Compressive strength assessment of high strength concrete after fire using ultrasonic test method

Determinação da resistência à compressão em concretos de alta resistência após incêndio através de ensaios de ultrassom

Evaluación de resistencia a compresión del hormigón de alta resistencia después incendio utilizando el método de ensayo ultrasónico

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Abstract
This paper aims to evaluate the non-destructive ultrasonic pulse velocity (UPV) test method for determining the compressive strength of high strength of concrete (HSC) after fire. The compressive strength was determined through destructive cylinder test and by measuring ultrasonic pulse velocity. A total of 10 equations that relate compressive strength of concrete to UPV were evaluated in a total of 20 concrete samples. None of the equations were well suited for the case of HSC. The paper proposed a new equation and the UPV test showed suitable to assessment post-fire damaged HSC.
Keywords: High strength concrete; Post-fire damaged; Compressive strength; Ultrasonic pulse test.

Resumo
Este trabalho tem como objetivo avaliar o ensaio não destrutivo de Velocidade do Pulso Ultrassônico (VPU) para a determinação da resistência à compressão em Concretos de Alta Resistência (CAR) após o fogo. A resistência à compressão foi determinada por meio do ensaio destrutivo em corpos de prova cilíndricos e pelo teste de ultrassom. Um total de 10 equações que relacionam a resistência à compressão do concreto com o VPU foram avaliadas em um total de 20 amostras de concreto. Nenhuma das equações foram adequadas para o caso de CAR. O artigo propôs uma nova equação e o teste VPU mostrou-se adequado para avaliação de CAR após incêndio.
Palavras-chave: Concreto de alta resistência; Após incêndio; Resistência à compressão; Ensaios ultrassom.

Resumen
Este artículo tiene como objetivo evaluar el método de ensayo no destructivo de Velocidad de Pulso Ultrasónico (VPU) para determinar la resistencia a compresión del Hormigón de Alta Resistencia (HAR) después del fuego. La resistencia a la compresión se determinó a través de un ensayo de cilindro destructiva y midiendo la velocidad del pulso ultrasónico. Se evaluaron un total de 10 ecuaciones que relacionan la resistencia a compresión del hormigón con la VPU en un total de 20 amuestras de hormigón. Ninguna de las ecuaciones era adecuada para el caso de HAR. El documento propuso una nueva ecuación y la prueba VPU se mostró adecuada para evaluar HAR después del incendio.
Palabras clave: Hormigón de alta resistencia; Después del incendio; Resistencia a la compresión; Pulso ultrasónico.

1. Introduction

Mechanical properties of concrete, such as compressive strength, degrade when it is exposed to high temperatures. After a fire, it is necessary to check the integrity of the structure to decide on its release for use, on the need for structural recovery or, in extreme cases, to order it to be demolished. In situ testing techniques for checking the quality of post-fire damaged concrete include visual inspection, non-destructive testing, and the extraction of concrete cores for cylindrical destructive tests in the laboratory, emphasizing that the latter should be avoided considering the structure already in place weakened by the fire.

The test to determine these properties through the ultrasonic pulse velocity (UPV), a non-destructive test, can be used to assess the integrity of the concrete after fire, it is a simple and relatively inexpensive procedure (Hwang, et al., 2018).

There is no single relation between the ultrasound pulse velocity and the compressive strength of concrete. Several factors influence this relation, for example: the type of aggregate, the water-cement ratio, the type of cement, the age of the concrete, curing conditions and time, air content, moisture, and material density (Rashid & Waqas, 2017).

After a general review with several ultrasound tests in the laboratory, Breysse (2012) stated that the maximum aggregate size is the factor that most influences UPV, followed by the curing time and addition of minerals.

It is possible to obtain the compressive strength in situ of the concrete after fire by measuring the UPV directly on the damaged surface according to Yakub & Bailey (2016). More recently, Hedjazi & Castillo (2020) evaluated the effect of the addition of different types of fibers in concrete through resistance testing and its correlation with the measurement of ultrasonic pulse velocity at the ages of 7, 28 and 56 days; a new empirical equation of correlation was obtained by the authors for the different types of fibers.

Zárate *et al.* (2022) obtained linear and logarithmic correlations with good correlation between the measurement of ultrasonic pulse velocity (UPV) and resistance at 28 days for cylindrical concrete specimens. A similar work was carried out by Ofuyatan *et al.* (2021), but with cubic specimens of concrete; the correlation obtained between compressive strength and ultrasonic pulse velocity (UPV) was linear.

The authors also state that the relation proposed in this study that relates the UPV with the compressive strength of concrete is valid and can be used in cases where the structure is heated in a non-uniform manner, that is, generating temperature gradients in the cross section.

There are several works in the literature relating the mechanical properties of concrete to UPV. However, there are still several uncertainties about its applicability for post-fire situations, mainly for the concretes typically used in Brazil. There are also doubts about which equations best relate the UPV to the mechanical properties of these concretes. In other hand, the focus of this paper is on HSC which applicability has increased in Brazil in the last decades. Adding information about these questions is the main objective of this paper.

In this regard, experimental research was conducted at the Structures and Materials Laboratory of the Federal University of Pernambuco with 20 cylindrical concrete samples to determine the compressive strength after fire (residual strength). Non-destructive tests performed with the ultrasound device and destructive cylinder tests were performed.

2. Methods for Determining Compressive Strength of Concrete Using UPV Tests

Table 1 presents respectively 6 analytical equations that relate UPV to the compressive strength of concrete fc (Eq. 1 to Eq. 6). All are recommended for traditional concretes and at room temperature (not for the post-fire situation). References to the publication of each equation were also included in the Table 1.

Table 1 - Compressive strength of concrete at room temperature through UPV.

Reference	Analytical relation	Equation
Teodoru (1988)	$fc = 2.59 \cdot 10^{-2} e^{1.612\,UPV}$	(1)
Ravindrajah & Tam (1988)	$fc = 6 \cdot 10^{-2} e^{1.44\,UPV}$	(2)
Qasrawi (2000)	$fc = 36.72\,UPV - 129.077$	(3)
Evangelista (2002)	$fc = 8.54 \cdot 10^{-2} e^{1.2882\,UPV}$	(4)
Bogas *et al.* (2013)	$fc = 2.3 \cdot 10^{-2} e^{1.6\,UPV}$	(5)
Rashid e Waqas (2017)	$fc = 38.05\,UPV^2 - 316.76\,UPV + 681,62$	(6)

Source: Authors (2022).

Table 2 shows 4 equations that relate the UPV to the compressive strength of concrete (Eq. 7 to Eq 10). All were adjusted for the post-fire situation, that is, they relate residual properties of concrete to the UPV. Again, the references were also listed in the Table 2.

The reduction factor of the compressive strength of concrete after fire Kc,res is defined by Equation 12 and the UPV reduction factor by equation 13. All those equations will be applied, on the following items, in terms of comparisons related to cylindrical test.

Table 2 – Compressive strength of post-fire concrete through UPV.

Reference	Analytical relation	Equation
Yang *et al.* (2009)	$K_{c,res} = 1.0037\,K_{V,res} - 0.0581$	(7)
Silva (2009)	$f_c = 8.667 \cdot 10^{-3}\,UPV + 0.7084$	(8)
Yiching *et al.* (2011)	$K_{c,res} = 1.030\,K_{V,res} - 0.0634$	(9)
Hernandez *et al.* (2015)	$f_c = 2 \cdot 10^{-6}\,UPV^2 + 1.1 \cdot 10^{-3}\,UPV + 3.359$	(10)

Source: Authors (2022).

$$f_{c,\theta} = K_{c,res}\ f_c \qquad \text{Equation 11}$$
$$UPV_\theta = K_{V,res}\ UPV \qquad \text{Equation 12}$$

3. Experimental Program Methodology

Table 3 shows the mix and the consumption of the materials of the high strength concrete (HSC) tested. A total of 20 cylindrical test samples were prepared, all with dimensions 10cm x 20cm (diameter x height).

The concrete strength was 95.1 MPa at 28 days, determined by mean of 2 cylindrical samples. It is noteworthy that this strength is still little used by building industry in Brazil, however, as previously mentioned, the use of HSC has been increasing in last years.

The coarse and fine aggregates were determined according to NBR NM 248 (2003). Its characterization is shown in Table 4 and Figure 1.

Table 3 – Summary of HSC mixture proportions.

Parameter	HSC Concrete
Water-cement ratio	0.28
Cement (kg)	4.805
Medium sand (kg)	5.620
Gravel (kg)	6.389
Water (L)	1.328
Additive (kg)	0.024
$f_{c,28}$ (Mpa)	95.1

Source: Authors (2022).

Table 4 – Characterization of aggregates.

Parameter	HSC Concrete
Gravel fineness module	5.86
Maximum dimension of the gravel (mm)	12.5
Sand fineness module	1.67
Maximum dimension of sand (mm)	1.20

Source: Authors (2022).

Figure 1 – Particle size distribution of aggregates.
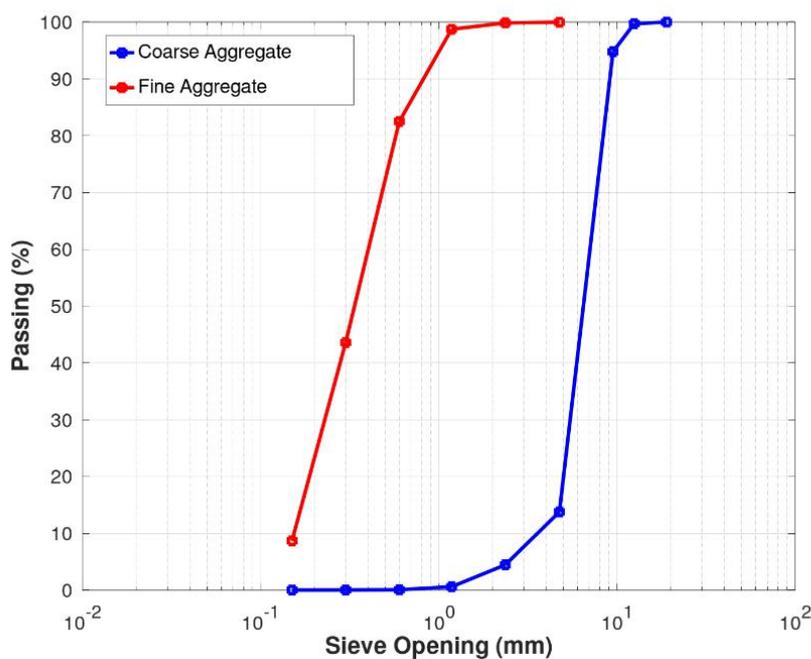
Source: Authors (2022).

After 24 hours of initial cure, the samples were placed in immersion tanks for 28 days. After this period, they were stored outdoors in room temperature. To avoid concrete spalling, all samples were placed for 7 days before the test in an furnace

at 105°C in order to reduce their moisture.

The HSC samples were tested at 36 days age, both UPV test and cylindrical test. The HSC samples were heated for at a rate of 5°C/min. These were heated to three different temperature levels: 200°C, 400°C and 600°C. Again, concrete strength was determined by a mean of 4 cylindrical samples for each temperature group. After reaching the temperature level, they were maintained at this temperature for another 3 hours, enough time for the entire specimen to reach the same temperature ("steady-state"). Then, the samples were also cooled slowly inside the furnace for 24 hours. A group without heating also were tested for room temperature reference.

The small constant heating rate of 5°C/min was applied for minimize temperature gradient along sample cross-section and avoid spalling. It is a common practice for post-fire tests of mechanical properties (ISO834, 2014).

The sample heating procedures took place in an electric furnace (Figure 2). The internal dimensions were 60 cm x 60 cm x 75 cm, totaling 0.27m³ and capable of reproducing lower heating rates.

Figure 2 - Electric furnace used for samples heating.

Source: Authors (2022).

The recording of the temperature of the gases inside the furnace, as well as the temperature of the concrete in the center of the specimens was performed with type K thermocouples.

Finally, after cooling, the ultrasound tests were performed with Proceq's 54 kHz Pundit Lab equipment, with 50 mm diameter transducers according to BS EN 12504-4 (2004).

Then the destructive cylindrical tests were performed on a 3000 kN INSTRON universal machine. The compressive strength tests of concrete followed NBR 5739 (2018). In all tests, the tops of the specimens were rectified at the top.

All data were automatically stored by the HBM Quantum X data acquisition system, both in mechanical and thermal tests.

4. Results and discussion

4.1 Room temperature samples

For this evaluation, a comparison was made with cylindrical tests and UPV tests as stated before. These results are shown in Table 5.

Table 5 – Compressive strength of samples at room temperature.

Equation	UPV test (Mpa)	Cylindrical test (Mpa)	Abs. error (Mpa)	Perc. Error (%)
1	67.1		36.7	35.3
2	67.2		36.6	35.2
3	50.0	103.8	53.8	51.8
4	45.6		58.1	56.0
5	56.2		47.6	45.8
6	45.5		58.3	56.2

Source: Authors (2022).

None of the equations (1 up to 6) are well suited for the case of HSC at room temperature, errors greater than 35% were found.

As previously shown, several factors may affect the relation between compressive strength and UPV, for example, coarse aggregate diameter, water-cement ratio, age of concrete, moisture, among others. This may justify the non-adequacy of these equations.

The tested concrete has high compressive strength (103.8 MPa at 36 days), lower water-cement ratio (0.28) and coarse aggregates of smaller diameter (gravel with a maximum diameter of 12.5mm). These variables considerably influenced the relation between UPV and the compressive strength of concrete.

It is noteworthy that none of the equations presented satisfactory results for the residual situations (post-fires). What was to be expected since they were not developed for this situation. Thus, equations 1 to 6 are not evaluated for post-fire samples.

4.2 Post-fire samples

Table 6 shows the residual compressive strength values (post-fire) for heating at a rate of 5°C/min, depending on the maximum temperatures reached during the heating phase, that is, 200°C, 400°C or 600°C. As said before, the temperature of the samples rises slowly, reducing the temperature gradient along the sample cross-section throughout the test. At the end, the uniform temperature condition is achieved in the entire sample ("steady-state").

Table 6 - Residual compressive strength (post-fire).

Maximum temperature (°C)	Equation	UPV test (MPa)	Cylindrical test (MPa)	Abs. error (MPa)	Perc. Error (%)
200	7	90.0	103.8	13.8	13.3%
	8	39.6		64.2	61.8%
	9	91.9		11.9	11.5%
	10	48.7		55.1	53.1%
400	7	65.1	85.2	20.1	23.6%
	8	29.6		55.6	65.3%
	9	66.4		18.8	22.1%
	10	29.2		56	65.7%
600	7	35.4	42.0	6.6	15.7%
	8	17.5		24.5	58.3%
	9	35.9		6.1	14.5%
	10	13.0		29	69.0%

Source: Authors (2022).

Once again none of the equations (7 up to 10) were suitable for determine the compressive strength for the HSC concrete. Equations 7 and 9 showed better evaluations. Even so, the error reached considerable values between 10% and 25%.

In this way, it is found that the equations presented here cannot estimate the compressive strength of HSC concrete with good accuracy for the post-fire situation as well as at room temperature (item 4.1).

4.3 Proposed equation for HSC

It is worth noting that the dispersion of the UPV values recorded in the ultrasound test for the same temperature level was very low (CV always below 1.5%), indicating a good reproducibility of the test. This indicates that it is not impossible for the test to be applied to determine the compressive strength of HSC, but only a lack of accuracy in the evaluated equations (Eq. 1 to 10), since they were not calibrated for this type of concrete.

Figure 3 shows the values of compressive strength of the tested concrete, both at room temperature and in post-fire conditions (200°C, 400°C and 600°C). The values were determined through cylindrical tests and their respective UPV measurements according to the ultrasound test. Linear, logarithmic, polynomial and exponential regressions are also presented for these data with their equations and R² value.

Figure 3 – Relation of compressive strength and UPV for HSC concrete
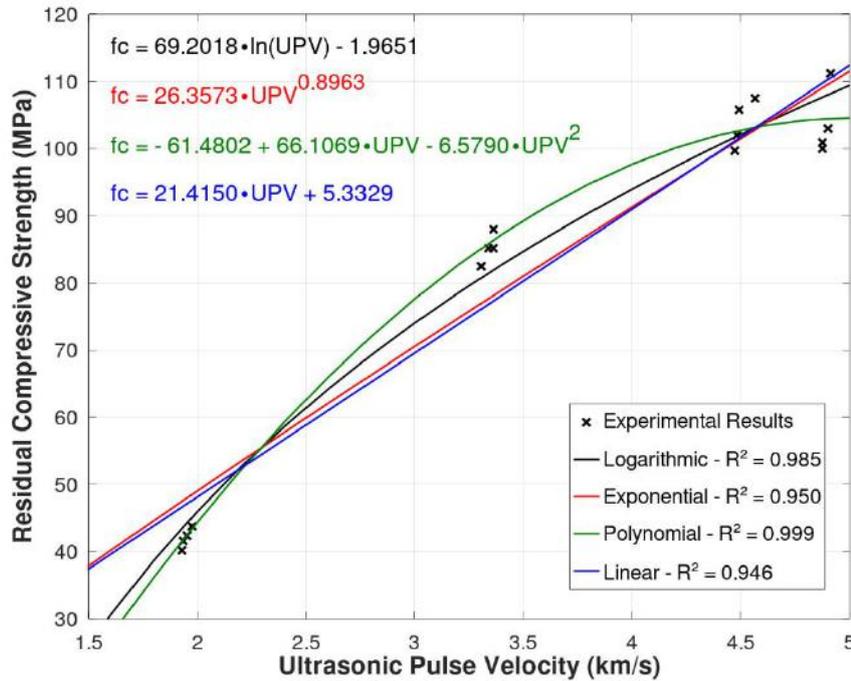
Source: Authors (2022).

It is observed that the best relation (greater R²) occurs in the polynomial regression shown in Figure 3 (Eq. 13). This equation may be used to determine the compressive strength of concretes like tested concrete (HSC).

$$f_c = -6.58 \cdot UPV^2 + 66.11 \cdot UPV - 61.48 \qquad \text{Equation 13}$$

5. Conclusion

This paper presented an experimental program with 20 cylindrical concrete samples to evaluate the determination of the compressive strength of HSC through the UPV test. In view of the data presented in this study, the following stands out:

- The UPV test can be used to determine the compressive strength of concrete, both at room temperature and post-fire (residual).
- But carefully, the equations are not valid for all concretes. The coarse aggregate diameter, water-cement ratio, age of concrete, moisture influences the relation between UPV and concrete compressive strength.
- None of the equations 1 up to 10 showed good results to assess compressive strength for HSC.
- The equation 13 may be used to determine the strength for HSC.

UPV tests with others concretes strengths, mixture proportions and specially others coarse aggregate diameter may contribute for advances in this subject, and it is a suggestion for future researches.

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