Experimental Study on the Effects of Fly Ash on Sand Fixation with Microbial Induced Carbonate Precipitation

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Abstract. In order to study the sand-fixing effect of microbe induced mineralization after mixing fly ash with eolian sand, different samples of eolian sand were treated. The effects of blending fly ash on microbially induced mineralization and sand fixation were evaluated based on the comparison of permeability, water retention, surface strength, and wind erosion resistance. After three times of microbial induced mineralization treatment with 30% fly ash contained, it showed:(1)the permeability coefficient decreased by 79.4%;(2) the cumulative evaporation decreased by 26.5%;(3)the surface strength increased by 19.9%;(4)and the wind erosion rate decreased by 21.2%.The yield of calcium carbonate was negatively correlated with the wind erosion rate and positively correlated with the surface strength. From the experiment, it can be concluded that mixing fly ash is more practical than simply using microbial induced mineralization to fix sand, which can significantly reduce the permeability, improve the water retention performance, improve the surface strength and wind erosion resistance of the solidified layer of aeolian sand.

1. Introduction
According to statistics, the area of desertified land in China accounts for about 17.87% of the total land area [1], of which the area of desertified land in the west accounts for more than 90% of the total area of desertified land. Land desertification has become a key factor restricting the development of western regions in China. Wind sand control measures such as mechanical sand fixation, chemical sand fixation, and biological sand fixation [2] are often inadequate for long-term sand fixation, high cost, and high added value. Finding a sand-fixing material with good sand-fixing effect, convenient application, and environmental friendliness has become an urgent task in the research of wind-proof and sand-fixing in the western region.

Microbial Induced Calcite Precipitation (MICP) technology can effectively improve the stiffness and strength of soil and reduce the permeability of soil, which has been applied in the fields of soil improvement, leakage and plugging of rock and soil, biological cement, contaminated soil restoration, oil extraction, and protection of stone cultural relics [3].Rehabilitation, oil extraction, protection of stone cultural relics, etc. [3].The application of MICP technology in windbreak and sand fixation has also been studied, and current researches focused more on the direct effects of mineralization on aeolian sand[4][5][6][7]. But wind-blown sand particles are small, less powder and clay content, poor water
retention performance. If only the microbial induced mineralization treatment technology is used, the amount of mineralization agent is large, the cost is high, and the microbial treatment agent has a good permeability, it will be difficult to control the amount of application alone, and it is easy to cause a large number of treatment agent infiltration into the deep soil, resulting in waste.

As the main solid waste residue of coal industry, fly ash may cause, if improperly handled, regional groundwater pollution, induce environmental problems such as dust, and occupy a large amount of land\[8\]. But, it was discovered that adding fly ash to soil can significantly improve soil and aeolian sand properties\[9-14\].

In order to explore the effect of microbial induced mineralization sand fixation under the participation of fly ash, indoor solidification study was carried out on aeolian sand from Xinjiang region of China. The effect of mixed fly ash on microbial induced mineralization of sand fixation was evaluated, and the mechanism of sand fixation was analyzed based on the yield of calcium carbonate.

2. Materials and methods

2.1 Test materials

Aeolian sand is taken from the mobile dune in the southern margin of the Guerbantonggute desert in Xinjiang region. The parent material of the soil is mainly alluvial parent material and aeolian parent material, with no cohesion between particles, natural moisture content of 0.48% and dry density of 1.49g/cm³\[15\]. The content of sand, powder and clay in aeolian sand is 90.27%, 7.47% and 2.26% respectively. Before test, the dirt was removed from sand by screening. The fly ash used in the test is of high-calcium with particle size distribution range from 38.5 μm to 50μm. The samples used in this test include plain aeolian sand and 30% fly ash content aeolian sand. The corresponding particle grading curve and corresponding soil type are shown in figure 1.

The microbe used was Sporosarcina pasteurii (ACTT 11859), purchased from the national germplasm preservation center of the United States. Bacillus pasteurelis octadecans is a kind of high efficiency urease microorganism, with biosafety level 1 and facultative anaerobic type.

The composition and content of culture medium for expanded culture are shown in table 1. Except urea, all the other components of the medium were sterilized by heat and humidity. According to the inoculation amount of 2% (v/v), the mother microbe solution was added into the culture medium, and the microbe solution was obtained by oscillating culture for 24h at 30°C.

| composition | Casein peptone | The urea | Sodium chloride | Deionized water | pH  |
|-------------|----------------|----------|-----------------|-----------------|-----|
| content     | 15.0 g         | 20.0 g   | 5.0 g           | 1.0 L           | 8.5 |

2.2 Experimental method

The study was carried out in a laboratory at Xinjiang University. The test was conducted in a 250mL shake incubator at 30°C with a shaking speed of 150 rpm. The microbial culture solution was inoculated into the culture medium, and the test was carried out for 24h. The fly ash content was added into the culture medium, and the sample was obtained by freeze-drying. The yield of calcium carbonate was determined by the weight difference before and after the test.

Figure 1. granule grading curve and soil type diagram
2.2 Sample preparation

The samples were divided into 8 groups according to the soil used for the test, the type of treatment agent and the number of treatments. For details, please refer to Table 2.

Table 2 test scheme

| Test number | The experiment with          | Treatment agent type                  | Processing times |
|-------------|------------------------------|---------------------------------------|------------------|
| S1T         | Wind-blown sand              | Microbial mineralization treatment agent | 1 time           |
| S2T         | Wind-blown sand              | Microbial mineralization treatment agent | 2 times          |
| S3T         | Wind-blown sand              | Microbial mineralization treatment agent | 3 times          |
| S1W         | Wind-blown sand              | Distilled water                       | 1 time           |
| SF1T        | 30% fly ash content aeolian sand | Microbial mineralization treatment agent | 1 time           |
| SF2T        | 30% fly ash content aeolian sand | Microbial mineralization treatment agent | 2 times          |
| SF3T        | 30% fly ash content aeolian sand | Microbial mineralization treatment agent | 3 times          |
| SF1W        | 30% fly ash content aeolian sand | Distilled water                       | 1 time           |

In the experiment, the microbial induced mineralization treatment agent contained bacteria solution and cementing solution, and the preparation method of the bacteria solution was shown in 1.1. The cementing solution was 0.5mol/L mixed solution of calcium chloride and urea (equal molar concentration).

Sample preparation method: Firstly, 1500 g aeolian sand was loaded into a sand table with the size of 30mm×20mm×3.5mm, and the surface of the sand sample was scraped. Secondly, bacteria solution and cementing solution were sprayed successively on the surface of aeolian sand according to the application amount of 3L/m², with the sand table being naturally dried at room temperature for one week to ensure the continuous internal reaction of the sand sample. Thirdly, electric oven was used to completely dry the sample and terminate the internal reaction of the sand sample. Then the test sample was prepared separately for the permeability test of aeolian sand. The test mold was made of a cylindrical PVC pipe with a diameter of 5cm and a height of 20cm, which was filled with 200g soil samples. A glass petri dish with a diameter of 10cm and a height of 1.5cm was used for the water retention test of aeolian sand, where 80g soil samples were added to the petri dish and equal amount of distilled water was sprayed.

2.3 Test methods

The observation items in this study include the wind-erosion resistance, surface strength and calcium carbonate yield of the eolian sand samples. The specific test methods are as follows.

2.3.1 Permeability: based on the method described in literature [8], the permeability coefficient of the cylindrical sample was measured by the method of variable head.

2.3.2 Water retention: the Petri dishes were kept in a oven at 40℃ for continuous drying for 6 hours, the changes of water content before and after drying were recorded, and the evaporation rate was calculated.

2.3.3 Wind erosion resistance: the self-made wind erosion blowing device is used to test the wind erosion resistance of microbial induced mineralization sand fixation, as shown in figure 2. During the
test, the sand table was placed in the middle section of the wind tunnel and was in the same straight line with the wind direction. Under the wind speed of 10m/s, it was continuously blown away for 8min to record the mass loss of the sand sample.

![Schematic diagram of wind erosion device](image)

2.3.4 Surface strength: SF digital dynamometer was used to measure the surface strength of the sample. Each sample was measured at 5 different positions to ensure that the distance between the measuring points was not less than 3cm, the pressure peak of the five measuring points was read, and the ratio of the average maximum stress to the probe area was taken as the surface strength.

2.3.5 Calcium carbonate yield: the increased weight of the sand table after the test was taken as the mineral yield induced by microbe mineralization. The sand table before and after the treatment was weighed and the calcium carbonate yield during the treatment was calculated.

3. Results and analysis

3.1 Permeability test

![Influence of mixed fly ash on the permeability of samples](image)

Figure 3. influence of mixed fly ash on the permeability of samples

Figure 3 shows the different effects of microbial induced mineralization and fly ash on the permeability of aeolian sand samples. The permeability coefficient of the samples decreased gradually with the increase of the number of microbial treatments. Among them, the permeability coefficient of S3T sample changed most significantly, and its permeability coefficient ($1.04 \times 10^{-4}$m/s) was about 54% of that of S1W sample ($1.92 \times 10^{-4}$m/s). By comparing the permeability coefficient of aeolian sand samples before and after mixing fly ash, it can be found that the permeability coefficient changed more significantly after mixing fly ash into eolian sand. Among them, the permeability coefficient of S1W sample ($1.92 \times 10^{-4}$m/s) is about 4.2 times that of SF1W sample ($4.6 \times 10^{-5}$m/s), and the permeability coefficient of S3T is about 4.8 times that of SF3T sample ($2.15 \times 10^{-5}$m/s). For the eolian sand samples mixed with fly ash, the permeability coefficient is generally smaller than that of the plain
eolian sand samples, but the overall change is relatively gentle, the reason for which should be related to the fact that the pores between the particles of eolian sand are filled tightly with fly ash, so that the water cannot penetrate rapidly.

3.2 Water retention test
The figure 4 shows the influence of mixed fly ash on water retention of samples. The evaporation of water in desertified area is large, which requires sand fixation material not only excellent sand fixation performance, but also good water retention performance, which is beneficial to the growth of sand plants. The evaporation test results show that the untreated samples (S1W) have poor water retention performance and lose more than 90% water after 6h. The cumulative evaporation rate of the samples (SF1W) mixed with fly ash is 70%. With the increase of the number of microbial treatment, the calcium carbonate crystals formed by microbial mineralization gradually increased, filling the pores between particles. Therefore, the cumulative evaporation rate of the two types of aeolian sand samples showed a downward trend. In general, the water-retention performance of the samples mixed with fly ash is better than that of the samples mixed with fly ash. After three times of microbial treatment, the cumulative evaporation rate of the SF3T samples is about 73.5% of that of S3T.

![Figure 4. Influence of mixed fly ash on sample surface strength](image)

3.3 Wind erosion resistance test
The wind erosion rate is characterized by the mass loss of sand table per unit time. The results showed that the wind-erosion resistance of aeolites was significantly improved after microbial mineralization treatment, and the mass loss rate could be reduced to 0.246g/min after a single microbial treatment, that is, only a small amount of aeolites particles in the surface layer were lost. By comparing S1W and SF1W samples, it is found that mixing fly ash is beneficial to enhancing the wind-erosion resistance of aeolian sand, but there are still obvious wind-erosion phenomena. After single microbial treatment, the wind erosion of both samples was significantly restrained. The results showed that the effect of multiple microbial treatment was not significant compared with that of single microbial treatment. Therefore, single spraying of microbial treatment agent can meet the demand for the key areas to prevent wind erosion.
4. Discussion

MICP technology is realized by injecting a variety of reaction fluids, including bacteria solution, into the soil to be strengthened. Its core principle is urea-hydrolysis reaction, and its main catalytic component is urease. Urea decomposition is slow under normal conditions, and the rate of urea hydrolysis can be greatly improved by introducing urease microorganisms into the reaction system. Another function of urease microorganisms is reflected in their electronegative cell membrane. When the environment contains a large number of calcium ions, the calcium ions tend to be distributed around the microbial body, and the ureolytic products combine with the calcium ions to form calcium carbonate.[16] Taking the solidification of aeolian sand as an example, when the content of calcium carbonate in the reaction system reaches supersaturated state, part of it will be deposited in the vicinity of the pores of aeolian sand particles in the form of precipitation, filling the pores between particles and reducing the porosity. The other part ACTS as a "bridge" connecting particles, which is reflected in the improvement of mechanical strength of aeolian sand on the macro level, as shown in figure 7. The above effects also effectively control the permeability coefficient, cumulative evaporation rate and other indicators of aeolian sand samples.
the contact area between sand particles and improving the integrity of aeolian sand.[12] In addition, the change of particle size composition will enable more calcium carbonate to be used for cementing aeolian sand particles and fly ash particles during microbial treatment of samples, so the surface strength, wind erosion resistance and other indicators are also improved compared with the unmixed samples.

5. Conclusions
(1) When fly ash is mixed in aeolian sand, the content of powder particles and the cohesion between grains increase, which can significantly reduce the permeability of aeolian sand and improve its water retention performance.

(2) Microbe induced mineralization can be used to improve the surface strength and wind-erosion resistance of aeolian sand, and the effect is significantly improved after mixing fly ash.

(3) The production rate of calcium carbonate is negatively correlated with the wind erosion rate and positively correlated with the surface strength, and the growth rate gradually slows down with the increase of treatment times.

References
[1] Ding xue, lei guoping, xu duanyang, et al. Effects of desertification evolution on regional ecosystem service value in Inner Mongolia from 1981 to 2010 [J]. Soil and water conservation research, 2018, 25(01):298-303.
[2] Wang lixian. Causes of desertification and its control measures in China [J]. World forestry research, 2000, 13(6):32-37.
[3] Phillips A J, Gerlach R, Lauchnor E, et al. Engineered applications of ureolytic biomineralization: A review [J]. Biofouling, 2013, 29(6): 715-733.
[4] Maleki M, Ebrahimi S, Asadzadeh F, et al. Performance of microbial-induced precipitation on wind erosion control of sandy soil [J]. International journal of environmental science and technology, 2016, 13(3): 937-944.
[5] Khaleghi M, Rowshanzamir M a. Biologic improvement of A sandy soil using single and mixed cultures: A comparison study [J]. Soil and Tillage Research, 2019, 186:112-119.
[6] Li chi, wang shuo, wang yanxing, et al. Field test study on microbial induced mineralization and its stability in desert [J]. Rock and soil mechanics, 2019, 40(04):1291-1298.
[7] Li duo. Study on microbial induced calcium carbonate precipitation solidifying desert aeolites [D]. Northwest a & f university, 2018.
[8] Wang jianxin, ulrich jing, zhao shibao, et al. Research progress and prospect of resource utilization of fly ash in China [J]. Chinese silicate bulletin, 2018, 37(12):3833-3841.
[9] Chang, A, C, Lund L J, Page A L, et al. The Physical Properties of Fly Ash - Amended Soils 1 [J]. Journal of Environmental Quality, 1977, 6 (3) : 267-270.
[10] Ghodrati M, Sims J T, Vasilas B I. Evaluation of fly ash as a soil amendment for the Atlantic Coastal Plain: I. Soil hydraulic properties and elemental leaching [J]. Water, Air, and Soil Pollution, 1995, 81 (3-4) : 349-361.
[11] Pathan S M, Aylmore L A G, et al. Properties of several fly ash materials in relation to use as soil amendments [J]. Journal of environmental quality, 2003, 32(2): 687-693.
[12] Yang kai, tang zejun, zhao zhi, et al. Wind tunnel test of sand fixation effect of fly ash and polyacrylamide [J]. Chinese journal of agricultural engineering, 2012, 28(04):54-59.
[13] Ye chenlei. Wind tunnel experiment study on fly ash improving desert soil [A]. Beijing dynamics society. Proceedings of the 23rd annual meeting of Beijing dynamics society [C]. Beijing dynamics society: Beijing dynamics society, 2017:2.
[14] Cheng gang, zhao liang, sun pengcheng, et al. Effect of fly ash on surface evaporation of sandy soil [J]. Journal of irrigation and drainage, 2011, 30(06):135-137.
[15] Xinjiang geographical society. Handbook of xinjiang geography [M]. Urumqi: xinjiang people's publishing house, 1993: 13550-134.

[16] Ivanov V, Chu j. Applications of microorganisms to geotechnical engineering for bioclogging and biocementation of soil in situ [J]. Journal of Reviews in Environmental Science and Bio/Technology, 2008, 7 (2): 139-153.

[17] DeJong J T, Mortensen B M, Martinez B C, et al. Bio-mediated soil improvement[J]. Ecological Engineering, 2010, 36(2): 197-210.