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Electrical and thermal characterisation of cement-based mortars containing recycled metallic waste

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ABSTRACT

The management and disposal of solid waste from industrial sources is a problem around the world. In recent years, several studies have been carried out to develop advanced construction materials based on the waste valorisation. As a result, building materials with self-healing and self-monitoring properties have been developed using electrically conductive metallic waste. Nevertheless, the addition of metallic waste may influence the electrical and thermal performance of the new building materials. This paper aims to evaluate the effect of the type and content of metallic waste (steel fibres and steel shavings) on the volumetric, electrical, and thermal properties of cement-based mortars designed with self-monitoring purposes. Physical, electrical, and thermal properties of cement-based mortars with four different contents of metallic waste were evaluated by measuring their bulk density, porosity, electrical resistivity, and thermal conductivity. In addition, metallic waste distribution inside the mortar specimens was measured by ultrasonic tests. All the properties were measured on specimens at two curing ages, 7 and 28 days. The main results showed that the addition of metallic waste produced a reduction of the bulk density and an increase of the porosity of cement-based mortars. Furthermore, it was proven that it is possible to evaluate the metallic waste distribution inside the mortars by ultrasound, and that this evaluation is more effective in specimens with fibres than in those with shavings. Likewise, it was proven that metallic waste can modify the electrical resistivity and the thermal conductivity of mortars, regardless of the type and amount of metallic waste. Finally, it was concluded that both the type and amount of metallic waste, and the curing time used in this research did not present a significant influence on the variation of the electrical resistivity and thermal conductivity of the evaluated cement-based mortars.

1. Introduction

Cement-based mortars are construction materials composed of cement, fine aggregates, and water. These composite materials are widely used in civil engineering due to their physical, mechanical, and thermal properties (Mindess et al., 2002). Nevertheless, the adverse environmental conditions, such as: freeze-thaw cycling (Cao and Chung, 2002), sulphates attack (Zhutovsky and Hooton, 2017), and contact with acids (Koenig and Dehn, 2016), combined with the external loads (Çavdar, 2014) can produce a reduction in their durability over time. With the aim of improving the mechanical resistance and durability of cement-based materials, different reinforcement additives (Brandt, 2008) such as crushed particles or fibres (Yoo et al., 2013) can be added to the cement-matrix (Bentur and Mindess, 2007). Some of these types of reinforcements are natural fibres (Pacheco-Torgal and Jalali, 2011), carbon fibres (Norambuena-Contreras et al., 2016), synthetic fibres (Quadir et al., 2016) and metallic fibres (Martinelli et al., 2015; Sengul, 2016).

Nonetheless, because of the high cost of commercial fibres and the need to dispose of solid waste from industrial sources, several studies have been carried out in recent years with the aim of developing innovative cement-based materials with advanced properties (Kim et al., 2014) by means of the valorisation of waste

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(Nagy et al., 2015). With this purpose, authors such as Chung (2012), Meehan et al. (2010) and Nguyen et al. (2015) focused on developing advanced cement-based materials with crack self-monitoring properties through the addition of electrically conductive fibres to the cement matrix and the measurement of electrical resistance variations in the composite material, as a physical indicator of material damage by cracking. Additionally, other studies have evaluated the use of metallic waste to develop cement-based materials with self-healing (Kim et al., 2014) and thermal-energetic (Corinaldesi et al., 2011) purposes with applications in industrial floors (Nagy et al., 2015) and thermo-solar plants (Girardi et al., 2017).

Furthermore, considering that the addition of metallic waste may also modify other properties of the cement-based materials, several studies have analysed the influence of solid waste on the physico-mechanical, thermal, and electrical properties of cement-based materials. For instance, Norambuena-Contreras et al. (2016) evaluated the effect of the addition of carbon powder waste on the physical and mechanical properties of cement pastes, resulting in a decrease in the bulk density and an increase in the porosity of materials, also affecting their mechanical properties. Nagy et al. (2015) compared the use of metallic and synthetic fibres in concrete, concluding that concrete with steel fibres presented higher values of bulk density and thermal conductivity than concrete with synthetic fibres. Similar results were reported by Corinaldesi et al. (2011) evaluating cement-based mortars but reinforced with rubber particles as waste.

On the other hand, Girardi et al. (2017) found that the thermal conductivity of concrete reinforced with metallic waste was double that of the reference material when adding a volume of 1% of waste. Khaliq and Kodur (2011) studied the influence of the fibre typology and the temperature on the thermal properties of concrete. Adding fibres of polypropylene, steel, or both, they concluded that steel fibres increased the thermal conductivity, while polypropylene fibres reduced it. Banthia et al. (1992) analysed the influence of the content of carbon and steel fibres on the variation of the electrical resistivity of cement pastes, concluding that the higher the percentage of fibres added, the lower the registered electrical resistivity. In this context, Lataste et al. (2008) and Solgaard et al. (2014) concluded that the variation of the electrical properties of cement-based materials with metallic fibres depends on the amount and morphology of the added fibres, and also on their physico-mechanical properties and distribution inside the material.

The current literature has identified some effects of the metallic waste on the cement-based materials. Nevertheless, there are still many open research questions that need to be addressed with the aim of understanding the phenomena associated with cement-based materials containing recycled metallic waste. For example, the effect on the properties of cement-based mortars of adding more than one type of metallic waste is not yet clear. Another less researched area concerns the optimum contents and types of metallic waste to yield cement-based composites with crack self-monitoring properties.

This paper has been prepared in the frame of a research project focused on the development of advanced cement-based mortars with crack self-monitoring purposes by the electrical conductivity control through the material. For this reason, electrically conductive metallic waste was mixed into the cement-based mortar. The main objective of this paper is to evaluate the influence of the type and amount of metallic waste on the volumetric, electrical, and thermal properties of cement-based mortars. To this end, nine different cement-based mortars with the same water/cement ratio but with two different types of metallic waste (steel fibres and steel shavings) added in four different contents (ranging from 4% to 16% by cement weight), were manufactured and evaluated at two different curing times (7 and 28 days).

2. Materials and methods

2.1. Materials

The raw materials used for the manufacturing of cement-based mortars were: Portland-Pozzolana Cement type IP (ASTM C595/C595M-16) with density 3.09 g/cm^3, fine sand (size between 0.15 and 2.0 mm) with density 2.81 g/cm^3, and a polymer synthetic-based superplasticiser with density 1.08 g/cm^3 (from Sika S.A. Chile). Gradation (ASTM C33-07) and physical properties (ASTM C128-01) measured for the fine sand used are shown in Table 1. Additionally, two electrically conductive types of metallic waste from industrial sources were mechanically cut and added to the cement-based mortars: steel wool fibres (Fig. 1(a)) and steel shavings (Fig. 1(b)). Steel fibres were composed of low-carbon steel, with a density of 7.180 g/cm^3 and an average electrical resistivity of 2.23×10^{-5} Ωm. These fibres had an average diameter of 0.133 mm (Fig. 1(c)), with an average aspect ratio of 44 and an initial length range of 2–14 mm, which means that both short and long fibres were added to the cement-based mortars. Similarly, steel shavings added to the mortars were formed of ferritic stainless steel, with a density of 7.980 g/cm^3 and an average electrical resistivity of 1.67×10^{-5} Ωm. These shavings had an average width of 1.310 mm (Fig. 1(d)) and an initial length within the range of 3–21 mm, which means that both short and long shavings coexist, resulting in four different types of geometry, see Fig. 1(b).

2.2. Preparation of test specimens

Table 2 presents the proportions by weight and volume of the raw materials used in this study. Cement-based mortar specimens were composed of cement, water, superplasticiser additive, and four different metallic waste amounts: 4%, 8%, 12% and 16% by unit weight of cement. These amounts of metallic waste were chosen in order to avoid difficulties during the mixing process and to achieve a good distribution. A water/cement ratio by weight of 0.5 was set for all the mortar mixtures with the aim of obtaining a normal consistency according to EN 196-3:2005 + A1:2009. Raw materials were mixed using a standard laboratory planetary mixer, adding the materials in the following order: first the cement and fine sand; second the water with the superplasticiser additive; and, finally, the metallic waste, when applicable. The mixing and manufacturing methodologies of the cement-based mortar specimens were as follows:

- First, cement and sand were mixed under dry conditions for 60 s at 75 rpm. At the same time, water and additive were

Table 1
Gradation and physical properties of the sand.

Sieve size (mm)	% Passing
2	100
1.18	92
0.6	71
0.3	9
0.15	0
Physical property	**Value**
Fineness modulus (−)	2.28
Bulk density (g/cm^3)	2.810
Specific gravity (−)	2.920
Water absorption (%)	1.4
Specific surface (cm^2/g)	17.84