Journal of Cleaner Production 119 (2016) 118–127

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Study of natural hydraulic lime-based mortars prepared with masonry waste powder as aggregate and diatomite/fly ash as mineral admixtures

Shuqiang Xu [a, b], Julin Wang [a, b, *], Qi Jiang [c], Sheng Zhang [a]

[a] Beijing Key Laboratory of Electrochemical Process and Technology for Materials, Beijing University of Chemical Technology, Beijing, 100029, China
[b] Key Research Base of State Administration of Cultural Heritage for Evaluation of Science and Technology Research in Cultural Relics Protection Field, China
[c] China Household Electrical Appliances Research Institute, Beijing, 100053, China

ARTICLE INFO

Article history:
Received 4 September 2015
Received in revised form
16 November 2015
Accepted 23 January 2016
Available online 1 February 2016

Keywords:
Mortars
Diatomite
Fly ash
Waste marble powder
Pozzolanic effect
Mechanical properties

ABSTRACT

NHL-based mortars were prepared by using waste marble powder (WMP) as aggregate and introducing diatomite and fly ash to partially replace natural hydraulic lime (NHL). Physical property evaluation showed that compressive and flexural strength of mortars prepared with diatomite were greatly enhanced, fly ash addition had noticeable improvement on mortars' flexural strength. Diatomite had a more positive effect on mortars' compressive strength than fly ash and 20% mineral addition made mortars achieve better mechanical properties. Apparent density of prepared mortars was decreased after introduction of diatomite and fly ash. Acid and sulfate resistance properties of mortars were improved by the presence of mineral. Diatomite was more effective than fly ash in improving the sulfate resistance of mortars. Microstructure, ultrasonic velocity and thermal properties characterization suggest that the improvement of mortars' properties could be attributed to pozzolanic reaction between mineral admixtures and calcium hydroxide ($Ca(OH)_2$) which mainly occurred during curing period at the range of 14–28 days.

1. Introduction

Ancient cultural relics and historical record revealed that lime with pozzolanic mineral addition was used to prepare hydraulic mortars in ancient civilization (Callebaut et al., 2001; Velosa et al., 2007). Air lime was gradually replaced by hydraulic lime after the discovery of hydraulic binder at 18th century. At the beginning of 20th, Portland cement (PC) became the dominant construction material because of its merits such as faster setting rate and higher mechanical properties (Sabbioni et al., 2001), which led to the shrinkage of hydraulic lime application. Recent years, it was well known that PC mortars presented several problems associated with physicochemical and mechanical properties when they were used to restore cultural relics, and it generated huge damage to the relics (El-Turki et al., 2010a,b). NHL has moderate mechanical strength and it can maintain matrix appropriate gas and water permeability. Relevant research demonstrated that the use of NHL will not introduce soluble salt (Kalaitzaki et al., 2005) and it will greatly reduce the pollution of the environment compared with the use of cement (Grist et al., 2015). Application of NHL is experiencing a resurgence because of its superiority in the field of restoration of old relics (El-Turki et al., 2010a,b).

With the increase in demand for NHL, the consumption of energy and resources, as well as the generation of carbon dioxide (CO_2) and harmful dust, will rise during its production (Tsai et al., 2014). Exploiting alternative fuels and adopting pozzolan as partial cement replacement were both effective approach to enhance sustainability of concrete construction (Gäbel and Tillman, 2005; Pimraksa et al., 2013; Alexandre et al., 2014; Bras et al., 2010; Lucia et al., 2012; Noor-ul et al., 2015). The use of fly ash (Ravina, 1998; Mahdi et al., 2015; Dinakar et al., 2013) and perlite (Yu et al., 2003; Lanzón and García-Ruiz, 2008) as partial substitution of cement enhanced mechanical strength of concrete. Diatomite incorporation also improved compressive and flexural strength of concrete mortars (Ergün, 2011; Fragoulis et al., 2005). Zhao et al. (2015) found that the introduction of fly ash and ground granulated blast furnace slag to the concrete mortars increased initial

* Corresponding author. Beijing University of Chemical Technology, China. Tel.: +86 13910664281.
E-mail address: julinwang@126.com (J. Wang).

http://dx.doi.org/10.1016/j.jclepro.2016.01.069

slump flow, lowered mechanical properties at the early curing period until 90 days. Gritsada Sua-iam and Makul (2014) pointed that compressive strength of concrete mortars decreased with fly ash content and Degirmenci and Yilmaz (2009) concluded that the use of diatomite decreased mechanical strength of concrete mortars. Thus, a certain pozzolan was not suitable for all cementious system, therefore, it is important to design and develop an appropriate formula through experiment.

NHL, mainly including NHL-based grout (Bras and Henriques, 2012; Xu et al., 2014, 2015; Baltazar et al., 2013; Baltazar et al., 2014) and NHL-based mortars (Lanas et al., 2004; Grist et al., 2013; Xu et al., 2014, 2015), was not extensively studied until recent decades. Especially, there were only a few researches on the use of pozzolan as partial replacement of NHL. Grilo et al. (2014a,b) concluded that the addition of metakaolin enhanced strength of NHL-based mortars, and the strength underwent a decrease during later curing period. Iucolano et al. (2013) and Liguori et al. (2015) employed glass fiber for the reinforcement of NHL-based mortars, at the same time NHL was replaced by zeolite at proper proportion. They found that mortars made with chopped glass fiber showed lower plastic shrinkage and durability of mortars was improved, the zeolite addition further enhanced mechanical properties of these mortars.

Diatomite is a common pozzolan and it has been used as replacement in mortars and grouts. Besides, there is relatively abundant resources and accessibility for diatomite (Posi et al., 2013). Fly ash is an industrial by-product, which derives from coal combustion residues with good crystallinity. It is estimated that 50 million tons of fly ash are generated each year in China and it will cause severe pollution without proper utilization. This work selected diatomite and fly ash as partial replacement of NHL to prepare mortars.

It is estimated that 200 million tons of construction waste are generated each year, which accounts for about 40% of urban total waste in China. Masonry (brick and stone) waste that come from modern industry, architecture and scientific research are hazardous to environment. It will also cause environment pollution when natural aggregates are used in the preparation of hydraulic mortars, for that large amount of CO_2 will be released during the exploitation of these natural aggregates (Miguel et al., 2015). Therefore, the use of WMP as aggregate in mortar is of great significance from the ecological point of view. So far researchers (Topçu et al., 2009; Hebhoub et al., 2011; Enrique et al., 2015; Uygunoğlu et al., 2014; André et al., 2014) had employed waste marble as aggregate in concrete and had demonstrated the feasibility of waste marble as aggregate to prepare concrete.

Most of the ancient architectural sites are in the open air environment. Mortars are susceptible to deterioration due to acid rain, and acid may also come from groundwater. It had frequently caused the structural damage and incomplete of architecture because of the long exposure to corrosive acid environment and seriously affect stability of the architecture (Fattuhi and Hughes, 1988). Natural weathering processes, such as freeze and thaw, rising damp and salt attack are also key durability issues that affect the mortars' life cycle performance. Sabbioni et al. (2002) found that there were non-water-soluble sulfates (ettringite) in Venice Arsenal structures when hydraulic mortars were used with sulfates material in it, and the formation of ettringite caused severe expansion and cracking of Venice Arsenal structures. So these issues associated with aggressive environments should be considered when hydraulic mortars were used to restore or reinforce the architecture relics.

The aim of this work is to prepare mortars suitable for masonry architecture restoration. Diatomite and fly ash were utilized to replace partial NHL, and MWP was used as the aggregate to prepare mortars. Feasibility of the use of diatomite and fly ash in NHL-based mortars was evaluated. Physical and mechanical properties of mortars with different formulations were investigated. The possible mechanism of the property improvement was also proposed and discussed.

2. Materials and methods

2.1. Materials

2.1.1. NHL

The main binder NHL2 was supplied by Chaux De Saint-Astier company, France. The chemical composition of NHL2 was detected by X-ray fluorescence analysis (XRF, Philips PW1010 XRF) spectrometer and the results were shown in Table 1. The mineralogical compositions of NHL2 were obtained by using Rigaku D/max 2200 X-ray diffractometer. XRD results showed that the main components in NHL2 include dicalcium silicate (C_2S), portlandite, calcite and small amount of quartz.

2.1.2. Mineral admixtures

Diatomite and fly ash were the mineral admixtures to substitute partial NHL2. Diatomite was a commercial product supplied by Dahua company in Jilin province, China. Fly ash was obtained from Beijing Construction Material Chemical Plant. Their chemical compositions were shown in Table 1. Both two materials used were environmentally acceptable according to Teixeira et al's. (2016) and Ergün's (2011) research.

2.1.3. Aggregate

The admixtures of WMP were used as aggregate. The WMP was supplied by Lichang stone company in Beijing, China. XRD result indicated that quartz, calcite, dolomite, chlorite, tremolite and albite were the main components of WMP.

2.2. Mix proportions

Mortars were prepared by binder (NHL2) and aggregate (WMP) with a ratio of 1: 2. NHL2 was substituted by diatomite and fly ash with 0%, 10% and 20% ratio, respectively. Water binder ratio (W/B) 0.7 was adopted for all mortars. The mix proportions were presented in Table 2. The prepared mortars were termed as control (C), Series-I (D10, D20) for samples containing diatomite, and Series-II (F10, F20) for samples containing fly ash.

2.3. Mortar preparation and curing

Required components for different mortars were accurately weighed, mixed and dry-homogenised. Then, accurate amount of water was gradually added to this mixture according to 0.7 W/B. The mixtures were mixed in a Hobart mixer and compacted by a vibration table operating at 12,000 ± 400 r/min. The prepared mortars were molded in prismatic casts with a size of $40 \times 40 \times 160$ mm^3 and demolded 48 h later. Curing was conducted in a constant temperature humidity chamber (20 °C and RH 70%) for a fixed period (14, 28, 90 days). The flow table test was

Table 1
Oxide compositions (wt.%) of NHL2, diatomite and fly ash.

Material	CaO	SiO_2	Fe_2O_3	Al_2O_3	K_2O
NHL2	74.42	15.18	4.36	2.35	2.28
Diatomite	11.71	71.35	7.98	4.87	3.1
Fly ash	6.32	55.68	15.62	14.38	5.68