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TECHNICAL PAPER

Physical–mechanical behavior of concretes exposed to high temperatures and different cooling systems

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Over their lifetime, concrete structures can suffer from different pathologies, one of them is exposure to high temperatures, which diminishes their load-bearing capacity. This study describes how 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. Several physical–mechanical characteristics were analyzed such as compressive strength, splitting tensile strength, porosity, capillary suction, and carbonation depth. Ultrasound nondestructive tests were conducted to quantify deterioration. A petrographic study using a stereomicroscope and microscopy of polarization was performed on thin sections to evaluate aggregate composition and concrete characteristics, focusing on interface areas. Physical and mechanical properties were affected by the increase in temperature, with damage worsening through the appearance of cracks and microcracks when water is used as a cooling system.

KEYWORDS
concrete, nondestructive tests, petrography, temperature

1 | INTRODUCTION

The exposure of concrete structures to the high temperatures that are present during a fire affects their life cycle and mechanical characteristics. Knowledge of the residual mechanical properties of the structure is very necessary.[1] When it is exposed to high temperatures, concrete suffers physical and chemical modifications—irreversible in most cases. The degree of deterioration depends on the temperature reached, exposure time, cooling system, and concrete composition.

It is recognized that the behavior 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.[2] Owing to the fact that aggregates occupy the biggest volume within the concrete mass, their behavior is very important, and their coefficient of thermal expansion varies according to their mineralogical composition.[3] The thermal expansion coefficients of rocks generally increase with the silica content. Quartz aggregates exhibit a higher coefficient (12 microstrain/°C) than calcareous ones (5 microstrain/°C).[4]

The different coefficients of thermal expansion of the aggregates, regarding the cement paste, produce internal microcracks and a weakening at the aggregate–mortar interface. Moreover, chemical reactions and transformations are generated in all concrete components. Most aggregates present a stable behavior below 500°C, whereas the allotropic transformation from quartz α to quartz β occurs at 573°C, as well as a significant expansion of 1.2%. Calcareous aggregates experience decarbonation between 600 and 900°C and basalts do not show phase changes below 800°C.[5] All aggregate transformations are revealed through their color changes as exposure time increases. Above 300°C, the classic gray color of concrete turns pink as a consequence of the presence of iron in the mineralogical composition of the aggregates.[6] As this process of change is permanent and irreversible, it is possible to estimate the maximum temperature reached by a concrete structure after a fire.[7]

It was determined that the paste dehydrates up to 105°C, so it shrinks. At higher temperatures, concrete expands despite this initial shrinkage.[8] At 180°C, hydrated calcium silicate starts to dehydrate; from 500°C onward, most aggregates stop being stable and changes are irreversible. Concrete exhibits a high density of microcracks that weakens the aggregate–mortar interface,[5] directly affecting its mechanical strength. There is great variation among the results published by different authors regarding strength reduction. A reduction in tensile strength of <25% has been observed for temperatures <250°C, but the decrease is more intense for temperatures >300°C,[9] reaching a reduction of 40%. When 550°C is reached, this reduction is between 55 and 70%.[6] For temperatures >770°C, a drastic fall in the residual strength was verified, making the concrete friable at temperatures >900°C.

The process described below can be worse depending on the cooling system used during fire extinguishing. Overheated concrete is exposed to fast cooling methods, owing to the fact that the water spray has a lower temperature. This rapid change generates a thermal shock, which manifests itself in the appearance of microcracks in the concrete, which in turn affect its internal structure.[10] For this reason, it is important to perform petrographic studies to evaluate the deterioration suffered by the structure after a fire has taken place.

Several authors correlate the nature, extent, and even a quantification of the cracking scenario with the maximum temperature reached by a concrete structure during a fire.[11] This temperature directly determines the degree of microstructural damage, and the performance of concrete exposed to high temperatures can be evaluated by different techniques, such as microscopic studies and ultrasonic speed tests.[12] A microscopic study not only allows an estimation of the maximum temperature reached, but also the measurement of the depth of the damage suffered by the concrete, measured from the exposed surface.

The propagation speed of ultrasonic pulses is a test used to diagnose concrete structures affected by different pathologies, in this case, exposure to high temperatures. It allows an evaluation of characteristics related to concrete quality in a fast, secure, affordable, and nondestructive manner. Changes in the ultrasonic propagation speed of hardened concretes are directly related to the presence of cavities, pore structure, cracks, and microcracks in the concrete tested.

2 | EXPERIMENTAL METHODOLOGY

Three concretes were designed with different water/cement (w/c) ratios (0.45, 0.50, and 0.56) in order to study the behavior of concrete during exposure to high temperatures and different cooling systems. Portland cement, natural sand, and coarse aggregate from Patagonia (the most commonly used material in southern Argentina) were used to produce the concrete of the samples. Little international research was found on concrete produced with this coarse aggregate and exposed to high temperatures. The characteristics of the concretes are shown in detail in Table 1. Different w/c ratios were used to evaluate concretes of different quality. Concretes with a lower w/c ratio have a denser internal structure and this can affect their behavior when they are heated.

A total of 104 normalized cylindrical concrete samples measuring 15 × 30 cm were cast.[13] Curing was performed in the laboratory until the tests took place 90 days after casting.

Samples were grouped into equal batches that were exposed to temperatures of 250, 500, and 680°C for 1 hr. An electric oven with automatic temperature control was used for the thermal treatment. Another group of samples was not subjected to any treatment in order to compare its performance as reference samples or patterns.

The heating of the test specimens up to 250 and 500°C was carried out using a heating process very close to that indicated by the curve defined in ISO 834.[14] However, 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. The rate of heating was very similar to that described by this standard, but was 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 to this latter temperature exhibits very significant damage, whereas at lower exposure temperatures its residual properties make the analysis more interesting.

TABLE 1 Characteristics of the materials of the concrete

Mix no.	1	2	3
Cement content (kg/m^3 of concrete)	350	320	290
w/c ratio	0.45	0.50	0.56
Fine aggregate: natural sand (kg/m^3 of concrete)	853	878	896
Coarse aggregate: rounded gravel maximum nominal size: 25 mm (kg/m^3 of concrete)	1050	1050	1050
Plasticizer additive (% by weight of cement)	0.35	0.35	0.35
Slump (cm)	8	9	9

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

1. *Open air*. Room temperature was about 20°C (air-cooled).
2. *Light water spray*. Each sample was sprayed with 200 mL of water after being removed from the oven (water spray 1).
3. *Heavy water spray*. Samples were sprayed with 600 mL of water (water spray 2).

The amount of water used for cooling was such that, for water spray 1, the surface of the specimen remained dry after rapid evaporation of the water, whereas for water spray 2, some moisture was retained on the surface of the specimen. Hand sprayers were used for both spray types, applying water to the whole surface of the specimens. The water pressure was so low that it can be considered negligible for the results of the tests conducted.

Initially, the exposure time to high temperatures was intended to be 90 min, but this had to be reduced to 60 min, because samples with higher w/c ratios exposed to temperatures of 680°C degrade in the oven, preventing any kind of testing. This occurs due to the great loss of strength that concrete experiments at high temperatures, depending on the aggregate.[8,15,16] Other studies[7] involve longer exposure times (24 hr) to simulate thermal actions generated during industrial processes and not as a consequence of a fire, for which the time is shorter.

To evaluate the different concretes, tests such as those for compressive strength[12] were performed for all exposure temperatures and cooling systems. Regarding water spray 1, the following were determined: splitting tensile strength,[17] carbonation depth, density, absorption, porosity,[18] and water sorptivity.[19] These last two parameters are important for establishing the alteration present in the pore structure of the concrete. Besides, changes in ultrasonic speed can reflect changes in the concrete structure at high temperature because the ultrasonic waves are very sensitive to both surface and subsurface discontinuities (such as cracks or fissures). Therefore, the propagation speed of ultrasonic pulses was determined before and after exposing the samples to the heating cycle. Equipment that operates at 24 KHz (accuracy: 0.1 μs) was used. As the ultrasonic pulse speed (UPS) may be affected by the moisture content of the samples, measurements were taken between 48 and 72 hr after removing the samples from the oven. The storage conditions of the samples up to the time of testing were similar to laboratory conditions.

In order to conduct a more in-depth analysis, petrographic studies were performed on thin sections using a stereomicroscope and polarization microscopy. Samples exposed to 680°C were soaked in resin to prevent their disintegration when preparing the cuts. Aggregate composition and concrete characteristics were evaluated, focusing on the aggregate–mortar interface zone. A stereomicroscope was used as well as an Olympus BH-2 petro-chalcographic polarization microscope (trinocular with video camera) for digital image processing.

3 | RESULTS AND DISCUSSION

A visual inspection of the samples took place after removing them from the oven; changes in the surface color were noted. Samples exposed to 250°C turned pale pink color, those exposed to 500°C turned gray, and those exposed to 680°C turned a lighter shade of gray.

More severe crack patterns were noted as both maximum temperature of exposure and w/c ratio increased. For all dosages, the damage visible on the samples after being removed from the oven increased when water at 20°C was sprayed over them. It is worth mentioning that the water spray evaporated almost immediately, leaving some traces of moisture on the sample surfaces, which were cooled using a greater amount of water (600 mL, water spray 2).

3.1 | Physical and mechanical properties

The compressive strength results after 90 days f'_c are displayed in Figure 1. The failure mode of reference samples and those exposed to 250°C—tested under compression—was conical. Those exposed to higher temperatures exhibited an almost horizontal cracking plane. This unusual behavior is due to the influence of cracks in these concretes after being overheated. Figure 2 shows the percentages of residual compressive strength for the different kinds of concrete and cooling system. Figure 3 displays some stress–strain curves obtained during compression tests.[20]

The results for splitting tensile strength f'_t, carbonation depth d, absorption capacity C, and water sorptivity S are given in Table 2, and density ρ, absorption A, and porosity P in Table 3 for all concrete qualities and temperature ranges studied. These tests were run 90 days after casting and after the proper heating cycle.

Figure 2 shows that the percentages of residual compressive strength were lower for water spray 2 for all concrete types and, in general, were also slightly lower for concretes with a lower w/c ratio because of its denser internal structure.[21] The curves in Figure 3 show, as expected, a significant drop in the elastic modulus of concrete exposed to higher temperatures.

Splitting tensile strength results showed a greater loss than those for compressive strength. This occurs because the cracking generated all over the concrete mass affects the tensile strength more than the compressive strength. The reduction was about 30% for samples exposed to 250°C, <60% for those exposed to 500°C, and, finally, about 77% for those exposed to 680°C.

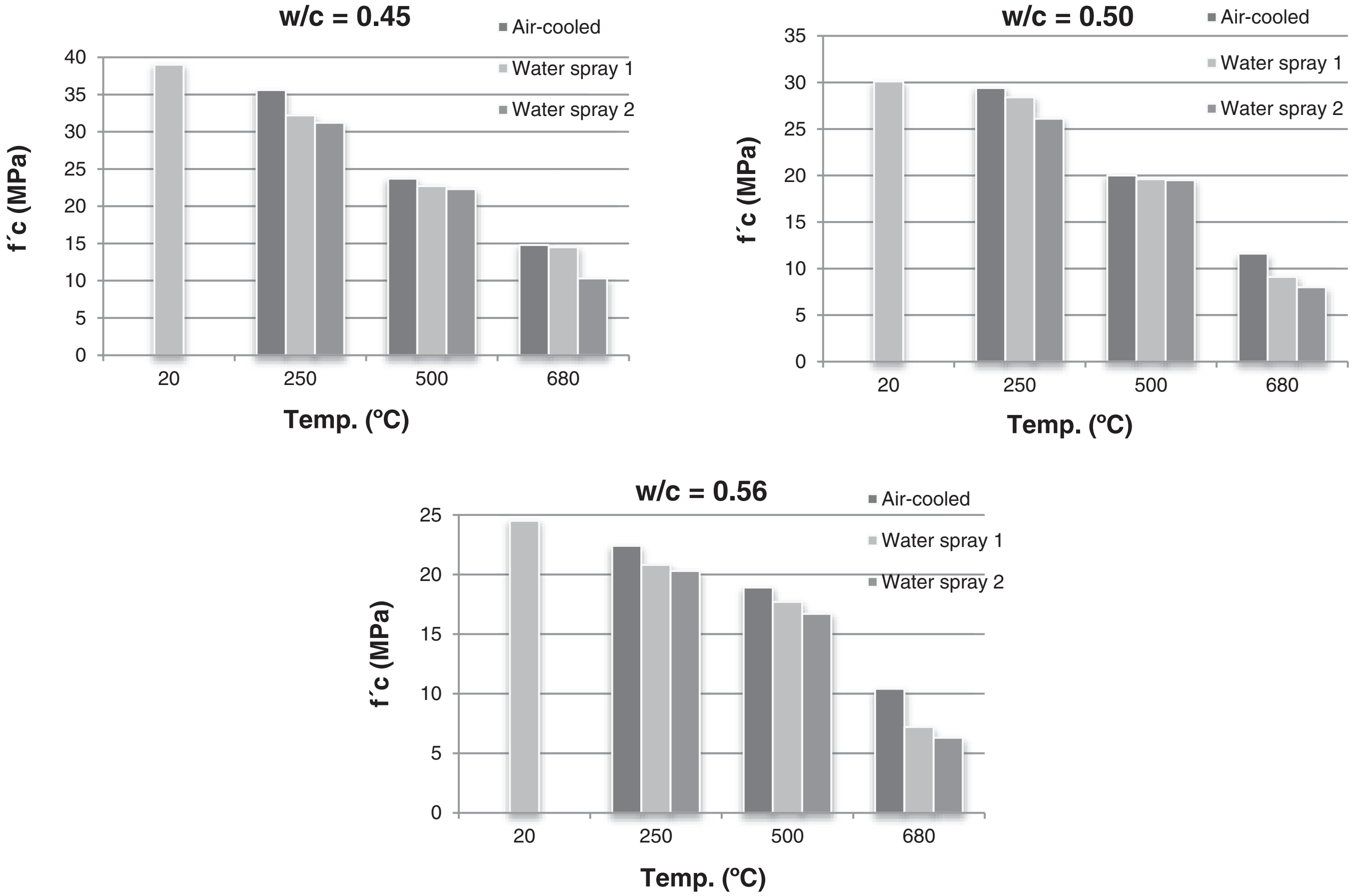

FIGURE 1 Compressive strength after 90 days for all concretes and cooling systems.

The same behavior from capillary absorption results was observed for all concretes. First, a reduction (compared with the reference samples) in the absorption capacity and water sorptivity values of the samples exposed to 250°C was noticed, and then a significant increase in those values for the remaining temperature ranges. This fact is related to the progressive growth of concrete carbonation as the exposure temperature increases. For samples exposed to 250°C, the crack pattern is not significant, surface concrete layers experienced a modification of the pore structure due to carbonation, making water entry through the capillaries difficult. For higher temperatures, the process of internal deterioration is critical and capillary suction values increased.

3.2 | Ultrasonic testing

This section describes the results obtained during the measurement of ultrasonic pulse speed (UPS) based on the temperature that samples were exposed to and the cooling system type, grouped by w/c ratio.[22]

Figure 4 shows that UPS descends in an approximately linear manner based on the temperature to which the concrete sample was exposed. There is a similar scenario for both water spray systems; UPS decrement is less for samples cooled in the open air than for moistened ones. It 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[8]; they worked with lower temperatures, and slower and lengthy heating processes.

It is worth mentioning that UPS measurements are altered by the presence of materials with different densities, for example, metal reinforcement. For example, for steel reinforcement with a higher density in concrete, higher propagation speeds ensue. For this reason, this method should be used carefully.

3.3 | Petrographic studies

The coarse aggregate used in these concretes is composed of polymictic boulder with a high content of volcanic rocks, most of them present vitreous pastes. Volcanic glass composition presents iron, mainly in a ferrous state. The fine aggregate consists of quartz natural sand with subordinate amounts of feldspar and quartzite rocks. Furthermore, a low content of chalcedony, carbonate shells, and altered volcanic glass was identified. Microscopic observations of the samples at different temperatures and air-cooled are discussed in the following sections.

3.3.1 | Stereomicroscopic observations

The reference concrete sample showed good compactness; aggregate–mortar contact zones were clearly defined; and no

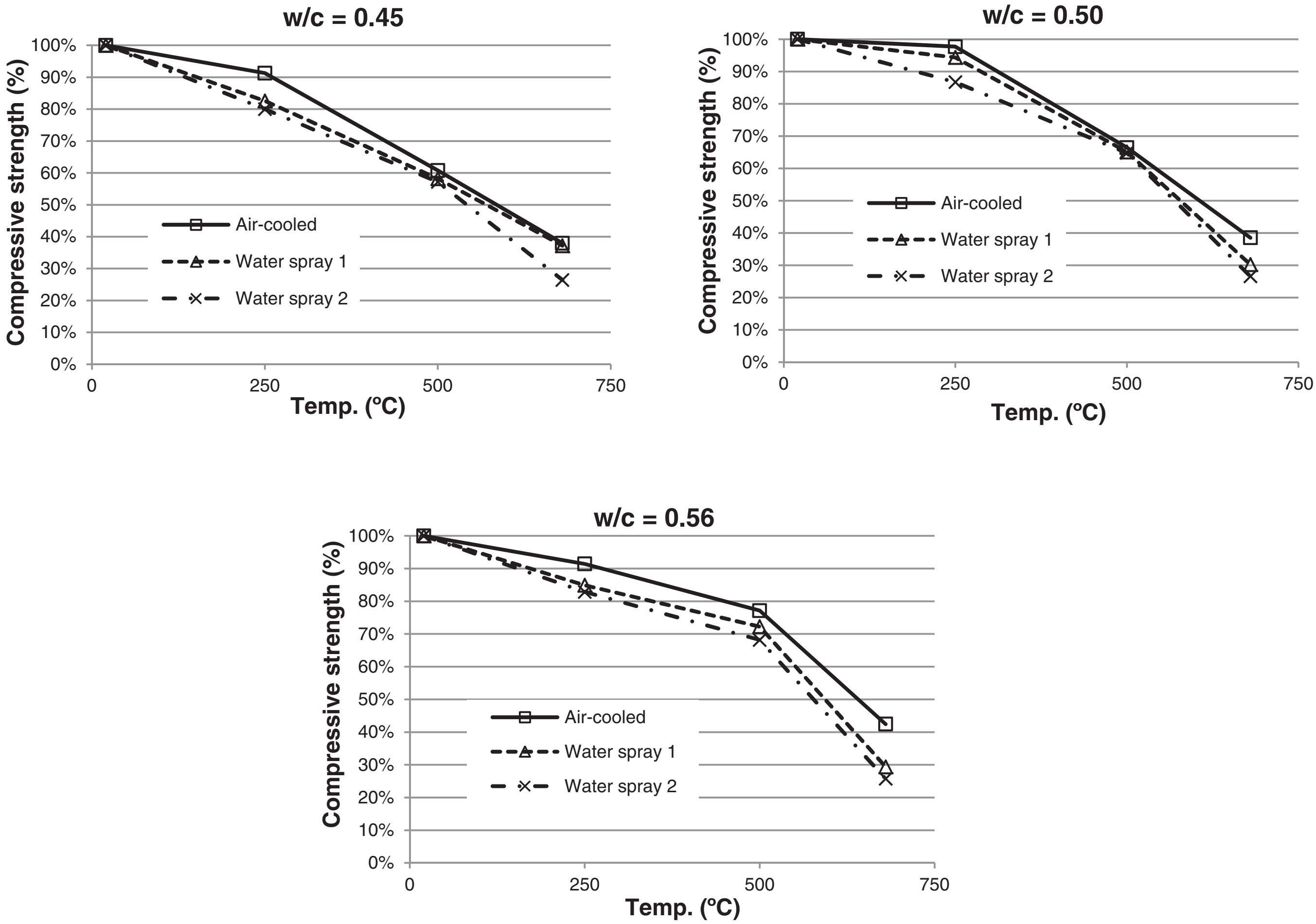

FIGURE 2 Percentages of residual compressive strength for different concretes and cooling systems.

reaction rims or microcracks were observed. Figure 5a displays aggregate composition and mortar status. Fine and coarse aggregate clasts are clear and accidental air cavities are empty.

Peripheral and central areas of the sample exposed to 250°C were analyzed. There were no significant differences in the concrete characteristics compared with the reference sample, even though aggregate particles separate easily from the mortar. There were no variations between the peripheral and the core area of the sample.

A color change of the aggregates due to iron oxidation, present in the minerals, was noticed at 500°C. Clast separation is more evident than at 250°C and it also affects the fine aggregate particles. The process develops with greater intensity in the peripheral zone than in the core. Figure 5b shows a concrete sector where the aggregate particles are clearly separated from the mortar.

When the temperature is raised to 680°C, the color change of the aggregate particles is accentuated and

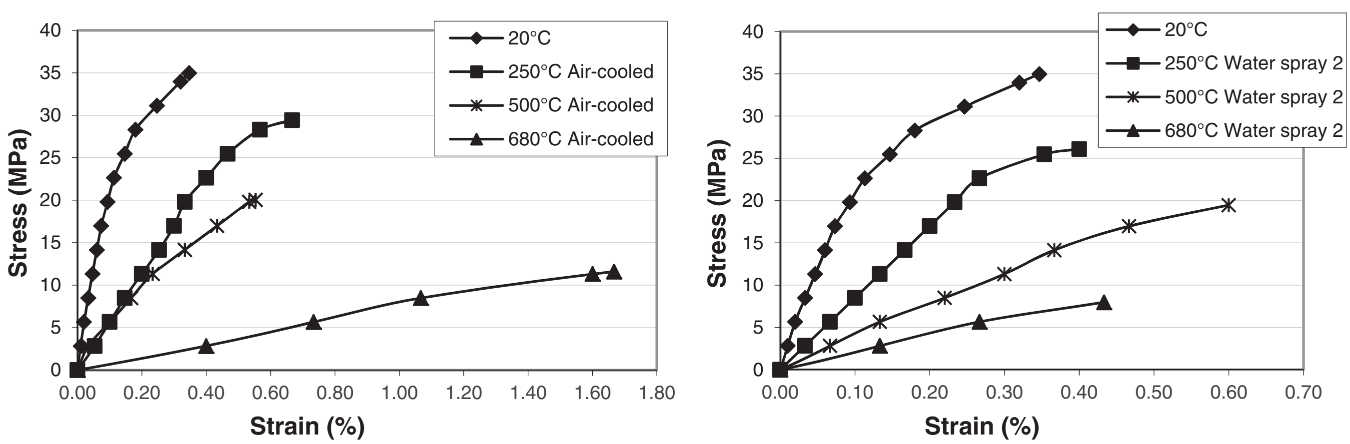

FIGURE 3 Stress–strain curves for different temperatures and cooling systems, corresponding to concretes with w/c = 0.50.

TABLE 2 Splitting tensile strength f'_t, carbonation depth d, absorption capacity C, and water sorptivity S

	f'_t (MPa)				d (mm)			
Water spray 1	**Pattern**	**250°C**	**500°C**	**680°C**	**Pattern**	**250°C**	**500°C**	**680°C**
w/c = 0.45	3.2	2.3	1.4	0.9	3	12	18	22
w/c = 0.50	3.0	1.9	1.3	0.7	3	13	19	24
w/c = 0.56	2.2	1.5	0.9	0.5	4	13	20	25
	C (g/m^2)				S (g/m^2 seg$^{1/2}$)			
	Pattern	**250°C**	**500°C**	**680°C**	**Pattern**	**250°C**	**500°C**	**680°C**
w/c = 0.45	4411	2867	5093	5340	10.3	7.7	18.2	21.9
w/c = 0.50	4523	3647	5120	5376	11.1	8.0	20.0	24.4
w/c = 0.56	4507	3941	5098	5328	11.2	8.1	21.9	25.4

TABLE 3 Density ρ, absorption A, and porosity P

	Pattern			250°C			500°C			680°C		
Water spray 1	ρ (g/cm^3)	A (%)	P (%)	ρ (g/cm^3)	A (%)	P (%)	ρ (g/cm^3)	A (%)	P (%)	ρ (g/cm^3)	A (%)	P (%)
w/c = 0.45	2.40	5.1	8.7	2.39	5.2	8.8	2.36	5.4	11.4	2.32	5.5	12.5
w/c = 0.50	2.36	5.2	9.2	2.34	5.5	10.3	2.32	5.6	13.5	2.31	5.6	13.6
w/c = 0.56	2.35	5.2	9.1	2.34	5.4	10.1	2.33	5.6	13.2	2.30	5.7	13.8

vitrification is noticed in some aggregate components. Major crack development is noticed on the coarse aggregate grains, in some cases followed by cracks in the paste. Mortar separation is more accentuated and it even affects the sample core. Figure 5c shows reddish aggregate particles separated from the mortar.

3.3.2 | Polarization microscopy

Figure 5d shows the reference sample. The coarse aggregate particle is a volcanic rock. Quartz predominates in the composition of the fine aggregate. Aggregate–mortar contact zones are clearly defined. There are neither cracks nor reaction rims. At 250°C, a separation between the

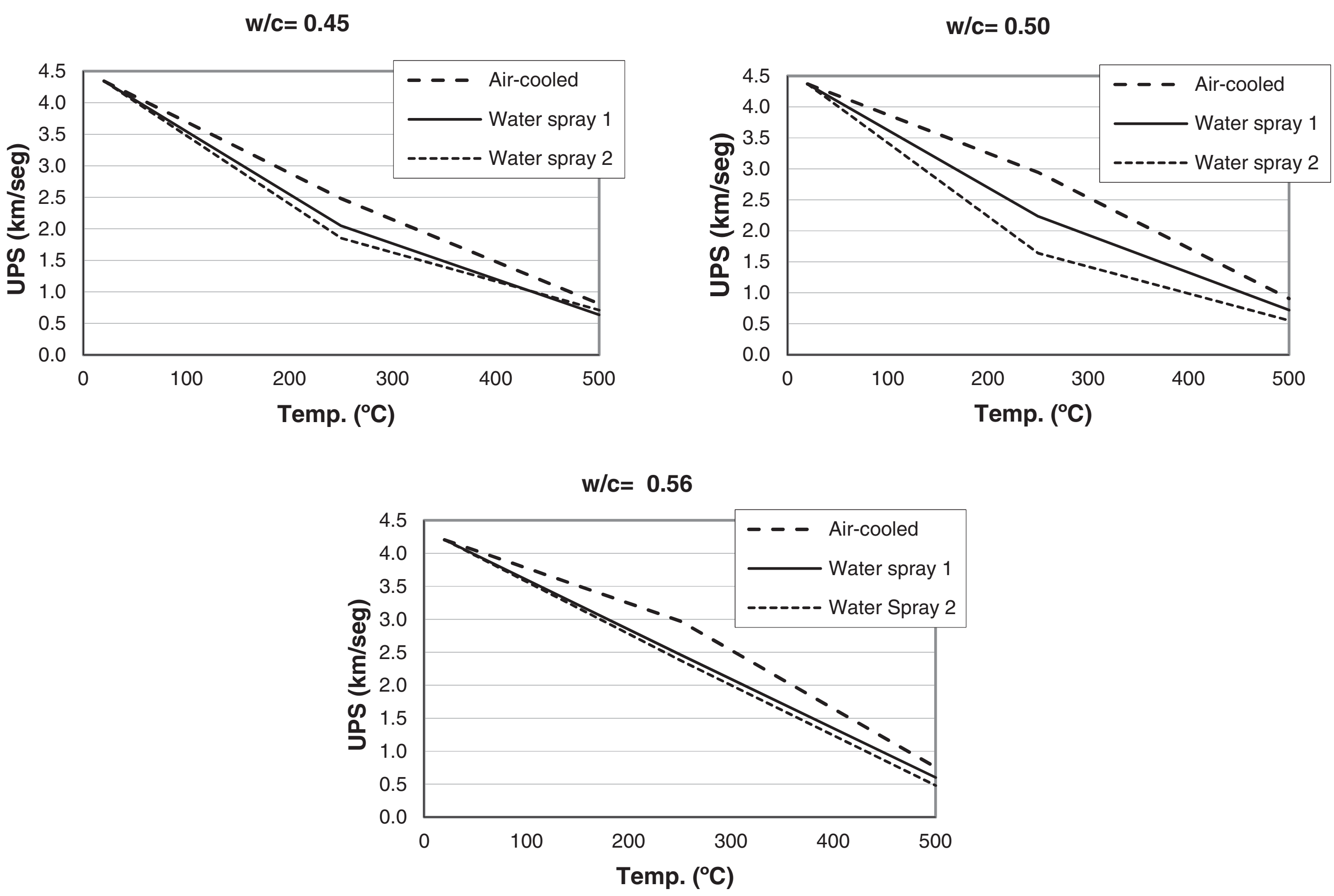

FIGURE 4 UPS variation for different concretes and cooling systems.

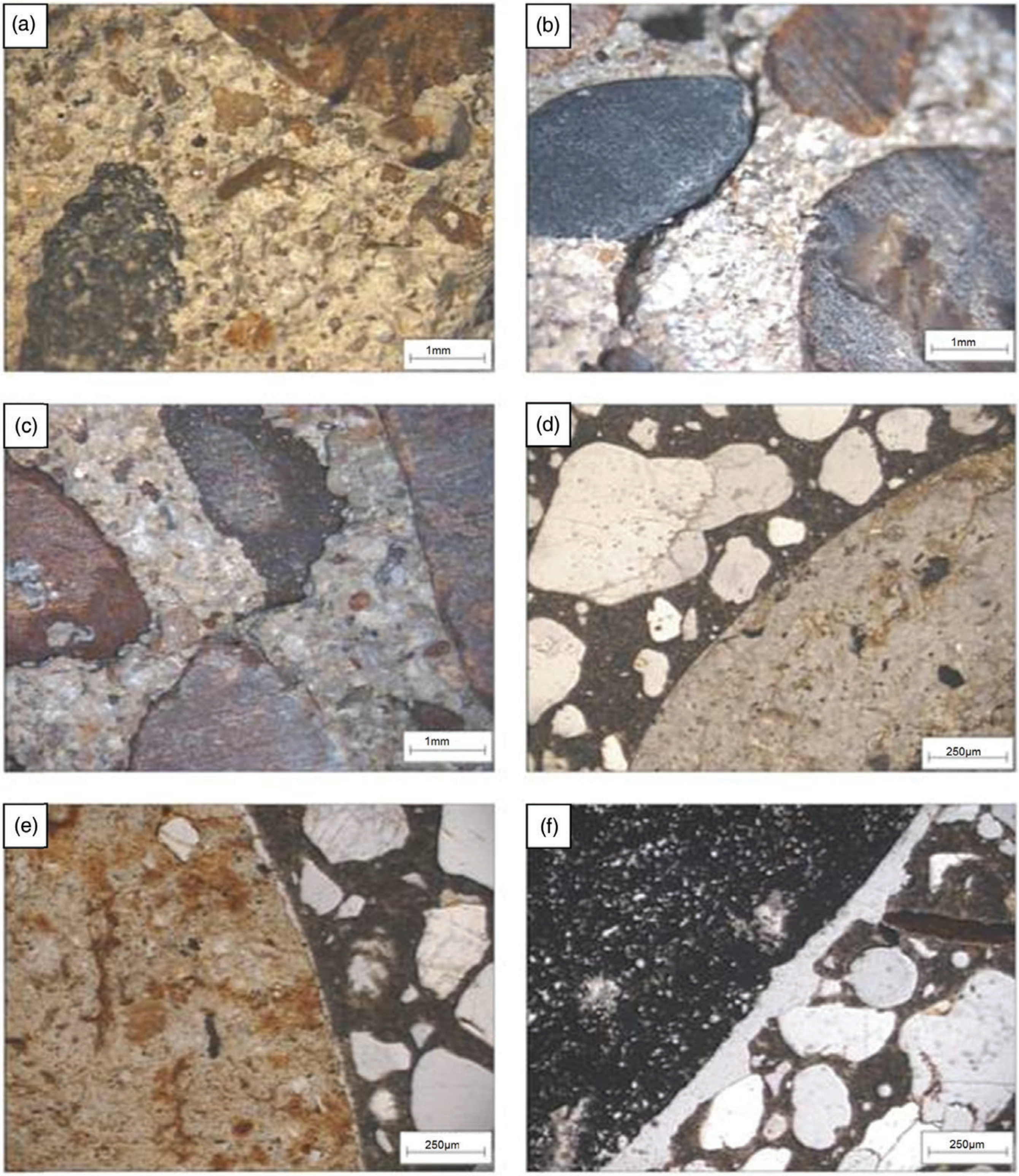

FIGURE 5 (a) Reference sample under stereomicroscope, (b) aggregate particles separated from the mortar (500°C), (c) color change of the grains (680°C), (d) reference sample under polarization microscope with parallel light, (e) coarse aggregate particle showing color change and some separation from the mortar (500°C), and (f) similar to panel (e) but showing a more accentuated process (680°C).

boulder and the mortar can be seen. The sample exposed to 500°C has reddish-colored particles (Figure 5e) due to iron oxidation, and aggregate grains are separated from the mortar, even in the core.

Samples exposed to 680°C show a more significant oxidation of the mineral containing iron, as aggregate grains. The mortar and some coarse aggregate particles show cracking. This phenomenon affects the entire sample (from the external areas to the core). Figure 5f shows an external area.

4 | CONCLUSIONS

According to the tests performed for this research, the following conclusions can be drawn for the concretes described in this article:

- The compressive strength of the samples exposed to 250°C suffered a minor reduction. This loss increased with the increase in both the exposure temperature and the volume of water used for cooling.
- The splitting tensile strength results showed bigger losses than those of the compressive strength tests.
- The carbonation depth increased significantly with the rise in temperature.
- The absorption capacity and water sorptivity decreased in samples exposed to 250°C in comparison with reference samples, and there was a significant increase in these values for the remaining exposure ranges, irrespective of concrete quality.
- Ultrasonic pulse tests showed the deterioration of the concrete exposed to high temperatures and rapid cooling, with significant decrements in ultrasonic propagation speed values. Nevertheless, these tests must be used carefully.
- It was noticed that from 250°C onward, coarse aggregate particles separate from the mortar. Samples exposed to 500°C showed a color change in the aggregates due to iron oxidation present in the minerals. These phenomena did not take place in the sample core. At 680°C, the color change of the aggregate particles was more intense and vitrification processes were noticed on some aggregate components. Fine and coarse aggregate clasts showed several cracks; in some cases, cracking is also present in the paste, affecting the sample core. This was noticed through the reduction in ultrasonic speed.
- Modifications to the physical and mechanical properties are due to the weakening of the interface area and the development of microcracks generated by the heating and rapid cooling processes.

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