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# Strength loss contributions during stages of heating, retention and cooling regimes for concretes

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**Abstract.** Concrete suffers strength loss when subjected to elevated temperatures during an accidental event such as fire. The loss in strength of concrete is mainly attributed to decomposition of C-S-H gel and release of chemically bound water, which begins when the temperature exceeds 500˚C. But it is unclear about how much strength loss occurs in different stages of heating, retention and cooling regimes. This work is carried out to separate the total strength loss into losses during different stages of heating, retention and cooling. Tests were carried out on both Ordinary Portland Cement (OPC) based concrete and Ground Granulated Blast Furnace Slag (GGBFS) blended concrete for 200˚C, 400˚C, 600˚C and 800˚C with a retention period of 1 hour for each of these temperature levels. Furnace cooling was adopted throughout the experiment. This study reports strength loss contribution during heating, retention and cooling regimes for both OPC based and GGBFS based concretes.

**Keywords:** heating; retention; cooling; strength loss; blended concrete

## 1. Introduction

Concrete is the most widely accepted construction material. Its characteristics such as mouldability and high compressive strength have made it a versatile building material. Concrete offers good resistance to heat because of its low conductivity and incombustible nature and further, no toxic fumes are emitted from concrete surface when it is heated. Because of all these characteristics concrete can be rated as the best building material as far as resistance to elevated temperature is concerned.

Concrete is possibly exposed to elevated temperatures during fire accidents or when it is near to furnaces and reactors. The mechanical properties such as strength, modulus of elasticity and volume stability of concrete are significantly reduced during these exposures. This may result in undesirable structural failures. Therefore, the properties of concrete retained after a fire are of vital importance for determining the load carrying capacity and for reinstating fire-damaged structures.

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Fire resistance of concrete is affected by many factors, including constituent materials such as the type of aggregate and cement used in its composition, size of structural members and moisture content of concrete. The other factors include rate of heating, maximum temperature attained, duration of exposure at the maximum temperature, method of cooling after the maximum temperature is reached and the level of applied load. The influence of elevated temperatures on the mechanical properties of concrete is more important for fire resistance studies. Heat-resistant materials are increasingly being used for structural purposes. The need for such building materials is of particular interest in chemical and metallurgical industries and also for the thermal shielding of nuclear plants. In such installations structural members may be subjected to sustained and cyclic thermal exposures at the lower heat levels, at which the use of refractory materials is not essential. Concrete generally resists the effects of high temperatures, but in some cases it is aimed to produce concrete which is more resistant to fire, as a functional requirement.

An assessment of degree of deterioration of the concrete structure after exposure to high temperatures can help engineers decide whether structure could be repaired or to be demolished. There are already several publications that deal with the residual strength of concrete. But it is unclear regarding how much strength is lost in the heating stage, heat retention stage (soaking) and cooling stage separately. Most of the works have focused attention on total strength loss in concrete at elevated temperatures. The objective here was to work out a method to separate the total loss into three sub-heads that is in heating, in retention and during cooling stages. Performing this separation for different grades of concrete at several temperatures and at different heating rates, cooling rates and retention periods, can actually give a very useful database to understand the loss in compressive strength at any specified time of thermal exposure without any ambiguity. This clear information enables one to decide the correct type of repair work to be under-taken. The present work is an attempt in this direction.

## 2. Experimental methodology

### *2.1 Normal concrete*

Cement used was 43 grade ordinary Portland cement. The nominal mix proportion used was 1:2:4. The river sand used had a specific gravity of 2.65 and classified as zone 3. 50% of coarse aggregate of size less than 20 mm and remaining 50% of size less than 12.5 mm was used which gave well graded aggregates, with specific gravity of 2.69. Water cement ratio of 0.48 was chosen. The concrete was mixed in a concrete mixer and poured into moulds of size 100 mm ×100 mm × 100 mm and were compacted by table vibration. The cubes were demoulded after 24 hours and cured for 28 days in water. Cubes were taken out of the curing tank after 28 days and kept outside for some time to dry, after which they were used for further experiments.

### *2.2 Blended concrete*

Concrete blended with GGBFS was made with the same nominal mix proportion of 1:2:4. 30% of cement was replaced with GGBFS. Mixing, placing, demoulding and curing followed are the same as discussed above for normal concrete.

Fig. 1 Programmable electric furnace

### *2.3 Methodology*

Exposure studies were carried out using electric furnace as shown in Fig. 1. Tests were carried out for 200℃, 400℃, 600℃ and 800℃. For each temperature, four different tests were carried out. Three specimens were taken for each testing and an average value was taken as the final result. The four tests are:

*Test 1*: Finding the compressive strength of the cubes without exposing to elevated temperatures, for reference.

*Test 2*: Finding the residual compressive strength of the cube as soon as it reaches the desired elevated temperature. For this, the furnace is switched off as soon as the cubes reach the desired temperature and the door is opened. The cubes are handled using long forceps and tested under the compression testing machine, immediately.

*Test 3:* Finding the residual compressive strength of the cubes after a retention period of 1 hour. The procedure adopted is same as explained in Test 2.

*Test 4:* Finding the residual compressive strength of the cubes after they have undergone a complete cycle of heating, retention and cooling to the room temperature in the specified rates.

The difference in the residual strengths of Test 2 and Test 1, gave the value of the loss in strength during the heating stage. The difference in the residual strength of Test 3 and Test 2 gave the value of the loss in the strength during the retention period. The difference in the residual strength of Test 4 and Test 3 gave the value of the loss in strength during the cooling stage.

## 3. Results and discussion

### *3.1 Standardization of electric furnace operating conditions*

#### *3.1.1 Furnace performance with no charge*

In order to understand the behaviour of the working of the furnace, it was operated for various temperatures (200℃, 400℃, 600℃, 800℃). To decide the rate of heating to be chosen, the maximum rate of heating of the furnace was observed. Any rate less than the maximum rate of heating of the furnace is acceptable. Theoretically the solution for this is to set the rate of heating as infinity i.e.; time for heating has to be set as zero. Practically the time for heating was set to a minimum value of 1 minute and retention period was arbitrarily set as 1 hour so that the heater does not automatically switch off after 1 minute. The maximum rate of heating experiment was carried out for 800℃. The experiment was carried out with no charge. This is presented in Fig. 2.

It was found that rate of heating was more up to 400℃ and then at a slower rate up to 800 ℃. A rate slower than the maximum rate of heating was assigned for different temperatures. An arbitrary cooling rate was assigned for different temperatures and furnace performance was checked. A retention period of 1 hour was assigned for each case. The experiments were carried out with no charge.

A total of 8 different heating or cooling rates can be assigned at a time in the furnace. In order to understand this, a complete cycle of heating, retention and cooling was carried out assigning 8 sets of values for 200℃, 400℃, 600℃ and 800℃.

From the Figs. 3-5, it was found that the furnace was behaving according to the chosen heating and cooling rates almost throughout the cycle. An average value of 9℃/min as the common heating rate and 0.8℃/min as the common cooling rate were chosen for further experiments.

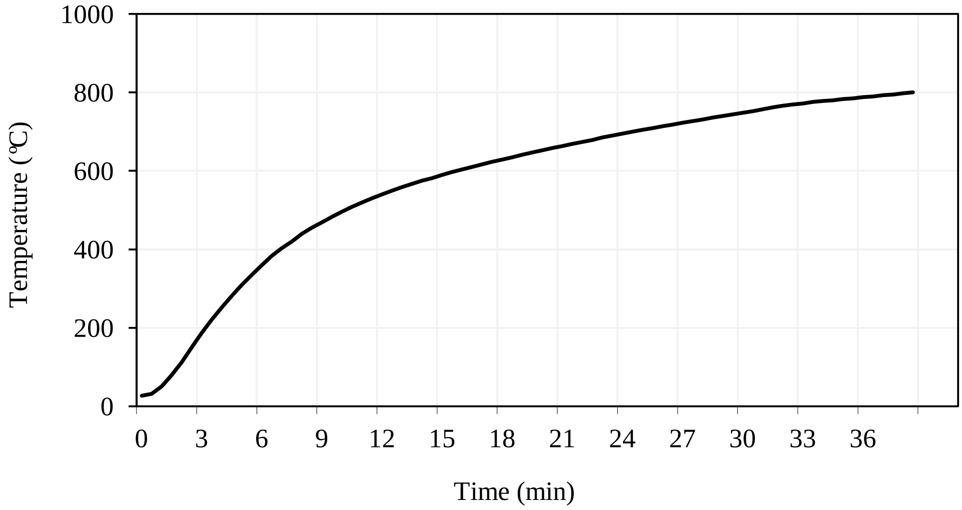


Fig. 2 Maximum rate of heating of furnace with no charge

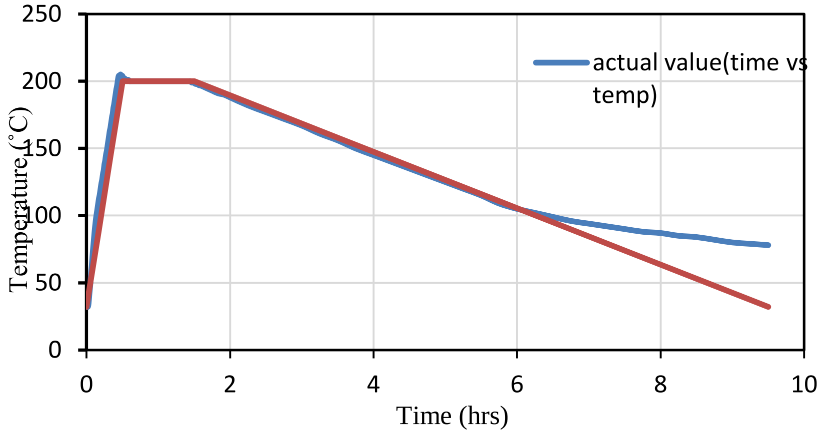


Fig. 3 Furnace performance at 200℃ and no charge

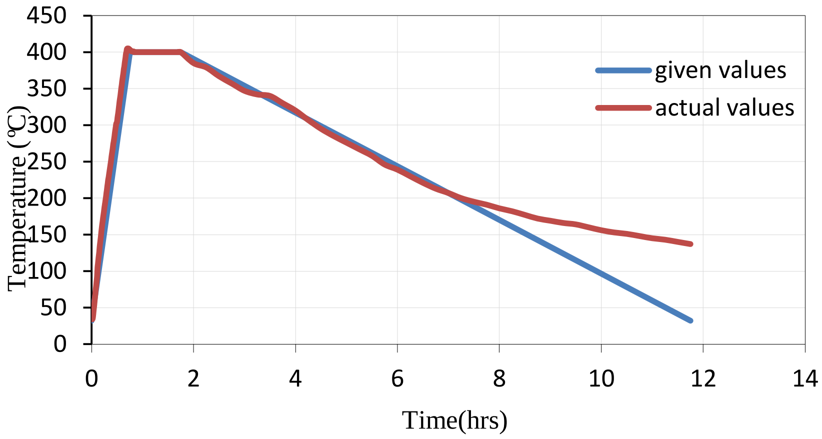


Fig. 4 Furnace performance at 400℃ and no charge

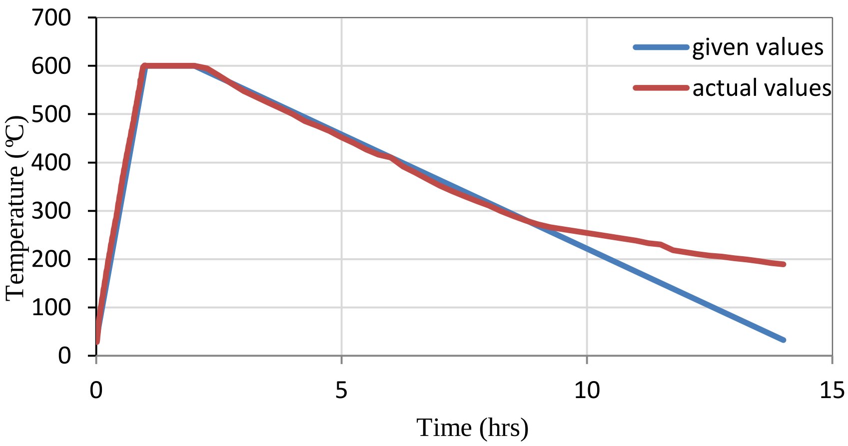


Fig. 5 Furnace performance at 600℃ and no charge

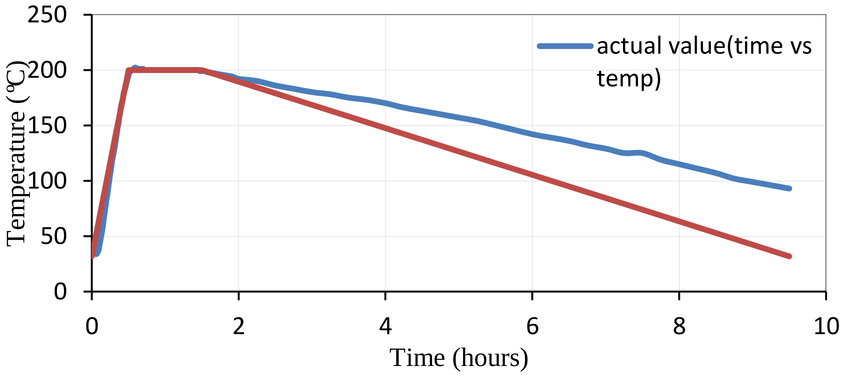


Fig.6 Furnace performance at 200℃ with 40kg charge

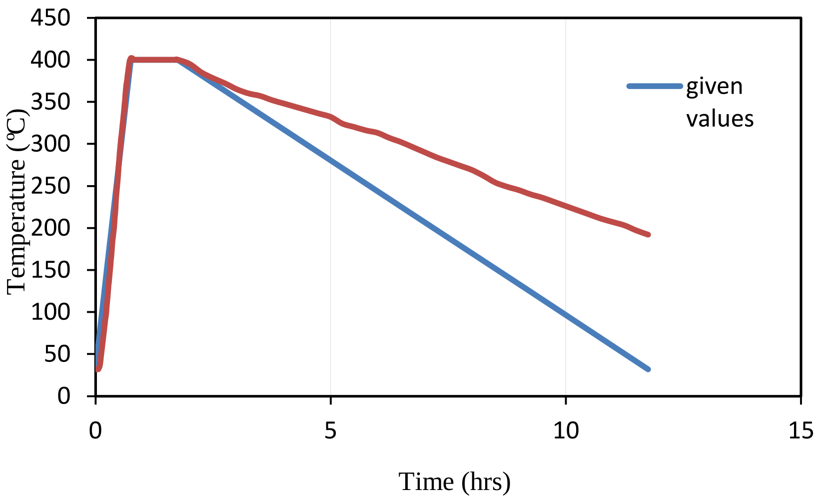


Fig. 7 Furnace performance at 400℃ with 40kg charge

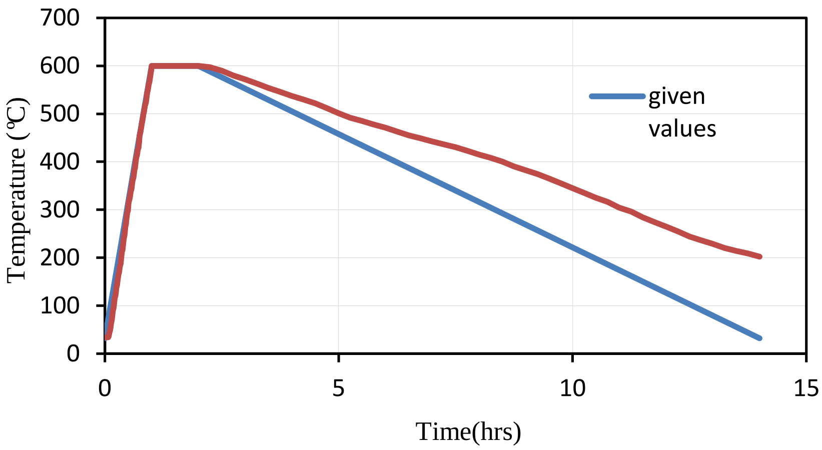


Fig. 8 Furnace performance at 600℃ with 40kg charge

### *3.1.2 Furnace performance with variation in charge*

To study the performance of furnace when it is loaded with concrete cubes, experiments were repeated with 20kg, 40kg and 60kg charge for each experiment. The variation for the case of 40kg charge is presented below in Figs. 6-8.

From the above experiments, it was found that there is a lag in both rising and the cooling limb of the graphs. The lag in the rising limb in more evident in the graph drawn to a larger scale. Whereas the lag in the cooling is very much evident and the lag increases as the charge increases. For 60kg and 40kg (800℃) charge, there is a lag throughout the rising limb whereas for other charges, there is initial lag which gets compensated at the end of the rising limb. That means the furnace has a capacity to heat almost up to 40kg charge without a lag at the end of the rising limb. The rate of heating and cooling tends to slow down as the charge in the furnace increases.

The rate of heating was fixed as 9℃/min and the cooling rate was fixed as 0.8℃/min. It is also reported that as the charge increases, the rate of heating and cooling also decreases. The furnace was found to heat almost up to 40kg charge without a lag at the end of the rising limb.

### *3.1.3 Contributions to strength loss by rising limb, retention period and decay limb*

Here the various strength loss contributions have been explained for both OPC based concrete and GGBFS blended concrete.

### *3.2 OPC based concrete*

Table 1 shows the residual compressive strength of the cubes at different stages of heating and cooling processes.

From the above Table 1, it is observed that for 600℃ and 800℃ a decreasing pattern in their residual compressive strength is evident. Unlike expected, 200℃ and 400℃ show a variation from this pattern. For 200℃, there is an increase in the residual strength after the retention period and in 400℃ there is more or less no change in the residual strength even after heating the cubes to 400℃. Both these results vary from the expected pattern because of a phenomenon called autoclave effect in concrete.

As we know, concrete is a heterogeneous mixture of cement, fine aggregate, coarse aggregate and most importantly water. It is this water that initiates the chemical reaction in cement to form a C-S-H gel. This chemically bonded water which breaks out from the C-S-H gel gets converted to steam at 100℃ and the pores within the concrete gets filled with this steam as the heat rises above

Table 1 Residual compressive strength at different stages (OPC)

| Temp (℃) | Normal strength (MPa) | Residual strength at rising limb end (MPa) | Residual strength at rising+ retention limb end (MPa) | Residual strength at rising + retention and cooling end (MPa) |
|---|---|---|---|---|
| 200 | 47.0 | 44.8 | 51.6 | 44.3 |
| 400 | 44.0 | 44.0 | 43.7 | 34.6 |
| 600 | 47.3 | 40.1 | 38.0 | 28.0 |
| 800 | 45.7 | 30.5 | 26.9 | 08.7 |

Table 2 Loss of strength in percentage (OPC)

| Temp (℃) | Normal strength (%) | Loss in rising limb (%) | Loss in rising+ retention limb (%) | Loss in full cycle (%) |
|---|---|---|---|---|
| 200 | 100 | 4.5 | 9.7 | 5.6 |
| 400 | 100 | 0.0 | 0.6 | 21.4 |
| 600 | 100 | 15.3 | 19.7 | 40.8 |
| 800 | 100 | 33.2 | 41.0 | 81.0 |

Table 3 Total loss split in three stages (OPC)

| Temp (℃) | Normal strength (MPa) | Loss in rising limb (MPa) | Loss in retention limb (MPa) | Loss in cooling limb (MPa) | Total loss (MPa) |
|---|---|---|---|---|---|
| 600 | 47.3 | 7.2 | 2.1 | 10.0 | 19.3 |
| 800 | 45.7 | 15.2 | 3.6 | 18.3 | 37.0 |

Table 4 Percentage of total loss in each stage (OPC)

| Temp (℃) | Loss in rising limb (%) | Loss in retention limb (%) | Loss in cooling limb (%) | Total loss (%) |
|---|---|---|---|---|
| 600 | 39 | 11 | 50 | 100 |
| 800 | 40 | 11 | 49 | 100 |

100℃ within the concrete. Further as the temperature is increased, the pressure within the pores due to the steam keeps building up like the pressure within pressure cooker. So there is an outward pressure from within the pores which resists the external compressive force that we apply on the cubes while testing. This gives a higher compressive strength than expected. It is more evident after the retention period for 200℃ as by that time, heat would penetrate deeper into the cubes and more pores are filled with steam. For 400℃ autoclave effect is predominant in the heating stage as by that time itself heat would penetrate into the cube. But there is not much interference of autoclave effect after retention in 400℃ because thermal cracks start forming at 400℃ and the pore pressure is released through those cracks, giving us the correct value of residual strength.

Table 2 shows the loss of strength in each limb or stage of the experiment i.e., rising limb, retention limb, and cooling limb. Loss in the rising limb is obtained by subtracting residual strength after rising limb from normal strength. Loss in retention period is obtained by subtracting the residual strength after the retention period from the residual strength after the rising limb. Loss in the cooling limb is obtained by subtracting the residual strength after the full cycle from the residual strength after the retention period. All these have been expressed in percentage.

Table 3 presents data for 600℃ and 800℃. The temperatures of 200℃ and 400℃ are not considered, as results are affected by autoclave effect.

Table 4 shows the percentage of the total loss lost in each stage of the experiment. Proper pattern is obtained for 600℃ and 800℃ cases. 200℃ and 400℃ experiments are affected by autoclave effect. What can be observed is that a major share of the total loss occurs during the cooling stage, followed by the heating stage and least is lost during the retention period. Loss in cooling stage is more than heating stage as cooling stage requires more time. As there are evident results that loss is more during heating and cooling stages, it means cracking due to temperature gradient is playing more role in the loss of strength i.e. expansion and contraction. There is also an increase in the loss of strength as the temperature increases. The most important conclusion from Table 4 is that around 40% of the total loss is during the heating stage, around 10% is in the retention period and around 50% of it is in the cooling stage. Explosive spalling was noticed in a few specimens. This may be due to high water content.

### *3.3 GGBFS blended concrete*

Table 5 shows the residual compressive strength of the cubes blended with GGBFS at different stages of heating and cooling processes. GGBFS blended concrete also shows a similar pattern of decreasing compressive strengths for 600℃ and 800℃. Autoclave effect is present in 200℃ and 400℃.

As we know, the maximum strength of GGBFS blended concrete which is more than normal strength of OPC based concrete is attained after 3 months. Therefore the residual strength of matured GGBFS blended concrete after exposure to elevated temperature is expected to be higher than OPC based concrete. Therefore replacing 30% of cement by GGBFS can be considered as a good solution when the fire endurance property is concerned. Here also a similar contribution pattern can be observed. 50% of the total loss is in the cooling limb, 10% of the total loss in the retention period and around 40% of total loss is in the rising limb. Explosive spalling was observed in a few specimens, which may be due to high moisture content. The contributions to strength loss by rising limb, retention limb and cooling limb were found to be almost similar in both OPC based and GGBFS blended concrete.

Table 5 Residual compressive strength at different stages

| Temp (℃) | Normal strength (MPa) | Residual strength after rising limb (MPa) | Residual strength after rising + retention limb (MPa) | Residual strength after full cycle (MPa) |
|---|---|---|---|---|
| 200 | 44.0 | 45.0 | 44.0 | 43.0 |
| 400 | 42.0 | 44.0 | 43.0 | 38.0 |
| 600 | 44.0 | 37.5 | 35.5 | 28.0 |
| 800 | 40.5 | 29.0 | 26.0 | 10.0 |

Table 6 Percentage of total loss in each stage

| Temp (℃) | Loss in rising limb (%) | Loss in retention limb(%) | Loss in cooling limb(%) | Total loss (%) |
|---|---|---|---|---|
| 600 | 41 | 13 | 47 | 100 |
| 800 | 38 | 10 | 52 | 100 |

## 4. Conclusions

Elevated temperature tests at 200℃, 400℃, 600℃ and 800℃ were conducted for OPC based concrete and GGBFS blended concrete. Heating rate of 9℃/min, retention period of 1hour and cooling rate of 0.8℃/min were chosen. From the above experiments, the following conclusions have been drawn,

- Autoclave effect was present for 200℃ and 400℃ cases of experiments. This is due to the presence of high water content which gets converted to steam at 100℃ and at such low temperatures like 200℃ and 400℃, there are not enough cracks for the steam to escape out of the specimen. Proper mix design to find the optimum water content should solve this problem.
- 600℃ and 800℃ followed a similar pattern of decreasing compressive strength at each stage showing the absence of autoclave effect. This means there are enough cracks for the steam to come out of the specimen. This shows extensive cracking that starts at around 500℃.
- In these experiments, major loss of strength occurred during the cooling period. Followed by the heating period. Least strength loss occurred during the retention period.
- Loss of strength due to temperature gradient is predominant in these experiments.
- By conducting similar experiments with different types of concrete, heating up to different temperatures, with different rates of heating, cooling and different retention periods and different cooling regimes, we can actually get a database using which a new case of elevated temperature can be assessed.
- In these experiments, around 50% of the strength loss occurred during the cooling period. Around 40% occurred in the heating stage and only 10% of the strength loss occurred in the 1 hour retention period.

## References


Allen, D.C. and Desai, P.M. (1967), "The influence of aggregate on the behaviour of concrete at elevated temperature", *Nuclear Eng. Des.*, **6**, 65-77.

Arioz, O. (2007), "Effects of elevated temperatures on properties of concrete", *Fire Saf. J.,* **42,** 516-522.

Bingol, A.F. and Gul, R. (2009), "Effect of elevated temperatures and cooling regimes on normal strength concrete", *Fire Mater.,* **33**, 79-88.

Biolzi, L., Cattaneo, S. and Rosati, G. (2008), "Evaluating residual properties of thermally damaged concrete", *Cement Concrete Compos.,* **30**, 907-916.

Culfik, M.S. and Ozturan, T. (2002), "Effect of elevated temperatures on the residual mechanical properties of high –performance mortar", *Cement Concrete Res.*, **32,** 809-816.

Ikponmwosa, E.E. and Salau, M.A. (2010), "Effect of heat on laterised concrete", *Maejo Int. J. Sci. Tech.*, **4**(1), 33-42.

Poon, C.S., Shui, Z.H. and Lam, L. (2004), "Compressive behaviour of fibre reinforced high performance concrete subjected to elevated temperatures", *Cement Concrete Res.*, **34**, 2215-2222.

Toumi, B., Resheidat, M., Guemmadi, Z. and Chabil, H. (2009), "Coupled effect of high temperature and heating time on the residual strength of normal and high –strength concretes", *Jordan J. Civil Eng.,* **3**(4).

Yaragal, S.C., Babu Narayan, K.S., Venkataramana, K., Kulkarni, K.S., Chinnagiri Gowda, H.C., Reddy, G.R. and Sharma, A. (2010), "Studies on normal strength concrete cubes subjected to elevated temperatures", *J. Struct. fire Eng.,* **1**(4), 249-262.

Yaragal, S.C., Babu Narayan, K.S. and Adari, S. (2012), "Strength characteristics of concrete exposed to elevated temperatures and cooled under different regimes", *J. Struct. fire Eng.*, **3**(4), 301-310.