Residual strength in concrete after exposure to elevated temperature

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The loss of concrete strength when exposed to higher temperature and the recovery of lost strength due to rehydration of concrete with time have been studied in a test programme. The concrete has been exposed to four different temperatures for a duration of four hours. The paper presents the details of the test programme, results and also compares the same with earlier investigations carried out abroad. The data will be helpful in assessing the residual strength of concrete after fire and in assessing the structural adequacy of fire-distressed structures.

Damage in concrete structures due to fire depends to a great extent on the intensity and duration of fire. The distress in the concrete manifests in the form of cracking and spalling of the concrete surface. Sometimes, due to severe exposure the reinforcement gets exposed and twisted and the overall stability of the structure becomes doubtful. It then becomes necessary to assess the structural adequacy of such fire-affected structures considering the residual strength of concrete and reinforcing bars.

The residual strength of concrete after a fire is generally less than the original design strength. It is difficult to estimate the reduction in concrete strength in a fire-affected structure. The usual practice for assessment of concrete strength is to conduct several tests like rebound hammer test, ultrasonic pulse velocity test, resonant vibration test and actual compressive strength test of cores taken out from the fire-exposed structures.

Another method of assessing the residual compressive strength is to assess the temperature of exposure to which concrete has been subjected to, and estimate therefrom the loss in compressive strength. This method of assessing the residual compressive strength has been used by investigators in some fire-distressed structures[1,2].

Earlier, various investigators have carried out work on the loss of compressive strength of concrete exposed to high temperature[3,4,5]. The loss of compressive strength of concrete with temperature as obtained by Harada[3] is given in Fig 1.

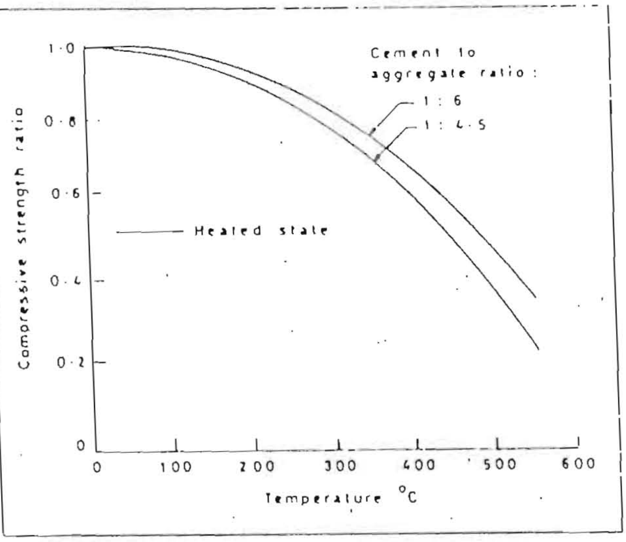

Fig 1 Loss of compressive strength of concrete with temperature

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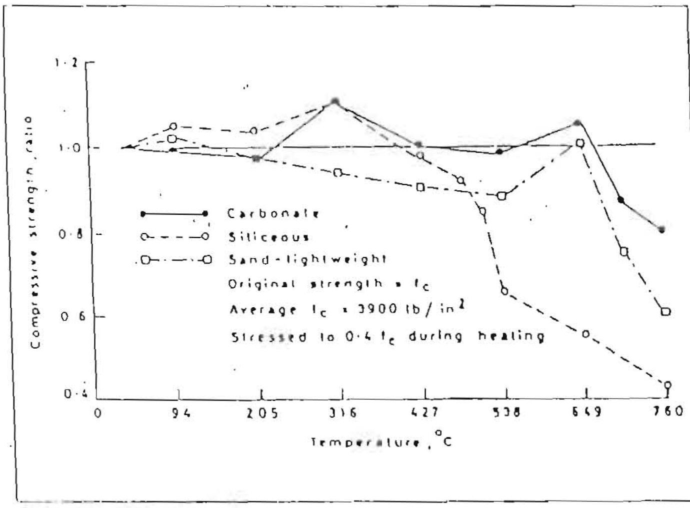

Fig 2 Compressive strength of concrete at high temperature

Table 1 : Details of 100-mm concrete cube [illegible]

Cement-aggregate ratio	Time elapsed before testing	No. of control cubes	Number of cubes [illegible] 200°C	400°C	600°C	[illegible]
1:6	One day after exposure	3	3	3	3	
	90 days after exposure	3	3	3	3	
	180 days after exposure	3	3	3	3	3
	365 days after exposure	3	3	3	3	
1:4.5	One day after exposure	3	3	3	3	
	90 days after exposure	3	3	3	3	
	180 days after exposure	3	3	3	3	3
	365 days after exposure	3	3	3	3	3

* Cubes found crumbled at the time of testing and thus [illegible] tested in compression

Some investigators working on the subject have found that concrete gains its strength instead of losing between temperature range of 100 to 300°C. *Fig* 2 shows some test results reported by Abrams[6]. Specimens were heated to test temperatures while stressed to 0.4 f_c'. It may be observed that there is gain in compressive strength for concrete with carbonate and siliceous aggregate types.

It may be noted from Figs 1 and 2 that the loss of compressive strength in concrete when exposed to "high" temperature may be reduced to about 25 to 30 percent of the initial strength. The loss of strength of concrete with temperature as given in the Technical Report 15 of the Concrete Society, London[7] is reproduced in *Fig* 3(a) and the same has been further simplified to a straight line plot as in *Fig* 3(b) for consistency with other documents[8,9].

It has also been observed by Harada[3] that concrete which has been heated at temperature below 500°C rehydrates while cooling down and gradually regains most of its strength. The compressive strength is reported to recover to about 90 percent of the original strength after about one year. *Fig* 4 shows the recovery of compressive strength of normal-weight concrete heated at various temperatures with time.

After comparing the findings of various authors and considering that no data for loss of compressive strength is available in India, a test programme was undertaken at the Central Building Research Institute (CBRI), Roorkee, to assess the loss of compressive strength in concrete due to exposure to elevated temperature. The paper gives the details of the test parameters taken for investigation and discussions on the loss of compressive strength and subsequent recovery during the cooling period.

Test samples

A test program was undertaken wherein 60 concrete [illegible] each of cement-aggregate ratio 1:6 and 1:4.5 were cast. [illegible] the total 120 cubes, 24 cubes consisting of 12 of 1:6 [illegible] 1:4.5 cement-aggregate ratio were treated as control [illegible] and tested for compressive strength after 28 days. [illegible] remaining cubes, 24 each (12 cubes of each mix) were [illegible] to 200, 400, 600 and 700/800°C. Out of these 24 cubes, [illegible] (3 cubes of each mix) were tested for compressive [illegible] one day after exposure, 6 cubes after 90 days, 6 after 1[illegible] and remaining 6 after 365 days. Initially, it was proposed [illegible] the cubes will be exposed to the highest temperature [illegible] but this exposure caused extensive cracking in the [illegible] cubes. It was also found that if such cubes were allowed [illegible] remain for a longer period after exposure, they start [illegible] signs of crumbling as can be seen from *Fig* 5. It was also [illegible] that the colour of the surface turned to white. For this [illegible] the temperature of exposure was subsequently reduced [illegible]

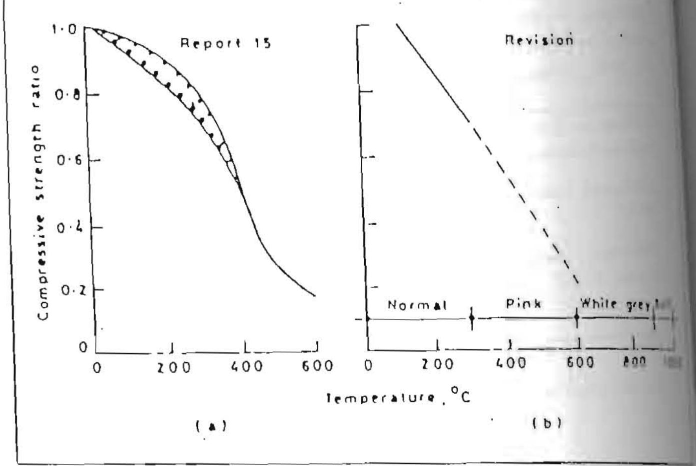

Fig 3 Compressive strength on cooling

Table 2 : Compressive strength ratio of concrete cubes at elevated temperatures

Cement-concrete ratio	Time elapsed before testing	Exposure temperature				
		200°C	400°C	600°C	700°C	800°C
		Ratio of compressive strength (based on average of 3 cubes)				
1:6	One day after exposure	1.05	1.13	0.68	-	0.21
	90 days after exposure	1.11	1.04	0.82	-	0.45
	180 days after exposure	1.12	1.02	0.87	0.75	-
	365 days after exposure	1.18	1.07	0.90	-	-
1:4.5	One day after exposure	1.10	1.06	0.71	-	0.32
	90 days after exposure	1.08	1.12	0.74	-	0.42
	180 days after exposure	1.12	1.04	0.80	0.65	-
	365 days after exposure	1.18	1.10	0.82	0.78	-

*Cubes found crumbled at the time of testing and thus could not be tested in compression

700°C.

The cubes were exposed to the elevated temperature for a duration of 4 hours. Three cubes were fired simultaneously in a furnace and were tested in a compression testing machine at one day, 90 days, 180 days and 365 days after firing. *Table* 1 gives the details of the cubes exposed to various temperatures and tested thereafter at different time intervals. The sand used for making the cubes was locally-available river sand, having fineness modulus of around 1.3 and 20-mm down siliceous coarse aggregate.

The compressive strength of the cubes exposed to elevated temperature and expressed as ratio of the compressive strength of the control cubes (tested after 28-day curing in the laboratory) is given in *Table* 2. It may be noted that three cubes of 1:6 cement-aggregate ratio, exposed to 800°C and scheduled

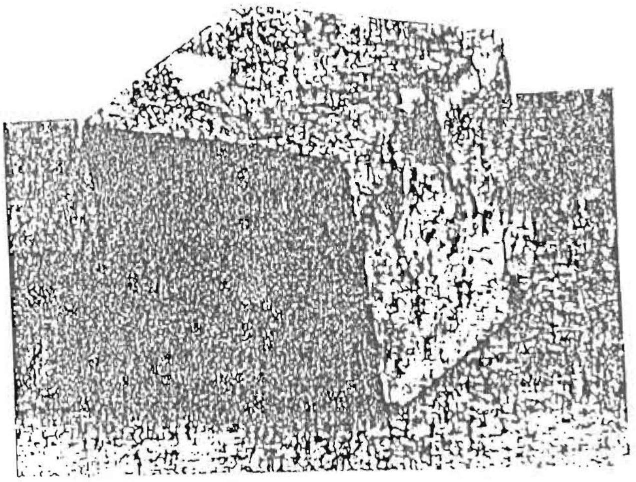

Fig 5 Cube fired at 800°C and allowed to remain for one year

to be tested after 365 days could not be tested since the same showed signs of crumbling. After noting this phenomenon, the temperature of exposure was reduced to 700°C for 3 sets of concrete cubes. The strength ratio given in *Table* 2 are reproduced in *Fig* 6 for cubes of 1:6 and in *Fig* 7 cubes of 1:4.5 cement-aggregate ratio.

Discussion of test results

From *Figs* 6 and 7 it may be concluded that the compressive strength marginally increases upto an exposure temperature of about 400°C. At temperature higher than 400°C the strength reduces drastically and goes down to as low as 25 to 30 percent of the initial strength. This is in broad agreement with the observations of Abrams[5] as given in *Fig* 2 , although the percentage increase in strength in his test series was less than

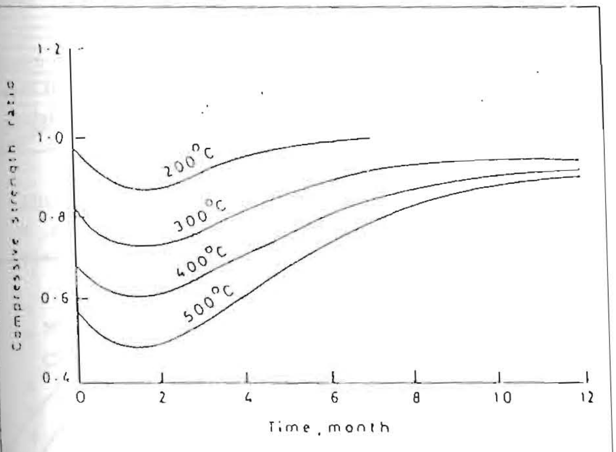

Fig 4 Natural recovery of compressive strength of concrete heated at various temperature

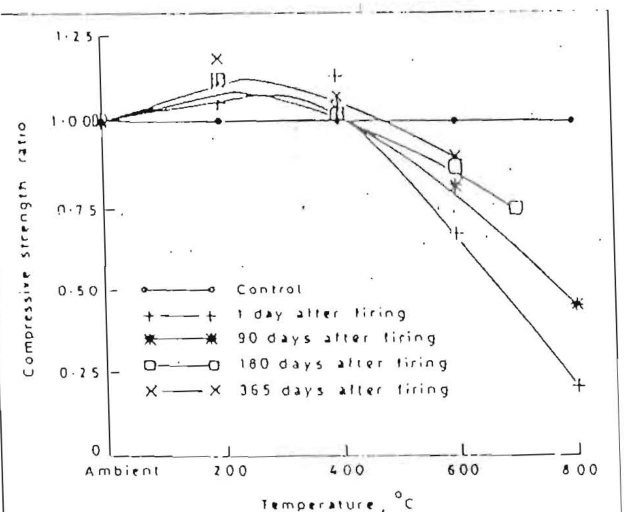

Fig 6 Change in compressive strength on exposure to elevated temperature (1: 6 cement-aggregate ratio)

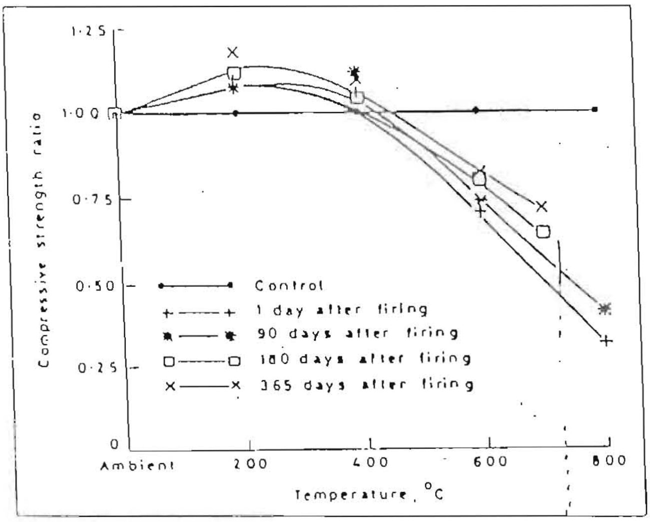

Fig 7 Change in compressive strength on exposure to elevated temperature (1: 4.5 cement - aggregate ratio)

that obtained in this study.

There is some difference of opinion as regards the increase of compressive strength of concrete at the temperature range 200 to 400°C. Harada[3], Malhotra[4] and others have shown no such increase on heating, *Figs* 1 and 8.

Fig 9 shows the average change in compressive strength of concrete considering concrete cubes of both 1:6 and 1:4.5 cement- aggregate ratio. In absence of adequate test data, the curves as given in *Fig* 9 for assessing the residual strength after different period of exposure may be assumed for design purpose. The use of this will lead to conservative results since it is known that the strength reduction of concrete stressed at the time of heating is less than that of unstressed concrete. Malhotra[4] has reported the influence of loading and the cement-to-aggregate ratio on the compressive strength as shown in *Fig* 8 for concrete made with Portland cement, fine aggregate consisting of sand from river deposit and coarse aggregate consisting of flint. *Fig* 8 indicates that loss in compressive strength is substantially less when the concrete is stressed. Since majority of structural concrete will be stressed at least under dead load at the time of exposure to fire, some modification to the previous data of *Fig* 9 is advisable.

The observations of Harada[3] (*Fig* 4) regarding recovery of compressive strength with time after exposure due to rehydration has also been confirmed in the present study. *Fig* 9 shows the recovery of strength with time as obtained in the present study based on *Fig* 9. The recovery has been observed even for concrete cubes heated beyond 600°C. Quantitative assessment of the recovery of compressive strength may be obtained from *Table* 2.

Conclusions

The following conclusions have been drawn based on the present study :

(i) The test results presented in this paper give an indication about the increase in compressive strength for exposure to lower temperature range and decrease to higher range.

(ii) With time, there is a recovery of compressive strength due to rehydration of concrete. The recovery may be about 80 percent of the initial strength.

(iii) The curves presented for the loss of compressive strength due to exposure to high temperature may be used conservatively since the results are based on unstressed concrete cubes.

(iv) The results presented in this paper are useful for investigation of structures distressed due to accidental fire. For assessing the structural safety

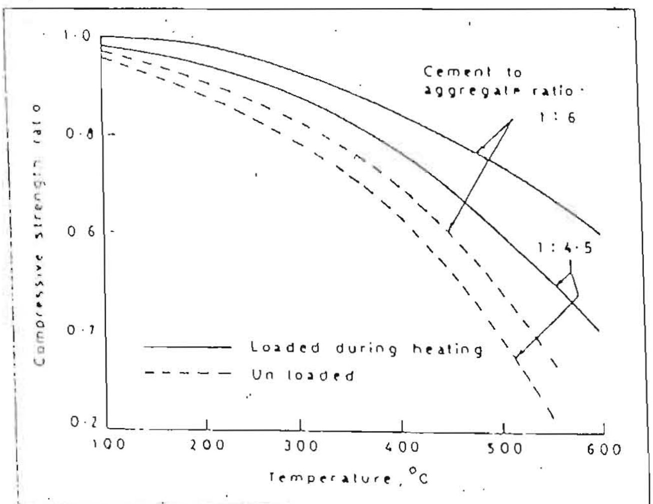

Fig 8 Influence of loading and cement-to-aggregate ratio on the compressive strength of a normal weight concrete at elevated temperatures

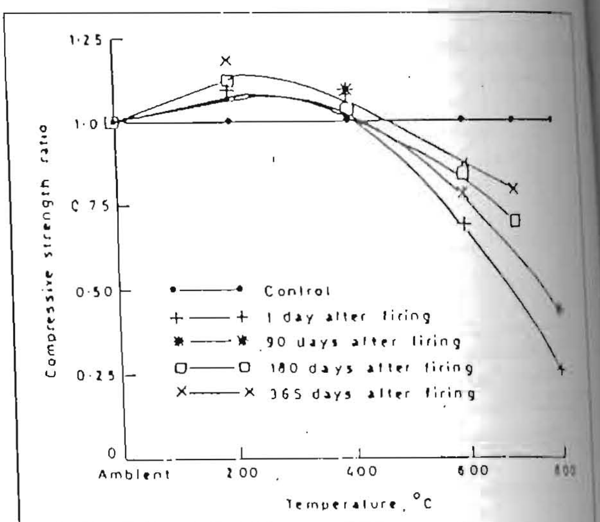

Fig 9 Change in compressive strength on exposure to elevated temperature (Average)

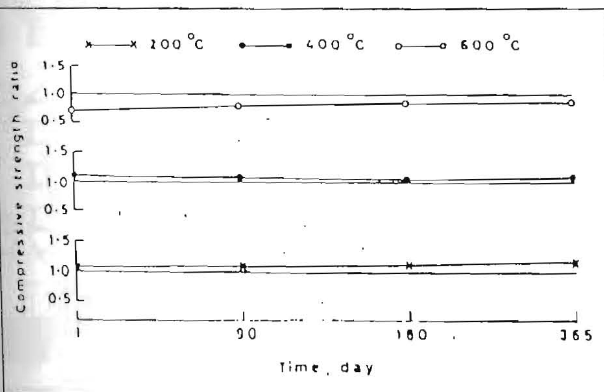

Fig 10 Recovery in compressive strength with elapse of time after exposure to elevated temperature

quacy or fire-damaged structures, one way of assessing the residual compressive strength is by estimation of temperature of exposure, for which the results reported in this paper may be helpful.

Acknowledgement

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