Evaluation of Consolidation Treatments of Soils Used in Historical Sites

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Abstract. This study aims to evaluate the effectiveness of different consolidation treatments on earthen sites when exposed to ultraviolet radiation and dry-wet, and explore changes of samples in physical parameters, mechanical properties, water resistance and structures. The innovative treatments with the combination of organic and inorganic materials were used and compared to two commercial single materials, namely micron lime and ethyl silicate. The organic-inorganic treatment showed superiority in weight difference, surface hardness, compressional wave velocity, unconfined compressive strength, but its water resistance was slightly worse than organic materials after 38 days of accelerated aging. This innovative treatment with reasonable reinforcing sequence may be able to minimize some limitations by adjusting the amount and proportion of the consolidants.

Keywords: Consolidation, Dry-wet Cycles, Ultraviolet Radiation.

1 Introduction

As an important part of cultural heritage, earthen sites have sustained severe damage. The exposure of the Great Wall to outdoor conditions and frequent drying and wetting of the soils has caused noticeable degradation, resulting in the loss of coherence, surface stripping and partial loss of soils. There are a great number of studies thus far on weather-resistant materials. Reinforcement materials currently used are either inorganic materials or organic materials. Previous engineering cases showed that single materials cannot achieve the desired goal very well. Adding organic substances into lime, such as sticky rice slurry, tung oil, egg white and animal blood, et al., is a unique feature of traditional lime technology in China [1, 2]. The effectiveness of single and composite materials were compared and found that a composite material with reasonable reinforcing sequence could greatly improve the properties of soils [3].

Lime water, a traditional inorganic consolidants, was economical. Micron lime (BM), combined with the latest material science, obtained good infiltration depth. Ethyl silicate (BE) was used widely in heritage conservation, whereas its durability was not satisfied. Commercial nanolimes were applied for lime mortar consolidation due to their stability and compatibility, and their combined application with ethyl silicate exhibited some benefits [4]. The combination of inorganic and organic materials is a new thinking for use in the protection
of cultural relics in the future. The consolidant effectiveness should not be lost as a consequence of exposure to environmental processes [5, 6].

In the above context, the present study deals with the evaluation of different consolidation treatments in order to reinstate the cohesion of the weathered materials, enhance the durability of treated soils and reduce the degradation rate of the Great Wall of Ming dynasty in Yongchang, Gansu province, China. Ultraviolet radiation (UV) and dry-wet cycles (D-W) are common and serious aging factors for earthen sites in northwest of China. All laboratory tests were aiming to study the performance characteristics and deterioration process induced by UV and D-W, including surface hardness, compressional wave velocity, unconfined compressive strength (UCS) and water resistance. The evaluation was based on measuring durability in order to meet requirements or identify an efficient application.

2 Materials and methods

2.1. Sampling and consolidation
Soils were collected from the Great Wall of Ming dynasty in Yongchang, Gansu province, China. The disturbed soil was made into 50 mm cubic samples [3]. BM, BE, BM+BE (micron lime +ethyl silicate) and BE+BM (ethyl silicate +micron lime) were deposited on air-dried samples from six sides with a pipette under laboratory conditions. Subsequently, the above samples and untreated samples (Ut) were moved into a sealed box for 6 hours to prevent rapid evaporation of ethanol and enhance penetration depth.

2.2. Methods for evaluation of the applied products

Performance of UV. All the samples were remained under laboratory conditions for four weeks. UV aging test was then conducted on the samples. UV test machine equipped with 15-watt and 30-watt lamps, has been used for accelerated aging.

Performance of D-W. Similarly, samples were subjected to dry-wet cycles 4 weeks later, performed as per the following phases: 12 h curing at RH=96% and T=20 ºC; 10 h drying at RH=0% and T=40 ºC; 2 h cooling at T=20 ºC, prior to the following cycle.

Characterization techniques. The effects of UV and D-W were evaluated once daily until the parameters reached a constant value by measuring weight difference, surface hardness and UCS, following which the treated samples were tested every three days. The aging tests were carried out until the weights of the samples are basically unchanged. Uniaxial compression tests were then conducted using an electro-hydraulic servo tester (CSS-WAW1000DL) at a constant loading rate of 0.1 mm/min.

Disintegration test. Disintegration test after the 38th day of aging was conducted on the samples to evaluate water resistance of these consolidation treatments.

3 Results and discussion

3.1 Assessment of the effects of UV aging

Weight different refers to the change in weight after artificial aging compared with that of before artificial aging. The treated and untreated samples exhibited quite different weight differences as shown in Fig.1 (a). The weight decreases for samples treated with BM were significantly larger than samples treated with BE. This can be ascribed to the differences in the two impregnating solutions (BM and BE) in terms of density, viscosity, presence of
volatile solvent, etc. Notably, even if the samples treated with BM+BE used the same amount of consolidants as the samples treated with BE+BM, a smaller weight decrease was obtained for the treatment with BE+BM. Fig. 1 (b) shows even if samples treated with BE+BM, BE, as well as BM+BE exhibited comparable surface hardness, their degree of variation is remarkably different. The samples treated with BE+BM remained stable at 94 HA in surface hardness from 8 to 38 days of UV aging, while BM+BE treatment fluctuated seriously during this period. Surface hardness of the samples reinforced by BE decreased slightly with UV time. By contrast, the samples treated with BM and Ut experienced a noticeable decrease in surface hardness, which was much lower than those of the former three. All samples visually showed a rise in compressional wave velocity but overall there is no statistically significant difference from 14 days to 38 days as illustrated in Fig.1 (c). Compressional wave velocity of samples treated with BE+BM and Ut were overall larger than those of the other three groups. Fig. 2 shows the uniaxial stress-strain curves after UV aging. After application of BE, BM+BE and BE+BM, samples showed significantly higher UCS values compared to BM and Ut samples.

![Fig. 1. Changes in physical and mechanical parameters versus UV: (a) weight difference; (b) surface hardness; (c) compressive wave velocity.](image)

The wave velocity and surface hardness are lower at the beginning, whereas the weight is larger. Thereafter, the mass decreased, while the wave velocity and surface hardness increased significantly. Ultraviolet radiation made the samples drier at this stage. The samples treated with BE+BM showed superiority in terms of weight difference, surface hardness, compressional wave velocity and UCS when they were subjected to UV exposure. Particularly, compressional wave velocity increased only in samples treated with BE+BM compared with Ut. The increase in compressional wave velocity induced by BE+BM could be explained by the deposition of the products on surface of soil particles, which indicated that fine pores were reduced [7]. After application of BM+BE and BE, samples showed a similar pattern although BM+BE samples fluctuated seriously with UV time. This indicated that the properties of BM+BE samples varied greatly with UV time. It is notable that the weight went up sharply during 26 to 29 days. This is because the samples were kept in an indoor environment for a long time during weighing, measuring surface hardness and wave velocity. The samples absorbed moisture from the air. The decreasing wave velocity of the samples on these days confirms this opinion. The fluctuation of surface hardness and velocity versus UV time is related to inevitable inhomogeneity in sample preparation and reinforcement. The samples treated with BM were slightly higher than Ut in terms of surface hardness and UCS.

3.2 Assessment of the effects of D-W

The weight of all the samples declined with D-W (Fig. 3(a)). D-W has the least impact on the samples treated with BE+BM among these consolidation treatments. The weight of samples treated with BM+BE dropped noticeably between 17 and 20 cycles. This is owing to the fact that the surfaces are smoother after application of consolidants, which could lead to weight
loss in the process of measurement. María Barajas [7] also found that treatment with an inorganic compound (KSE) could generate a micro-porosity and the obtained surfaces are smoother than untreated sample. The samples treated with BM and Ut fell rapidly during D-W. It should be mentioned that the weight of samples treated with BE+BM and BE did not substantially change between 11 and 38 cycles and remained steadily at 1.5% and 2% respectively. Fig. 3 (b) shows that BE+BM was the most effective at increasing surface hardness during D-W. The repeated actions of D-W caused the reduction in surface hardness for the samples treated with BM+BE, BE and Ut. The lowest surface hardness was obtained by the sample treated with BM except of Ut, which fluctuated during the aging period. This indicated that surface hardness of BM samples is less affected by D-W than the other four treatments. Compressional wave velocity depends on density, porosity and water content of the soils, consequently it can be related to its compactness and conservation conditions [8]. The samples treated with BE+BM, Ut, BE and BM+BE experienced a similar trend with fluctuation at different ranges, among which BE+BM samples had the highest value of compressional wave velocity and BM+BE samples was the lowest. By contrast, BM samples saw a rising trend with the increase of D-W (Fig. 3 (c)). All these treated samples exhibited a significant increase in UCS after D-W as plotted in Fig. 4. BE+BM was found to be more effective than BE, BM, even though not being threefold as much. The increase in UCS is one of the key parameters positively influencing samples resistance to D-W, hence some benefits in terms of durability should be expected [9].

Water migration during repeated actions of D-W caused irreversible structure damage of the sample. This will affect the mechanical properties of the sample, thus reducing its surface hardness, compressional wave velocity and UCS. All these consolidants had a positive effect on soils to resist D-W. In particular, BE+BM exhibited superiority in terms of these parameters, thus had favourable durability to D-W. D-W decreased the surface hardness of BE and BM+BE samples, while BM-treatment fluctuated. BE and BM+BE samples fluctuated in compressional wave velocity as the number of D-W increased, whereas BM showed an upward trend during this aging process. This indicated that BM had better resistance to D-W than BM+BE and BE. In case of the high surface hardness and low compressional wave velocity, the penetration depth corresponding to samples treated with BM+BE was low, indicating that the applied consolidants accumulated on the sample surface, thus induced an over-strengthening. Other study confirmed that water based colloidal silica (12 nm) accumulated on the surface after application on porous limestones, and tetraethylsilicate-treated samples could produce an over-strengthening due to the high consumed product by capillarity absorption [10]. Weight rose during 23 cycles to 29 cycles, whereas surface hardness and velocity fell despite the rise of surface hardness of BE+BM samples. The water content of the samples grew, and BE+BM showed good resistance to D-W.

Fig. 2. Physical and mechanical parameters variation treated with different cycles of D-W: (a) weight difference; (b) surface hardness; (c) compressional wave velocity.
Fig. 3. Stress-strain curves of uniaxial compression tests on samples after UV aging.

Fig. 4. Stress-strain curves of uniaxial compression tests on samples after D-W aging.

3.3 Disintegration test

The samples treated with BE and BE+BM did not present any signs of disintegration under laboratory conditions, expect for forming a few bubbles in the early immersion stage [3]; hence, disintegration test was conducted on samples after UV and D-W to study water resistance of the treated samples and untreated samples.

**Disintegration test after 38 days of UV exposure.** All the samples produced a lot of bubbles immediately upon immersion in water as shown in Fig. 5. After 30 s of immersion only samples reinforced by Ut and BM presented some signs of disintegration. Water quickly entered the pores inside the samples. Thereby, the samples became soft and silty, lost its structure in 120 s, and then sank into the bottom of the container gradually. The sample treated with BM+BE presented considerable slower degradation rate compared with BM and Ut. Many continuous bubbles emerged from the sample, then two micro-cracks appeared at the top of the sample at about 90 s. The crack expanded, and a hard surface layer was exposed at 112 s. The sample treated with BM + BE became breakable after 12h, only remaining fragmented hard surface layer. The samples treated with BE+BM and BE did not change very much at the early stage of immersion. However, the sample surface reinforced by BE+BM was flaked off after 12 h, whereas many cracks and debris appeared at the top of the samples treated with BE, and there was no significant change from then on to 36 h.

Fig. 5. Disintegration process after UV: (a) 0 s; (b) 10 s; (c) 30 s; (d) 60 s; (e) 120 s; (f) 36 h.
Disintegration test after 38 days of D-W. The samples treated with BM and Ut produced a large number of bubbles immediately upon immersion in water (see Fig. 6). Meanwhile, the water surrounding the samples increasingly became turbid. The samples became silty, and then lost its structure in 90 s. There was a crack appeared on the sample treated with BM+BE at 60 s and then it expanded. The top of the samples began to collapse at 160 s, and the internal non-reinforced soils were exposed, producing small bubbles. The sample treated with BM + BE became breakable after 12h, only remaining fragmented hard surface layer. The results of disintegration test of the samples treated with BE+BM and BE after 38 days of D-W were similar to that UV except that a micro-crack appeared on the samples treated with BE+BM at 420 s. All the samples did not exhibit any obvious changes from 12 to 36 h.

The sample treated with BM did not show significant improvements in water resistance when compared with Ut (Table 1). Samples treated with BE+BM, BM+BE and especially BE showed better water resistance, although their water resistance declined after treatment with UV and D-W. UV had a greater influence on water resistance of the samples reinforced by BE and BE+BM, whereas the sample treated with BM+BE was more easily influenced by D-W. The soils reinforced by BM + BE showed an obvious boundary between the interior of the samples and the shallow hard surface layer, forming a weak interface, which is harmful to earthen sites. The crack appeared on the BE+BM sample expanded quickly. Water entered the interior of the soils through the crack, and this weakly strengthened part was easy to be damaged. This sample used half the amount of organic consolidant compared to the BE sample. However, BE has favourable permeability and adhesiveness. Therefore, the water resistance of BE+BM sample after 38 days of accelerated aging was slightly worse than that of BE. The amount and proportion of the composite materials should be further studied to achieve a better ageing resistance.

![Disintegration process after D-W: (a) 0 s; (b) 10 s; (c) 30 s; (d) 60 s; (e) 120 s; (f) 36 h.](image)

Table 1. Comparison of disintegration weight percent after treatment with UV and D-W aging.

| Samples | UV | D-W | Before treatment |
|---------|----|-----|-----------------|
| BM      | 100| 100 | 100             |
| BE      | 9.18| 6.22| 0.85            |
| BM+BE   | 63.64| 82.22| 27.18         |
| BE+BM   | 49.67| 40.63| 0.83           |
| Ut      | 100| 100 | 100             |
UV and D-W had a little effect on weight difference, surface hardness, compressional wave velocity, and UCS in 38 days, but water resistance dropped significantly compared with that before ageing. Therefore, UV and D-W had a negative effect on the samples. The frequent drying and wetting of water inside pores of soil expanded the cracks and pores and promoted the development of new micro-fracture thus did great damage to earthen sites. UV induced chemical reactions in consolidants (especially organic materials) thus reducing the effect of the consolidating treatment.

4 Results

1) All the consolidation treatments in this study have improved the dry-wet cycle resistance and UV resistance of soils, especially the samples treated with BE+BM.
2) The water resistance of BE+BM sample after 38 days of D-W is slightly worse than that of BE. The sample forms a shallow hard surface layer and creates an over-strengthening after application of BM+BE. BM+BE is not recommended as consolidant for the consolidation of historic sites. Water resistance of all the samples declines after treatment with UV and D-W. UV has a great influence on water resistance of the samples reinforced by BE and BE+BM.
3) The UCS, surface hardness and wave velocity tests show the strength of consolidated soil is generally improved but the wave velocity is reduced compared to untreated samples when subjected to D-W and UV except samples treated with BE+BM.
4) BE+BM and BM+BE-treatments with the same amount of the products shows different properties in UV and D-W; hence, the sequence of the consolidants are critical for the consolidation of earthen sites. The combination of organic materials and inorganic materials is a promising method in the protecting of earthen sites.

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