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Study on the lightweight hydraulic mortars designed by the use of diatomite as partial replacement of natural hydraulic lime and masonry waste as aggregate

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HIGHLIGHTS

- Diatomite replacement enhances strength characteristics of NHL mortars.
- Acid and sulfate resistance of NHL mortars were improved with diatomite incorporation.
- The use of diatomite reduces total amount of raw materials to prepare NHL mortars.

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ABSTRACT

In order to increase energy and resources utilization efficiency, and to find hydraulic mortars with improved properties, in this paper we employed diatomite as partial replacement of natural hydraulic lime NHL2 (NHL) and masonry waste powder (MWP) as aggregate in the preparation of mortars. Diatomite was used at 0%, 10% and 20% replacement by weight for NHL2 and the mortars were designed with different water binder ratios (w/b). The physical, mechanical, and anti-aggressive properties such as freeze and thaw, and acid and sulfate resistance properties of mortars were tested after 14, 28 and 90 days of curing. The introduction of diatomite reduced the density of mortars, and it also reduced the total amount of raw materials, especially the amount of NHL, to prepare same volume of mortars. Diatomite replacement generally enhanced the compressive and flexural strength of hydraulic mortars. The enhancement mainly happened after 14 days of curing when pozzolanic effect was noticeable. Diatomite replacement percentage and w/b influenced porosity, compactness and strength of mortars. There existed optimal diatomite replacement percentage and w/b for mortars to attain largest strength. The introduction of diatomite improved acid and sulfate resistance of mortars greatly. All the hydraulic mortars studied in this paper can still well develop strength under freeze and thaw condition.

1. Introduction

Natural hydraulic lime (NHL) is produced from fired limestone which contains a certain amount of clay impurities below the sintering temperature, and it had been used as construction mortars in ancient Greek and Roman periods [1]. Since the discovery of Portland cement, the cement has been widely applied in construction and has even been used as binder material in the repair of ancient architectures (Lea 1976). As a consequence, the application of NHL shrunk. Recently, because of the superiority of NHL in old relic's restoration field, its application is experiencing resurgence [2]. There were property studies of NHL-based mortars [3,4] and NHL-based grouts [5,6]. Cement and NHL have important roles in modern construction and industry, and there is still demand for large amount of their production. Their production will generate CO_2 and harmful dust, and will also consume significant amount of energy [7]. There have been efforts to alleviate environment and energy problems associated with the production of cement and NHL. Altering cement or NHL composition and

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exploiting alternative fuels are among approaches to lessen greenhouse gas emissions [8]. In order to further reduce the use of cement and NHL, some researchers [9,10] employed pozzolan to partially replace them.

Pozzolan has the ability to react with lime in the presence of water at ordinary temperatures generating compounds with cementitious properties [11]. The common pozzolanic materials include natural products, such as calcined clays, metakaolin, diatomite and zeolites, and by-products, such as fly ash, silica fume and slag. Relevant researches concluded that the use of perlite as partial replacement of cement enhanced strength of concrete [12,13]. The use of fly ash as partial replacement of cement in the preparation of mortars also improved the strength [14,15], and the strength increased with fly ash replacement percentage [16]. Bingöl and Tohumcu [17] investigated the effect of curing condition on compressive strength of concrete mortars prepared with fly ash and silica fume incorporation. They found that the strength increased for both mortars, and strength increased with increasing silica fume content but decreased with increasing fly ash content. Studies on the use of diatomite as partial substitution of cement have also got some findings. Diatomite as partial replacement of cement increased the water demand to prepare mortars and enhanced the strength of mortars [18]. Ergün [19] found that the compressive strength of mortars prepared with different diatomite replacement percentage (5%, 7.5% and 10%) increased by 10–28% at the age of 7 days. He also found that low water demand depending on superplasticizing admixture in concrete specimens was propitious for strength enhancement. Another research [20] pointed out that the introduction of diatomite decreased strength of mortars but made mortars obtain good freeze and thaw resistance and sulfate resistance.

However, there were only a few studies on the use of pozzolan as partial replacement of NHL. Grilo et al. [21,22] found that the strength of mortars increased when metakaolin was added to prepare NHL-based mortars. A decrease of strength with aging was observed with metakaolin incorporation. High humidity condition was advantageous for hydration and pozzolanic reaction. To our knowledge, there was no research on the use of diatomite as partial replacement of NHL.

Diatomite has been used in variety of applications, mainly as filtration agent and functional fillers for paints and plastics [20]. Diatomite has also been used as pozzolanic additives for Portland cement, mortars and grouts. Diatomite is characterized as natural pozzolan [18], as it satisfies the requirements of TS EN 197-1 [23] concerning the active silica content. Amorphous silica (opal-A) in diatomite can react with $Ca(OH)_2$ to generate calcium silicate hydrate (CSH). Considering relatively abundant diatomite resources and its accessibility [24], simple manufacturing technique, low energy consumption and low impact on environment, we selected diatomite to partially replace NHL in our present work.

A large amount of masonry wastes (waste brick and stone) are generated in modern construction or from the ancient architectures. These masonry wastes are often thrown away directly without proper disposal, and this makes negative impact on the environment. For the purpose of utilizing recycled wastes and relieving environmental problems, researchers [25–29] have utilized waste marble as aggregate in concrete manufacturing. Hebhoub et al. [29] used recycled waste marble at different percentages to substitute for natural aggregate in the preparation of concrete mortars, and they found that the compressive strength of mortars increased maximally by 25.08% when the substitution went up to 75%. They demonstrated the feasibility of using waste marble as aggregate to prepare concrete mortars.

Masonry buildings are greatly affected by weathering processes such as freeze and thaw, rising damp and salt attack [30]. The situation is more severe when masonry buildings are exposed to marine environments. Marine environments are very aggressive, since sea water consists mainly of chlorides and sulfates [31]. Sabbioni et al. [32] found that there were non-water-soluble sulfates (ettringite) in Venice Arsenal structures when hydraulic mortars were used in the presence of sulfates, and the formation of ettringite caused severe expansion and cracking of Venice Arsenal structures. In addition, degradation of hydraulic mortars exposed to aggressive acid environments is also a key durability issue that affects the mortars' life cycle performance [33]. Most of hydraulic mortars are susceptible to deterioration due to acid rain, and acid may also come from groundwater or chemical waste [34]. So these issues associated with aggressive environments should be considered when hydraulic mortars were used to restore or reinforce the architectural heritage.

The experimental research program outlined in this paper used diatomite as partial replacement of NHL and MWP as aggregate, and also adjusted the diatomite replacement percentage and w/b to prepare NHL-based mortars. Some properties of mortars, namely, density, porosity, mechanical strength and aggressive environment resistance were investigated. We aimed to achieve the goal of conserving energy, improving resource utilization efficiency and lessening environmental problems, and also to manufacture NHL-based hydraulic mortars with beneficial properties.

2. Materials and methods

2.1. Materials

The primary binder used in this paper is NHL2 which was supplied by CHAUX DE SAINT-ASTIER company. The replacement material diatomite was a commercial product supplied by DAHUA company in Jilin province. The chemical analysis of NHL2 and diatomite was carried out with X-ray fluorescence analysis (XRF), by using a PHILIPS PW1010 XRF spectrometer. The test results were shown in Table 1.

The mineralogical compositions of NHL2, diatomite and MWP were obtained using Rigaku D/max 2200 X-ray diffractometer, with a Cu Ka1 radiation. Diffractograms were recorded from 5 to 75 2θ, at an angular speed of $0.02^\circ\ 2\theta\ s^{-1}$. Dicalcium silicate ($C_2S$), portlandite, calcite and small amount of quartz are main components in NHL2. Amorphous silica (opal-A) is found as the main phase in XRD pattern of diatomite. Diatomite used in this paper satisfies the requirement that the content of active SiO_2 shall be not less than 25% by mass in standard TS EN 197-1 [23].

MWP (0–1 mm) was supplied by Lichang stone company in Beijing and Fig. 1 depicts its grading analysis. XRD result shows that the main components in MWP include quartz, calcite, dolomite, chlorite, tremolite and albite.

2.2. Sample preparation

In order to evaluate the effect of diatomite replacement percentage and w/b on physical and mechanical properties of mortars, diatomite was used at 0%, 10% and 20% replacement by weight for NHL2, and also appropriate w/b were designed for each group to achieve a comparable consistency of mortars. Specific diatomite replacement percentage and w/b were shown in Table 2. The mortars were named as control group (C-0.5, C-0.6, and C-0.7), Series-I (D10–0.5, D10–0.6, and D10–0.7) for 10% diatomite replacement, and Series-II (D20–0.62, D20–0.7, and D20–0.8) for 20% diatomite replacement. The integers and decimals in the notation demonstrate the diatomite replacement percentage of NHL and w/b, respectively. The flow table consistency was determined based on EN 1015-3:1999/A2:2006 and the average value for each mortar is also presented in Table 2.

The different components of the mortars were accurately weighed, mixed and dry-homogenised. Then, accurate amount of water was gradually added to this mixture according to w/b. The mortars were molded in prismatic $40 \times 40 \times 160$ mm casts [35] and demolded 48 h later. Curing was conducted in a constant temperature humidity chamber (20 °C and RH 70%) until the test days (14, 28, 90).

Table 1
Chemical compositions (wt.%) of NHL2 and diatomite.

Material	SiO_2	CaO	Fe_2O_3	Al_2O_3	K_2O
NHL2	15.18	74.42	4.36	2.35	2.28
Diatomite	71.35	11.71	8.36	5.25	3.48