High-Temperature Behavior of SCC in Compression: Comparative Study on Recent Experimental Campaigns

Patrick Bamonte[1] and Pietro G. Gambarova, F.ASCE[2]

Abstract: The 20 years since the introduction of self-compacting/self-consolidating concrete (SCC) have given plenty of opportunities for researchers, designers, and contractors to become familiar with SCC innovative properties and structural effects. The workability and durability of SCC have been investigated extensively, together with the tendency of SCC members to spall in fire, because of pore pressure, thermal self-stresses, and applied stresses. The interest for the constitutive behavior of SCC at high temperatures, however, is relatively recent, as most of the studies (not more than a dozen in total) have been published in the last 10 years. Though limited in number, these studies shed sufficient light on the behavior of SCC at high temperatures, in quasi-steady conditions, as demonstrated in this paper. This paper describes 11 experimental campaigns carried out in Belgium, China, Croatia, France, Germany, Greece, Italy, Sweden, and the United States, each with its own specimens, mix designs, test procedures, and methods for the treatment of test results. The experimental results considered in this paper concern both normal-strength and high-performance/high-strength concretes, generally devoid of fibers, unstressed during the heating process, and tested in uniaxial compression. The conclusion of this comparative study is that at high temperatures, SCC tends to behave similarly to ordinary vibrated concrete (VC), and that American Concrete Institute (ACI)-ASCE provisions for ordinary calcareous or siliceous concrete at high temperatures or past cooling are also applicable to SCC.

Author keywords: Self-compacting concrete; High temperature; Compressive strength; ACI-ASCE provisions (for concrete exposed to high temperature).

Introduction

Self-compacting/consolidating concrete (SCC) has been used in an increasing number of structures in the last 10 to 15 years, very often in difficult or even extreme environmental conditions in which concrete durability is a must (tunnel linings; off-shore structures; containment shells; and bridge girders, pylons, caissons, and segmental elements) (Okamura and Ouchi 2003). SCC has also been used in constructions exhibiting highly congested reinforcement and (more recently) in many buildings that require the concrete to be pumped (as in tall buildings). In most of these structures the risk of fire is rather high; therefore it is imperative to be aware of the mechanical decay of the various cementitious materials, including SCC, at high temperatures.

Although thermal effects on vibrated concrete have been investigated extensively and codified in the last 20 years [ASCE 1992; ACI 2007; EC2–EN 1992-1-2 (European Committee for Standardization 2004); EC4–EN 1994-1-2 (European Committee for Standardization 2005); Phan and Carino 1998], and several studies have been devoted to the spalling of both VC and SCC in fire (Jansson and Boström 2008; Kodur and Dwaikat 2009), only in the last few years has proper attention been given to the mechanical properties of SCC at high temperatures (*hot properties*) and after cooling (*residual properties*), with a recent peak concerning the effect of fiber reinforcement and the state of stress during the heating process. The reasons for this late interest in SCC at high temperatures may be found by addressing the following question: Why should SCC behave differently from ordinary vibrated concrete at high temperatures?

The answer lies in the nano-, micro-, and mesostructure of SCC. In addition to the cement, the water and the fine aggregates (which come in similar quantities in the mixes of both VC and SCC, totaling approximately 55–60% by mass), a typical SCC mix contains less medium and coarse aggregates (35–40% instead of 45–50%), which are balanced by adding ultrafines (up to 10–12%) and relatively large amounts of chemical admixtures (such as superplasticizers, generally from 1 to 3% by cement mass) (Okamura and Ouchi 2003). Ultrafines often take the form of calcareous powders. Therefore, the cementitious matrix is more compact (or dense) than in vibrated concrete, and the micropores (called also capillary pores) are more dispersed and less interconnected. High temperatures would therefore be expected to cause more mechanical damage, because the low connectivity (or lack of connectivity) of the pores prevents vapor pressure in the pores from being released. (The higher the vapor pressure in the pores, the higher the tensile stresses in the cementitious matrix around the pores and the higher the damage.) In contrast, a more compact and homogeneous mesostructure (owing to the higher content of fine and ultrafine aggregates) is less affected by thermal incompatibility among the constituents, to the advantage of concrete integrity at high temperatures. Faced with these contradictory properties, the only answer as to whether SCC might be more temperature-sensitive than VC comes from the experimental evidence accumulated so far. However, in addition to the closer and less interconnected porosity, and the better thermal compatibility between the coarse aggregate and the mortar, none of the other sources of mechanical

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decay found in vibrated concrete play a different role in self-consolidating concrete in principle (Loukili 2011; Fares et al. 2009). Therefore, with the same cement type and content, water–cement ratio, aggregate type and shape, additives and admixtures, self-consolidating concrete would be expected to behave similarly to vibrated concrete at high temperatures, but only a thorough examination of the test results from different sources can have the final word.

Within this context, the most significant test results available in the literature on SCC under compression are presented and discussed in this paper, and systematic comparisons are conducted—a task that is not as simple as one might expect because of the different heating rates, specimen types, and test procedures, not to mention the data treatment and presentation. The agreement among the different experimental campaigns carried out worldwide is, however, more than satisfactory. Moreover, comparing the results on SCC at high temperatures with the code provisions for ordinary vibrated concrete confirms what has been more or less overtly indicated since the earliest tests on SCC at high temperatures, namely that the thermal and mechanical behavior of self-compacting/consolidating concrete at high temperatures is hardly different from that of vibrated concrete, at least in quasi-steady thermal conditions and uniaxial loading. This is a general trend that may be contradicted by the behavior of single mixes. (The dispersion of the results is unavoidable and rather large, given the many chemo-physical and technological factors influencing the concrete's performance.)

Causes of Concrete Decay at High Temperatures

As it is well known (Bažant and Kaplan 2002), there are several factors that come into play when considering the concrete thermo-mechanical properties at high temperatures:

- Chemo-physical changes in hydration products and expulsion of adsorbed water;
- Capillary porosity and expulsion of free water;
- Aggregate-cement mortar kinematic compatibility;
- Aggregate chemo-physical stability;
- Additives and admixtures;
- Thermal transients; and
- State of stress during the heating process (*preloading*).

Setting aside thermal transients and preloading, which have no direct connections with concrete properties (being related to the structural context), there are factors active at the nano and micro level (such as chemo-physical changes in the hydration products, nano- and microporosity, aggregate stability, additives, and admixtures) and factors active at the meso level (such as aggregate-cement kinematic compatibility). In principle, all of these factors play similar roles in vibrated concrete and in self-compacting/consolidating concrete, as synthetized in the so-called *concrete thermometer* (Khoury 2000):

- From 105°C on, all evaporable water is expelled, in addition to the water contained in the aggregates;
- From 180 to 850°C, dehydration of calcium silicate hydrate (CSH) gel occurs with the highest rate of reaction at 200°C, and decomposition commences at approximately 700°C;
- From 400 to 600°C, dissociation of calcium hydroxide occurs with the highest rate of reaction between 450 and 500°C;
- From 500 to 650°C, quartz (SiO_2) exhibits a crystalline transformation from α-quartz (trigonal) to β-quartz (hexagonal), accompanied by significant expansion of volume;
- Between 600 and 900°C, decarbonation of calcareous aggregates occurs, and the rate of reaction starts growing markedly at 700°C; and
- On cooling, the free lime (CaO) resulting from decarbonation combines with atmospheric moisture to form calcium hydroxide, with an increase in volume close to 44%, followed by cracking and swelling in the concrete.

However, the extensive literature review in Boel et al. (2008) and Fares et al. (2009, 2010) shows that in SCC:

- The initial capillary pores are smaller than in VC, even if the total porosities are rather similar;
- Open porosity (capillary pores) is generally lower than in VC (from $-1/3$ to $-1/5$), as superplasticizers and powders facilitate microstructural packing and cement hydration, to the detriment of the water content in the open pores;
- Gas permeability is a few times smaller than in VC (up to 1/5–1/6 at 20°C);
- The higher content of fines and ultrafines makes SCC mesostructure more homogeneous than that of VC; therefore, the thermal expansion of the mortar (hydrated cement + fines + ultrafines) is closer to that of medium-large aggregates than in VC, to the advantage of thermal compatibility at any temperature;
- Up to 300–400°C, the combined effects of cement-paste rehydration (resulting from the migration of water in the pores, as demonstrated by the decreasing content of anhydrous cement) and better bonding properties in the new hydration products introduce a rather sizeable increase in residual compressive strength (up to $+20\%$), in spite of the increasing porosity;
- However, in both VC and SCC, microcracks appear at the interface between the medium-coarse aggregate particles and the mortar at 300°C; and at 450–600°C, microcracking spreads to the aggregate (favored by the allotropic transformation of quartz at 575°C) and to the paste (Fares et al. 2009);
- In both VC and SCC, porosity increases by 100% (= doubling) from 20 to 600°C, mostly because of the expulsion of bound water and the dissociation of calcium hydroxide, with the collapse of the gel structure; between 400 and 500°C, porosity increases by 50%; however, there are no clear-cut indications about a possible different evolution between VC and SCC at high temperatures (Fares et al. 2009); and
- The increasing residual compressive strength often found in SCC between 150 and 350°C has also been observed in VC (with calcareous/basalt aggregate + portland/blended cement, and siliceous aggregate + portland cement, $f_c = 40$–70 MPa; see Bamonte et al. 2006), in addition to mortars (Bamonte and Gambarova 2013); hence, rehydration and better bonding properties are not typical of SCC, even more because strength increases often seem to be rather casual, as they may or may not occur in different specimens of the same mix.

Therefore, many reasons exist for interest in SCC behavior
- at high temperatures and for the possible differences compared with VC.

Typical Test Procedures

Characterizing structural materials within the framework of *fire* requires preliminary clarification that the focus should be on the materials' *high-temperature behavior*, and not on *fire resistance*, which applies to structural members or to the whole structure as such, and not to materials. The main difference between high temperature and fire is related to the high heating rate that is typical of any fire, and that can reach values close to—or even higher than—100°C/min in the early phases of a fire. The consequences for the materials and for the structures are highly unsteady thermal conditions. On the contrary, characterization of materials by testing in a lab is usually carried out at rather low heating rates (typically

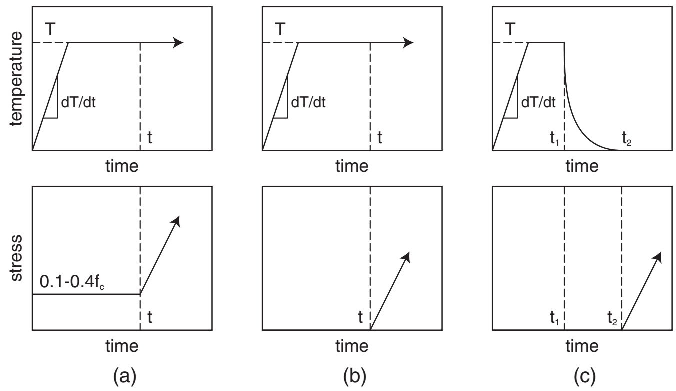

Fig. 1. Typical test procedures for concrete exposed to high temperatures (adapted from Phan and Carino 2002, reproduced with permission from ACI): (a) hot tests on preloaded or stressed specimens; (b) hot tests on unstressed specimens; (c) residual tests on unstressed specimens ($f_c = f_c^{20}$ = compressive strength of the virgin material)

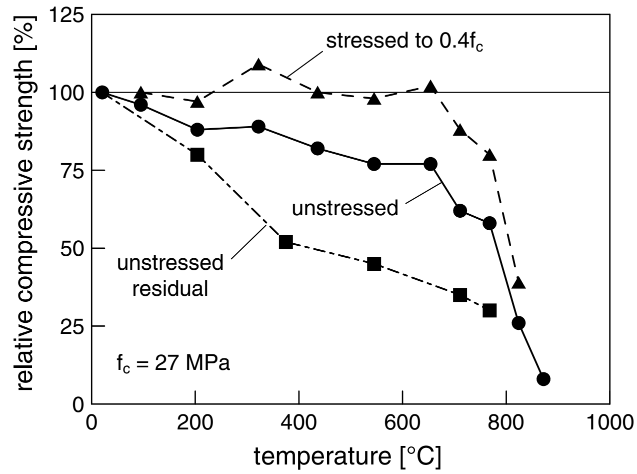

Fig. 2. Typical test results on ordinary carbonate/calcareous concrete exposed to high temperature (adapted from Abrams 1971, reproduced with permission from ACI)

1–5°C/min), for two main reasons: (1) to make sure that the specimens are subjected to a thermal field that is as uniform as possible; and (2) to avoid structural effects that are dependent on the size and geometry of the specimens, such as self-stresses and spalling, which might lead to severe localized damage, making an objective characterization of the material impossible.

The most common test procedures used to investigate the mechanical behavior of concrete at high temperature are depicted in Fig. 1 (Phan and Carino 2002). Because of the dependency of concrete's behavior on the actual stress state, the most realistic procedure for testing at high temperatures should be based on specimens loaded before being heated and kept loaded throughout the heating process [Fig. 1(a); preloaded or stressed specimens; this is the situation of a concrete member being mostly subjected to permanent loads, such as the lower columns in a multistory building]. Such a test procedure is rather demanding, however, because the loading frame should incorporate a furnace (generally a split-tube furnace, consisting of two hinged halves embracing the specimen).

Performing hot tests without any preloading [Fig. 1(b); unstressed specimens] is definitely simpler, and can be done, for example, using the so-called *preheating technique*, in which a specimen is first heated and then kept at high temperature throughout the test by means of proper insulation (Bamonte and Gambarova 2012); any severe temperature drop should be avoided for 10–15 min, the amount of time required by testing. Hot strength measured on unstressed specimens is close enough to the situation of any lightly loaded structural member during a fire. Residual tests, however, are the simplest [Fig. 1(c)], as the specimen is loaded after being heated and past cooling to ambient temperature. Hence, testing in residual conditions is the same as testing ordinary undamaged specimens.

(1) *Residual tests* are traditionally performed on unstressed specimens; (2) the cooling rate should be even lower than the heating rate, to limit any further damage to the concrete during the cooling phase; and (3) the residual strength in compression is at least from 15 to 30% lower than the hot strength.

An example of the typical results obtained using the previously mentioned test procedures is shown in Fig. 2. Preloading appears to be beneficial for the compressive behavior of concrete, as strength tends to stay close to the original strength up to 600°C. On the contrary, the residual compressive strength is more temperature sensitive ($f_c^{400}/f_c^{20} = 50–55\%$ and $f_c^{600}/f_c^{20} < 40\%$, where f_c^T = compressive strength at the temperature T). Finally, hot compressive strength measured on unstressed specimens falls between the two previous strengths, as the loss at 400–600°C is between 20 and 25%. The curves of Fig. 2 come from the well-known tests conducted by Abrams (1971) on low-grade concretes, which still form the basis of ASCE and American Concrete Institute (ACI) provisions; today's concretes (and especially high-performance/high-strength silica-fume concretes) are generally more temperature-sensitive.

On the basis of these findings, and keeping in mind the limits of the tests in representing a reality that is much more complex, the high-temperature behavior of concrete is generally investigated in hot conditions, without preloading, or in residual conditions.

Provisions for Ordinary Concrete

The temperature-triggered strength decay in compression is plotted in Figs. 3(a and b), according to the provisions by ASCE-ACI, and by Eurocodes 2 and 4. The well-known results cited by Phan and Carino (1998, $f_c = 50–100$ MPa) are also reported. Fig. 3(a) refers to concretes with carbonate/calcareous aggregates, and Fig. 3(b) to concretes with siliceous aggregates.

The continuous and noncontinuous thick curves come from the Structural Fire Protection Manual of ASCE (1992) and from ACI 216-07.1 (ACI 2007), in which a clear distinction is made between stressed hot tests (dash-dotted curves), unstressed hot tests (continuous curves), and residual tests (dashed curves).

The dark gray area refers to the provisions by the Eurocodes: In this case, for both calcareous and siliceous aggregates, the only distinction is between hot tests (the upper limit of the area, EC2), and residual tests (the lower limit, EC4), with no reference to stressed hot tests: (1) in the case of calcareous concretes [Fig. 3(a)], the ASCE-ACI and the Eurocodes only partially agree (hot strength on unstressed specimens up to 450°C), and only ASCE-ACI agrees satisfactorily with the test results concerning residual strength; (2) in the case of siliceous concretes [Fig. 3(b)], the provisions of ASCE-ACI and the Eurocodes largely agree, and the test results (hot unstressed and residual tests) are well represented by the codes; (3) overall, the spread between the hot strength of preloaded concrete and residual strength according to ASCE-ACI appear too severe, especially for calcareous concretes; and (4) overall, the

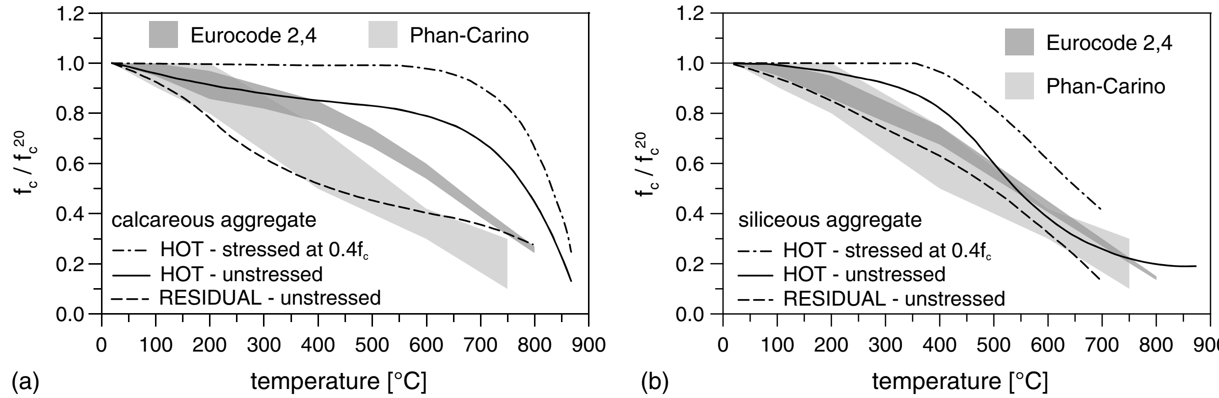

Fig. 3. Provisions by ASCE-ACI and EC2-EC4 for concrete with (a) calcareous aggregates; (b) siliceous aggregate [dark gray area refers to the provisions by EC2 and EC4, whereas the light gray area refers to the hot and residual tests on stressed/unstressed specimens examined by the data from Phan and Carino (1998)]

spread between hot strength (with/without preloading) and residual strength according to the Eurocodes is too low for both the calcareous and siliceous concretes.

Comparison with Available Literature

There has been no more than a dozen well-documented research projects devoted to the constitutive behavior of SCC exposed to high temperatures over the last 20 years. Eleven test campaigns are taken into consideration in this paper (Persson 2004; Reinhardt and Stegmaier 2006; Noumowé et al. 2006; Sideris 2007; Fares et al. 2009; Bamonte and Gambarova 2010, 2012; Annerel and Taerwe 2011; Tao et al. 2010; Khaliq and Kodur 2011; Jelcic Rukavina et al. 2013). As mentioned in the introduction, the experimental procedures are rather different (Fig. 4), not to mention the geometry of the specimens, the mix designs, and the reference temperatures adopted in the different experimental campaigns (Figs. 5 and 6).

The key results presented in these 11 experimental campaigns are presented next, to conduct comparisons with the provisions of the codes for ordinary vibrated concrete (Figs. 7–12) and draw general conclusions on the behavior of SCC at high temperatures with reference to uniaxial compression. (Information on other thermomechanical properties such as tensile strength in bending, fracture energy, and thermal diffusivity can be found in Bamonte and Gambarova 2012). Not all of the results of each experimental campaign are reported. The focus is on (1) SCC mixes; (2) concrete grades consisting of between 40 and 125 MPa; (3) plain concretes (no fibers or rather limited amounts of polypropylene-pp fibers, typically $v_f = 0.1\text{–}0.2\%$); (4) ordinary siliceous or carbonate/calcareous aggregates; (5) unstressed specimens (no preloading during the heating process); and (6) mixes exhibiting no spalling during the heating process. Table 1 lists the main characteristics of each experimental campaign. However, some common features of the experimental campaigns and a few specific issues concerning the tests and the data treatment are presented briefly and commented on in the following section.

Common Features of the Experimental Campaigns

- The experimental campaigns were evenly subdivided between high-temperature testing (hot tests, five campaigns) and testing after cooling (residual tests, six campaigns); in three cases, the hot tests were followed by the residual tests;
- The reference temperatures consisted of between 20 and 550–800°C, but in a couple of cases (Noumowé et al. 2006; Reinhardt and Stegmaier 2006) only one reference temperature was considered in addition to room temperature;
- The heating rate consisted of between 0.5 and 5°C/min, and the cooling rate between 0.25 and 5°C/min; however, in one case

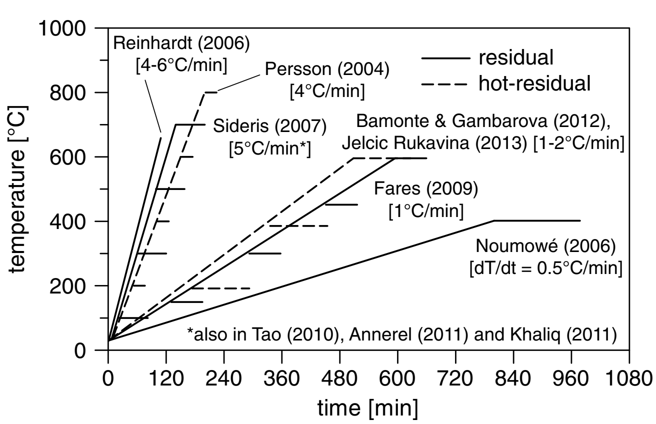

Fig. 4. SCC at high temperatures, considering the temperature-time ramps adopted in the experimental campaigns

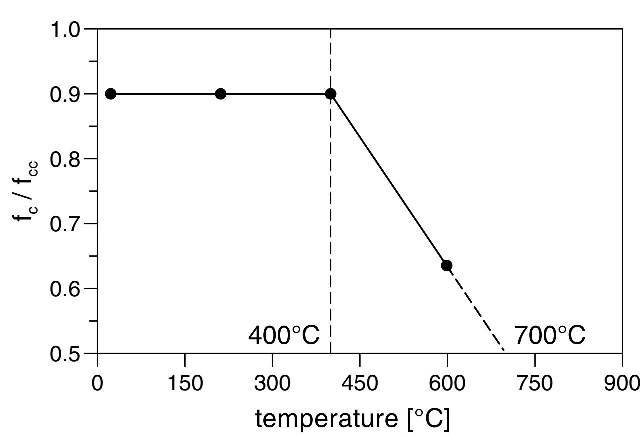

Fig. 5. Plots of the ratio between the residual cylindrical and cubic strengths in compression (data from di Prisco et al. 2003)

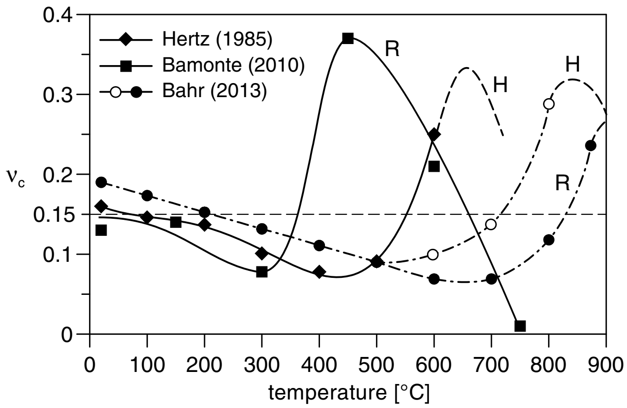

Fig. 6. Poisson's ratio in hot and residual conditions as a function of the temperature [the continuous curves refer to a vibrated concrete with $f_c = 20$ MPa (Hertz 1985) and to a self-compacting/consolidating concrete with $f_c = 125$ MPa (Bamonte and Gambarova 2010); the dashed-dotted curves refer to an ordinary concrete with $f_c = 35$ MPa (Bahr et al. 2013)]

(Reinhardt and Stegmaier 2006) the heating rate was variable, and in a couple of cases (Sideris 2007; Jelcic Rukavina et al. 2013) the specimens were left cooling naturally inside the oven;

- In most of the tests the specimens were left resting at the reference temperature for 1–2.5 h, but in a few cases shorter periods (Persson 2004) or longer periods (Annerel and Taerwe 2011; Tao et al. 2010; Jelcic Rukavina et al. 2013) were adopted, from 0.5 to 12.5 h;
- In approximately 60% of the tests, the concrete mix contained portland cement (with fly ash, metakaolin, or limestone powder in certain cases), whereas in the remaining 40% of the tests, blended cements were used (limestone cement in most cases, with/without silica fume or fly ash);
- The aggregates were siliceous or mixed siliceous-calcareous in approximately two-thirds of the campaigns; in two-thirds of the campaigns, limestone/calcareous powders/fillers were added to the mix, in addition to blast-furnace slag in the mixes tested by Khaliq and Kodur (2011);
- A few mixes (less than one-third) contained a relatively small amount of pp fibers [not more than 0.2% by volume, except in the tests by Bamonte and Gambarova 2010 (the only ones concerning an ultra high-strength concrete) and in some tests by Persson 2004];
- In most campaigns, the diameter of the cylinders consisted of between 75 and 160 mm, and the height-to-diameter ratio was 2; in a few campaigns, however, the specimens were different: Sideris' specimens were cubes (each side = 100 mm); Reinhardt and Stegmaier cylinders were short cores (height/depth ratio = 1); Bamonte and Gambarova's cylinders (2010) and the cylidners of Jelcic Rukavina et al. were more elongated (diameter-to-height ratio = 3); and in Bamonte and Gambarova's tests (2010) the smallness of the cylinders (diameter = 36 mm) was justified by the high strength of the material and by the limited size of the aggregates ($d_a = 4.0$ mm); and
- Based on the previously mentioned criteria, in most cases only a few of the mixes tested in each experimental campaign were considered in this paper, as indicated by the superscript *a* in the second column of Table 1. (The superscript *b* indicates the total number of the mixes tested in each campaign.)

Specific Issues Concerning the Tests and Data Treatment

Persson (2004) Hot and Residual Tests [Figs. 7(a), 8(a), 13(a and b)]

The plots of f_c and E_c refer to the limestone concretes tested by the author, and each temperature level includes the normalized mean values worked out by considering all concrete grades.

Sideris (2007) Residual Tests [Fig. 8(c)]

The original results on cubes were corrected, as the ratio of the compressive strengths measured on long cylinders f_c and on cubes f_{cc} depends on temperature (Fig. 5, di Prisco et al. 2003); in virgin conditions the ratio f_c/f_{cc} is close to 0.9 in both SCC and high-performance/high-strength concrete (HPC/HSC).

Reinhardt and Stegmaier (2006) Residual Tests [Fig. 8(c)]

The cylinders were cored out of large cubes (side = 300 mm) after being subjected for 120 min to the standard fire ISO 834 [1975, similar to ASTM E119 (ASTM 1988)]; the final length of the cylinders was reduced to 100 mm (h/Ø = 1) by cutting off the extremities, which were subjected to very high temperatures ($T_{max} > 1{,}000$°C); according to thermal analysis, the average temperature reached in the cylinders before coring was close to 540°C; strength values were corrected to take care of the differences between short cylinders (h/Ø = 1) and long cylinders (h/Ø ≥ 2).

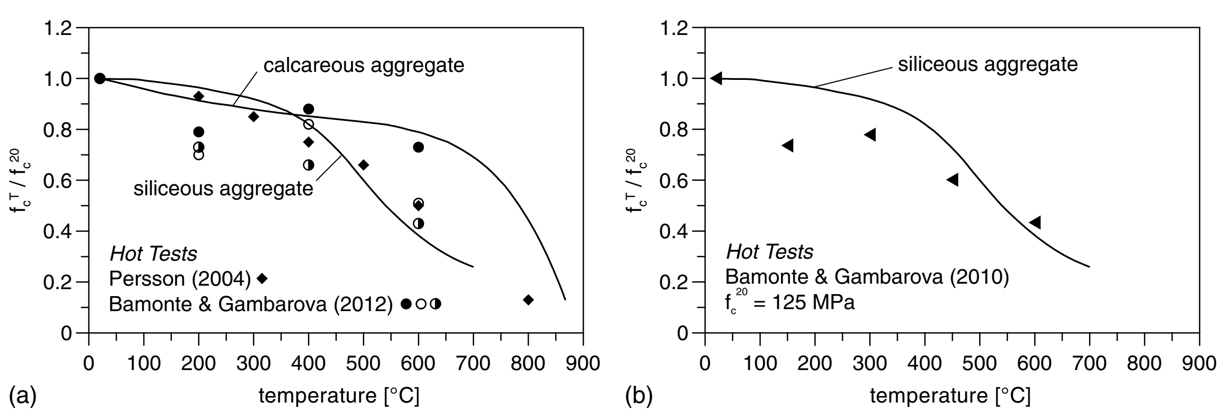

Fig. 7. Compressive strength: hot tests by (a) Persson (2004) and Bamonte and Gambarova (2012); (b) Bamonte and Gambarova (2010) (the full curves refer to ASCE-ACI provisions)

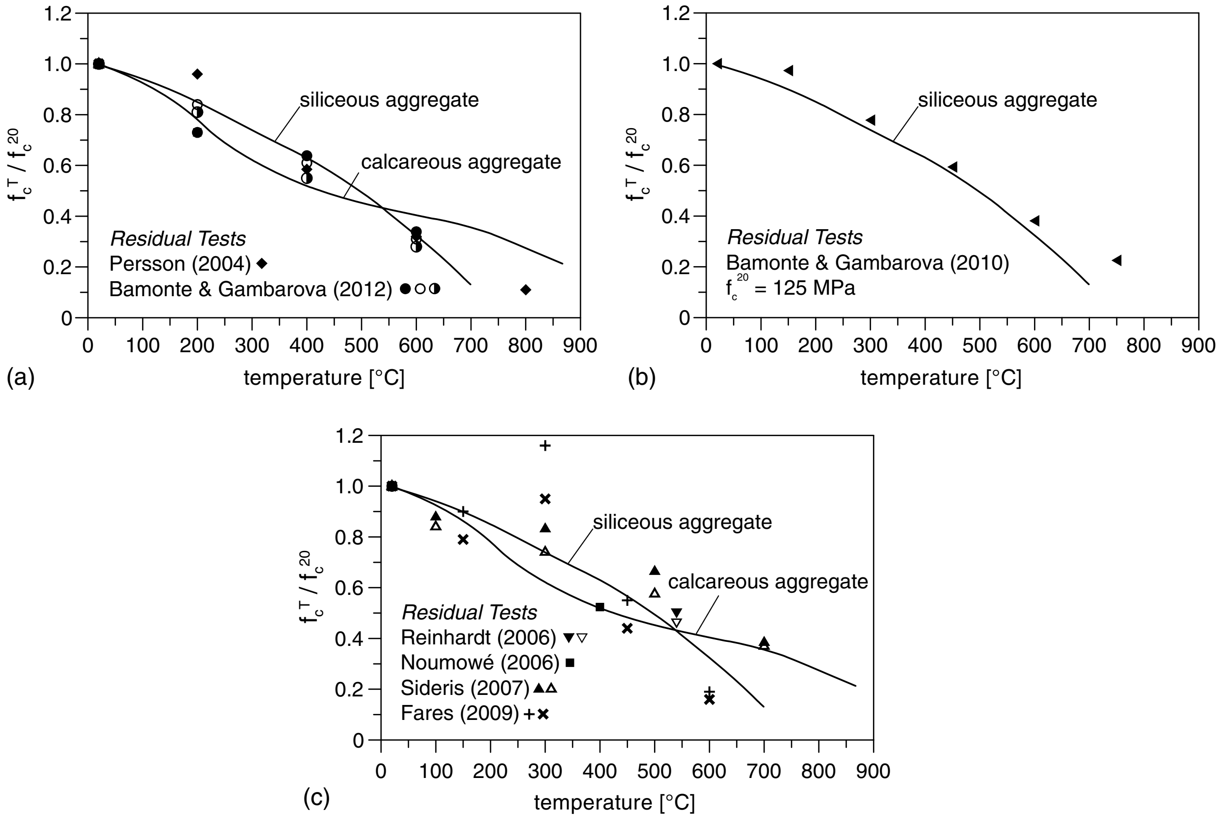

Fig. 8. Compressive strength: residual tests by (a) Persson (2004) and Bamonte and Gambarova (2012); (b) Bamonte and Gambarova (2010); (c) Sideris (2007), Fares et al. (2009), Reinhardt and Stegmaier (2006), and Noumowé et al. 2006 (the full curves refer to ASCE-ACI provisions)

Fares et al. (2009) Residual Tests [Figs. 8(c) and 13(b)]

Because the bulk modulus E_{bulk} (and not the Young's modulus E_c) was measured to compare the results of Fares et al. with the results of the other experimental campaigns, E_c had to be inferred from E_{bulk} through the following relationship valid in the elastic domain

$$(E_c^T/E_c^{20}) = (E_{\text{bulk}}^T/E_{\text{bulk}}^{20})(1-2\nu_c^T)/(1-2\nu_c^{20})$$

where the suffix 20 represents 20°C, the virgin material in ordinary environmental conditions. According to the scanty indications available in the literature on the hot and residual values of Poisson's ratio (Hertz static tests, Hertz 1985; Bamonte and Gambarova 2010; Bahr et al. 2013, dynamic tests, Fig. 6), this ratio exhibits a decrease with temperatures up to 300–600°C followed by an increase with a peak at 450–800°C and by a sharp reduction (Hertz 1985; Bamonte and Gambarova 2010; Bahr et al. 2013). The water expulsion and cement-paste shrinkage probably justify the initial decrease, and thermal microcracking the subsequent increase (the material becomes softer). The results of Fares et al. were therefore corrected [Fig. 13(b)] in accordance with the dash-dotted curves plotted in Fig. 6, as Bahr's results refer to a rather ordinary concrete, whereas Hertz's and Bamonte's results refer to a low-strength and to an ultra high–strength concrete, respectively.

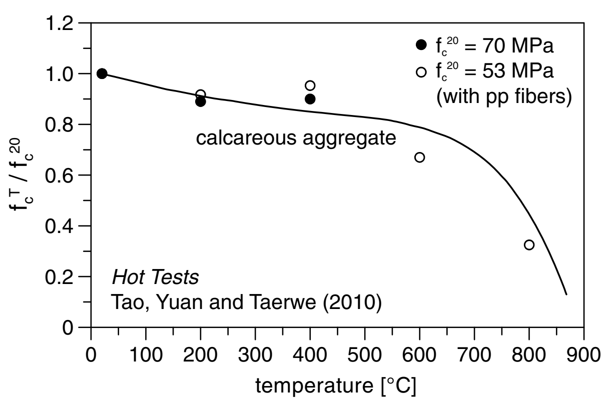

Fig. 9. Compressive strength: hot tests by Tao et al. (2010) (ASCE-ACI provisions are reported only for calcareous concrete, as aggregates are calcareous)

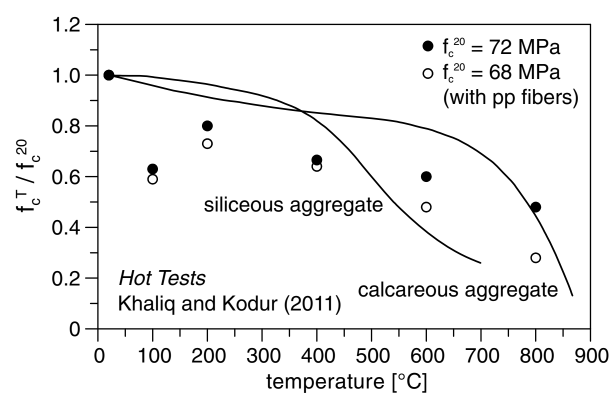

Fig. 10. Compressive strength: hot tests by Khaliq and Kodur (2011) (ASCE-ACI provisions are reported for both calcareous and siliceous concretes, as slag and fly ash are contained in the mix)

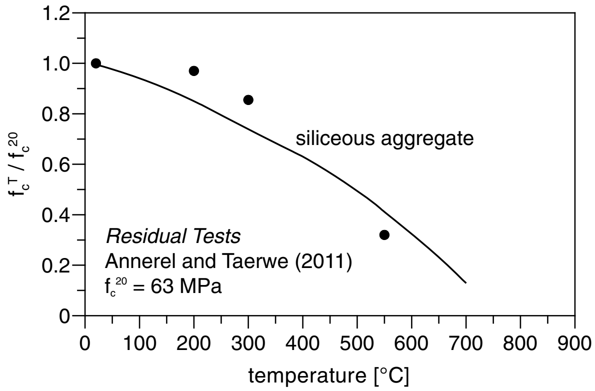

Fig. 11. Compressive strength: residual tests by Annerel and Taerwe (2011) (ASCE-ACI provisions reported only for siliceous concrete, as aggregates are mostly siliceous)

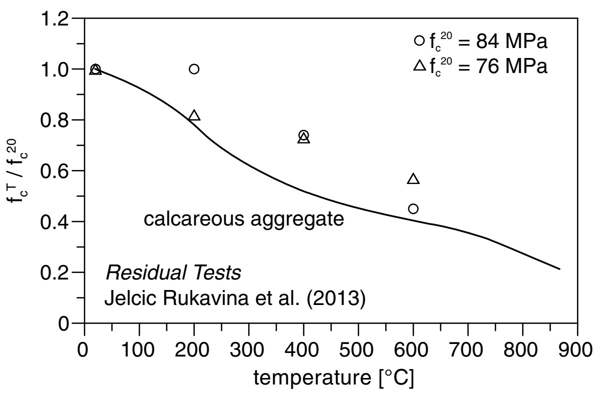

Fig. 12. Compressive strength: residual tests by Jelcic Rukavina et al. (2013) (open circle: with metakaolin or fly ash, and open triangle: without admixtures or with limestone powder; ASCE-ACI provisions are reported only for calcareous concrete, as aggregates are calcareous)

Khaliq and Kodur (2011) Hot Tests (Fig. 10)

Slag and fly ash may be the cause of the somewhat greater temperature sensitivity of the two mixes compared with the other mixes.

Jelcic Rukavina et al. (2013) Residual Tests (Fig. 12)

The two mixes containing Portland cement as such or partly replaced with metakaolin (mean strength $f_c^{20} = 84$ MPa) and the two mixes with Portland cement partly replaced with fly ash or limestone powder (mean strength $f_c^{20} = 76$ MPa) behaved very similarly at high temperatures; consequently, each couple is represented with a single symbol in Fig. 12.

Comments on the Test Results

Hot Tests—Strength

The test results by Persson [2004, Fig. 7(a)] and by Tao et al. (2010, Fig. 9) adhere very well to the curves suggested by ASCE-ACI for siliceous and calcareous aggregates, respectively. In the case of mixed aggregates, the results by Bamonte and Gambarova [2012, Fig. 7(a)] and the results by Khaliq and Kodur (2011, Fig. 10) consist of between the ASCE-ACI curves for siliceous and calcareous aggregates above 400°C. In the latter case, below 400°C there is a sizable heat sensitivity, with a downward spike at 100°C, something often found between 100 and 200°C [Bamonte and Gambarova 2012, Fig. 7(a)] similarly to high-performance/high-strength concretes.

This phenomenon is caused by the rather isolated capillary porosity, typical of SCC and HPC/HSC, which prevents the release of pore pressure and favors cement-paste microcracking to the detriment of mechanical performance. A general agreement above 300°C with ASCE-ACI curves is also exhibited by the ultra-high performance siliceous microconcrete investigated by Bamonte and Gambarova [2010, Fig. 7(b)], but the downward spike at 150°C is confirmed.

Residual Tests—Strength

The test results by Persson [2004, Fig. 8(a)], Bamonte and Gambarova [2012, Fig. 8(a) and 2010, Fig. 8(b)], and Annerel and Taerwe (2011, Fig. 11) follow the ASCE-ACI curve for siliceous concrete rather well, in addition to the case of the UHPC mix. The trends exhibited in Fig. 8(c) by the results of Sideris (2007), Fares et al. (2009), Reinhardt and Stegmaier (2006), and Noumowé et al. (2006) generally confirm the validity of the ASCE-ACI curves, which in residual conditions are largely unaffected by aggregate type, at least below 550°C. However, the tests by Fares et al. (2009) exhibit a significant spike at 300°C, something that would require an in-depth analysis. Last but not least, the test results by Jelcic Rukavina et al. (2013, Fig. 12, calcareous aggregates) systematically exhibit higher values than those indicated by the ASCE-ACI curve for calcareous aggregate, although the general trend is rather similar.

Elastic Modulus (Secant for $\sigma \leq f_c/2$)

Overall, the values for secant elastic modulus fall within the envelope of the hot/residual tests concerning vibrated concrete, examined by Phan and Carino (1998, Fig. 13). As expected, the values of the hot moduli [Fig. 13(a)] are generally lower than those of the residual moduli [Fig. 13(b)] below 400°C, most probably because of the transient thermal creep occurring at high temperature, which can hardly be separated from the elastic strain. The best performance in residual conditions is exhibited by the UHPC examined by Bamonte and Gambarova [Fig. 13(b)]. A possible explanation may be found in the smallness of the aggregate ($d_a = 4.0$ mm), which favors kinematic compatibility at high temperatures, in both the heating and cooling phases, between the aggregate particles and the cementitious mortar.

Fibers' Role

Even though the role played by fibers—and specifically by pp fibers—was not among the objectives of this study, a few mixes contained rather small amounts of pp fibers, as those tested by Tao et al. (2010) and Khaliq and Kodur (2011). In both experimental campaigns, a first mix containing a small amount of pp fibers (0.1% by volume) and a second white mix were investigated in hot conditions (Figs. 9 and 10, respectively). In both cases, adding pp fibers brought in a reduction of the compressive strength in virgin conditions (−24 and −6%, respectively), but the normalized curves at high temperatures were rather similar (and in some cases very similar) with or without fibers. In the tests of Tao et al., the white mix spalled above 400°C (probably because of the rather high heating rate, Table 1, 5°C/min), whereas the fibrous mix behaved regularly up to 800°C, following closely the ASCE-ACI curve for calcareous aggregate. In Khaliq and Kodur's tests, the white mix had an edge on the fibrous mix below 400°C, and was even better above 400°C. Furthermore, the heat sensitivity was greater than in the other mixes, most probably because of the fly ash and blast furnace slag contained in the mixes, whose effect could not be mitigated by the fibers.

Table 1. Main Features of the Experimental Campaigns Examined in This Paper

Authors (year)	Test procedure (number mixes)	T_{ref} (°C)	$\Delta T/\Delta t$ (°C/min)	Δt at T_{ref} (h)	f_c (MPa)	Cement	Aggregate [fibers % by volume]	Specimens (mm) Ø/h; a	Figures (symbol)
Bamonte and Gambarova (2010)	Hot/res (1[a]/1[b])	20–750	+1, +2/ − 0.25	2	125 (135[c])	PRT	Quartzitic [pp = 0.6%]	36/110	7(b), 8(b), 13(b) (black triangle left)
Bamonte and Gambarova (2012)	Hot/res (3[a]/3[b])	20–600	+1, +2/ − 0.25	2	50, 80, 90	BLN/PRT	Mixed + lms powder	100/200	7(a), 8(a), 13(b) (closed circle, open circle, half circle)
Persson (2004)	Hot/res (10[a]/16[b])	20–800	+4/ − 1	0.5	40–88	BLN/PRT	Gneiss+granite + lms powder [pp = 0, 0.2, 0.4%]	100/200	7(a), 8(a), 13(a and b) (closed diamond)
Sideris (2007)	Residual (2[a]/8[b])	20–700	+5/Natural cooling in oven	1	43, 54	BLN	Granite	100	8(c) (closed triangle, open triangle)
Noumowé et al. (2006)	Residual (1[a]/4[b])	20, 400	+0.5/ − 0.5	2.5	76	BLN + sf	Calcareous [pp = 0.2%]	160/320	8(c) (closed square)
Reinhardt and Stegmaier (2006)	Residual (5[a]/9[b])	≅540	≤6 ([d])	—	53, 72	BLN + fa	Quartzitic + clc powder	100/100	8(c) (inverted closed triangle, inverted opened triangle)
Fares et al. (2009)	Residual (2[a]/3[b])	20–600	+1/ − 1	1	37, 54	BLN/PRT	Mostly slc + lms filler	160/320	8(c), 13(b) (+ ×)
Annerel and Taerwe (2011)	Residual (1[a]/2[b])	20–550	+5/ − 5	12.5	63	PRT	Siliceous + lms powder	150/300	11 (closed circle)
Tao et al. (2010)	Hot (2[a]/5[b])	20–800	+5	([e])	70, 53	PRT	Calcareous + lms powder [pp = 0, 0.1%]	75/150	9 (closed circle, open circle)
Khaliq and Kodur (2011)	Hot (2[a]/4[b])	20–800	+5	2	72, 68	PRT + fa	Calcareous + slag [pp = 0, 0.1%]	75/150	10 (closed circle, open circle)
Jelcic et al. (2013)	Residual (4[a]/4[b])	20–600	+2/Natural cooling in oven	([e])	70–85 (75–92[c])	PRT or PRT + mtk/fa/lms powder	Dolomite + dolomite powder	75/225	12 (open circle, open triangle)

Note: BLN = cement type II; clc = calcareous; fa = fly ash; lms = limestone; mtk = metakaolin; pp = polypropylene; PRT = cement type I; sf = silica fume; slc = siliceous.

[a]Number of mixes examined in this paper.

[b]Total number of mixes tested in the experimental campaign.

[c]Estimated for h/Ø = 2: $(f'_c)_{2Ø} = 1.08(f'_c)_{3Ø}$.

[d]$\Delta T/\Delta t$ variable; specimens obtained by coring large cubes ($a = 300$ mm) subjected to ISO 834/ASTM E119 fire for 120 min; natural cooling in the oven.

[e]Rest period sufficient to have $\Delta T_{max} \leq 20$°C in specimen's mid-height section ($\Delta T_{max} = \Delta T$ between the lateral surface and the axis of the specimen).

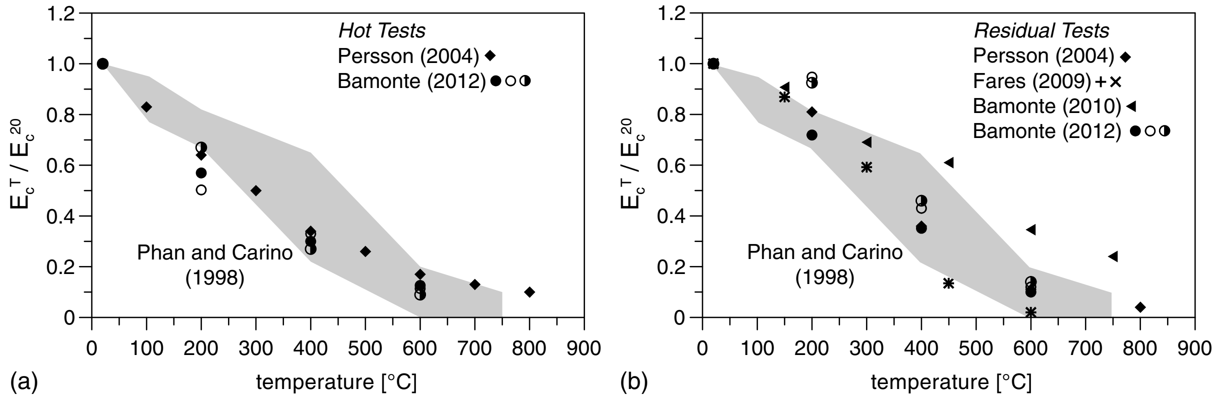

Fig. 13. Elastic modulus: (a) hot tests by Persson (2004) and Bamonte and Gambarova (2012); (b) residual tests by Persson (2004), Bamonte and Gambarova (2010, 2012), and Fares et al. (2009) (the two symbols + and × are superimposed)

In addition to the strength in compression and the elastic modulus, further parameters are required to describe the mechanical behavior of a family of materials and to make comparisons with other materials. In the case of cementitious composites, the strength in tension, the fracture energy, the Poisson's ratio, and the strains at the stress peaks in tension and in compression can be cited, besides the stress-strain curves. Only a few of these properties, however, are treated in each of the research projects mentioned in this paper, which have in common the strength in compression and the elastic modulus as a function of the temperature. More or less extended information on other parameters can be found in a number of well-documented papers. For instance, the stress-strain curves in compression are presented in detail in Fares et al. (2009), Bamonte and Gambarova (2010, 2012), and Annerel and Taerwe (2013). In the last of the papers listed previously, analytical formulations are also provided for the loading branches (up to the stress peak), but not for the softening. In general, there are no major differences between SCC and VC. Differences may arise concerning specific types of self-consolidating concretes (e.g., light, heavy), creep and shrinkage, or multi-axial stress states, but information on these issues is still too limited for SCC, and making comparisons and drawing conclusions is hardly possible.

Concluding Remarks

The agreement among the results of tests conducted on the behavior of SCC at high temperatures obtained by different scholars, in different laboratories, with different techniques and specimens confirms that there are no systematic differences between vibrated concrete and self-compacting concrete (without fibers or with rather small amounts of polypropylene fibers) in terms of temperature-triggered decay under quasi-steady thermal conditions. This conclusion holds not only for uniaxial compression—as shown in this paper—but also for other properties such as indirect tensile strength in bending or by splitting, fracture energy, and thermal properties (and especially for thermal diffusivity), as shown in a number of papers on SCC at high temperatures. In general, SCC is more brittle than VC at any temperature, and admixtures (like fly ash, silica fume, and metakaolin) tend to increase heat sensitivity, but this is no different from what happens in vibrated concrete.

The question still largely unanswered, however, is to what extent the findings concerning quasi-steady thermal conditions and uniaxial compression apply to more complex stress states and to transient thermal conditions. (SCC tends to be more sensitive to spalling than VC, because of the more isolated and finer porosity that makes SCC similar to vibrated high-performance/high-strength concrete in terms of fire sensitivity). Further studies should therefore focus on these specific issues, in addition to the effect of adding fibers, be they polymeric, metallic, or hybrid. (At high temperatures, however, small amounts of fibers have little effect on the mechanical performance of SCC, whose strength in compression may even be slightly diminished by fibers).

The normalized curves suggested by ASCE-ACI for hot compressive strength measured on unstressed specimens are also valid for SCC with either siliceous or calcareous aggregates. Between 150 and 200°C, however, in certain SCC mixes the hot compressive strength may exhibit a downward spike because of the damage produced by the high pressure of the vapor in the pores, something that does not occur at higher temperatures, when microcracking allows vapor pressure to be released. Residual compressive strength may even increase (up to 20% compared with the strength of the virgin material) because of complex phenomena concerning cement rehydration and better hydrates. The analogous normalized curves for the residual compressive strength of VC are also acceptable for SCC.

As for the elastic modulus, the hot tests and the residual tests fall within the envelope of many results concerning either ordinary or high-performance/high-strength vibrated concretes. However, the differences between the hot and residual values are rather limited and dubious, as the hot values may—or may not—include the effects of transient thermal creep, which tends to reduce the value of the hot modulus.

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