

Non-Destructive Assessment of Heated Rc Columns Cooled by Two Cooling Methods

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Abstract : Fire constitutes a major hazard to the buildings. The structural members exposed to high temperatures during fire accidents. The phenomenon observed was the structural members undergo dehydration of concrete, thermal distress in the form of cracking and spalling due to excessive heating. This leads to cause degradation of concrete strength. After tackle the fire hazard, the next step is to find the suitability of the building for repair or restoration, which involves assessment of fire severity and fire damage. Nondestructive testing (NDT) is the most practical and widely used methods to obtain in place strength or even for new structure strength. It is an effective tool for damage assessment and quality assurance, as well. In this paper, reinforced concrete (RC) columns made with OPC mix and HVFA mix, exposed to high temperatures ranging from 100 to 800°C. After heating, the specimens were brought to room temperature by air cooling and water quenching methods. The specimens were tested for residual compressive strengths and material integrity of concrete columns, by non-destructive testing methods, to understand how parameters like cooling condition and exposure duration influence the mechanical properties of conventional concrete mix and fly ash concrete mix. OPC concrete mix columns performed better strengths over HVFA mix columns when they cooled by air. Whereas water quenched HVFA mix columns upkeep the concrete quality grading on comparing the OPC mix specimens.

Keywords: OPC concrete, HVFA concrete, temperature, pulse velocity.

I. INTRODUCTION

Concrete is one of the most widely used construction materials, due to, its availability and fire resistance. This performance is due to ingredients like cement and aggregates. It has the slow rate of heat transfer (conductivity) that enables the concrete to act as an effective fire-resistant material, not only for the structural member but also to protect the adjacent members from fire damage. The rate of increase of temperature through the cross-section of a concrete element is relatively slow and so internal zones do not reach the same high temperatures as a surface exposed to fire (Raja Shaker, 2009). Usage of sustainable materials like fly ash in concrete improves the durability of concrete and the rate of gain in strength, thereby reducing the rate of liberation of heat, which is beneficial for mass concrete.

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There are changes in the properties of concretes, particularly in the range of 100 to 300°C. Above 300°C, there is a change in the physical and mechanical properties of concrete elements. This behaviour of concrete subjected to high temperatures is a result of many factors such as thermal incompatibility causes cracking, heating rate, high temperatures, dehydration of cement gel, etc. Concrete will suffer by cracking and spalling under the uneven heat transmission and the degradation of strength of structural members take place during fire accidents. Usually, the fire could be extinguished by applying water jet, air cooling or by any other technique, which can bring the concrete to room temperature.

Out of all these methods, the water jetting method makes the concrete cool all of a sudden. Therefore, the strength of concrete will be affected not only during heating the concrete but also during the cooling of the concrete. The rapid cooling of heated concrete, similar to rapid heating, can cause strength deterioration (Jonotka and S C Mojumdur 2005, Hassan and Sawsan Akram 2007). On the other hand, environmental factors such as heating rate, duration of exposure to a maximum temperature, cooling rate and loading conditions affect the heat resistance of cementing materials (Rahul P Chadha and A R Mundhada, 2012). These factors reduce the strength of concrete, thereby the strength of structural members. Therefore, it is necessary to predict the response of structural health at high temperatures to restore the strength of a member or to give rehabilitation measures for a particular structure. The degradation of strength can be estimated by applying non-destructive methods, i.e. rebound hammer and ultrasonic pulse velocity (UPV) meter tests. These are the most practical and widely used methods to estimate the residual strength of a structural member without destroying the structural members. Also, it serves to test the material integrity of concrete as per IS 13311 (part I): 1992. Several experimental studies have been carried out to understand how the pulse velocity was affected by the damage of concrete caused by high temperatures. Besides that, it is also used for detection, characterization, location and sizing of discontinuities or defects, to determine the quality of manufacture or casting of structure and lastly, it is used to get residual strength retained by the member after heating.

II. LITERATURE REVIEW

Omer Arioz (2009) studied the retained properties of concrete exposed to high temperatures compressive strength and split tensile strength. Different sizes of concrete cubes, i.e. 100 mm, 150 mm and 200 mm were exposed to temperatures from 200 to 1200° C. It was observed that the strength of concrete decreased with an increase in temperature, i.e. the strength of concrete is inversely proportional to temperature. The same relation holds for split tensile strength of concrete exposed to fire.



It was observed the experiment that the size of the concrete specimen and residual compressive strength are independent, i.e. irrespective of the size of the concrete specimen, the residual compressive strength is dependent only on the exposure temperature. However, this is not the case in split tensile strength. In splitting tensile strength, the retained tensile strength for 100mm cubes, 150 mm cubes and 200 mm cubes at 400 °C temperature were found to be 45, 87 and 98%. This difference in retained splitting tensile strength can be attributed to the slow conductivity of concrete. It was seen that non-destructive tests like rebound hammer and ultrasonic pulse velocity are applied successfully for the concrete specimen.

Wasim Khaliq and Venkatesh Kodur (2012) studied the behaviour of high strength fly ash concrete columns under fire conditions. In order to compare the fire resistance property of the fly ash concrete column with the conventional concrete column, both the specimen's one in fly ash and the other in concrete were cast. Along with fly ash concrete and normal concrete, polypropylene was used to check if there is an increase in the fire resistance of the concrete column. In the test results, it was observed that the melting of polypropylene fibre facilitated heat transfer in high fly ash concrete (HFAC) column. While high fly ash concrete columns failed at 100 minutes, a high fly ash concrete column with polypropylene (HFACP) failed at 165 minutes. It is to be observed that while the percentage of fly ash is the same in both the specimens, however, the only change in both the specimens is the use of polypropylene fibre (0.22% by volume). Another important conclusion is the slight difference in temperature between HFAC and HFACP. This difference in temperature can be attributed to fire-induced spalling, which causes a reduction in cross-section of HFAC and higher thermal conductivity of HFAC than that of HFACP. The form of thermal response is obtained in High Strength Concrete Column (HSC) and High Strength Concrete with Polypropylene (HSCP) Column. In terms of Spalling, it occurred only in HFAC after 12 minutes of fire and resulted in a 17% loss of volume, however, unlike HFAC, HFACP showed no spalling during the entire test tenure. This change can be attributed to the more permeable microstructure of HFACP, allowing removal of pore pressure from the concrete. At the end of the experiment, it was concluded that both HFAC and conventional high strength concrete have similar fire response. However, the axial deformation of the high strength concrete column is more than that of HFAC and HFACP.

Rahul P Chadha and A R Mundhada (2012) studied the effect of fire on the flexural strength of reinforced concrete beams. A total of 12 specimens were cast, 6 with a concrete cover of 25 mm and another 6 of cover 30 mm. The specimens were heated in an electric furnace at 550°C for 1-hour and 2 hours respectively, and then the same specimen was heated at 750 and 950 °C. After heating the specimens, they were air-cooled until their temperature reached room temperature. It was observed that there was a reduction in flexure strength by 34.84%, 44.37% and 61.99% at 550 °C, 750 °C and 950 °C respectively for 30 mm cover. It was also observed that spalling is induced from 750 °C, which resulted in a weight loss of 4 and 12% at 950 °C. A concrete beam had a larger cover size, i.e. 30 mm recorded a lesser

loss of flexural strength than the cover of 25 mm size. Finally, it was concluded that repair at 550 °C and 750 °C is possible, however at 950°C major retrofitting might be required and the structure can't be further relied upon for its use.

III. MATERIALS AND MIX DESIGN

The materials for the experimental work are as follows

Cement: Ordinary Portland cement (OPC) of 43grade has been used in the present work. Its specific gravity is 3.13. Table 1 shows the physical properties of the cement.

Fly ash: The fly ash used for the experimental program is locally available low calcium Class-F fly ash procured from Simhadri super thermal power project (NTPC) Visakhapatnam. While mixing concrete uniform blending with cement was ensured as per clause 5.2.1.1 of IS 456-2000.

Table 1 Physical properties of cement

S. No	Physical properties	Test results
1	Fineness (as the residue left on IS 90-micron sieve) %	8.2
2	Standard Consistency(%)	31
3	Setting Time	
	a) Initial (minutes)	124
	b) Final (minutes)	274
4	Compressive strength	
	a) 3 days (MPa)	29.6
	b) 7 day (MPa)	40.3
	c) 28day (MPa)	62.4

Fine aggregate: Locally available river bed sand conforming to Zone II of IS: 383-1970 classification is used. The fineness modulus is obtained at 2.65, and the specific gravity of the fine aggregate is 2.66. The sand is adequately air-dried before using it in concrete to avoid bulking.

Coarse aggregate: The coarse aggregate used in the concrete mix is saturated surface dried aggregate, locally available hard blue granite which is angular in shape. The specific gravity is 2.78 and fineness modulus is 7.76. Grading of coarse aggregate is done to obtain the optimum density. The fraction of coarse aggregate passing through 20 mm and retained on 10 mm is taken as 70% of total aggregate. The remaining 30% fraction is aggregate passing through 10 mm and retained on 4.75 mm.

Water: Locally available potable tap water is used.

Chemical admixture: Chemical admixture (Complast SP 430) is used to achieve the workability of the HVFA concrete mix and is conforming to IS 9103-1999. The dosage used in the present study is 0.25 litres per 50 kg of cement.

Mix proportions

According to IS 456-2000, the minimum grade of concrete for RCC members is M20 grade, which is normal strength concrete. Mix proportions are achieved for normal strength concrete (M20) based on the guidelines of IS: 10262-2009. Optimized mix design was obtained for the desired strength and workability (J Kumari and K Srinivasa Rao, 2013). The target strength is 27.6 MPa as per mix design. Two concrete mixes are used in this experimental study. One is a conventional concrete mix made with ordinary Portland cement designated as OPC mix and the other with high volume fly ash designated as HVFA mix. Table 2 shows the OPC and HVFA concrete mix proportions for M20 grade concrete.

Table 2 Mix proportions per m³ of concrete mix

S. No.	Ingredients	OPC concrete mix	HVFA concrete mix
1.	Cement used	320 kg/m ³	160 kg/m ³
2.	Fly ash	Nil	160 kg/m ³ (50%)
3.	Fine aggregate	623.95 kg/m ³	623.95 kg/m ³
4.	Coarse aggregate	1211.0 kg/m ³	1211.0 kg/m ³
5.	Water to binder ratio	0.52	0.45
6.	Superplasticizer SP430	Nil	250 ml per 50 kg of cement

IV. CASTING AND TESTING METHODOLOGY

All the columns are 1200 mm long and 150 mm x 150 mm in cross-section. All these columns were designed in accordance with IS 456-2000. The clear cover provided to the reinforcement was 20 mm, as shown in Fig.1a. The clear cover was maintained using cover blocks. The cover blocks are kept inside the mould on all sides as shown in Fig.1b to provide clear cover to reinforcement.

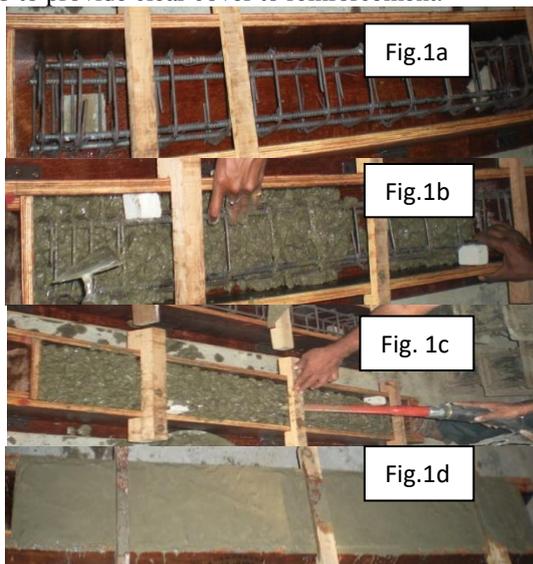


Fig. 1a, 1b, 1c, 1d Stages of the casting of a column

The columns were cast in a horizontal position by concreting in 3 layers. Each layer was compacted using a needle vibrator, as shown in Fig.1c, for a time of 1-2 minutes. The surface of the concrete in the mould was

levelled with the trowel. It was marked for identification, as shown in Fig.1d. These columns were de-moulded after 24 hours of casting and kept for curing for 28 days in a water tank filled with fresh water. After 28 days of curing, the columns were taken out and stored under laboratory air drying conditions before NDT testing and temperature exposure. Each specimen was tested for probable compressive strength of concrete and the concrete quality grading using a rebound hammer test and ultrasonic pulse velocity test, respectively, before heating. The test was performed on two longitudinal side faces of the column by drawing grid lines at 150 mm c/c on two side faces of the column, leaving a concrete cover distance of 20mm from the edge of the column. The columns were tested for probable compressive strength of concrete with a rebound hammer, as shown in Fig.2. Subsequently, pulse velocities are measured by direct probing on the same grid points by the UPV test, as shown in Fig. 3.



Fig. 2 Rebound hammer test Fig. 3 UPV test on columns

Temperature exposure: The test specimens were heated to temperatures ranging from 100 to 800°C at an interval of 100°C for two durations 1-hour and 3 hours. Two RC columns made with OPC concrete mix and HVFA concrete mix were heated simultaneously to a temperature for a specified duration of exposure. When the target temperature is attained, the specimens were kept at that temperature for a duration of 1-hour and 3 hours. For the air cooling of specimens, the furnace was switched off after exposure. Consequently, the specimens were left on a separated part of the furnace, from where they could be dragged out, from the unseparated part of the furnace, until the temperature of columns reaches to room temperature under air cooling method.

While, for water quenching, the specimens were removed immediately after heat exposure and were immersed in a curing tank arranged nearby. The specimens were allowed to cool in the water until the specimens cool down to room temperature. The specimens were later removed from the water, wiped dry and tested for residual compressive strength of concrete with rebound hammer. Similarly, pulse velocities are tested on the same points by the UPV test.

V. RESULTS AND DISCUSSIONS

Residual compressive strength is the concrete compressive strength of heated column expressed as a percentage of 28 days strength of concrete of the corresponding control concrete column at room temperature. Probable compressive strength of concrete for RC column specimens is determined by rebound hammer at room temperature.

The average compressive strength of OPC concrete mix and HVFA concrete mix specimens are 39.7 and 35.6 N/mm² respectively. The structural health performance by NDT methods such as rebound hammer test and UPV test becomes very useful for the assessment of the residual strength and material integrity of RC members. It is also helpful for examining the deterioration of strength of the specimens.

A. Probable compressive strength of heated columns by rebound hammer

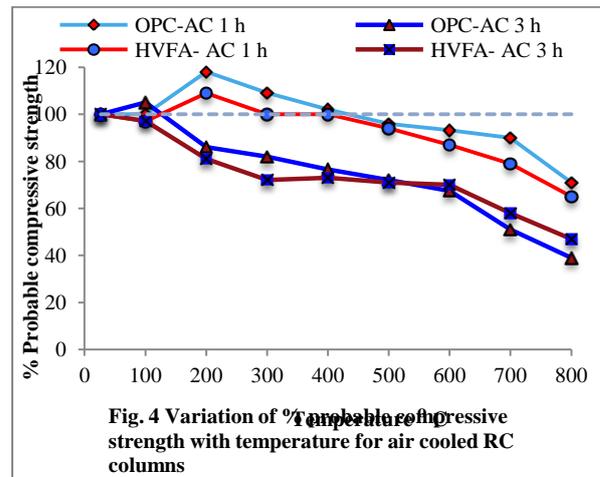
Table 3 and Table 4 shows the details of the residual compressive strengths of OPC mix and HVFA mix RC columns heated to temperatures 100 - 800°C for 1-hour and 3 hours exposure durations and for the specimens cooled by air cooling and water quenching methods. The corresponding variations of compressive strengths of both OPC mix and HVFA mix RC columns are also plotted in Fig.4 and Fig.5 for air-cooling (AC) and water quenching (WQ) methods, separately.

Table 3 Variation of residual compressive strength for air cooled RC columns

Temperature °C	% Probable compressive strength of concrete			
	Air cooling method			
	Water quenching method		1-hour duration	
	OPC	HVFA	OPC	HVFA
27	100	100	100	100
100	100	97	105	97
200	118	109	86	81
300	109	100	82	72
400	102	100	77	73
500	96	94	72	71
600	93	87	68	70
700	90	79	51	58
800	71	65	39	47

Air cooling: Fig. 4 shows the variation of probable residual compressive strength of concrete with temperature for 1-hour and 3 hours exposures and air-cooled specimens. The probable compressive strengths measured for OPC mix and HVFA mix specimens heated for 1-hour duration were retained their original strengths (% strength of corresponding unheated specimens) up to 400° C temperature exposures. On further heating, the probable strength of OPC mix RC columns slightly dropped 7% and 10% with the rise in temperature to 600 and 700°C, but there is a substantial drop in the strength, 29% at 800°C. After that, for HVFA concrete mix columns, strength reduction has been observed as 13, 21 and 35% at 600, 700, and 800°C, While both types of concrete mix specimens have strength differed by only 2 % at 500 °C. Finally, for an increase in temperature up to 700° C, the OPC columns retained 90% of strength and HVFA columns retained about 80% of the strength. At 800 °C temperatures, both columns lost more than 30% of their strength.

Hence, it is confirmed to say that OPC concrete mix columns performed better strength by retaining 10% more (up to 700 ° C) than the strength of HVFA concrete mix columns by air cooling method.

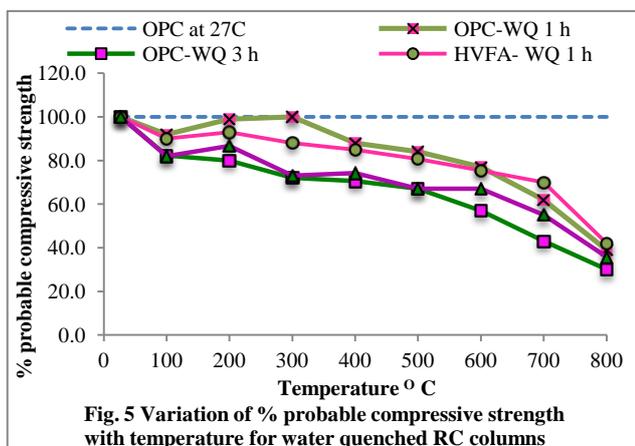


Similarly from the same Fig.4 and Table 4 the plots represent compressive strengths of concretes exposed for 3 hours are much lower than the 1-hour exposure plots. This trend is obvious, that the deterioration in strength was much greater in contrast to the columns that were exposed to 1-hour. The deterioration is much greater due to the long exposure time allows the propagation of heat from the periphery to the core while compromising the strength of concrete during the heat spread. Referring to Fig. 4 It can be seen that, at 100° C, the strength of OPC column just above the strength of the unheated column. Further increase in temperature, the performance of OPC columns heated up to 400° C and exposed for 3 hours are having a similar trend of 1-hour exposures with substantial deterioration. In air cooling, both the type of concrete mix specimens prone to suffer as the propagation of heat is continuous towards the core of the concrete, and there may be a possibility of widening the micro-cracks leads to a reduction in strength. This might be the reason for OPC columns lowered the strength at high temperatures 600, 700 and 800° C. Thus, the HVFA columns, showed improved strengths at the same temperatures.

Table 4 Variation of residual compressive strength for water quenched RC columns

Temperature °C	% Probable compressive strength of concrete			
	Water quenching method			
	1-hour duration		3hours duration	
	OPC	HVFA	OPC	HVFA
27	100	100	100	100
100	92	90	82	82
200	99	93	80	87
300	100	88	72	73
400	88	85	71	74
500	84	81	67	67

600	77	75	57	67
700	62	70	43	55
800	39	42	30	36



Water quenching: Referring to Fig.5 the variation of probable compressive strengths with temperature for 1-hour exposure, and cooled by water, which is done by quick quenching of the hot specimen in the water that approximately resembles the event of fire extinguishing done by using water jets in a real situation. It is evident there is a substantial drop in strength for both OPC and HVFA concrete (RC) columns to their air-cooled equivalents. This might have occurred due to thermal shocks while quenching the hot specimen in water, causes uneven contractions in the concrete matrix. OPC columns are shown better performance. Whereas, HVFA concrete columns showed relative performance in the compressive strengths having 2 to 12% fall concerning to their counter columns. The strength of HVFA concrete mix columns with their corresponding OPC column specimens cooled similarly is found to be comparable at 600° C temperature and retained slightly better strengths at 700 and 800° C. whereas at 800° C the strength of both concrete mixes observed to fall below 50% of its original concrete strength.

Likewise, it is evident that Fig 5 depicts the plots, declining strength of specimens exposed for 3 hours is below the 1-hour plots. With longer exposure duration the columns experiences to thermal stresses for a long time causes concrete prone to suffer in slow cooling by air, and the distress also happens to the specimens due to thermal shocks in sudden cooling in water. In both cases, the distress of concrete is obvious. The concretes for 3 hours heating and quenching in water have distress occurred for both OPC mix and HVFA mix columns. And the strengths were declining with marginal fluctuations between OPC concrete columns and HVFA concrete column specimens. They showed a similar trend, whereas HVFA concrete mix columns perform progressive improvement in strength up to 500° C and at 600, 700 and 800° C maintained substantial strengths of 10, 12, and 6% over OPC columns. In water quenching, the propagation of heat towards the core of the concrete member is discontinuous when compared to air-cooled concrete member. Therefore, the concrete experience only thermal shocks, causes micro-cracks on concrete surfaces. But,

HVFA concrete experienced thermal stress to expel pore pressure, while heating. Which, were earlier than thermal shocks in water results the strength variations

Different researchers carried out similar studies regarding the effects of high temperatures on the properties of concrete. Similar to the results of the current study, researcher Chan et al., 1999 found that the temperature range between 400 and 800°C had a significant effect on strength loss and Jianzhuang Xiao and Gert Konig, 2004 stated that the compressive strength of ordinary concrete reduced drastically when the temperature reached beyond 400°C. At 800°C, the strength loss is about 80%.

Moreover, it is observed that significant strength loss happened within the first 1h duration of exposure for both concrete mixes. The bulk loss in compressive strength of concrete by water quenching method for OPC and HVFA mix RC columns is 8 - 51% and 10 - 58% respectively. Whereas by the air-cooling method, the columns lost 4- 29% and 6- 35% strength at 500-800°C temperatures for the 1-hour duration. These results showed air cooling of concrete columns retained higher residual strengths for the 1-hour duration of exposure. The strength decline trends by rebound hammer are similar to the observations of the researchers Mahdi SalehEssa and Mohammed Mansoor Kadhum, (2010) and Saeed Ahmed Al. Sheikh (2011) for RC rigid beams. Likewise, the OPC mix RC columns cooled by air performed better over HVFA mix RC columns in compression. This may be attributed to the fact that the OPC concrete is comparatively permeable than HVFA concrete mix. The permeability of OPC concrete might have facilitated the concrete to expel pore water pressure (thermal stress) generated at high temperatures. As a result, OPC concrete retained slightly more strengths than HVFA concrete by air cooling method.

For the 3h duration of exposure, it is obvious, the strength loss is more, for the water quenching method, and the strength loss of OPC and HVFA concrete RC columns is 18- 64% and 18-70% respectively. This shows that strength loss is more or less similar for both concrete. However, by air cooling method the strength loss is 19- 53% and 14- 61% for OPC and HVFA concrete mix respectively. It shows that HVFA concrete suffered more at high temperatures due to the high density and low permeability of concrete.

On the whole, the residual compressive strengths of concrete from 100 to 800°C for 1, and 3 hours duration of exposure by air cooling method vary from 118 to 47% for OPC concrete RC columns and for HVFA concrete RC columns it is from 97 to 39%. And for water-cooled specimens, the residual concrete strength variation is 92 to 36% for OPC concrete mix columns and 90-30% for HVFA concrete columns. This result shows HVFA concrete mix retained relatively equal residual strengths with OPC concrete mix and comparable. The reductions in compressive strength of concrete when exposed to high temperatures can be attributed to the dehydration of concrete by driving out of free water at lower temperatures and chemically combined water at higher temperatures.

The loss of physically bound water significantly affects the mechanical properties of the concrete exposed to high temperatures (Omer Arioiz 2009, M S Khan and H Abbas 2014 and Phan et al. 2001). A rapid decrease in the compressive strength is observed in the temperature range of 700°C-800°C for all parametric study for OPC and HVFA concrete columns by both the cooling methods.

B. Concrete quality grading of RC columns by Ultrasonic Pulse Velocity (UPV) test

The average pulse velocity of OPC concrete mixes RC columns before heating is 4.3 km/s, also for HVFA concrete mix RC columns, the pulse velocity obtained as 4.3 km/s. Then the columns are exposed to high temperatures from 100 to 800°C at an interval of 100°C, for 1 and 3 hours duration of exposure and brought to room temperature by air cooling and water quenching methods (legend marked as AC and WQ). Again, specimens were tested for quality grading of the concrete by ultrasonic pulse velocity test. The absolute values of pulse velocities of the heated columns for 1 and 3 hours exposures and cooled by both cooling methods are shown in Table 5 and Table 6. And Fig.6 to Fig.9 depicts the variation of residual pulse velocities in km/s with an increase in temperature.

The absolute values of pulse velocities from Table 5 indicate the concrete quality grading as 'good' for unheated OPC and HVFA concrete columns as per criterion specified by Table 2 of IS IS13311 (part I): 1992. Also, both types of concrete columns exposed up to 300°C temperatures maintained the concrete quality grading as good (in terms of material integrity).

Table 5 Variation of pulse velocities with temperature for air cooled specimens

Temperature °C	Pulse velocities of air cooled RC columns in km/s			
	OPC concrete mix		HVFA concrete mix	
	1-hour	3 hours	1-hour	3 hours
27	4.3	4.3	4.3	4.3
100	4.2	4.5	4.4	4.2
200	3.7	3.9	4.1	3.9
300	3.9	3.6	3.8	3.4
400	3.7	3.3	3.5	3.2
500	2.9	2.3	2.2	1.5
600	2.4	1.8	1.5	1.3
700	1.5	1.2	1.2	0.7
800	1.3	1.1	0.9	0.7

The material integrity is also 'good' for the columns exposed for 3h duration of exposure by the air-cooling method. This result shows both OPC and HVFA concrete are heat resistant up to 300°C temperature exposure, regardless of the method of cooling. This trend may be attributed to the accelerated hydration of cement gel of concrete and evaporation of excess water from concrete for 1h and 3 hours duration of exposure respectively. For the concrete exposed beyond 300°C temperature and up to 400°C, the concrete quality grading is designate as medium. Beyond 500°C temperature, the concrete quality grading is poor, and

it requires further tests according to Table 2 of IS13311 (part I): 1992.

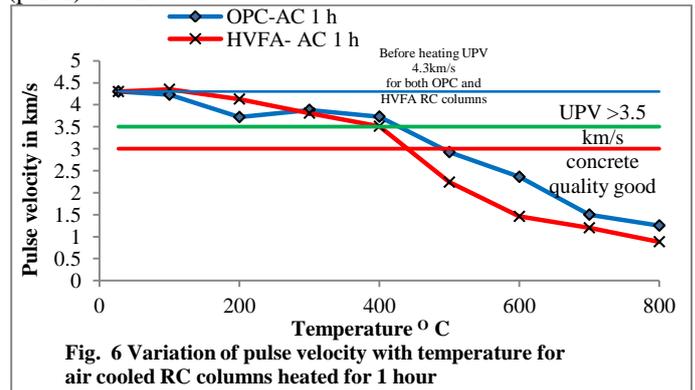


Fig. 6 Variation of pulse velocity with temperature for air cooled RC columns heated for 1 hour

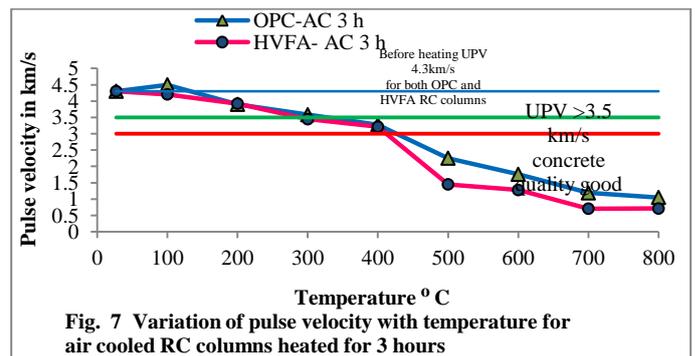


Fig. 7 Variation of pulse velocity with temperature for air cooled RC columns heated for 3 hours

Table 6 Variation of pulse velocities with temperature for water quenched specimens

Temperature °C	Pulse velocities of water quenched RC columns in km/s			
	OPC concrete mix		HVFA concrete mix	
	1-hour	3 hours	1-hour	3 hours
27	4.3	4.3	4.3	4.3
100	4.1	4.3	4.1	4.1
200	4.1	3.9	4.2	3.8
300	3.7	3.0	3.9	3.1
400	3.3	2.7	3.7	2.9
500	3.0	2.6	3.5	2.9
600	2.8	2.7	2.8	2.8
700	2.4	2.6	2.4	2.9
800	2.1	1.8	2.0	2.7

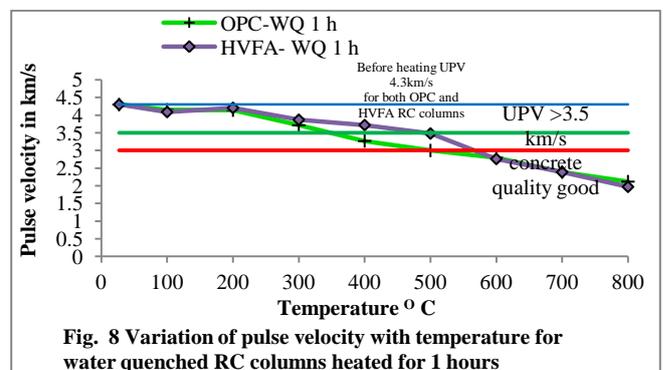
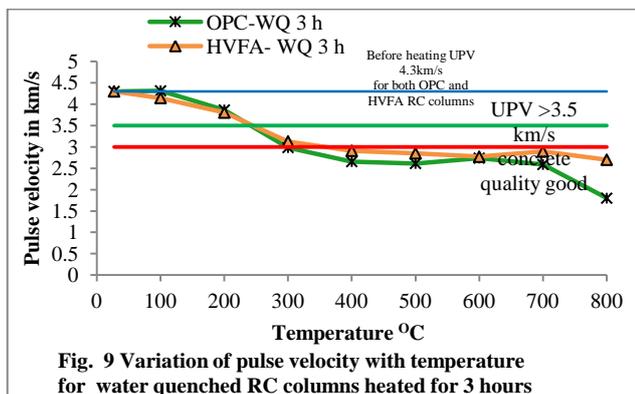


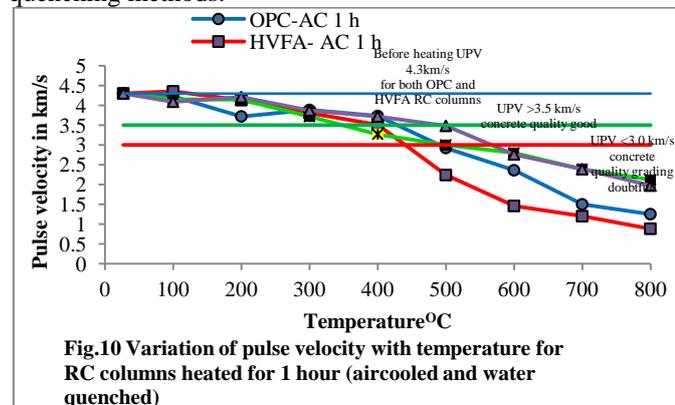
Fig. 8 Variation of pulse velocity with temperature for water quenched RC columns heated for 1 hours



These results showed the pulse velocity pronounced, HVFA concrete performed equally well with OPC concrete at higher temperatures. The loss of strength due to the increase in temperature may be the loss of both steel strength, and concrete strength occurred simultaneously. Pulse velocities measured for concrete specimens reduced from 4.3 to 1.1km/s for OPC concrete RC columns and it is reduced from 4.3 to 0.7 km/s for HVFA concrete RC columns with an increase in temperature from 100 to 800°C. Similar findings were obtained by the researcher (Omer Arioz 2009 and Handoo et al. 2018).

A. Effect of temperature on the method of cooling

Referring to Fig.10 and Fig.11, both OPC and HVFA concrete RC columns heated up to 400°C temperatures for 1 hour duration of exposure maintained concrete quality grading, relatively same by both air cooling and water quenching methods.



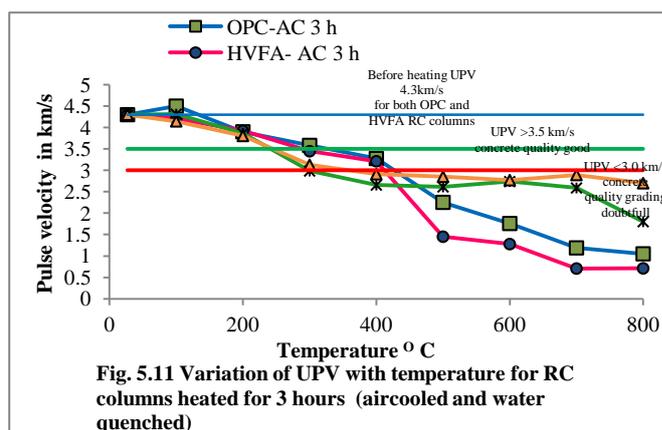
From Fig.10, a straight forward comparison of pulse velocities is made between air-cooled and water quenched specimens that were exposed for one hour. Both OPC and HVFA concrete mix RC columns heated up to 400°C temperatures maintained concrete quality grading, relatively similar, and represented as good quality concrete mix by both air cooling and water quenching methods.

Further, it can be observed interestingly that the pulse velocities of water quenched specimens showed improved performance over air-cooled ones at higher temperatures, from 500 to 800° C. which is a contrary sign while considering the fact of an occurrence of thermal shock. Even supposing the predominant property of concrete, permeability plays a major role in heat conduction. This property of concrete mix provides low heat conductivity. The temperature is not migrated to the core of the concrete specimen, up to the temperature exposure 400°C. Beyond 400°C, as the temperature rises, the heat conductivity is

continuous to migrate towards the core of concrete, thereby material integrity reduces by air cooling of specimens. Whereas, the specimens quenching in water heat migration towards the core of concrete discontinuous. NK Raut and VKR Koduru, (2011) reported that the measured temperature at a middle depth of concrete is less than the temperature at the rebar's, and this is due to the high thermal capacity and lower thermal conductivity of concrete which slows down heat migration towards inner layers of concrete. Therefore, beyond 400° C water quenching method, specimens uphold the quality of concrete over air-cooled ones.

It is observed that the method of cooling influences significantly the residual compressive strength and pulse velocity of columns with an increase in temperature. From Fig. 11, the comparison is made between air-cooled and water quenched specimens that were exposed for three hours.

It shows that the air-cooled HVFA concrete mix specimens performed lower than the water quenched HVFA concrete mix specimens, which is evident that the heat migration is continuous towards the core of the specimen, which in terms thermal conduction of reinforced concrete. Whereas, heat (thermal) conduction through the specimens is discontinuous in the case of immediate water quenching attribute to upkeep the concrete integrity.



Similar trends are observed in cases of OPC concrete mix specimens that were water quenched specimens carry on concrete quality over air-cooled ones. The plots represented in Fig. 11 more evident to focus on the pulse velocity variations from 500 to 800°C.

Pulse velocity variation for water quenched specimens is flatter than air-cooled specimens signifies the continuity and discontinuity of the heat conduction towards core concrete.

B. Visual observations of columns heated to high temperatures.

When reinforced columns exposed to high temperatures, the surface structure does not change until temperature exposure reaches 700°C. Surface cracks were observed at 800°C temperature for OPC concrete. In general spalling of concrete is the most obvious sign for standard and high strength concrete. However, the spalling of concrete is not observed for both types of concrete RC columns up to 700°C temperature exposure.



When columns are subjected to temperatures up to 300°C, the colour of the concrete does not change. However, the colour of the concrete is affected significantly by the increase in temperature exposure beyond 300°C. This change is also influenced by the method of cooling of the concrete.

The colour of the columns changed to light yellow at 300°C temperature, after cooling them to room temperature by air cooling method. However, the colour does not change for the water quenching method for both the types of concrete mix. From 400°C to 600°C temperature, the specimens turned to brown colour. Subsequently, the columns exposed to temperatures 700°C and 800°C became red-hot condition when they removed from the furnace, after cooling to room temperature they turned to smoke grey colour. At this instance, surface cracks appear on OPC concrete columns, and surface spalling observed for HVFA columns. In addition to this, white scales (white deposits) are formed on the surface of the columns when they are exposed at 700°C and 800°C temperature and cooled by the water quenching method. The drastic reduction in strength and formation of cracks and white scales on the surface of the concrete columns represents the distress in concrete that occurred in the form of cracking (between cement and aggregate) at 700 and 800°C temperatures.

VI. CONCLUSIONS

- Compressive strengths of conventional concrete columns (OPC) carried slightly higher strengths than HVFA concrete columns for 1-hour duration of exposure at all temperatures by air cooling. The maximum increase in compressive strength was observed between 200°C-300°C for 1-hour exposure duration. And the strength increased at 100°C for 3 hours duration of exposure.
- The bulk loss of strengths by water quenching method is 8 - 61%, 10 - 58% of the compressive strengths at 100-800°C for OPC and HVFA concrete columns, respectively. Whereas by air cooling method, the columns lost 4 -29% and 6- 35% strength at 500°C-800°C temperatures for the 1-hour duration, shows that both concrete columns have higher residual strengths by air cooling method than water quenching method for the 1-hour duration of exposure.
- The pulse velocities of unheated specimens and also those exposed up to 300°C exhibited concrete quality grading represents as good. However, the specimens exposed to 300°C to 400°C indicate concrete quality grading as medium quality. Therefore, both types of concrete columns are heat resistant up to 400°C temperatures. The drastic reduction in strength and formation of white scales on the surface of both concrete columns represents distress in concrete that occurred in the form of cracking at 700 and 800°C temperatures.
- Method of cooling pronounced the effect of temperature exposure on the performance of concrete. Specimens heated up to 400°C temperatures exhibited better performance by air cooling whereas beyond 400°C temperature exposures the water-cooled specimens exhibited best in upholding concrete quality as the propagation of heat towards core concrete is discontinuous.
- OPC concrete mix performance is better than the HVFA mix by air cooling method, and so it is recommended to reduce % of fly ash in HVFA to enhance its performances.
- UPV results provide a qualitative assessment for the performance of columns at high temperatures. Furthermore, this data obtained may be useful for the planning of necessary repair and rehabilitation of structural members to be carried out, for the strengthening of the fire affected reinforced concrete columns.

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