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Research Paper

Investigation of Ultrasonic Pulse Velocity Reduction in Reinforced Concrete Members Exposed to High Temperature

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Nowadays, the fire resistance of reinforced concrete members is generally defined by material characteristics at elevated temperatures and temperature functions. However, the influence of steel reinforcement in concrete members exposed to high temperatures on the ultrasonic pulse velocity (UPV) measurements has still been limited. In this paper, the quality of concrete and steel reinforcement/concrete interface was assessed under high temperatures using UPV measurements. The specimens were classified into four categories: the control tested cubes without rebar; tested cubes with plain and ribbed steel rebars. Tested cubes with dimensions of 100x100x100 mm were cast and cured for 28 days at room temperature (20ºC). After drying all specimens at 105ºC for 48 hours, these cubes were subjected to four different temperature levels ranging from 150ºC to 400ºC for 4 hours before being cooled to room temperature. According to the measured values of UPV, the higher the temperature attained in specimens, the greater the following changes occurred in concrete: (i) the degradation within the concrete; (ii) the debonding of steel reinforcements in concrete.

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1 Introduction

Reinforced concrete (RC) structures generally exhibit good fire-resisting properties based on their low thermal conductivity [1]. However, as a result of environmental factors (i.e., rate of heating, maximum exposure temperature, and heating duration), concrete and steel reinforcement change in mechanical and physical properties when exposed to fire. Based on previous studies, the structural capability of fire-damaged RC members is reduced because of the material characteristics of concrete and steel reinforcement [2-5]. The UPV test is a prevalent non-destructive technique to control the quality of concrete and damaged RC structures [6-8]. For example, Lin et al. [7] studied the relationship between residual compressive strength and UPV of concrete with and without water curing when subjected to high temperatures ranging from 400ºC to

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600ºC. According to the test results, curing condition of the concrete specimens has a substantial effect on the residual compressive strength and UPV relationship, while the water-cement ratio in the concrete mixture does not have a considerable effect on this relationship. Choi et al. [8] investigated the compressive and tensile strength of concrete exposed to high temperatures up to 800ºC using UPV measurements. Almost researchers explored that the relationship between residual compressive strength and UPV is linear.

On the other hand, the bond between steel reinforcement and concrete plays an important role in RC members. One of the main effects on the bearing capacity is a reduction in the bond strength of damaged RC members caused by exposure to high-temperature conditions [9-13]. Most previous experimental studies assessed the bond strength obtained from the destructive tests. Hlavička [14] conducted the pull-out tests to assess the bond strength between steel reinforcement and concrete at different temperatures. This experiment showed a decrease in both the compressive and bond strength as the temperature increased.

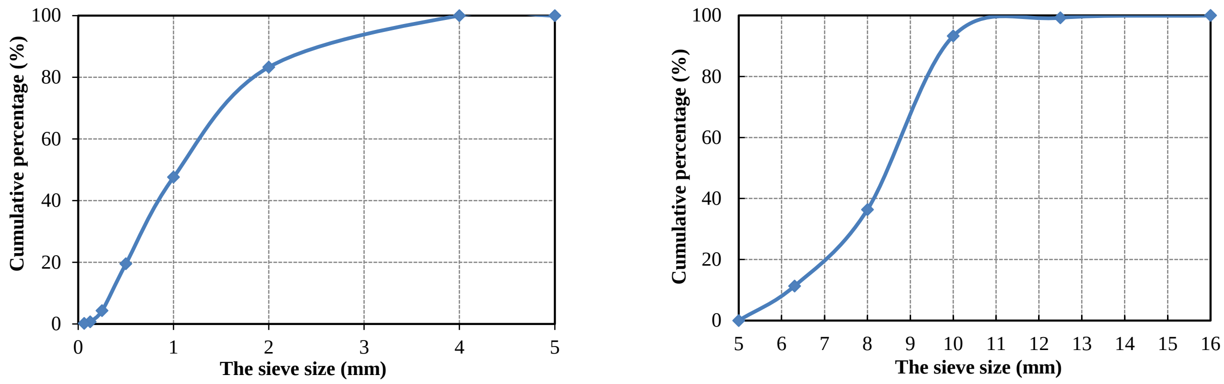
There are limited investigations of UPV reduction in damaged concrete with embedded steel reinforcements caused by heating. The present paper aims to assess the influence of the high temperature on the change in pulse velocity in damaged RC members using a series of cubic specimens. In this experimental work, tested specimens were exposed to high temperatures ranging from 150 to 400ºC. After that, the UPV test was carried out to determine the influence of heat-generated damages on the material characteristics, such as the steel/concrete interface.

2 Experimental program

2.1 Materials and tested specimens

2.1.1 Concrete

The mix designs based on cement CEM I 52.5N, fine aggregates, and coarse aggregates have a maximum nominal size of 5 and 15 mm. The mixing proportion of concrete used is given in Table 1. In particular, the grain size distributions of fine and coarse aggregates were determined by the sieving method to select aggregate proportions for the designed concrete mix. The grain size analysis provides the cumulative percentage retained on each sieve. Fig. 1 displays the granulometric curves for fine and coarse aggregates used in this study. The cumulative percentage of fine and coarse aggregates is satisfy according to the European standard EN 12620:2013 [15].



(a) (b)

Fig. 1 – Granulometric curves by sieving of (a) fine and (b) coarse aggregates

2.1.2 Steel reinforcement

In this study, the mechanical properties of steel rebars used were verified using the tension test. The experimental program utilized two sets of steel rebars cut to a length of 25 cm. The first set included plain steel rebars of grade Fe E235, which were 12 mm in diameter. The yield and ultimate tensile strengths of ϕ12 mm plain steel rebars were 235 and 410 MPa, respectively. Meanwhile, the second set included ribbed steel rebars of grade Fe E500, which were 12 and 16 mm in diameter.

For ribbed steel rebars, the average of yielding strength was 500 MPa and the average of ultimate strength was 550 MPa. Furthermore, based on the tension test, the percentage of ultimate elongation ranged from 12 to 22% for all steel rebars.

Table 1 - Concrete mix

Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water ($liter/m^3$)	W/C ratio
350	720	980	190	0.54

2.1.3 Test specimens

In this experimental study, three sets of cubes and one set of three cylinders were produced from the same concrete batch with the given concrete mix in Table 1. All specimens were cured in laboratory conditions at 20°C temperature and 100% relative humidity for 28 days.

Table 2 – Compressive strength of concrete at 28 days

Sample	Maximum load(kN)	Compressive strength(MPa)	Mean compressive strength(MPa)	Standard deviation (MPa)	Coefficient of variation (%)
1	486.4	51.2			
2	466.2	49.1	50.3	1.1	2.2
3	482.5	50.8			

The first set consisted of three cylindrical specimens with a diameter of 100 mm and a length of 200 mm. According to the compression test of these specimens at 28 days (Fig. 4a), the compressive strengths of three cylinders represent in Table 2. As a result, the mean compressive strength of the concrete used was 50.3 MPa. The second set was used for heating test, which was divided into three sample sets including 12 cubic specimens. Each sample set contains three cubic specimens with the same level of temperature. Each cubic specimen with dimensions of 100x100x100 mm was individually prepared for the heating test, as shown in Fig. 2 (a). These cubic specimens were classified into four groups. The first set has three specimens without reinforcement, denoted S1. Meanwhile, three sets compose specimens with reinforcement, denoted S2, S3, and S4, which correspond to plain and ribbed rebars of 12 mm in diameter, and ribbed rebars of 16 mm in diameter, respectively. Figs. 2 (b) and (c) illustrate the direct transmission mode for the two groups. As the Fig. 2(c), two thermoplastic tubes with a length of 2 cm were attached to each steel rebar to ensure an anchorage length for embedded rebar in a cube-shaped concrete specimen.

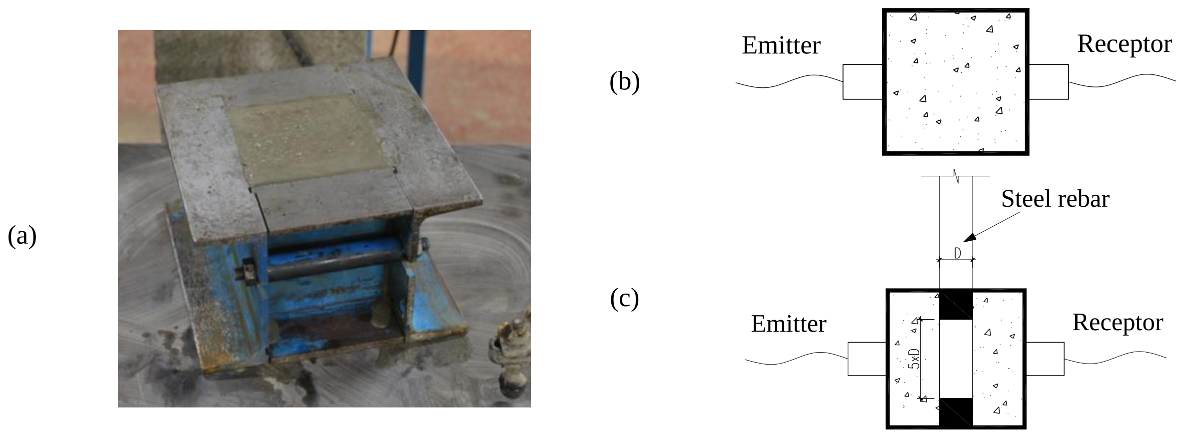
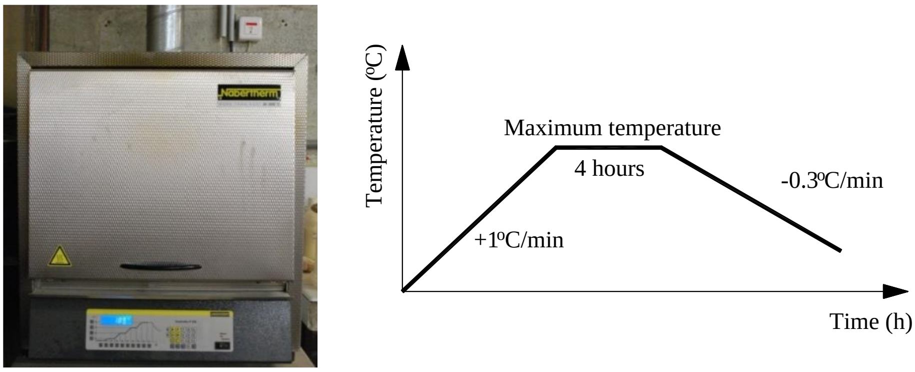


Fig. 2 – (a) Manufacturing test specimen; (b) Specimen without steel rebar; (c) Specimen with steel rebar

2.2 Experimental procedure

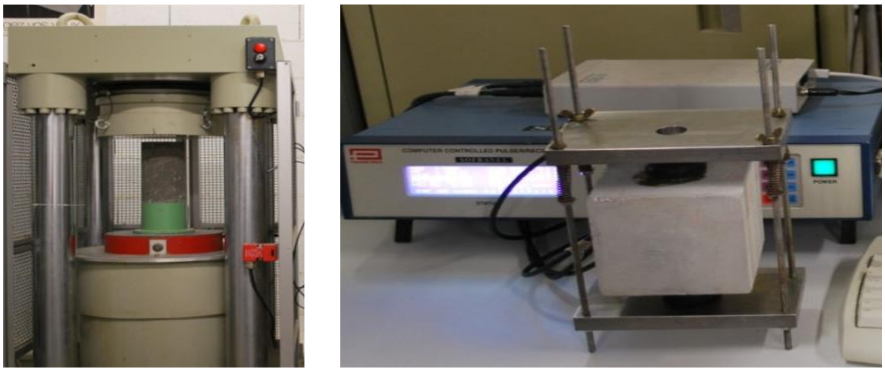
Several researchers observed that a negative effect of temperature on the compressive strength depends on the concrete mix, the type of aggregate, the heating and cooling method, and the moisture content [16-19]. The drying process has an impact on the material properties due to porosity (i.e., capillary pressure and drying-induced microcracks) [19]. Besides, the effect of moisture content on compressive strength of concrete was reliably determined following drying processes [20, 21]. To properly account for the influence of high temperature on the compressive strength of concrete, moisture and capillary water had been eliminated from all specimens before high-temperature testing. After the drying processes, the effect of temperature on strength was decreased [17]. In this study, all specimens were dried at 105ºC with no heating rate for 48 hours until a stable mass. Then, the UPV tests were conducted on these specimens at room temperature (20ºC) that exhibited the initial properties of non-heated specimens (denoted V_{T0}). Besides, each specimen was separately subjected to high-temperature tests using the heating and cooling scenarios in a furnace, as shown in Fig. 3(a).

For the high-temperature testing in this study, the specimens were heated and cooled in a cycle as, illustrated in Fig. 3(b), to assess the initial and residual mechanical properties of concrete under high-temperature exposure. This temperature-time curve displays the heating process, the maximum temperature exposure time, and the cooling down process inside the furnace. The low heating and cooling rates were chosen based on the technical guidelines of the RILEM TC 129-MTH [22].



(a) (b)

Fig. 3– High-temperature heating test: (a) Furnace and (b) Temperature–time curve



(a) (b)

Fig. 4 – (a) Compression test and (b) UPV measurements

All specimens gradually warmed at a continuous rate of 1ºC/minute until a maximum target temperature was attained. This experiment specified the maximum target temperatures as 150, 200, 300, and 400ºC. When reaching the maximum temperature, they maintained this temperature for four hours. Then, they were cooled to room temperature with a cooling rate of 0.3ºC/minute. These slow heating and cooling rates allow for homogenous thermal stress and prevent heat-induced cracking caused by large changing thermal gradients.

After the heating test, an ultrasonic pulse velocity (UPV) test was used for each tested specimen to estimate the mechanical properties and to detect internally damaged concrete. The UPV was measured in direct transmission mode in the center of the test specimens using SOFRANEL equipment and two transducers with a 0.5 MHz frequency and a 25 mm diameter. The emitter and receptor were placed on two opposite surfaces of each specimen, as illustrated in Fig. 4(b). At each level of maximum temperature (150, 200, 300, and 400°C), the UPV measurement for a specimen without reinforcement was carried out three times in three perpendicular directions, whereas it was measured two times for specimens with reinforcement.

3 Experimental results

The UPV value reduces significantly and presents the behaviour of heating concrete. Fig. 5 illustrates the linear relationship between UPV and temperature of four sets of cubic specimens. The UPV measurement represents the quality of concrete material, as well as the influence of steel rebar on RC members, which has degraded due to heating. The UPV for non-heated concrete specimens S1, S2, S3, and S4 was 4802, 4721, 4749, and 4839 m/s, respectively. When the temperature increased to 150°C, the UPV in specimens without reinforcements dropped to 4062 m/s, corresponding to a reduction of 740 m/s. In specimens with steel rebar, these UPV at the same temperature level ranged from 4036 to 4145 m/s. These values are reduced by around 690 m/s, which equals one-sixth of its value when non-heating. As a result, when the UPV value of the concrete is greater than 4000 m/s, the concrete has a higher density [23-25]. Therefore, the measurements of UPV describe the good quality of all measurements tested at a 150°C temperature.

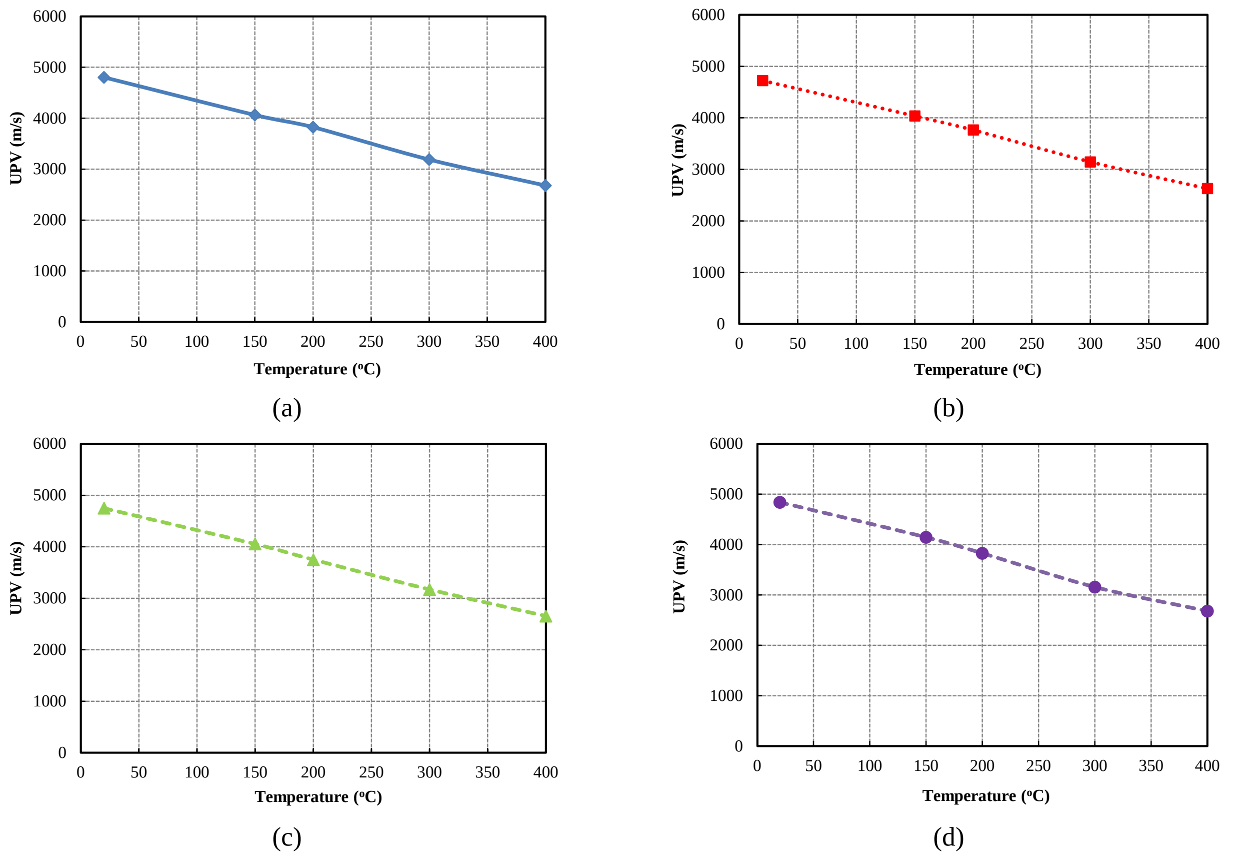
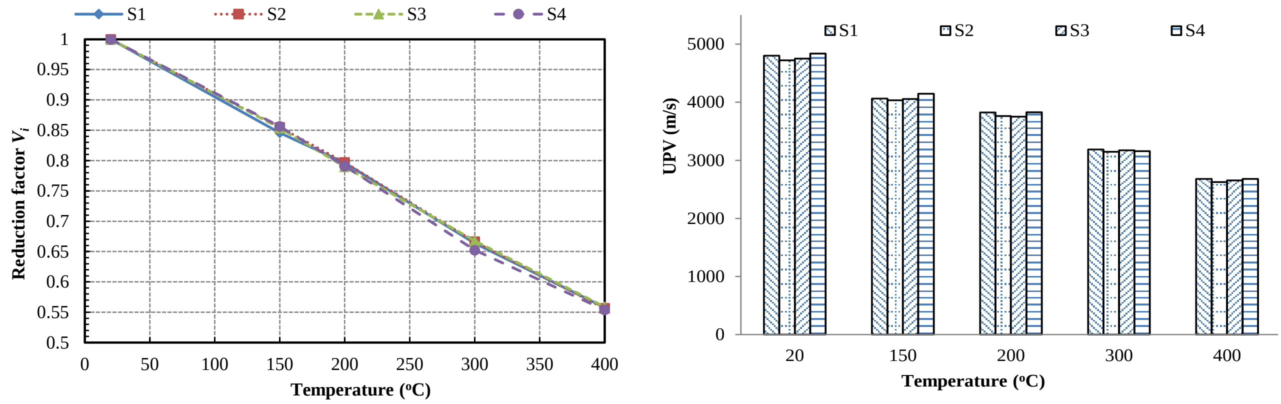


Fig. 5 – The UPV-temperature relationship in specimens (a) without rebar, (b) with a 12 mm plain rebar, (c) with a 12 mm ribbed rebar, and (d) with a 16 mm ribbed rebar

The cementitious material undergoes substantial changes when a concrete specimen is heated to higher temperatures. There are fundamental changes in the concrete micro-structure at high temperatures, as follows: (i) Dehydration followed by C-S-H decomposition from 180°C and more obviously beyond 300°C; (ii) Acceleration of carbonation from 200°C, and (iii) Decomposition of portlandite $Ca(OH)_2$ between 450°C and 550°C.

From this experimental data, a decrease in UPV is attributable to the specimen porosity, decohesion at the aggregate-cement paste interface and the steel-concrete interface, dehydration of the cement paste, and the presence of heat-induced cracks. For example, the decrease in the concrete and steel/concrete interface quality began at 200°C when the velocities of UPV measurements were less than 4000 m/s. At 200°C, the UPV average value for specimens without steel rebar was 3823 m/s, and for other specimens with steel rebar varied from 3751 to 3828 m/s. Furthermore, the UPV of four sets dropped to 2679, 2627, 2655, and 2680 m/s when temperatures reached 400°C. Fig. 6 (a) displays the relationship between temperature and a reduction factor (V_i) of UPV. A reduction factor (V_i) is the ratio between the velocity at high temperatures (VT) and room temperature (V_{To}). Although considering different types of steel rebar in specimens, a reduction factor in all specimens decreased gradually to around 0.85, 0.79, 0.66, and 0.55 when temperatures reached 150, 200, 300, and 400°C. However, the loss of concrete quality is assumed to start when the UPV reduction factor goes down below 0.85 at 150°C.

On the other hand, Fig. 6(b) illustrates the histogram of the UPV and temperature relationship. After normalizing the histogram data to consider the presence of reinforcement, the velocity of four sets of tested specimens at the same temperature level is similar, with a slight difference of 1%. This is because the coefficient of variation of UPV values ranged from 0.99 to 1.01%. It represents the repeatability at the testing point in all specimens based on the previous study [26].



(a) (b)

Fig. 6 – The relationship between UPV and temperature: (a) Reduction factor V_i of four cubic specimens; (b) histogram.

4 Conclusions

This paper focuses on the effect of high temperatures on UPV propagation in concrete specimens with and without steel rebar. The main conclusions from UPV tests can be drawn as follows: (i) The results of UPV tests indicate the linear relationship between UPV and temperature for tested specimens. These UPV values in all tested specimens were reduced by approximately 55% after being heated from room temperature to 400°C, corresponding to the degraded concrete and the degraded steel/concrete interface. The quality of concrete material and steel/concrete interface is greatly affected after 200°C because of a more than 20% reduction in UPV. (ii) At the tested temperature, there is a slight influence of steel rebar diameter on UPV measurement on RC members because of the small variation, which corresponds to the repeatability of testing equipment.

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