Study on Unconfined Compressive Strength of Zinc Contaminated Soil Solidified by Magnesium Phosphate Cement under Acid Rain

Zhanjun Huang¹, Qihui Zhou², Zunjing Liu³, Bohao Zhou*³ and Hongli Zhou⁴

¹ Nanchang Rail Transit Group Limited Corporation, Nanchang, 330038, China
² Power China Huadong Engineering Corporation Limited, Hangzhou, 311122, China
³ Institute of Geotechnical Engineering, Zhejiang University of Technology, Hangzhou 310014, China
⁴ School of Civil and Transportation, Hohai University, Nanjing 210016, China
Email: chokbh@163.com

Abstract. In this article, through the preparation of artificial contaminated soil in laboratory and simulated acid rain pollution to zinc magnesium phosphate cement (MPC for short) solidified soil erosion, the unconfined compressive strength characteristics of a single heavy metal (Zn) pollution under the above conditions was studied. In addition, water glass was added to improve the acid resistance of magnesium phosphate cement solidified soil. The effects of the mixing ratio of curing agent (MgO/KH₂PO₄, M/P for short), initial pH value by simulating acid rain, and the water glass content on the physical and mechanical properties of solidified zinc contaminated soil were analyzed. Studies have shown that when M/P=4, solidified soil contaminated by zinc has better solidification strength and solidification effect than M/P=6; adding water glass can increase the unconfined compressive strength of solidification of zinc contaminated soil by cement. 4% water glass content has a better effect to improve the strength of solidified soil; When the cement with M/P=4 has better engineering characteristics and acid resistance than that with M/P=6. Therefore, water glass can improve the engineering properties of solidified soil contaminated by zinc under sour environment effectively.

Keywords. Magnesium phosphate cement, solidification, pH, zinc contaminated soil, water glass, unconfined compressive strength.

1. Introduction

Recent years, the accelerating of urbanization and the relocating of industrial enterprises result in a large number of heavy metal pollutants have been left on the original address, causing serious pollution to the surrounding soil, and even posing a great threat to humans and the ecological environment. The investigation found that the content of heavy metal zinc accounts for a very great proportion in the contaminated soil by Cheng SP and Yuan JJ [1, 2], thus it does need to be repaired and treated.

Fu Shifa and Cao Liwen et al. find the soil is polluted by heavy metals will change its structure, pore characteristics, and soil quality, resulting in changes in soil permeability, plasticity, compressibility, and strength, causing damage to buildings [3, 4]. Solidification/stabilization (S/S for short) technology is one of the most effective methods for remediation of sites polluted by heavy metals. Paria S, Zhao Shuhua and Abu Qdais et al. find the advantages of this method is convenient
construction, low cost, improved foundation soil strength, and ability to hinder biodegradation [5-7].

At present, scholars at home and abroad have done many studies about solidified heavy metal contaminated soil for the engineering characteristics. Sun YJ and Wang Fei et al. have shown that solidified materials, solidified components and other factors will affect the strength characteristics of solidified soil contaminated by heavy metal [8, 9]. Buj I and Ding Yaokun et al. used MPC solidified soil contaminated by heavy metal and conducted research on its properties of mechanical. They discovered that solidified strength of MPC solidified heavy metal contaminated soil is better than Ordinary Portland Cement [10, 11].

At present, there are few relevant studies under complex environments on the durable features of solidified soil what is polluted, and acid rain, as a normal problem, has been paid attention to by a large number of people of insight worldwide. Du Yanjun and Bakhshipour Z et al. have done some studies about the destructive characteristics of solidified soil contaminated by heavy metal under acid rain environment and found that acid rain will have a particularly significant effect on the durability of solidified soil contaminated by heavy metal [12-14]. Although there have been a large number of studies on MPC solidified soil contaminated by heavy metal, there are still few studies on the acid resistance of it under the erosion of acid rain [15]. Therefore, in order to promote the acid resistance, it does need to detect proper additives to make MPC solidified soil contaminated by heavy metal have better engineering properties.

Most of methods of preparing acid resistant cement at home and abroad are to add water glass into cement by a certain proportion because of water glass with good acid resistance and high cohesive force. Hu wenlei and Shi Caijun et al. microscopically analyzed of the effect of water glass on MPC and found that water glass is able to indirectly improve the structural compactness [16, 17]. However, the effects of adding water glass on durability and engineering properties that under the dual effects of acid rain and heavy metals remains to be studied.

The paper based on unconfined compressive strength test, the impact of acid rain on the unconfined compressive strength characteristics of zinc contaminated soil solidified by magnesium phosphate cement. The single variable method was used to analyze the effects of curing agent ratio (M/P), pH value of acid rain, and water glass addition on the physical and mechanical properties of solidified zinc contaminated soil.

2. **Experiment Methods**

2.1. **Materials and Samples Preparation**

Soft kaolin with chemical composition content as shown in table 1 was used in this experiment as soil.

| Table 1. Kaolin chemical composition content. |
|---------------------------------------------|
| Index | SiO₂ | Al₂O₃ | CaO | TiO | MgO | Fe₂O₃ | Na₂O | K₂O |
|-------|------|-------|-----|-----|-----|-------|------|-----|
| Content | 47.86 | 38.26 | 0.19 | 0.13 | 0.08 | 0.06  | 0.05 | 0.04 |

In the laboratory, mix over burned magnesium oxide (MgO, M for short), potassium dihydrogen phosphate (KH₂PO₄, P for short), borax (Na₃B₅O₃·10H₂O, B for short) and fly ash in a certain proportion and add an appropriate amount water makes the final product magnesium phosphate cement. The MPC obtained by the above method is used as the curing agent for the test. Two ratios of MPC components were used, M: P= 4 and 6 (the ratio of moles to moles, which can be abbreviated as M4 or M6).

The selection and addition of heavy metals is based on the literature survey results of the pollution of urban industrial land in China, which shows that the average concentration of zinc in the soil is between 1189~16478 mg/kg [18]. Therefore, zinc was preferably a single pollutant by heavy metal, the concentration of which is 5000 mg/kg.

The simulated acid rain was made by the mixture in which the ratio of SO₄²⁻/NO₃⁻ to concentration
was 5:1. The mixture is diluted to three different pH solutions divided in pH value of 2, 4, 7.

Sodium metasilicate nonahydrate (Na$_2$SiO$_3$·9H$_2$O, also called water glass) is used in the test as an additive.

2.2. Experiment Method

For zinc contaminated soil solidified by MPC, there are two kinds of MPC: M4 and M6, the MgO and KH$_2$PO$_4$ content both are 10% of the dry soil, the heavy metal content is 0% and 0.5%, and the water glass content is 0%, 2% and 4% of the dry soil weight. The MPC solidified soil was pre-cured for 28 days and then leached in simulated acid rain for 2 h, 5 h, 17 h, 24 h, 48 h and 96 h, respectively. The effect of repeated leaching on the strength properties of the solidified system lasted for 10 days for 8 times, and finally the unconfined compressive strength was measured after natural air drying for two days. At the same time, the components without heavy metals were used as a comparative study.

Taking a special case of the triaxial test of the unconfined compressive strength test, the soil sample is subjected to vertical pressure without lateral stress, and the minimum principal stress $\sigma_3$ is 0, and the limit value of the maximum principal stress $\sigma_1$ is taken as the representative value of the unconfined compressive strength (UCS for short). The UCS test method of cement solidified contaminated soil is the same as that of ordinary cement soil. The determination of UCS is based on the (ASTMD2166-06) specification, which uses the conventional vertical loading instrument to act the vertical load on the specimen until the failure of the sample under the condition of ensuring the axial strain velocity 1%/min [19]. The ratio of the maximum pressure to the cross-sectional area of the acting surface obtained by the test is the maximum stress of UCS.

3. Analysis of Results

3.1. Influence of Different Cement Components

Figure 1 shows the unconfined compressive strength of solidified soil contaminated by zinc with M/P=4 and 6 and water glass content of 0%, and each component is referred to as MiZnj (k), where i represents m/p, j represents the content of heavy metals, and k represents the content of water glass. Figure 1 shows that M4Zn0 has the highest unconfined compressive strength after standard curing for 38d. Without any additives, the unconfined compressive strength of MPC solidified zinc contaminated soil is significantly lower than the strength of MPC itself, indicating that heavy metal zinc will affect the strength of cement solidified soil. Comparing the unconfined compressive strength of M4Zn0.5 (0%) and M6Zn0.5 (0%) specimens after standard curing for 38 days and accelerating simulated acid rain with the initial pH value of 2, 4 and 7, the $q_u$ corresponding to M4Zn 0.5 (0%) is 38.06%, 154.22%, 62.8% and 78.42% higher than that of M6Zn 0.5 (0%), which indicates that MPC has better solidified strength than M/P= 6 when the cement component M/P= 4.

![Figure 1. Effect of different cement components on unconfined compressive strength of solidified soil contaminated by zinc.](image-url)
3.2. Influence of pH value

Figure 2 shows the unconfined compressive strength of solidified soil under different pH values when the water glass content is 2% and 4%. It can be seen from figures 1-2 that the $q_u$ of $M_6Zn_0.5(0\%)$ samples after 38 days of standard curing under the condition of pH of 2, 4 and 7 increased by 26.13%, 11.71% and 13.16% respectively, indicating that strong acid has a strong erosive effect on zinc pollution solidified soil. From the unconfined compressive strength of the same sample under different pH values under the experimental conditions of different water glass content, it can be seen that adding water glass can improve the strength and acid resistance of solidified contaminated soil.

![Figure 2. Unconfined compressive strength of solidified soil under different pH values.](image)

(a) Water glass content is 2%
(b) Water glass content is 4%

3.3. Influence of Water Glass

Figure 3 shows the unconfined compressive strength values of solidified soil contaminated by zinc under different water glass content when M/P= 4 and 6, among them the content of heavy metal zinc is 0.5%. Comparing the pH value of 2, 4, 7 with the addition of 2%, 4% of water glass and $q_u$ without adding water glass, it can be seen that adding water glass under strong acid conditions can increase the strength of strong acid resistance, and under weak acid conditions it can improve unconfined compressive strength, water resistance can be improved in pH= 7 environment, and adding 4% water glass is better than 2% to increase the strength of zinc contaminated solidified soil. When adding water glass, M/P= 4 compared with M/P= 6, the unconfined compressive strength under any environment of M/P= 4 is higher than M/P= 6, indicating that M/P= 4. The acid resistance of the solidified soil is stronger than M/P= 6.

![Figure 3. Unconfined compressive strength of solidified soil under different water glass content.](image)

(a) M/P= 4
(b) M/P= 6
4. Conclusion

The paper analyzes the unconfined compressive strength characteristics of solidified soil contaminated by zinc, and the influence of cement composition, pH value and water glass on its engineering performance. The main conclusions are as follows: heavy metal zinc ion will change the failure characteristics of solidified soil; the cement component of M/P = 4 has higher curing strength than M/P = 6; water glass can increase the curing strength of solidified soil contaminated by zinc, especially when the water glass content is 4%, and 4% water glass can availably promote the acid and water resistance of solidified contaminated soil; therefore, water glass can be effectively used to enhance the engineering properties of MPC solidified soil contaminated by zinc in acid rain environment.

Acknowledgments

This work was supported financially by the Provincial Fund-East China Institute Joint Fund / Key Project (LHZ19E090001) and National Natural Science Foundation of China (No.51778585). We thank DING Yaokun for his guidance on the test.

References

[1] Cheng S P 2003 Heavy metal pollution in China: Origin, pattern and control Environ. Sci. Pollut. R.
[2] Yuan J J 2020 Ecology of industrial pollution in China Ecosyst. Health. Sust. 6.
[3] Fu S F and Lin S E 1989 Geotechnical problems of contaminated soil Geotech. Invest. Survey. 3 6-10.
[4] Cao L W, Lian X Y, Hong L, Wang Y and Yang Z G 2009 Experimental study on geotechnical properties of soil contaminated by metal ions Proc. 3rd National Geotech. and Eng. Conf.
[5] Paria S and Yuet P K 2006 Solidification/stabilization of organic and inorganic contaminates using Portland cement: A literature review Environ. Rev. 14 217-255.
[6] Zhao S H, Chen Z J and Zhang T P 2013 Advances in Solidification/Stabilization Technology Treatment of Heavy Metals in Contaminated Soils J. Soil. Sci. 44 1531-1536.
[7] Abu Q H, Begday I V, Shkarlet K Y, Harin K V, Bluzhina A S and Likhovid A A 2019 Leachability of heavy metals from stabilized/solidified mine tailing in Russia Eng. Res. 07 62-75.
[8] Sun Y J, Ma J, Chen Y G, Tan B H and Cheng W J 2020 Mechanical behavior of copper-contaminated soil solidified/stabilized with carbide slag and metakaolin Environ. Earth. Sci. 79.
[9] Wang F, Cai Z Y and Xu J 2020 Effects of Curing Temperature and Dosage on the Performance of GGBS-MgO-CaO in Stabilizing/Solidifying Heavy Metal-Contaminated Site Soil J. Test. Eval. 48 3515-3524.
[10] Buj I, Torrasb J and Casellasb D 2009 Effect of heavy metals and water content on the strength of magnesium phosphate cements J. Hazard. Mater. 170 345–350.
[11] Ding Y K 2015 Study on the Solidification Mechanism of Magnesium Phosphate Cement on Heavy Metal Contaminated Soil under Acid Rain Zhejiang University of Technology.
[12] Du Y J, Jin F and Liu S Y 2011 Research progress on solidification/stabilization of contaminated sites in heavy metal industry Rock. Soil. Mech. 32 116-124.
[13] Du Y J, Jiang N J, Shen S L and Jin F 2012 Experimental investigation of influence of acid rain on leaching and hydraulic characteristics of cement-based solidified/stabilized lead contaminated clay J. Hazard. Mater. 225 195-201.
[14] Bakhshipour Z, Asadi A, Huat B B K, Sridharan A and Kawasaki S 2016 Effect of acid rain on geotechnical properties of residual soils Soils. Found. 56 1008-1020.
[15] Xu S F, Wu X H, Cai Y Q, Ding Y K and Wang Z 2018 Strength and Leaching Characteristics of Magnesium Phosphate Cement-Solidified Zinc-Contaminated Soil under the Effect of Acid Rain Soil. Sediment. Contam. 27 161-174.
[16] Hu W L 2011 Research and Engineering Application of Sodium Silicate Glass High Temperature Adhesive South China University of Technology.

[17] Shi C J, Yang J M, Yang N and Chang Y 2014 Effect of waterglass on water stability of potassium magnesium phosphate cement paste Cement. Concrete. Comp. 53 83-87.

[18] Liao X Y, Chong Z Y and Yan X L 2011 Urban Industrial Contaminated Sites: A New Issue in China's Environmental Remediation Field Environ. Sci. 32 784-794.

[19] A.S.T.M. D2166-06 2006 Standard Test Method for Unconfined Compressive Strength of Cohesive Soil.