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Effect of inorganic silicate consolidation on the mechanical and durability performance of sandstone used in historical sites

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HIGHLIGHTS

- A technique to strengthen sandstone using a type of inorganic silicate consolidant.
- Mechanical tests show that the strength of treated samples is generally increased.
- Salt crystallization tests show that the salt-resistant ability of the treated samples is increased.
- Low concentrations, with repeated treatments, can improve the treatment effect.

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ABSTRACT

Sandstone was widely used in the construction of monuments and sculptures in ancient times; numerous archaeological sites still remain along the Silk Road. Deterioration of the archaeological sites is one of the most serious problems that needs urgent attention. Organosilicon material has been considered to be an effective type of chemical consolidant for heritage structures that need strengthening. In recent years, the negative effects of organic materials have gradually been realized, e.g., shorter life and poorer compatibility. Therefore, inorganic materials have been re-evaluated by conservation researchers because of their long-lasting effects and good compatibility with stone substrates. An innovative inorganic silicate solution based on a potassium silicate solution, a high mole ratio potassium silicate solution, was developed. This paper describes the characterization of the new material as well as results from testing after treatment with different concentrations and consolidation times. In this study, the authors aim to explore if the newly developed inorganic consolidant has potential for future use in sandstone treatment. The effectiveness of the new inorganic consolidant was evaluated in terms of absorbed consolidant amount, mechanical properties (e.g., surface hardness, ultrasonic wave velocity, elasticity modulus and compressive strength modulus), and salt crystallization resistance. The treated groups showed better mechanical strength than the control group. The salt-resistant ability of the treated samples was also greatly improved. According to the laboratory tests, the new inorganic silicon consolidant holds great potential for reinforcing weathered sandstone.

1. Introduction

Most monuments and ancient buildings are made of stone; their degradation patterns have been analysed in several references [1,2]. The physical and chemical properties, as well as the mineral compositions and textural characteristics of stones, are the intrinsic factors that determine the form of weathering, while the natural environment is the driving force promoting the weathering process [1], such as temperature and humidity changes, moisture transportation, air pollution, biological activities, etc. Among them, discoloration and deposits induced by sulphide, dust and biological colonization do not have too much relative impact on the stability. However, some discoloration and deposit features, such as black crusts, are very sensitive to dissolution and direct washing out by rain. The latest study also shows that biological colonization by microbial organisms, algae or lichens has a positive influence on maintaining the stability of the micro-environment in terms of temperature and humidity [3]. Temperature and humidity changes are the main factors responsible for building deterioration [4]. Water acts as a vehicle for weathering processes because of aggressive atmospheric pollutants and causes disintegration,

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surface erosion, cracking through freezing-thawing or wetting-drying cycles inside the pores, dissolution and transportation of soluble salts that can induce salt attacks [1,2,5–9].

In China, grottoes are very important in terms of culture. Ancient people excavated these for daily living and religious activities. Most of these grottoes were built directly on mountains or cliffs where natural stone was the predominant material, such as sandstone, limestone and marble. Among these materials, sandstone is regionally distributed in the middle and northwest of China, and it is easily carved because of its relatively low strength [10]. However, at present, weathering has become an issue that affects the preservation condition of these grottoes because low mechanical strength also leads to serious degradation in terms of delamination or alveolization, as presented in Fig. 1.

Chemical consolidation treatment is a widely accepted conservation method that has been proven to be sufficiently effective to slow down the degradation speed in recent decades [11–13]. However, the slowing down of the ageing process of historic stone relics is still mostly achieved through the use of organic coating treatments. Presently, the majority of materials that have been tried in the conservation of stone relics include epoxy resins [14], acrylic resins [15,16], organosilicon products [2,17] or hybrid formulations based on organic consolidants [18–20]. Organosilanes are consolidants that had been fairly popular in the past and indeed are still used by many stone conservators at present. However, there are some stone artefacts, e.g., limestone objects, where deterioration has worsened since being treated with organosilanes [21]. Other difficulties associated with silanes include application safety and environmental sustainability [21]. Some researchers reported that the poor compatibility of organic consolidants might be a major problem because most cultural sites were built with inorganic materials such as stone and/or soil [22,23].

The above shows the urgent need for the development of an alternative, more compatible material for stone conservation. Inorganic materials seem to have more potential for stone consolidation treatments. Recently, a type of high mole ratio potassium silicate solution (hereinafter referred to as PS), which is particularly applicable to the protection of the earthen and sandstone sites in arid regions, was developed. This induces colloidal silicon dioxide (product of hydrolysis reaction by K_2SiO_3) and calcium silicoaluminate hydrate (reaction with calcium and aluminium in stone substrates) at particle-particle contacts, which increases the strength and cohesion of materials. The PS consolidant used in the Jiaohe Ruins (heritage site of earthen structures) conservation project was proved to be very effective in terms of improving the intrinsic properties with regard to reducing the impact of environmental damage [6,24,25]. In contrast, reports of sandstone conservation applications with PS solution are scant.

In this paper, all laboratory tests aimed to study critical properties and parameters of stone specimens related to both their performance characteristics and deterioration process. More specifically, the effectiveness of the consolidation materials on properties defining the internal cohesion and mechanical properties, the microstructure, and the movement of aqueous solutions and salt durability were studied. Mechanical properties reflect the effect of the consolidation treatment on the internal cohesion of the stone matrix and the adhesion between stone constituents. Therefore, laboratory tests aimed at surface hardness and uniaxial and triaxial compressive strength as well as compressive wave velocity were carried out [5,26–30]. Finally, salt crystallization ageing tests were carried out with the aim of evaluating the effect of different consolidation treatments for durability and internal cohesion of stone specimens by visual observation and material loss determination [2]. Although the material properties could be described by a large number of different techniques, in this study, emphasis was given to the above because they are the most widely accepted and their results could be interpreted in a straightforward fashion.

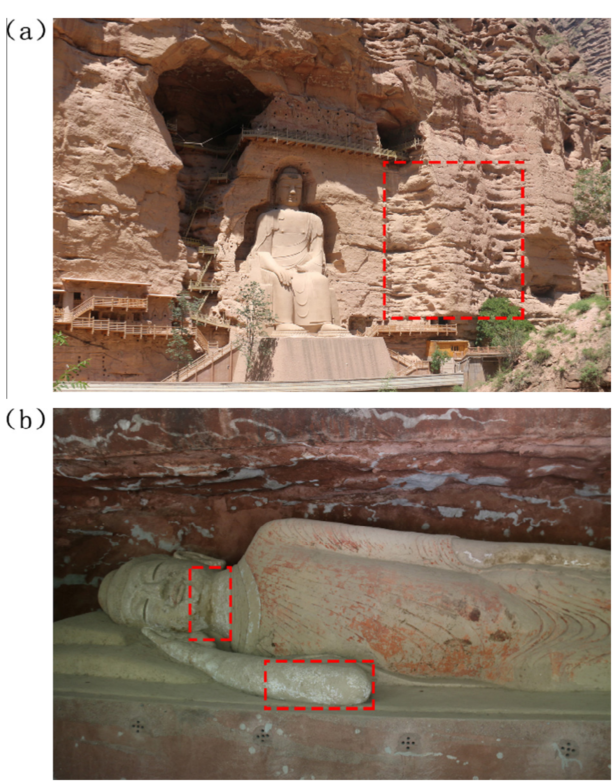

Fig. 1. Main deteriorations of Binglin Grotto, China (a cultural heritage site on the World Heritage site list): (a) alveolization forms on the cliff next to a Buddha and (b) delamination on parts of the arm and neck of a Buddha caused by salt attacks.

2. Materials and methodology

2.1. Characterization of mineralogical and physical properties

The sandstone used in this experiment was collected from quarries near Binglin Grotto, in Gansu, China. In 2014, UNESCO added it to the List of World Heritage sites. It should be noted that in areas near Binglin Grotto, neither coeval quarries nor outcrops of materials similar to those used in the sculpture could be found. Studies should be carried out with the lowest degree of damage and show the fullest respect for their physical integrity according to safeguarding principles for the architectural heritage followed by the scientific community. Taking into account their similarity in terms of appearance, mineralogical composition, texture and structure, one type of sandstone was chosen for the first stage of the experiment, and further research will be carried out on naturally weathered sandstone detached from the sculptures according to the results of this study.

The porosity and density of the sandstone were obtained as recommended by RILEM [31] and EN1936 [32]. The porosity ranged from 14.94% to 17.65%, and the average bulk density was approximately 2330 kg/m^3. Mineralogical analysis was carried out by X-ray powder diffraction (XRD), with approximately 26.4% quartz, 25.6% calcite, 24.4% gypsum and 9.7% clay and other mineral compositions. Clay exists between mineral particles as a cementing material, as observed in Fig. 2.

Fifty-three cylinder sandstone samples that were 5 cm in diameter, including 8 samples with heights of 10 cm and 45 with heights of 3 cm, were prepared. All 53 samples were artificially weathered by a freeze-thaw process. The freeze–thaw process