The Relationship between Physical and Chemical Characteristics and the Loss of Pisha Sandstones

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Abstract. Pisha Sandstones are widely distributed in the wind-water erosion intersection zone of northwestern China. In this region, serious soil and water loss has caused the riverbed of the lower Yellow River to become higher than the adjacent ground. Fifty-two samples of four types of Pisha Sandstones (purple, white, pink and gray) from different depths (0 m, 2 m and 10 m) were examined in laboratory experiments to gain a better understanding of the relationship between erosion and the loss of Pisha Sandstones as well as the mechanisms of erosion. All of the samples were analyzed using chemical methods, X-ray diffraction and scanning electron microscopy. The mineral and chemical compositions of Pisha Sandstones were found to be very different from those of ordinary soil and varies greatly during the whole erosion process (sampling depth). Wind-water erosion also affected the microstructure between the deep and surface Pisha Sandstones, ultimately causing gravitational erosion and the loss of Pisha Sandstones. Although not all of the observations could be explained, it was apparent that wind erosion, water erosion and gravitational erosion had both direct and indirect effects on the loss of Pisha Sandstones.

1. Introduction
In northwestern China (mainly in the border region of Shanxi, Shaanxi and Inner Mongolia Provinces), an area of more than 11 000 km² is covered by Pisha Sandstones, a type of fluvial clastic deposition sandstones and shales formed during the Triassic, Jurassic and Cretaceous periods. Pisha Sandstones are subject to severe soil erosion due to their geological, topographic and climatic conditions as well as human activities. These sandstones are hard when dry but become soft when wet[1,2]. Due to the nature of these sandstones, this area of northwestern China is plagued by a high erosion rate (over 20,000 t/km²•yr)[3] as well as sparse vegetation. This condition has attracted increasing attention in recent years[4-7].

The extremely high sediment load makes the Yellow River globally unique. The Yellow River is an alluvial river that carries approximately 1.6 billion tons of sediment annually, produced by soil erosion from the Loess Plateau (most of the silt load is deposited in the lower reaches (25%) and the estuary (50%); only approximately 25% of the sediment load is transported into the sea). Although the area of the Pisha Sandstones only accounts for 2.6% of the total area of the Loess Plateau, its coarse sediment yield accounts for 30% of the total coarse sediment in the upper-middle reaches of the Yellow River [8,9].
The large amount of deposition has caused the river bed to rise three to five meters on average, to a maximum of 10 m, which is higher than the adjacent ground surface. Therefore, the river is well known globally as a ‘suspended river.’ Flood control protected areas on both banks of the lower Yellow River are densely populated, and many cities, railways, highways, oilfields and coalfields are distributed there. If the Yellow River crested, it would cause huge economic losses and threaten hundreds of millions of people's lives. Furthermore, Pisha Sandstone areas exhibit severe soil and water loss, serious deterioration of the ecological environment as well as the industrial and agricultural production environments, with sparse vegetation, gullies and desertification across the landscape (Fig. 1). Hence, all of the problems caused by sediment deposition must be adequately addressed.

Figure 1. Geomorphologic illustration of the Pisha Sandstone region

Studies investigating the soil erosion of the Pisha Sandstones have focused on weathering characteristics on the surface[10] and the major factors affecting the nature and extent of rock weathering, the results of soil and water conservation tests[11,12], and the impact of measures used to control soil erosion[13,14].

Many important findings have been reported. However, the soil erosion resulting in sediment yield in the Pisha Sandstone region is closely related to the weathering process and is an important consideration for studies seeking a better understanding of the operative mechanisms of soil erosion. Elucidating the differentiation and deposition processes will aid in understanding the chemical and physical characteristics of Pisha Sandstones with different erosion degrees. Pisha Sandstones have mainly eroded on the slopes in this area; to more fully understand the differences in the extent of erosion among sandstones of the same color, the characteristics of the Pisha Sandstone of different layers are studied in this paper.

2. Materials and Methods

2.1. General Characteristics of the Sampling Area
The Pisha Sandstone samples used in these experiments were collected from the Two-tiger Ditch, which is located in Zhun-ge-er County, Erdos City, Inner Mongolia, China, at 39°46′30″N–39°48′20″N, 110°35′30″E–110°37′32″E (Fig. 2). Zhun-ge-er County is situated in the southeast of the Erdos Plateau, a typical region affected by both wind erosion and water erosion on the northern Loess Plateau of China, which is one of the most dominant coarse sediment source areas for the upper and middle Yellow River of China.
This region is exposed to a temperate continental semi-arid and seasonal wind climate. According to statistical data from the local weather bureau, the region has the following features: a long, cold winter and short, hot summer, with average annual precipitation of 386.4 mm, with 60%-80% occurring from July to September, mostly in the form of rainstorms. The annual average evaporation is 2234.4 mm, with a drying index of d≥5, while the wind speed is 2.2 m/s. The annual average sunshine hours, sand blowing days and sandstorm days are approximately 3000 h, 32.8 d, and 15.2 d, respectively. Wind and water erosion occur alternately and accelerate in this region. The frost-free period is 153 d, while the maximum depth of frozen soil is 1.5 m during the freezing period, which lasts from November to March.

2.2. Sample Pre-Treatment and Analysis

A total of 52 samples were used in this experiment and were selected to reflect the typical rock types of Pisha Sandstones from the Erlaohu Ditch at different depths of 0 m, 2 m, 10 m and representing different colors of purple, white, pink and gray. The internal samples were too hard to shovel and had to be dug out from 2 m or 10 m with an excavator. The samples were dried and ground into powder before the experiment was conducted.

The mineralogical compositions of the rocks were determined using quantitative X-ray diffraction (XRD, Rigaku, D/max-2500PC) analysis at the Rock-mineral Analysis and Test Center of Henan Provence. A scanning electron microscope (JEOL, JSM-6700F) was used to evaluate the microstructure, while the pH value and chemical compositions were determined with a conventional chemical analytical method.

3. Results

3.1. Mineral Composition of the Samples

An XRD analysis of three representative sandstones (Fig. 3) indicated that the sandstones are enriched with quartz, feldspar, clay minerals and calcite. An XRD analysis of the purple sandstones (10 m) (Fig. 3 (a)) showed that the sandstones contained quartz (25%-30%), montmorillonite (20%-25%), potassium feldspar (10%-15%), anorthose (10%) and calcite (15%-20%). Fig. 3(b) reveals that the pink sandstones (5 m) contained quartz (35%-40%), montmorillonite (15%-20%), potassium feldspar (15%), anorthose (15%-20%) and calcite (5%-10%). Fig. 3(c) reveals that the red sandstones (0 m) contained quartz (15%), montmorillonite (15%-20%), potassium feldspar (25%), anorthose (25%-30%) and calcite (10%).
Figure 3. X-ray diffraction results for the Pisha Sandstones

The extents of weathering and water erosion were both serious in the superficial zone, where the weathering product (feldspar) accumulated and where the calcite decomposed and reduced by reacting with the H₂O and CO₂ under the effects of long-term water erosion; this process generated soluble Ca(HCO₃)₂, causing rock damage. As a result, the content of feldspar (potassium feldspar and anorthose) in the deep sandstone is lower than at the surface, whereas the content of calcite is greater.

Furthermore, the long-term hydrolysis of feldspar can be expressed by many different simplified expression equations[15-25].

Potassium feldspar:

\[
3\text{K[AlSi}_3\text{O}_8\text{]} + 2\text{H}^+ + 12\text{H}_2\text{O} \rightarrow 6\text{H}_2\text{SiO}_4 + \text{KA}_3\text{Si}_3\text{O}_10(\text{OH})_2 \text{ (illite)} + 2\text{K}^+
\]

\[
2\text{K[AlSi}_3\text{O}_8\text{]} + 2\text{H}_2\text{CO}_3 + 9\text{H}_2\text{O} \rightarrow 4\text{H}_2\text{SiO}_4 + \text{Al}_3\text{Si}_2\text{O}_5(\text{OH})_4 \text{ (kaolinite)} + 2\text{K}^+ + 2\text{HCO}_3^-
\]

\[
2\text{K[AlSi}_3\text{O}_8\text{]} + \text{H}_2\text{O} \rightarrow 4\text{SiO}_2(\text{quartz}) + \text{Al}_3\text{Si}_2\text{O}_5(\text{OH})_4 + 2\text{K}^+
\]

Albite:

\[
7\text{Na[AlSi}_3\text{O}_8\text{]} + 6\text{H}_2\text{CO}_3 + 20\text{H}_2\text{O} \rightarrow 6\text{Na}^+ + 6\text{HCO}_3^- + 3\text{Na}_0.33\text{Al}_2.33\text{Si}_3.67\text{O}_{10}(\text{OH})_2
\]

(montmorillonite) + 10\text{Si(OH)}_4

\[
2\text{Na[AlSi}_3\text{O}_8\text{]} + 6\text{H}_2\text{CO}_3 + \text{H}_2\text{O} \rightarrow 2\text{Na}^+ + 2\text{HCO}_3^- + \text{Al}_3\text{Si}_2\text{O}_5(\text{OH})_4 + 4\text{SiO}_2(\text{aq})
\]

\[
4\text{Na[AlSi}_3\text{O}_8\text{]} + 6\text{H}_2\text{O} \rightarrow 4\text{Na}^+ + 4\text{OH} + 2\text{Al}_3\text{Si}_2\text{O}_5(\text{OH})_4 + 8\text{SiO}_2
\]

Calciclase:

\[
\text{Ca[Al}_2\text{Si}_2\text{O}_6\text{]} + 2\text{CO}_2 + 3\text{H}_2\text{O} \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^- + \text{Al}_3\text{Si}_2\text{O}_5(\text{OH})_4
\]
The above equations indicate that kaolinite is the main weathering material of feldspar. This mineral is often a powder, and its erosion resistance is low[26]. Therefore, feldspar is one of the important causes of the weak erosion resistance of the Pisha Sandstones.

Research[27] indicates the loss of uniaxial compressive strength (UCS) controlled primarily by the proportions of quartz and clay minerals. The difference between UCS\text{dry} and UCS\text{wet} in the clay-rich Cretaceous Greensand was 78%, whereas in the Siliceous Sandstone, the strength decreased by only 8%. Compared with ordinary soil, the quartz content of Pisha Sandstones is relatively low and the montmorillonite content is relatively high (Table 1). The presences of these minerals is another reason for the poor mechanical properties of these sandstones.

| Depth (m) | Color | Quartz | Feldspar | Clay minerals | Calcite | Dolomite | Hematite |
|----------|-------|--------|----------|---------------|---------|----------|---------|
|          |       | Potash | Anorthose | Montmorillonite |        |          |         |
| 0        | purple | 14.5   | 12.5     | 10.0          | 5.0     | 1.0      | 10.0    |
|          |       | max    | 45.0     | 22.5          | 32.5    | 25.0     | 3.0     |
|          |       | average | 30.9   | 16.4          | 18.2    | 16.1     | 1.4     |
|          | white | min    | 38.0     | 15.0          | 10.0    | 5.0      | 1.0     |
|          |       | max    | 55.0     | 22.5          | 25.0    | 10.0     | 1.0     |
|          |       | average | 44.6   | 19.4          | 16.3    | 7.5      | 1.0     |
|          | pink  | min    | 13.0     | 22.5          | 17.5    | 15.5     | 1.0     |
|          |       | max    | 25.5     | 25.0          | 22.5    | 22.5     | 2.0     |
|          |       | average | 18.7   | 23.3          | 19.2    | 16.7     | 1.3     |
|          | gray  | min    | 21.5     | 17.5          | 12.5    | 17.5     | 1.0     |
|          |       | max    | 39.5     | 20.0          | 20.0    | 27.5     | 1.0     |
|          |       | average | 30.5   | 18.8          | 16.3    | 22.5     | 1.0     |
| 2        | purple | 15.0   | 15.0     | 10.0          | 27.5    | 2.0      | 5.0     |
|          |       | max    | 26.0     | 30.0          | 17.5    | 30.0     | 2.0     |
|          |       | average | 20.3   | 21.7          | 13.3    | 29.2     | 2.0     |
|          | white | min    | 19.5     | 15.0          | 15.0    | 10.0     | 1.0     |
|          |       | max    | 47.5     | 25.0          | 25.0    | 17.5     | 2.0     |
|          |       | average | 33.2   | 19.5          | 21.0    | 14.5     | 1.2     |
|          | pink  | min    | 15.0     | 15.0          | 15.0    | 17.5     | 1.0     |
|          |       | max    | 31.0     | 25.0          | 27.5    | 27.5     | 1.2     |
|          |       | average | 24.3   | 20.0          | 21.3    | 22.5     | 1.3     |
|          | gray  | min    | 30.1     | 14.8          | 12.7    | 19.2     | 0.7     |
|          |       | max    | 36.4     | 16.2          | 15.7    | 22.0     | 1.3     |
|          |       | average | 33.2   | 15.6          | 14.1    | 20.8     | 1.0     |
| 10       | purple | 7.5    | 18.0     | 15.5          | 24.5    | 1.5      | 3.0     |
|          |       | max    | 12.5     | 25.5          | 21.5    | 31.0     | 2.0     |
|          |       | average | 10.2   | 21.5          | 19.5    | 28.2     | 1.8     |
|          | white | min    | 31.5     | 11.5          | 15.0    | 15.0     | 1.0     |
|          |       | max    | 41.0     | 17.5          | 21.5    | 20.5     | 1.0     |
|          |       | average | 37.5   | 14.8          | 18.2    | 18.3     | 1.0     |
|          | pink  | min    | 5.0      | 12.5          | 12.0    | 31.5     | 1.0     |
|          |       | max    | 9.5      | 18.0          | 17.5    | 37.0     | 1.0     |
|          |       | average | 7.5    | 15.0          | 15.3    | 34.4     | 1.0     |
|          | gray  | min    | 32.5     | 10.5          | 10.5    | 17.5     | 1.0     |
|          |       | max    | 41.0     | 15.0          | 15.5    | 22.5     | 1.0     |
|          |       | average | 38.7   | 12.5          | 13.0    | 20.1     | 1.0     |

Quartz contained in rocks tends to change into clay minerals when only a weathering process occurs[28]. However, Table 1 shows that the content of quartz on the surface is higher than the inside of the rocks, whereas the clay mineral content is lower. The small and loose structure of clay mineral particles and the hydrophilia of clay mineral components cause them to be easily washed away by water; therefore, during or after rainfall, the clay minerals on the surface enter into the deep rock mass with rainwater and cause the clay mineral component of the inner layer to increase. Furthermore, the density of the Pisha Sandstones after chemical weathering decreases, and the strength of the rock decreases, finally resulting in rock decay. Furthermore, the bedding plane that is high in clay minerals
is susceptible to creep failure because of its adhesion properties, especially during the rainy season, and these strata are often weakened by underground water. This condition aggravates slope deformation and promotes gravitational erosion[29-31].

The content of the montmorillonite is highest in the clay mineral components (Table 1); thus, the impact of montmorillonite on sandstones is greater than that of other clay mineral components. Montmorillonite is produced in a weathering or sedimentary environment. This mineral is quite stable in the weathering zone, and it does not cause rock mass destruction in a dry environment. However, when water flow occurs, the volume can expand by approximately 150%, causing great pressure on the rock mass. At the beginning of the rainy season, the montmorillonite is exposed to the water and swells, which leads to the destruction of the rock microstructure and lays the foundation for the invasion of various erosion forces. During evaporation or under the influence of temperature, dissolved minerals can produce chemical precipitation through recrystallization, and repeat dissolution and crystallization ultimately cause the destruction of the rock structure.

3.2. Chemical Composition of the Samples

The rock is an aggregate of minerals, whereas the chemical composition is the material basis of the minerals. The characteristics of minerals are closely related to their chemical composition. The chemical composition of minerals is highly variable; to ensure rigorous analysis of the components, chemical testing of samples is necessary. Test and analysis results (Table 2) indicate that the chemical composition of Pisha Sandstones is mainly composed of 8 components. The average content of SiO$_2$, the most abundant component, was 47.2%-68.9%, followed by Al$_2$O$_3$, Fe$_2$O$_3$, CaO and MgO, at 7.7%-16.8%, 2.6%-9.0%, 2.2%-11.2% and 1.0%-6.3%, respectively. The Na$_2$O and K$_2$O contents were 2.1%-4.3% and 0.3%-2.8%, respectively, and the minimum average content of TiO$_2$ was 0.2%-1.0%.

Clay minerals have a strong cation exchange capacity due to their fine particles and crystal texture. Cation exchange and absorption caused by groundwater variation are the first processes causing changes to a rock’s property. In the natural world, clay particles are often negatively charged, and the properties of the absorbed cation exchange can be represented by the cation exchange capacity and various cation exchange capacities. The main exchangeable cations in soil are Ca$^{2+}$, Mg$^{2+}$, K$, Na^+$, H$, and Al$^{3+}$, among others[32,33]. Determination of the cation exchange capacities of these cations contributes to an understanding of the engineering properties of soil.

Table 2 shows that the total average content of Na$_2$O, K$_2$O and CaO in the Pisha Sandstones was 8.6%. Although their content was far lower than that of the other components, these minerals are chemically reactive. These active components can cause local enrichment or be transported away under certain climatic conditions with the flow of water; as a result, the pores of rocks are gradually enlarged, and chemical weathering is aggravated, eventually leading to the destruction of the rock mass structure. The degree of chemical weathering in rocks is controlled by many factors, such as the topography and geomorphology and the lithologic and climatic (mainly rain) characteristics. Active molecules are the first to weather: the weathering order was CaO > Na$_2$O > K$_2$O, Fe$^{3+}$, Mg$^{2+}$, and other low-level chemical components were easily increased under acidic conditions.

The results in Table 2 also show that the four colors of representative Pisha Sandstones were quite different in Fe$_2$O$_3$ content, and the content of Fe$_2$O$_3$ in purple and pink sandstones was higher than in white and gray sandstones. This finding indicated that the purple and pink sandstones were characterized by ferruginous cementation, whereas the white and gray sandstones were characterized by silica cementation. Al$_2$O$_3$ mainly occurred in the clay minerals, and a low content of Al$_2$O$_3$ indicates low clay mineral content and a high weathering degree of rock. Because clay minerals in the inner layer are higher after the argillation of water and soil, Al$_2$O$_3$ exhibited an increasing trend, whereas CaO exhibited a declining trend, as shown in Table 2, indicating that calcite reacts with CO$_2$ and H$_2$O in the process of water erosion. Furthermore, the content of Al$_2$O$_3$ and Fe$_2$O$_3$ increases first with depth and then decreases (except for pink rocks, which increase with increasing depth of the Pisha Sandstones). This process can be interpreted as a result of the iron and aluminum components precipitated in the cracks and pores of the central part of the rocks from the upper weathering rock, with cementation filling in the central cracks.
The maximum pH of the Pisha Sandstones was 10.26, the minimum value was 8.91, and the average value was 9.49. The pH of rainwater is usually less than or equal to 7.0, suggesting that fissure water, pore water formed by rainwater, reacted with relatively unstable chemical composition in the rocks. The chemical reaction is constant because the chemical reaction continues to achieve a new balance with the migration of water, causing the fractures and pores of the rocks to expand gradually and the weathering degree of the rocks to strengthen gradually. This process is slow, but the structural damage is substantial, which reduces the mechanical strength of the rock. Because the migration speed of groundwater in the Pisha Sandstones is limited, silicon cannot migrate quickly and forms clay minerals, such as montmorillonite.

**Table 2.** The chemical composition of Pisha Sandstones (unit: %)

| Depth (m) | Color | pH  | SiO₂ | Fe₂O₃ | Al₂O₃ | CaO  | MgO  | TiO₂ | K₂O  | Na₂O  |
|-----------|-------|-----|------|-------|-------|------|------|------|------|-------|
| 0         | purple| min | 8.93 | 54.2  | 7.8   | 14.1 | 9.9  | 1.0  | 0.2  | 0.3   | 2.4   |
|           |       | max | 10.02| 66.6  | 2.6   | 7.7  | 2.2  | 6.1  | 0.9  | 2.3   | 3.3   |
|           |       | average | 9.29 | 56.9  | 5.9  | 13.4 | 4.9 | 4.0  | 0.6  | 1.9   | 2.8   |
|           | white | min | 9.10 | 68.9  | 2.6  | 10.8 | 2.7  | 1.7  | 0.3  | 1.8   | 2.9   |
|           |       | max | 9.56 | 59.5  | 3.0  | 12.7 | 5.1  | 2.6  | 0.4  | 2.4   | 3.4   |
|           |       | average | 9.25 | 64.3  | 2.8  | 12.1 | 3.4  | 2.1 | 0.4  | 2.0   | 3.1   |
|           | pink  | min | 8.91 | 57.0  | 3.5  | 9.0  | 11.2 | 1.3  | 0.3  | 1.6   | 2.9   |
|           |       | max | 9.84 | 48.0  | 6.3  | 13.0 | 8.4  | 6.3  | 1.0  | 1.8   | 3.6   |
|           |       | average | 9.30 | 53.2  | 5.6  | 11.3 | 8.0  | 3.5  | 0.6  | 1.7   | 3.2   |
|           | gray  | min | 8.98 | 55.3  | 4.7  | 14.1 | 2.2  | 4.0  | 0.4  | 2.3   | 2.7   |
|           |       | max | 9.27 | 56.8  | 4.3  | 14.5 | 2.6  | 1.6  | 0.6  | 2.3   | 2.9   |
|           |       | average | 9.13 | 56.0  | 4.5  | 14.3 | 2.4  | 4.3  | 0.5  | 2.3   | 2.8   |
| 2         | purple| min | 9.91 | 59.3  | 7.8  | 15.9 | 2.6  | 1.0  | 0.5  | 1.7   | 2.1   |
|           |       | max | 10.04| 47.2  | 8.8  | 16.8 | 2.7  | 5.9  | 0.7  | 2.0   | 2.3   |
|           |       | average | 9.95 | 53.3  | 8.3  | 16.4 | 2.6  | 2.6  | 0.6  | 1.8   | 2.2   |
|           | white | min | 9.05 | 62.1  | 3.9  | 12.0 | 2.7  | 2.2  | 0.4  | 1.7   | 3.0   |
|           |       | max | 10.26| 56.5  | 4.4  | 16.3 | 3.0  | 2.5  | 0.6  | 2.5   | 3.4   |
|           |       | average | 9.85 | 59.8  | 4.1  | 14.2 | 2.9  | 2.4  | 0.5  | 2.1   | 3.2   |
|           | pink  | min | 9.89 | 63.6  | 5.5  | 14.4 | 2.4  | 1.0  | 0.6  | 1.9   | 2.6   |
|           |       | max | 10.04| 57.0  | 6.7  | 16.0 | 2.9  | 3.1  | 0.7  | 2.3   | 3.1   |
|           |       | average | 9.97 | 60.8  | 5.9  | 15.1 | 2.7  | 1.6  | 0.6  | 2.1   | 2.8   |
|           | gray  | min | 9.15 | 58.1  | 3.8  | 13.7 | 2.2  | 3.5  | 0.3  | 2.1   | 2.8   |
|           |       | max | 9.52 | 59.7  | 4.5  | 15.2 | 3.5  | 4.6  | 0.7  | 2.8   | 3.7   |
|           |       | average | 9.37 | 59.0  | 4.2  | 14.5 | 2.8  | 4.2  | 0.5  | 2.5   | 3.1   |
| 10        | purple | min | 9.85 | 57.5  | 6.0  | 15.1 | 2.7  | 4.2  | 0.5  | 1.1   | 3.2   |
|           |       | max | 10.21| 52.3  | 8.2  | 15.9 | 3.2  | 5.4  | 0.8  | 1.5   | 3.7   |
|           |       | average | 10.07| 55.1  | 7.2  | 15.4 | 3.0  | 4.8  | 0.7  | 1.3   | 3.5   |
|           | white | min | 9.52 | 65.4  | 2.7  | 12.2 | 2.5  | 2.8  | 0.2  | 2.3   | 3.6   |
|           |       | max | 10.10| 60.8  | 3.8  | 13.2 | 3.1  | 3.6  | 0.4  | 2.7   | 4.3   |
|           |       | average | 9.95 | 63.1  | 3.3  | 12.8 | 2.8  | 3.2  | 0.3  | 2.5   | 3.9   |
|           | pink  | min | 9.66 | 56.8  | 7.5  | 15.1 | 2.2  | 2.7  | 0.7  | 1.7   | 2.8   |
|           |       | max | 10.25| 51.3  | 9.0  | 16.3 | 3.0  | 3.5  | 1.0  | 2.0   | 3.5   |
|           |       | average | 9.92 | 54.6  | 8.2  | 15.8 | 2.6  | 3.2  | 0.8  | 1.8   | 3.1   |
|           | gray  | min | 9.92 | 61.5  | 3.8  | 14.4 | 2.8  | 3.7  | 0.3  | 2.1   | 2.7   |
|           |       | max | 10.37| 56.2  | 5.1  | 15.5 | 3.5  | 4.4  | 0.6  | 2.5   | 3.5   |
|           |       | average | 10.18| 59.7  | 4.4  | 14.6 | 3.2  | 4.1  | 0.5  | 2.3   | 3.2   |
3.3. Microstructure of Samples

A scanning electron microscope (SEM) image of the middle and inner Pisha Sandstone samples (Fig. 4(b), 4(c)) shows that the structure is compact, and close contact between the particles results in lower porosity, while the structure of the surface-weathered Pisha Sandstones is relatively loose, with larger gaps between particles, and the particles are more pliable than the surface samples (Fig. 4(a)). Micro-fissures and corrosion pores with clear direction are found in the mineral particles at 2 m (Fig. 4(b)). These fissures and pores provide channels for water with dissolved O₂ and CO₂ to enter into the rock, and these small particles can greatly enlarge the interface of the water-rock reaction to promote chemical erosion.

![Microstructure photographs of Pisha Sandstones from different depths](image)

**Figure 4.** Microstructure photographs of Pisha Sandstones from different depths

The possible erosion mechanism of Pisha Sandstones is as follows: after the rainy season, the relative humidity is high; in the vadose zone pore system, part of the moisture on the surface of the fissure or inside the intergranular pores condenses into liquid water and slowly dissolves the minerals that it comes in contact with. With increased total solution and the evaporation of moisture in the crystal or between particles, the saturation index of the solution between particles increases and the solution gradually tends to saturate. Some components such as CaCO₃, K₂CO₃ and Na₂CO₃ may be deposited from the solution by further evaporation at the end of the dry season, filling the residual intergranular pores within the crystals. The iron oxides, aluminum oxides and clay minerals are deposited with these soluble components in situ and nearby during the weathering process.

During the rainy season, the precipitated component will be dissolved by low-salinity rainfall and will enter the zone of saturation, whereas the liquid phase of the solution in the particles or between particles enters the infiltration water via molecular diffusion due to the concentration gradient and then enters the inner Pisha Sandstones, coming into contact with fresh rocks, where the process of erosion is continued. Physical fissures that provide channels for erosion liquid will be formed between the particles and rocks with different weathering degrees under a dry-wet, cold-warm circulation (such as
diurnal and seasonal changes) due to the substantial differences in the physical and mechanical behaviors of clay minerals, oxides and rock-forming minerals. The lack of clay minerals on the surface of Pisha Sandstones during the erosion caused by wind and water weaken the cementation, thereby weakening the connections between particles and the stability of rock, so that a large amount of soil and water is lost during the flood season (from approximately June to October).

The above process cycles with the seasons. The surface-soluble constituents and clay minerals continuously decrease during this circulation process, and the extent of the structural degradation of the rock-forming minerals is constantly increasing. The water and soil losses in the Pisha Sandstone area are the result of water erosion, wind erosion and gravitational erosion of rocks, as shown in Fig. 4. Water erosion and wind erosion occur alternately at first, causing some sandstone loss with rainfall, and the gravitational erosion is also involved in another instance of sand loss during the water-wind erosion process.

4. Conclusions
There is a large amount of sand, gravel, debris, and mottled purple rock in the Pisha Sandstone region. In this region, water erosion (mainly in the summer) and wind erosion (mainly in the spring) are very serious, and gravity erosion also exists. Soil loss is very serious in this region, which is one of the coarse sandstone areas of the Yellow River. A comparison of Pisha Sandstones with different degrees of erosion (different horizontal depth) reveals the following:

1) Compared with ordinary soil, the quartz content of Pisha Sandstones is relatively low and the montmorillonite content is relatively high. The mineral and chemical composition of Pisha Sandstones is mainly altered by cation exchange during the erosion process. The content of clay minerals increases on the surface due to wind erosion, and these minerals then enter the inner rocks through water erosion. Whereas feldspar is easily weathered, it plays a tremendous role in weakening the corrosion resistance ability, causing gravitational erosion and, ultimately, Pisha Sandstone loss.

2) Influenced by physical and chemical processes, the microstructure of Pisha Sandstones on the surface is looser than that of the inner rocks, the porosity is greater, and the particles are relatively smooth; at the same time, channels from water erosion can be clearly observed in the SEM images.

3) The relationship between mineral and chemical composition formation and sandstone erosion does not follow a simple unidirectional relationship but a bidirectional relationship. The wind-water erosion weakens the mechanical property of rocks; furthermore, high-intensity and short-duration rainfall triggers the substantial gravitational erosion and sandstone loss in this area.

5. Acknowledgements
This work was funded by the State Key Research Development Program of China (Grant No. 2017YFC0504503), Central Public Research Cost (Grant No. HKY-JBYW-2016-23), and the National Natural Science Foundation of China (Grant No. 51309114).

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