Study on the microstructure and soil quality variation of composite soil with soft rock and sand

Abstract: Aiming at the remediation of Mu Us Sandy Land, which is one of the four major sandy areas in China, the local soft rock was selected as the remediation material for sand improvement, and the soil quality changes after the compounding of soft rock and sand were analyzed. The results show that the clay minerals in the soft rock are closely cemented to each other, forming a rich pore structure with a high hydrophilic, large specific surface and interlayer space. With the treatment of 1:1 and 1:2 soft rock/sand, there are more attachments on the surface of soil particles, and most of the particles are in contact with each other. The content of polysaccharides in the compound soil after the mixture of soft rock and sand is significantly higher than that of total sand treatment. With 1:1 of soft rock/sand, the content of free ferric oxide increased gradually with the depth of the soil layer. The organic carbon content in the 0–10 and 20–30 cm soil layers showed a good change. After the addition of arsenic sandstone, the soil cementation of compound soil and the content of polysaccharides and organic carbon have been significantly changed. Soft rock is a kind of natural material conducive to the improvement of sandy soil.

Keywords: soft rock, sand, composite soil, microstructure

1 Introduction

There are various types of sandy land in China. It is an important arable land reserve resource to supplement. The Mu Us Sandy Land is one of the four major sandy areas in China, with serious sanding and fragile ecology [1]. It is a priority area for the management of China’s ecological security pattern. With the rapid economic development, the exploitation of land is increasing, and the conflict between humans and land is becoming more and more prominent [2–4]. At present, agricultural production activities in vulnerable and sensitive areas such as sandy areas have become an important measure to increase arable land resources in many parts of the world. However, the extremely poor soil permeability and nutrient retention capacity are the fundamental reasons that limit the development of agricultural production in coarse soils such as sandy lands [5]. At present, most of the land remediation projects for sandy land involve the direct bulldozing of sand dunes to form large-scale leveled arable land, and then agricultural production is carried out with the support of facility agriculture. However, this method does not improve the texture of the soil in any way and is prone to the risk of a sharp decline in groundwater resources. In the meantime, it can accelerate the mineralization of soil organic matter and reduction of nitrogen due to large-scale facility agriculture.

There have been many improvement measures for sandy soils, such as the addition of organic matter and soil conditioners. These methods can change the functional structure of microorganisms in sandy soils, thus improving the soil structure and enhancing water and nutrient retention, but high costs are incurred for widespread use [6–9]. It is difficult to form a good soil structure in sandy areas due to the lack of cementing material, and the current remediation of sandy areas is mainly based on tree
planting, grass planting, and spraying of sand-fixing agents. There is a lack of new materials in large-scale sandy area remediation. Soft rock is rich in colloidal material and has a clayey texture, which gives the sandy soil good air permeability and water and fertility retention [10]. The simple process of compounding soft rock with sand is of great practical importance as it enables large-scale sand remediation to be accomplished in an engineering manner. Although this technology addresses a regional problem, it is likely to have applicability to similar semi-arid areas with sandy soils around the world.

Soil agglomerates are the basic units of soil structure and act as indicators of changes in soil quality, influencing the cycle of soil water, fertility, gas, and heat. The formation, turnover, and stabilization of natural soil agglomerates is a very complex process that results from the combined action of soil electrolyte concentrations, exchange fluid types, clay minerals, carbonates, organic matter, and iron oxides [11–13]. The content, type, and morphology of various cementing substances in soil agglomerates formed under different environments show great differences. Soft rocks with a high clay content and strong water retention ability are widely distributed in the Mu Us Desert. Studies have shown that by mixing soft rocks with wind-blown sand soil in a certain proportion, it is possible to effectively alter the soil structure and enhance its water retention ability, thereby creating improved soil suitable for crop growth. Currently, there is extensive evaluation being conducted on this type of improved soil. Some scholars have investigated the mechanism and impact of soft rocks on sand fixation and have discovered that soft rocks can effectively consolidate surface, sand particles, increase soil water content, and create favorable conditions for vegetation growth [14]. Additionally, other scholars have examined the influence of soft rocks on nitrogen and phosphorus in sandy soil, providing a foundation for plant cultivation and fertilization when using soft rocks for sand treatment [15]. The utilization of soft rocks for sand remediation has a significant impact on the soil structure, as the physical properties of soil are determined by the contact mode of soil microstructural units [16]. Therefore, the use of soft rocks aims to improve the nature of sandy soil by altering its microstructure. The influence of planting plants on sandy soil improvement also leads to significant changes in nutrient content and enzyme activity. However, existing studies have rarely explored the effects of soft rock on the microstructure and soil quality of the improved sandy soil.

In this study, the local soft rock was selected as the remediation material for sand remediation, and the microstructure and evolution of cementing material of soft rock and sand compounding soil were analyzed to investigate the stability mechanism of soft rock and sand compound into the soil.

2 Materials and methods

2.1 Overview of the land remediation project

The technical means of compounding soft rock containing colloidal material into the sand and compounding it with different proportions of sand to form soil has been used in the wind–sand soil area of Yulin City, Yuyang District. This technology has led to the agglomeration of sandy soils, improved the physical properties of the tillage layer, increased water and fertility retention, and met the basic needs of crop growth. The experimental area was set up in 2010 and is shown in Figure 1. The soil texture category of the experimental area is compact sandy soil, and 12 years have passed since the current sampling period. During the planting period, potatoes and maize have been grown with good economic and ecological benefits.

2.2 Sample collection and analysis

After the maize and potato harvest, samples were collected and mixed in 0–10, 10–20, and 20–30 soil layers, and each plot was mixed into one mixed sample using the five-point method. The soil samples were divided into two parts: one in situ for microstructure determination and one with plant and animal debris and large gravel removed, air-dried and ground through 0.25 mm sieves for the determination of free iron oxide and polysaccharides. The content of the particulate organic carbon (POC) was determined by the wet screen method [17]. For the determination of POC, a 20 g sample of air-dried soil with a particle size of 2 mm was weighed and placed in a 250 mL triangular bottle. Then, 60 mL of sodium hexametaphosphate solution (5 g L\(^{-1}\)) was added, and the mixture was shaken for 10–15 min. After that, it was oscillated on a reciprocating shaker at a temperature of 18°C and a speed of 90 rpm min for 18 h. The resulting dispersion liquid was screened using a 53 μm sieve and washed with pure water to clarify the sieve water. The upper part of the sieve contained the particulate organic matter, which was separated and dried at 80°C overnight (24 h) in an aluminum box, and then weighed. The underscreened part, with particles smaller than 53 μm, represented the mineral-bound organic matter. It was dried in a water bath at 90°C and then further dried in an oven for 24 h. The percentage of each group in the total soil was
calculated based on their weights. The soil particles that passed through the 53 μm sieve were ground using a 0.149 mm screen. A certain weight of the sample was taken to determine its organic carbon content, which was then multiplied by its percentage in the soil to calculate the POC content. The free iron oxide in the soil was determined by the sodium bisulfite–citrate–sodium bicarbonate extraction method [18]. The free iron oxide was extracted using the sodium dithionite-sodiumcitrate-sodium bicarbonate method (DCB) method, which involved the combination of sodium disulfite, sodium citrate, and sodium bicarbonate. The o-phenanthroline colorimetric method was employed to determine the extracted iron oxide. The DCB solution was mixed with the soil sample and heated in a water bath at 80°C while continuously stirring until the soil sample turned grey. The supernatant was separated by centrifugation, and then 100 g L⁻¹ hydroxylamine hydrochloride, acetoacetate/sodium acetate buffer solution, and 1 g L⁻¹ phenanthroline were added to the solution. The solution was allowed to develop color for 1.5 h at room temperature (20°C). The absorbance was measured at a wavelength of 520 nm using a 1 cm colorimetric dish. The soil polysaccharide content was measured by hydrolyzing 5.0 g of each soil sample in a 100 mL triangular flask. After hydrolysis, the solution was filtered while still hot. Then, 5.0 g of CaCO₃ was added to the filtrate to completely neutralize the solution. The solution was filtered again and the volume was adjusted to 100 mL. The light absorption value was determined by taking 1.0 mL of the hydrolysate in a test tube and treating it with the anthrone and sulfuric acid method at a wavelength of 620 nm [19]. The soil microstructure was observed by a scanning electron microscope (SEM) [19]. The soil microstructure is randomly dispersed on a conductive carbon glue substrate and then captured using an electron microscope.

Figure 1: Location of the experimental area.
after gold spraying. The imaging parameters include a working distance of 30 mm and magnifications of 100×, 500×, 1,000×, and 2,000×.

3 Results and analysis

3.1 Analysis of the soft rock microstructure

The clay minerals in the soft rock are dominated by multi-angled, disordered wind, and dust particles. The authigenic clay in the cemented material of the soft rock is dominated by montmorillonite and green montmorillonite mixed layers, interspersed with a small amount of illite. The montmorillonite is often filamentous and dominated by calcareous montmorillonite, which is mainly distributed in intergranular cementation positions. The green montmorillonite layer is often honeycombed and distributed in the form of thin films and coverings surrounding the mineral or filling the pore space. Illite is mainly present as a clay bridge formation.

The clay minerals in arsenic sandstone are closely cemented to each other, forming a rich pore structure with a high hydrophilic, large specific surface, and interlayer space. And because of the weak interlayer linkage between montmorillonite and green montmorillonite layers, they are easily swollen and have strong ion-exchange properties.

The results of SEM and energy spectrum analysis in Figure 2 show that the intergranular cementing material in the soft rock is mainly flake calcite and filamentous calcareous montmorillonite, which cement each other to form large intergranular pores within the soft rock, with a small amount of illite attached to form clay bridges between the grains. Cementation is the precipitation of minerals in the pores of clastic sediments, forming authigenic minerals and cementing the sediments into rock, which is an important factor in reducing the porosity of the reservoir. Cementation primarily clogs pores without reducing intergranular volume and creates pore channels of varying pore sizes [17]. Montmorillonite is an aluminosilicate clay mineral with a 2:1 layered structure, which is structurally represented by two silicon–oxygen tetrahedra sandwiched between a layer of aluminum–oxygen octahedra [20–22]. The charge of the montmorillonite crystal layers and the broken bonds at the edges make it negatively charged, and the resulting electrostatic gravitational force can draw polar water molecules between the layers to swell the crystals. Water absorption and swelling are one of the characteristics of montmorillonite. The montmorillonite in soft rock is mainly filamentous calcareous montmorillonite, and the water absorption and swelling rate can be 5–15 times.

Montmorillonite in soft rock is a weathering product of feldspar, which comes from several sources. On the one hand, it is the hydrolysis and weathering of feldspar into montmorillonite. On the other hand, feldspar is hydrolyzed to kaolinite, which is converted into montmorillonite by cation adsorption under certain conditions. Furthermore, mica in soft rock can also be converted into montmorillonite by hydrolysis and weathering under certain conditions [23,24].

3.2 Analysis of pore morphology inside the soft rock

As shown in Figure 3, after observing under an SEM, the pore type of the soft rock is very rich and pore connectivity is general. The pores between the clay minerals are mainly 100–300 nm. The pore radius ranges from 50 to 400 μm, with a maximum of 500 μm, and is mostly filled with authigenic silica and clay minerals to form primary intergranular pores, intergranular solution pores, intra- and intergranular solution pores, and microfractures. Intergranular pores refer to the pores between mineral particles or crystal particles. Intergranular pores are mainly pores between mineral grains such as clay. They are mostly triangular and their size is mainly controlled by the size of the mineral grains and the degree of compaction [25]. Intragranular pores are pores within mineral grains. They are mainly pores resulting from the dissolution of soluble minerals such as quartz, calcite, and dolomite [11,26]. Dissolved pores are irregularly shaped and developed in clusters and are characterized by curved pore walls.

3.3 Analysis of the microstructure of soft rock compounded with sand

The observation of the soil microscopic images obtained under an SEM reveals the morphology of the surface of the soil particles and the interaction between the particles. Figure 4 shows SEM images of different ratios of the compound soil after many years of planting. As can be seen in


### Table

<table>
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<th>Element</th>
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<td>Ca O</td>
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<tr>
<td>Fe O</td>
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**Figure 2:** SEM and energy spectrum analysis of arsenic sandstone filamentous montmorillonite.

**Figure 3:** Microstructure of the soft rock section.
the low magnification (100 and 500×) images, there is more cemented material between the soil particles in the 1:1 soft rock/sand treatment, and as the sand content increases, the particles become dispersed and the cemented material gradually becomes less.

In the high magnification images (1,000 and 2,000×), in comparison to the 1:5 soft rock/sand treatment, the 1:1 and 1:2 soft rock/sand treatment has more adhering material on the surface of the soil particles. The particles are well bonded to each other with more cementing material, and the soil has good agglomeration while retaining a certain amount of pore space. Several scholars have demonstrated that the addition of soft rock to aeolian sand soil in varying proportions leads to a noticeable increase in the sand

Figure 4: SEM images of compound soils with different proportions. (a)–(d), (e)–(h), and (i)–(l) are images of soft rock/sand at 1:1, 1:2, and 1:5, respectively, (a), (e), (i), (b), (f), (j), (c), (g), (k) and (d), (h), (l) are microscopic images at magnifications of 100, 500, 1,000 and 2,000×, respectively.
content over the years of experimentation. Furthermore, the content of silt and clay also increases. This study provides additional evidence supporting these conclusions, specifically in relation to microstructures [27,28].

3.4 Changes in polysaccharide patterns in arsenic sand compounded into soils

The soil polysaccharide content was altered by different compounding ratios. The polysaccharide content in the 1:1 and 1:2 ratios of soft rock/sand was significantly higher than that in the whole sand. The highest polysaccharide content was found in the 1:2 ratio of soft rock/sand (Figure 5), and in the 10–20 cm soil layer, the 1:2 ratio of soft rock/sand was significantly higher than in the other treatments. Among the three treatments, 1:1 and 1:2 ratios of soft rock/sand significantly increased the polysaccharide content of the soil in the 0–30 cm layer compared to the whole sand, while in the 10–20 cm layer, 1:5 ratios of soft rock/sand was close to the whole sand treatment. In the 20–30 cm layer, the highest polysaccharide content was found in the 1:1 ratio of soft rock/sand, while the lowest polysaccharide content was found in the whole sand treatment. The addition of soft rock to sandy soil increased the content of polysaccharides. This increase can be attributed to the planting of crops after the addition of soft rock [29]. Polysaccharides in sandy soil are derived from plants and microorganisms, and they get adsorbed by montmorillonite present in the soft rock. This adsorption process helps in reducing the decomposition rate of polysaccharides [30].

3.5 Free iron oxide variation pattern of the soft rock compounded into the soil

Figure 6 shows the free iron oxide content of each compound ratio in different soil layers. In general, the variation of the free iron oxide content gradually increased with the depth of the soil layer under the 1:1 ratio of soft rock/sand. The free iron oxide content was 2.63 times higher in the 20–30 cm than that in the 0–10 cm. This is because of agglomerate cement, which severely affects the free iron oxide content, resulting in a greater variation in the free iron oxide content with soil depth under the 1:1 ratio of soft rock/sand. The other treatments were not significantly different compared to the all-sand treatment. The content of free iron oxide in sandy soil is primarily influenced by the presence of cement in the soft rock. The impact becomes more pronounced as the proportion of the soft rock added increases [31].

3.6 Changes in the carbon content of the soft rock and sand compounded into soil

Soft rock and sand compound soils were studied for soil POC after crop cultivation. The results showed (Figure 7) that it was 0–10 cm (2.72 g kg\(^{-1}\)) > 10–20 cm (2.70 g kg\(^{-1}\)) > 20–30 cm (2.45 g kg\(^{-1}\)). The content of soil POC did not show a significant difference \((P > 0.05)\) in 10–20 cm soil layers. In the 0–10 cm soil layer, the 0:1 ratio of softrock/sand had the lowest POC content of 1.73 g kg\(^{-1}\), which was significantly increased by 74.74 and 94.90% \((P < 0.05)\) compared to the 1:5 and 1:1 ratio of soft rock/sand. There was no significant

![Figure 5: Polysaccharide content of different proportions of arsenic sandstone and sand compound soils.](image1)

![Figure 6: Free iron oxide content of different proportions of soft rock/sand compound soils.](image2)
difference between the 1:5 and 1:1 ratio of soft rock/sand ($P > 0.05$). In the 20–30 cm soil layer, the 1:2 ratio of soft rock/sand had the lowest POC content at 1.92 g kg$^{-1}$. There were no significant differences between the other three treatments, with the 0:1, 1:5, and 1:1 ratio of soft rock/sand increasing by 46.20% ($P < 0.05$), 29.27% ($P > 0.05$), and 34.07% ($P < 0.05$) compared to the 1:2 ratio of soft rock/sand. The addition of soft rock can effectively enhance the soil’s carbon content. This is because the soft rock provides an improved growth environment for plants, leading to the accumulation of crop root exudates over time, which in turn promotes an increase in the soil carbon content [32,33]. Consistent with previous studies, it has been found that the implementation of plant restoration measures leads to a significant increase in soil carbon content.

### 4 Conclusion

In this study, soft rock was used as a natural colloidal material to improve the sandy land, and soil quality changes were analyzed after the soft rock was compounded with sand. The intergranular colloidal materials in the soft rock are mainly flake calcite and filamentous calcareous montmorillonite, which are colloidal with each other and form large intergranular pores in the soft rock. A small amount of illite is also present between the grains to form clay bridges. The clay minerals in the soft rock are closely cemented to each other, forming a rich pore structure with high hydrophilicity, large specific surface, and interlayer space. It also has strong ion-exchange properties due to the weak interlayer linkage between the montmorillonite and green montmorillonite layers, which are easily swollen.

With soft rock/sand ratios of 1:1 and 1:2, there is more adherence on the surface of the soil particles. There is also more surface contact between the grains and more cementing material between the grains to bind them together well, retaining some pore space while the soil has good agglomeration. The addition of soft rock improves the soil structure of the sand and the material itself and facilitates the improvement of the soil structure of the sand.

The polysaccharide content of the compound soil of soft rock to sand was significantly higher than that in the all-sand treatment. The variation of the free iron oxide content gradually increased with the depth of the soil layer, with the 20–30 cm free iron oxide content 2.63 times higher than that of the 0–10 cm. The organic carbon content of particles in the 0–10 and 20–30 cm soil layers varied significantly, while there was no significant change in the organic carbon content of particles in the 10–20 soil layers. The addition of soft rock resulted in a significant increase in soil cementation and significant changes in the polysaccharide content and POC content of the sandy soils. In summary, soft rock is a natural material that is beneficial for sandy soil improvement, and the addition of this material has a significant improvement effect on the sandy soil structure and soil quality.

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### Conflict of interest: The authors do not have any possible conflicts of interest.

### Ethical approval: The conducted research is not related to either human or animal use.

### Data availability statement: All data generated or analyzed during this study are included in this published article.

### References


