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Potential Role of Feldspathic Sandstone as a Natural Water Retaining Agent in Mu Us Sandy Land, Northwest China

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Abstract: This paper analyzed the water-retention mechanism of feldspathic sandstone (fine- (< 1 mm diam.) and gravel-sized (2–3 cm diam.) in Mu Us Sandy Land, Northwest China. The objective of this study is to study the effect of feldspathic sandstone amendment on water retention in sandy land. The results showed that as the proportion of fine feldspathic sandstone in the sandy land soil increased, the soil texture changed from sand to silt loam, the capillary porosity gradually increased from 26.3% to 44.9%, and the soil saturated hydraulic conductivity decreased from 7.10 mm/min to 0.07 mm/min. Feldspathic sandstone gravel formed micro-reservoirs in the sandy land soil, playing the role of a 'water absorbent' and 'water retaining agent' in sandy land. Amendment with feldspathic sandstone can increase water retention in the arable layer of sandy land by 67%. This study provides a theoretical basis for the amelioration of sandy land on a large scale. It can be concluded that amendment with feldspathic sandstone can improve the physical properties of sandy land soil and increase soil water retention.

Keywords: feldspathic sandstone; sandy land soil; water retaining agent; Mu Us Sandy Land; soil saturatd hydraulic conductivity

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1 Introduction

Drought and water shortage constrain the revegetation and ecological improvement of sandy lands. The control of sandy lands can improve ecological conditions and potentially resolve the problems related to the large population and limited arable land of China. If scientists can identify methods of increasing the moisture content and water holding capacity of sandy land, then sandy land soil could be stabilized and the amount of arable land could be increased.

The development of super absorbent polymers (SAPs) has provided a new way to conserve soil water and reduce soil erosion. The SAPs have excellent water retention properties (Huang *et al*., 2004; Wang and Liu, 2004; Zou *et al*., 2012). However, the SAPs are expensive and could be ineffective in some areas due to antagonism between the polymer and metallic cations in the soil such as calcium and magnesium (Zhao *et al*., 2005). Therefore, a variety of alternative water absorbent polymers have been developed. Various materials contained some of those new polymers may contribute to environmental pollution (Zhang *et al*., 2002). Amendments, such as municipal sewage sludge, lake sediment and municipal sewage sediment, can increase soil moisture content and nutrient supply; however, the availability of these materials is limited (Shen, 2002). Long-term application of these materials could result in heavy metal contamination in soil. Straw, plastic-film, and gravel mulches can significantly increase soil water re-

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tention (Zhang *et al*., 2000; Li, 2003), but the effectiveness of these materials varies among seasons. The application of mulches is labor intensive and expensive. Plastic film mulch is difficult to degrade and can pollution the environment. Natural materials such as wood chips, straw, or pozzolan do not cause environmental pollution (Gicheru, 1994; Pérez, 2009); however, the application of these materials on a large scale is impractical because the materials retain water for only a short time and their availability is limited. The above measures can achieve good results in laboratory and small plot experiments, but they have a number of shortcomings including high cost, limited availability, the potential to cause pollution *etc*. Therefore, these measures can not be used to increase soil water retention in sandy lands on a large scale.

Deserts cover 3.14×10^7 km^2 worldwide, accounting for about 21% of the total land area of the earth. In China, deserts cover 1.74×10^6 km^2, accounting for about 18.1% of the total land area of China. The man-made, water-retaining materials described above can not improve soil water conditions over such large areas. In contrast, natural water retaining materials are inexpensive, readily available, and environmentally friendly. High costs make the use of synthetic water retaining materials impractical for remediating sandy land.

The Mu Us Sandy Land is one of the severe desertification areas in China. Feldspathic sandstone covers an area of 16 700 km^2 in the sandy land. Feldspathic sandstone has low diagenetic potential and structural strength. It is also highly subject to weathering and rapidly expands when it comes into contact with water, resulting in severe soil erosion (Ye *et al*., 2006; Wang *et al*., 2007).

Sandy land soil with little or no structure is highly permeable under both wet and dry conditions and it retains little or no water. We hypothesized that feldspathic sandstone could be an effective agent for increasing water retention in the surface of sandy land. The objective of this study is to analyze the effect of fine- (< 1 mm diam.) and gravel-sized (2–3 cm diam.) feldspathic sandstone on the texture, capillary pore space, saturated hydraulic conductivity, and water retaining ability of sandy land soil. The results of this study could potentially be used not only to reduce soil erosion but also to increase the use of sandy land areas for agricultural production.

2 Materials and Methods

2.1 Study area

The Mu Us Sandy Land is a well known desertified area in China, distributed in the southern Ordos City of Inner Mongolia Autonomous Region, the northern Yulin City of Shaanxi Province, and the northeastern Yanchi County of Ningxia Hui Autonomous Region. The feldspathic sandstone and sandy land soil samples used in this study were collected from the Yuyang District which is situated in the northern Yulin City. The Yuyang District (37°49′–38°58′N, 108°58′–110°24′E) is a sand marsh in the ecotone between arable land and grassland. Wind erosion, water erosion and desertification are all serious problems in the district. In the area, the elevation is 1000 m to 1600 m. The average annual temperature is 8.1℃, the maximum temperature 38.6℃, and the minimum temperature –32.7℃. The average annual frost-free period is 155 days. Average annual precipitation is 414 mm, and average annual evaporation 1904 mm. The average wind speed is 3.5 m/s, and the maximum wind speed 18.7 m/s. The maximum frozen depth is 1.48 m. Sand ridges in the area consist mainly of red or gray Cretaceous feldspathic sandstone. Aeolian sandy soil is the main soil type, and it covers 93.4% of the total sandy land area of the Mu Us Sandy Land.

2.2 Experiment methods

Sandy land soil and feldspathic sandstone samples were air-dried, passed through a 1-mm sieve, and then mixed to the following ratios: 1∶0, 5∶1, 2∶1, 1∶1, 1∶2, 1∶5 and 0∶1 (sandy land soil∶feldspathic sandstone, w/w). The bulk density, mechanical composition, porosity, and saturated hydraulic conductivity were determind for each mixture.

Water transport in the mixtures of sandy land soil and feldspathic sandstone was simulated in transparent containers (70 cm (in length) × 70 cm (in width) × 50 cm (in height)). A 20-cm layer of sandy land soil was put in the bottom of each container, and then a 30-cm layer of mixture (sandy land soil∶feldspathic sandstone, 2∶1, w/w) was spread on the top of the sand. The lower part of the container was connected with the ground. Water was added to the mixture until free drainage was observed from the bottom of the container. Mixed samples were collected at 6 h, 18 h, 30 h, 42 h, 54 h, 102 h, 294 h, 318 h, 342 h, 390 h, 438 h, 510 h, 606 h, 678 h, 798 h, 894 h, 990 h, and 1110 h after adding water. The mixture samples were collected from the 30-cm layer, and the feldspathic sandstone gravel was removed from the mixture, and then the moisture contents of the mixture and the feldspathic sandstone gravel were determined separately. A control experiment using pure sandy land soil at the bottom of the container was designed, and the moisture content was also measured.

Soil moisture content was measured by the drying method (Lao, 1988); soil particle composition was determined by the pipette method (Lao, 1988); and the soil capillary porosity was measured by the cutting ring method (Lao, 1988). The constant head method was used to determine soil saturated hydraulic conductivity (Lao, 1988).

2.3 Calculation method

Saturated hydraulic conductivity (Ks) refers to the amount of water passing through a unit area of soil per unit time at a given water potential gradient when the soil is saturated with water. The Ks value is related to many aspects, such as solute transport, unsaturated hydraulic conductivity, *etc.*, and it is necessary when calculating water flux through the soil profile and designing irrigation and drainage systems. The Ks value is constant for some soils, reflecting soil permeability and drainage (Fares *et al.*, 2000). As Ks increases, soil water drainage increases. Therefore, in this study, Ks was selected as an indicator of soil drainage.

The Ks of the mixture of sandy land soil and feldspathic sandstone was calculated by using Equation (1). According to the least squares method, b could be calculated through Equation (2), and a through Equation (3).

$$y = ax^b \tag{1}$$

$$b = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} = -2.4539 \tag{2}$$

$$a = (\bar{y} - b\bar{x})^{10} = 7.5464 \tag{3}$$

where y is soil saturated hydraulic conductivity (Ks); x is the proportion of the feldspathic sandstone; x_i is the ith proportion of the feldspathic sandstone (i = 1, 2, 3, …, 7); y_i is the Ks of the ith proportion; and a and b is the parameters.

3 Results

3.1 Amendment with fine feldspathic sandstone

3.1.1 Soil texture and porosity

Soil clay content and porosity are the main factors affecting soil water retention. The water holding capacity increases as bulk density and capillary porosity increase. In this study, the unamended sandy land soil (1 ∶ 0) contained 94.07% of sand and 3.20% of silt, respectively (Table 1). In contrast, the proportion of silt-sized particles in the feldspathic sandstone (< 1 mm) (0 ∶ 1) was 72.94%, which was 23 times that of the unamended sandy land soil. The proportion of sand-sized particles in the mixtures decreased as the feldspathic sandstone increased. Furthermore, the proportions of clay-sized particles in both the unamended sandy land soil and the feldspathic sandstone were low, with clay percentages of 2.73% for the sandy land soil and 7.49% for the feldspathic sandstone. The proportion of clay-sized particles increased from 2.73% to 8.24% as the ratio of sandy land soil and feldspathic sandstone increased from 1 ∶ 0 to 1 ∶ 1. Adding larger amounts of the feldspathic sandstone to the sandy land had no significant effect on the proportion of clay-sized particles.

Amendment with feldspathic sandstone had a significant effect on soil texture. According to the USDA (United States Department of Agriculture) classification system based on grain size, the texture of the soil changed from sand to sandy loam, loam, and then silt loam as the proportion of feldspathic sandstone in the sandy land soil increased. Soil texture has a direct impact on water storage, permeability, and fertility of soil. Amendment with feldspathic sandstone significantly improved the texture of the sandy land soil.

Table 1 Texture and capillary porosity of samples containing different proportions of sandy land soil and feldspathic sandstone

Ratio of sandy land soil and feldspathic sandstone	Sand (%)	Silt (%)	Clay (%)	Capillary porosity (%)
1 ∶ 0	94.07	3.20	2.73	26.33
5 ∶ 1	74.79	20.08	5.13	28.17
2 ∶ 1	64.67	30.04	5.29	30.13
1 ∶ 1	46.84	44.92	8.24	33.89
1 ∶ 2	33.76	58.58	7.66	38.18
1 ∶ 5	20.61	72.18	7.21	42.20
0 ∶ 1	19.57	72.94	7.49	44.94

Capillary porosity gradually increased from 26.33% to 44.94% as the proportion of the feldspathic sandstone in the sandy land soil increased (Table 1). It indicated that amendment with feldspathic sandstone transformed non-capillary porosity into capillary porosity. Non-capillary porosity affects soil permeability, whereas capillary porosity affects the soil water retention capacity. The transformation of non-capillary porosity into capillary porosity reduced the permeability and increased the ability of sandy land soil to retain water.

3.1.2 Soil hydraulic conductivity

The value of Ks decreased exponentially as the proportion of the feldspathic sandstone in the sandy land soil increased (Fig. 1, Table 2). The results showed that the sandy land soil had the highest Ks, reaching 7.10 mm/min. The Ks value declined significantly ($p < 0.01$) when feldspathic sandstone was mixed into the sandy land soil. When the ratio of sandy land soil to feldspathic sandstone was 5∶1, the Ks value was 1.61 mm/min, which was 4.4 times less than that of the sandy land soil (1∶0). It indicated that drainage was significantly reduced in the mixture of 5∶1. When the ratio of sandy land soil and feldspathic sandstone was 2∶1, the Ks value was 0.49 mm/min, which was 14.5 times less than the sandy land soil. The Ks value continued to decline as the proportion of the feldspathic sandstone in the sandy land soil increased; however, there was no significant difference ($p < 0.01$) among the treatments of 2∶1, 1∶1, 1∶2, 1∶5, and 0∶1. The Ks of the fine feldspathic sandstone (0∶1) was only 0.07 mm/min. This value was equivalent to soil with low permeability (Liang *et al.*, 2009). It indicated that the hydraulic conducitivity of feldspathic sandstone was low. As the proportion of feldspathic sandstone in the sandy land soil increased, the rate of soil drainage decreased and the water retention capacity of the soil gradually increased.

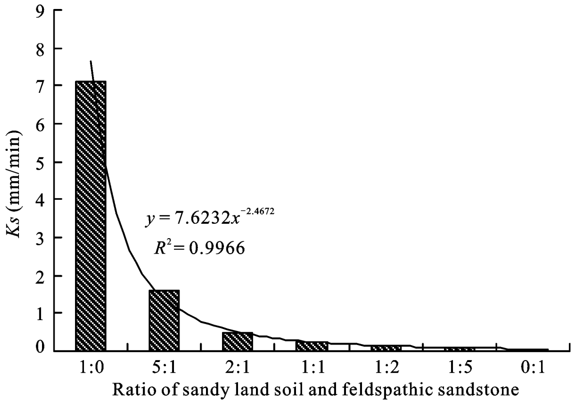

Fig. 1 Relationship of saturated hydraulic conductivity (Ks) and ratio of sandy land soil and feldspathic sandstone

Table 2 Saturated hydraulic conductivity (Ks) of different ratios of sandy land soil and feldspathic sandstone

Ratio of sandy land soil and feldspathic sandstone	Ks (mm/min)	Significance
1∶0	7.10±0.36	aA
5∶1	1.61±0.15	bB
2∶1	0.49±0.01	cC
1∶1	0.26±0.01	cC
1∶2	0.13±0.01	cC
1∶5	0.10±0.01	cC
0∶1	0.07±0.01	cC

Notes: The means were compared using Duncan's New Multiple Range test. Different lowercase letters indicate significant differences at $p < 0.05$, and different uppercase letters indicate differences at $p < 0.01$

3.2 Amendment with feldspathic sandstone gravel

The water contents of both feldspathic sandstone gravel as well as the mixture of sandy land soil and feldspathic sandstone decreased across time (Fig. 2). The water content of the feldspathic sandstone gravel decreased by 10.73%, the slope of the line was 0.0095. It had the same change trend for the mixture (2∶1, sandy land soil∶feldspathic sandstone, w/w), and the water content decreased by 13.01% with the slope being 0.0126. The results showed that the feldspathic sandstone gravel had the ability to retain water and slow the rate of water loss.

Changes in the water content of sandy land soil can be divided into three phases. During the first phase of the experiment (from 0 h to 54 h), the water content of the sandy land soil decreased rapidly from 15.90% to 3.26%. During the second phase (from 54 h to 342 h), the water content of the sandy land soil decreased slowly from 3.26% to 0.64%. During the third phase (from 342 h to 1110 h), the water content of the sandy land soil remained stable. Changes in the water content of the feldspathic sandstone gravel could be divided into two phases. During the first phase (from 0 h to 54 h), the water content of the feldspathic sandstone gravel gradually increased from 19.29% to 21.39%. After 54 h, the water content of the feldspathic sandstone gravel declined continuously. In comparison, the water content of the mixture varied between 14.76% and 15.87% during the first 54 h, and then declined continuously. The results indicated that the sandy land soil had low water retaining capacity and rapid moisture loss. In comparison, the feldspathic sandstone was able to absorb and store moisture when the sandy land soil was wet. While absorption was going on (i.e., during the first 54 h of the experiment), the moisture content of the mixture remained stable. After 54 h, the feldspathic sandstone gravel released water, slowing the decline in the total soil water content. In contrast, sand particles in the sandy land soil had no water to release. Overall, the results show that the feldspathic sandstone gravel has significant water retention ability, and the water that is retained in the gravel can be gradually released into the surrounding soil.

The water content of the feldspathic sandstone gravel increased during the initial 54 h (Fig. 2), indicating that both the hydraulic conductivity and the permeability of feldspathic sandstone gravel are low. Because of its low permeability, the sandy land soil reached saturation firstly and became a channel for water drainage. After adding water, there was drainage from the lower part of the container, although the feldspathic sandstone gravel still had not reached saturation. Some moisture was gradually lost from the sandy land soil by drainage and evaporation. Some moisture moved from the sandy land soil and was absorbed by the gravel due to differences in matric potential. Amendment with feldspathic sandstone gravel changed the texture of the sandy land soil, increasing both the proportion of fine particles and the capillary porosity. Overall, the feldspathic sandstone gravel increased the water retaining capacity of the sandy land soil significantly.

3.3 Case study results

The results of the laboratory studies described above indicated that feldspathic sandstone was able to absorb water and then release it as the soil dried. Based on these results, a field study was carried on a field (133 ha) at the Yuyang District, Yulin City, Shaanxi Province. Potatoes (*Solanum tuberosum* L.) were used as a test crop. The planting density was 6 holes/m^2. Feldspathic sandstone (40% fine and 60% gravel) was mixed into the sandy soil at a ratio of 1 ∶ 2. Unamended sandy land soil was used as a control treatment. Potato yield (33 750 kg/ha) and quality were the same in both treatments. Water consumption in the soil amended with feldspathic sandstone was 0.3 m^3/m^2. In comparison, water consumption in the unamended land was 0.9 m^3/m^2. Overall, amendment with feldspathic sandstone reduced water use by 67%. Fine- and gravel-sized feldspathic sandstone both increased soil water retention in the sandy land. This field trial also indicated that the water retaining capacity of feldspathic sandstone enhanced soil water use efficiency. The significant water-saving role of feldspathic sandstone has made the large-scale reclamation of sandy land possible.

4 Discussion and Conclusions

This study about the nature of feldspathic sandstone is focused on three main aspects. The first aspect is to define the distribution range of feldspathic sandstone and to classify it according to its composition (Wang *et al.*, 2007). Several researchers have studied the chemical composition, physical structure, and physical properties of feldspathic sandstone (Zhu *et al.*, 2007; Li *et al.*, 2011). Some studies have also been done to determine why feldspathic sandstone is easily erodible and also to identify the best soil and water conservation techniques for controlling soil erosion in areas with feldspathic sandstone deposits (Bi *et al.*, 2003; Zhang *et al.*, 2009). Previous studies have focused on the adverse effects of feldspathic sandstone on the environment. In contrast, this paper focused on the unique water retaining proper-

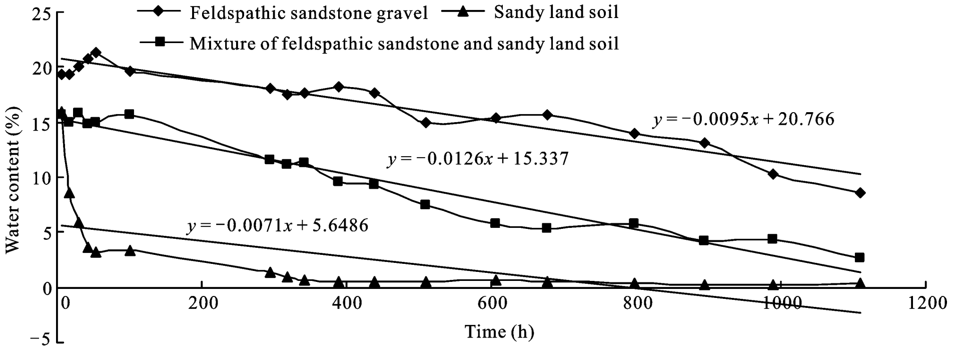

Fig. 2 Changes in water content of mixture, sandy land soil and feldspathic sandstone gravel across time

ties of feldspathic sandstone, with the goal of utilizing this resource as well as controlling its adverse effects on the environment.

Feldspathic sandstone can be used as a natural water retaining agent to increase the moisture content of sandy land. Feldspathic sandstone is widely distributed and inexpensive. Amendment with feldspathic sandstone changed the physical properties of mixed soil and increased water retention. Specifically, amendment with feldspathic sandstone reduced the sand content of the mixture from 94% to 20% and increased the silt content from 3% to 73%. Amendment with the mixture also increased capillary porosity from 26% to 45% and reduced soil saturated hydraulic conductivity from 7.10 mm/min to 0.07 mm/min. This means that the permeability of sandy land was reduced. Amendment with feldspathic sandstone increased the proportion of silt- and clay-sized particles in sandy land soil but also the capillary porosity of soil and water retention capacity. Overall, the addition of feldspathic sandstone transformed the sandy land soil into a water retaining soil with high permeability.

Feldspathic sandstone gravel functions as a mini-reservoir in soil. The gravel absorbs moisture from the surrounding soil when the soil moisture content is high. The moisture is released from the gravel as the sandy land soil dries, thus slowing the decline in soil moisture content. It can be concluded that the feldspathic sandstone could be an effective amendment for sandy land. The ratio (2∶1) of sandy land soil to feldspathic sandstone can reduce water consumption by 67% while maintaining potato yield and quality. Feldspathic sandstone formations are primarily formed by marine or lacustrine deposition. Regardless of location, these formations are similar in Mu Us Sandy Land. Therefore, this practice may be useful for ameliorating sandy soils around the world.

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