Construction and Building Materials 73 (2014) 523–534

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Lime mortars with ceramic wastes: Characterization of components and their influence on the mechanical behaviour

Gina Matias [a,*], Paulina Faria [b], Isabel Torres [c]

[a] ITeCons – Institute for Research and Technological Development in Construction Sciences, Rua Pedro Hispano, s/n, 3030-289 Coimbra, Portugal
[b] UNIC, Department of Civil Engineering, Faculty of Sciences and Technology, Universidade Nova de Lisboa, Quinta da Torre, 2829-516 Caparica, Portugal
[c] Department of Civil Engineering , Faculty of Sciences and Technology, University of Coimbra, Rua Luís Reis Santos – Pólo II, 3030-788 Coimbra, Portugal

HIGHLIGHTS

- Lime mortars with ceramic dust and fragments have been often used in the past.
- Solutions for the disposal of waste from the ceramic industry are urgently needed.
- Dust fraction of industrial ceramic waste may demonstrate pozzolanic activity.
- Dust and fragments of ceramic wastes increase the mechanical strength of air lime mortars.
- Ceramic waste incorporated in mortars compositions may work as a natural pigment.

ARTICLE INFO

Article history:
Received 31 May 2014
Received in revised form 11 September 2014
Accepted 24 September 2014

Keywords:
Ceramic waste
Old mortar
Air lime mortar
Pozzolan
Filler
Aggregate

ABSTRACT

Considering the fundamental importance of preserving the built heritage and of ensuring the good performance achieved by incorporating ceramic particles in lime mortars in ancient times, it is important to study solutions that use materials the available today, in order to produce mortars intended to repair and replace the old ones. Solutions incorporating industrial ceramic waste might be profitable for several reasons, namely for economic, environmental and technical aspects. In this paper, seven ceramic waste products collected from ceramics factories are characterized. Their mineralogy, dimensional features and pozzolanicity were determined. Three of these products, with different particle size fractions (obtained directly from milling, dust only and fragment fractions only), were selected, incorporated into air lime mortars, and their mechanical strength was determined. In the present work, evidence of mechanical efficiency, when common sand or air lime were partially replaced by ceramic wastes, was made clear, drawing attention to the sustainability of this type of mortars, hence, encouraging further research.

1. Introduction

Hydrated lime mortars with the addition of several materials have been very often used in the past. These additions, especially pozzolans, were intended to improve the behaviour of mortar, and were mainly obtained from natural sources. Products such as heat treated clays and ash have been often detected in old mortars. Heat treated clays from ceramic products, such as bricks and tiles that were milled and incorporated in lime mortar, were common ingredients in ancient times and were used when natural pozzolans were not available.

It has been observed that heat treated clays can provide hydraulic characteristics to air lime mortars. Silica (SiO_2) and alumina (Al_2O_3), which are found in pozzolanic materials, may, when combined with $Ca(OH)_2$ and water, form calcium silicates and aluminates, if certain conditions (which will be addressed later) are gathered. The final product can therefore harden in the presence of water, which does not happen when a mortar contains only air lime [1].

In the specific case of heat treated clay, the degree of pozzolanic activity depends on several factors. The type of clay and the amount of silica and alumina available to react with the $Ca(OH)_2$ and fixate the calcium hydrate (CaH) [2] are the main characteristics of interest. However, other aspects such as the degree of crystallinity, mainly conditioned by the thermal treatment conditions (heating period, temperature and type of cycles), and the specific

* Corresponding author. Tel.: +351 239 79 89 37; fax: +351 239 79 89 39.
E-mail address: ginamatias@itecons.uc.pt (G. Matias).

http://dx.doi.org/10.1016/j.conbuildmat.2014.09.108
0950-0618/

surface area of the particles, are also crucial [2,3]. The temperature of the thermal treatment seems to be an aspect of critical importance. According to researchers [1,4–9] the amount of amorphous material produced is strongly influenced by the clay mineralogy, and the ideal temperature to develop reactivity also varies.

Mortars containing ceramic fragments became popular during the Roman Empire as their hydraulic properties met with the requirements for the construction of baths, water conduits, reservoirs and cisterns [10]. This mixture, known as *opus testaceum* and *cocciopesto* [3,11] has been well documented by Catone and Vitruvius [12]. The knowledge of its principles spread throughout Europe, North Africa and Asia [2,6]. Nonetheless, evidence has been found of prior use of these type of products as masonry elements [12–15].

In addition to their common use from empirical knowledge, mortars made with heat treated clays obtained from milled by-products were also known to be quite long-lasting and reliable. Its considerable number of advantages led to their use for many centuries. This type of mortars can be easily found in historic buildings and archaeological sites till this day, which is a good indicator of its longevity.

Research has been undertaken over the years to understand and explain why mortars with ceramic waste were regularly used in the past. Some researchers characterized old mortars used in historical buildings so as to understand, not only the characteristics of the ceramics used in the past, such as the temperature treatment and mineralogy of the clay, but also how the mortars were produced in terms of proportions and aggregates size distribution. Other researchers have revealed that newer ceramics might have potential as pozzolans or as aggregates when incorporated into lime and cement mortars along with being compatible with old buildings masonry on which this technique was applied in the past [3,4,7–9,11–13,16–21].

Nowadays, the ceramic industry creates a significant amount of waste for disposal. Most factories reject large amounts of final products due to high quality requirements. In brick and roof tile factories, whose main raw materials are clay and silica, the paste is subjected to heat treatment at relatively high temperatures, which involves high energy costs. Final products frequently exhibit small defects like cracking and warping, and are therefore unmarketable. A small number of factories reintroduce parts of the defective materials into the production cycle and sometimes waste is sold for exterior sports floor paving. However, this does not happen very often. Therefore, it is very important to find solutions that may use larger quantities of this type of waste.

In the specific case of Portugal, in 2003 it was estimated that 37% of the waste produced by ceramics factories originated from heat treated products and its most common destination was landfill disposal [22]. According to the information collected from The European Pollutant Release and Transfer Register [23], in Portugal, manufacturers of ceramic products, including tiles, bricks, stoneware and porcelain, produced about 102,329 tonnes of non-hazardous waste in 2011, 7.8% of which was not recovered. Even though this percentage may be small, it still represents 8029 tonnes of waste whose most probable destination is landfill.

Apart from these environmental advantages, there are other benefits from using ceramic waste. When used to partially replace the constituents of mortars, ceramic particles help to reduce the consumption of natural aggregates or binder. The production of binder requires the consumption of energy and, consequently of fossil fuels. It also involves the emission of a considerable amount of CO_2 and a consumption of appreciable quantities of natural resources. When it comes to aggregates, the massive extraction of natural sand can have disastrous environmental consequences. Therefore, the incorporation of ceramic waste into mortars may offer environmental advantages as well as economic and technical benefits, in particular when the pozzolanic reactions and filler behaviour are considered.

Previous research has shown that, while there have been some studies on mortars with ceramic waste, most of them concern cement mortars. On the other hand, publications regarding air lime mortars have not provided an in-depth description of industrial ceramics and are not up-to-date. For the mentioned reasons the time is ripe for systematizing this characterization. The research work presented in this paper is therefore looking at the industrial ceramic waste produced from common clays used to manufacture building materials (bricks and roof tiles) and ornamental ceramics (pottery), obtained locally from the central region of Portuguese Mainland.

Once all the relevant details about the clay production processes (materials used, thermal treatment and production stages) were gathered, the collected samples were milled and their physical and chemical properties were characterized. Some of the waste materials were then incorporated into air lime mortars mixtures in different proportions, partially replacing the natural sand or binder. The mechanical behaviour of the mortars was analysed aimed at providing an insight into the contribution of these wastes to the performance of mortars, when compared to common mortars without additions.

2. Preparation and characterization of the materials

2.1. Industrial production characteristics

Samples of waste composed of roof tiles, bricks and pottery were collected from ceramic industries located in the central region of Portuguese Mainland. They were used to represent the most common ceramic waste materials. Seven different products were gathered from four selected companies, along with relevant information about the current production and ceramic waste treatment procedures.

It was found that most factories do not use the waste dismissed by the quality inspection process (which sorts out items with flaws caused by production mistakes or breakage during handling). Deposits with large amounts of waste that have accumulated over time are a common sight outside these industrial facilities. The hardness of the products means that degradation is almost non-existent, which creates a long term problem of waste management.

The information gathered from the selected factories is summarized in Table 1. The products are defined by their commercial designation given by the producer. For this reason some tiles are defined as "high quality" in comparison to regular ones. The thermal treatment mainly occurs in a tunnel and the duration presented is refers to the entire heating period. The heating temperature is the maximum temperature that is reached in that period. The period of time at maximum temperature was not given by the factories.

As a consequence of the great amount of waste available for some sub-products, and considering the similarities in their composition, for the purpose of this analysis, W4 and W5 (Table 1) are mixtures of three different types of roof tiles, defined in terms of the nature of their materials, their production process, and the quantities of waste. Their proportions are presented in Table 2 in percentage.

Regarding the production characteristics, in terms of thermal treatment, temperature values ranging from 900 °C (bricks) to 1100 °C (pottery) were recorded. A study by Pereira-de-Oliveira et al. [9] on ceramic tiles reported signs of pozzolanicity in clays heated from 600 °C to 1200 °C, although it is more common to find references to optimal conditions of around 800 °C, particularly in studies where the ceramic material was heat treated [1,24]. All