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A COMPREHENSIVE METHOD OF EROSION RESISTANCE AND GROWTH PROMOTION FOR PISHA SANDSTONE

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ABSTRACT: Pisha sandstone is a special type of soft rock that is severely eroded by wind, rainfall, and gravitational force. The surface of the area in the region consisting of this sandstone has been degraded as a result of excessive human activities, and the vegetation cover in this area is extremely low. In order to develop new methods to control further erosion and mitigate the adverse impacts of landslides, the material components, nutrient contents and the shear strength of Pisha sandstone were studied and field experiments via utilizing a new comprehensive method based on a hydrophilic polyurethane (W-OH) was carried out. The results revealed that in Pisha sandstone the main minerals are quartz, feldspar, plagioclase, montmorillonite, illite, and kaolinite. The montmorillonite was found to be the main cementitious material, however, is easy to expand when meets water. The research also showed that the nutrient content is low, and the organic matter, total nitrogen, total phosphorus, total potassium and available phosphorus corresponds to the sixth-level, the nitrogen content corresponds to the fifth-level and the available potassium corresponds to the forth-level, according to the six-level classification of soil nutrient content grading table. In the field experiment, vegetation coverage rate in the treated area increased to more than 95% after 4 months, and shallow trenches literally disappeared. The amount of sediment erosion was reduced by more than 90%, indicating that the effect of erosion prevention and promoting vegetation growth is significant. A demonstration project of 0.2 km^2 was carried out in Odors in 2015 by this method which has resulted in promising outcomes, and the method has been widely accepted by the local community and soil conservation bureau.

Keywords: Field experiment; Growth promotion; Mineral component; Sediment yield; Shear strength; Water and soil conservation

1. INTRODUCTION

Pisha sandstone was formed in Jurassic, Triassic and Cretaceous period [1]. It is widely distributed in a region adjacent to Shanxi, Shaanxi and Inner Mongolia autonomous region in the Yellow River basin and Ordos Plateau (Fig. 1) [2], [3]. It is composed of a thick layer sandstone, arenaceous shale, and mudstone [4], [5]. The total area that Pisha sandstone underlies is approximately 16,700 km^2 [6], [7]. The Pisha sandstone has a low degree of diagenesis, poor bonding mechanism, and low compressive strength. As a result, it is extremely hard when it is dry but rapidly disintegrates when encounters water [7]-[9]. Due to the special properties of Pisha sandstone, in the condition of rainfalls, erosion occurs frequently in gullies and the erosion rate is considerably large [10]. The soil erosion modulus can reach about 3,000 ~ 4,000 t/ (a· km^2) on average according to the available statistical data. Coarse sediment (particle size＞0.05 mm) [11] derived from the Pisha sandstone area is the primary source of coarse sediment into the reaches of the Yellow River [12]and accounts for 71.1% of the total coarse sediment yield (0.301 billion tons per year) [13]. About half of the coarse sediment is deposited so that the lower reaches of the Yellow River have gained the reputation as the “Hanging River” [14]. Consequently, the Pisha sandstone area is called the most severe soil erosion region in both Loess Plateau and in the world [4], [5], [15].

Since 1950s, the control measures for water and soil conservation in Pisha sandstone areas have been mainly biological and engineering measures [16]. Among them, the biological measures have been the most widely applied measures. They include forest shelter belt, windbreak and sand fixation forest, slope protection plants, and seabuckthorn flexible dam to cite a few examples [12], [15]. Engineering measures have mainly included slope engineerings, such as Terrance, level trench, scale-hole, intercepting ditch, protection engineering of gully head and channel engineering [7]. Nevertheless, there are some limitations to these measures and they cannot achieve the comprehensive goals of soil solidification, erosion resistance, vegetation growth promotion, and steep slope governance [14].

Recently, Pisha sandstone solidification and improvement combined with vegetation growth have become a trend to protect and utilize this resource as well as controlling its adverse effects on the environment [17]. Wu, et al. [18] studied a kind of hydrophilic polyurethane as a sand fixation agent. Su [19] analyzed the influence of EN-1 on engineering mechanical characteristics and simulated slope resistance to scour of Pisha sandstone weathered soil. Han et al. [20] proposed to compound soil with Pisha sandstone and aeolian sandy soil to improve the water retention characteristics. Li et al., [21] used Pisha sandstone via alkali activation process to produce a new raw structural material.

In order to develop a new efficient method to protect Pisha sandstone erosion, a novel hydrophilic polyurethane composite material (W-OH) was introduced [22] and based on that a new method combined with vegetation measures were proposed for the first time to protect Pisha sandstone. The utilization of the proposed W-OH based method has successfully demonstrated an effective sand fixation capable of controlling desertification and achieving ecological restoration [23]. In this paper the characteristics of Pisha sandstone and the causes of erosion are discussed, the results of the field experiment, based on the aforementioned comprehensive method, are presented and the effectiveness after four months of implementation is evaluated.

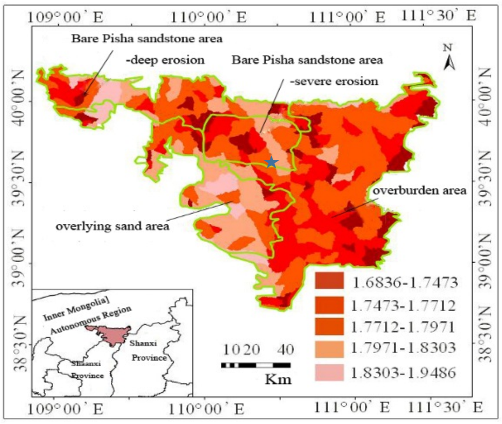

Fig. 1 Distribution of Pisha sandstone,★ is the experimental plot.

2. MATERIALS AND METHODS

2.1 Materials

Pisha sandstone was taken from the Erlaohu Gou in Ordos, Inner Mongolia Autonomous Region in China which belongs to bare Pisha sandstone area. Horizontal stratified sampling method combining artificial and mechanical excavation [24] was used to obtain the samples with a bulk density ranging of 1.36 ~ 1.58 g/cm3, and a water content of 7.9 ~ 21.1%. The liquid limit (WL) was 32.2%, plasticity (IP) was 10.6, specific gravity (Gs) was 2.65, and the optimum water content (Wop) was 17%.

W-OH is a type of hydrophilic polyurethane composite (produced by Toho Chemical Industry Co. Ltd,). This plyometric material does not contain any heavy metal ion and has no harmful effect on vegetation or animals [23].

2.2 Methods

The mineral components were analyzed by X-ray diffraction method based on "transfer target polycrystalline X-ray diffraction method General" (JY / T 009-1996) by X-ray diffractometer (XRD-7000S, produced in Shimadzu Corporation).

2.3 Field Experiment

In order to study the effect of the novel material and the proposed technique field experiment was conducted. The experimental field plot was selected as the area in the middle of Erlaohu Gou in Inner Mongolia Ordos (110°36′2.74″ E and 39°47′38.79″ N, Fig. 1) and was constructed and monitored from May to October in 2014. The topography in this area belongs to the transitional zone of Loess plateau and the Ordos plateau and the typical bare Pisha sandstone area. The climate is arid and semi-arid temperate continental monsoon climate with cold winter, hot summer and there are more wind and sand in winter and spring. According to the meteorological data of Jungar Banner, the average annual rainfall is 400 mm, but the inter-annual change is large and the distribution is extremely uneven in one year (The total rainfall reached 250.2 mm in 2014). The longest months of rainfall are often concentrated from July to September, accounting for 70~80% per year. Moreover, short-term heavy rainfall often occurs and the highest intensity rainfall can reach 80 mm per month. However, because of the harsh climate and sterile soil, the overall vegetation coverage rate is less than 30%.

For the design of the experiment, the treated slope in Erlaohu Gou with a height of approximately 43.5 m, a vertical height of 29.9 m, an average gradient of 44.5° was chosen. According to the changes of slopes, the slope area was divided into three regions: consolidation and waterproof area, consolidation and growth promotion area, and consolidation and green area. Moreover, a meteorological station, a water and sediment monitoring station and a rainfall station were built to observe rainfall intensity, temperature, humidity, wind, sediments and other parameters.

At the top of the slope, a stereo configuration with trees, bushes, and grass was established, and Chinese pines were planted, water drainage ditches were dug, and a cellar/tank was built to collect rainfall to make full use of. For the consolidation and waterproof area, the slope exceeded 60° and 8~10% W-OH solution was sprayed on the surface. However, in consolidation and growth promotion area, the slope was about 30~60°, the spayed concentration of W-OH was about 4~5%, bushes and grass were planted and the micro irrigation systems were constructed to provide water for the vegetation. In consolidation and green areas with less than 30°slope, trees, bushes, and grass were planted. Lastly, at the bottom of the gully, two shunt barrels and collecting barrels were installed to collect rainfall erosion sediment and runoff. Each barrel's height and diameter were 1 m, respectively. Between the shunt barrels and the collecting barrels nine tap holes with the same size were set up and the one in the middle was joined with the collecting barrels through a honeycomb duct.

3. RESULTS AND DISCUSSION

3.1 Mineral Components in Pisha Sandstone

From Table 1 it can be seen that the main minerals in Pisha sandstone included quartz, feldspar, plagioclase, montmorillonite, illite, kaolinite, calcite, dolomite and hematite. In which, quartz, feldspar, plagioclase, and hematite were primary minerals, accounting for about 70%~80%, while kaolinite, montmorillonite, calcite, and dolomite were secondary minerals from weathered primary minerals. Therefore, Pisha sandstone is a kind of sandstone that has a low degree of rock diagenesis.

The characteristics of quartz consist of high strength, hardness and good performance for water resistance. It forms a strong skeleton of Pisha sandstone together with feldspar and a slight amount of calcium carbonate. Montmorillonite (accounting for more than 15% for red Pisha sandstone, and approximately 10% for white one) is a type of the common clay mineral and is the most important cementitious material in the matrix of Pisha sandstone. However, when it absorbs water, the volume expands drastically, and the maximum volume expansion rate can reach approximately 400%. This is the main source of expansion in Pisha sandstone. Montmorillonite gradually softens with producing enormous pressure and lose the bonding capacity after it absorbs water, resulting in the destruction of the structure. Moreover, the crystal of montmorillonite is small and scaly, and it is hydrophilic. Thus, it is easy to be entrained by water, which is an important reason for the erosion of Pisha sandstone. Kaolinite, the product of feldspar and other silicate minerals, is an aqueous aluminosilicate. The properties of kaolinite are high water absorbability and strong plasticity, while once exposed to water, it will soften, inflate and loses the bonding capacity rapidly. Moreover, montmorillonite, kaolinite, and other expansion of clay minerals will be easy to be weathered under certain conditions and decomposed into silica and alumina in a long-term in hot and humid conditions.

Table 1 Mineral components in Pisha sandstone

No.	Mineral contents /%								
	Quartz	Plagioclase	Feldspar	Montmorillonite	Illite	Kaolinite	Dolomite	Calcite	Hematite
1-1	38-43	25	20	5-10	1	2	1	2	-
1-2	28	30-35	15	15-20	1	2	1	1	1
1-3	23-28	20-25	20-25	10-15	2	3	1	10	-
1-4	25-30	10	10-15	20-25	3	4	1	15-20	1
1-5	35-40	25	15	10-15	1	2	1	5	-

3.2 Nutrient Content

It can be seen from Table 2 that in both the red and white Pisha sandstone, the pH ranges from 8.91 to10.04 and thus, it is alkaline. The content of organic matter is approximately 0.15%-0.78%. The contents of total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus and available potassium are in the range of 0.017%-0.054%, 3.5×10-6%-1.9×10-5%, 9.07×10-5%-2.75×10-4%, 0.10-0.91 mg/kg, 39.6-53.8 mg/kg and 27.3-80.8 mg/kg. According to the six-level classification of soil nutrient content grading table in China, pH, organic matter, total nitrogen, total phosphorus, total potassium and available phosphorus belong to the sixth-level, available nitrogen is the fifth-level and the available potassium is the forth-level, indicating that the overall nutrient content in Pisha sandstone is extremely low, resulting in difficult growth of vegetation.

Table 2 Surface nutrient content of Pisha sandstone

Color		pH	Organic matter (%)	Total nitrogen (%)	Total phosphorus (%)	Total potassium (%)	Available nitrogen (mg/kg)	Available phosphorus (mg/kg)	Available potassium (mg/kg)
White	Maximum	10.04	0.78	0.054	9.5×10^{-6}	2.75×10^{-4}	53.8	0.31	78.5
	Minimum	8.91	0.17	0.017	3.5×10^{-6}	9.07×10^{-5}	42.4	0.10	55.2
	Average	9.51	0.44	0.026	6.6×10^{-6}	2.04×10^{-4}	47.9	0.20	62.8
Range		＞8.5	＜0.60	＜0.05	＜0.040	＜0.60	30-60	＜3.0	40-85
Grade		Six-level	Six-level	Six-level	Six-level	Six-level	Five-level	Six-level	Four-level
Red	Maximum	9.15	0.20	0.036	1.9×10^{-5}	2.42×10^{-4}	50.9	0.91	52.6
	Minimum	9.00	0.15	0.020	5.9×10^{-6}	9.22×10^{-5}	48.1	0.69	27.3
	Average	9.08	0.17	0.030	1.2×10^{-5}	1.67×10^{-5}	49.5	0.77	44.8
Range		＞8.5	＜0.60	＜0.05	＜0.040	＜0.60	30-60	＜3.0	40-85
Grade		Six-level	Six-level	Six-level	Six-level	Six-level	Five-level	Six-level	Four-level

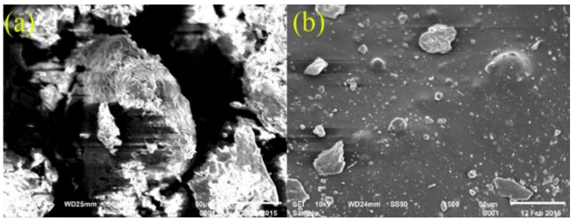

Fig. 2 The SEM images of red Pisha sandstone (a) original Pisha sandstone particles; (b) solidification layer on Pisha sandstone by spraying W-OH solution

As can be observed from Fig. 2, the original sandstone particles are discrete in SEM and the adhesion between particles is poor, so it is not stable and easy to become collapsible when meets water or wind. However, when W-OH solution was sprayed on the surface, a consolidation layer is formed and the particles are bonded together tightly. Thereby, the integrity is improved and the porosity is decreased significantly. Subsequently, the Pisha sandstone particles could not be easily destroyed under the condition of water or wind.

3.3 Field Experimental Results

The results and effects had been observed and studied in the following four months.

Sediment yield: after finishing constructing the experimental and control areas, on the second day it rained and lasted for 15 hours. The field observation showed that the consolidation and waterproof area and the consolidation and growth promotion area did not change (Fig. 3a). The surface in consolidation green area had no obvious gully, and there were no Pisha sandstone particles in different barrels. However, in the control area, some shallow ridges appeared, indicating that the consolidation layer had a certain effect of anti-erosion.

Table 3 Results in treated and control area during 7~8 month.

Date	7.10	7.22	7.28	8.20	8.12	8.22
Rainfall （mm）	16.40	8.60	23.20	35.69	20.69	34.49
Rainfall intensity I_{30}(mm/h)	26.00	4.40	15.60	41.29	26.89	20,00
Rainfall erosion force (MJ·mm/(ha·h))	94.80	9.43	77.20	373.39	131.00	133.30
Sediment yield in treated area (kg)	8.60	0.00	1.80	11.99	0..49	1.60
Sediment yield in control area (kg)	216.10	42.00	27.30	1895.79	52.19	18.70
Reduced rate of sediment yield (%)	96.00	100.00	93.40	99.49	99.20	91.40

Twenty days later, the surface in the consolidation and waterproof area did not change and the consolidation layer remained completely, however, in the consolidation and vegetation promotion area a few small cracks appeared in some unsmooth places. As for the consolidation green area, the seeds began to sprout, seabuckthorn and Boston ivy began to grow new leaves, and green could be seen in some parts. Sediments of Pisha sandstone particles were found in different barrels and it demonstrated that with the increase of rainfall and rainfall intensity, the sediment yield showed a trend of increase in both experimental and control areas (Table 3). When the rainfall reached 41.2 mm/h, the sediment yield of control area reached 1895.7 kg and the average unit loss was 11.8 kg/m^2. However, in the treated area, the sediment yield was just 11.9 kg and the unit loss was 0.074 kg/m^2, the decreased rate was more than 99%. The results indicated that the consolidation layer had a significant effect on improving the performance of water, gravity, and wind erosion resistance of Pisha sandstone slopes. In addition, the sediment yield also had a direct relationship with the rainfall erosion force and the proportion of vegetation coverage.

On the other hand, the consolidation layer in the consolidation and waterproof area stayed intact with a certain thickness, but in some places, a few cracks began to appear with the exaptation of time (Fig. 3a). This indicated that under the effect of water and gravity erosion force some changes on Pisha sandstone surface have taken place, leading to a minor damage in some places where the material was not sprayed uniformly. As time went by, the quantity of the grooves increased gradually, the width and the depth also increased. By the end of August, there were 10 grooves in the control area, 6 cm in width and 10~15 cm in depth on average. Some of them appeared across the entire growth promotion area. The monitoring results showed that the grooves appeared from the edge of the control area, for which the depth increased with the rainfall intensity, and gradually moved towards the middle, resulting in the destruction or the collapse of the entire slope. These were also one of the major forms of water erosion.

In the treated area, where the amount of sprayed solution was small, the vegetation coverage was large, even though the rainfall was heavy, however, the slope surface initially showed a small erosion. Nevertheless, as the vegetation coverage rate increased the gullies disappeared and vegetation played an important role in preventing weathered Pisha sandstone from further erosion.

Fig. 3 Comparison of treated and control area. (a) a few cracks in the consolidation and waterproof area, (b) comparison with two plots in September in 2014

As can be seen from Fig. 4 the vegetation coverage and the growth promotion of green area increased fast and the vegetation coverage rate gradually increased. Three months after the implementation the rate reached 95%, and the height grew up to 50~60 cm (Fig. 4b). However, the rate of the vegetation coverage was very slow in the control area. It only occupied 8% with a height of 10 cm on average. Therefore, it was obvious that with the increase of the vegetation coverage rate, the surface roughness and permeability of Pisha sandstone could be enhanced to protect Pisha sandstone from water and wind erosion. This also indicated that material measure including W-OH combined with vegetation could have a significant effect on preventing Pisha sandstone from water, wind, and gravity erosion.

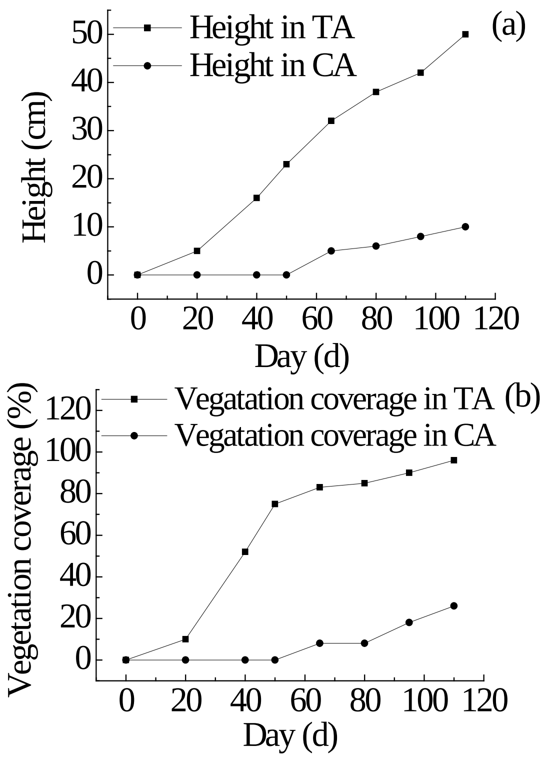

Fig. 4 Vegetation coverage and height in treated and control area from May to September 2014

4. CONCLUSIONS

In order to develop and evaluate the new comprehensive method to control Pisha sandstone erosion, the material components, nutrient content and the shear strength were studied and a field experiment based on the hydrophilic polyurethane (W-OH) together with vegetation measure was carried out. The results showed that in Pisha sandstone the main minerals are Quartz, feldspar, plagioclase, montmorillonite, illite, and kaolinite. Quartz, feldspar, plagioclase, and hematite are the primary minerals. The montmorillonite is the main cementitious material but it is easy to expand when meets water, leading to the structural destruction of Pisha sandstone. Organic matter, total nitrogen, total phosphorus, total potassium and available phosphorus belong to the sixth-level, available nitrogen corresponds to the fifth-level and the available potassium corresponds to the forth-level, indicating that the overall nutrient content in Pisha sandstone is extremely low and results in the difficult growth of vegetation. The treated area was divided into three sections according to the slope gradients and vegetation coverage, consolidation and waterproof area, consolidation and growth promotion area and consolidation and green area. The new method comprising of W-OH combined with vegetation was adopted. Four months later, the vegetation coverage rate reached more than 95%, and almost no shallow grooves formed in the treated area, however, several deep grooves appeared and vegetation coverage was still less than 30% in the control area. The sediment yield in the treated area had been reduced by more than 95% compared with that in the control area. This new method could reach the comprehensive efficiency of Pisha sandstone conservation both in water erosion resistance and ecological restoration. These results also indicated that combining materials with vegetation measures could be used as an efficient comprehensive method to protect water and soil from loss and erosion in the Pisha sandstone area.

5. ACKNOWLEDGEMENTS

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