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An investigation of the effect of high temperature on the strength compression and ultrasonic pulse velocity of self-compacting concrete

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Hadji Ben salah
ORCID: https://orcid.org/0000-0002-6484-7628
Department of Civil Engineering, Ziane Achour University of Djelfa, Algeria
E-mail: b.hadji@univ-djelfa.dz
Hani Mostefa
ORCID: https://orcid.org/0000-0002-1540-6113
Department of Civil Engineering, Ziane Achour University of Djelfa, Algeria
Eskisehir Technical University, 26555, Eskisehir, Türkiye
E-mail: mostefahani.edu@gmail.com

Abstract

One of the most significant mechanisms of deterioration in self-compacting concrete (SCC) structures over the course of their service life is exposure to elevated temperatures. For this reason, the effects of elevated temperatures on the residual mechanical properties of SCC made of various cementitious additions (silica fume (SF), limestone filler (LF), and crushed dune sand (SD)) was investigated via partially substituting amount of Portland cement in the SCC. The SCC was formed and heated with the coupling procedure of heating-cooling at ambient temperatures ranging from 20, 150, 400, 600, and 800 °C. The compressive strength (CS) and ultrasonic pulse velocity (UPV) were measured after cooling at room temperature of 20 °C. The findings show that CS and UPV exhibit intriguing outcomes for all self-compacting concretes. Otherwise, the UPV decreases with temperature in the range of 250 and 800 °C. In addition, at 600 °C, SCC-SF and SCC-SD have the highest residual compressive strengths, 31.20 and 23.80 MPa, respectively.

Keywords: Self-compacting concrete (SCC). Elevated temperatures. Silica fume (SF). Limestone filler (LF). Crushed dune sand (SD). Ultrasonic pulse velocity (UPV).

1. Introduction

Self-compacting concrete is one of the construction industry's current buzzwords (Okamura *et al*., 2000). One of the more cutting-edge results of concrete research is SCC, which can compact with its own weight without revealing segregation or bleeding and can smoothly flow inside the densely packed reinforcing region (Roy *et al*., 2023).

The self-compacting concrete (SCC) is a modern type of concrete that is gaining popularity in the construction and civil engineering sectors. SCC is renowned for its exceptional flowability and self-leveling properties, allowing it to easily fill intricate forms and densely reinforced areas. This unique characteristic eliminates the need for excessive vibration during placement, resulting in time and labor savings during construction.

Generally, concrete is fire-resistant material, its residual compressive strength is modestly reduced after fire exposure up to 300 °C (Sideris and Manita, 2013), while other researchers observed that the drop in residual compressive strength may be significant even at temperatures lower than 200 °C (Hager and Pimienta, 2004). However, there is a phenomenon known as spalling that reduces the fire resistance of concrete (Khoury and Anderberg, 2000).

This study aims to understand the effects of elevated temperatures on the mechanical properties of SCC composed with different cement additives (SF, LF, and SD). In addition, the CS and UPV were analyzed after a heating-cooling process at a room temperature of 20 °C.

2. Materials and methods

2.1 Used materials

Cement: A CEM II/B42.5N type portland cement was used. This cement is delivered by the company LAFARGE Holcim Algeria. The physico-mechanical, chemical, and mineralogical characteristics are presented in Tables 1 and 2, respectively.

Table 1 – The chemical properties of cement, limestone filler and silica fume.

Elements	Cement (%)	Limestone filler (%)	Silica fume (%)
Sio2	17.49	-	93.17
Al2O3	4.51	-	0.60
Fe2O3	3.02	0.04	1.25
CaO	62.78	55.20	1.20
MgO	2.15	0.71	1.02
SO3	2.38	-	2.10
Na2O	0.05	-	-
K2O	0.64	-	1.00
LIO	8.10	43.98	-
Mineralogical composition of cement			
C3S	55.41	**C3A**	2.25
C2S	13.65	**C4AF**	14.83

Limestone filler (LD): LD is a byproduct of crushing limestone rocks that is primarily made of the mineral calcite ($CaCO_3$).

Crushed dune sand (SD): Dune sand that has been finely crushed as a cement additive comes from the Biskra region.

Silica fume: The silica fume is taken from the GRANITEX society in Algeria. It has a specific surface area of more than 15 000 cm^2/g and a density of 2300 kg/m^3.

Table 2 – Physical-mechanical properties of Cement, Limestone filler, silica fume and Crushed dune Sand.

Characteristics	Cement CEM II/B42.5N		Limestone filler	Silica fume	Crushed dune Sand
Specific density (kg/m^3)	3050		2670	2300	2770
Apparent density (kg/m^3)	1120		980	-	1300
Specific surface area (m^2/kg)	350		-	> 15000	-
Compressive strength (MPa)	2 days	20.70	-	-	-
	28 days	45.20	-	-	-

Mixing water: To mix the concrete, the civil engineering department's laboratory's tap water is used.

The three types of soil, sand, gravel 3/8, and gravel 8/16 were defined through the sieving meshes of the grain size distribution analysis test ASTM C136 (2006), as shown in Figure 1. The sampling process for obtaining soil samples is a critical factor in determining the inherent characteristics of soil (Hani and Evirgen, 2023a; Hani and Evirgen, 2023b).

Sand : The sand used in this study is sourced from 'Oued Messaad' which is located 80 km south of the Djelfa region, Algeria. The sand has a maximum grain diameter of 5 mm.

Gravel: The gravel, crushed and calcareous, originates from 'Boussaada, Algeria' and is available in two sizes: 3/8 and 8/16.Table 3 provides the physical and mechanical characteristics of the two types of soil (sand and gravel).

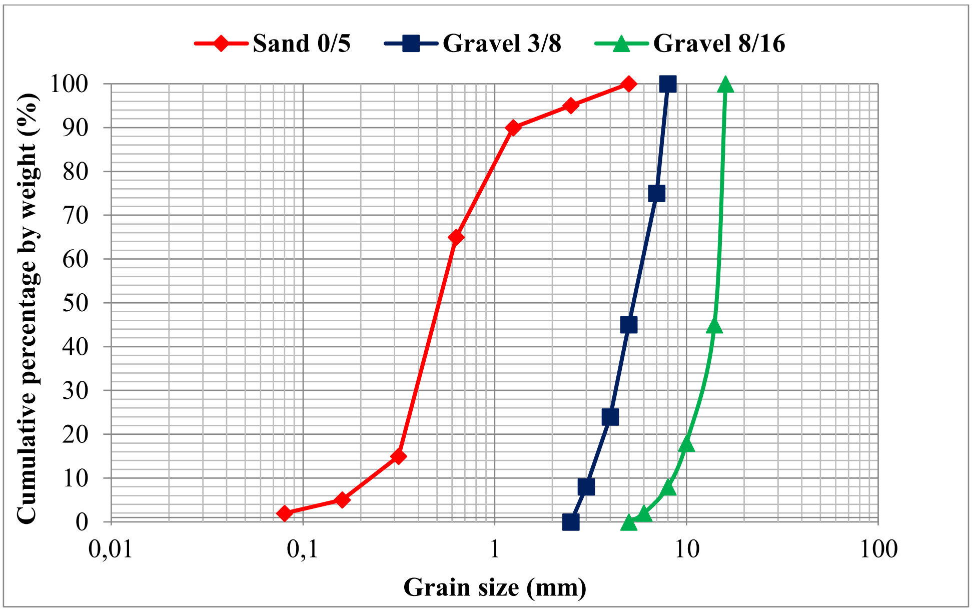

Figure 1 - Particle size distribution of the used sand and gravel.

Table 3 – Physical and mechanical characteristics of sand and gravel.

Type of soil	Apparent density (kg/m^3)	Absolute density (kg/m^3)	Fineness modulus	Sand equivalent	Degree of absorption (%)	Los Angeles Coefficient (%)
Sand	1598.30	2453.30	2.54	85	-	-
Gravel 3/8	1370.20	2660.00	-	-	2.30	23.00
Gravel 8/16	1360.50	2660.00	-	-	2.20	23.50

2.2 Formulation of self-compacting concretes:

The requirements proposed by Su *et al.* (2003) are used in this study to ensure self-compacting concrete. Moreover, the following data proposed by Brouwers *et al.* (2005) is presented to select the proportions of constituents in 1 m³ of concrete.

$$C + G + S + W + A + SP = 1\ m^3 \tag{1}$$

Where: Cement (C), Gravel (G), Sand (S), Air (A), Water (W), and superplasticizer (SP).

A total of five mixtures were prepared: four combinations of self-compacting concrete (SCC) and one ordinary vibrated concrete (OVC). Table 4 summarizes the mixture compositions of concrete. The OVC was created using the same water-to-cement (W/C) ratio as the SCCs and was composed according to the Dreux-Gorisse method (Dreux and Festa, 1998).

Table 4 –The mixtures compositions for 1 m^3.

Mixture	Cement (kg)	Limestone filler (kg)	silica fume (kg)	Sand dune (kg)	Sand 0/5 (kg)	Gravel 3/8 (kg)	Gravel 8/16 (kg)
OVC	380	0	0	0	806.64	269.11	680.24
SCC	380	-	-	-	855.65	299.48	598.95
SCC-LF	342	38	-	-	853.40	298.69	597.38
SCC-SF	342	-	38	-	854.83	299.19	598.38
SCC-SD	342	-	-	38	854.57	299.10	598.20
		W/L= 0.5	W = 190 L	G/S = 0.5	Sp= 3.50%		

The construction of the concrete followed the latest guidelines from the French Association of Civil Engineering (2000). The compositions that were examined are listed in Table 5.

Table 5 –A summary of the findings of tests done on SCC and OVC in their fresh form.

Mixture	Subsidence (cm)	Spreading out (cm)	Time T_{50} (s)	Capacity of filling (%)	Stability with the sieve (%)	Visual appreciation
OVC	8.00	-	-	-	-	-
SCC	-	69.00	3.65	83.00	8.50	Good
SCC-LF	-	68.00	3.72	85.00	6.00	Good
SCC-SF	-	63.00	3.59	87.00	7.50	Good
SCC-SD	-	70.00	3.81	86.00	7.00	Good

From the Table 5, It is noticed that the properties of self-compacting concrete in its fresh form are adequate.

3. Test methods

3.1 Heating system:

The heating process for the specimens was done using an electric furnace with a maximum temperature capacity of 1200 °C. The specimens were exposed to five different temperatures: 150, 250, 400, 600, and 800 °C. The heating rate was set at 3 °C per minute, following the recommendations of RILEM (Schneider *et al.*, 2004). The specimens were initially at a room temperature of 20 °C, which is considered the reference temperature. To ensure a uniform temperature throughout the specimens, a constant temperature was maintained for 1 hour after reaching the required temperature. After the heating process, the specimens were allowed to cool inside the closed furnace at a cooling rate of approximately 1 °C per minute. Once the furnace temperature dropped below 50 °C, the specimens were taken out and allowed to cool naturally to room temperature. Concrete properties were measured at specific temperatures as shown in Table 6 below.

Table 6 –Concrete properties at specific temperatures (Hachemi *et al.*, 2023).

Temperatures (°C)	Results
150	Free water evaporates, ettringite dehydrates, and CSH dehydrates
250	CSH dehydration is advanced at this temperature
400	CSHs partially dehydrate, and portlandite starts to decompose
600	The decomposition of portlandite may lead to a change from α-quartz to β-quartz around 575 °C
800	The degradation of concrete initiates the formation of cracks

The temperature versus time relations captured in the furnace are displayed in Figure 2.

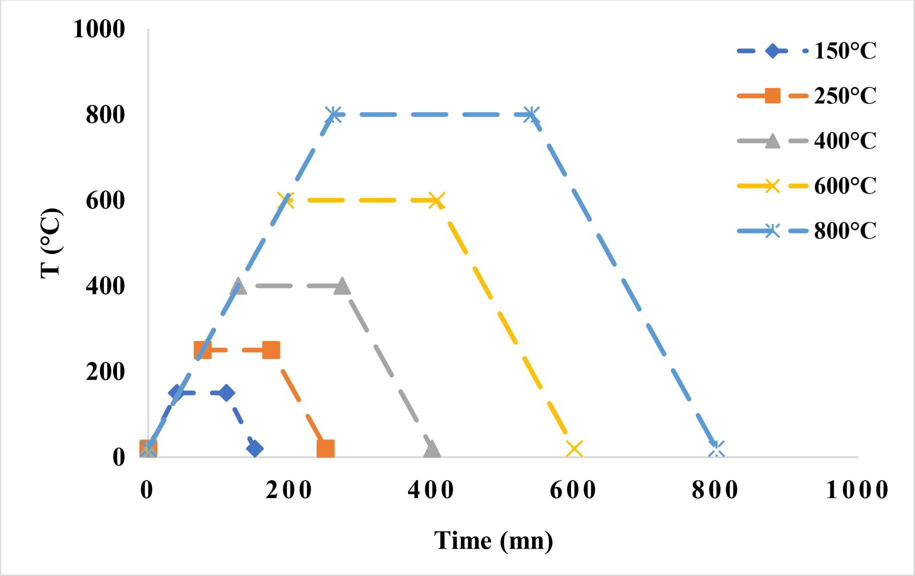

Figure 2 - Temperature evolution over time throughout the heating process (Hachemi *et al.*, 2023).

3.2 Compressive strength:

In this study, the European Standard NF EN 12390-3 (2003) is followed when conducting the compression test, using three cubes for each mixture volume 10x10x10 cm^3, and the average values of the resistance of the samples are defined as the compressive strength (Figure 3).

Figure 3 – Concrete axial compression test equipment.

3.3 Ultrasonic pulse velocity:

Concrete quality testing has traditionally been done using the ultrasonic pulse velocity (UPV) method. Concrete proportions and concrete alterations both have an impact on the UPV emanating from concrete.

For quick confirmation of concrete uniformity at ambient temperature and following each heating-cooling cycle, the value of the UPV was established.

The same dimensions of cubes as in the aforementioned compressive strength test are used for the UPV tests. Using ultrasonography, three cubes of each mixture were measured for their average UPV. Between the cube surface and the transmitter and receiver, grease was employed as an interface agent. The test for the UPV was conducted in line with French Association for Standardization AFNOR P 18-418 (1989). The following equation can therefore be used to get the longitudinal impulsion wave speed S.

$$S = L / t \tag{2}$$

Where S is the impulsion speed, L is the length of the specimen, and t is the time.

4. Results and discussion

4.1 Compressive strength:

The compressive strength results for all self-compacting concrete mixtures are presented in Figure 4. This Figure clearly demonstrates that SCC-SF, which incorporates silica fume, exhibits superior compressive strength compared to the other concretes: SCC, SCC-SD, and SCC-LF.

The observed results can be attributed to the characteristics of the additives used and their impact on enhancing the density of the solid structure.

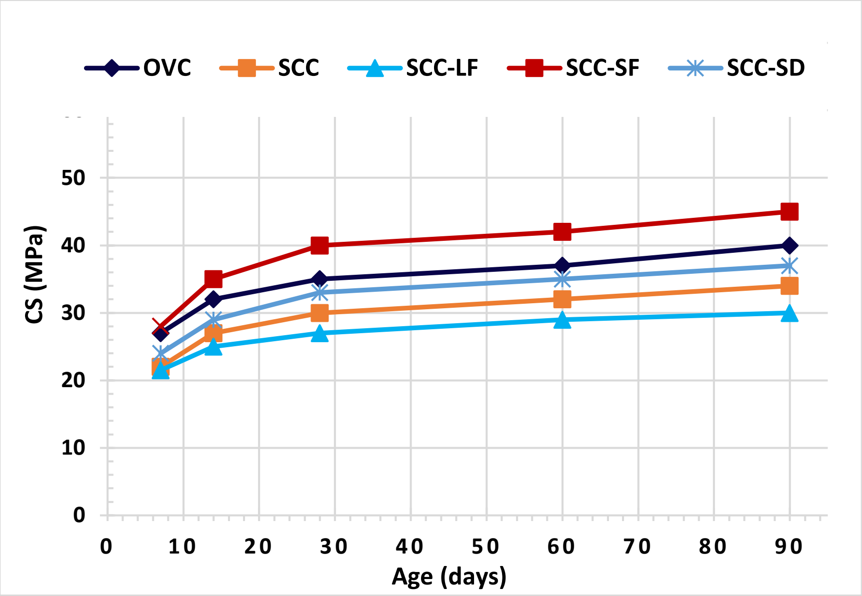

Figure 4 – The progress of concrete compressive strength as a function of age.

Compressive strength measurements were conducted on three concrete specimens at a specified temperature value. Figure 5 illustrates the progression of concrete's compressive strength in relation to temperature, whereas Figure 6 depicts the development of the relative compressive strength as a function of temperature.

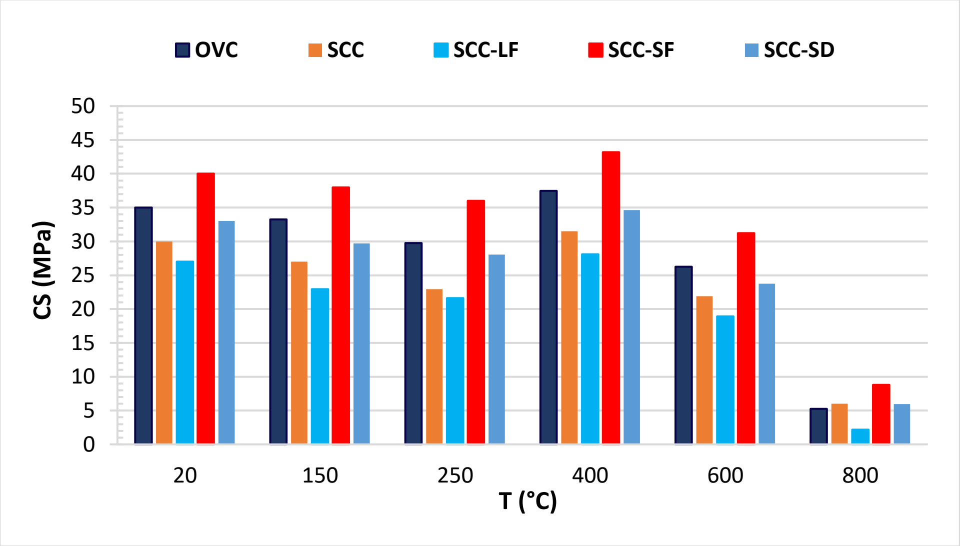

Figure 5 – Compressive strength of concrete versus temperature.

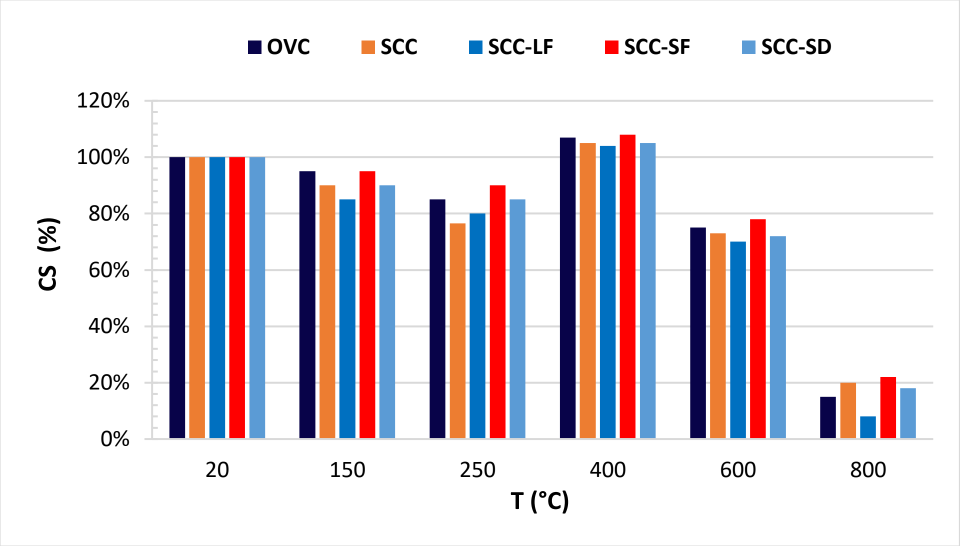

Figure 6 – Relative compressive strength of concrete versus temperature.

The results show that there is a moderate reduction in the residual compressive strength of all concretes below 250 °C. In this area, the compressive strength of SSCsf concrete decreased by approximately 10%, SCC and SCCsd concrete by 15%, while SCClf concrete suffered a reduction in strength of approximately 20%.

The reduction in compressive strength of concrete exposed to high temperatures is attributed to the evacuation of free water and a part of hydration water from the concrete. It leads to an increase in porosity, which weakens the material (Tanyildizi and Şahin, 2015).

Another contributing aspect involves the decrease in the cohesive strength of Van der Waal forces among the layers of CSH. The reduction of surface energy in calcium silicate hydrate (CSH) results in the creation of silanol groups (Si-OH:OH-Si), which are characterized by a decreased binding strength (Khoury *et al.*, 2007).

According to Hachemi and Ounis (2015), their research findings reveal the presence of microcracks in the cement paste following exposure to temperatures of 150 °C and 250 °C.

The compressive strength of self-consolidating concrete (SCC) exhibited a marginal increase at around 400 °C. The initial strength exhibited an increase ranging from -10 to +8% for SCC-SF, -10 to +5% for SCC and SCC-SD, and -15 to +4% for SCC-LF. Many hypotheses have been proposed to elucidate the observed augmentation in compressive strength at approximately 400 °C. One of them posits that the extraction of moisture from the interlayer of cement gel might potentially decrease the disjoining pressure and enhance the cohesive forces among the particles. Consequently, this could lead to an increase in the compressive strength of concrete (Behnood and Ghandehari, 2009; Chen *et al.*, 2009; Zain *et al.*, 2000). In addition, Xing *et al.* (2011) hypothesize that the increase in compressive strength of specimens exposed to 400 °C might be due to a shorter duration of exposure at the center of a cube specimen at the same temperature. The transportation of moisture in concrete is rather gradual, so some hydrated cement grains in the concrete specimens continue to hydrate and gain strength after exposure to high temperatures (Chen *et al.*, 2009).

The present investigation demonstrates a notable reduction in the compressive strength of all concrete specimens as the temperature is elevated within the range of 400 to 800 °C. The primary factors contributing to the decrease in strength are the dehydration of calcium silicate hydrate (CSH) and the volumetric expansion resulting from the conversion of $Ca(OH)_2$ to CaO. It has been noticed that cement paste initiates dehydration at around 180 °C. The entire decomposition of the CSH gel occurs at an approximate temperature of 800 °C. Furthermore, it should be noted that compressive strength at temperatures beyond 400 °C may also be influenced by an additional parameter. The development of microcracks at the interfaces between the aggregates and cement matrix is a consequence of the thermal incompatibility between these components (Hachemi and Ounis, 2015).

As a result, the use of silica fume and Sand dune as addition improved the compressive strength of self-compacting concrete after exposure to high temperatures.

4.2 Ultrasonic pulse velocity:

The results of the UPV of the test specimens show that the speed of sonic waves continuously decreases as temperature rises (Figure 7).

The UPV of concrete is subject to variations resulting from changes in the concrete itself as well as being impacted by the proportions of the concrete mix (Tanyildizi and Şahin, 2015).

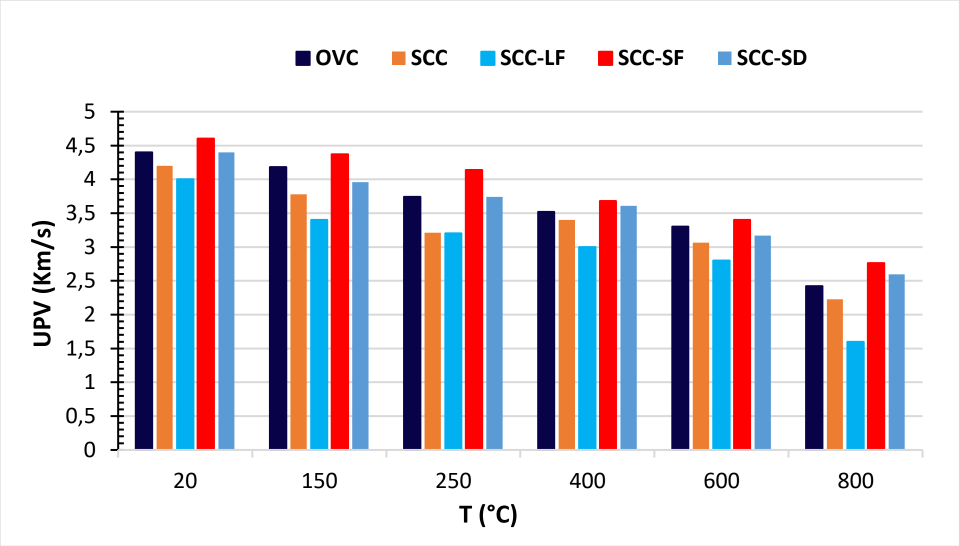

Figure 7 – Ultrasonic pulse velocity versus temperature.

All specimens can be classified as being in perfect condition after UPV tests at 20 °C and after exposure to 150 and 250 °C; their UPV is greater than 3.5 km/s. After being exposed to 600 °C, all test components' findings for UPV are less than 3.50 km/s. When the temperature approaches 800 °C, the UPV decreases by 40% for SCC-SF and SCC-SD, 47% for SCC, and 60% for SCC-LF. Cracks caused by incompatible deformation between the cement paste and the aggregates are responsible for this significant level of damage.

5. Conclusions

This study investigated the behavior of self-compacting concrete exposed to elevated temperatures of 150, 250, 400, 600, and 800 °C. The compressive strength and ultrasonic pulse velocity of SCC were determined at a room temperature of 20 °C after exposure to different heating-cooling processes. The following results can be drawn:

- The SCC properties in this study have identical requirements to those of the French Association of Civil Engineers.
- The increase in temperature leads to a decrease in the compressive strength values of the SCC concrete type, and it depends on the nature of the additions from 20 to 800 °C.
- SCC-SF and SCC-SD have the best compressive strength, reaching 31.20 and 23.80 MPa, respectively, at 600 °C.
- The ultrasonic pulse velocity of all self-compacting concrete decreases with increasing temperature, and its acceleration process decreases in the range of 250 to 800 °C. In addition, the ultrasonic pulse velocity of SCC-SF and SCC-LF exhibits the highest speed values compared to other self-compacting concretes in this same temperature range.

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