Evaluation of Efficiency of Non-destructive Testing Methods for Determining the Strength of Concrete Damaged by Fire

J.S. Kalyana Rama and B.S. Grewal

Abstract An engineering assessment was performed on concrete cubes casted from M25 concrete for checking the efficiency of non-destructive testing methods namely Schmidt's rebound hammer test and Ultra Sonic Pulse Velocity test. The study was aimed at checking the viability of these above named non-destructive tests. Firstly, in the case of undamaged concrete structures and later on in the case of concrete structures damaged by fire, and then to compare the results to find out the efficiency of non-destructive testing methods. It is assumed that in the case of an undamaged structure the concrete is a homogenous mixture with equal strength at all depths. Hence, the non-destructive tests even if they are able to measure the surface strength like in case of the rebound hammer test may give a pretty accurate value when compared to the compressive tests performed in the laboratory. In the case of a structure, which has been damaged by fire, the concrete may no longer be homogenous at all depths and there might be considerable changes in its internal structure. Hence, this study is an attempt to carry out non-destructive tests on such concrete samples, which have been damaged by fire and then find out the viability and accuracy of the results when compared to the compressive tests performed in the laboratory.

Keywords Non-destructive testing · Rebound hammer test · Ultrasonic pulse velocity

1 Introduction

One of the advantages of concrete over other building materials is its inherent fire-resistive properties; however, concrete structures must still be designed for fire effects. Structural components still must be able to withstand dead and live loads

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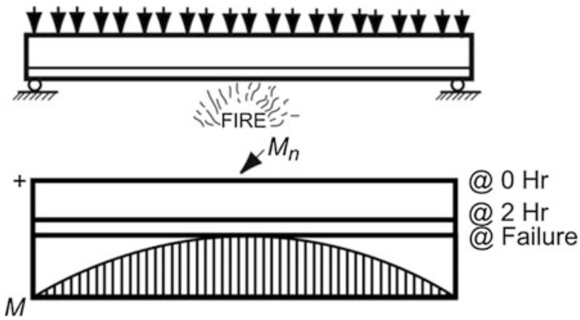


Fig. 1 Effect of fire on the resistance of a simply supported reinforced concrete slab (*Source* ASTM E119)

without collapse even though the rise in temperature causes a decrease in the strength and modulus of elasticity for concrete and steel reinforcement. In addition, fully developed fires cause expansion of structural components and the resulting stresses and strains must be resisted. In the design of structures, building code requirements for fire resistance are sometimes overlooked and this may lead to costly mistakes. It is not uncommon, to find that a concrete slab floor system may require a smaller thickness to satisfy strength requirements than the thickness required by a building code for a 2-h fire resistance.

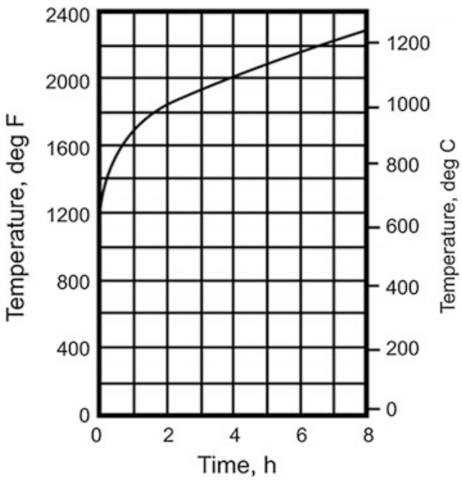
For sound and safe design, fire considerations must, be part of the preliminary design stage. Determining the fire rating for a structure member, can vary in complicity from extracting the relevant rating using a simple table to a fairly complex and elaborate analysis. In the United States, structural design for fire safety is based on prescriptive approach. Attempts are being made to develop performance based design approach for structural design for fire. State and municipal building codes throughout the country regulate the fire resistance of the various elements and assemblies comprising a building structure.

Figure 1 shows the effect of fire on the resistance of a simply supported reinforced concrete slab. If the bottom side of the slab is subjected to fire, the strength of the concrete and the reinforcing steel will decrease as the temperature increase. However, it can take up to 3 h for the heat to penetrate through the concrete cover to the steel reinforcement. As the strength of the steel reinforcement decreases, the moment capacity of the slab decreases. When the moment capacity of the slab is reduced to the magnitude of the moment caused by the applied load, flexural collapse will occur. It is important to point out that duration of fire until the reinforcing steel reaches the critical strength depends on the protection to the reinforcement provided by the concrete cover.

1.1 ASTM E119 Standard Fire Test

The fire-resistive properties of building components and structural assemblies are determined by fire test methods. The most widely used and nationally accepted test

Fig. 2 Time temperature curve (*Source* ASTM E119)



procedure is that developed by the American Society of Testing and Materials (ASTM). It is designated as ASTM E119, Standard Methods of Fire Tests of Building Construction and Materials. A standard fire test is conducted by placing a full size assembly in a test furnace. Floor and roof specimens are exposed to a controlled fire from beneath, beams are exposed from the bottom and sides, walls from one side, and columns are exposed to fire from all sides. The temperature is raised in the furnace over a given period of time in accordance with ASTM E 119 standard time-temperature curve shown in Fig. 2. This specified time-temperature relationship provides for a furnace temperature of 540 °C at 5 min from the beginning of the test, 700 °C at 10 min, 930 °C at 1 h, 1,010 °C at 2 h, and 1,100 °C at 4 h.

1.2 Review of Work Done

To properly maintain the civil infrastructures, engineers required new methods of inspection. Better inspection techniques are needed for deteriorating infrastructure Rens et al. [1]. Now in the present century NDT has become more sophisticated, as it has developed from a hammer to Impact Echo and Impulse response Lim and Cao [2]. Shaw and Xu [3] have recognized the importance of being able to test in situ, and this trend is increasing as compared to traditional random sampling of concrete for material analysis. NDT methods may be categorized as: penetration tests, rebound tests, pull out tests, dynamic tests, and radioactive methods. According to McCann and Forde [4], five major factors that need to be considered in NDT survey are: required depth of penetration, required vertical and lateral resolution, contrast in physical properties between target and its surrounding, signal to noise ratio for the physical properties between the target and its surroundings, and historical information concerning the methods used in the construction of the structure. Breysse et al. [5] described the various aims of NDT methods such as to detect the condition of RC structures, rank the structures according to present condition, and compare the different Sanayei et al. [6] performed static truck load test on a newly constructed bridge, to capture the response of bridge when a truck traveled across it. Amini and Tehrani [7] designed experimentally four sets of exposure conditions, weight and compressive strength of the samples had been measured before and after the freeze thaw cycles, and the results were analyzed. Loizos and Papavasiliou [8] performed a comprehensive monitoring and data analysis research study by using Falling Weight deflectometer (FWD) for in situ evaluation of recycled pavements. Proverbio and Venturi [9] evaluated the reliability of rebound hammer test and UPV test on concrete of different composition and strength. Rens et al. [10] explained application of NDE methods for bridge inspection. Malavar et al. [11] used pull off tests to evaluate effects of temperature, moisture, and chloride content on CFRP adhesion. Pascale et al. [12] carried out an experimental program involving both destructive and nondestructive methods applied to different concrete mixtures, with cube strength varying from 30 to 150 MPa, to define a relation between strength and parameters. Almir and Protasio [13] used NDT methods to determine the compressive strength of concrete. Rens and Kim [14] inspected a steel bridge using several NDT methods. Bhadauria and Gupta [15] presented case study of deteriorated water tanks situated in the semitropical region of India. Amleh and Mirza [16] performed concrete cover test using NDT. Sharma and Mukherje [17] used ultrasonic guided waves for monitoring progression of rebar corrosion in chloride and oxide environment. Terzic and Pavlovic [18] applied NDT methods that is Image Pro Plus (IPP) and Ultrasonic Pulse Velocity (UPV), on the corundum and bauxite-based refractory concretes. Shah and Hirose [19] presented an experimental investigation of the concrete applying nonlinear ultrasonic testing technique. Ervin et al. [20] created an ultrasonic sensing network to assess reinforcement deterioration. Lee et al. [21] used UPV methods for determining setting time of concrete especially high-performance concrete (HPC). Shah et al. [22] described laboratory-based NDE techniques based on measurements of mechanical waves that propagate in the concrete. Methods for non-destructive testing of concrete such as rebound hammer testand ultrasonic pulse velocity test are also described in related Indian standards [23, 24]. The present study focuses on the assessing the behavior of a concrete specimen damaged by fire using Non-Destructive Testing tools rebound hammer and pulse velocity.

2 Preparation of Test Specimen

For the purpose of this work, twelve samples of concrete of grade M30 were prepared. The design mix of the concrete is given in Table 1. Each sample was a cube of size 150 mm × 150 mm.

Table 1 Design Mix for M30 concrete

Material	Quantity (kg/m^3)
Cement	380
Aggregate 20 mm	924
Aggregate 10 mm	359
Fine aggregate	711
Water	160
Admixture	1.90

2.1 Heating of Test Specimen

Cube sample number 1, 2 and 3 were tested in an undamaged condition for their compressive strength, whereas cube sample number 4, 5 and 6 were heated up to a temperature of 250 °C, cube sample number 7, 8 and 9 were heated up to a temperature of 500 °C and cube sample number 10, 11 and 12 were heated up to a temperature of 1,100 °C before carrying out the requisite tests. The heating of the cubes was carried out as per ASTM E 119 [25] instructions at a rate of increase of temperature given in Table 2. Details of the concrete specimens are presented in Table 3.

Table 2 Rate of heat application toe the test specimen with respect to time

Time (min)	Temp (°C)
5	540
10	700
60	930
120	1,010
240	1,100

Table 3 Details of concrete specimen prepared

Sample no.	Weight (kg)	Density (kg/m^3)	Test condition
1	8.30	2,459.26	Undamaged
2	8.36	2,477.04	Undamaged
3	8.18	2,423.70	Undamaged
4	8.21	2,432.59	Heated at 250 °C
5	8.28	2,453.33	Heated at 250 °C
6	8.15	2,414.81	Heated at 250 °C
7	8.09	2,397.04	Heated at 500 °C
8	8.23	2,438.52	Heated at 500 °C
9	8.17	2,420.74	Heated at 500 °C
10	8.12	2,405.93	Heated at 1,100 °C
11	8.32	2,465.19	Heated at 1,100 °C
12	8.29	2,456.30	Heated at 1,100 °C

3 Results and Discussion

All these cubes were initially tested for their strength using Non Destructive tests, namely Schmidt's rebound hammer test and Ultrasonic Pulse Velocity Test before being subjected to testing under compression testing machine for checking the actual value of the compressive strength of the cube. Figures 3, 4, 5 and 6 present the details about the rebound numbers obtained for the cubes to be tested.

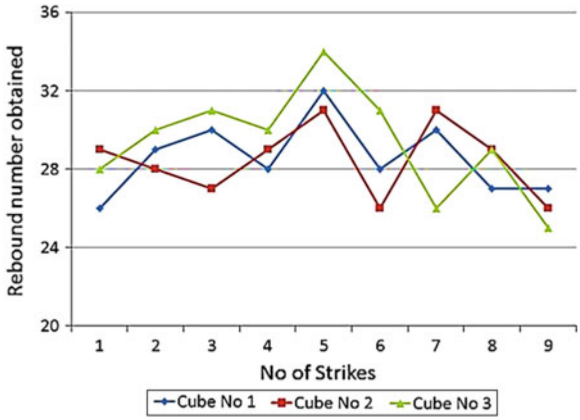


Fig. 3 Rebound numbers achieved for undamaged cubes

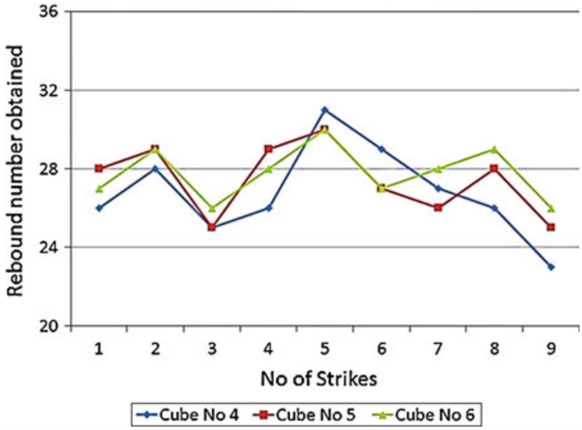


Fig. 4 Rebound numbers achieved for cubes damaged at 250 °C

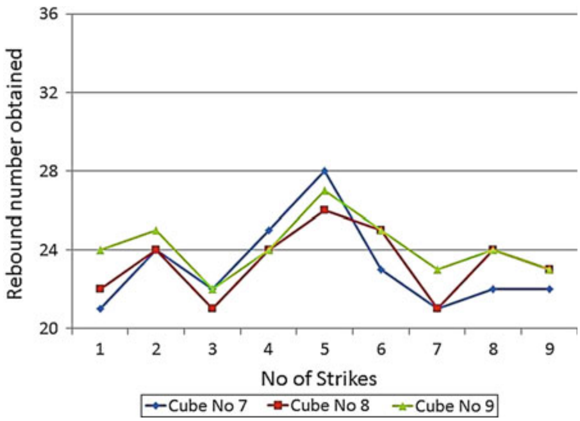


Fig. 5 Rebound numbers achieved for cubes damaged at 500 °C

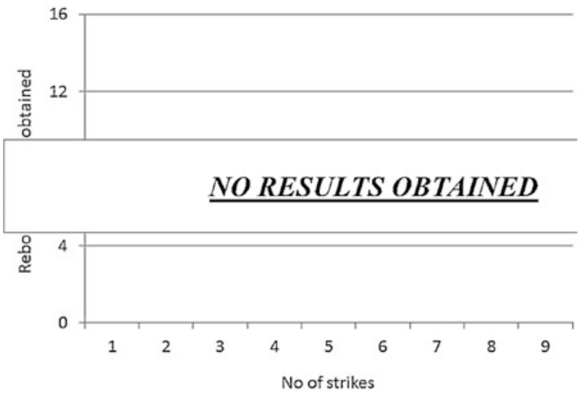


Fig. 6 Rebound numbers achieved for cubes damaged at 1,100 °C

3.1 Performance of Ultrasonic Pulse Velocity

After carrying out the rebound hammer test, the concrete specimens were subjected to Ultrasonic Pulse Velocity test, which is used to find out the quality of the concrete. The results obtained from this test are given in Table 4.

3.2 Performance of Compressive Machine Test

Once, the Non Destructive tests are completed the concrete cubes are to be subjected to compressive tests using Compression testing machine, the results of which are given in Table 5.

Table 4 Test results obtained using ultrasonic pulse velocity test

Sample no.	Heated at (°C)	Distance between transducers (mm)	Time (μs)	Speed (kmph)	Quality of concrete
1	–	150	36.2	4.143	Good
2	–	150	37.5	4.002	Good
3	–	150	37.9	3.957	Good
4	250	150	41.1	3.649	Good
5	250	150	42.1	3.563	Good
6	250	150	40.4	3.708	Good
7	500	150	47.9	3.128	Doubtful
8	500	150	49.6	3.021	Doubtful
9	500	150	50.5	2.968	Doubtful
10	1,100	150	808	0.185	Very poor
11	1,100	150	874	0.171	Very poor
12	1,100	150	786	0.191	Very poor

Table 5 Compressive strength achieved using compression testing machine

Sample no.	Heated at (°C)	Comp. strength (N/mm^2)
1	–	38.8
2	–	39.6
3	–	39.4
4	250	36.0
5	250	35.1
6	250	35.6
7	500	28.9
8	500	28.4
9	500	30.7
10	1,100	6.2
11	1,100	6.0
12	1,100	6.3

3.3 Analysis of Data

Comparing the compressive strength obtained using Compressive Machine Test and the Non Destructive test, it is found that the variation between the two results is more in case of undamaged samples but as the concrete specimen are subjected to increasing temperatures this variation continuously decreases. But at a temperature of 1,100 °C the rebound hammer is not able to give any reading whereas the compressive machine indicates strength of 6 N/mm^2. This is although of no significance where the required strength of a structural element is concerned. Detailed test results are compared in Table 6.

Table 6 Comparative results for rebound hammer test and compression testing machine

Sample no.	Heated at (°C)	Average rebound number	Compressive strength (N/mm^2)		Ratio actual/RHT	Average ratio
			RHT	Actual		
1	–	28.2	23.3	38.8	1.66	1.62
2	–	28.4	23.6	39.6	1.63	
3	–	29.3	25.0	39.4	1.58	
4	250	26.7	22.7	36.0	1.58	1.54
5	250	27.4	23.2	35.1	1.51	
6	250	27.6	23.4	35.6	1.52	
7	500	23.3	19.8	28.9	1.46	1.48
8	500	23.1	19.6	28.4	1.45	
9	500	24.1	20.5	30.7	1.49	
10	1,100	–	–	6.2	–	–
11	1,100	–	–	6.0	–	
12	1,100	–	–	6.3	–	

Table 7 Reduction in strength of concrete with increase in temperature

Concrete specimen	Compression testing machine reading (N/mm^2)	% decrease in strength
Undamaged	39.3	0
Heated up to 250 °C	35.6	9.4
Heated up to 500 °C	29.3	25.4
Heated up to 1,100 °C	6.2	84.2

In addition when the data is studied to check the decrease in strength of concrete with increase in temperature, it is found that the decrease in strength up to 250 °C is about 10 %, which further falls to 25 % at temperature of 500 °C. After the temperature crosses 500 °C, the decrease in strength is observed to be sharper and by the time the temperature reaches a value of 1,100 °C, the reduction in strength is almost 85 %. The reduction in strength is given in Table 7 and also shown in graphical form in Fig. 7.

Checking for the accuracy of the Schmidt's rebound hammer testas compared to the compression machine testing, from Table 8 it was found that the accuracy of results given for undamaged cubes by rebound hammer test were having an accuracy of 62 % when compared to results obtained by compression machine testing. When the same tests were performed for cubes heated up to 250 °C, the accuracy increased to 65 % and it further increased to 69 % when the tests were conducted for cubes heated at 500 °C. No data could be derived for cubes heated at

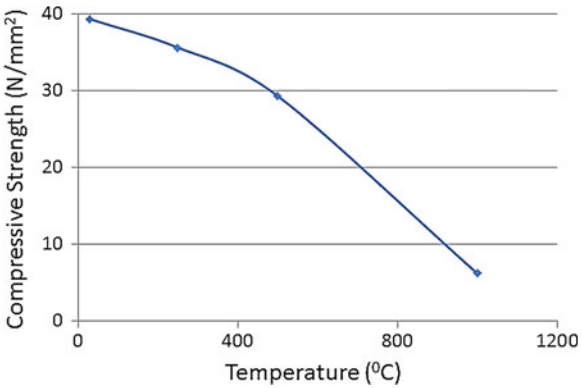


Fig. 7 Reduction in compressive strength of concrete with increase in temperature

Table 8 Comparative results for rebound hammer test and compression testing machine

Concrete specimen	RHT (N/mm^2)	CTM (N/mm^2)	% accuracy of RHT
Undamaged	24.0	39.3	61
Heated up to 250 °C	23.1	35.6	64
Heated up to 500 °C	19.9	29.3	68
Heated up to 1,100 °C	–	6.2	–

1,100 °C as the rebound hammer test failed to give any reading for concrete specimens heated at that temperature.

4 Conclusions

In conclusion it can be said that concrete although doesn't melt under high temperatures but it may go out of shape slightly and there is a significant reduction in strength and also appearance of cracks when subjected to higher temperatures. Therefore, any building or structure which has been damaged by fire should certainly be checked for its strength to ensure whether it is fit for occupancy and usage after the accident or not. In case of severe fires where temperatures are high, the damage will be to a much higher extent as compared to a fire of small scale as the relation between loss of strength of concrete and increase in temperature is not linear as shown in Table 7 and Fig. 7.

It has been observed that the accuracy achieved using Schmidt's rebound hammer testimproved as the damage caused to the concrete by high temperatures in fire increased as shown in Table 8. The tests carried out using Ultrasonic Pulse Wave Equipment further confirmed the extent of damage to the concrete and were in agreement to the readings achieved using the hammer test.

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