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Compressive strength and microstructure of alkali-activated mortars with high ceramic waste content

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ABSTRACT

The present work investigated alkali-activated mortars with high ceramic waste contents. Tile ceramic waste (TCW) was used as both a recycled aggregate (TCWA) and a precursor (TCWP) to obtain a binding matrix by the alkali-activation process. Mortars with natural siliceous (quartz) and calcareous (limestone) aggregates, and with other ceramic waste materials (red clay brick RCB and ceramic sanitaryware CSW waste), were also prepared for comparison purposes. Given the lower density and higher water absorption values of the ceramic aggregates, compared to the natural ones, it was necessary to adapt the preparation process of the recycled mortars by presaturating the aggregate with water before mixing with the TCWP alkali-activated paste. Aggregate type considerably determined the mechanical behaviour of the samples cured at 65 °C for 3 days. The mortars prepared with the siliceous aggregate presented poor mechanical properties, even when cured at 65 °C. The behaviour of the limestone aggregate mortars depended heavily on the applied curing temperature and, although they presented the best mechanical properties of all those cured at room temperature, their compressive strength reached a maximum when cured at 65 °C, and then decreased. The mechanical properties of the mortars prepared with TCWA progressively increased with curing time (53 MPa at 65 °C for 28 days). An optimum 50 wt% proportion was observed for the limestone/TCWA mortars (≈43 MPa, 3 days at 65 °C), whereas the mechanical properties of that prepared with siliceous particles (10 MPa) progressively increased with the TCWA content, up to 100 wt% substitution (23 MPa). Limestone particles interacted with the binding matrix, and played an interesting beneficial role at the 20 °C curing temperature, with a slight reduction when cured long term (28 days) at 65 °C. The results demonstrated a potential added value for these ceramic waste materials.

1. Introduction

Portland cement (PC) manufacturing is an energy-intensive process that requires high temperatures (1450-1550 °C), consumes natural resources (mainly limestone and clay) and generates vast greenhouse gas emissions to the atmosphere (approximately 1 t of CO_2 per ton of produced cement. As reported in [1], it is one of the primary causes of global warming, and accounts for 7% of worldwide CO_2 emissions. As highlighted by Pachecho-Torgal [2], global warming will lead to not only increasingly extreme atmospheric events, but also to the thawing of the world's permanently frozen ground, and thermal expansion of water, both of which will result in a rising sea level.

These problems have encouraged the scientific community and cement industry to seek alternatives to reduce the energy consumed during PC production, and to develop alternative binders with lower environmental costs. Among the low CO_2 binders that are being investigated (calcium sulphoaluminate, alkali-activated materials, hybrid alkaline cements, etc.) [3], those developed by alkali-activation have allowed the reuse of a wide variety of industrial by-products as precursors to develop binding matrices. Mellado et al. [4] compared the CO_2 emissions of alkali-activated fluid catalytic cracking catalyst (FCC) waste mortars developed with commercial waterglass and sodium hydroxide solutions with those activated with an alternative active silica source (to substitute commercial waterglass). Although these authors concluded that the most important parameter to contribute to CO_2 emissions in geopolymeric mortars is the synthesis of commercial waterglass, mortars prepared with commercial solutions still reduce CO_2 emissions by 13% compared to PC mortars. As pointed out by Behera et al. [5], the alkali-activation of industrial waste also helps minimise the exploitation of non-renewable raw materials, and to

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reduce pollution, energy consumption and the areas employed to dispose waste, all of which help mitigate global warming.

As reviewed by Payá et al. [6] different industrial waste types have been successfully used by the scientific community to develop alternative binders by alkali activation. Ground granulated blast furnace slag, metakaolin and fly ash are among the most widely used [6–8], and others like fluid catalytic cracking catalyst (FCC) waste [6], sugarcane bagasse ash [8], ceramic products (bricks, tiles, etc.) [9,10], or different types of glass [6], have also proved successful.

Industrial waste may also be used as recycled aggregate. As indicated by Behera et al. [5] and Silva et al. [11], the quality, quantity, size and type of recycled aggregates to be used need to be precisely characterised because they strongly influence the mechanical properties and durability of the concrete being designed. As observed by Elchalakani and Elgaali [12], recycled concrete strength is greatly influenced by the quality of aggregates. This conclusion has been corroborated in different studies where ceramic waste has been used as recycled aggregate in PC systems. Mechanical properties diminished, compared with the reference concrete, in the research by Alves et al. [13], who used fine ceramic aggregates. Medina et al. [14] reported improved mechanical properties in concrete made with recycled aggregate from ceramic sanitaryware (CSW). Among the different waste materials used as aggregates, special attention must be paid to construction and demolition waste (CDW) as it generates vast volumes of waste. According to the data reported in [2], it is estimated that 970 million tons of CDW are generated yearly in Europe, and approximately 140 million tons are produced in the US. Similarly according to [15], the average annual production of CDW generated in Spain was 15.89 t for the 2009–2013 period. A specific CDW type is ceramic tiles, which are manufactured in large amounts in eastern Spain, which was the study area of the present work. According to the data provided by the Spanish Association of Ceramic Tile and Pavement Manufacturers (ASCER), 85.63% of the 167 Spanish companies registered in year 2013 that produced ceramic tiles and related products were located in the provinces of Valencia and Castellón (E Spain). As reported by Stock [16], the Spanish industry made 420 of the 11,913 million m^2 of tiles produced in 2013, is the fifth top manufacturing country (after China, Brazil, India and Iran) and accounts for 3.5% of world production. Thus investigating the potential use of large amounts of tile ceramic waste (TCW) in alkali-activated mortars as both a precursor and recycled aggregate is an interesting and attractive option for tile and cement industries both interested in recycling and producing sustainable materials.

The objective of this study was to develop mortars with high ceramic waste contents provided by ceramic tiles companies. This TCW was used as a recycled aggregate (sand) and also as a precursor to produce the binding matrix by the alkali-activation process. TCW was physically and chemically characterised, and the evolution of the mechanical properties and the developed microstructure were analysed in mortars cured at room temperature and at 65 °C. The compressive strength of the TCW recycled mortars was compared with that presented by the mortars that contained natural aggregates (limestone and quartz) and those prepared with other ceramic aggregate types (brick and sanitaryware waste-derived sand). Mortars that combined different proportions of natural/TCW aggregates were also investigated.

2. Materials and methods

2.1. Experimental flow chart

Alkali-activated tile ceramic waste mortars (TCW) were developed using natural and recycled aggregates. The TCW used herein is presented in Fig. 1, and was provided by some tile manufacturing companies located in the province of Castellón (east Spain). Most particles had a diameter that fell within the 4–16 mm range. Waste was

Fig. 1. Ceramic waste provided by ceramic tiles companies.

used to obtain the binder for the alkali-activation process (TCWP, as a powdered material), and as a recycled aggregate (TCWA, as a granulated material) in the developed mortars.

Siliceous (quartz) and limestone sands were used as natural aggregates, and mortars with different proportions of the natural/TCWA aggregates were prepared to assess the evolution of the mechanical properties depending on the aggregates mixture. Other ceramic materials, such as red clay brick (RCB) and ceramic sanitaryware (CSW) waste, were also used as recycled aggregates for comparison purposes. The experimental process that we followed is described in Fig. 2. A further description of the different process steps is provided in Sections 2.2–2.5.

2.2. Preparation and characterisation of tile ceramic waste powder

The TCW powder (TCWP, as a precursor or binder) for the alkali-activation process was prepared by crushing original particles to less than 2 mm in a jaw crusher (BB200 model, Retsch) and then grinding in a jars turner roller (Gabrielli Roller 1). Grinding was achieved by turning two cylindrical alumina 5-litre volume jars for 6 h (190 rpm for the first 10 min and 140 rpm for the remaining time). Each jar was filled with 1500 g of ceramic waste and 6500 g of alumina balls. As shown in Fig. 3, both the crushed particles before milling (Fig. 3a, optical microscopy) and the milled TCWP particles (Fig. 3b, SEM–

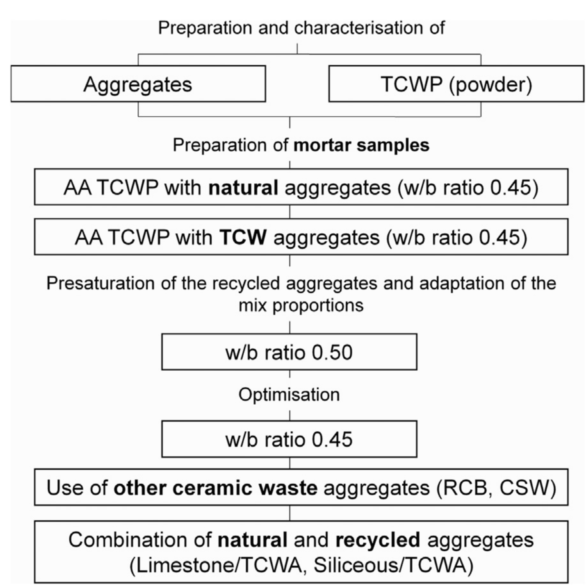

Fig. 2. Experimental flow chart of the alkali-activated TCW mortars with natural and recycled aggregates.