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Research Article

Experimental Studies on the Mechanical Properties of Loess Stabilized with Sodium Carboxymethyl Cellulose

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This research investigated the use of sodium carboxymethyl cellulose (CMC) as a reinforcement to improve mechanical properties of loess soil found in northwestern China. The mechanical properties of loess were determined by unconfined compressive strength and split tensile strength tests. Three different contents of CMC were adopted: 0.5%, 1.0%, and 1.5%. The results showed that utilizing CMC reduced the maximum dry density of the loess. The compressive strength, tensile strength, and Young's modulus are enough to construct low-rise buildings when the CMC content exceeds 1.0%, based on existing standards. This research thus provides a prospective sustainability method for loess stabilization.

1. Introduction

Loess is a clastic, predominantly silt-sized sediment that covers about 6.6% of the total area of China. The most extensive concentrations are situated in northwestern China, covering parts of Gansu, Xinjiang, Shanxi, Shaanxi, and Henan provinces [1, 2]. Loess has been used as a building material to construct houses for thousands of years and still comprises nearly 20% of houses built in rural parts of these provinces [3, 4]. Scholarly interest in loess construction materials has grown in recent years due to its low cost, local availability, and the sustainability of in situ construction for local residents [5–7]. However, loess construction materials have lower resistance to bending moments, as well as lower tensile and compressive strength properties. These deficiencies make loess construction material brittle, weak, and poor in damage resilience [8, 9]. To overcome these problems, stabilization techniques are used to enhance loess's natural durability and strength [10–14]. According to the literature, cement and lime are the most used additives for loess stabilization. However, this solution requires higher energy consumption and higher greenhouse gas emission during production [15, 16]. Natural fibers are also common additives for loess reinforcement, in order to reduce the size of shrinkage cracks and to improve its durability and tensile strength, but other researchers reported that adding these fibers may reduce the compression strength [17–19].

Therefore, several researchers have tried to find more effective and eco-friendly alternatives for soil improvement [20–27]. A review by Coulson and Fuller demonstrated that biological products could be used in various construction applications, including adhesives and masonry units [21]. Indeed, more and more biopolymers are being used to enhance the strength and durability properties of unfired earth, including sodium carboxymethyl cellulose (CMC), lignosulphonate, alginate from seaweed, tannins gums, resins, and other plant- and animal-based polymers [20–27]. CMC is a cellulose derivative, with carboxymethyl groups (-CH_2-COOH) bound to some of the hydroxyl groups of the glucopyranose monomers that make up the cellulose backbone [28–31]. It is synthesized by the alkali-catalyzed reaction of cellulose with monochloroacetic acid at room temperature [32]. Cellulose is one of the most abundant renewable resources on earth [33, 34]. Given its lower energy consumption and greater use of renewable resources, CMC coincides better than cement to the concept of green building material. In other words, it can help creation of structures that minimize damage to the environment and employ recyclable resources [35].

The aim of this study is to investigate the physical and mechanical properties of loess stabilized with CMC. Soil specimens were generated by compaction and oven-dried to a constant weight. Their basic physical and mechanical properties were tested, including optimum water content, maximum dry density, compressive strength, and tensile strength. Furthermore, the microstructures of loess stabilized with CMC were investigated with the aid of SEM imaging.

2. Materials and Methods

2.1. Materials

2.1.1. Loess. The loess for the experiments was sourced from the northern Gansu province of China because of its availability and abundance in this region [1, 36]. Its physical and mechanical properties were tested according to the Chinese standards for soil testing (GB/T 50123) [37], which are given in Table 1. Figure 1 shows the grain size distribution of the loess samples using sieve analysis and hydrometer test, as prescribed in GB/T 50123.

2.1.2. CMC. The CMC used in this experiment is manufactured by the Shanghai Shenguang Edible Chemicals Corporation Limited company, and its product model is FH9 (acid resistant). Its particle size is fine, with 10% max retained in 60 mesh. The viscosity of its 1% aqueous solution is 200–500 mPa·s. Its degree of substitution is about 0.90. Its purity is greater than 98.0% [38]. CMC is available as a white powder, with a density of 0.5–0.7 g/cm^3. It has high hygroscopicity and dissolves in water easily. As to price, the retail price of industrial CMC is approximately 6800 CNY/t; by comparison, the wholesale price of ordinary Portland cement is approximately 425 CNY/t [39].

2.2. Small Cylinder Samples. After dry mixing the loess and CMC, a certain amount of water was sprinkled in and a wet mix was prepared. The moist mix was then compacted in a dismountable cylindrical mould, using a matched circular steel rammer (300 g) free-dropping from 240 mm high. Layers that are too thick may potentially have areas that are not compacted because the tamper is not powerful enough to compact the deep lifts of the soil [40]. Therefore, it was compacted in four layers with 20 knocks per layer, according to GB/T 50123. The resulting samples had an average length of 80 mm and a 39.1 mm diameter. The composition and number of samples are listed in Table 2. In total, 228 samples were made. All the samples were oven-dried at 40°C for 3 days. The oven was used to accelerate the drying process; 40°C represents the temperature in Gansu province on a sunny summer day.

2.3. Test Method. The test campaign we carried out can be divided into three phases according to the characteristics to be studied: unconfined compression tests, indirect tension tests, and scanning electron microscope (SEM) analysis. Both the compression tests and the indirection tension tests were carried out in a 30 kN electromechanic testing machine under displacement control.

Table 1: Physical and mechanical properties of loess used in the tests.

Property	Composition
Moisture content (%)	7.8
Liquid limit (%)	28.17
Plastic limit (%)	20.30
Plasticity index (%)	7.87
Optimum moisture content (%)	18.06
Maximum dry density (g/cm^3)	1.700

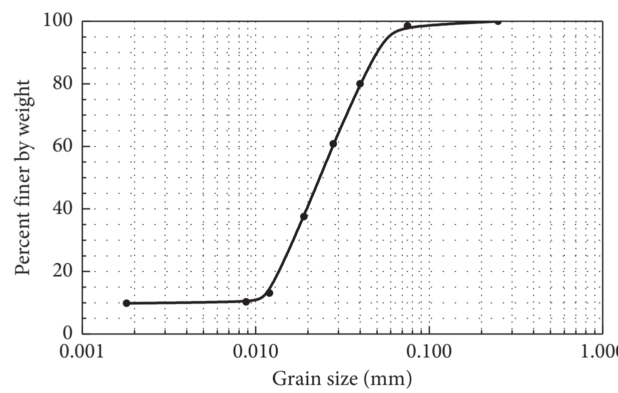

Figure 1: Grain size distribution of the loess.

Table 2: Mixture types and number of cylindrical samples.

Mixture type	CMC content (%)	Water content (%)	Number of samples
A	0.0	12.4	12
		14.2	12
		15.9	12
		18.1	12
		20.0	12
B	0.5	17.6	12
		19.7	12
		21.8	12
		23.7	12
		25.1	12
C	1.0	18.2	12
		20.1	12
		21.7	12
		23.8	12
D	1.5	15.6	12
		18.3	12
		20.1	12
		22.0	12
		22.8	12

2.3.1. Unconfined Compression Test. Although there is some existing guidance for earthen materials, there is still a general lack of standardization, particularly regarding the mechanical testing of individual units. Procedures are often based on those used for concrete, blocks, and fired bricks [22]. Different procedures may lead to different results. Cubic and rectangular specimens are known to show higher strengths than slender cylindrical samples [41]. It has also been proven that the effect of the confining pressure on the peak value of the compressive strength is negligible. Hence, the unconfined compressive strength can be used to represent the mechanical properties of the loess specimens [42, 43]. The unconfined compressive strength (UCS) of each specimen was calculated according to the GB/T 50123 standard, 1999. This study used similar samples and procedures as earlier research [41]. The samples were tested under direct compression, and the displacement rate was equal to 0.01 mm/s (Figure 2).

Figure 2: Unconfined compression test.

2.3.2. Indirect Tension Test. The indirect tension test is a common test, often referred to as the splitting tensile test. The tensile strengths of the stabilized loess specimens were determined by the using indirect tension test method proposed by the British Standards Institution (EN 13286-42): "Test Method for the Determination of the Indirect Tensile Strength of Hydraulically Bound Mixtures" [44]. In this test, the slenderness ratio of the specimens is 2.05. Two pieces of plywood with a dimension of $4 \times 4 \times 80$ mm were used as bearing strips. The samples were tested under compression, and the displacement rate was equal to 0.002 mm/s. This test determined the tensile strength by applying a vertical force on two parallel faces of a horizontally laid cylinder. The sample was then split vertically along its length (Figure 3). The tensile strength can be determined indirectly by using this expression from the EN 13286-42 [44]:

$$R = \frac{2F}{\pi HD}, \quad (1)$$

where R is the indirect tensile strength, F is the maximum applied force, H is the length of the sample, and D is the diameter of the sample.

3. Results and Discussion

In general, the results of soil experiments usually show large discreteness. The coefficient of variation (CoV) is frequently used to characterize the discreteness. The CoV in some of the literature reached 30% or higher [22, 41]. This may be attributed to the inherent peculiarity of soil or accidents during experiments. In this work, to avoid the influence of accidents in the experiment and to make the results more reliable, the data with large deviations were rejected. The results presented in this paper all have CoV values below 15%.

3.1. Moisture-Density Relationship. The weight of the initial and oven-dried loess samples determined their water content and dry density. The moisture-density curves for the loess, compacted with and without CMC, are shown in Figure 4. For the samples without CMC, the optimum water content (w_{opt}) was 18% and the maximum dry density $\gamma_{d\max}$ was approximately 1.70 g/cm^3. w_{opt} varied in a narrow range of 20–22% and $\gamma_{d\max}$ was about 1.60 g/cm^3 for all the CMC additions. In other words, CMC increased w_{opt} and decreased $\gamma_{d\max}$ of compacted the loess at the same time.

As stated above, CMC is a kind of highly water-absorbent material. Thus, the mixture needed more water than pure loess and more water evaporated during the drying process. Besides this, the dry density of CMC is far smaller than the compacted loess. All these reasons lead to higher w_{opt} and lower $\gamma_{d\max}$ in the specimens stabilized with CMC.

3.2. Unconfined Compressive Strength. The compressive strength of the unstabilized soil samples is generally 1–3 MPa [43]. It is mainly determined by using the soil type and manufacture method. The maximum UCS of the pure loess is 2.07 MPa in this study, which is close to the referred value [43]. The results of the unconfined compression test are presented in Figure 5. It shows the maximum value of UCS in specimens without CMC (No CMC) and those with 0.5% CMC, 1.0% CMC, and 1.5% CMC are 2.07, 1.75, 4.11, and 5.5 MPa, respectively. It can also be clearly observed that compared to specimens without CMC (No CMC), the 0.5% CMC has a lower UCS, while the specimens with 1.0% and 1.5% CMC have higher UCS. The strength of loess consists of two parts: a framework formed by soil particles and connections made by CMC. When the CMC proportion is 0.5%, soil particles play a more important role than CMC since there is too little CMC to offer high connection strength. When the CMC proportion is increased, however, CMC can not only make up for the reduction of soil strength but also provide a reliable connection. Therefore, the specimens stabilized with 1.0% and 1.5% CMC showed higher UCS than those with 0.5% or without CMC.

Chan and Low [45] used the same test method as in this research. Their soil consisted primarily of silty to sandy soils, which obtained compressive strengths between 1.2–1.39 MPa and 2.16–2.17 MPa, respectively, for 5% and 10% cement-stabilized earth specimens. For similar soils

Figure 3: Indirect tension test.

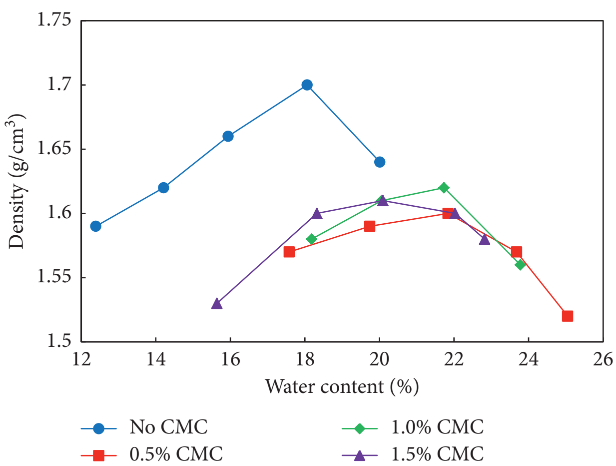

Figure 4: Moisture-density relation for CMC-stabilized soil.

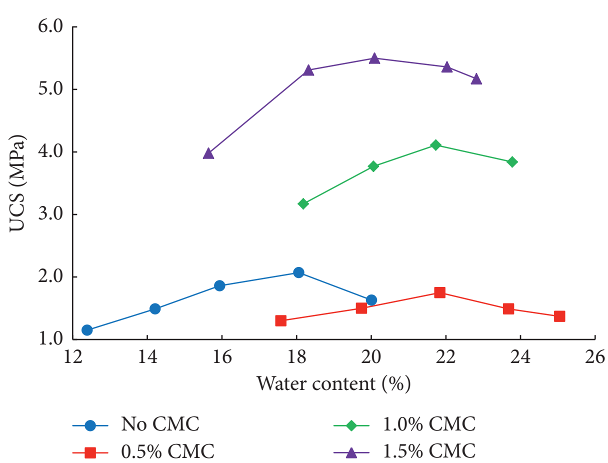

Figure 5: Moisture-UCS relation for CMC-stabilized soil.

stabilized with 5% cement and 9% kaolin, Sturm et al. [41] obtained a compressive strength of 1.1 MPa. Hossain and Mol [46] stabilized clayey soil with volcanic ash and cement kin dust. The UCS of the cylindrical specimens (39 mm diameter and 78 mm length) was between 3.1 and 6.01 MPa. Taallah et al. [47] made rectangular specimens (100 × 100 × 200 mm) of soil stabilized with different cement and fiber proportions, using a static compaction method with 10 MPa of compaction pressure. Galán-Marín et al. [48] obtained compressive strength ranging from 2.2 to 4.4 MPa for natural polymer-stabilized clay soil with rectangular specimens, while Dove et al. [22] obtained a compressive strength ranging from 0.5 to 1.78 MPa for alginate-stabilized clay soil with rectangular specimens. These results show that fiber has almost no effect. The results of this test cannot be directly compared with the target compressive strength for the compressed earth blocks that are over 2 MPa [41, 49–54]. Since the specimens are slender, they can be regarded as unconfined and are therefore expected to have a lower compressive strength [41]. Thus, CMC-stabilized soil meets the abovementioned requirements of UCS.

3.3. Young's Modulus (E_s). The stress-strain curves of samples derived from the force-deformation relations are shown in Figure 6. The curves show that CMC considerably increased the deformability of the stabilized soil samples, indicating that the compacted stabilized loess could bear a larger deformation before failure. Furthermore, the stress-strain curves of pure loess showed higher dispersion compared with the CMC-stabilized samples. This means that the CMC steadied the performance of specimens under compression and made the results more reliable.

There are many different methods to obtain E_s of a material, and different methods may lead to different results [45]. To avoid the influence of the initial contact gap and the vibration near bearing capacity, the tangent modulus between 40% and 70% of the maximum stress was selected to represent Young's modulus in this research. The results are shown in Figure 7. The effect of CMC and water content on Young's modulus shows a very similar trend with the one for UCS and dry density. The maximum Young's modulus of specimens without CMC is 315.59 MPa. The maximum Young's moduli of specimens with 0.5%, 1.0%, and 1.5% CMC are 276.95 MPa, 501.04 MPa, and 611.31 MPa, respectively.

Chan and Low [45] used clay stabilized with 10% cement to make cylindrical specimens, and their test results yielded

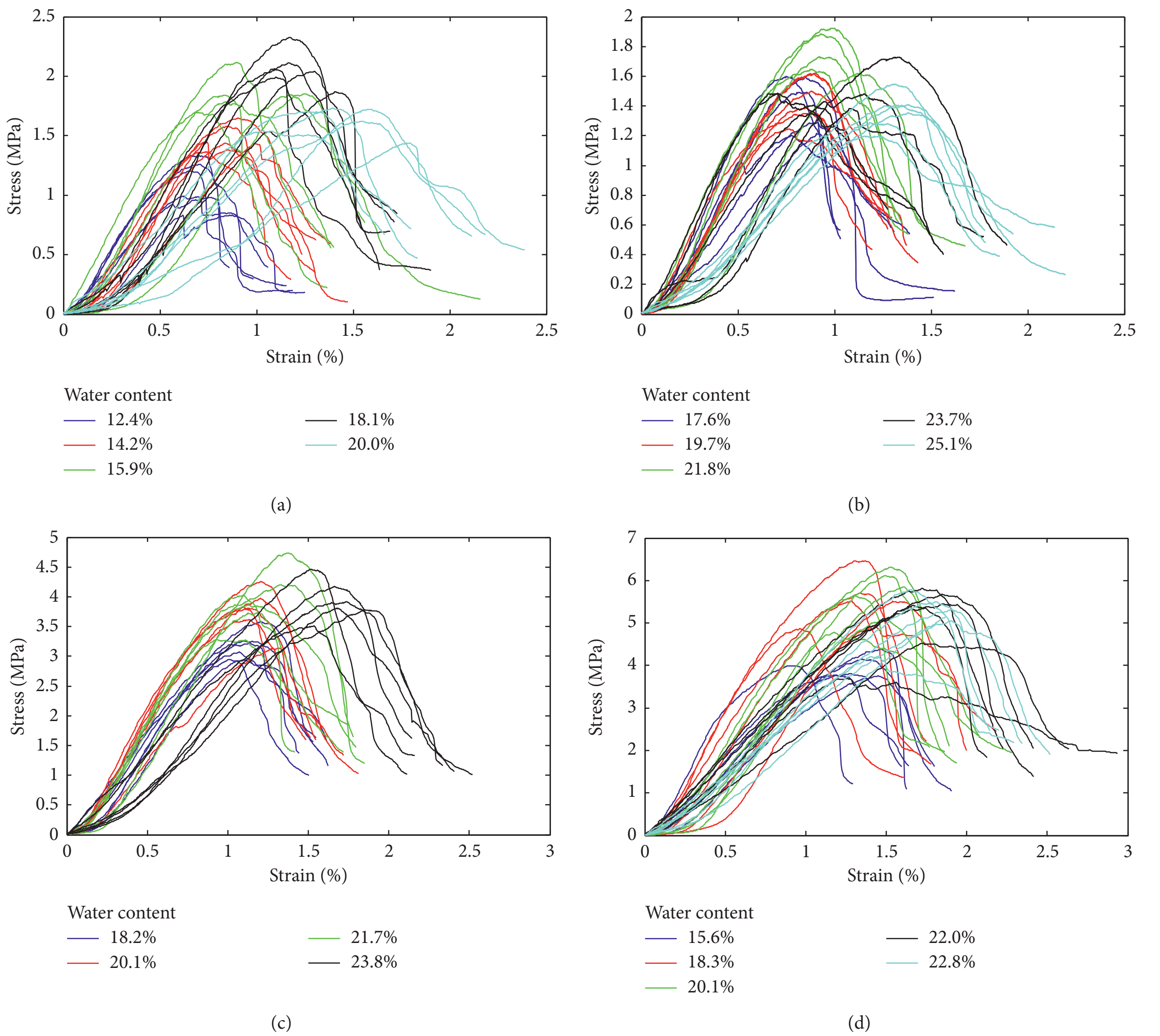

Figure 6: Compressive stress-strain curves of specimens: (a) without CMC and with (b) 0.5% CMC; (c) 1.0% CMC; (d) 1.5% CMC.

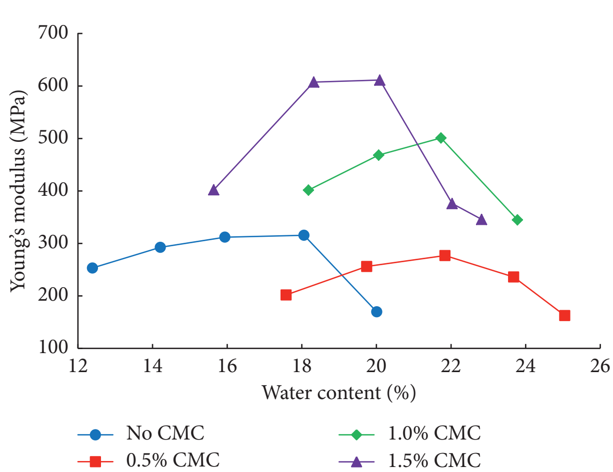

Figure 7: Moisture-E_s relation for CMC-stabilized soil.

Young's modulus values of 80–150 MPa. The results of Reddy and Gupta [55] were all higher than 1000 MPa. This huge difference may be attributed to the way Young's modulus is defined and calculated. The HB195 [53] Australian Earth Building Standard proposes Young's modulus of 200 MPa for earth buildings. Therefore, Young's modulus values derived from this paper agreed with those proposed by earth construction standards and previous studies.

3.4. Indirect Tensile Strength. The results of this phase of testing are shown in Figure 8 and indicate that the indirect tensile strength of the loess stabilized by CMC is about 90% lower than its compressive strength. This is largely because of the ease with which cracks can propagate under tensile pressure. The maximum indirect tensile strength of the pure loess was 0.25 MPa. With a similar pattern to the result

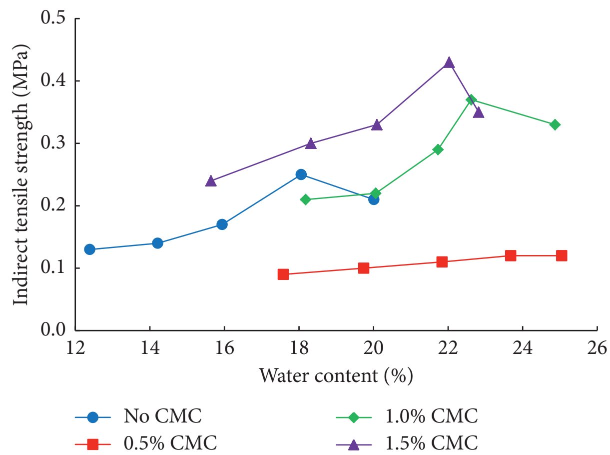

Figure 8: Moisture-indirect tensile strength relation for CMC-stabilized soil.

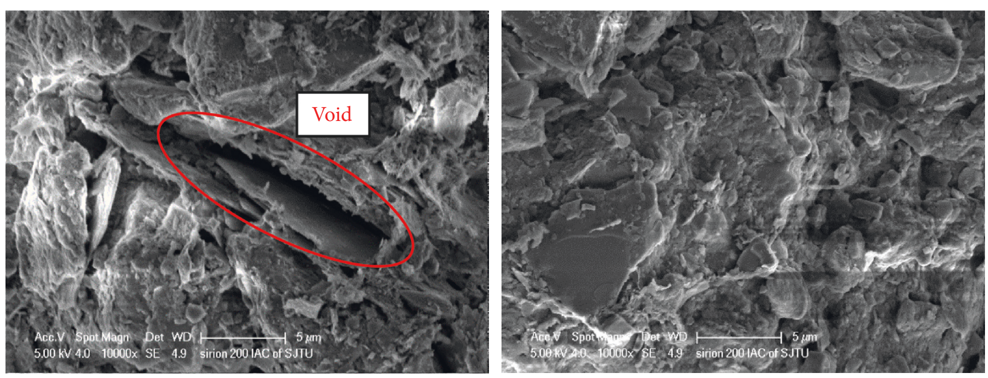

Figure 9: SEM images of the specimen samples under magnification of 1000: (a) without CMC; (b) with 1.0% CMC.

found from UCS tests, in the case of 0.5% CMC content, there was a decrease of 52% in the maximum indirect tensile strength compared to the loess without CMC; however, for the cases of 1.0% and 1.5% CMC, there was increases in the maximum indirect tensile strength of 48% and 72%, respectively. Similar tests by Sturm et al. [41], who used cylindrical specimens of soil stabilized with 5% cement and 9% kaolin, showed a tensile strength of around 0.058 MPa, which is about 5% of the specimens' compressive strength. In this study, the ratio was about 9%. Yetgin et al. [56] used soil stabilized with fibers to make cubic specimens for tensile strength tests and obtained tensile strengths between 0.4 and 0.75 MPa. Other studies have also shown that fiber can improve the tensile strength more effectively than other materials. Nevertheless, compared with the above results, the CMC-stabilized loess tested in this study demonstrated a considerably high tensile strength.

3.5. SEM Analysis. The analysis reported in the previous section showed that CMC could increase the strength and Young's modulus of compressed loess specimens when the CMC proportion is high enough. To determine the mechanism that governs this stabilization process, field-emission scanning electron microscope (FE-SEM) analysis was carried out on the specimen pieces after the strength tests, using the Sirion 200 SEM (FEI, Oregon, USA) at the Instrumental Analysis Center of Shanghai Jiao Tong University. Figure 9 shows the SEM images of samples without CMC (Figure 9(a)) and with CMC (Figure 9(b)). The high porosity observed in the pure loess specimen disappeared in the CMC-stabilized loess specimens. No chemical reaction took place, just the dissolution and solidification of the CMC. The CMC dissolved in water and filled the voids, and then it coagulated and connected the soils when the water evaporated. There should be more voids in the specimens stabilized with CMC due to the high stickiness of CMC. However, the CMC filled them, and because of its lower density, the specimens' dry density decreased. Likewise, CMC connected the soil particles effectively after the water evaporated. This connection is much stronger than what pure loess could provide.

4. Conclusions

A series of tests was carried out to evaluate the influence of CMC on the physical and mechanical properties of loess, including optimum water content, maximum dry density, unconfined compressive strength, indirect tensile strength, and Young's modulus. The following conclusions can be drawn:

(1) The CMC-stabilized loess obtained higher optimum water content and lower maximum dry density than the raw loess

(2) The maximum compressive strength and tensile strength attained were 4.11 MPa and 0.37 MPa, respectively, when CMC content was 1.0% which is enough to construct low-rise buildings according to existing relative standards

(3) The CMC increased Young's modulus of the loess; this characteristic gives CMC-stabilized loess better deformation capacity

(4) SEM analysis revealed that the dissolved CMC filled the cavity and finally connected the soil particles effectively, after water evaporation

Notation

CMC: Sodium carboxymethyl cellulose
D: Diameter of the cylindrical specimens, in mm
E_s: Young's modulus, in MPa
F: Maximum force, in N
H: Height of the cylindrical specimens, in mm
R: Indirect tensile strength, in MPa
SEM: Scanning electron microscope
UCS: Unconfined compressive strength, in MPa
w_{opt}: Optimum water content, in %
$\gamma_{d\,max}$: Maximum dry density, in g/cm^3.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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