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Use of coal fly ash in a sprayed mortar for the passive protection against fire of metallic structures

Luis F. Vilches Arenas, Constantino Fernández-Pereira, Carlos Leiva Fernández, Joaquín Olivares del Valle and José Vale Parapar

University of Seville, School of Industrial Engineering, Department of Chemical and Environmental Engineering, Camino de los Descubrimientos s/n E-41092 Seville, Spain.

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1. INTRODUCTION

Passive fire protection protection can be understood as a series of rational construction measures that are taken in order to lessen the possibility of a fire starting, prevent its spreading, and ensure the stability of a facility until the fire is controlled and extinguished. A construction element is fire resistant during the time, expressed in minutes, that the said element maintains the following qualities when subjected to a standard fire resistance test (which is supposed to try to reproduce the changes in temperature in time during a real fire): it remains stable, does not spread, does not emit flammable gases and is thermally insulated[1].

The standard fire resistance test described in Spanish Regulation UNE-23.093[2], which is the most widely-used, corresponds to the equation:

$$T = 20 + 345 \cdot \log_{10}(8 \cdot t + 1)$$

where T is the temperature of the test oven in ºC and t, the time in minutes from the beginning of the test.

1.1. Protection of metallic structures

Metallic profiles, which are so versatile and resistant when designing supporting structures, have the disadvantage of being vulnerable to fire. In regard to fire security measures[3-5], about 550ºC is considered the minimum critical temperature for structural elements, which reach that temperature in five minutes in the standard fire resistance test; considering how good a thermal conductor steel is, unprotected elements will hardly take that long to reach that temperature, thus producing a problem with stability.

The speed at which metallic elements heat up in a fire depends on two factors: the shape factor (exposed surface/volume) and the type and nature of the protection.

When the method of protection consists in placing a material between the steel element and the fire (whether sprayed mortar or panels), the choice of material is important. Not only must it be a good insulator, it has to maintain its integrity under intense heat in case of a fire. Whether it is fixed to the structure or sprayed, the way joints come together, etc. must all be carefully thought out in the design and then executed meticulously.

2. EXPERIMENTAL

2.1 Wet gunite pilot plant

To study the possible application of fly ash in sprayed mortars used in passive fire protection, a gunite pilot plant was designed to wet-spray the insulating materials. Figure 1 gives a general view of the plant.

Figure 1. General view and location of the gunite pilot plant

The elements that comprise the pilot plant are the following:

Mixer

This consists of a vertical-axis hopper/mixer on a metallic structure, whose purpose is to mix the different materials in previously established amounts, as well as to discharge the material into the means of transport when the lockgate at the bottom of the hopper is opened. The volume of the mixer is 50 L so that it can project 1-m^2 surfaces up to about 5 cm thick. The mixing system consists of a series of teflon rods at a 45º angle, attached to the arm, which rotates around the axle by means of a 1.5-kW, variable speed motor (0-50 rpm).

Drive Pump

In order to pump the paste from the mixer to the spray nozzles, we chose a volumetric, positive displacement pump with the following characteristics: a flowrate of 10-150 L/h, adjustable by means of a manual regulator; a propulsion pressure of 4 bar and 0.4 kW of power.

Air Regulation System

The laboratories' central air supply system was used, which supplies an air flow of 80 m^3/h at a service pressure of 11 bar. The air pressure at the entrance of the nozzles was 3 bar; there was a manual regulator set at that pressure at the air injection in the laboratory where the tests were carried out.

Spray nozzles

The recommendations of different authors for the atomization of high viscosity fluids, such as the mortars tested in this study, were taken into account when designing the nozzles; pneumatic atomizers were decided to be best for this type of paste. Of these, the internal mixture pneumatic atomizers produce the most complete air-paste mixture. The critical elements that guarantee that they work well are the air injection device in the nozzle, the air-paste mixing system, and the shape and size of the nozzle tip[6]. Thus, two air-injection devices with the following characteristics were designed:

- Coaxial air injection (B-1), in which the air is injected into the paste flow by means of a coaxial tube inside the atomizer. The air discharge nozzle was designed in order to be able to test different diameters.

- Transverse air injection into the paste flow channel (B-2) by means of tangential openings that create a helicoidal movement of the air-paste mixture. The air drags the paste along and forces its dispersion as a result of the turbulence created by the helicoidal movement of the air.

The nozzle tips were designed with different lengths and diameters since the characteristics of the dispersion may be influenced by loss of the force of the air and by the velocity at which the mixture leaves the nozzle. 100-mm-long nozzle tips with an output diameter of 10 and 20 mm were used for the coaxial air injection opening, while 180-mm long nozzle tips with an output diameter of 10 and 20 mm were used for the transverse air injection opening. With these dimensions output velocities of up to 90 m/s and air-mass and paste-mass relationships of up to 5 can be tested.

Spraying System

The pastes were sprayed onto a concave surface of approximately 1 m^2 on which the plates and profiles to be covered were fixed. In order to prevent spattering, this device was covered with a wooden structure, enclosed by three perpendicular panels and a sliding cover on top.

2.2. Spraying Procedure

There are many factors that can influence the final characteristics of the wet-sprayed mortars, e.g. the nature of the materials that comprise the paste (binders, fillers and additives), the type of mixer and pumping equipment and their operating conditions, the type of nozzle used, and other environmental conditions. Given the great number of variables that come into play in the process, and as all the variables must be optimized in each machine since they cannot be extrapolated from one machine to another, we tried to eliminate the effects of some of them by making experimental levels for some variables constant. Thus, in order to reduce the number of tests, the following factors were considered constant:

- We worked with a single composition and always with the same proportion of FA (more than 70% w/w), ordinary Portland cement, vermiculite and other additives. Fly ash coming from Los Barrios power plant in the South of Spain was used in this project.

- The paste was kneaded in the mixer for exactly 5 minutes with a constant proportion of water at ambient temperature.

- We worked with the maximum paste and air flows (paste flow: 100 L/h; air flow: 80 m^3/h) with a discharge air pressure of 3 bar at the nozzle. This meant that in all the tests, the air/mass proportion was constant at approximately 2.5.

- We sprayed at a constant distance of 1 m and always perpendicular to the sprayed surface.

- We sprayed onto carbon steel profiles and plates that had neither undergone any surface treatment nor been cleaned previously.

2.3. Properties of the Sprayed Product

The machine described in Section 3 was used to determine the properties of the sprayed mortar. The B-2 injection nozzle was used with a 180-mm-long nozzle tip with discharge diameters of 10 and 20 mm; 28 x 18-cm plates and 10-cm-long IPN80 and HEB100 profiles were sprayed, as shown in Figure 2.

Plates Profiles

Figure 2. Metal plates and profiles covered by means of guniting

Mechanical Properties

Table 1 shows the results obtained in mortars sprayed onto plates for the diameters of the nozzle tips used; it also shows the results of the same product conformed by simple compaction.

Conformation	**ρ (kg/m3)**	**σ_c (kPa)**	**Adhesion/Cohesion (kPa)**	**Porosity Total (%)**
Simple compaction plates	880	870		
10-mm nozzle tip	688	470	1.7	64
20-mm nozzle tip	539	160	2.6	71

Table 1. Physical properties of sprayed plates and comparison with simple compaction plates

From the above table, we can conclude the following:

- The discharge velocity affects the physical properties of the material; note how at a lesser velocity (20-mm nozzle tip) lower densities (ρ) are obtained as well as lower resistances to compression (σ_c).
- The guniting operation confers clearly different properties on the product, as can be observed by comparing the gunited product with the same product obtained in the form of plates conformed by simple compaction. Guniting considerably reduces both the density of the product and its mechanical resistance.
- All of the problems in the adhesion/cohesion test (ASTM E 736-86)[4], had to do with adhesion; i.e., the product remained cohesive.

Insulating Properties of the Sprayed Product

A. Sprayed plates

The sprayed plates were subjected to the standard fire resistance test. The temperature was registered by a thermocouple placed between the sprayed mortar and the metal plate. Figure 3 shows the results.

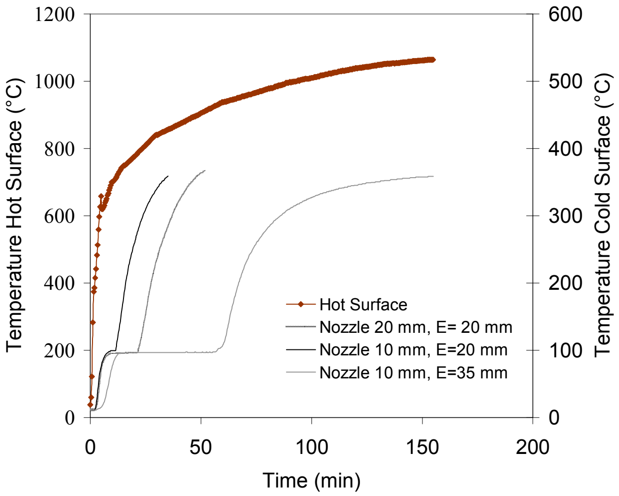

Figure 3. Thermal behavior of the sprayed plates

Based on the above chart, we can conclude the following:

- The samples present a rough surface texture (more normal in mortars sprayed at a higher velocity, i.e. those obtained with the 10-mm nozzle tip), which makes defining a medium thickness for the plates difficult (see Figure 4). Despite this, the plates obtained with the 10-mm nozzle tip present a lower evaporation plateau, perhaps due to the difference in porosity (density) between the mortars obtained with the different nozzle tips. Thus, greater water vapor-air mixture pressure gradients could be generated in the less porous samples (10-mm nozzle tip), which would cause the evaporation plateau to last less time[7, 8].

10-mm nozzle tip

20-mm nozzle tip

Figure 4. Superficial appearance of the sprayed plates

- Much higher evaporation plateaus were achieved in the thicker samples, with values of nearly 60 minutes for a thickness of approximately 35 mm.

Finally, the mechanical stability of the sprayed product after the thermal test should be noted. It was consistent and no fissures or cracks were detected.

B. Sprayed / gunited profiles

In order to analyze the insulating properties of the sprayed mortar, the paste was sprayed onto one of the sides of IPN80 and HEB100 profiles (both with high exposed surface/volume relationships) with the 20-mm nozzle tip. The rest of the sides of the profile were covered with insulating plates made of the same material, but conformed by simple compaction, so that the two types of profiles were protected on all sides by an insulating layer with a thickness of 2 and 3 cm, respectively. To achieve this, it was necessary to manually reduce part of the sprayed material. Figure 5 shows the results obtained, compared with those obtained with the same profiles completely covered with plates (casing). For the gunited profiles, the temperature of the steel was only recorded on the side containing the sprayed mortar.

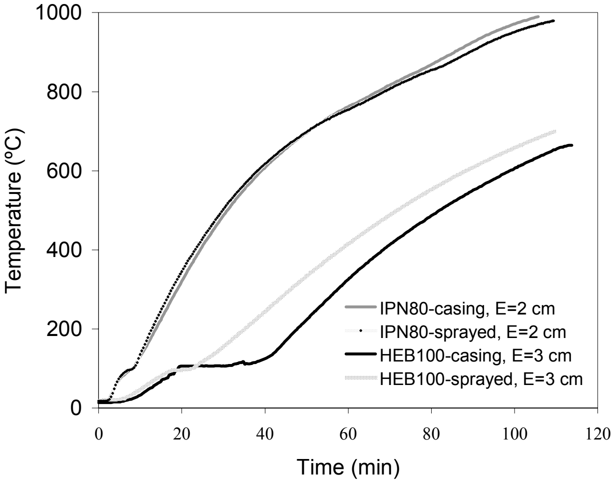

Figure 5. Comparison between the effect of the sprayed mortar and the plated mortar

In the above figure, we see how for 3-cm thicknesses, the evaporation plateau of the sprayed profile is noticeably lower. This is because the sprayed mortar is less dense and thus contains relatively less water. In order to achieve the same insulation for this profile, the sprayed mortar would either have to be thicker or denser.

The thermal conductivities measured (according to regulation UNE 23820 EX[9]) are similar (0.248 and 0.240 W/m·K for the plated and sprayed profiles, respectively). We see that the sprayed product is slightly less conductive at higher temperatures, probably due to its greater porosity, while the plated product is less conductive at lower temperatures as a result of the positive contribution of the evaporation plateau.

RESULTS AND CONCLUSIONS

The insulating properties determined for the product under study indicate that mortars made with fly ash can possess properties similar to or even better than some of the commercial products currently used in passive fire protection. Based on the results obtained, we can be certain that the mortar tested can be used for the protection of metallic structures, whether enclosed by plates or sprayed.

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