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Effects of cooling type on mechanical properties of concrete produced with slag-modified cement exposed to high temperatures

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ABSTRACT. Effects of different cooling methods on residual mechanical properties of normal-strength concretes produced with slag-modified cements were not reported in previous literature. Therefore, a (2 x 2 x 4) factorial experiment was carried out in the present study to investigate the compressive strength and elastic modulus of slag-modified cement concretes with different strength levels (characteristic compressive strength of 20 and 30 MPa) subjected to different maximum temperatures (200, 400, 600, or 800ºC) and cooling procedures (slow or fast cooling). According to analyses of variance (ANOVA), air-cooled specimens showed higher residual mechanical properties. Higher residual elastic modulus was observed in concretes with higher initial strength, whereas residual strength was only affected by initial strength for higher temperatures. Effects of different cooling methods were more pronounced in slag-modified concretes than in concretes produced with ordinary Portland cement, especially for temperature up to 400ºC. Since slag-modified concretes have lower calcium hydroxide content, volume expansion and cracking propagation due to lime rehydration during slow cooling were mitigated, leading to higher post-fire mechanical properties. In contrast, these types of concrete exhibited significant temperature difference along their cross-section when fast cooling was used, so that a substantial thermal shock caused limited post-fire mechanical properties.

Keywords: concrete; slag-modified cement; fire; strength; stiffness; cooling procedures.

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Introduction

Since concrete is composed of materials with different thermal and mechanical properties, it undergoes various transformations in its chemical composition and physical structure when exposed to fire (Ma, Guo, Zhao, Lin, & He, 2015; Memon, Shah, Khushnood, & Baloch, 2019; Xu, Wong, Poon, & Anson, 2001). The mechanical properties of concrete exposed to high temperatures mainly depends on the following factors: maximum temperature exposure, concrete strength before fire, aggregates type, cement type, presence of fibers and mineral admixtures, time of exposure, loading condition and type of cooling (Lublóy, Kopecskó, Balázs, Restás, & Szilágyi, 2017; Ozbay & Lachemi, 2012). Typically, concrete under compression may maintain acceptable cohesion when subjected to temperatures up to 600ºC. In general, conventional concrete presents about 25% of compressive strength loss when it reaches temperature levels of 300ºC and strength losses of about 75% for temperature increases of 600ºC (Chan, Peng, & Anson, 1999; Phan & Carino, 1998; Schneider, 1982).

A large number of works have already investigated the effects of fire on strength, stiffness, microstructure and durability of concrete (Ma et al., 2015; Memon et al., 2019; Xiao, Xie, & Xie, 2018). Most of the residual properties previously reported were obtained under conditions of natural cooling, which are obviously different from those obtained after the cooling regime used in a real fire, as water is commonly used for fire extinguishing (Botte & Caspeele, 2017). A literature review was conducted to identify the main research papers published in the last two decades and focused on the effects of slow cooling (SC) and fast cooling (FC) procedures on the residual mechanical properties of concretes. A summary of these studies is presented in Table 1. This table lists the maximum temperature levels investigated in these studies, in addition to the values of relative residual factors of different mechanical properties (e.g., compressive strength, elastic modulus, tensile strength) associated with the exposure of different types of concrete to the maximum temperature levels. It is important to highlight that experimental curves obtained in these studies were also plotted in the next sections of this manuscript, in order to provide detailed comparisons between the results of the present study and the quantitative dataset obtained in previous papers compiled in Table 1. However, the general trend is that lower reductions of compressive strength occur in cases of natural/furnace cooling, when compared to those obtained after water spraying/quenching cooling, as large thermal shock occurs when the material is cooled down abruptly. Many studies also show that the strength reduction of normal-strength concrete was greater than that verified in high performance concrete.

Previous studies revised by Wróblewska and Kowalskihis (2020) indicated that the negative impacts of FC hold particular importance in concrete heated to moderate temperatures (300–350°C). These specimens exhibit greater stiffness compared to those subjected to higher temperatures, rendering them more vulnerable to the detrimental effect of stress induced by FC. Moreover, the authors observed that FC methods may compromise the durability of structural elements, as concrete cracking increases gradually due to the sudden cooling process. According to Abrams (1983), concretes containing siliceous aggregates exposed to 800°C presented greater strength losses than concretes containing limestone aggregates or lightweight aggregates subjected to the same temperature level.

The concrete elastic modulus drastically reduces with temperature increases (Bamonte & Gambarova, 2007; Neville, 2011; Schneider, 1988). Despite this, few previous works (Botte & Caspeele, 2017; Liu, Chen, Che, Liu, & Zhang, 2020; Nassif, 2006; Nassif, Rigden, & Burley, 1999) have investigated the effects of different types of cooling on the residual modulus of elasticity of concrete. Although Botte and Caspeele (2017) and Nassif (2006) indicated that heating and subsequent water cooling resulted in a significant decrease of the modulus of elasticity of concrete, they did not report the relative elastic modulus reductions with the temperature increase for different cooling methods. On the other hand, the experimental data recently published by Liu et al. (2020) indicated that the residual elastic modulus of high-strength concrete exposed to 500°C is about 10% of the original elastic modulus, for both air-cooling and water-cooling methods.

Table 1. Literature review on previous studies dealing with different cooling methods of concrete exposed to high temperatures.

Study	Type of concrete	Type of cement	Type of aggregate	Compressive strength range before fire		Mechanical properties investigated	Maximum exposure temperature and its associated range of relative residual mechanical property factors (a)	Types of cooling investigated
				Cube	Cylinder			
Abadel, Abbas, Albidah, Almusallam, and Al-Salloum (2022)	Ordinary and fiber-reinforced concrete	OPC	Silica sand and limestone coarse aggregates	-	32 – 42 MPa	f_c	600 °C; 0.40-0.76 (f_c)	SC (air cooling at room temperature) for 1 day; FC (immersion in water) for 24 h
Fayadh, Qasim, and Farhan (2021)	Ordinary, high-strength, ultra-high-strength, and fiber-reinforced concrete	OPC	Not reported	-	35 – 78 MPa	f_c	1000 °C; 0.41-0.67 (f_c)	SC (air cooling for 1 day); FC (immersion in water at 25 °C after heating or CO_2 fire extinguisher for laboratory purposes)
An, Song, Liu, and Meng (2021)	Ordinary and fiber-reinforced concrete with FA and SF	Not reported	River sand and limestone crushed stone	-	30 – 38 MPa	f_c (static and dynamic tests)	800 °C; 0.11-0.25 (f_c)	SC (air cooling); FC (water cooling)
Liu et al. (2020)	Concrete containing FA	OPC 42.5R	Local gravel, medium sand and desert sand	44 – 51 MPa	-	E, f_c	700 °C; 0.63-0.68 (f_c) / 500 °C; 0.11-0.15 (E)	SC (room temperature); FC (immersion in water for 0.5 h)
Segalin, Balestra,	Ordinary concrete	ASTM Type I (PM)	Quartz sand and basaltic coarse	-	58 MPa	f_c	400 °C; 0.70-0.73 (f_c)	SC (natural cooling); FC

Savaris, and Bressiani (2020)		(American Society for Testing and Materials [ASTM], 2022)	aggregate					(immersion in water)
Awad (2020)	Reactive power concrete	OPC	Local fine aggregates	90 – 116 MPa	-	f_c, f_t	500 °C; 0.36-0.91 (f_c); 0.44-0.62 (f_t)	SC (room temperature); FC (immersion in water or foam curing)
Carvalho et al. (2019)	Ordinary concrete	ASTM Type III cement (2022)	Limestone gravel and sand	-	15 – 40 MPa	f_c	800 °C; 0.42-0.61 (f_c)	SC (room temperature); FC (spraying water)
Botte and Caspeele (2017)	Ordinary concrete	CEM I 52.5 N	Silica sand and siliceous gravel	-	~ 47 MPa	f_c, E, f_b	600 °C; <0.06 (f_c); 0.12-0.17 (f_b)	FC (spraying water for 5 minutes or immersion water)
Shaikh and Vimonsatit (2016)	Concrete containing FA	ASTM Type I cement (2022)	Crushed granite rock	-	40 – 55 MPa [(b)]	f_c	800 °C; 0.13-0.23 (f_c)	SC (inside the furnace); FC (immersion in water)
Awal, Shehu, and Ismail (2015)	Concrete containing POFA	OPC	River sand and granite gravel	27 – 44 MPa	-	f_c	800 °C; 0.30-0.50 (f_c)	SC (room temperature); FC (spraying water)
Nadeem, Memon, and Lo (2014)	Concrete with FA and metakaolin	lOPC	Crushed granite and river sand	70 – 130 MPa	-	f_c	800 °C; 0.19-0.48 (f_c)	SC (furnace cooling); FC (immersion in water)
Yaragal and Narayan (2012)	Ordinary concrete	OPC 43 grade	River sand and coarse aggregates	22 MPa	-	f_c, f_t	550 °C; 0.45-0.64 (f_c); 0.24-0.52 (f_t)	SC (furnace cooling or natural cooling at room temperature); FC (sand bath cooling, Sprinkling water for 5 and 10 minutes or immersion in water)
Bingöl and Gül (2009b)	Ordinary concrete	ASTM Type I cement (2022)	Siliceous river sand and gravel	-	20 – 35 MPa	f_b	700 °C; 0.11-0.59 (f_b)	SC (air cooling); FC (immersion in water)
Bingöl and Gül (2009a)	Ordinary concrete	ASTM Type I cement (2022)	Siliceous river sand and gravel	-	20 – 35 MPa	f_c	700 °C; 0.32-0.45 (f_c)	SC (air cooling); FC (immersion in water)
Peng et al. (2008)	Fiber-reinforced concrete	OPC grade 42.5	Medium sand and crushed limestone	-	84 – 89 MPa	f_c, f_t	800 °C; 0.06-0.34 (f_c); 0.10-0.24 (f_t)	SC (furnace cooling); FC (immersion in water or spraying water for 1 hour)
Husem (2006)	Micro-concrete	OPC 32.5 and 42.5 grades	Limestone aggregates	59 – 85 MPa	-	f_c, f_f	1000 °C; 0.00-0.30 (f_c)	SC (air cooling); FC (immersion in water)
Nassif (2006)	High-strength concrete	OPC	River/limestone gravel and marine sand	63 – 70 MPa	-	f_c, E	470 °C; 0.43-0.47 (f_c)	SC (air cooling); FC (spraying water for 5 minutes)
Abramowicz and Kowalski (2005)	Ordinary concrete	OPC	Siliceous aggregates	-	25 – 50 MPa	f_c	500 °C; 0.45-0.52 (f_c)	SC (room temperature); FC (immersion in water for 10 seconds)
Luo, Sun, and Chan (2000) and Chan, Luo, and Sun (2000)	Ordinary and high-performance concrete	OPC	River sand and crushed granite	35 MPa; 97 – 114 MPa	-	f_c	1100 °C; 0.07-0.12 (f_c)	SC (furnace cooling); FC (immersion in water)
Nassif et al. (1999)	Ordinary	Not reported	Siliceous sand	Not	Not	E	470 °C; 0.12-	SC (air cooling); FC

concrete	and coarse limestone aggregate	reported	reported	0.19 (*E*)	(spraying water for 5 minutes)

[(a)] The relative residual mechanical property factors were calculated as the ratio between the residual mechanical property after heating/cooling processes and the initial value of the mechanical property of specimens that were not subjected to the heating and cooling processes. [(b)] All of the authors presented in this table conducted their experimental mechanical tests after a 28-days curing period of concrete, except for Shaikh and Vimonsatit (2016), which reported data of concrete subjected to a curing period of 56 days. Notes: E = modulus of elasticity; FA = fly ash; f_c = compressive strength; f_f = flexural strength; f_t = tensile strength; OPC = ordinary Portland cement; POFA = palm oil fuel ash; SF = silica fume; f_b = bond strength between concrete and reinforcement.

Some previous works observed that the modulus of elasticity of concrete is strongly influenced by the type of aggregate used in the mixture (Neville, 2011; Schneider, 1988). Schneider (1988) carried out an experimental program focused on the study of elastic modulus reductions in fire-damaged concretes containing different types of aggregates. Concretes containing siliceous and basaltic aggregates presented greater elastic modulus reductions with the temperature increase, unlike concretes containing limestone aggregates. However, concretes containing lightweight aggregates showed a smaller elastic modulus decrease than concretes containing siliceous aggregates. The author still explains that the elastic modulus reductions with temperature increases are mainly due to the rupture in the internal bonds between the hydrated cement paste and the aggregates. On the other hand, Kodur and Harmathy (2002) reported that normal concretes containing different types of aggregates and exposed to high temperatures, presented similar elastic module.

Distinct conclusions about the residual strength/stiffness of normal-strength concretes and high-strength concretes have been observed. Ali, O'Connor, and Abu-Tair (2001) and Kodur and Phan (2007) reported the occurrence of spalling and lower fire endurance in high-strength concretes, due to their lower permeability. Lau and Anson (2006) verified that elastic modulus reductions were more evident in high-performance concretes than in normal concretes.

The use of supplementary cementitious materials (e.g., blast furnace slags) as clinker replacement in Portland cement has decreased cement and concrete's carbon footprint, consumption of virgin material, embodied energy and clinker production impacts (Silva, Saade, & Gomes, 2013). In fact, many studies have shown the importance of blast furnace slags for the cement industry, in terms of reducing environmental impacts and providing technical benefits (Özbay, Erdemir, & Durmuş, 2016). Previous research indicated that the type of cement affects the residual mechanical properties of fire-damaged cementitious materials (Lublóy et al., 2017; Zemri & Bouiadjra, 2020). For temperature exposure levels up to 400°C, Hager, Tracz, Choińska, and Mróz (2019) concluded that concretes produced with slag-modified cement presented lower permeability and higher compressive strength than concretes produced with ordinary Portland cement (OPC), while the difference between their tensile strength may be considered insignificant. Lublóy, Kopecskó, Balázs, Szilágyi, and Madarász (2016) observed that the increase of the slag content of cement improved the relative residual compressive strength of concrete exposed to temperatures up to 800°C.

All of the previous studies dealing with the effects of different cooling methods in the residual strength and stiffness of concrete have focused on concretes with the following ASTM cements: Type I (OPC), Type III (Portland cement with high early strength) and Type I(PM) (pozzolan-modified Portland cement) (ASTM, 2022). To the authors knowledge, there is a lack of evaluations of the effects of cooling regimes on the residual strength and stiffness of fire-damaged concretes produced with slag-modified cement. Few previous studies (Nassif, 2006; Nassif et al., 1999; Botte & Caspeele, 2017; Liu et al., 2020) evaluated the effects of different types of cooling on the residual modulus of elasticity of concrete. All of them dealt with concretes with high original compressive strength levels. Therefore, the quantification of the effects of different cooling types on the residual elastic modulus of normal-strength concretes is still unknown.

Normal-strength concretes produced with slag-modified cements have been largely used in the construction industry. Research is needed to investigate the effects of cooling procedures on the residual strength and stiffness of concretes produced with these blended cements, as previous results obtained for concretes produced with OPC cannot be generalized to define design criteria for fire resistance of concretes with slag-modified cements. The experimental program of this research filled a gap in the literature concerning the determination of the residual mechanical properties (compressive strength and elasticity modulus) of concrete produced with slag-modified cement exposed to high temperatures and different cooling methods. This work firstly reported a systematic evaluation of the quantitative effects of the initial concrete strength, cooling method and maximum exposure temperature level on the different residual mechanical parameters of concrete produced with this type of cement (slag-modified cement), based on results of statistical analyses of variance (ANOVA) derived from a factorial experiment. Comparisons between the results of this work, predictions of design codes, and results of previous works dealing with OPC concretes indicated that the effects of different cooling methods on the residual concrete strength and stiffness seem to be more pronounced in slag-modified cement concretes than in OPC cement concretes.

Material and methods

Concrete specimens were produced with the Portland cement CP II-E-32 defined by ABNT NBR 16697 (Associação Brasileira de Normas Técnicas [ABNT], 2018a), which is equivalent to the slag-modified cement defined by ASTM C595 (American Society for Testing and Materials [ASTM], 2020). This type of cement contains 6% - 34% of ground granulated blast-furnace slag. The chemical composition of this type of cement has been widely reported in previous literature, based on results of X-ray fluorescence (XRF) and X-ray diffraction (XRD) analyses. These XRF analyses of CP II-E-32 cement indicated contents of CaO (65-72%), SiO_2 (16-18.5%) and Al_2O_3 (5-6%), in addition to low concentrations of Fe_2O_3 (2-4%), SO_3 (3-4%), and eventual traces of MgO (~2%). Moreover, XRD analyses revealed typical signatures associated with the presence of tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), tetra-calcium aluminates (C_4AF), calcite and gypsum. To decrease the CO_2 emission levels of concrete materials, ground granulated blast furnace slags have been widely used around the world in Portland cement production (Mehta & Monteiro, 2005; Samad & Shah, 2017). For example, while OPC is almost absent in the Brazilian market, the slag-modified cement CP II-E is one of the most consumed types of cement in Brazil (Rocha, 2022), which is an important justification for developing the present research.

Siliceous aggregates were used in this work. Natural quartzite sand extracted from the Piranga River (Porto Firme, Minas Gerais State, Brazil) was used as fine aggregate, and gneissic gravel (Ervália, Minas Gerais State, Brazil) with a maximum diameter of 25 mm was used as coarse aggregate. Siliceous fine and coarse aggregates were selected for the investigation of the present work because they are widely used in different regions of Brazil. For example, siliceous fine and coarse aggregates are widely used in the region where the present study was developed (Zona da Mata, mesoregion of Minas Gerais State, Brazil). The concrete mixture design was performed according to ABNT NBR 12655 (Associação Brasileira de Normas Técnicas [ABNT], 2015).

The present experimental program consists of compression tests of concrete cylinders of two different normal-strength levels (20 and 30 MPa), subjected to four distinct maximum exposure temperatures (200, 400, 600, and 800°C) and two different cooling methods (air-cooling and water-cooling). Extra specimens (ST) instrumented with three thermocouples were also produced for temperature monitoring during the exposure of specimens to elevated temperatures. Therefore, a (2 x 2 x 4) factorial experiment was elaborated according to a completely randomized design with 6 repetitions. The different factors investigated in this experimental design were (i) the compressive strength of concrete, (ii) the maximum exposure temperature, and (iii) the cooling regime. The response variables of this factorial experiment were compressive strength and static elastic modulus. Reference specimens that were not exposed to high temperatures were also evaluated.

To produce the specimens, cement, sand, gravel, and water were mixed in the suitable amounts, using a concrete mixer with capacity for 150 L. The fresh mixture was poured into oiled cylindrical molds (diameter of 10 cm and height of 20 cm). The specimens were kept inside the molds for 24 hours. Once demolded, they were submerged in a water-curing tank during 28 days. Three thermocouples were embedded into the fresh mixture used to cast the ST specimens, in order to evaluate the internal temperature profiles at the mid-height of different cross-sections of the concrete cylinder, during the fire simulation. The thermocouples 0, 1, and 2 were located close to the cylindrical surface of the specimen, at the midway between its center and its cylindrical surface, and at the center of the specimen, respectively (Figure 1a). After a conventional 28-days curing period, compression tests of the reference concrete specimens were carried out, whereas the other specimens were placed into an electric muffle furnace for heating (Figure 1b). The rate of heating was about 4°C $min.^{-1}$ The thermocouple 3 was used to measure the temperature inside the furnace chamber. After reaching the target maximum temperature inside the furnace, the time required to stabilize the temperatures in the three thermocouples of the TS specimen was assessed with a data acquisition system (DAQ). Fig. 1b shows the experimental setup used to obtain the temperature inside the furnace and inside the TS specimen over the time. When the temperature in the four thermocouples reached the maximum target temperature, the furnace was turned off. To observe the temperature measured by the 0, 1, 2 and 3 thermocouples, a compact DAQ 9178 chassis containing an NI 9219 module was used.

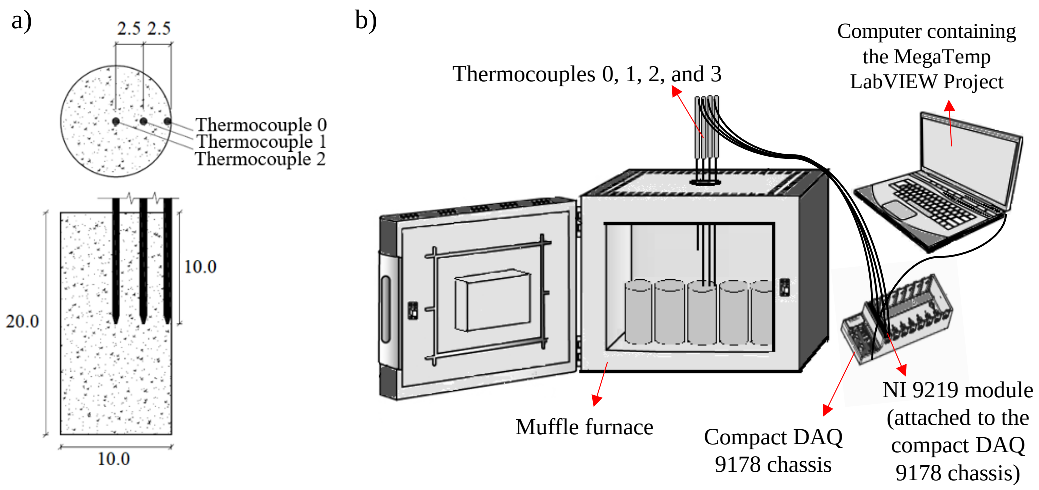

Figure 1. Exposure of specimens to high temperatures: position of the thermocouples in TS specimens (a) and experimental setup for application of heating/cooling regimes (b); dimensions in centimeters.

Immediately after the heating process, specimens subjected to fast cooling (FC specimens) were removed from the furnace and exposed to water quenching for ten minutes (the water temperature was 22°C), in order to simulate fire combating actions, in which water was applied to the burning structure. After the fast cooling, the specimens were immediately instrumented for determination of their residual static elastic modulus $E_{c,R}$ according to prescription of the ABNT NBR 8522 (Associação Brasileira de Normas Técnicas [ABNT], 2017) and residual compressive strength $f_{c,R}$ according to recommendations of the ABNT NBR 5739 (Associação Brasileira de Normas Técnicas [ABNT], 2018b), using an universal testing machine (model EMIC DL60000). The other specimens (SC specimens) were air-cooled during (17 ± 1) h after opening the furnace door. After they reached the room temperature, they were tested using the same testing procedures and universal testing machine, in order to determine their residual strength and stiffness.

Results and discussion

Residual compressive strength

A relative residual compressive strength factor ($\Phi_{c,j}$) was calculated for each specimen, as indicated in Equation (1):

$$\Phi_{c,j} = \frac{f_{c,R,j}}{f_{cm}} \qquad (1)$$

This factor was defined as the ratio between the residual compressive strength of the specimen j ($f_{c,R,j}$) and the average strength of reference samples that were not subjected to heating and cooling processes (f_{cm}).

Grubbs' tests (5% significance level) did not identify outliers in any series. In order to evaluate possible significant differences between the average relative residual strength factor of each series, an ANOVA at the 5% significance level was carried out. When the ANOVA detected that the compared means were significantly different, the Tukey test (5% significance level) was applied in order to identify the means that were significantly different from each other.

Influence of exposure temperature on residual compressive strength

Figure 2a and 2b show the averages of the relative residual compressive strength factors ($\Phi_{c,ave}$) as a function of the exposure temperature, for each concrete strength level and type of cooling. According to the Tukey's test, they were statistically different at the 5% significance level. Then, it was possible to confirm that the higher the temperature reached, the lower the residual compressive strength of concrete. Comparisons between these results and results of previous works and fire design codes are discussed in the next subsection.

Influence of type of cooling on residual compressive strength

For each compressive strength and exposure temperature level, the means of relative residual compressive strength obtained for each type of cooling were compared using the Tukey's test. The specimens subjected to water cooling presented statistically lower residual compressive strength, when compared to the air-cooled specimens, as also shown in Figure 2a, 2b, and in previous research (Husem, 2006; Khoury, 1992).

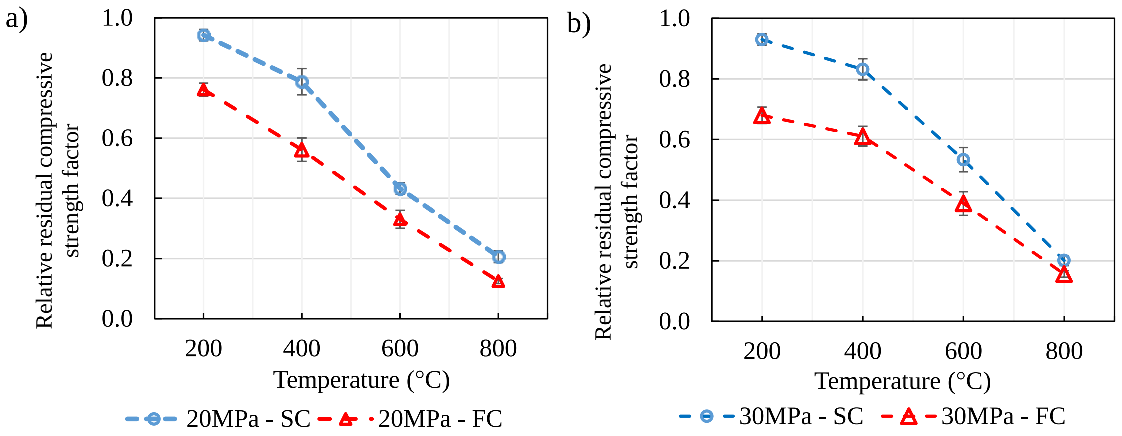

Figure 2. Relative residual compressive strength with increasing temperature for the 20MPa/SC and 20MPa/FC series (a); 30MPa/SC and 30MPa/FC series (b).

Influence of pre-fire compressive strength level on the residual compressive strength

For each type of cooling and maximum temperature level, the means of relative residual compressive strength obtained for each concrete strength level were compared using the Tukey's test. For the 5% significance level, no significant difference was verified when slow cooling was used. Therefore, the compressive strength had low influence on the relative residual compressive strength factor when slow cooling was used. However, the concrete strength significantly affected the relative residual strength factor of specimens subjected to fast cooling. In this case, for higher temperature levels (600 ºC and 800 ºC), specimens with characteristic compressive strength of 30 MPa presented a greater relative residual strength factor. For lower temperature levels, the 20 MPa specimens presented a higher relative residual strength factor.

Residual elastic modulus

The relative residual elastic modulus factor of each specimen ($\psi_{c,j}$) was also determined, as indicated in Equation (2):

$$\psi_{c,j} = \frac{E_{c,R,j}}{E_{cm}} \qquad (2)$$

This factor was defined as the ratio between the residual elastic modulus of the specimen j ($E_{c,R,j}$) and the average static modulus of elasticity of the reference specimens that were not subjected to heating and cooling processes (E_{cm}).

The values of relative residual elastic modulus were subjected to Grubbs' tests (5% significance level) for detection of outliers. One outlier was found in the following series: 20MPa/600°C/SC, 20MPa/600°C/FC, 20MPa/400°C/FC, and 30MPa/600°C/FC. All of them were excluded from the next statistical analyzes. Significant differences between the average relative residual elastic modulus obtained for each series were analyzed through ANOVA and Tukey tests (5% significance level).

Influence of maximum temperature on the residual elastic modulus

Figure 3a and 3b plot the values of relative residual elastic modulus factors ($\psi_{c,ave}$) against the exposure temperature, for each compressive strength level and type of cooling. According to the Tukey's test, there were significant differences between the compared averages, which proves that increases in the temperature cause decreases in the elastic modulus of concrete. In any case, the relative residual elastic modulus factor was lower than 20% for temperature exposures higher than 600°C. After exposed to 800°C, concrete presents a very low residual elastic modulus, regardless of the pre-fire compressive strength (20 MPa or 30 MPa) or the type of cooling (SC or FC).

Influence of the type of cooling on the residual elastic modulus

The Tukey's test was used to evaluate the influence of the type of cooling on the residual elastic modulus of concrete, considering a given strength level and cooling process. In almost all cases, the means were statistically different. No difference was found between the average relative elastic modulus factors of the series of specimens with compressive strength of 30 MPa and subjected to a maximum temperature of 800°C.

In general, air-cooled specimens presented a larger relative residual elastic modulus factor, except in the 20MPa/600°C and 30MPa/600°C series, in which fast-cooled specimens presented a higher relative residual elastic modulus factor.

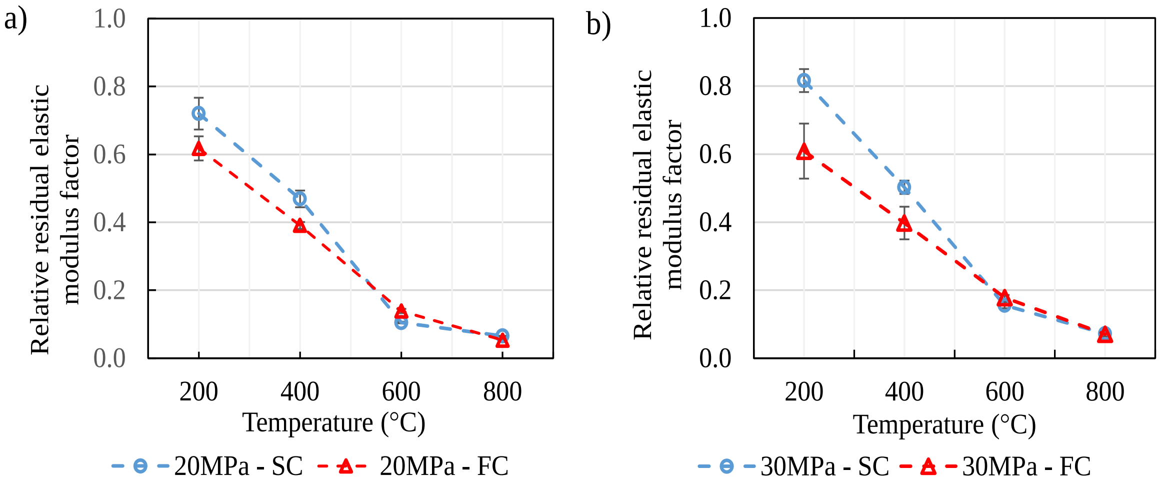

Figure 3. Relative residual elastic modulus with increasing temperature for the 20MPa/SC and 20MPa/FC series (a); 30MPa/SC and 30MPa/FC series (b).

Influence of pre-fire compressive strength level on residual elastic modulus

The influence of pre-fire compressive strength level on the elasticity modulus of concrete was also evaluate with statistical analyses. For specimens submitted to slow cooling, only in the SC/400°C case there were no significant differences in the means of the relative residual elasticity modulus, according to the Tukey's tests. In the other cases, the higher the strength characteristic to compression of the specimens the greater the relative residual elasticity modulus. For specimens subjected to fast cooling, lower temperatures (200 and 400°C) resulted in statistically equal relative residual elastic modulus. For higher temperatures (600 and 800°C), the specimens with characteristic compressive strength of 30 MPa presented a larger relative residual elastic modulus.

Comparisons with dataset of design codes and previous literature

Figure 4 compares the relative residual compressive strength factors obtained in this study with those proposed by the European standard EN 1994-1-2 (Comite Europeen de Normalisation [CEN], 2005) for siliceous aggregates concretes in two different cases: during fire and after cooling. The residual elastic modulus factors were not directly presented in the EN 1994-1-2 (CEN, 2005). Then, the residual elastic modulus factor (during fire) was determined according to the methodology used by Yu, Zha, Ye, and Wang (2014), Espinos, Romero, and Hospitaler (2012) and Way and Wille (2016).

The residual compressive strength factors presented in the standard code were predominantly lower than those of normal-strength concretes produced with slag-modified cement and siliceous aggregates exposed to temperatures of 200-800 °C and subjected to slow cooling. In this case, the benefits provided by the slag materials can be attributed to reactions between the slag and the calcium hydroxide (CH) of the cementitious matrix, leading to the formation of calcium silicate hydrates (C-S-H) (Malhotra & Mehta, 2017; Özbay et al., 2016). One of the main chemical changes verified in the XRD spectra of slag-modified concrete samples exposed to high temperatures by Shumuye, Zhao and Wang (2021) was the dehydration of C-S-H structures and the transformation of the CH into CaO due to the exclusion of the chemically bonded water. The CaO formed during the thermal decomposition of CH may be rehydrated during the slow cooling process, leading to a 44% volume expansion and cracking propagation (Hager, 2013; Xiao et al., 2018). According to Sadawy and Nooman (2020), increases in the blast furnace slag content remarkably decreased the intensities of XRD peaks of CH due to pozzolanic effects, leading to the formation of additional contents of C-S-H. Since concretes produced with slag-modified cements had lower CH contents, the propagation of cracks during the slow cooling was mitigated, leading to the improvements in ⍰$_{c,ave}$ indicated in Figure 4a.

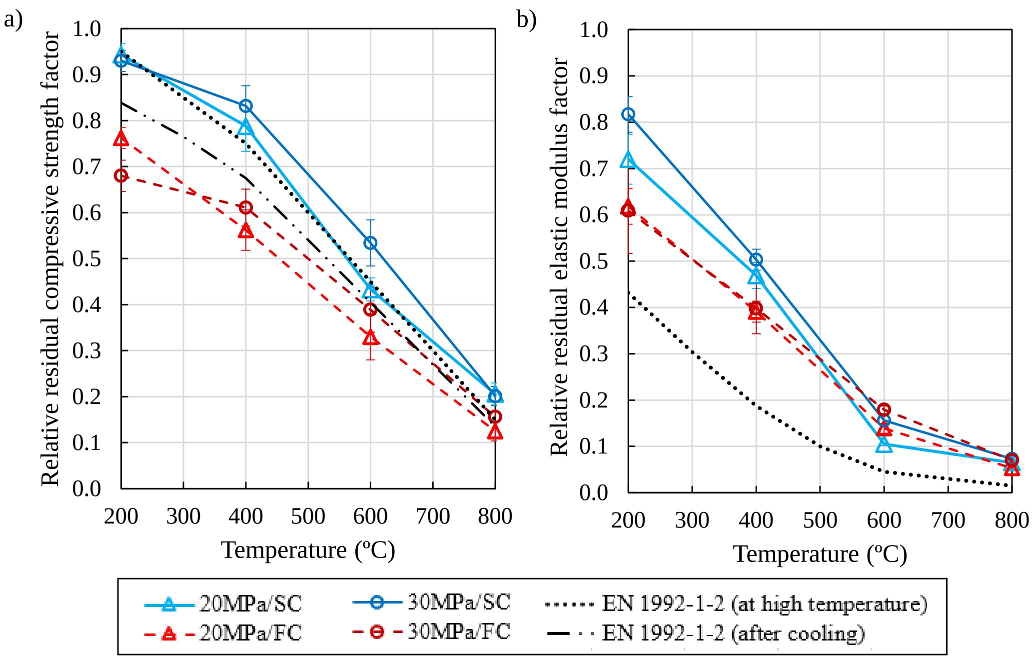

Figure 4. Comparison between the relative residual compressive strength (a) and elastic modulus (b) factors obtained in this work and those presented in the EN 1994-1-2 (CEN, 2005).

On the other hand, the residual compressive strength of concretes produced with slag-modified cement was lower than that predicted by the design codes when fast cooling was used. In this case scenario, the $\Phi_{c,ave}$ values verified in the present research were up to 25% lower than the factors defined by the standard code. Such different behavior observed in concretes produced with slag-based cements can be incorporated into future design standards, in order to improve the process of verification of fire-damaged concrete structures. According to previous research (Ingham, 2009; Peng et al., 2008), the thermal shock induced by water quenching is the main cause for the severe damage associated with this fast cooling method. Concretes produced with blended cements have reduced concentration of CH and enhanced interfacial transition zone (ITZ) due to the formation of additional C-S-H structures (Ma et al., 2015; Malik, Bhattacharyya, & Barai, 2021). In fact, Ashraf et al. (2009) observed that slag materials react with the CH compounds, forming secondary C-S-H structures in the cementitious matrix and a quite apparent glassy phase hump (2θ = 25-35°) in XRD diffractograms. Such microstructural refinement was responsible for a hydrated cement paste with lower thermal conductivity. Then, a more abrupt temperature difference along the specimens' cross-section was verified during the application of the fast cooling method, so that a substantial thermal shock caused the low values of $\Phi_{c,ave}$ presented in Figure 4a.

Moreover, Figure 4b indicated that the relative residual elastic modulus factor curve (at high temperature) estimated from the tables of the EN 1994-1-2 (CEN, 2005) seems to be too conservative, since slag-modified cement concretes with siliceous aggregates presented $\Phi_{c,med}$ values up to 38% higher than the relative residual elastic modulus factors presented by this design standard, even in the case of fast cooling.

In the light of the literature review presented in the introduction section, the relative residual compressive strength factors obtained in this work were compared to those reported by different authors (Abramowicz & Kowalski, 2005; Bingöl & Gül, 2009a; Carvalho et al., 2019; Yaragal & Narayan, 2012) that also investigated the distinct effects of air and water cooling processes on concrete exposed to elevated temperatures, as indicated in Figure 5. Table 1 shows that the compressive strength has been the most investigated residual mechanical property of concrete exposed to high temperatures and different cooling methods. Then, some comparable studies of Table 1 were selected for analysis in Figure 5. For example, only data related to ordinary concrete (without fibers or mineral admixtures) was indicated in Figure 5. Since the present work focused on the investigation of normal-strength concretes, experimental data related to high-strength concretes was not discussed in this section. Therefore, Figure 5 represents only concretes with 28-days compressive strength (before fire) lower than 35 MPa.

In general, concretes with siliceous aggregates evaluated in this work and in the studies of Abramowicz and Kowalski (2005) and Bingöl and Gül (2009a) presented lower relative residual strength than concretes with limestone aggregates of Carvalho et al. (2019), Abadel et al. (2022), and An et al. (2021). The exceptions are few concretes tested by An et al. (2021) and Abadel et al. (2022), which eventually presented lower relative residual strength than concretes tested in the present research and in the experimental programs of Abramowicz and Kowalski (2005) or Bingöl and Gül (2009a). Although Abadel et al. (2022) used limestone coarse aggregates, they used silica sand as fine aggregates, which could help to explain the observed exception. Limestone aggregates present lower thermal expansion than siliceous aggregates and concretes made with limestone suffer less damage than siliceous concretes (Arioz, 2007; Hertz, 2005; Kore Sudarshan & Vyas, 2019). Since different types of siliceous aggregates (e.g., quartz sand, granite gravel, gneiss gravel and others) have been widely used in concrete production around the world, extensive research must be developed to better clarify their limitations after exposure to high temperatures. For both types of aggregates, most of the papers presented in Fig. 5 verified that fast cooling provided lower residual compressive strength than slow cooling. An opposite behavior was only observed in concretes tested by Abadel et al. (2022), which can be related to effects of a post-fire recuring with a very long period of water immersion (24h).

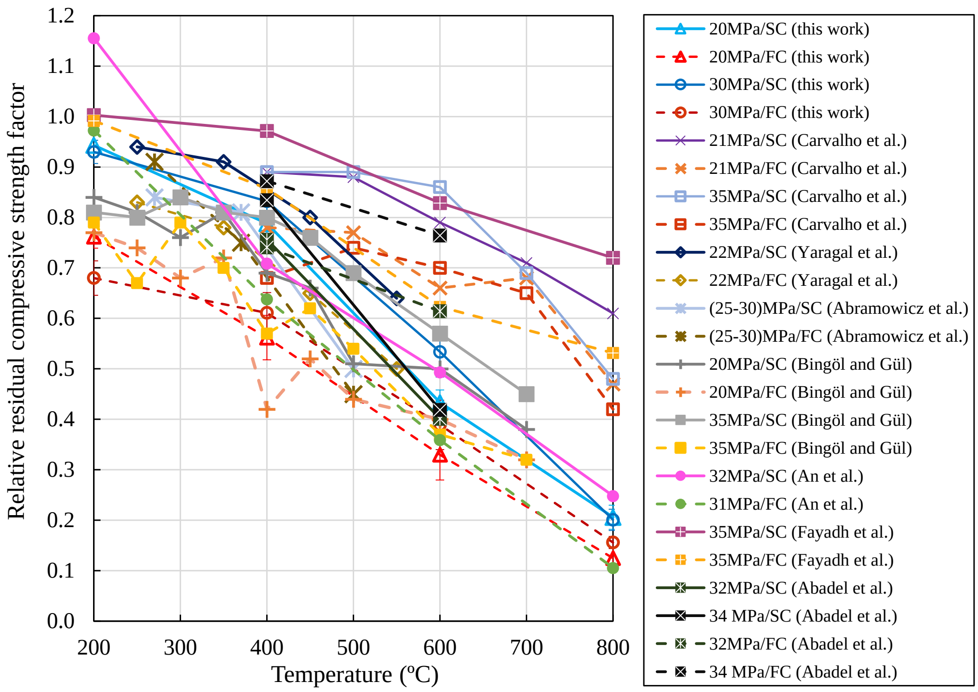

Figure 5. Comparison between relative residual compressive strength factors reported in previous works for various cooling methods.

Among the concretes produced with siliceous aggregates and subjected to slow cooling, the slag-modified concretes analysed in this study presented higher relative residual strength factor than the OPC concretes of Abramowicz and Kowalski (2005) and Bingöl and Gül (2009a), for exposure temperatures up to 400°C. In fact, previous research (Hager et al., 2019; Shumuye, Zhao, and Wang, 2019) reported that concrete produced with slags have a more structured C-S-H gel, lower thermal expansion and better fire resistance. Hager et al. (2019) reported the same behavior after comparing the residual strength of slow cooled concretes produced with OPC and slag-modified cements.

The post-fire behavior of slag-modified cement concretes subjected to fast cooling was firstly investigated in the present research and the results indicated that after fast cooling, such higher residual strength of slag-modified cement concretes was no longer verified. After fast cooling, the relative residual strength factors of the slag-modified cement concretes tested in the present study were very similar to those reported for OPC cement concretes by Bingöl and Gül (2009a), for maximum temperature levels between 200 and 700°C. Then, it is possible to conclude that the effects of different cooling methods on the residual strength factor were more pronounced in slag-modified cement concretes than in OPC cement concretes, especially for temperature levels up to 400°C. In fact, significantly lower differences between slow and fast cooling results of residual strength of OPC cement concretes were reported by Abramowicz and Kowalski (2005), for temperature exposure levels up to 500°C.

The relative residual elastic modulus factors determined in this research were also compared to those available in the literature (Figure 6). According to Table 1, previous works that dealt with normal-strength concretes exposed to elevated temperatures and different cooling regimes focused on determining their residual compressive strength, tensile strength or bond strength between concrete and reinforcement. Given the scarcity of experimental data of residual elastic modulus of normal-strength concrete, the results of residual elastic modulus obtained in this paper could only be compared to results of concretes produced by Liu et al. (2020), which are high-strength concretes. Since Botte and Caspeele (2017) and Nassif (2006) did not provide the values of elastic modulus obtained in their research, they were not discussed in this section. Results of Nassif et al. (1999) were also included in Figure 6, although these authors did not mention the initial compressive strength (before fire) of their concretes. Nassif et al. (1999) and Nassif (2006) probably reported different properties of the same concretes, as the methodology of these works is very similar. Then, the following assumption was made in this section: Nassif et al. (1999) also dealt with high-strength concretes (28-days compressive strength between 63 and 70 MPa) produced with OPC cement.

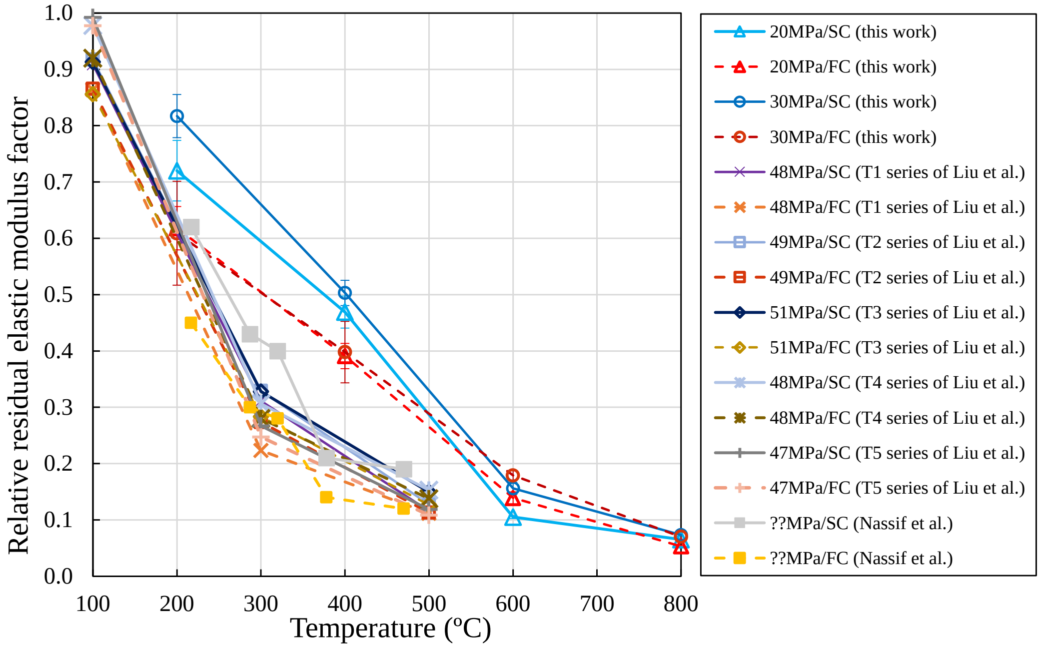

Figure 6. Comparison between relative elastic modulus factors reported in previous works for different cooling methods.

The specimens tested by Liu et al. (2020) and Nassif et al. (1999) and the concretes evaluated in the present research were produced with siliceous aggregates. Then, the main differences between them were the type of cement and the strength level. Some authors reported lower residual properties in high-strength concretes than in normal strength-concretes (Ali et al., 2001; Kodur & Phan, 2007; Lau & Anson, 2006), which is accordance to the results presented in Figure 6: the normal-strength concretes investigated in this research presented residual elastic modulus up to 60% higher than the high-strength concretes, for maximum exposure temperatures ranging from 200 to 500°C.

Among all concretes represented in Figure 6, the difference between the residual elastic modulus after slow and fast cooling was significantly higher in the concretes investigated in the present research. A very similar behavior was highlighted as the general trend observed for the residual compressive strength factors. Therefore, it is possible to suggest that the effects of different cooling methods on the residual elastic modulus factor seem to be more pronounced in slag-modified cement concretes than in OPC cement concretes. Further research is needed to complement the available experimental database with elastic modulus results of high-strength concretes produced with slag-modified cement.

Conclusion

This study investigated the effects of elevated temperatures on the mechanical performance of normal-strength concretes produced with slag-modified cement, considering different cooling regimes and initial compressive strength levels.

Previous results obtained for concretes with OPC cannot be generalized to define criteria for fire resistance of concretes with slag-modified cements. When fast cooling methods were used, the residual compressive strength factors of slag-modified concretes were lower than those predicted by current design codes. Therefore, the effects of variations in the cooling procedures on the residual concrete strength and stiffness were more pronounced in slag-modified cement concretes than in OPC cement concretes.

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