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Non-destructive evaluation and contrasts of concrete overheated and abruptly cooled

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Abstract

Concrete structures can suffer different pathologies, one of which may be due to exposure to high temperatures. In this briefing article, different concrete types were exposed to high temperatures. To simulate fire extinction, where the temperature of the overheated concrete descends suddenly, different cooling systems were applied: slowly cooling in the open air and fast cooling by spraying different water volumes. Physical and mechanical properties were affected by the increase of the temperature, making damages worst, when water is used as a cooling system. Sclerometer and Ultrasound non-destructive tests were conducted to quantify deterioration and a relationship with the compressive strength results was performed.

Keywords

Concrete structures; Thermal effects; Non-destructive testing

List of notation

f´c	is the compressive strength of concrete
w/c	is the water/cement ratio
SI	is the sclerometer index
UPS	is the ultrasonic pulse speed

1. Introduction

The exposure of concrete structures to high temperatures that are present during a fire, affects their life-cycle and mechanical characteristics. When it is exposed to high heat, concrete suffers physical and chemical modifications, irreversible in most cases. The degree of deterioration depends on reached temperature, exposure time, cooling system and concrete composition (Kodur and Dwaikat, 2012).

It is recognized that the behaviour of concrete subjected to high temperatures is a result of many factors, such as heating rate, peak temperatures, dehydration of calcium silicate hydrate (C–S–H) gel, phase transformations, and thermal incompatibility between aggregates and cement paste (Savva et al., 2005). Aggregates behaviour is very important, due to the fact they occupy the biggest volume within the concrete mass and its coefficient of thermal expansion varies according to its mineralogical composition (Netinger et al., 2011). The thermal expansion coefficients of rocks generally increase with the silica content. Quartz aggregates present a bigger coefficient (12 microstrains per Celsius degree) than calcareous ones (5 microstrains per Celsius degree) (Smith et al., 2001).

The different coefficient of thermal expansion present in the aggregates, regarding the cement paste, produces internal micro-cracks and a weakening in the aggregate-mortar interface. Moreover, chemical reactions and transformations are generated in all concrete components. Most aggregates present a stable behaviour below 500°C, while the allotropic transformation from quartz α to quartz β occurs at 573 °C, as well as, a significant expansion of 1,2%. Calcareous aggregates experiment a decarbonation between the 600° and 900°C and basalts do not show phase changes below the 800°C (Bazant and Kaplan, 1996). All aggregate transformations are revealed because their colour changes, as exposure time increases. Above 300°C, the classic grey colour of concrete turns pink, as a consequence of the presence of iron in the mineralogical composition of the aggregates (Guise et al., 1996). Since this process of change is permanent and irreversible, it can be estimated the maximum temperature reached by the concrete structure after a fire.

It was determined that the paste dehydrates until 105°C so it shrinks. At higher temperatures, concrete expands despite this initial shrinking (Giaccio et al., 2005). At 180°C hydrated calcium silicate starts to dehydrate; from 500°C on, most aggregates stop to be stable and changes are irreversible. Concrete presents a high density of micro-cracks that weakens the aggregate-mortar interface (Bazant and Kaplan, 1996) affecting directly its mechanical strength. There is a great variation among the results published by different authors, regarding strength reduction. It has been observed a reduction below the 25% in tensile strength for temperatures under 250°C and the decrement is more intense for temperatures above 300°C (Barragán et al., 2000) reaching a reduction of the 40%. When 550°C are achieved, this reduction is between the 55% and the 70% (Guise et al., 1996). For temperatures over 770°C, it was verified a drastic fall in the residual strength, turning the concrete friable over 900°C.

The process described below can be worse depending on the used cooling system during fire extinctions. Overheated concrete is exposed to fast cooling methods, due to the fact that the water spray has a lower temperature. This rapid change generates a thermal shock, reflected in the appearance of micro-cracks in the concrete, which affects its internal structure (Peng et al., 2008).

The propagation speed of ultrasonic pulses and the sclerometer index are tests used to diagnose concrete structures affected by different pathologies, in this case, an exposure to high temperatures. Both techniques allow evaluating characteristics related to concrete quality in a fast, secure, affordable and non-destructive manner. The use of ultrasonic pulse speed as an index to evaluate the mechanical performance of concrete subjected to heating and cooling conditions can be found in the works of Yang et al. (2009), and Suhaendi and Horiguchi (2006).

Variations of the ultrasonic propagation speed of hardened concretes are directly related to cavity presence, pore structure, cracks and micro-cracks in the tested concrete. Besides, during the curing process, mentioned speed increases rapidly as the concrete gains strength. While the sclerometer index, evaluates concrete surface hardness.

2. Experimental procedure

Three concretes were designed with different water/cement ratios: 0.45, 0.50 and 0.56 to study its behaviour to high temperature exposure and different cooling systems. It was used Portland cement, natural sand and coarse aggregate from the Patagonia - most used material at the south of Argentina - to elaborate the concrete of the samples. Few international researches of concrete elaborated with this coarse aggregate and exposed to high temperatures were found. Characteristics of the concretes are showed in Table 1.

Normalized cylindrical concrete samples of 15 X 30 cm (ASTM C39, 2014) were moulded. Curing was performed in the laboratory, until the tests took place, 90 days after elaboration. Samples were grouped in equal batches that were exposed to temperatures of 250°C, 500°C and 680°C for an hour. An electric oven with automatic temperature control was used for thermal treatment (Figure 1). Another group of samples was not subjected to any treatment, to compare its performance as reference samples or patterns.

The heating of the test specimens up to 250 ˚C and 500 ˚C was carried out using a heating process very close to the indicated by the curve defined in ISO 834 (1975). For the specimens heated to higher temperatures, given the possibilities of the oven available, it was not possible to follow the curve defined by this standard with total accuracy, however, the rate of heating was very similar to that described by this standard, but were offset the products temperature-time, in such a way to establish an equivalent temperature of exposure to 680 °C. It must be considered that the concrete exposed at this last temperature presents very important damages; while for the lower temperatures of exposition, its residual properties turn the analysis more interesting.

To simulate the conditions present at fire extinctions, where sudden cooling of the overheated concrete takes place, samples were cooled using different methods:

- Open air: room temperature is about 20°C (Air-cooled).
- Light water spray: each sample was sprayed with 200ml of water, after being removed from the oven (Water Spray 1).
- Heavy water spray: samples were sprayed with 600ml of water (Water Spray 2).

The amounts of water used for colds were such that, for the Water Spray 1, the surface of the specimen remained dry after a rapid evaporation of water, while for the Water Spray 2, was achieved retain some moisture on the specimen surface. Both sprinkles were made by hand sprayers, applying water to the whole surface of the specimens. The water pressure was so low that it is considered negligible for the results of tests conducted.

Initially, it was planned an exposure time to high temperatures of 90 minutes but it had to be reduced to 60 minutes, since samples of greater water/cement ratio exposed to temperatures of 680°C degrade in the oven, preventing the performance of any kind of test. This occurs due to the great loss of strength that concrete experiments at high temperatures, depending on the aggregate (Barragán et al., 2000; Mindeguia et al., 2015; Khoury, 2008). Other studies (Giaccio et al., 2005) show longer exposure times (24 hrs.) simulating thermal actions generated during industrial processes and not as a consequence of a fire which lifetime is shorter.

To classify the different concretes, tests such as compressive strength (ASTM C39 2014) were performed for all exposure temperatures and cooling systems. On the other hand, the propagation speed of ultrasonic pulses (UPS) and the sclerometer index (SI), using a Schmidt hammer, were established before and after exposing the samples to the heating program. To determine the UPS, an equipment that operates at 24 KHz (accuracy: 0.1 µ) was used. This emission frequency was chosen because when 54 KHz transducers were used, it was not possible to obtain readings from the samples exposed to 500°C due to the pattern cracking. This is because, the higher the transmission frequency is, the greater difficulty for the ultrasonic waves to pass through the discontinuities in the concrete mass caused by cracking. For samples exposed to 680°C, measurements could not be taken with either of the two transducers. Because the UPS may be affected by the moisture content of the samples; measurements were taken between 48 and 72 hrs. after having removed samples from the oven. Storage conditions thereof until the time of testing were similar laboratory conditions.

3. Results

3.1 Physical properties

A visual inspection of the samples took place after being removed from the oven; changes in the superficial colour were noticed. Samples exposed to 250°C turned to pale pink colour, those exposed to 500°C turned grey and the ones exposed to 680°C turned to a lighter grey.

It was noticed a more severe crack patterns as both, the maximum temperature of exposure and the water/cement ratio increased. For all dosages, the damage shown on the samples after being removed from the oven was increased when water at 20˚C was sprayed over them. It is worth to mention that water spray evaporated almost immediately, leaving some traces of moisture on the sample surfaces that were cooled using a greater amount of water, 600ml (Water Spray 2).

Figure 2 shows the top view of the specimens subjected to different temperatures and cooled on open air. It can be seen the difference of colours and the high cracking of the specimen subjected to 680 °C.

3.2 Mechanical properties

Compressive strength results after 90 days (f'c) are shown in Table 2. Resistance percentages can be seen with respect to the pattern concrete. The failure mode of reference samples and those exposed to 250˚C – tested by compression - was conical. Those exposed to higher temperatures, shown an almost horizontal cracking plane. This unusual behaviour is due to the influence of cracks in these concretes, after being overheated. It should be taken into account that the incidence of high temperature over the concrete specimens is given mainly on their surface and decreases towards the interior of the specimens, therefore, for the lower exposure temperatures, it is not expected to obtain very significant decreases in the resistance.

In Table 2 it can be seen that in all cases, the specimens cooled with water spray obtained lower values of compressive strength than the air-cooled specimens. Although some of the differences are not very significant, it can be noted the negative influence of an abrupt cooling.

For example, for the concrete with w/c= 0.45, subjected to a temperature of 250 °C, it can be seen that the compressive strength, in the case of the air-cooled specimen was 91.3% with respect to the pattern, which implies a loss of 8.7 %. On the other hand, in the case of water spray 2, the compressive strength was 80.0% with respect to the pattern, i.e. the loss was of 20.0%. This loss of compressive strength is more than twice the obtained for air-cooled. In addition, the amount of water used in the cooling has an important role and it might be of interest, for other investigations, to analyse more options for this variable.

3.3 Non-destructive tests.

Under this section are displayed the results obtained using the two most widespread non-destructive tests to examine concrete structures. Figure 3 displays the variation of sclerometer index (SI) and Figure 5 the measurement of ultrasonic pulse speed (UPS), both based on the temperature that samples were exposed to, and the cooling system type, grouped by w/c ratio (Lin et al., 2011).

The SI for concretes exposed to 250°C and for any type of cooling system, remained almost constant. There are small increases up to the 10%, which can be seen in most of the air cooled concretes. This apparent irregularity may be related to the fact that concrete inside the oven lost all surface moisture, which could fictitiously collaborate with SI increase. From this temperature on, an abrupt decrease of the SI occurs; for concretes with a more open pore structure (w/c = 0.56 and w/c = 0.50) a difference can be observed between the different cooling system types, whereas for concretes with a w/c = 0.45, the behaviour is similar regardless the cooling system type.

Figure 4 shows that UPS descends approximately in a linear manner, based on temperature to which the concrete sample was exposed to. There is a similar scenario for both water spray systems; UPS decrement is less for open air cooled samples than for moistened ones. There was not possible to take measurements on samples exposed to 680˚C due to major cracking on them. Similar results have been published by other authors (Barragán et al., 2000); they worked with inferior temperatures and using slower and lengthy heating processes.

The advantage of the UPS is that it is more representative of the actual situation of the entire concrete sample than the SI which only takes into account what happens on its surface. Nevertheless, it should be noted that the surface is precisely the most exposed in the event of a fire (Kang et al., 2016).

It is worth to mention that UPS measurements can be altered by the presence of different density materials like metal reinforcements. For example, higher propagation speeds are expected with larger amounts of steel reinforcement. For this reason, this method should be used carefully.

It is interesting to relate the UPS with concrete compressive strength. To this end, it was built Figure 5 where a regression line is presented. As it can be appreciated the graph shows a trend, with the UPS increase, the compressive strength increases as well. Furthermore, in Figure 6 can be seen the relationship obtained between SI and the compressive strength of the concrete exposed to different temperatures. It can be observed a polynomial trend line of second order.

The expressions shown in Figures 5 and 6, although exist a logical dispersion in the results, can be used to an initial qualitative assessment of the state of concrete affected by high temperatures and with different types of cooling, such may be the case of a fire.

4. Conclusions

According to the performed tests for this research, it can be concluded:

The compressive strength of the samples exposed to 250°C suffered a light reduction. This loss increased as, both the exposure temperature and the volume of water used for cooling, grew.

Non-destructive tests showed the deterioration of the concrete exposed to high temperatures and abruptly cooled, with significant decrements in the sclerometer index and ultrasonic propagation speed values.

Relationships between the compressive strength of concrete with the UPS and the SI were obtained. Nevertheless, these expressions must be used carefully and mainly as an initial qualitative assessment of the state of concrete affected by high temperatures and with different types of cooling, such may be the case of a fire.

Ultrasound non-destructive tests seem more reliable for analyzing the overall deterioration degree of the concrete than Sclerometer Index which only takes into account what happens on its surface. Nevertheless, the SI also showed good results, since the surface is precisely the most exposed. Furthermore, the UPS measurements can be altered by the presence of different density materials like metal reinforcements. The combination of both non-destructive tests is desirable.

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Figure captions

Figure 1. Electric oven used for thermal treatment.

Figure 2. Top view of specimens subjected to different temperatures and cooled on open air. Top, left: Pattern. Top, right: 250 °C. Bottom, left: 500 °C. Bottom right: 680 °C.

Figure 3. SI variation for different concretes and cooling systems.

Figure 4. UPS variation for different concretes and cooling systems.

Figure 5. Relationship between f'c and UPS.

Figure 6. Relationship between f'c and SI.

List of tables

Table 1. Concrete composition.

Table 2. Compressive strength after 90 days of all concretes and cooling systems.

Table 1
Concrete composition.

Material content (kg per m^3 of concrete)	**water/cement ratio**		
	0.45	**0.50**	**0.56**
Cement	350	320	290
Fine aggregate (natural sand)	853	878	896
Coarse aggregate (rounded gravel, maximum nominal size: 25mm)	1050	1050	1050
Plasticizer additive	1.23	1.12	1.02

Table 2
Compressive strength after 90 days of all concretes and cooling systems.

		20 °C		250 °C		500 °C		680 °C	
		f´c (MPa)	(%)	f´c (MPa)	(%)	f´c (MPa)	(%)	f´c (MPa)	(%)
a/c = 0.45	Pattern	39	100.0%						
	Air-cooled			35.6	91.3%	23.7	60.8%	14.8	37.9%
	Water spray 1			32.2	82.6%	22.7	58.2%	14.5	37.2%
	Water spray 2			31.2	80.0%	22.3	57.2%	10.3	26.4%
a/c = 0.50	Pattern	30.1	100.0%						
	Air-cooled			29.4	97.7%	20	66.4%	11.6	38.5%
	Water spray 1			28.4	94.4%	19.6	65.1%	9.1	30.2%
	Water spray 2			26.1	86.7%	19.5	64.8%	8	26.6%
a/c = 0.56	Pattern	24.5	100.0%						
	Air-cooled			22.4	91.4%	18.9	77.1%	10.4	42.4%
	Water spray 1			20.8	84.9%	17.7	72.2%	7.2	29.4%
	Water spray 2			20.3	82.9%	16.7	68.2%	6.3	25.7%

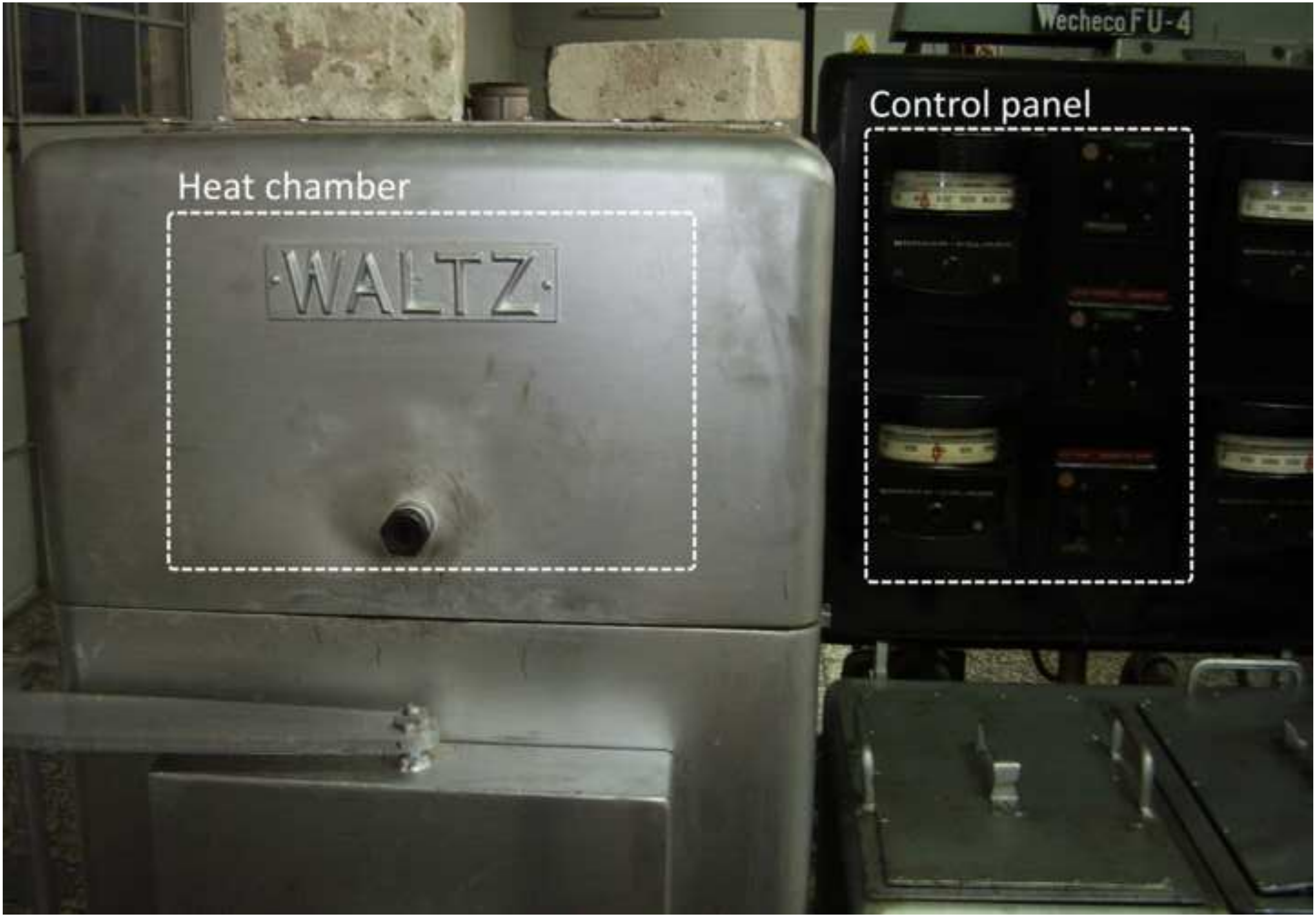
Wecheco FU-4
Control panel
Heat chamber
WALTZ

Figure 2

Figure 3

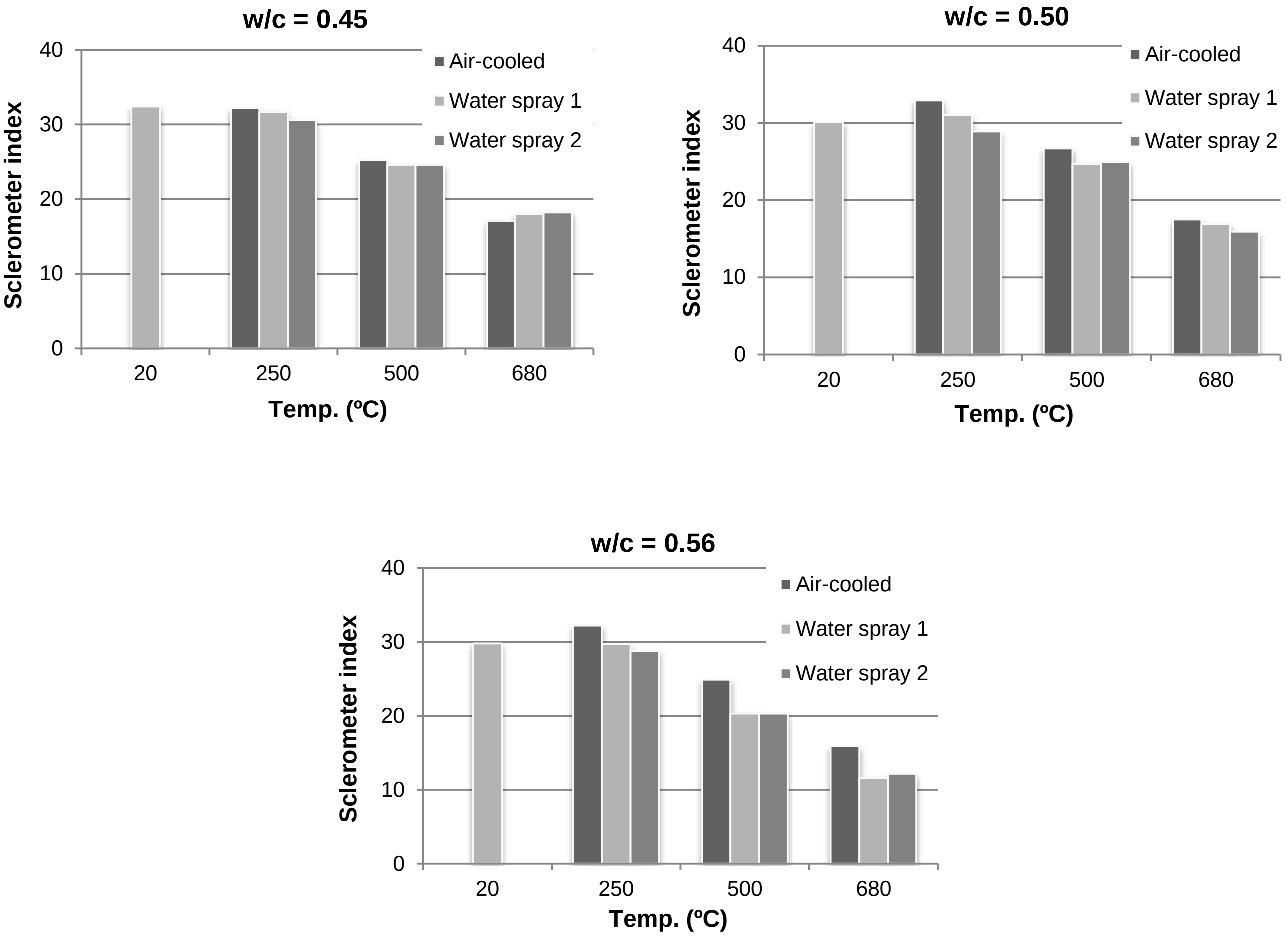

Fig. 3. SI variation for different concretes and cooling systems.

Figure 4

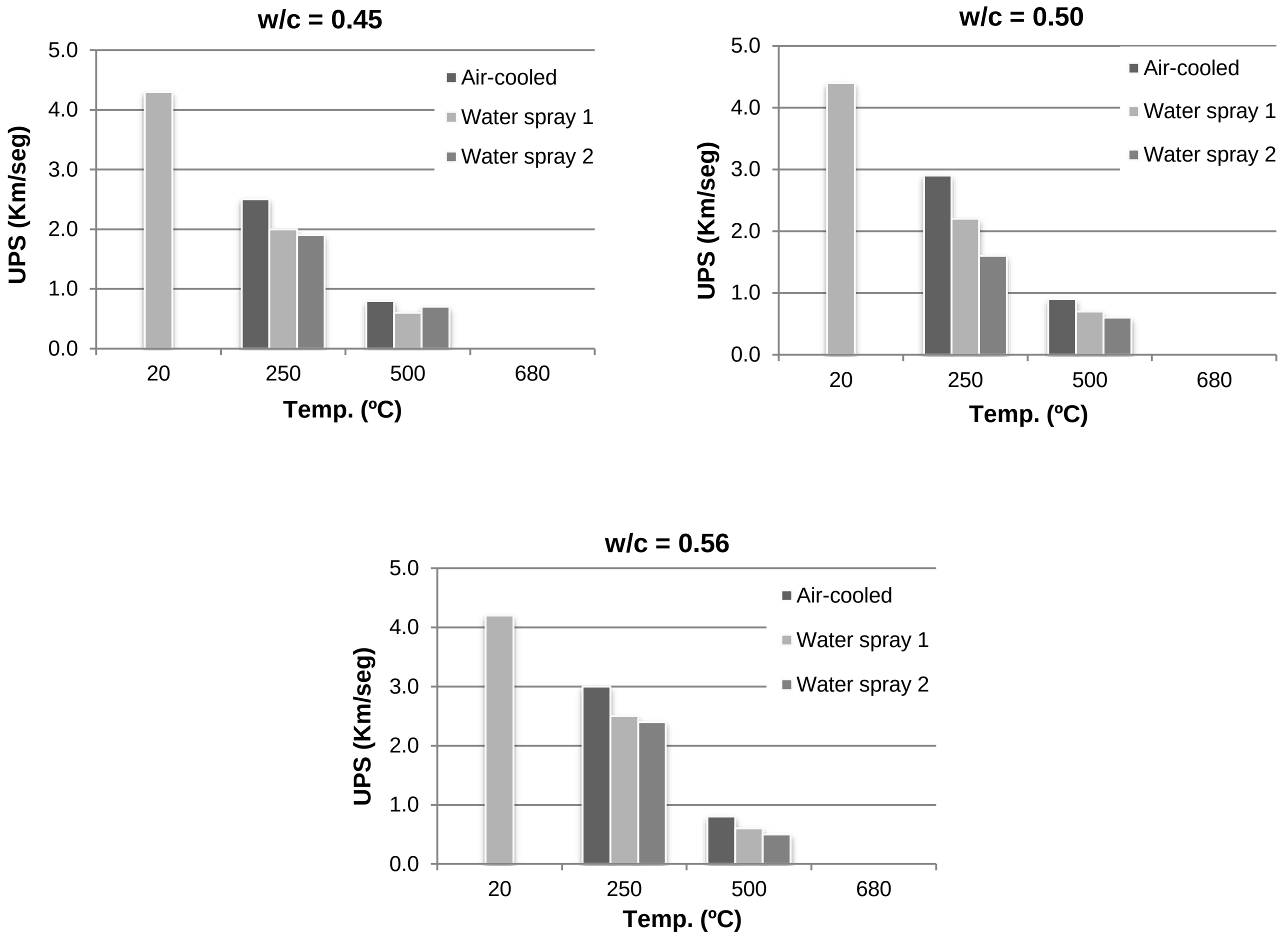

Fig. 4. UPS variation for different concretes and cooling systems.

Figure 5

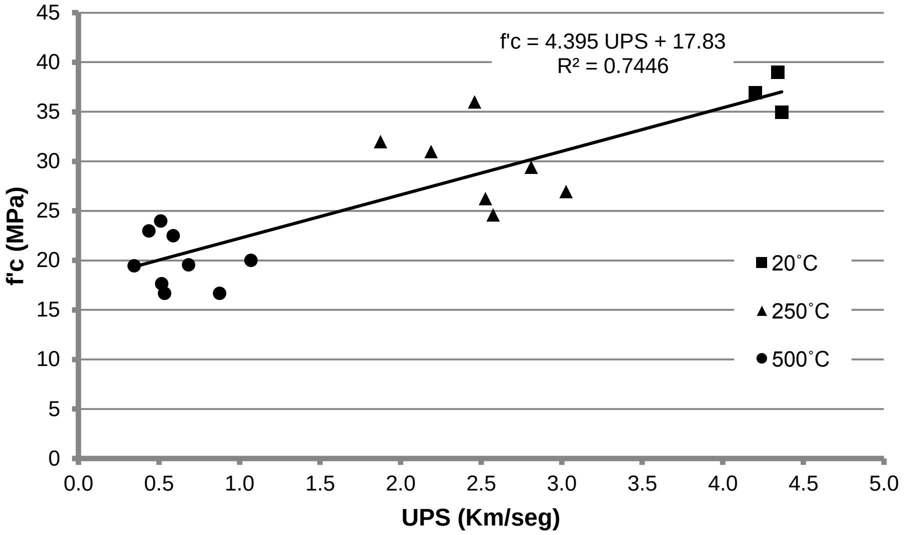

Fig. 5. Relationship between f'c and UPS.

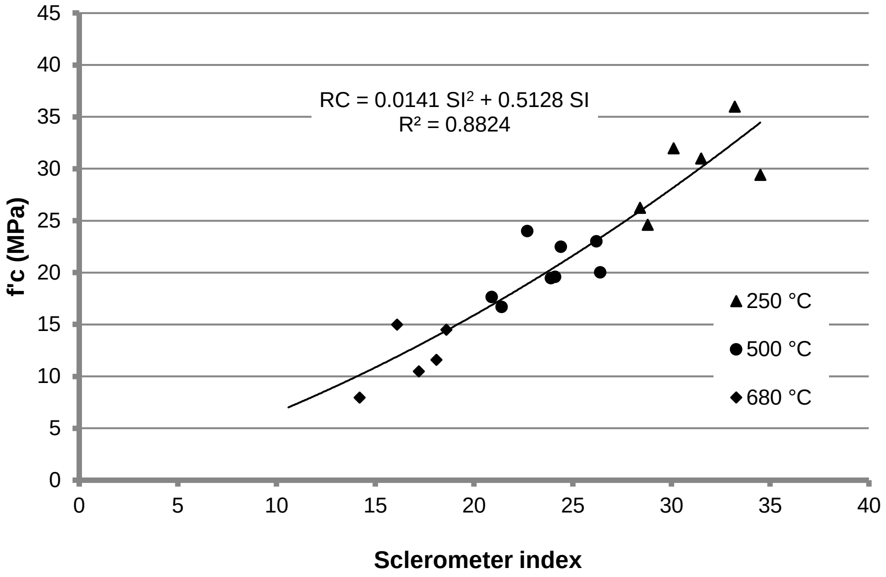

Fig. 6. Relationship between f’c and SI.