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Grouting performance improvement for natural hydraulic lime-based grout via incorporating silica fume and silicon-acrylic latex

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HIGHLIGHTS

- Grouting performance of NHL-based grouts was improved by SF and silicon-acrylic latex.
- Bleeding and water absorption of modified grouts decreased.
- Interfacial bond, mechanical and durability properties were improved.
- Combined use of SF and silicon-acrylic latex made grouts have the best performance.

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ABSTRACT

Natural hydraulic lime (NHL) based grout has been widely used in construction project related to ancient architecture in recent decades. In order to improve grouting performance of NHL based grout, silica fume (SF) and silicon-acrylic latex (SAL) were incorporated in the preparation of grout. For the grout in fresh state, compared with control grout, bleeding rate of modified grout with SF and SAL incorporation decreased. Wettability, interfacial bond and simulated grouting properties of grout were improved. For the grout in hardened state, water absorption of grout decreased. Compactness, mechanical strength and salt resistance were improved. SAL played a more important role in improving both grout's flexural strength and interfacial bond property between grout and consolidated matrix. Generally, combined use of SF and SAL made the grout with the most beneficial grouting performance.

1. Introduction

In masonry research field, grouting is defined as the introduction of a liquid form of binder into a masonry building, to fill the cracks and voids in the structure and compensate mechanical strength of the structure [1,2]. In earthen constructions, cracking is a typical decay pattern and it has huge influence on earthen structures' integrality and stability, since mechanical properties of earthen sites near the crack are poor. So, it is of great significance to consolidate the cracked earthen structures. Grouting is one of the most widely used reinforcement techniques to improve the integrality of these structures. The main factors affecting the grouts' reinforcement effect include the following aspects. Injectability (fluidity) is an important characteristic to ensure that the grouts can well fill the cracks and voids. Stability (bleeding, shrinkage), mechanical properties and compatibility between grouts and consolidated matrix are also essential. Poor performance of these properties may cause the failure of the grouting [3]. So, the performance of grouting depends on both the characteristics of the grouts and the reinforced structures as well. The performance of fresh grouts is as important as that of the grouts in hardened state [4].

At present, many kinds of grouting materials, including cement based grouts, lime based grouts and sticky rice based grouts, have been applied in grouting reinforcement project of building structures. Cement based grouts is the most widely used reinforcing material in modern architectural structure, such as road, bridge, pipe, house and other municipal engineering. However, it is not suitable for the reinforcement works of ancient building structures.

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The main reason is that the strength and rigidity of cement are too large, which results in poor compatibility with the reinforced matrix in chemical, physical and structural aspects, causing serious damage to the reinforced ancient building structure [5–7]. The sticky rice based grouts had some application in the reinforcement of the ancient building cracking. Wall cracks and detachment caused by hollowing of the Imperial Palace ancient buildings were filled by sticky rice based grouts modified with Tung oil and the intruded grouts played a role in blocking the seepage channels of the wall. A recent monitoring campaign highlighted that, after about ten times of exposure to severe precipitations, slight grouts erosion occurred and no salt efflorescence was observed [8]. Sticky rice plaster was applied for the crack consolidation of the ancient stone tower in Xiangji Temple. One month after the grouting intervention, the cracks of stone tower were well filled and no new cracking was visible [9]. However, degradation and microbial growth may be an adverse effect of sticky rice grouting. Compared with masonry structure, earthen structure is more fragile with much lower mechanical strength. So, the crack of earthen structure is usually very complex and it is difficult to consolidate. Many kinds of materials had been used in practical consolidation of crack in earthen site, among which lime based grout [10,11], potassium silicate solution based grout [12] and calcined ginger nuts-based grouts [13] were the most dominant. However, in some cases the grouting effect of these materials was unsatisfactory in some aspects. So, great efforts still need to be made in the development of new crack consolidation product in earthen site.

Since the use of natural hydraulic lime (NHL) as binder material for restoration has several merits regard to moderate mechanical strength, water vapor permeability, compatibility with reinforced matrix, it has been widely used in the field of reinforcement and restoration of ancient buildings, and it became a research hotspot in recent decades [14–16]. It can also be considered to be employed in the restoration of earthen site. Several studies have been done to investigate the factors which influence the performance of NHL-based grouts, moreover the modification methods were also explored. Fly ash dosage, water binder ratio and temperature have an effect on bleeding, injectability and rheological properties of NHL-based grouts [3,17]. Besides, addition of superplasticizer and silica fume (SF), preparation technology such as adding time of superplasticizer and rotation rate influence fresh grouts' fluidity, stability and hardened grouts' compressive strength [18,19]. In Fernando Jorne et al.'s [20,21] research, simulated porous samples prepared with crushed stone and brick powder with different particle size and porosity were injected with NHL-based grouts. The distribution of grouts in the simulated porous samples was evaluated through ultrasonic tomography detection, in particular the regularity of wave speed distribution was considered. They concluded that parameters of the consolidated matrix such as permeability, water absorption, voids volume and grain size distribution influenced grouting performance. Optimal design of grouts can be achieved through adjusting the above parameters related to grouts' performance. However, the interfacial bonding properties between grouts and consolidated matrix, which directly influence grouting performance, were not studied in those researches.

The research background of this paper was based on the crack grouting intervention in a rammed earthen site (Fig. 1). The mausoleum of the king of Dingtao in Shandong Province is the largest in scale, and is most well-preserved with unique structure among Huangchangticou tombs during the Western Han Dynasty period which have been excavated. It has very high archaeological research and exhibition value. However, after its excavation, there were different forms of diseases such as surface weathering, salt erosion and cracking on the rammed tomb wall and the rammed soil area. Fig. 1b shows the typical cracking on the rammed tomb wall. In this work, NHL-based grout was supposed to be applied in the crack grouting intervention of the earthen site. In order to improve comprehensive performance of the NHL-based grouts, especially interfacial bonding properties between NHL-based grouts and soil matrix, SF and silicon-acrylic latex (SAL) were incorporated in the preparation of NHL-based grouts. SF is pozzolanic mineral and SAL is interfacial agent which is supposed to improve interfacial bonding properties between different matrixes. Main characters of service of grouts including fluidity, wettability, bleeding, shrinkage, mechanical bonding and durability properties were tested and compared, to evaluate modification effect of SF and SAL incorporation. This paper provides new information for a conscious choice of grouts formulation in earthen site.

Fig. 1. The earthen site to be protected, a: overall view of mausoleum of the king of Dingtao; b: typical cracking disease on the tomb wall.

2. Experimental

2.1. Materials

The main binder for grout preparation was NHL2, which is supplied by CHAUX DE SAINT-ASTIER Company. XRD test results showed that the main mineralogical compositions of NHL2 include dicalcium silicate (C_2S), calcium hydroxide and calcite. SF was purchased from Beijing sino-sina Construction Technology Company. The chemical compositions of NHL2 and SF were detected with

Table 1
Main oxide compositions of NHL2 and SF (wt%).

Material	SiO_2	CaO	Fe_2O_3	Al_2O_3	K_2O
NHL2	15.18	74.42	4.36	2.35	2.28
SF	94.78	0.37	0.56	1.02	1.51