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Consolidation effect of composite materials on earthen sites

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HIGHLIGHTS

- A technique to improve the consolidation effect used on earthen sites.
- The RGB color space was applied to evaluate the colour changes of the treated samples.
- The concept of composite reinforcement was proposed.
- The sequence of consolidation of organic and inorganic materials was critical in the composite materials.

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ABSTRACT

Conservation practices employed thus far have proven that single materials cannot suitably protect earthen sites. This study compares the effectiveness of single and composite materials, to explore whether composite materials are potential candidates for use in conservation. Soils from the Great Wall of Yongchang, Gansu Province, China, were treated with five types of materials, namely, inorganic materials, organic products, composite materials composed of organic and inorganic materials in different orders, and ethanol. Changes in the colour, weight, mechanical properties, water resistance, microstructures, and element composition were evaluated after treatment. Better reinforcing effects were obtained by applying an organic material and then using an inorganic material. Results showed that a composite material with reasonable reinforcing sequence can greatly improve the properties of soils; hence, composite materials are promising for use in the protection of cultural relics in the future.

1. Introduction

Earthen sites are numerous, diversified, and distributed widely. Many ancient furnaces, ancient granaries, and ancient tombs are made of soils. Survey data of UNESCO show that earthen sites account for 10% of the world's cultural heritage, however, these sites have been exposed to the elements for millennia, thereby sustaining severe damage. The proportion of earthen sites is as high as 57% of the world's endangered heritage [1,2]. In China, the Great Wall, which was built for trade, management, and defence, occupies an important position in Chinese history, culture, and national spirit. Most historical sites in the Gansu Province, China, are made of soils. The Great Wall has undergone severe decay owing to exposure to the elements. This has threatened its durability and preservation, due to the occurrence of various forms of decay, such as surface stripping, fissures, gullies, and collapses. Among them, surface stripping is dominant, and can be observed on almost all the walls (Fig. 1). Temperature and humidity changes are the main factors responsible for this decay. Soils in certain layers of the wall get saturated owing to heavy rainfall and snowfall, then disintegrate rapidly. They then mix with water to form a mud flow. Once the mud dries, surface stripping occurs. The properties of soils then get gradually modified with depth owing to freeze–thaw cycles, soluble salt crystallization cycles, biological growth, and wind erosion. Surface soils have low mechanical strength, and are hence highly soluble in water, which in turn reduces the stability of the Great Wall. The surface-stripped layer is then transported and migrated due to wind erosion, following which a fresh surface corresponding to the next soil layer is exposed to the elements. The Great Wall has thus been severely degraded. Therefore, it is imperative to reinforce and repair soil ruins. Dropping infiltration is one of the major consolidation techniques for earthen sites, employed to preserve the external weathered layers of soils and reduce their

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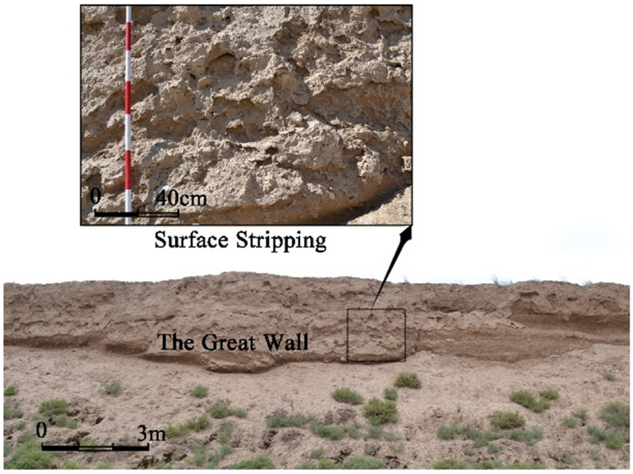

Fig. 1. Surface stripping on the Great Wall.

degradation rates. This method is mainly used to reinforce the top of the Great Wall to obtain a greater infiltration depth.

Research on the protection of earthen sites can be traced back to the 1960s [3]. In 1965, the International Council on Monuments and Sites (referred to as ICOMOS) was established to provide a platform for the protection of earthen ruins. Thereafter, the Getty Museum, Australian Heritage Commission, International Centre for the Study of the Preservation and Restoration of Cultural Property in Rome, and other institutions joined the preservation efforts [4].

Recent years have witnessed an increase in studies on weather-resistant materials [5–7]. The use of consolidants for improving the physicochemical and mechanical properties of deteriorated exposed earthen ruins should meet the requirement of minimal intervention as per principles for the conservation of heritage sites. Therefore, there are few studies on the use of consolidants in actual sites. Giacomo Chiari applied a variety of organic materials on the Selcucia and Hatra sites in Iraq, and proposed some requirements for the characteristics of consolidants [8]; Peru used ethyl silicate for the surface reinforcement of adobe buildings [9]. In China, a high-molar ratio potassium silicate solution (PS) was employed for the conservation of sandstone and earthen sites in arid areas [10].

Hence, although some new materials have been applied to earthen sites, there are still various problems in conservation practices. The materials can be classified into two categories. Organic materials, such as organosilicon materials [11,12] and acrylic resins [13,14], have proven to be effective in the protection of porous sandstone and earthen archaeological sites because of their favourable permeability and adhesiveness. Unfortunately, their poor compatibility and poor aging resistance render them unsuitable for practical use. Inorganic materials, such as limewater [15,16] and inorganic silicate [10], have longer life and better compatibility. However, their drawbacks, such as weak reinforcement strength, poor permeability, and the production of salt crystals [17] limit their use.

Previous conservation studies have demonstrated that there is no single consolidation product that is universally applicable for the protection of earthen sites. Therefore, one needs to assess the suitability of combined consolidation products, using simple and practical methods for heritage consolidation. Based on existing materials, a composite composed of organic and inorganic materials in different orders, was developed. This study evaluates different consolidation treatments to assess the suitability of composite materials for future use in the consolidation of earthen sites.

Composite reinforcement minimizes the overall disadvantages, and improves consolidation through the selection of organic and inorganic materials in various concentrations and different consolidation orders. When developing materials, it is also important to compare the parameters [18,19]. This study presents the results of laboratory tests conducted on six groups of samples, in order to analyse the differences in the strengthening performance between composite and traditional single materials. Micron lime, ethyl silicate, micron lime + ethyl silicate, ethyl silicate + micron lime, ethanol, and control group were tested. The colour parameters were studied in the RGB colour space. Since dropping infiltration was employed as the consolidation method in this study, the surface hardness was measured in order to analyse the changes in the surface mechanical properties. The time variation of the weight and compression wave (P-wave) velocity revealed the whole features of the soils, and served as a reference for changes in other data. A disintegration test was conducted to obtain the water resistance parameters. Unconfined compressive strength tests were carried out to evaluate the strength of the soils. The experimental approaches employed herein were aimed at evaluating the consolidation effect of the composites on earthen sites. Finally, synthetic evaluation was conducted using the obtained results.

2. Materials and methods

2.1. Preparation of samples

The disturbed soils used in this study were collected from the Great Wall of the Ming Dynasty, located in Yongchang, Gansu Province, China (Fig. 2). The disturbed soils were crushed fully, dried in an oven at 108 °C for more than 8 h, and then filtered by a test sieve of diameter of 2 mm. The moisture content and dry density of the remoulded samples were determined via a geotechnical compaction test, to be 16.5% and 1.6 g/cm^3, respectively. After storing for 24 h in a humidifier, the prepared soils were pressed to 50 mm cubes by a machine which was specially designed by Dunhuang Academic, China, for use in earthen sites (Fig. 3). The cubic samples were then dried naturally in an indoor environment for 28 days.

2.2. Selection of consolidants and application method

The variety of consolidants and application methods employed are important factors when seeking an optimum consolidation treatment. The inorganic material used in this study was micron lime. In the early 19th century in the UK, limewater was used for stone reinforcement. However, the consolidation effect of limewater was often limited owing to its low solubility at normal temperature, consequently, its use waned. In recent years, with the development of nanotechnology, the permeability and strengthening performance of traditional limewater has greatly improved. Nanosized calcium hydroxide and calcium oxide are considered novel and promising consolidants, and have been applied in the restoration and protection of murals and stone relics [16,20–23]. Ethyl silicate, which is widely used in moist earthen sites, was selected as the organic material. Micro lime and ethyl silicate were used since they are widely available and inexpensive (Fig. 4), and have also proven effective in many practical projects. The properties of the materials are presented in Table 1.

Conventional consolidation methods can be classified as coating, dropping infiltration, trickling infiltration, spraying, and soaking. In this study, the consumption of the consolidants was determined by using equation (1) [24], and the results are shown in Table 2. BM, BE, BM + BE, BE + BM, and Et were deposited on all the surfaces of the naturally dried samples with a pipette. The samples were treated with ethanol (Et) to study the influence of the solvent. Subsequently, the samples were placed in a sealed box for 6 h to prevent the rapid evaporation of Et and enhance the penetration depth of the consolidant. Thereafter, the samples were stored in laboratory conditions for 28 days.

$$S = [1 - \rho_d/(G_s \cdot \rho_\omega)] \cdot V \cdot S_r \quad (1)$$

where S is the volume of the consolidant (cm^3), ρ_d is the dry density of the samples, G_s is the specific gravity of the samples (2.71), ρ_ω is the density of water (1.0g/cm^3), V is the total volume of the samples (cm^3), and S_r is the maximum saturation (65%).

2.3. Experimental methods

Changes in the weight, surface hardness, and P-wave velocity as functions of the curing period were evaluated. The RGB colour space was used to quantitatively evaluate the colour difference before and after the consolidation treatments, and the disintegration and compressive strength of the soils were tested on the 28th day of storage.