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Study on reinforcement of soil for suppressing fugitive dust by bio-cementitious material

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Abstract. Microbial-induced reinforcement of soil, as a new green and environmental-friendly method, is being paid extensive attention to in that it has low cost, simple operation and rapid effects. In this research, reinforcement of soil for suppressing fugitive dust by bio-cementitious material was investigated. Soil cemented by bio-cementitious material had superior mechanical properties, such as hardness, compressive strength, microstructure, wind-erosion resistance, rainfall-erosion resistance and freeze-thaw resistance. The average hardness of sandy soil, floury soil and clay soil is 18.9 º, 25.2 º and 26.1 º, while average compressive strength of samples is 0.43 MPa, 0.54 MPa and 0.69 MPa, respectively; meanwhile, the average calcite content of samples is 6.85 %, 6.09 %, and 5.96 %, respectively. Compared with the original sandy soil, floury soil and clay soil, the porosity decreases by 38.5 %, 33.7 % and 29.2 %. When wind speed is 12 m/s, the mass loss of sandy soil, floury soil and clay soil cemented by bio-cementitious material are all less than 30 g/(m2·h). After three cycles of rainfall erosion of 2.5 mm/h, the mass loss are less than 25 g/(m2·h) and the compressive strength residual ratio are more than 98.0 %. Under 25 cycles of freeze-thaw, the mass loss ratio are less than 3.0 %.

1 Introduction

Fugitive dust is a significant contributor to air pollution with harmful effects to human health [1-3]. Of all air pollution by the pollutants, fugitive dust is particular serious in that fugitive dust are very difficult to collect, separate and degrade [4-5]. Control of fugitive dust is becoming a hot spot at home and abroad for a time [6-8]. Generally, two measures can be taken to control fugitive dust pollution—physical method and chemical method. Physical method mainly includes sprinkling water, covering dust-controlling nets and building fence [9-11], while chemical method contains the dust-depressor type of wetting, hygroscopic, bond and complex [12-16]. Due to high energy consumption, large investment, complex operation and likely secondary pollution to the environment, physical and chemical methods are relatively difficult to be applied to the control of fugitive dust in large areas [17-19].

Nevertheless, bio-cementitious material, as a new green and environmental material, has stable and reliable effects, no secondary pollution, which, therefore, has become the most promising method in the control of fugitive dust. Firstly, CO_2 was absorbed, transformed and produced bicarbonate ions under the enzymatic action of *Paenibacillus*. Secondly, bicarbonate ions were transformed into carbonate ions under the condition of alkaline environment. Meanwhile, calcium ions in the fugitive dust were attracted to the bacteria cell wall due to the negative charge of the latter and upon addition of substrate to the bacteria. Finally, calcium ions were mineralized and precipitated to carbonate particles at the cell surface serving as the nucleation site. Fugitive dust was cemented in the process of forming calcite, and calcite-consolidation-layer was prepared ultimately which had a certain mechanical properties. The mechanism of mineralization and cementation of fugitive dust by bio-cementitious material based on CO_2 capture and utilization could be explained from the following equations:

$$CO_2 + H_2O \longleftrightarrow HCO_3^- + H^+ \quad (1)$$

$$HCO_3^- + OH^- \longleftrightarrow CO_3^{2-} + H_2O \quad (2)$$

$$Ca^{2+} + Cell \longleftrightarrow Cell\text{-}Ca^{2+} \quad (3)$$

$$Cell\text{-}Ca^{2+} + CO_3^{2-} \longleftrightarrow Cell\text{-}CaCO_3 \quad (4)$$

This research, reinforcement of soil for suppressing fugitive dust by bio- cementitious material was investigated. The hardness and compressive strength of different type's soil were presented successively, and the calcite content and porosity of samples were also verified accurately. Meanwhile, the wind-erosion resistance and rainfall-erosion resistance of samples were measured in wind tunnel teat and artificial simulation of rainfall devices. Finally, the freeze-thaw resistance of samples was demonstrated in the case of high and low temperature cycle. The results of these studies proved the feasibility of developing more environmentally friendly bio-cementitious material and showed that different types soil have a strong influence on microstructure and properties of samples cemented by bio-cementitious material.

2 Materials and methods

2.1 Experimental materials
Bio-cementitious material consisted of two parts: bacteria powder and calcium source. Bacteria power is Paenibacillus, while the calcium source is calcium nitrate. Cultivation of the *Paenibacillus* was conducted in sucrose culture (10 g of sucrose and 3 g of sodium hydrogen phosphate were dissolved in deionized water to 1 L, and the pH value was adjusted to about 7.0) at 35 °C for 24 h. The harvested microorganisms were kept in a refrigerator at 4 °C for stock prior to use in spraying process, while bacteria powder was used directly without cultivation in blending process.

2.2 Treating process
Wind erosion plates (internal diameter 20.0 cm, height 2.0 cm) were used in this study, and they were packed in the following order: first a layer of approximately 0.2 cm of gauze was placed at bottom of the wind erosion plates, followed by 2.0 cm of fugitive dust. All experiments were conducted at room temperature of 25±2 °C. Then, bacteria solution was sprayed evenly on the surface of fugitive dust after dissolved calcium nitrate. Afterwards, the samples were dried at room temperature of 25±2 °C until they were dried. The drying is stopped when the weight of the sample remains constant, which is achieved when its variation does not exceed 0.01%. The samples were collected and characterized.

2.3 Analysis of samples
The calcite content of samples was measured by Thermogravimetric-differential scanning calorimetry (TG-DSC), and it was carried out on STA449 F3 thermogravimetric analyzer (Nietzsche, Germany).

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The analyses were carried out simultaneously in a nitrogen atmosphere at a heating rate of 10 °C·min^{-1} between room temperature and 1000 °C.

Porosity was measured by the gravity method, using vacuum saturation. It consists of submitting the sample to a moderate oven-drying at a temperature of 60 ℃. The drying is stopped when the weight of the sample remains constant, which is achieved when its variation does not exceed 0.01%. The weight of the dried sample, denoted as m_d, is then measured with an accurate balance. Afterwards, the specimen is immersed under vacuum in a container filled with distilled water. The weight of the samples is measured at different times until it becomes stable; the sample is then considered as fully saturated with water and its weight denoted as *ms*. In addition, the volume of the sample (Vv) is precisely measured with a pycnometer. ρ_w is the volume density of water. Finally, porosity (p) is determined using the following formula:

$$P = \frac{m_s - m_d}{\rho_w Vv} \tag{5}$$

The wind-erosion resistance was conducted in wind tunnel test at 0 angle for 1 h, and the wind speed was 4, 6, 9, 12 m/s respectively. The wind-erosion resistance could be represented via the mass loss of unit area of samples. In other words, it could be represented by comparing the change of mass before and after experiment.

The rainfall-erosion resistance was conducted in the artificial simulation of rainfall devices. The rainfall duration on the surface of samples was 6 h, and the rainfall intensity was 2.5 mm/h, then dried at 60℃ in the oven for 24 h, and it was recorded as a cycle. The change of mass loss and compressive strength were obtained under the different cycles. According to the change, the rainfall-erosion resistance was evaluated accurately.

The freeze-thaw resistance was conducted in the constant temperature device. The non-dried sample first was in -20℃ for 6 hours, then was in 20℃ for 6 hours, and it was recorded as a cycle. The change of mass loss was obtained under the different cycles. According to the change, the freeze-thaw resistance was obtained.

3 Results and discussion

3.1 Hardness and compressive strength

The influence of different type's soil on hardness and compressive strength of samples cemented by bio-cementitious material are presented in Fig. 1. The experimental results indicate that different types soil significantly affect hardness and compressive strength of samples. It could be seen from Fig. 1 that average hardness of samples, cemented sandy soil, floury soil and clay soil is 18.9 º, 25.2 º and 26.1 º, while average compressive strength of samples is 0.43 MPa, 0.54 MPa and 0.69 MPa, respectively. The average hardness and compressive strength of samples cemented clay soil are largest, while that of samples cemented sandy soil are smallest. The results show that the performance of the soil was improved by bio-cementitious material effectively, and different type's soil had a strong influence on hardness and compressive strength. The reasons might be that clay soil itself has a certain bond force, but the sand soil is without bond force.

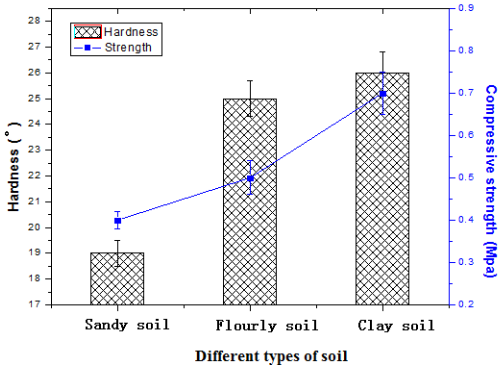

Fig.1 The hardness and compressive strength of samples cemented by bio-cementitious material

3.2 Calcite content

The influence of different type's soil on calcite content of samples cemented by bio-cementitious material are shown in Fig. 2. As Fig. 2 showed, average calcite content of samples, cemented sandy soil, floury soil and clay soil is 6.85 %, 6.09 %, and 5.96 %, respectively. Original calcite content in sandy soil, floury soil and clay soil is 0.21 %, 0.32 % and 0.28 %. However, the average calcite content of samples cemented sandy soil is larger than that others. The major causes for this end, among others, are the differences between particle size and pores of soil. Larger particle size and pores, which are conducive to the transfer, enrichment and transformation of carbon dioxide, result in more calcite.

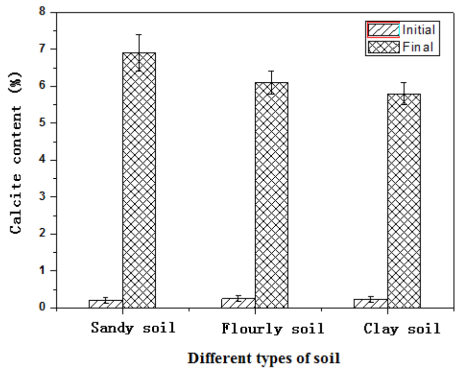

Fig. 2 The calcite content of samples cemented by bio-cementitious material

3.3 Porosity

The influence of different type's soil on porosity of samples cemented by bio-cementitious material are presented in Fig. 3. The results show that the initial porosity of samples, cemented sandy soil, floury soil and clay soil inclines to decrease, but the reduced range is different. Prudent observations of Fig. 3 indicates that the porosity of samples, cemented sandy soil, floury soil and clay soil effectively decreases by 38.5 %, 33.7 % and 29.2 %, respectively. The results are in keeping with the calcite content results, and more calcite filled with more pores in sandy soil.

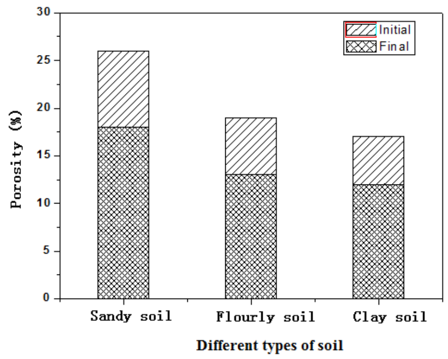

Fig. 3 The porosity of samples cemented by bio-cementitious material

3.4 Wind erosion resistance

The influence of different type's soil on wind erosion resistance of samples cemented by bio-cementitious material are shown in Fig. 4. Fig.4 showed, under different wind speed, the mass loss of original sandy soil is about 282, 1051, 1642 and 2189 g/ ($m^2 \cdot h$) respectively, the mass loss of original floury soil is about 312, 1223, 1805 and 2276 g/ ($m^2 \cdot h$) respectively, and the mass loss of original clay soil is about 504, 1415, 1981 and 2477 g/($m^2 \cdot h$) respectively. With the increase of wind speed, the mass loss is significantly increased.

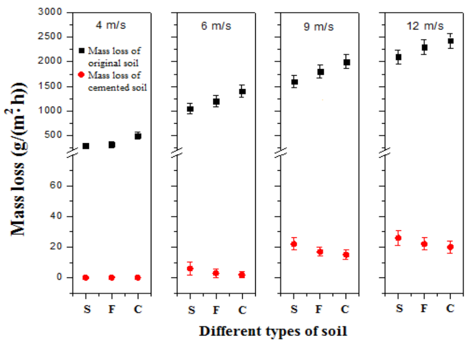

Fig.4 The wind-erosion resistance of samples cemented by bio-activated cementitious material

(S: sandy soil, F: floury soil, C: clay soil)

However, the mass loss of sandy soil, floury soil and clay soil cemented by bio-cementitious material are all less than 30 g/($m^2 \cdot h$), and no matter how much the wind speed, the change of the mass loss is not obvious. When the wind speed is 4 m/s, different type's soil samples cemented by bio-cementitious material could be achieved without obvious loss. As can be seen from Fig. 4, different type's soil has a certain influence on wind erosion resistance. In the same case, the wind erosion resistance of clay soil is better than that of sandy soil and floury soil.

3.5 Rainfall-erosion resistance

The influence of different type's soil on rainfall-erosion resistance of samples cemented by bio-cementitious material are shown in Fig. 5. Fig.5 showed, under the different number of cycle, the mass loss of original sandy soil, floury soil and clay soil is all more than 600 g/($m^2 \cdot h$), and the rainfall-erosion resistance is relatively poor.

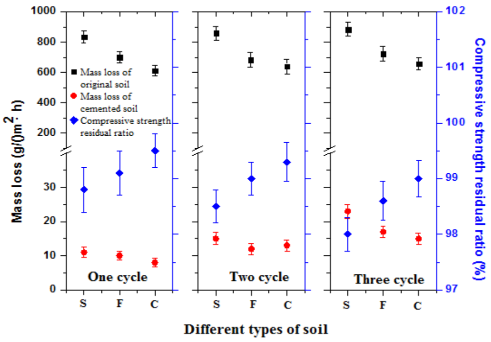

Fig.5 The rainfall-erosion resistance of samples cemented by bio- cementitious material

(S: sandy soil, F: floury soil, C: clay soil)

Nevertheless, in the one cycle, the mass loss of sandy soil, floury soil and clay soil cemented by bio-cementitious material are all less than 15 g/(m^2·h), then the change of the compressive strength was little and the compressive strength residual ratio are more than 99.0 %. Compared with the one cycle, the mass loss are all slightly increased and the compressive strength residual ratio are appreciably decreased in the two cycle. In spite of this, the mass loss are less than 25 g/(m^2·h) and the compressive strength residual ratio are more than 98.0 % in the three cycle. With the increase of number of cycle, the change of mass loss and compressive strength residual ratio are almost non-existent. It indicates that sandy soil, floury soil and clay soil cemented by bio-cementitious material have a good property of rainfall-erosion resistance.

3.6 Freeze-thaw resistance

Experimental data and numerical correlation on freeze-thaw resistance of samples cemented by bio-cementitious material are shown in Fig.6. Fig. 6 showed that the mass loss ratio of sandy soil cemented by bio-cementitious material at 1, 5, 10, and 15, 20 and 25 cycle is 0.13 %, 0.20 %, 0.58 %, 1.18 %, 1.89 % and 2.94 %. Then the mass loss ratio of floury soil cemented by bio-cementitious material at 1, 5, 10, and 15, 20 and 25 cycle is 0.08 %, 0.11 %, 0.20 %, 0.43 %, 0.71 % and 1.21 %, while the mass loss ratio of clay soil cemented by bio-cementitious material at 1, 5, 10, 15, 20 and 25 cycle is 0.05 %, 0.09 %, 0.15 %, 0.31 %, 0.59 % and 0.92 %. The experimental results show that the freeze-thaw resistance of sandy soil, floury soil and clay soil cemented by bio-cementitious material is apparently different. With the increase of number of cycle, the mass loss ratio is significantly increased, in particular in sandy soil. The freeze-thaw resistance of clay soil is better than that of sandy soil and floury soil.

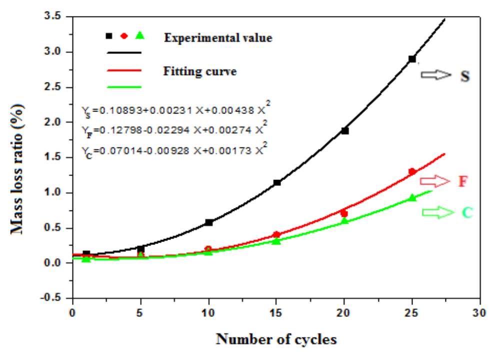

Fig. 6 The freeze-thaw resistance of samples cemented by bio-cementitious material

(S: sandy soil, F: floury soil, C: clay soil)

Basis on experimental data, numerical correlation of the freeze-thaw resistance at different number of cycle are carried out, and the equation could be found in Fig.6. The experimental value are in agreement with the simulated values, and the correlation curve could be effectively used to forecast and analyze the freeze-thaw resistance of samples.

4 Conclusions

This research, reinforcement of soil for suppressing fugitive dust by bio-cementitious material was investigated. The results obtained in this work can be summarized as follows: sandy soil, floury soil and clay soil cemented by bio-cementitious material have superior mechanical properties; furthermore, different type's soil have a certain influence on the mechanical properties. Using bio-cementitious material, the average hardness of sandy soil, floury soil and clay soil is 18.9 º, 25.2 º and 26.1 º, while average compressive strength of samples is 0.43 MPa, 0.54 MPa and 0.69 MPa, respectively; Meanwhile, the average calcite content of samples is 6.85 %, 6.09 %, and 5.96 %, respectively. Compared with the original sandy soil, floury soil and clay soil, the porosity decreases by 38.5 %, 33.7 % and 29.2 %. With the increase of wind speed, the change of the mass loss is not obvious; When wind speed is 12 m/s, the mass loss of sandy soil, floury soil and clay soil cemented by bio-cementitious material are all less than 30 g/(m^2·h). At the same time, the rainfall-erosion resistance of samples cemented by bio-cementitious material is proved; After three cycles of rainfall erosion of 2.5 mm/h, the mass loss are less than 25 g/(m^2·h) and the compressive strength residual ratio are more than 98.0 %. The experimental results show that the freeze-thaw resistance of sandy soil, floury soil and clay soil cemented by bio-cementitious material is apparently different. The freeze-thaw resistance of clay soil is better than that of sandy soil and floury soil. For different type's soil, different amounts of bio-cementitious material could be used to achieve the same effect.

Acknowledgements

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References

[1] Zhang zhihui, Wu Fan. Health impairment due to building construction dust pollution. J Tsinghua Univ (Sci &Tech), 2008, 48(6): 922-925.
[2] Zhao Pusheng, Feng Yinchang, Jin Jing, et al. Characteristics and control indicators of fugitive dust from building construction sites [J]. Acta Scientiae Circumstantiate, 2009, 29(8): 1618-1623.
[3] Ma Qaing, Wang Mei. Preparation and research on Dust Suppressant in Construction Site. Industrial safety and environmental protection, 2014, 40(8):61-63.
[4] Chen Li, Han Tingting, Li Tao, et al. Estimation of the effect derived from wind erosion of soil and dust emission in tianjin suburbs on the central district based on WEPS model. Chinese Journal of Environmental Science, 2012, 33(7): 2197-2203.
[5] He Jijun, Cai Qiangguo, Tang Zejun. Wind tunnel experimental study on soil wind erosion control with PAM. Journal of Soil and Water Conservation, 2007, 21(2): 12-15.
[6] Xu Xianying, Tang Jinnian, Jin Hongxi, et al. Study on sand-fixing benefits of three new-type chemical sand-fixing materials. Journal of Soil and Water Conservation, 2005, 19(3): 62-65.
[7] Han Fang, Zhu Jimao, Jin Longzhe. Research about the capability of new dust suppression medicament. Safety and Environmental Engineering, 2003, 10(4): 31-33.
[8] Wang Yinmei, Han Wenfeng, Chen Wenwu. Analysis of chemical sand-fixing materials for sand fixation in arid desert area. The Chinese Journal of Geological Hazard and Control, 2004,

15(2): 78-81.
[9] Zhang Huajun, Liu Fei,Zhang Xingkai,et al. The overview of road dust suppression agent. Science and technology of labour protection, 2000, 6: 40-42.
[10] Zhou Yufen. Effect of construction activities on particulate matter pollution along roadways. Journal of Southwest Agricultural University, 2004(4): 518-520.
[11] ZhaoXiuyong,Cheng Shuiyuan,Tian Gang,et al. Construction fugitive dust pollution and control in beijing. Journal of Beijing University of Technology, 2007(10): 1086-1090.
[12] Bai Xiangbing, Liu Jian, Yan Yingtao, et al. Fugitive dust pollution of city and situation and prospect of study on dust-depressor. Journal of Shaanxi University of Technology, 2005, 21(4): 43-46.
[13] Peng Xiaolan, Wu Chao. Progress of chemical dust suppressants and their application. Journal of Safety Science and Technology, 2005, 1(5): 44-47.
[14] Zhang Wen’an, Huo Leixia, Liu Hailong, et al. Study on preparation and properties of complex coal dust inhibitor. Coal Chemical Industry, 2009(5): 21-24.
[15] Amato F, Querol X, Johansson C, et al. A review on the effectiveness of street sweeping, washing and dust suppressants as urban PM control methods [J]. Science of the Total Environment, 2010, 408(16): 3070-3084
[16] Copeland C R, Eisele T C, Kawatra S K. Suppression of airborne particulates in iron ore processing facilities [J]. International Journal of Mineral Processing, 2009, 93(3-4): 232-238
[17] Karin E, Rolf M. Impact of fine materials content on the transport of dust suppressants in gravel road wearing courses [J]. Journal of Materials in Civil Engineering, 2011, 23(8): 1163-1170
[18] Medeiros M A, Leite C M M, Lago R M. Use of glycerol by-product of biodiesel to produce an efficient dust suppressant [J]. Chemical Engineering Journal, 2012, 180: 364-369
[19] Jin Longzhe,Yang Jixing,Ou Shengnan. Experimental study of wetting chemical dust-depressor. Journal of safety and environment,2007,7(6):109-112.