Properties of Concrete Subjected to Extreme Thermal Conditions

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ABSTRACT

Durability, high-temperature resistance, impact and blast resilience, radiation-shielding properties, irradiation endurance and – of course – good mechanical properties are required of the cementitious composites to be used in a variety of high-performance structures. Among these, tall buildings, road and railway tunnels, off-shore platforms, gasification plants, wind and solar mills for the production of "clean" energy should be mentioned, as well as nuclear power plants, and radioactive- and hazardous-waste repositories. Hence, understanding, measuring and modelling concrete behavior under extreme environmental conditions is instrumental in making concrete structures safer and more efficient. To this end, the hot and residual properties associated with the exposure to high temperature, fire and thermal shock are treated in this paper. Reference is made to ordinary vibrated concrete (Normal-Strength Concrete - NSC), as well as to a number of innovative cementitious composites, such as Fiber-Reinforced Concrete - FRC, High-Performance/High-Strength Concrete - HPC/HSC, Ultra High-Performance/Very High-Strength Concrete - UHPC /VHSC, Self-Compacting/Consolidating Concrete - SCC, Light-Weight Concrete - LWC, shotcrete and high-strength mortars. It is shown that these materials can be "tailored" according to a variety of requirements and functions, even if several aspects of their behavior (like spalling in fire and long-term mechanical properties under sustained high temperature) are still open to investigation.

Keywords: concrete, fire, high temperature, durability, fibers, high strength, mortars, shotcrete, spalling

1. INTRODUCTION

The rather long history of concrete is that of a tolerant material, which is incombustible, insulating, chemically stable (at low-medium temperatures), fire resistant, effective against radiations, rather cheap, "green" (because most of its constituents are often found in nature) and "flexible" (because of the possibility to optimize the constituents). These virtues are unquestionable, but the increasingly stricter requirements related to specific objectives (high strength, workability, mass reduction, toughness, fire resistance, durability to cite some of the most sought after properties of modern cementitious composites) are forcing the Industry to develop new – or at least largely innovative – concretes, whose thermo-mechanical properties are more or less different from those of ordinary concrete. There is no longer a single "Mr. Concrete", good for all seasons, but a variety of concretes, that force designers/contractors/owners to make choices for the best!

Among the challenges to be met by modern concrete, high temperature and fire are particularly demanding, because the composite nature of concrete is put to the test. It is true that high-temperature and fire are rather unlikely to occur in most structures, but many are the structures exposed to the thermal risk, from tunnels (with their lining and partitions) to tall buildings (with their "chimney" effect), from industrial plants (especially oil refineries, gasification facilities, off-shore platforms and chemical plants) to nuclear power plants (where steam jets due to punctured pipes, coolant losses and core heat-ups are hazards to be considered in the design).

Within this context, structural safety requires the thermo-mechanical properties of each concrete family to be well known, through an adequate characterization at high temperature, both in quasi steady conditions (to work out the stress-strain laws at different temperatures) and in highly unsteady conditions (to assess the spalling tendency).

A lot of scientific work has been done in the last twenty years on concrete behavior at high temperature, but certain materials like self-compacting concrete, shotcrete and even cementitious mortars are still little known with reference to high temperature, or the test results still need to be cross-examined to draw conclusions.

In this paper, starting from the well-known behavior at high temperature of ordinary concrete [1–4], the thermo-mechanical properties of high-performance/ultra high-performance/light-weight/self-compacting concrete, as well as those of shotcrete and cementitious mortars will be introduced, and some very recent results obtained in Milan on the last three families of cementitious materials will be presented.

Many occasions are fostering a renewed interest for the high-temperature behavior of structural cementitious materials: the excavation of increasingly longer road and railway tunnels; the construction of increasingly taller R/C buildings, as an alternative to steel buildings; the off-shore platforms, and – last but not least – the nuclear power plants, which – in spite of the recent Fukushima disaster (Japan, March 2011) and of the further efforts needed to make them safer – are continuing to be an active player in the production of cheap, clean and dependable electric energy. Limiting the attention to the rather complex structures commonly found in nuclear power plants and to the rather simple structures typical of tunnels (Fig. 1), an astonishing variety of cementitious materials is used (or can be used), as shown in the following:

- heavy concrete and self-compacting concrete in the primary containment structures, in the shielded facilities for fuel processing, and in the pools underneath the vessel;
- high-/ultra high-performance/fiber-reinforced concrete for the secondary containment shells and for the frames supporting heavy machinery (*steel fibers*);

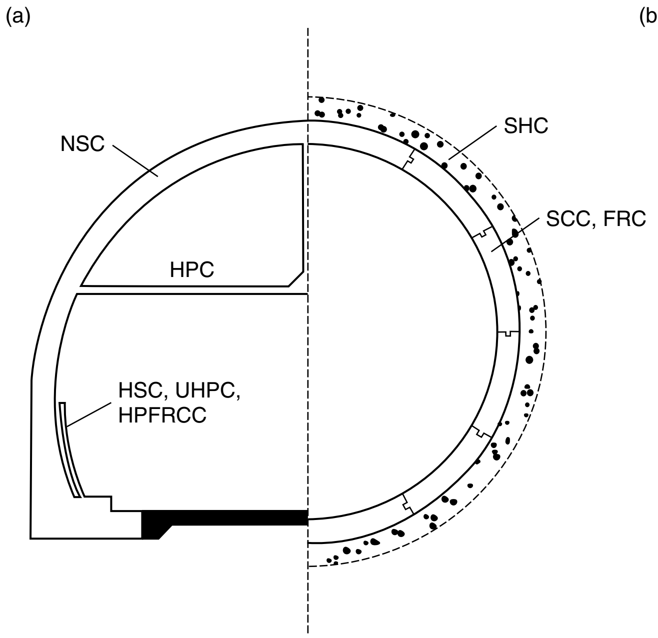


Figure 1. Typical section of road (a) and railway tunnels (b), and different cementitious composites: (a) cast-in-situ lining; and (b) segmental lining. Shotcrete = SHC; ordinary concrete = NSC; self-compacting/consolidating concrete = SCC; fiber-reinforced concrete = FRC; high-performance concrete = HPC, and ultra high-performance concrete = UHPC, HPFRCC.

- high-performance/self-compacting/polymer concrete for casks, caissons, dry-storage pads and underground waste repositories;
- shotcrete and ordinary concrete for tunnel linings;
- spalling-free fiber-reinforced concrete for cast-in-situ and segmental tunnel linings, as well as for firewalls and partitions (*polymeric or hybrid fibers = polymeric + steel fibers*);
- heat-resistant cementitious mortars for masonry firewalls (*polymeric fibers*).

Summing up, even if at first glance cementitious materials look like rather traditional and unsofisticated materials, extreme environmental conditions require special mixes to be formulated, particularly in the case of high temperature and fire, where the rather different requirements for static efficiency, insulation capability, integrity and long-term durability often collide, and force materials scientists and structural designers to join their efforts in order to obtain the best result in technical and socio-economical terms.

2. HIGH TEMPERATURE AS A DAMAGE SOURCE IN CONCRETE

Among the many damage causes in concrete, some - but not high temperature - have to do more with the “loads” than with the nature of the material in itself (*load-related mechanisms*), like – for instance - abrasion/erosion due to mechanical contact with water, vapor bubbles or vehicular traffic; fatigue due to mechanical, thermal or combined effects; external loads due to either environmental conditions like earthquakes, hurricanes, floods and tornadoes, or abnormal operations, like pipe breaks, water-hammer effects and missile impacts; and soil settlements, that may cause cracking.

Other mechanisms are more or less directly related to the nature of concrete (*concrete-related mechanisms*), with some having mostly chemical aspects (chemical attack, cement-aggregate reaction and leaching), and some exhibiting mostly physical aspects often related to the moisture content (thermal exposure, freezing-and-thawing cycles, irradiation, shrinkage, creep and fire exposure).

In the case of concrete exposed to high temperature, chemical and physical phenomena are intermingled, but the former tend to occur rather suddenly at certain temperatures, while the latter exhibit a rather regular evolution over a wide temperature range. Hence concrete damage at high temperature tends to have mostly a physical nature (including concrete mechanical or stress-related behavior), such a distinction being instrumental in identifying the specific properties concrete should have to face the challenges posed by high temperature.

2.1. Thermal Exposure (quasi-steady heating)

There are several situations where the large amount of heat generated – for instance – by the production and handling of steam, and by the nuclear-fission process (something – needless to say - that is typical of nuclear power plants) may subject structural and non structural members to sustained temperatures up to 150°C, with hot-cold cycles causing loss of mechanical properties and cracking in steam-piping penetrations, shield walls, pedestals of steam-driven equipment, members close to high-temperature piping and structures inside the primary containment. (For any temperatures below 56°C [5], the thermal exposure should be neglected). Higher temperatures (up to roughly 350°C [6]) may be expected in the case of steam leakages from broken pipes. As will be explained later, under quasi-steady thermal conditions concrete strength in compression may even improve (below 400°C [7]), because of the enhancement of the hydration processes at moderate temperatures, while both the tensile strength and the elastic modulus decrease with the temperature, and the specific fracture energy either increases (and starts decreasing above 400°C [8]) or keeps almost constant. Much higher temperatures can be reached in accidental situations, up to the full exhaustion of the concrete above 600–800°C [9].

2.2. Fire Exposure (highly-unsteady heating)

There are other situations, where large amounts of heat are produced in a rather short time (something that is typical of fires). Since concrete has good insulating properties, the ensuing high thermal gradients generally produce very severe thermal stresses in the exposed structures, with high and rapidly variable compressive stresses close to the heated surface and rather regularly-distributed tensile stresses in the core. However, the greater the exposure time, the greater the stress relaxation, because of the temperature-triggered loss of stiffness in the concrete. The major effects are: surface staining, cracking, spalling and – generally – increased deflection in heated members; the resisting sections are reduced and all buckling phenomena are enhanced. Temperature as high as 1200–1400°C can be reached in short time periods [10].

In the following, some results obtained in Milan and in other labs are presented and discussed, with reference to Normal-Strength Concrete, High-Performance Concrete, Ultra High-Performance Concrete, Light-Weight Concrete, Self-Consolidating Concrete, shotcrete and high-strength mortars. Comparisons will always be made with ordinary concrete, as presented in EC2-Fire Design [11].

Because of the relevance of concrete compressive strength, one should remember that the measured values depend on the testing modalities, as well as on specimen size and shape [12]. For instance:

- testing specimens at high temperature always yields larger values than testing after cooling down to ambient temperature (because of the extra damage accumulated in the material during the cooling process, since the kinematic incompatibility between the coarse aggregate and the mortar is no longer relieved by *transient thermal creep*);
- testing at high temperature specimens that were preloaded in compression during the heating process (*stressed specimens*) always yields larger values than testing non-preloaded specimens (*unstressed specimens*), because preloading in compression reduces concrete damage (*microcracking*) during the heating process;
- cubic specimens always yield larger results than elongated cylindrical specimens (h/∅ ≥ 2), because of the much greater lateral confinement caused in the cubes by platen-to-specimen friction; furthermore, the ratio between the cylindrical strength and the cube strength (= 0.80–0.85 for ordinary concrete) may decrease to 0.6–0.7 at high temperature and after cooling, because of the larger role of friction in testing heat-weakened cubes;
- small specimens (size < 100 mm) always yield larger values than large specimens (size > 150 mm), because of *size effect*;
- relatively high heating rates (> 5°C/minute) applied to rather large specimens (side or diameter > 100 mm) always induce high thermal gradients (and dangerous self-stresses = *structural behavior*), to the detriment of concrete mechanical properties (= *constitutive behavior*).

Hence, comparing the results coming from different experimental campaigns and from different authors is no easy matter, and should be performed with caution (see the examples recalled in Fig. 2 for SCC).

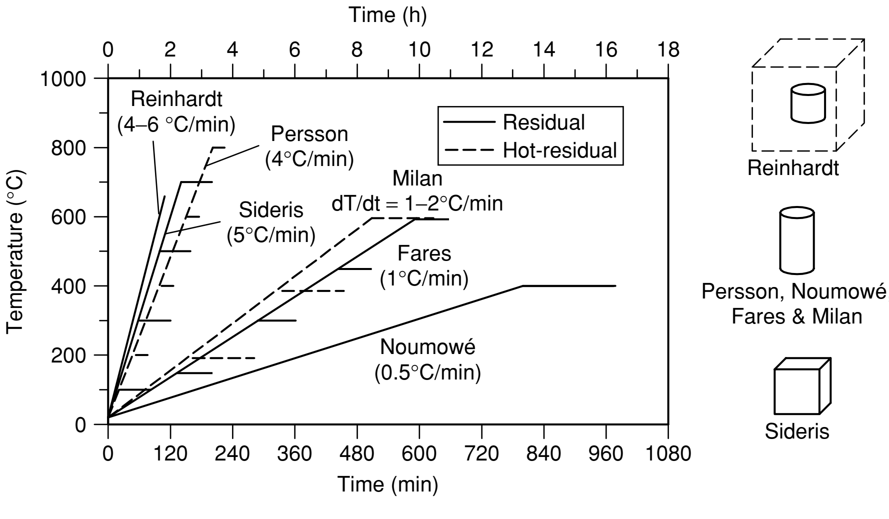


Figure 2. Thermal cycles with different heating rates and specimens geometries (adapted from [13]); *Milan* refers to the tests carried out by the authors in Milan – Italy.

3. NORMAL-STRENGTH CONCRETE

The behavior of normal-strength concrete at high temperature and in fire is well known in terms of good insulation properties (low thermal conductivity and thermal diffusivity, that allow the outer layers of a concrete member to insulate the core from the heat flow) and limited strength loss up to 400-500°C [2,3,14,15].

The strength and stiffness loss as a function of the temperature in quasi-steady conditions clearly appears in Figure 3a (specimens unstressed during the heating process [3]), while the role played by the test modalities (tests at high temperature on stressed/unstressed specimens, and residual tests) is shown in Figure 3b [1].

The progress of cement and concrete chemistry in the last 20–25 years allows the structural designer and the concrete consultant to make the most appropriate choice in terms of cement type and concrete mix design, according to a variety of structural/architectural/functional requirements. For instance, many combinations of strength/insulation properties are possible, as demonstrated in Figure 4,

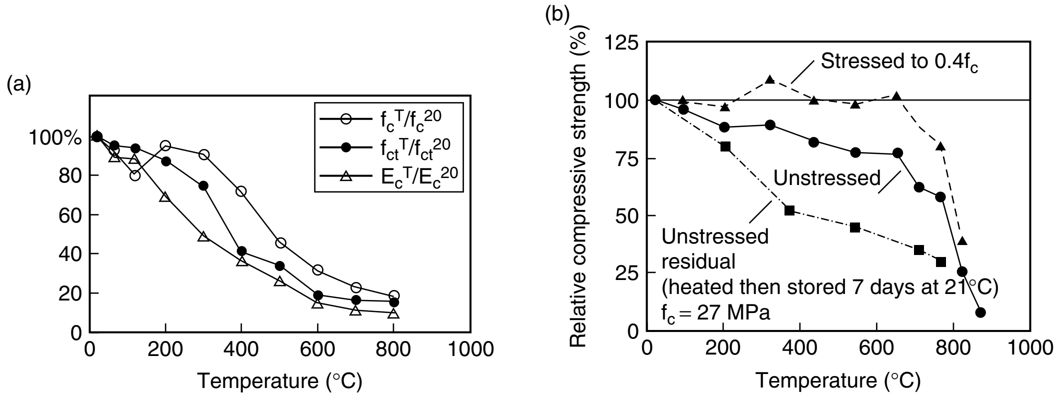


Figure 3. Normal-strength concrete: (a) typical normalized diagrams of the compressive and tensile strength (f_c and f_{ct}), and of the elastic modulus (E_c), as a function of the temperature [3]; and (b) effect of the test modalities on f_c [1].

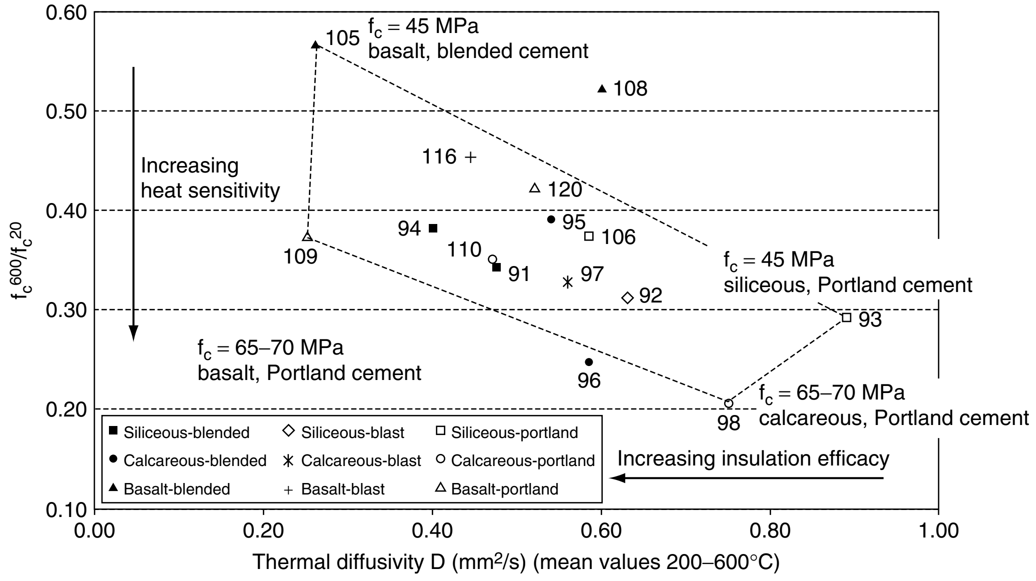


Figure 4. NSC and HPC: test results on 15 concretes containing blended/blast-furnace/Portland cement, and calcareous/basalt/siliceous aggregates; f_c = 45-70 MPa [16]. The two/three digit numbers identify each mix.

where the normalized residual strength at 600°C of 15 different concretes is plotted against their average thermal diffusivity D between 200°C and 600°C [16]. ($D = \lambda\ \rho^{-1}\ c^{-1}$, where λ is the thermal conductivity; ρ is the density; and c is the specific heat).

Concretes with high residual strength and low diffusivity should be used in thin structural members (to insulate the core and the reinforcement). On the contrary, concretes with high diffusivity should be adopted in massive members (where the heat-induced strength loss is of minor relevance) to limit the thermal gradients and the ensuing thermal stresses, and thus to reduce the risk of spalling. On the whole, blended cements (containing calcareous powders), calcareous or basalt aggregates, and medium water/cement ratios appear to guarantee the best performance at high temperature.

4. HIGH-PERFORMANCE CONCRETE

The thermo-mechanical behavior of high-performance/high-strength concrete has been thoroughly investigated in the last 20–25 years, with reference to both ambient and high temperature, and to durability [17]. While there is plenty of evidence that these materials are more durable, because of their more homogeneous microstructure and finer porosity, clear-cut conclusions on the mechanical behavior at high temperature can hardly be drawn, as too many parameters come into play (and more than in ordinary concrete). HPC/HSC looks slightly more temperature-sensitive than NSC in quasi-steady thermal conditions, and definitely more heat-sensitive in unsteady thermal conditions, whenever there is a risk of spalling (= more or less *sudden – and often explosive – bursting of the concrete into pieces starting from the heated surface*, see the section devoted to this topic). Such greater heat sensitivity is enhanced by silica fume, that is a rather cheap means to increase concrete strength. The risk of spalling can be prevented by adding small amounts of polymeric fibers to the mix (v_f = 0.1 – 0.5% by volume), at no cost for the thermal and mechanical properties at any temperature [18,19].

Among the many experimental results nowadays available in the literature, those by Chan et al. [20] can be cited. As shown in Figure 5a, above 700°C Chan's concretes have a very similar residual strength, in spite of their very different original strength (f_c close to 120, 90, 85 and 60 MPa at 20°C). For the lowest- and highest-grade concretes, the residual strength at 700°C is close to 2/3 and 1/3 of the original strength, respectively. However, the nature of the aggregates plays a leading role, since – for instance - using highly siliceous aggregates (like flint) may reduce the residual strength at 500°C to less than 10% of the original strength because of the splitting of the aggregates due to the expulsion of the crystallization water at high temperature [9].

As shown in Figure 5b, the difference between the "hot" and "residual" strengths is sizable and similar to that observed in normal-strength concrete [21]. The same holds for the elastic modulus.

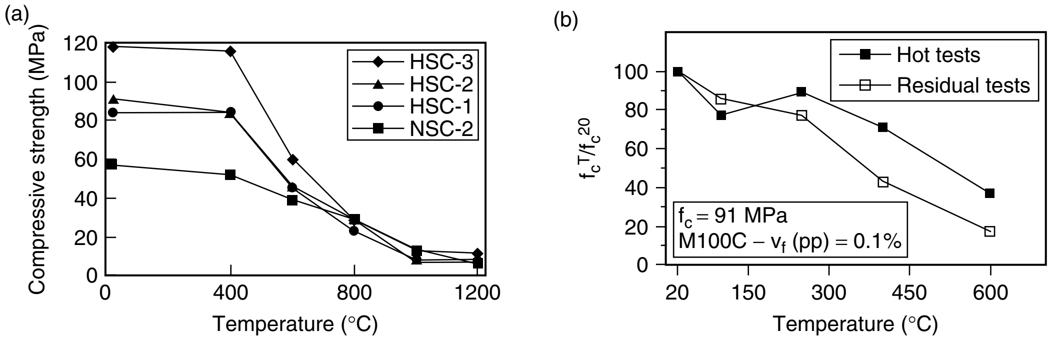


Figure 5. High-performance concrete: (a) residual compressive strength of various concretes [20] (Portland cement; crushed granite; no silica fume); and (b) hot and residual strength as a function of the temperature ([21]; 0.1% pp fibers; limestone aggregates).

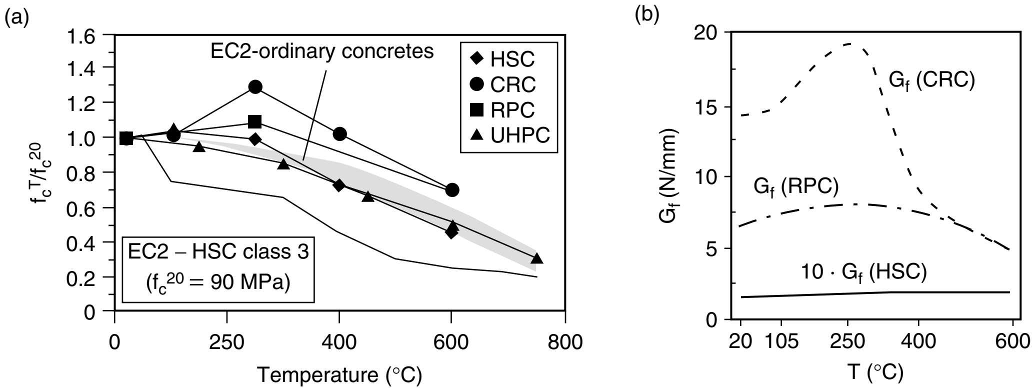


Figure 6. Ultra high-performance concrete: (a) residual compressive strength of RPC (f_c = 165 MPa), CRC (f_c = 160 MPa), UHPC (f_c = 125 MPa), and HPC/HSC (f_c = 95 MPa); and (b) residual fracture energy [24]. RPC, CRC and UHPC contain steel micro-fibers.

HPC/HSC is relatively less tough – or more brittle – than NSC, as the fracture energy (= energy to be supplied to the material to extend by one unit an already-formed cracked interface) increases less than linearly with the compressive strength. However, as already observed in NSC, the fracture energy tends to increase up to 400°C and then starts decreasing. One explanation may be that the thermal damage makes the microstructure more heterogeneous and the cracks more tortuous. According to other tests, however, the fracture energy tends to remain roughly constant up to 500°C (see Figures 6b, and 8a, b).

5. ULTRA HIGH-PERFORMANCE CONCRETE

Ultra high-performance/very high-strength concretes are generally characterized by a cylindrical compressive strength comprised between 120-130 and 160-180 MPa [22]. However, while at the lowest levels UHPCs can be considered as an evolution of HPCs [23], at the highest levels the differences with respect to HPC and NSC become so huge that these very strong materials are more similar to mortars than to concretes. For instance, such parameters as "water/binder ratio" and "maximum aggregate size" become meaningless, as most of the binder is a sort of super filler, not destined to take part in the hydration processes. From a mechanical point of view, neither the tensile strength nor the elastic modulus catch up with the compressive strength.

Very often UHPCs contain steel fibers (short, long or hybrid fibers), to increase their otherwise limited toughness. However, fiber contents in excess of a few percents by volume are necessary to give the material some ductility. This pseudo-plasticity ensues from the so-called "multiple cracking" with the formation of many thin cohesive microcracks.

In Figure 6a the residual compressive strength of four cementitious composites tested in Milan [24] is plotted as a function of the temperature: RPC = Reactive-Powder Concrete; CRC = Compact fiber Reinforced Concrete; UHPC = Ultra high-Performance micro-Concrete; and one HPC/HSC. Note that for both the RPC and CRC the residual strength is still close to 70% after heating to 600°C, while it is down to 50% in the HPC/HSC, and between 50 and 60% in the UHPC. In Figure 6b, the residual fracture energy of the above-mentioned materials (with the exclusion of the UHPC) is plotted as a function of the temperature. Note that RPC and CRC have a fracture energy that is two orders of magnitude higher than that of the HPC/HSC.

The main properties of the cementitious composites shown in Figure 6 are: UHPC : f_c = 125 MPa, c = 635 kg/m^3, w/c = 0.31; pp fibers v_f = 0.6%, d_a = 4.5 mm; quartzitic aggregates; RPC : f_c = 165 MPa, c = 933 kg/m^3, steel fibers 4%, s.f./c = 25%, w/b = 0.14; CRC : f_c = 160 MPa, c = 720 kg/m^3, steel fibers 6%, s.f./c = 30%, w/b = 0.16; HSC : f_c = 95 MPa, c = 510 kg/m^3, s.f./c = 10%, w/b = 0.29, mixed aggregates.

6. LIGHT-WEIGHT CONCRETE

Light-weight concrete (used mostly in buildings and seldom in environment-sensitive constructions) has some pluses and some minuses:

- the mechanical properties are less affected by high temperature than in ordinary concrete (*expanded-clay aggregates* [7,25]);
- the tensile-strain capacity is greater, which means light-weight concrete can deform more in tension prior to cracking;
- the insulating properties are better (lower thermal diffusivity);
- whenever the structural self-weight is at issue, the lower mass per unit volume of LWC offsets any other disadvantage (but limiting the self-weight is seldom a priority, except, for example, in the rehabilitation of existing buildings);

but:

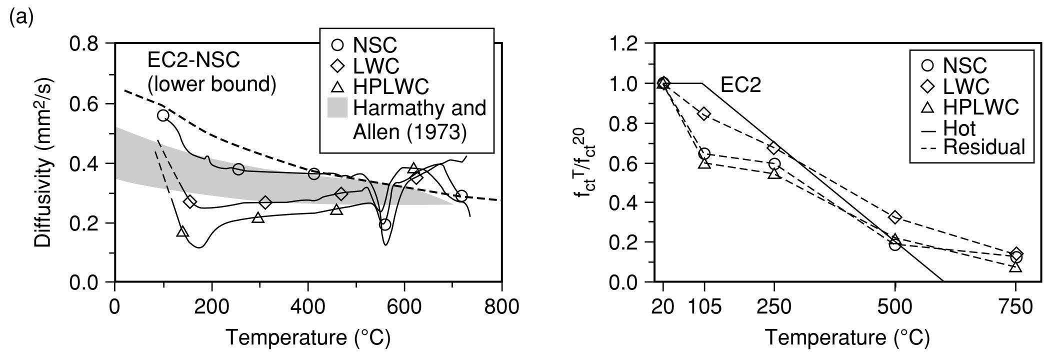
- there is a tendency to segregation in highly-workable light-weight concretes;
- the rate of carbonation of bar cover may be twice as much as in ordinary concrete;
- the abrasion resistance is lower;
- there is a higher moisture movement (swelling/shrinkage) than in ordinary concrete;
- both the modulus of elasticity and the bar-concrete bond are lower;
- the lower density diminishes the radiation-shielding capability (necessary in certain nuclear facilities).

In Figure 7a the thermal diffusivities of one ordinary concrete and two light-weight concretes, as well as the lower bound of the diffusivity specified in EC2 for ordinary concrete, are plotted as a function of the temperature [26]. The cloud refers to many rather old results cited in the literature.

To give an idea about the closeness of LWC's behavior at high temperature to that of NSC, for the same three concretes of Figure 7a the mechanical decay in tension is shown in Figure 7b, where the residual strength in direct tension is rather well matched by the bilinear diagram proposed in EC2 for ordinary concrete (strength at high temperature).

7. SELF-COMPACTING/CONSOLIDATING CONCRETE

One of the major success stories in concrete research and applications is represented by Self-Consolidating/Compacting Concrete – SCC, since no energy is required to compact the material, to envelop the reinforcement and to fill the formwork up to the most hidden nooks. Being concrete vibration no longer necessary, the cost saved in this way mostly balances the extra cost due to the better quality of the concrete, to the extra stiffness required by the formwork and to the more severe quality controls.



(b) Direct tension

Figure 7. Light-weight concrete: (a) thermal diffusivity (NSC/LWC/HPLWC: f_c = 30/39/56 MPa; c = 300/350/500 kg/m^3; s.f./c = 0/0/10%; w/c = 0.67/0.63/0.33; density = 2300/1809/1920 kg/m^3); and (b) normalized strength in direct tension, as a function of the temperature [26].

Because of its astonishing workability, SCC is particularly suitable for any structural member requiring high durability (where homogeneity, permeability and chemical resistance are at issue), which is typical of any structures in contact with soil and water or in an industrial environment, like – for instance – tunnel linings, off-shore structures, containment shells, tanks, bridges, slabs on grade, roadways and runways.

While many properties related to SCC's durability (as well as concrete spalling in fire) have been studied extensively in the past ten years, only recently the attention has been focused on SCC's high-temperature resistance (Persson, 2004 [28]; Sideris, 2007 [29]; Fares et al., 2009 [30], to quote only the most comprehensive studies). The various experimental campaigns, however, differed in many ways (heating rate; geometry of the specimens; control mode of the tests; test modalities, see also Fig. 2).

To have systematic information on the hot and residual behavior of normal-strength and high-performance SCCs, and to make comparisons with the results of other experimental campaigns, three limestone SCCs have been investigated in Milan (target strength: 50, 80 and 90 MPa; hot and residual properties between 20 and 600°C [13]).

In Figures 8a,b the plots of the residual fracture energy confirm that SCC's behavior is similar to that of ordinary concrete. Note that the dashed lines come from the formulation of the fracture energy given by CEB Model Code at ambient temperature [25]: $G_f = 0.2\ (10 + 1.25\ d_a)\ f_c^{0.7}$.

In Figure 8c the thermal diffusivity of the three SCCs is plotted as a function of the temperature, while the typical stress-strain curves at T = 400°C and past cooling are shown in Figure 8d. (Note the rather good repeatability of the displacement-controlled tests).

In Figure 8e,f the good agreement with Persson's results [28] demonstrates that the test results available in the literature are reliable, even if they were obtained in different ways (different heating rates, different geometries).

The conclusion is that there are no major differences between the high-temperature behaviors of SCC and ordinary concrete.

8. SHOTCRETE

Shotcrete has been used so far mostly for the stabilization of slopes and rocks in blasted-off tunnels, and for fire insulation in metallic structures. Its use for structural purposes, however, has been recently proposed for the final lining of blasted-off tunnels [31] and for a variety of structural members (walls, slabs, shells for the protection of steel tanks). In the case of tunnels, shotcrete properties at high temperature should be well understood, since fire is the most dangerous accident in a tunnel (and among the most dangerous in nuclear facilities). Unfortunately, there is hardly any experimental evidence on shotcrete physical and mechanical properties at high temperature, that may differ from those of ordinary concrete because of the accelerating agent [32], the larger cement content and the smaller aggregates. Shotcrete can be also fiber-reinforced [33].

For such reasons, an experimental campaign is in progress in Milan [34], and some of the results in residual conditions (compressive strength, elastic modulus and porosity) and at high temperature (thermal diffusivity) are presented in the following with reference to three shotcretes, C1 with an alkali-based accelerating agent (f_c = 20 MPa), and C2 and C2F with an alkali-free accelerating agent (C2: f_c = 50 MPa, no steel fibers; C2F: f_c = 45 MPa, with steel fibers, v_f = 0.4% by volume). In all cases, the water is added to the mix before spraying (*wet process*). The residual normalized curves of both the strength and the elastic modulus are shown in Figures 9a,b, while the thermal diffusivity and the porosity are plotted in Figures 9c,d.

The residual normalized curves are very close to those of ordinary concrete (that are somewhat over-evaluated by EC4 [35]) for Mixes C2 and C2F, while Mix C1 is definitely more affected by the temperature. In terms of thermal diffusivity D (Figure 9c), all mixes are definitely less diffusive than ordinary concrete, as expected because of shotcrete's well - known insulation properties. Finally, fibers tend to increase the porosity in Mix C2F compared to Mix C2 (Figure 9d). Mix C1, however, is definitely the most porous, partly because of its higher water-cement ratio (w/c = 0.51) compared to Mixes C2 and C2F (w/c = 0.44), while the cement content is the same (c = 450 kg/m^3) for all mixes.

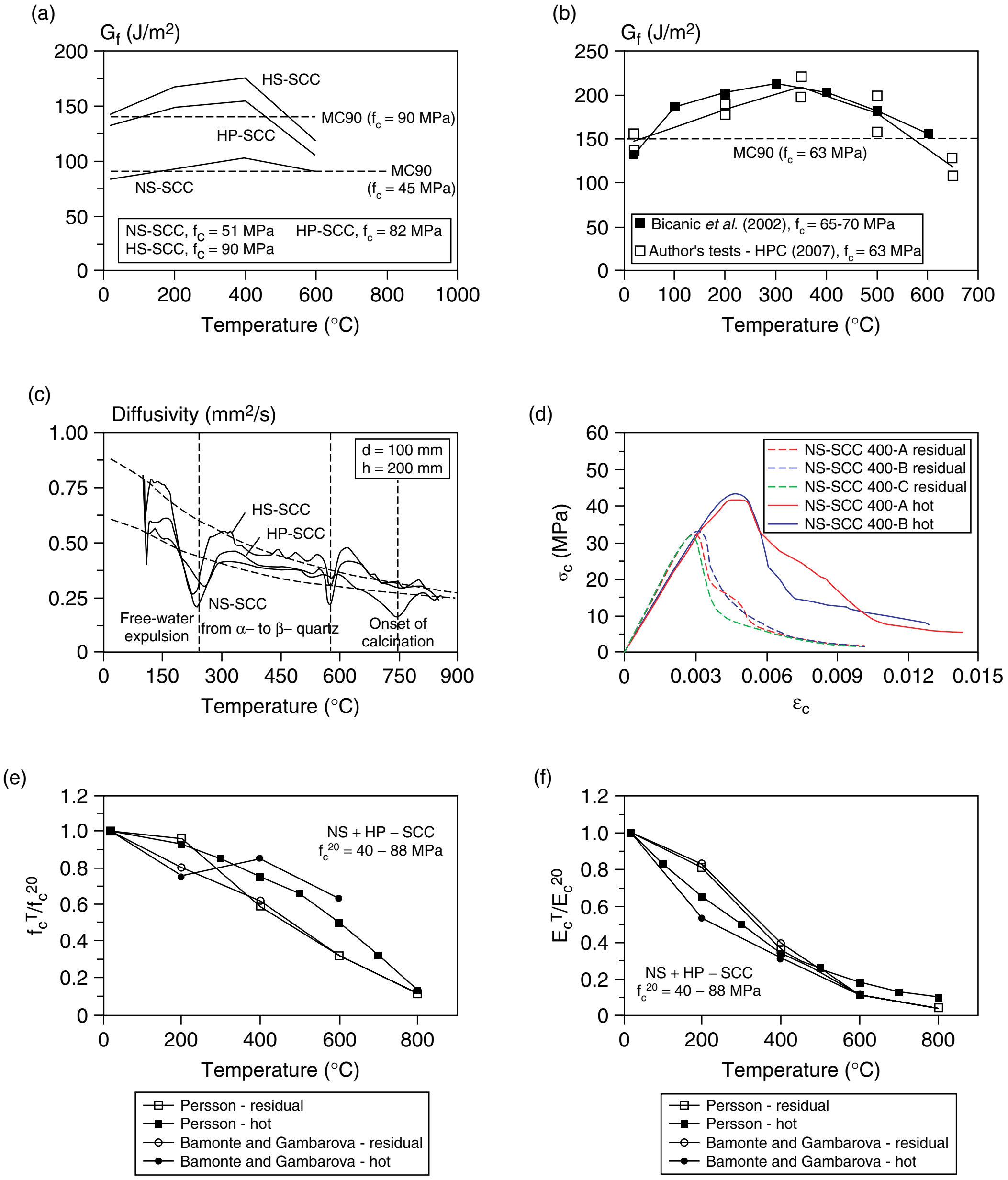


Figure 8. Self-compacting concrete [13]: (a) residual fracture energy of SCC and provisions by CEB MC90 [25]; (b) residual fracture energy of two vibrated HPCs [8, 27]; (c) thermal diffusivity and provisions by EC 2 for vibrated concrete; (d) typical stress-strain curves in compression (f_c^{20} = 51 MPa; hot and residual conditions); and (e,f) comparison with Persson's experimental results on SCC [28].

9. HIGH-STRENGTH MORTARS

High-strength mortars have been recently proposed by several producers to improve the fire performance of firewalls made of concrete blocks or clay bricks. Mortars behavior at high temperature, however, has received scanty attention so far - to say the least - and experimental evidence is badly needed. A partial answer comes from the results of an experimental campaign, that is still in progress at the Politecnico di Milano on three different mixes.

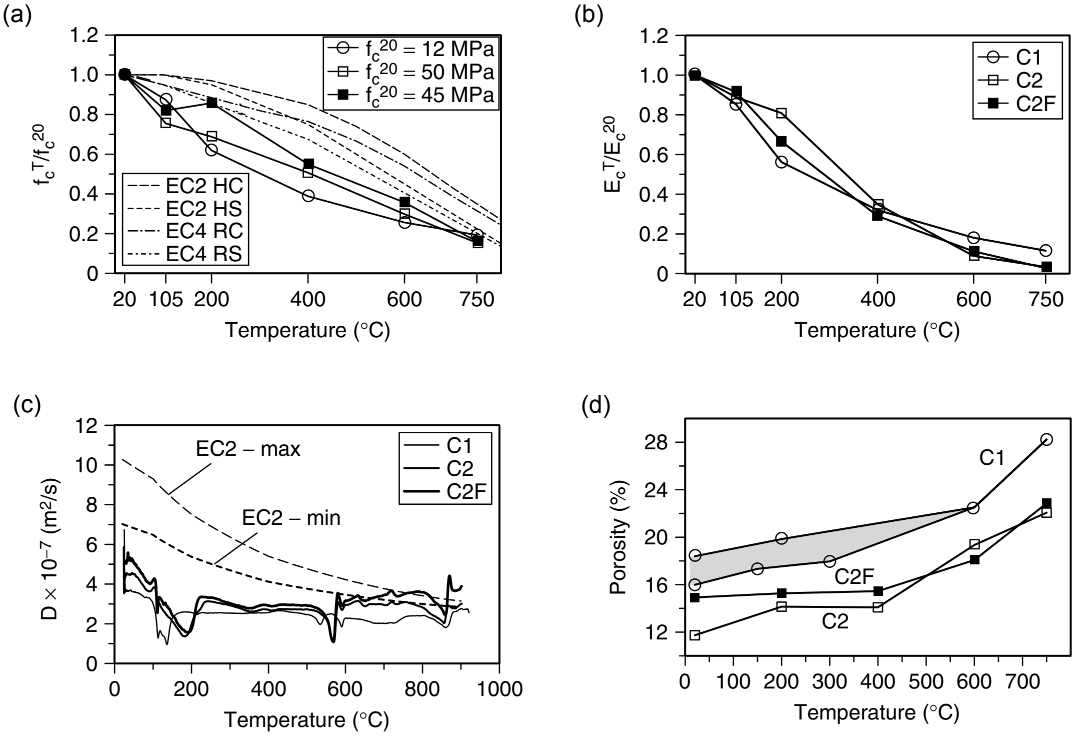


Figure 9. Shotcretes [34]: (a, b) normalized plots of the compressive strength and of the elastic modulus; and (c, d) thermal diffusivity and porosity, as a function of the temperature. C1 (alkali-based): f_c = 20 MPa; C2F/C2 (alkali-free, with/without steel fibers): f_c = 45/50 MPa, v_f = 0.4/0.0%.

The specimens of the three mortars (M5, M10 and M15) were slowly heated to 200, 400 and 600°C, and then slowly cooled to room temperature, in order to measure the residual compressive strength, the elastic modulus, the tensile strength in bending and the mass loss [36]. Also the thermal diffusivity was evaluated between 20 and 900°C, by instrumenting three cylinders (each with two thermocouples, the first along the axis and the second close to the heated surface). All specimens were cylinders (∅, h = 80, 160 mm in the residual tests; ∅ h = 100, 300 mm for the evaluation of the thermal diffusivity). The mixes were in accordance with UNI EN 13139 [37] in terms of cement, aggregates and lime, had a mass per unit volume close to 2000 kg/m^3 in the fresh state and to 1850 kg/m^3 in the hardened state, and the thermal conductivity in ordinary conditions was 0.80-0.90 W/m°C. Mix M5 represents ordinary mortars, even if - contrary to Mixes M10 and M15 - contains some polypropylene fibers (v_f = 0.2% by volume).

The cube strength (cube side = 40 mm; curing for 28 days at 22°C and 95% R.H.) was close to 8.5 MPa (Mortar M5), 16 MPa (Mortar M10) and 18 MPa (Mortar M15), while the cylindrical strength on larger specimens was definitely lower as expected (close to 5, 8.5 and 12 MPa, respectively; ∅, h = 80, 160 mm; curing in the formwork, i.e. in quasi sealed conditions). The residual normalized parameters (compressive and tensile strength, and elastic modulus) are plotted in Figures 10a,b,c, while the thermal diffusivity is plotted in Figure 10d.

In terms of normalized compressive strength and elastic modulus there are no sizable differences with respect to ordinary concrete (EC 2), provided that the larger decay of the residual strength is considered (up to –30% with respect to the hot strength). Furthermore, the three mixes behave in pretty much the same way above 300°C. As for the tensile strength in bending (Figure 10c), above 200°C the behavior of the mortars seem to be even better than that of concrete.

In terms of thermal diffusivity (Figure 10d), all mixes are less diffusive than ordinary concrete, probably because of the larger porosity ensuing from the higher water content (w/c up to 90% and more).

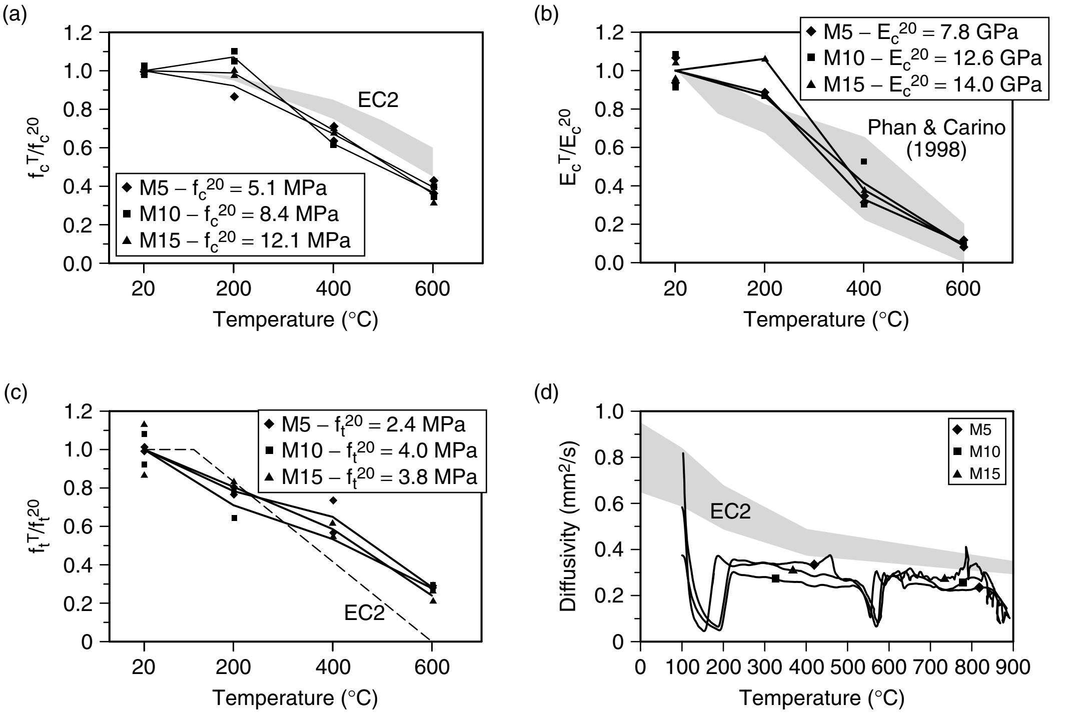


Figure 10. Ordinary and high-strength mortars: normalized plots of (a) compressive strength; (b) elastic modulus; (c) tensile strength in bending; and (d) plots of the thermal diffusivity [36].

10. SPALLING

Spalling in itself is not a property of concrete, since this more or less explosive phenomenon (triggered by the vaporization of the free water in the capillary pores) has to do with several factors, related to concrete microstructure (type of aggregates, type and amount of porosity, water content, water-cement ratio, fiber amount), to environmental conditions (heating rate and temperature) and to load conditions (high compressive stresses), see for instance Khoury [4], Dehn and Koenders [38, 39], Kodur and Dwaikat [40], Pimienta et al. [41]. and Figure 11a. Because of the role of concrete properties, however, there are certain concretes that are more spalling-prone than others, like high-performance concretes and especially those containing silica fume, as their porosity is less interconnected and with finer pores than in ordinary concrete, something that favors pressure build-ups in the capillary pores and microcracking in the cement paste.

How fibers (polymeric, inorganic or metallic) control spalling is still an open question, even if valuable contributions to explain the role of fibers have been offered in numerous papers published in the last ten years in major journals and proceedings of workshops and conferences [38, 39, 42]. Polypropylene fibers, however, are the best suited, as they prevent concrete from spalling, while other fibers - like steel fibers - control in some way concrete spalling by keeping concrete shards together, but do not avoid the spalling in itself [43].

What makes pp fibers so efficient in preventing concrete spalling is definitely not the volume they leave after melting (above 165°C), which implies that the larger the fiber number the larger their effectiveness against explosive spalling (something that lacks experimental evidence). What makes them so efficient is their volume expansion at and after melting (their linear coefficient of expansion is 8.5 times larger than that of concrete [44]), which brings high pressure in the volume occupied by each fiber, with the formation of a net of microcracks radiating from the volume occupied by the fibers, to the advantage of pore connectivity and vapor-pressure release.

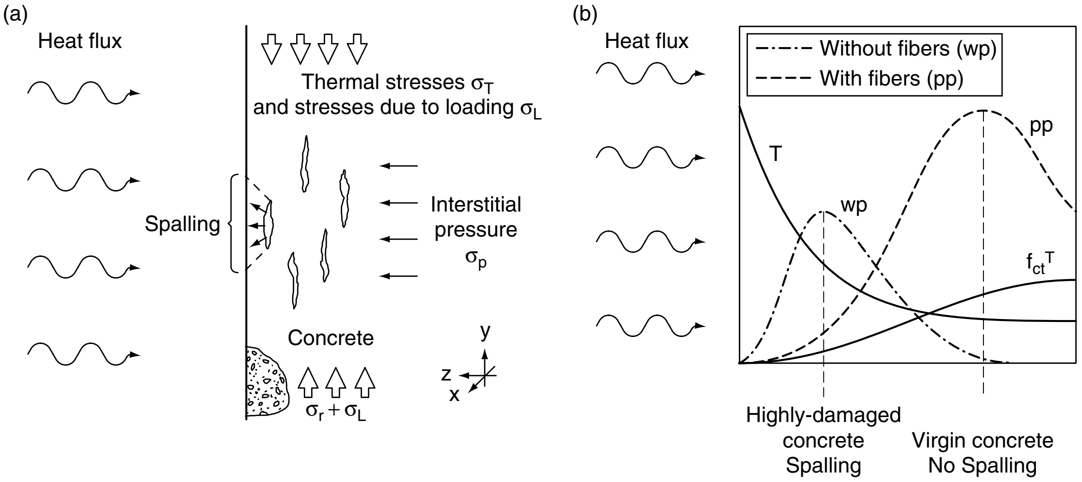


Figure 11. (a) Concrete spalling with load-induced stresses, thermal stresses and pore pressure (Khoury, 2000); and (b) effect of pp fibers according to Jansson and Boström [45]; pp/wp = pore pressure with/without pp fibers; T = temperature; f_{ct}^T = concrete tensile strength.

A second explanation is that pp fibers – by changing concrete thermal properties thanks to the above-mentioned net of microcracks - force the vapor-pressure build-ups to occur farther from the heated surface (Figure 11b). The pressure peaks may even be higher than in plain concrete, but – being in colder regions - they are more effectively resisted by the colder – and mostly undamaged – concrete [45].

Summing up, monofilament polypropylene fibers with 32-micron diameter and 12-mm length, and contents by mass between 1 and 2 kg/m^3 (roughly 0.1 and 0.2% by volume), have the highest ability to counteract explosive spalling.

11. CONCLUSIONS

The extreme variety of concretes available today, resulting from the great improvements and changes occurred in the last twenty years, gives designers and contractors many opportunities to build safer, more efficient and more durable tall buildings, bridges, tunnels, off-shore structures, gasification plants, waste repositories and nuclear facilities – just to cite a few major structures - but at the same time brings in new responsibilities (as it is always the case with multiple choices), and the necessity of investigating the thermo-mechanical properties of the new materials in extreme environmental conditions, as high temperature and fire.

In fact, cements are much finer, their bulk chemistry and mineral characteristics are rather different from those of the past, and supplementary cementitious materials (SCM) are playing an increasing role, that should be encouraged especially for mass concrete.

In terms of high-temperature and fire resistance, the behaviour of the different types of cementitious composites available nowadays can be synthesized as follows:

- Concretes with calcareous or basalt aggregates and blended cement (containing calcareous powders) have enhanced mechanical properties at high temperature.
- High-performance concrete containing polypropylene fibers can be heat-tolerant and spalling-free at high temperature.
- Ultra high-performance micro-concretes with hybrid fibers (polypropylene+steel fibers) have exceptional toughness and strength at any temperature.
- Steel fibers increase concrete toughness and impact resistance; polymeric fibers increase concrete resistance to spalling at high temperature and in fire.
- Light-weight concretes have good insulating and mechanical properties at any temperature.

- Self-compacting concretes are as heat-tolerant as vibrated concretes.
- Shotcrete containing alkali-free accelerating agents is as good as any good ordinary concrete, even at high temperature, with the plus of a lower thermal diffusivity (and higher insulation properties).
- Ordinary and high-performance mortars have better insulation properties than ordinary concrete and a mechanical decay at high temperature that is aligned with that of ordinary concrete; hence, in terms of insulation capability and mechanical strength, the mortar layers of the firewalls made of concrete blocks are definitely not the weakest ring of the resisting chain.

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