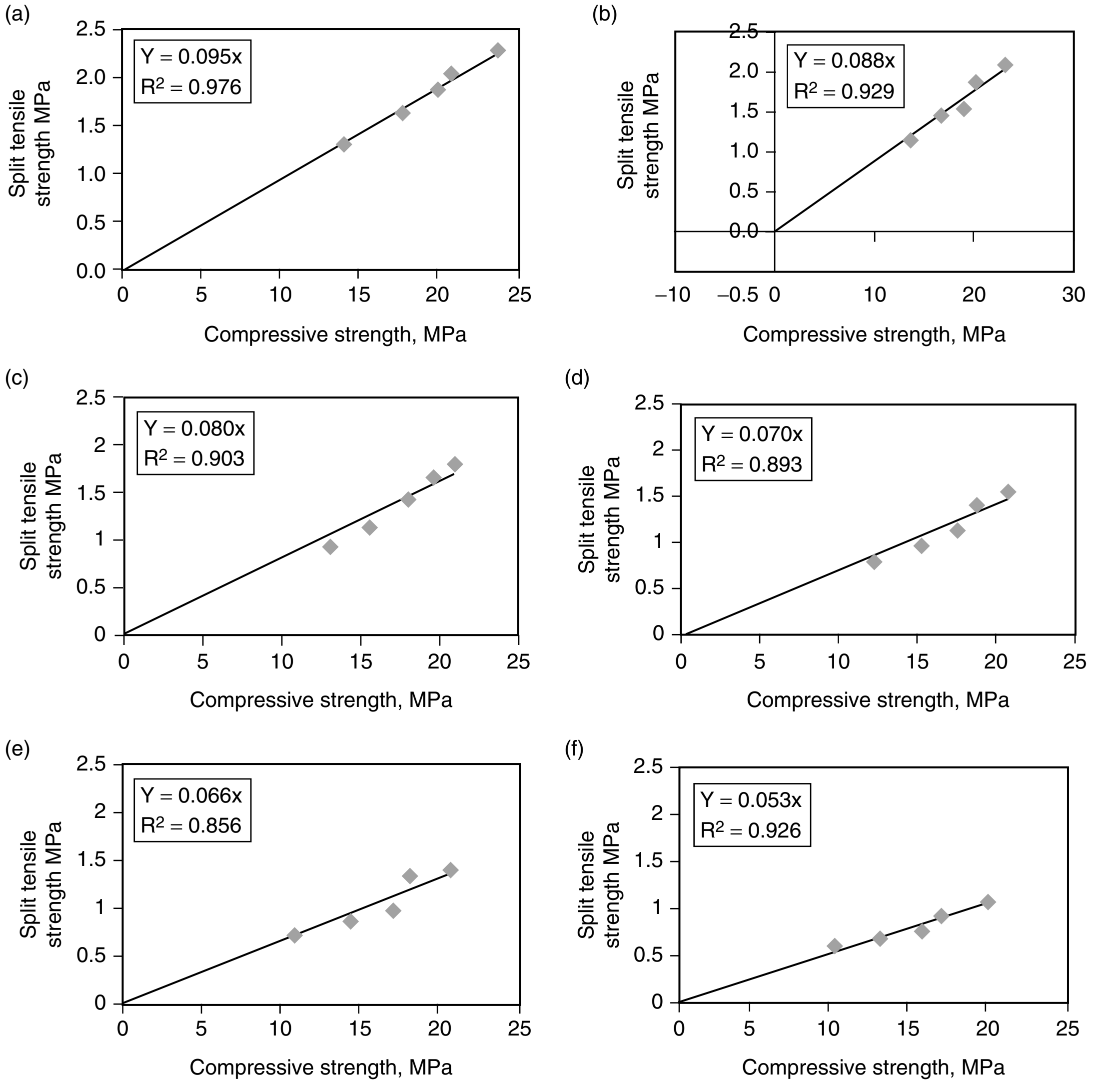

Figure 5. (a)-(f) Relationship between residual split tensile strength to residual compressive strength for all the cooling regimes in order.

Table 6. Comparison of actual split tensile strength of concrete and split tensile strength from predicted equation for the case of furnace cooling

Temperature (°C)	Compressive strength from destructive test (MPa)	Split tensile strength from destructive test (MPa)	Split tensile strength from prediction (MPa)	Absolute deviation in prediction (%)
150	23.63	2.29	2.27	0.9
250	20.62	2.06	1.98	3.9
350	19.86	1.88	1.90	1.0
450	17.60	1.62	1.69	4.3
550	13.96	1.30	1.34	3.1

Table 7. Absolute error in split tensile strength prediction from proposed equations for various regimes of cooling at different exposure temperatures

	Absolute deviation in prediction, (%)				
Temperature (°C)	Sand bath cooling	Air cooling	Sprinkling water for 5 minutes	Sprinkling water for 10 minutes	Sudden cooling in water
150	2.9	5.6	6.4	3.5	0.9
250	5.9	5.4	6.3	10.4	2.2
350	9.2	0.7	8.8	15.3	9.2
450	0.7	11.6	10.2	9.2	1.5
550	4.0	15.6	6.2	1.4	11.7

Similar analysis of results as in Table 6, is also carried out for the cases of the remaining cooling regimes studied. The error in prediction of tensile strength from compressive strength at various exposure temperatures for the cooling regimes is presented in Table 7.

5. CONCLUSIONS

(1) The total percentage weight loss of the specimen increases as the exposure temperature increases, for all the cases of cooling regimes, however this is maximum for furnace cooled and minimum for sudden cooling. The range of variation is from 4.0 to 8.0%.

(2) The residual coefficient of compressive strength decreases with increase in temperature except at early elevated temperature around 150°C due to autoclaving effect under furnace cooling.

(3) Rate of loss in strength of concrete is highly dependent on the type of cooling regimes. The loss of compressive and split tensile strength is minimum under furnace cooling as the heat gradient is gradual and maximum under sudden cooling, as the thermal shock is sudden.

(4) The loss in compressive strength at 550°C, is 35% and 55% for the cooling regimes of furnace and sudden respectively.

(5) Predictive equations for ascertaining split tensile strengths from compressive strengths are proposed for all the cases of cooling regimes studied.

REFERENCES

[1] A. F. Bingol. and Rustem Gul, 2008, Effect of elevated temperatures and cooling regimes on normal strength concrete, *Fire and Materials* Vol. 33, pp. 79–88.

[2] A. M. K. Abdelalim and G.E. Abdel-Aziz, 2009, Effect of elevated fire temperature and cooling regime on the fire resistance of normal and self-compacting concretes, *Engineering Research Journal*, Vol. 122, pp. 63–81.

[3] Ivan Janotka, Terezia Nurnbergerov, 2005, Effect of temperature on structural quality of the cement paste and high-strength concrete with silica fume, *Nuclear Engineering and Design* 235, pp. 2019–2032.

[4] K. D. Hertz, 2003, Limits of spalling of fire-exposed concrete, *Fire Safety Journal*, Vol. 38, Issue 2, pp. 103–116.

[5] Sammy Yin Nin Chan, Xin Luo, Wei Sun, 2000, Effect of high temperature and cooling regimes on the compressive strength and pore properties of high performance concrete, *Construction and Building Materials*, Vol. 14, pp. 261–266.

[6] Savva A, Manita P and Sideris K K, 2005, Influence of elevated temperatures on the mechanical properties of blended cement concretes prepared with limestone and siliceous aggregates, *Cement and Concrete Composites*, Vol. 27, 239–248.

[7] Y Xu, Y L Wong, C S Poon and M Anson, 2003, Influence of PFA on cracking of concrete and cement paste after exposure to high temperatures, *Cement and Concrete Research*, Vol. 33, 2009–2016.

[8] Xin Luo, Wei Sun, Sammy Yin Nin Chan, 2000, Effect of heating and cooling regimes on residual strength and microstructure of normal strength and high-performance concrete", *Cement and Concrete Research*, Vol. 30, pp. 379–383.