ON THE THERMO-MECHANICAL CHARACTERIZATION OF CEMENT MORTARS EXPOSED TO HIGH TEMPERATURE

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Abstract

Some recent technical documents on fire-resistant walls made of either cementitious blocks or clay bricks are bringing onto the stage the thermo-mechanical behavior of the mortars. Information on mortars decay at high temperature, however, is either contradictory or can hardly be found in the technical-scientific literature. This study aims to provide information on the thermo-mechanical behaviour of mortars in residual conditions. Three mortars are investigated (a *reference* mortar, cube strength $f_{cc} \approx 5$ MPa, and two higher-grade mortars, $f_{cc} \approx 10$ MPa and $f_{cc} \approx 15$ MPa, respectively). All mortars are tested past a high-temperature cycle at 200, 400 and 600°C. On the whole, the mechanical decay turns out to be very close to that of typical ordinary concretes, while the thermal diffusivity is markedly lower. A worked example about a concrete-block fire-resistant wall ends the paper.

Keywords: mortars, residual tests, mechanical properties, thermal diffusivity.

INTRODUCTION

Increasing attention has been devoted in the last years by the scientific and professional communities, and by code makers, to the risk of fire and high temperature in constructions, and to the ensuing detrimental effects on structural safety. In most cases, however, the structural damage due to a fire is more or less limited, especially in concrete and masonry structures, and people are more endangered by the smoke (in the early phases of a fire, when temperatures are still rather low) than by the weakening of the bearing structure.

Focusing on human safety, and leaving aside the structural behaviour as such, compartmentation is a major issue (= subdivision of the space inside a building into a number of sub-spaces, so that the fire and its effects remain confined to a single compartment).

Compartmentation is generally achieved by means of 2-D load-bearing or non-load bearing members (slabs, floors, partitions and walls, or windows and doors), whose compartmentation capacity requires two fundamental criteria to be met for any fire duration (Buchanan, 2002):

- Criterion E = Integrity: the given member should exhibit no cracks, no spalling, no excessive out-of-plane displacements, no disconnections along the boundaries, to avoid flame, gas and smoke transmission to nearby compartments.
- Criterion I = Insulation: the given member should limit heat transmission, from the internal hot surfaces (exposed to the fire) to the external cold surfaces, in order to avoid any spread of the combustion.

To meet Criterion E laboratory tests are required, as there are no other means to ascertain whether smoke and flames pass through walls or floors (due to cracking, open joints, ….).

Meeting Criterion I implies that any given member used in compartmentation should keep the average differential temperature between the hot surface and the cold surface, and the maximum differential temperature below certain limits, for any given fire duration ($\Delta T_{av} \leq 140$°C and $\Delta T_{max} \leq 180$°C, according to Eurocode 2 – EN 1992-1-2).

As for *stability* or *resistance* (Criterion R), meeting this criterion requires the preliminary determination of the thermal field inside the structural member, under one of the more or less realistic fire curves specified by the codes. Knowing the thermal field allows evaluating the mechanical decay of the material in each point, provided that materials mechanical properties at high temperature – and past cooling – are known. Then structural analysis makes it possible to assess the loss in terms of bearing capacity and to check whether the actual reduced bearing capacity guarantees an adequate safety level face to the loads applied in fire conditions (Bamonte et al., 2008).

Among the most common structures used in compartmentation, fire-resistant walls take the lion's share, especially in industrial buildings (Dal Lago, 2002). Firewalls generally consist of hollow bricks made of concrete (vibrated under pressure) or clay, with mortar layers interposed along the vertical and horizontal joints. The compartmentation capacity is partly due to the good insulating properties of the materials (concrete, clay and mortar) and partly to the voids of the blocks or bricks.

Within this context, the thermo-mechanical characterization of three commercial cementitious mortars is performed in this paper, in order to assess their compatibility with the properties of ordinary concrete, often used in the manufacture of hollow blocks. The three mortars, called "M5", "M10" and "M15" throughout the paper, belong to the classes M5, M10 and M15 of the Italian standard, with $f_{cc} \approx 5$, 10 or 15 MPa, respectively. Furthermore, M5 can be considered as a reference mortar, in spite of its fibre content (polypropylene fibres, $v_f = 0.1\%$ by volume), while M15 is a high-strength mortar.

1 EXPERIMENTAL PROGRAM

The thermo-mechanical characterization of any cementitious material generally requires the evaluation of such parameters as compressive strength, tensile strength, elastic modulus, mass per unit volume and thermal diffusivity as a function of the temperature (Felicetti and Gambarova, 1998; Bamonte and Gambarova, 2010).

In this project, twenty-four cylindrical specimens were required by the tests in compression and for the evaluation of the elastic modulus ($\varnothing \times h = 80 \times 160$ mm). Three further cylinders ($\varnothing \times h = 100 \times 300$ mm) were instrumented with two thermocouples each, to evaluate the thermal diffusivity.

All cylinders were stored for 28 days in quasi-sealed conditions at 20-25°C and 60-70 R.H. (The cylinders were left inside plastic pipes, without plugs at the extremities). Later, the specimens were sawn at the desired length and the end sections were ground and polished.

The same curing process was adopted for the prisms to be tested in bending (40 × 40 × 160 mm). The two stumps resulting from the fracture of each prism were tested in compression, to evaluate the cube compressive strength.

In Fig. 1a) one of the three specimens instrumented for the evaluation of the thermal diffusivity is placed inside the electric furnace, whose heating rate is controlled via a proportional integro-differential procedure. The uniformity of the thermal field is guaranteed by a steel pipe, whose temperature is the control parameter of the furnace.

Tab. 1 Main properties of the mortars

Lime, cement and siliceous aggregate (0-4 mm)	see EN 13139 (2006)
Soluble chloride	≈ 0.05%
Mass per unit volume (fresh/hardened state)	≈ 2000/1850 kg/m^3
Thermal conductivity (hardened state)	0.80-0.90 W/m°C

2 THERMAL CHARACTERIZATION

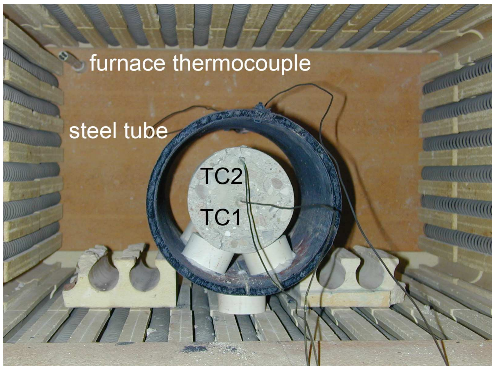
The thermal diffusivity is defined as: $D = \rho/(c\ \lambda)$, where λ is the thermal conductivity, c is the specific heat and ρ is the mass per unit volume. In a long cylinder ($h \geq 2\varnothing$) subjected to a constant heating rate (v_h = mean heating rate inside the specimen), the thermal diffusivity can be evaluated by means of the following equation:

$$D = v_h R^2/(4 \Delta T) \quad (1)$$

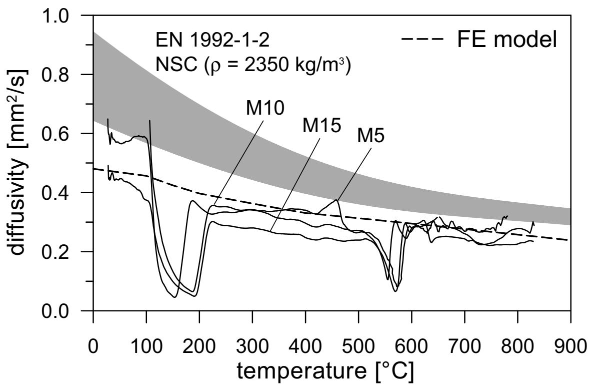
where $\Delta T = T_2 - T_1$ is the difference between the temperatures measured close to the heated surface and along the axis in the mid-height section, and R is the distance between the two measurement points (Fig. 1a).

Each of the three cylinders instrumented with 2 thermocouples was slowly heated from 20 to 900°C, and T_1 and T_2 were measured at regulars intervals. As shown in Fig. 1b, between 200 and 550°C the thermal diffusivity of the three mortars is roughly constant (= 0.25-0.35 mm^2/s) and by 30-35% lower than that of ordinary concrete, represented in Fig. 1b by the grey envelope. Hence, ordinary and high-strength mortars never act as thermal bridges in a firewall, thanks to their good insulation properties.

Water vaporization in the pores and crystalline changes in the quartz contained in the aggregate are responsible for the downward spikes at 150-200°C and 550-600°C, respectively. Below 100-150°C and above 700°C the values are dubious because of the thermal transients and of calcination (= dissociation of calcium carbonate), respectively.



(a)



(b)

Fig. 1 (a) Cylinders inside the electric furnace instrumented with 2 thermocouples (TC1 and TC2); and (b) thermal diffusivity versus temperature

3 RESIDUAL COMPRESSIVE STRENGTH

Twenty-four cylinders (diameter × height = 80 × 160 mm) were tested in compression in displacement-controlled conditions, with the mortars either undamaged (T = 20°C) or past a thermal cycle (T = 200, 400 and 600°C). For each mortar and temperature, two tests were carried out, all characterized by an outstanding repeatability.

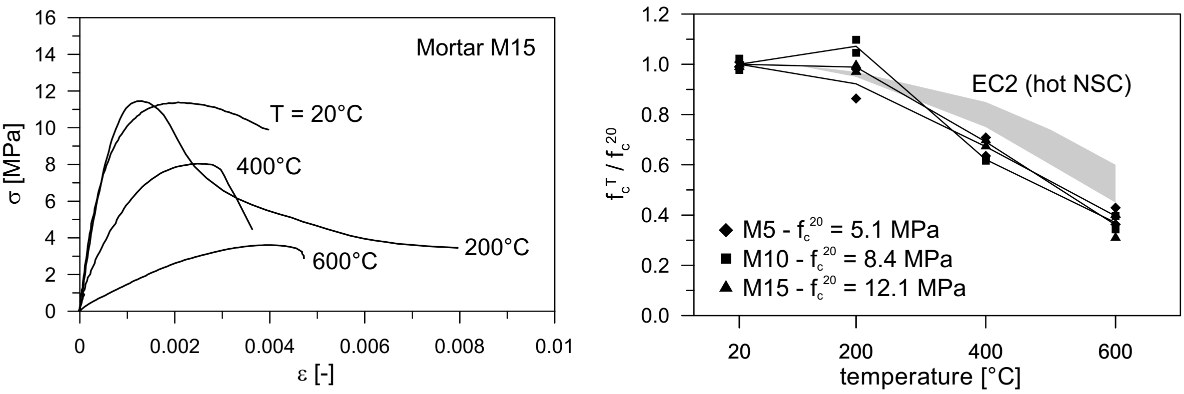
The thermal cycles were performed in quasi-steady conditions to guarantee the uniformity of the thermal field, and to avoid any self-stress. The heating/cooling rate and the rest at the reference temperature were 1.0/-0.25°C/minute and 120 minutes.

The displacement rate adopted in the tests was 2.5 μm/s (up to the peak load), 5.0 μm/s in the softening branch down to 50% of the peak load and 10.0 μm/s down to the crushing of the specimen. All specimens were instrumented with 3 LVDTs placed at 120° astride the mid-height section (L = 50 mm), to measure the shortening of the specimen and to make the drawing of the stress-strain diagrams feasible (Fig. 2a). Though rather low, the values of the cylindrical strength at 20°C (f_c = 5.1, 8.4 and 12.1 MPa) agree with producer's indications on small cubes (f_{cc} = 8, 14 and 17 MPa) and with the tests performed by the authors on small cubes (f_{cc} = 8.5, 16.1 and 18.0 MPa, not shown in the following), provided that the differences between small cubes (side = 40 mm) and rather large cylinders (h = 2∅ = 160 mm) are taken care of (in terms of size effect and platen-to-cube friction), and between curing in a controlled environment and in quasi-sealed plastic pipes, as done in this project.

Mortar M15 appears to have the best performance at any temperature, Fig. 2a. (At 600°C the residual strength of Mortar M15 is twice as much that of the reference Mortar M5).

In terms of normalized compressive strength (Fig. 2b), M10 and M15 behave somewhat better than M5 up to 300°C, while there are no practical differences above 400°C. The most important indication given by Fig. 2b, however, is that at any temperature mortars decay is very close to that of ordinary concrete (shaded envelope referring to hot concrete: mortars curves are lower as it should be, because they are residual curves, always lower by 15-25% compared to hot curves). As in certain concretes, the strength increase up to 250-300°C is nothing new, but – as in concretes – it is of no practical relevance.

Summing up, the strength decay similar to that of ordinary concrete is a clear indication that in any walls made of concrete blocks mortar layers are not the weakest link of the resistant chain.



(a) (b)

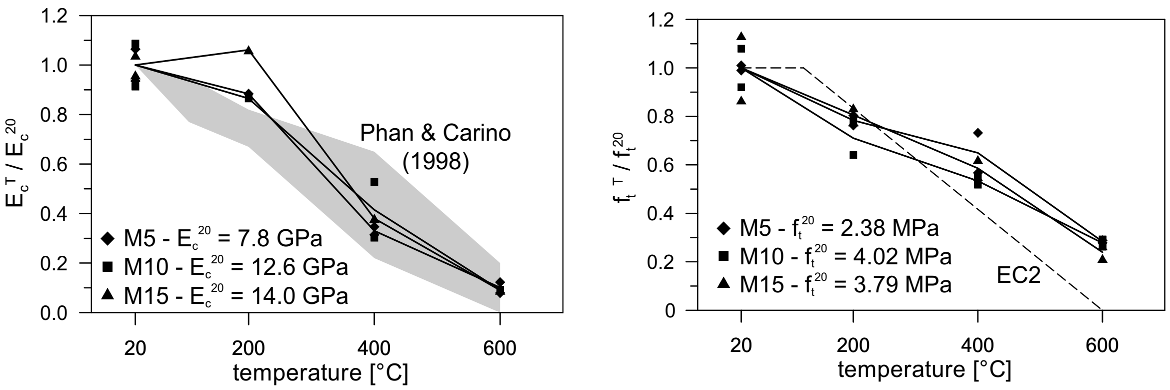
Fig. 2 (a) Stress-strain curves for the high-strength mortar M15; and (b) normalized plots of the cylinder strength as a function of the temperature; the gray band refers to EC2 provisions at high temperature, for calcareous (top curve) and siliceous (bottom curve) aggregates

4 RESIDUAL ELASTIC MODULUS AND TENSILE STRENGTH IN BENDING

The secant modulus was evaluated starting from the stress-strain curves, in the stress range 30-50% with respect to the peak of the stress-strain curves.

The values at 20°C are very low compared to those of ordinary concrete, something well known for mortars (Neville, 2002; see the values indicated in the insert of Fig. 3a).

The normalized curves (Fig. 3a) show that the decay of the modulus of M15 is the least up to 300°C; beyond this temperature, the values of the three mortars are very close and similar to those of ordinary concrete (grey envelope). Up to 200°C, however, the mechanical decay of the mortars is even lower than that of ordinary concrete, as shown by the grey envelope (Phan and Carino, 1998).



(a) (b)

Fig. 3 (a) Normalized plots of the secant elastic modulus as a function of the temperature; (b) plots of the normalized strength in tension by bending as a function of the temperature

The tensile strength was measured by testing in bending a number of prisms (40 × 40 × 160 mm) loaded at mid-span, in agreement with the Italian standard UNI EN 1015-11. The normalized curves (Fig. 3b) are very close and exhibit a rather linear decay with the temperature. As a reference, the normalized decay of the direct tensile strength of ordinary concrete at high temperature (from EC2) is reported as well in Fig. 3b. On the whole, above 250°C mortars seem to be less affected by high temperature. Such fact, however, may be more apparent than real, because the specimens loaded in direct tension and those loaded in indirect tension by bending behave differently at collapse, something that is well known.

5 APPLICATION

A rather simple example is worked out in the following to demonstrate that the three mortars in question allow Criterion I to be met in a typical fire-resistant wall made of concrete blocks.
Let us consider a block-type firewall, whose lateral view and cross section are indicated in Figs. 4a,b. The nominal dimensions of the blocks are L × h × b = 500 × 200 × 180 mm; the thickness of the front and back plates of each block, as well as that of the ribs, is 30 mm; the thickness of the mortar layers is 20 mm. Because of the symmetries of the problem, only the shaded portion (Fig. 4a) is considered in the 3D thermal analysis (extended to 150 minutes). The boundary conditions of the thermal problem are indicated in Fig. 4b.
A preliminary analysis (A0) was performed assuming the walls of the voids to be perfectly adiabatic, and the mean temperature of the walls was worked out as a function of the fire duration : $T_{AV} = F_0(t)$. Then, in the first analysis (A1) the average temperature in the voids was introduced through the function $F_0(t)$, and the updated time-evolution of the mean temperature of the walls was worked out: $T_{AV} = F_1(t)$. A second analysis was started having $F_1(t)$ as imposed mean temperature in the voids, and again the updated time-evolution of the mean temperature of the walls was worked out: $T_{AV} = F_2(t)$. A third analysis was performed and so on. After a rather limited number of analyses (n = 3), the perfect coincidence of the imposed mean temperature in the voids $F_{n-1}(t)$ with the actual mean temperature $F_n(t)$ allowed to stop the iterative process, since the solution had been reached.
The thermal analysis was performed by giving the concrete the thermal properties indicated in EC2 and the mortar those found in this project (mass per unit volume, not plotted in this paper, and diffusivity, see the dashed curve in Fig. 1b). As for the thermal conductivity of the mortar, the values indicated by the producer at 20°C were adopted (= 0.80 W/[m×K]), while its temperature dependence was assumed to be the same as in concrete. In the analysis, 3D tethraedric finite elements were used within the code ABAQUS.

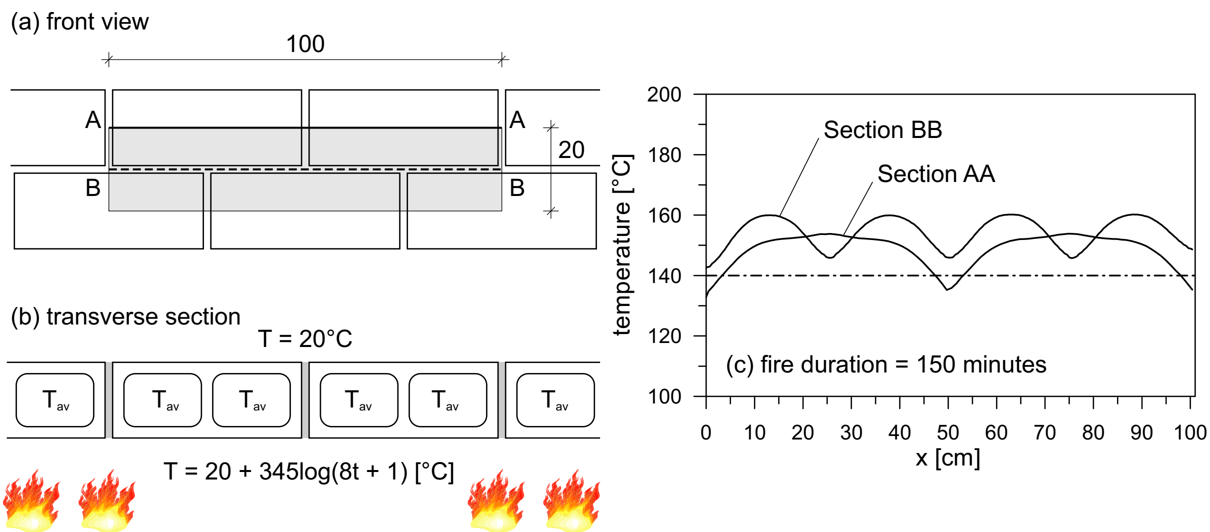


Fig. 4 (a) Portion of the fire wall discretized by finite elements; (b) boundary conditions of the thermal problem; and (c) plots of the temperature in Sections AA and BB along the cold face, for a fire duration of 150 minutes (the dash-dotted line refers to a 180 mm-thick concrete wall)

The results of the analysis are summarized in Fig. 4c, where the cold-face temperature is plotted along AA (thick curve) and BB (dashed curve), see Fig. 4a, 150 minutes after the beginning of the standard fire. (As the thermal properties and the mass per unit volume are very close for the three mortars, the analytical values hold for all three mortars).
In both sections AA and BB, assuming 20°C for the initial temperature of the cold face, the mean temperature at the cold face (T_{av} = 148 and 154°C) is below 140 + 20 = 160°C, and the maximum local temperature (T_{max} = 154 and 160°C) is below 180 + 20 = 200°C. (Note that the maximum temperature is reached in correspondence with the brick cavities, and not in correspondence with the vertical concrete ribs and mortar layers). Hence the system hollow blocks + mortar layers meets Criterion I, for a fire duration of 150 minutes. For the same fire duration, should the 180 mm-thick wall be made of solid concrete, the temperature at the cold face would be close to 140°C (dash-dotted line in Fig. 4c).

6 CONCLUDING REMARKS

The residual tests carried out on three cementitious mortars (M5, M10 and M15) exhibiting a cube strength in excess of 5, 10 and 15 MPa confirm their good thermo-mechanical properties at high temperature ($T \leq 600°C$), in terms of thermal diffusivity, compressive strength on cubes and cylinders, secant elastic modulus and tensile strength by bending. In detail:

- The three mortars exhibit a thermal diffusivity lower – on the whole – than that of ordinary concrete (from -25 to -40%), which is an indicator of the high insulation properties of the mortars.
- The two higher-grade mortars (M10 and M15) have definitely better residual-strength properties in compression than the reference mortar (M5), at any temperature; the normalized curves, of the compressive strength, however, are very close and rather similar to those of ordinary concrete, up to 600°C, while the normalized curves of the secant elastic modulus are very close, and better than those of ordinary concrete below 200°C; at higher temperatures, mortars are aligned with ordinary concrete.
- In terms of residual strength in indirect tension by bending, the three mortars behave similarly to ordinary concrete.
- The thermal analysis of a firewall made of hollow concrete blocks and mortar layers show that the better insulation properties of the mortar offset the thermal bridge created by the continuity of the layers across the wall; hence, mortar layers are never the weakest link of the chain in terms of strength (Criterion R) and insulation (Criterion I).

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