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High-temperature behavior of structural and non-structural shotcretes

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ABSTRACT

Sprayed concrete (shotcrete) is well known as a reliable and effective material for rock stabilization, fire proofing of metallic structures and jacketing of R/C members. Shotcrete structural applications, however, have been so far very limited mainly because of some concerns about material's durability and high-temperature behavior. The latter issue is the starting point of this research project aimed to investigate the thermo-mechanical properties of three shotcretes containing different accelerating agents (based on sodium silicates in one mix – C1, and on sulfo-aluminates in two mixes – C2/C2F, no steel fibers/with steel fibers). The objective is to check (a) whether the heat-triggered mechanical decay of shotcrete is similar to that of ordinary concrete, and (b) how shotcrete low thermal diffusivity and relatively large porosity evolve at high temperature.

The mechanical properties in compression are investigated both at high temperature (hot tests, C2 and C2F) and past cooling (residual tests, all mixes).

In terms of normalized mechanical decay, the two shotcretes containing an alkali-free accelerating agent behave similarly to ordinary concrete, while the shotcrete with an alkaline accelerating agent is more heat and age sensitive. Up to 850 °C, all mixes exhibit a markedly lower thermal diffusivity compared with ordinary concrete, and a higher porosity. Furthermore, the rather low mechanical properties of the shotcrete with an alkaline accelerator with respect to the base material make it hardly fit for structural purposes, while the two shotcretes with an alkali-free accelerator are as good as any ordinary concrete even at high temperature, as demonstrated by the basic structural application presented at the end of the paper, concerning the lining of a circular deep R/C tunnel exposed to the standard fire.

1. Introduction and nature of problem

The introduction in the last 15–20 years of *special* cementitious composites and their increasing use in highly-stressed members and in statically-demanding constructions requires the thermal and mechanical properties of these materials to be investigated at high temperature. As a matter of fact, fire is among the most dangerous load conditions, but – besides fire - quasi-steady high temperatures often occur in either incidental or service conditions in many of the structures where special concretes are used or will be used in the next future.

With reference to fire, such structures as tunnel linings (see – for instance – [7,8,24,27]), bridge decks, off-shore platforms, containment shells in chemical plants, and roadways should be mentioned, while high temperature may occur in the containment shells of nuclear power plants, as well as in waste-burning and gasification plants.

Among the *special concretes*, shotcrete should be mentioned, since this material is extensively used in the first-phase lining of blasted tunnels (=*provisional lining*, Fig. 1a) during the excavation process, while its use for the *final lining* is still debated, a major reason of concern being the high permeability of shotcrete [19,28]. Technical and economical reasons are, however, arising new interest for using shotcrete in both first- and second-phase linings, thanks to the better mechanical properties guaranteed by alkali-free accelerating agents (set accelerators) compared with alkaline accelerators. In such a case, water-tightness – that can be improved by adding a polymeric layer between the provisional and the final linings – is no longer the only property to aim at, since fire-resistance is required as well. The same holds for a number of

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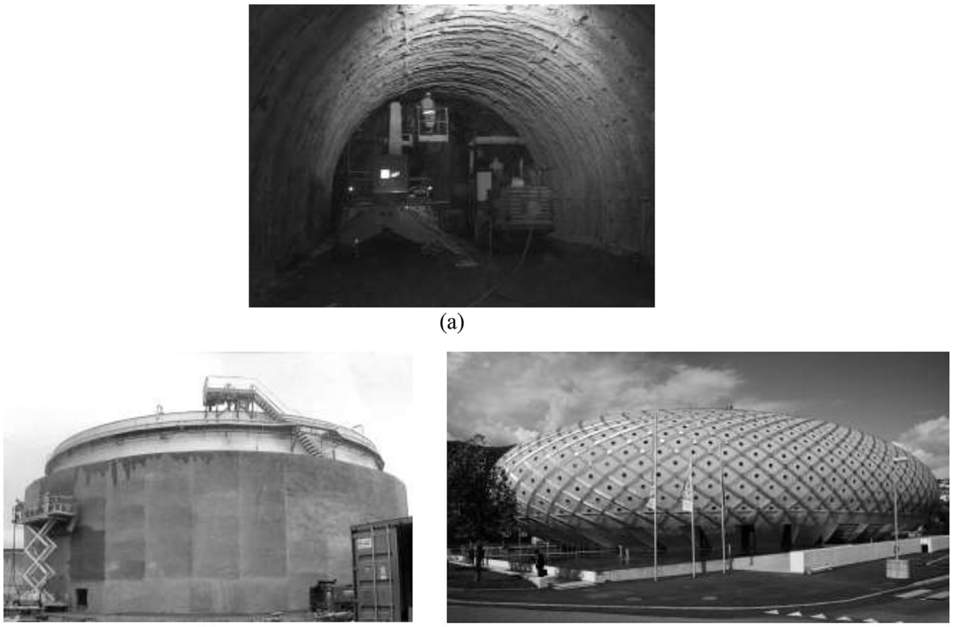
(a)
(b)
(c)

Fig. 1. Typical uses of shotcrete for: (a) rock and soil stabilization in first-phase tunnel linings (courtesy of Turin Subway Ltd, Turin, Italy); (b) strength against flying objects in R/C shields (protection of an oil tank along the French Atlantic Coast; courtesy of Mapei); and (c) Centro Ovale (Chiasso, Switzerland; courtesy of ©Ti-Press).

structural applications, like the thick shells used for protection against impact, blast and fire (Fig. 1b), and the thin prestressed shells used in certain buildings, whenever complicated shapes are at issue and shotcrete is instrumental in casting vertical or sub-vertical parts, for the very simple reason that ordinary concrete would slide away (Fig. 1c; see also [15,18]).

Unfortunately, no information can be found in the literature about shotcrete behavior at high temperature and under fire, since this material has been used so far in non-structural or lightly-stressed members (such as the afore-mentioned first-phase linings of blasted-off tunnels and underground constructions, see Refs. [2,27,28]) and in rock/soil stabilization, where the risk of fire is limited or nonexistent. However, beside tunnel linings, there are certain nonstructural or partially-structural applications, where high-temperature and fire resistance is required, as in the jacketing of R/C members [14].

Being a cementitious material, shotcrete is expected to have a high-temperature thermo-mechanical behavior similar to that of ordinary vibrated concrete [2,19,28], but the larger amount of cement and fine aggregates generally found in shotcrete, as well as the relatively-high content of accelerating agents, may alter the behavior of shotcrete at high temperature and in fire [16,22,25,29].

What matters in fire is not only strength (at high temperature, for the survival of the structure and for the safety of the rescue teams, and past cooling, to facilitate structural rehabilitation), but also toughness and integrity. Toughness allows the lining to resist the concentrated loads caused by rock pressure and is enhanced by small amounts of steel fibers, that are very effective in increasing structural ductility at any temperature [19,20]. Integrity is guaranteed by polymeric fibers, that increase concrete resistance to spalling in fire [9,17]. As a matter of fact, fiber melting and gasification at high temperature creates a network of microcracks, that allows pore pressure in the cement paste to be released. (In shotcrete, however, polymeric fibers are seldom used, because the extraporosity of the cement paste and the entrained air ensuing from the spraying process are very effective in favoring pressure release).

Summing up, to have shotcrete accepted by designers and owners as a structural material, the concerns about permeability and fire resistance should be dispelled.

To have first-hand information on shotcrete high-temperature behavior, a research project has been recently completed at the Politecnico di Milano on three shotcretes sprayed by means of the wet process (Mix C1, no fibers, alkaline accelerator based on sodium silicates, expected strength in compression 15–20 MPa; Mixes C2 – no fibers, and C2F – with steel fibers, both containing an alkali-free accelerator based on sulfo aluminates, expected strength 40–50 MPa).

The attention was focused on the stress-strain curves in uniaxial compression, on the mechanical decay in terms of compressive strength and elastic modulus, on the thermal diffusivity and porosity, and on the heat-induced mass loss, for 6 temperature levels (20, 105, 200, 400, 600 and 750 °C) in residual conditions and 5 in hot conditions ($T \leq 600\,^{\circ}\mathrm{C}$). To compare shotcrete and ordinary concrete, reference was always made to the provisions contained in both ASCE-ACI and European documents.

Beside some cubes cast in steel moulds, all specimens were cored cylinders (Fig. 2), extracted from shotcrete slabs cast in timber moulds in two different building sites. In this way, any possible difference between the shotcrete used in the tests and that sprayed against actual rock walls was minimized.

2. Mix-design and compressive strength of the virgin materials

The shotcretes considered in this project are used in the construction of the first-phase lining of the main tunnel of Turin Automatic Subway (Mix C1) and of the service tunnels of the Railway Brenner Base Tunnel (Mixes C2 and C2F), whose excavation is in progress through the Alps, between Italy and Austria. In the latter case, the service tunnels are bored by rock blasting, to connect the building sites to the pilot tunnel (now under construction) and later to the two shafts of the main tunnel (54 km-long, expected end of the construction 2025). On the contrary, the pilot