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Non-destructive assessment of heat-damaged concrete

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The damage assessment of concrete exposed to different temperatures has been essential to ensure structural safety and residual behavior. High temperatures have significantly weaken the integrity of concrete, which may have lead to partial or complete failure of concrete elements under loading conditions, posing safety risks. To investigate the extent of damage caused by high temperatures, an experimental study has been conducted involving visual inspection and non-destructive testing. Concrete cubes have been exposed to elevated temperatures under steady-state heating conditions, and the UPV test has been performed after they have been completely cooled to ambient conditions. Based on the test findings, a temperature-dependent relationship has been established for UPV velocity and transit time. The test results have indicated that cubes exposed to elevated temperatures exhibit a significant reduction in UPV values compared to unexposed cubes, with the extent of damage having increased with temperature. Developed temperature-dependent equations have aided in determining the quality of concrete after exposure to various temperature ranges. This study has aided in understanding the degree of damage at elevated temperatures.

Keywords: Damage assessment, Structural safety, Non-destructive test, Temperature, Ultra-sonic pulse velocity

1 Introduction

Concrete is widely recognized as a fire-resistant, non-combustible material commonly used in the construction industry. However, concrete undergoes significant changes when exposed to high temperatures, including thermo-mechanical and thermo-chemical alterations in its original composition and mechanical properties[1-3]. These high-temperature-induced alterations affect the performance of concrete. It has been observed that the physio-chemical and mechanical damage caused by heating reduces the load-bearing capacity of concrete elements[4]. High temperatures deteriorate the mechanical properties of concrete, particularly its compressive strength.

The most critical aspect after a structure is subjected to fire is evaluating its structural safety[5].Nevertheless, repairing damaged structures could be of economic interest, as the costs of demolition and rebuilding are significantly higher. Therefore, it is essential to assess the damage caused by fire to determine the appropriate course of action. The assessment of fire-damaged structures typically begins with a visual inspection as a preliminary evaluation[6], followed by more detailed assessments using various methods, such as material tests, destructive testing, and non-destructive tests (NDT). The destructive testing method is limited due to safety conditions when extracting cores from key structural elements, accessibility challenges, and the high cost and disruption involved also decrease the capability of existent structures[7]. Variations in compressive strength across structural elements and locations make the approach further difficult. Considering these difficulties, NDT has become a widely adopted alternative for evaluating fire damaged concrete.

Various tests are available for assessing concrete through NDT techniques, including Ultrasonic Pulse Velocity (UPV), Rebound Hammer testing, Ground Penetrating Radar (GPR), carbonation testing, and Electrical Half-Cell Potential (HCP). Each of these tests focuses on specific parameters within a concrete structure, but UPV has proven highly effective for assessing the homogeneity and quality of concrete in both fresh and hardened states[8]. In recent years, various experiments have demonstrated that ultrasonic wave propagation testing is a promising method for assessing concrete behavior under ambient conditions.

As studied by the authors[9], the UPV method can be applied to estimate concrete compressive strength, determine the material's dynamic modulus, assess concrete homogeneity, and identify the presence of cracks[10].The UPV method uses wave propagation

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*Corresponding author (E-mail: suvir_singh@yahoo.com) theory to measure the depth of the material and detect internal cracks[11]. Recently, however, UPV methods have also been used for post-fire evaluation[12-14]. The evaluation of residual strength in concrete becomes a challenge after fire due to the reduction in strength, which depends on the distance from the surface and is examined through destructive testing. The study[13] utilized the Ultrasound Pulse Velocity (UPV) method with point probes to analyze samples collected from a structure subjected to an actual fire. The study[14] examines the main differences between UPV and residual strength in post-heated concrete to address challenges in using ultrasonic testing for post-fire evaluation. The conducted studies are significant for understanding the impact of the UPV method in post-fire evaluation; however, there is still limited data on the extent of damage that occurs at sequential heating temperatures. This paper presents a series of tests to assess changes in pulse velocity and travel time in normal-strength concrete exposed to high temperatures ranging from 100 to 600°C. A relationship between temperature and UPV values is established, and a general equation for predicting UPV velocity and travel time is proposed. The paper also verifies the accuracy of this equation by comparing it with test data. The test results and proposed equations are important for determining the quality of concrete and assessing the degree of damage at elevated temperatures.

2 Materials and methods

2.1 Mix proportion

The mix proportion was designed to produce the most commonly used normal-strength concrete of grade M20. The materials used for preparing the concrete mix included cement, fine aggregate (FA), coarse aggregate (CA), and water. The river sand was used as fine aggregate, and siliceous crushed stones were used as coarse aggregate. Ordinary Portland cement of grade 43 and potable water were also included in the test. The coarse aggregate had a maximum size of 12.5 mm. The ingredients of the concrete mix comprise 1087 kg/m³ of coarse aggregate, 800 kg/m³ of fine aggregate, 383 kg/m³ of cement, and 191 kg/m³ of water. The water-to-cement ratio was 0.5. The mix design was prepared following the Indian Standard IS 10262[15].

2.2 Test specimen

A total of twelve cube specimens of size 150 x 150 x 150 mm, were fabricated using the same mix to evaluate damage behavior after exposure to elevated temperatures. Each single cube was exposed to every specified temperature at intervals of 100°C, ranging from ambient to 600°C, while four cubes were used to measure the compressive strength. The thermocouple was embedded at the center core, 75 mm depth of the specimen. The cube specimens were demolded 24 hours after casting and submerged in water for 28 days of curing. The average 28-day compressive strength of four cube specimens was obtained to be 25.34 MPa.

2.3 Test procedure

The concrete cubes were exposed to temperatures ranging from 100°C to 600°C until a steady-state heating condition was attained at each specified temperature. An electrical muffle furnace with a 600 mm× 600 mm cross-section was used to expose the concrete cubes to temperatures of 100°C, 200°C, 300°C, 400°C, 500°C and 600°C, respectively. The details of the furnace with concrete cube specimens are shown in Fig. 1. The furnace consists of a highly insulated chamber (the "muffle") that isolates the samples being heated from the heating elements. This prevents the sample from being directly exposed to the heat source, ensuring controlled and uniform temperature distribution. The insulated muffle ensures that heat is evenly distributed throughout the chamber, preventing hotspots and enabling consistent treatment of samples. The furnace is equipped with heating elements and thermocouples, which continuously measure the temperature inside the chamber. The controller adjusts the electrical supply to the heating elements to maintain precise temperature levels.Once equilibrium conditions were achieved at the specified furnace temperature in the

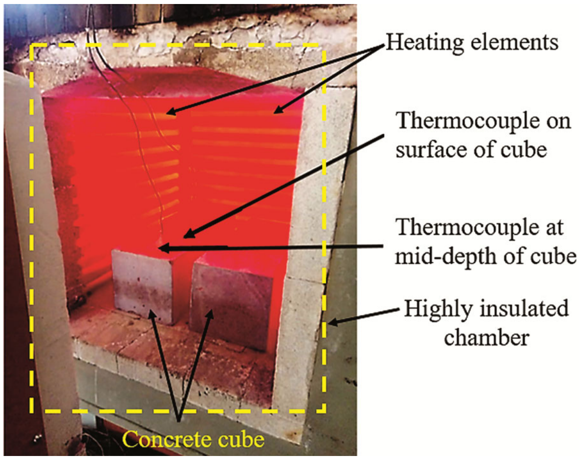

Fig. 1 — Temperature-exposed concrete cubes in a muffle furnace.

specimen, the furnace was switched off, and the specimens were allowed to cool. After the specimens had completely cooled to ambient conditions, the damage behavior was assessed using visual inspection and ultrasonic pulse velocity (UPV) method for each specified temperature.

2.4 Temperature exposure

The concrete cubes were placed in the muffle furnace at the specified temperature and were maintained in the furnace until the concrete core temperature matched the furnace temperature. The cubes were heated gradually, and the temperature was monitored and recorded at the surface ($T_{surface}$) and the center (T_{core}) of each cube using thermocouples connected to a data acquisition system. When the thermocouple embedded at the center of the specimens indicated the specified furnace temperature, it was assumed that the entire specimen is reached thermal equilibrium at the specified furnace temperature. The furnace temperature was then maintained for an additional 30 minutes to ensure steady-state heating conditions at the specified temperature. The time-temperature curve shown in Fig. 2 indicates that the furnace temperature initially increases to the specified temperature and is then maintained throughout the exposure period until steady-state heating conditions are achieved within the specimen. This entire process is repeated for all the specimens at a temperature range from 100 to 600ºC.

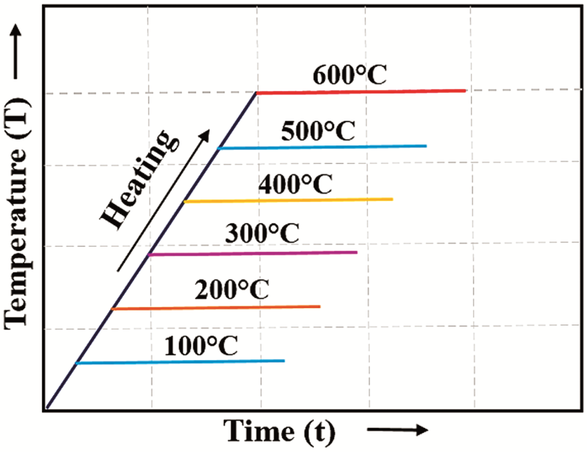

Fig. 2 — Furnace time-temperature curve employed for test specimens.

2.5 Damage behaviour assessment

Assessing the damage behaviour of concrete specimens exposed to different temperatures includes visual inspection and non-destructive testing. The colour changes in fire-exposed concrete serve as a visual marker of temperature exposure and potential structural degradation. Understanding these changes can help assess the severity of the different temperatures impact and estimate the depth of the damage.

2.5.1 Visual inspection

A systematic visual inspection was conducted to assess concrete cubes exposed to elevated temperatures. The fire-exposed test specimens are illustrated in Fig. 3, which includes both unexposed specimens and those subjected to temperatures ranging from ambient to 600°C. The physical appearance of the test specimens shows that, as the temperature increases, surface cracking and color changes occur. Micro-cracks are caused by thermal stress and vapor pressure generated by the evaporation of free moisture[16]. At 400°C, the concrete undergoes the decomposition of calcium hydroxide, releasing additional water and accelerating the reaction[17]. Consequently, specimens exposed to temperatures above 400°C show significant cracking, particularly at 500°C and 600°C.

The color changes observed in fire-exposed concrete provide critical clues about the temperatures the material has endured and the extent of thermal damage. These changes result from physical and chemical transformations in the concrete, including the cement paste and aggregates. Different temperature ranges induce distinct color changes in the concrete, as seen in the test specimens shown in Fig. 3. The unexposed concrete at ambient conditions shows no sign of damage and is grey in color. The concrete typically retains its original color with no

Fig. 3 — Concrete cubes after thermal exposure to elevated temperatures. (a) Ambient, (b) 100° C, (c) 200° C, (d) 300° C, (e) 400° C, (f) 500° C and (g) 600° C.

significant visible changes from ambient temperature to 300°C, which can be attributed to minor dehydration of the cement paste[18], though this is not visibly noticeable. However, in the temperature range of 400°C to 600°C, the concrete develops a pink or reddish color due to significant chemical changes in the cement and aggregates[19].

2.5.2 Non-destructive testing (NDT)

The Ultrasonic Pulse Velocity (UPV) method is used to assess the condition of fire-exposed concrete at different elevated temperatures. The UPV test is an in-situ, non-destructive testing (NDT) method used to evaluate the quality of concrete on-site. The quality of concrete is assessed by determining the velocity of an ultrasonic pulse as it travels through the material. This method provides valuable insights into the uniformity, internal cracks, voids, and honeycombing of concrete[20]. The UPV test relies on the transmission of ultrasonic waves through the material, measuring the time it takes for the ultrasonic pulse to travel from one surface of the concrete specimens to the other[21].A general illustration of the test equipment and circuit is shown in Fig. 4. The test equipment consists of a pulse-generating circuit that generates wave pulses and a transducer that converts electronic pulses into mechanical pulses, as shown in Fig. 4. It operates at an oscillation frequency in the range of 40 kHz to 50 kHz, and includes a pulse receiver circuit that detects the wave signals. When a pulse of ultrasonic waves is generated on one side of the material, it propagates through the material and is detected by a receiver on the opposite side or the same side. The time taken for the pulse to travel a known distance is recorded. The velocity of the UPV can be determined using Equation 1.

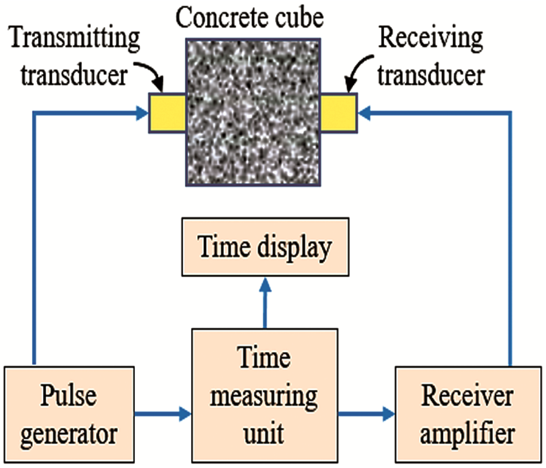

Fig. 4 — Graphical representation of the working principle of UPV test equipment[22].

$$\text{Pulse Velocity (v)} = \frac{\text{Width of structure (L)}}{\text{Time taken by pulse to go through (t)}} \quad \dots (1)$$

Higher wave velocities indicate good quality concrete and uniformity of the material used, while lower velocities may indicate poor quality concrete, which may contain cracks or voids. The qualitative grading of concrete based on UPV data, as per IS 13311-Part I[23], is given in Table 1.

In the UPV test, the transmitter and receiver were placed on opposite sides of the temperature exposed cube specimens to measure the ultra-sonic pulse velocity. The surface of the concrete cubes was divided into number of grid as shown in the Fig. 5a, and UPV values were measured at nine surface locations. This process was repeated at nine locations

Table 1 — Concrete quality grading as per IS 13311 (Part I)[23].

UPV Velocity (km/sec)	Concrete Quality Grading
Greater than 4.50	Excellent
Between 3.50 and 4.50	Good
Between 3.00 and 3.50	Medium
Less than 3.00	Doubtful

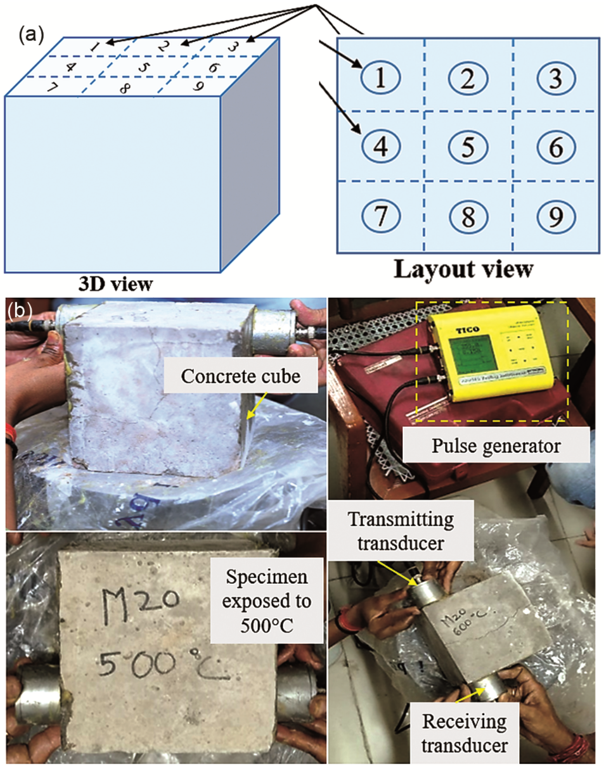

Fig. 5 — (a) UPV test measurements and (b) UPV test on temperature-exposed concrete cube.

on the same side of the cube to ensure the reliability and accuracy of the results. The concrete surface was thoroughly prepared for good acoustic coupling by applying grease. A small amount of pressure was applied to maintain proper contact of the transducer. The travel time of the pulse wave and its velocity were measured. The wave generated at the transmitting end propagated to the receiving end, and the time taken for the wave to travel and its velocity were recorded. The entire procedure was repeated for cubes exposed to temperatures ranging from 100°C to 600°C. The illustration of the UPV test, including the equipment used and the process followed, is shown in the Fig. 5b. By knowing the path length (i.e., the length of the specimen) and the travel time, the pulse velocity was calculated.

3 Results and Discussion

The UPV pulse velocity was measured at nine points, denoted as U1, U2, U3, U4, U5, U6, U7, U8, and U9, and shown in Fig. 6&7. The UPV and associated travel time of fire-exposed concrete cubes are crucial indicators of damage induced by thermal exposure. The plotted test results in Fig. 6&7 illustrate that UPV values decrease significantly as the temperature rises. This behavior is attributed to various physio-chemical reactions, such as dehydration of concrete, loss of bond between aggregate and cement paste, and thermal micro cracking, which occur in concrete at elevated temperatures[16]. The decrease in UPV is negligible in the temperature range of 100 to 300°C, as shown in Fig. 6. The modest increase in travel time in Fig. 7 for this temperature range suggests that only slight thermal stresses are generating micro cracks in the concrete matrix, which is essentially intact. At temperature of 400°C, there is a little decrease in UPV velocity, which is correlated with a slight increase in travel time. The formation and spread of micro cracks, as well as chemical alterations such calcium hydroxide breakdown, can be attributed to it[24]. Nevertheless, the UPV velocity rapidly drops

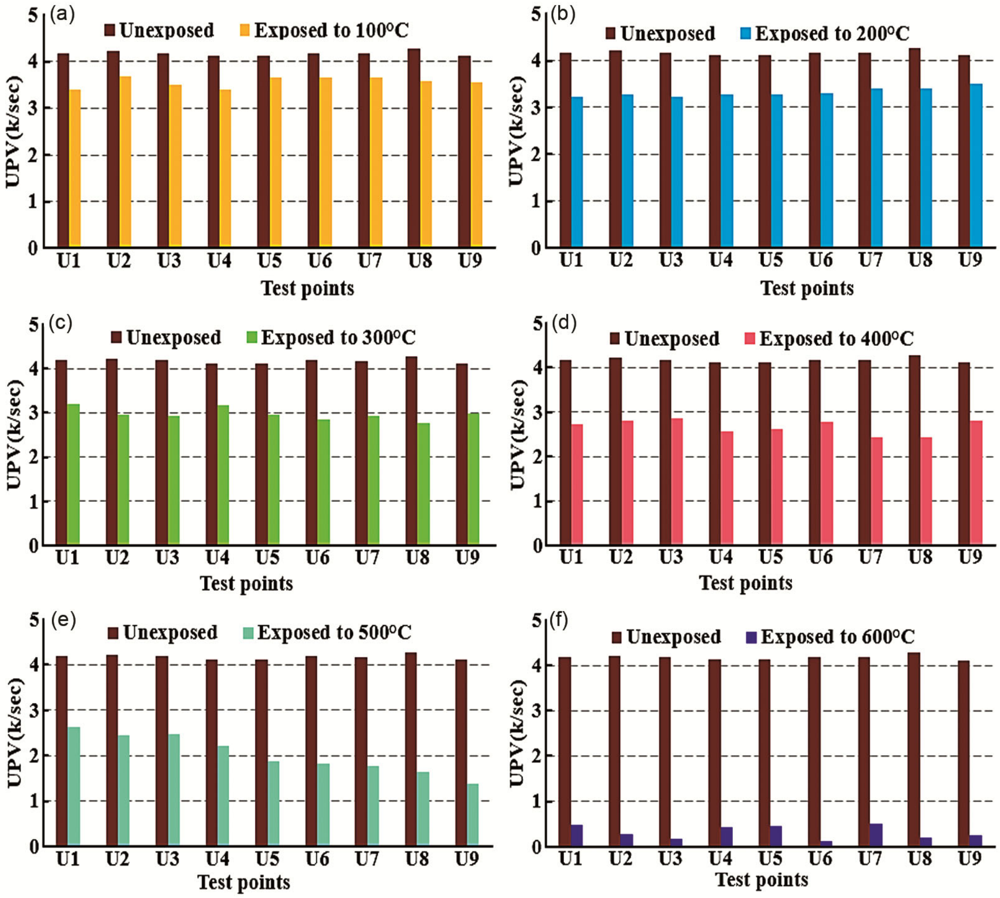

Fig. 6 — Test results UPV for unexposed and temperature-exposed cube specimens (a) 100° C, (b) 200° C, (c) 300° C, (d) 400° C, (e) 500° C and (f) 600° C measured at nine points.

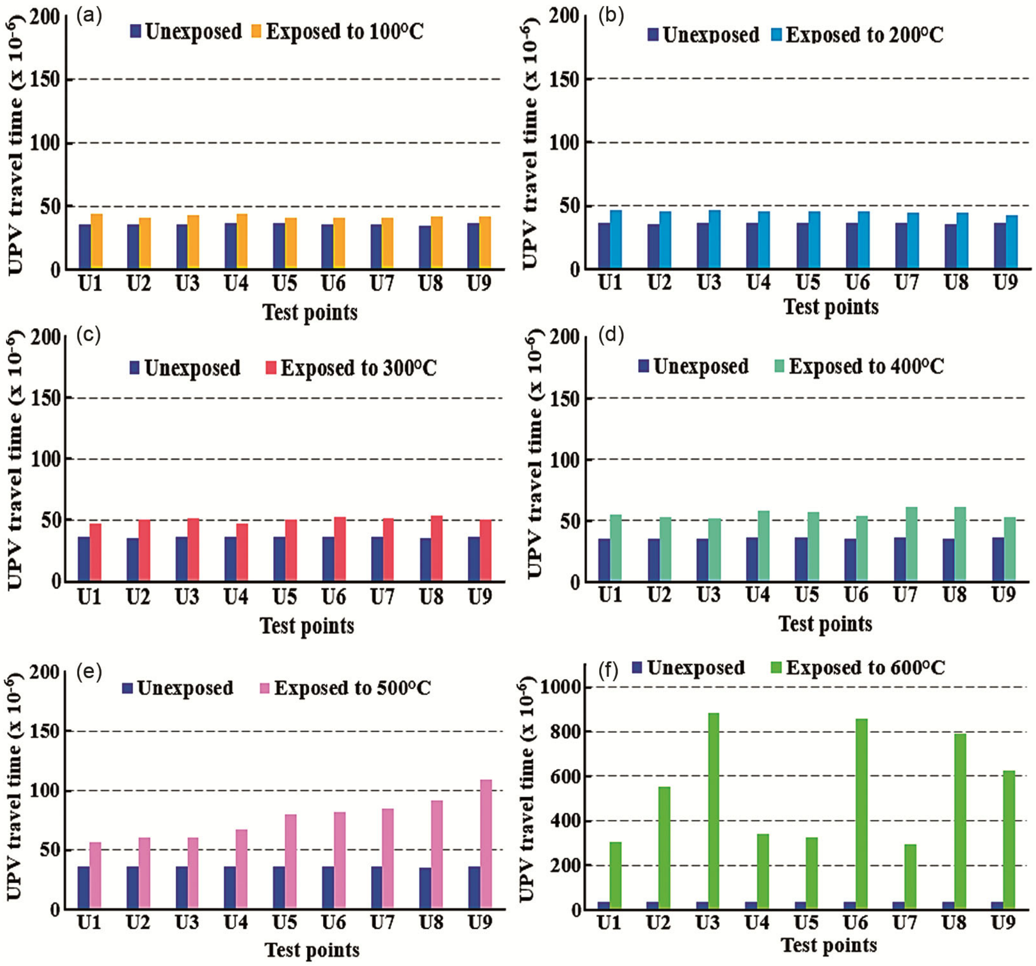

Fig. 7 — Test results of UPV travel time for unexposed and temperature-exposed cube specimens (a) 100° C, (b) 200° C, (c) 300° C, (d) 400° C, (e) 500° C and (f) 600° C measured at nine points.

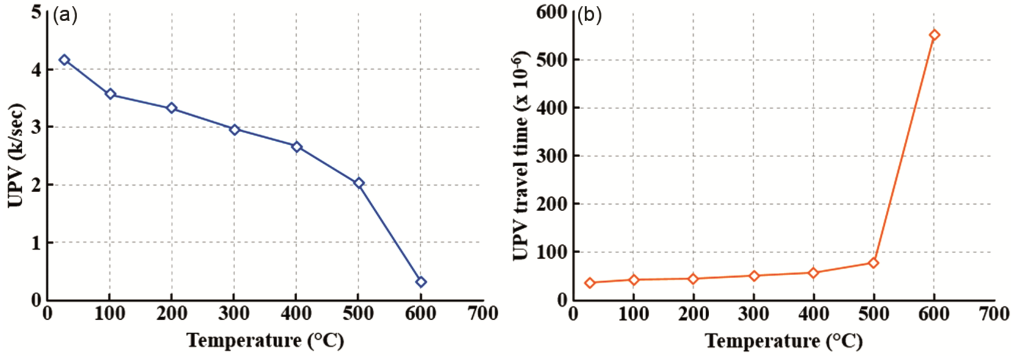

Fig. 8 — Average UPV test result for nine tested locations at various temperatures (a) UPV velocity and (b) UPV travel time.

and travel time significantly increases in the 500–600°C temperature range, can be seen in Fig. 6&7. This indicates severe internal damage, which includes aggregate expansion, extensive cracking, and microstructure collapse brought on by cementitious compound breakdown. The UPV measurements taken at different surface locations of the cubes show some variation due to the damage sustained at elevated temperatures. An average of the UPV values and travel time, calculated from the readings at nine measured points, is shown in Fig. 8. The UPV velocities obtained at temperatures of 27°C, 100°C,

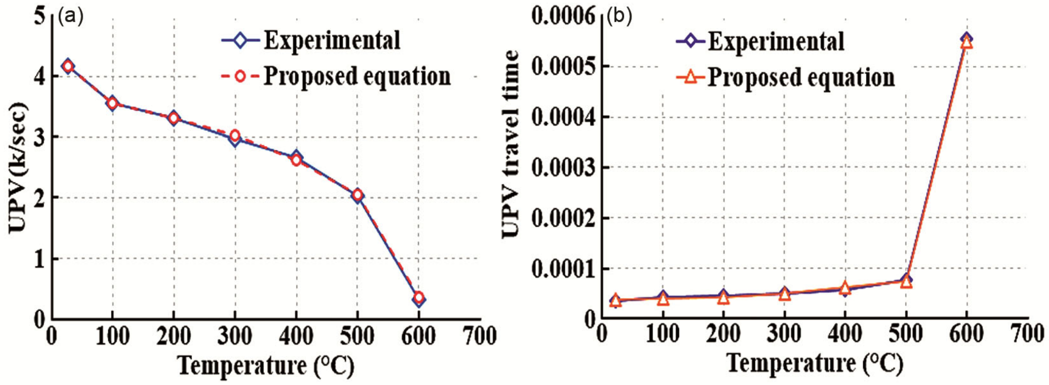

Fig. 9 — Validation of proposed equations with experimental data (a) UPV versus Temperature and (b) Travel time versus Temperature.

200°C, 300°C, 400°C, 500°C, and 600°C are4.173, 3.566, 3.322, 2.971, 2.671, 2.027 and 0.322, respectively, while the corresponding UPV travel times at the same temperatures are 35.950 × 10^{-6}, 42.091× 10^{-6}, 45.183× 10^{-6}, 50.576× 10^{-6}, 56.354× 10^{-6}, 77.200 and 553.290× 10^{-6}. The irreversible nature of thermal damage is demonstrated by the fact that the UPV values and travel times remain low even after the cubes have cooled to room temperature.

3.1 Temperature dependent correlation

The UPV values are significantly affected by sequentially increasing temperature, indicating the degradation of concrete quality with temperature. However, laboratory tests to determine the quality of temperature-affected members are usually not feasible frequently, as they involve huge efforts and expenses. Therefore, a temperature-dependent correlation for UPV velocity and travel time over the temperature range of 20–600°C was developed using the test data shown in Fig. 8. This is especially relevant for concrete element's exposed to elevated temperature. The data obtained from the equation is significant for defining the classification of temperature-affected concrete based on UPV readings. The primary aim of regression analysis is to evaluate the degree of concrete damage at different temperatures by assessing UPV velocity and travel time. The regression-based Equations (2-4) and (5-6), developed for UPV velocity and travel time of concrete at high temperatures, have coefficient of determination (R^2) values greater than 0.99. These equations are validated using experimental data collected from specimens subjected to a range of temperatures, as shown in Fig. 9. This indicates a high level of accuracy of the proposed equations in comparison with the test data.

3.1.1 UPV velocity

$$V_{UPV,T} = 299.38 \times 10^{-7}T^2 - 114.86 \times 10^{-4}T + 440.98 \times 10^{-2} \quad 20°\mathrm{C} \leq \mathrm{T} \leq 200°\mathrm{C} \quad \text{... (2)}$$

$$V_{UPV,T} = -730.55 \times 10^{-8}T^2 + 950.55 \times 10^{-6}T + 340.96 \times 10^{-2} \quad 200°\mathrm{C} \leq \mathrm{T} \leq 500°\mathrm{C} \quad \text{... (3)}$$

$$V_{UPV,T} = -170.55 \times 10^{-4}T + 105.99 \times 10^{-1} \quad 500°\mathrm{C} \leq \mathrm{T} \leq 600°\mathrm{C} \quad \text{... (4)}$$

3.1.2 UPV travel time

$$t_{UPV,T} = 157.87 \times 10^{-12}T^2 - 664.56 \times 10^{-11}T + 384.27 \times 10^{-7} \quad 20°\mathrm{C} \leq \mathrm{T} \leq 500°\mathrm{C} \quad \text{... (5)}$$

$$t_{UPV,T} = 475.56 \times 10^{-8}T - 230.32 \times 10^{-5} \quad 500°\mathrm{C} \leq \mathrm{T} \leq 600°\mathrm{C} \quad \text{... (6)}$$

Where,
T = Temperature in °C
$V_{UPV,T}$ = UPV velocity at temperature T
$t_{UPV,T}$ = UPV travel time at temperature T

4 Conclusion

The non-destructive technique, UPV, was used in this study to assess the damage in concrete exposed to different temperatures. The obtained test data is useful for understanding the degree of damage in temperature-exposed concrete. The critical observations from the test results are summarized below.

a The reduction in UPV values and the increase in travel time highlight the severity of fire-induced damage in concrete. The UPV velocity obtained at ambient temperature and 100°C indicates good concrete quality as per IS 13311:1992. However, at 200°C and 300°C, the concrete quality is classified as medium. At 400°C, 500°C, and 600°C, the concrete quality is classified as doubtful, highlighting that above 300°C, the quality becomes severely degraded due to chemical processes occurring in the concrete.

b The average UPV velocity measured at nine points for temperatures of 100°C, 200°C, 300°C, 400°C, 500°C, and 600°C decreased by 14.52%, 20.387%, 28.801%, 35.990%, 51.407%, and 92.278%, respectively, compared to the values measured at ambient temperature. This significant reduction in UPV can be attributed to the formation of pores and cracks due to various physio-chemical reactions in the concrete.

c The travel time obtained at different temperatures shows a significant increase, indicating the induced damage in the concrete. The travel time measured at 100°C, 200°C, 300°C, 400°C, 500°C, and 600°C increased by 17.083%, 25.684%, 40.684%, 56.757%, 114.742 and 1439.05%, respectively, compared to the values measured at ambient temperature.

d The developed temperature-dependent correlation for UPV velocity and travel time will assist in determining the quality of concrete after exposure to different temperatures. It may play a significant role in decision-making for repairing thermally exposed concrete.

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Conflict of Interest

The authors declare that there is no conflict of interest or personal relationships that could have appeared to influence the work reported in this paper.

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