Study On Solidification Treatment of Electrolytic Manganese Slag And Numerical Simulation of Slope Stability

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Abstract

Manganese slag contains a large number of easily migrated heavy metals and ammonia nitrogen and other pollutants, which have a negative impact on the ecological environment. To verify the feasibility of manganese slag as highway subgrade material, manganese slag samples were solidified by mixing fly ash, cement and quicklime, and the solidification effect was compared. The permeability coefficient, cohesion and internal friction angle of manganese slag were measured by permeability test and triaxial test. On this basis, optimization of manganese slag road sections under different slope heights and different slope ratios in a total of 50 schemes was carried out. GeoStudio software is used to perform finite element simulation on the slope stability of manganese slag slopes under dead weight and rainfall. This study provides a reference for highway construction projects using manganese slag.

Introduction

As an important metallurgical and chemical raw material, manganese metal is an important basic material and national strategic resource in the national economy (Celik O 2006; Kumar S et al. 2013), and is widely used in the fields of chemistry, medicine, metallurgy, construction materials (Sozen S et al. 2017; A L S 2017; Nasir M et al. 2020; Li J et al. 2020), etc. With the continuous excavation and mining of manganese ore in various countries, the content of manganese ore is constantly decreasing, coupled with the limitation of technology, resulting in about 9 ~ 11 tons of acid waste residue per ton of electrolytic manganese production. Electrolytic manganese slag is a mixture of acid leaching slag, sulfide slag and anode slag produced by acidolysis, neutralization, pressure filtration and impurity removal of manganese carbonate ore (Lan J et al. 2020). A large amount of manganese slag has caused serious social and environmental pollution problems in China, such as waste water, waste slag, heavy metal pollution, etc., which is the primary problem to be solved (Wang Y et al. 2021; Jianwei, Zhou et al. 2017).

Nowadays landfill has become the main way for relevant enterprises to deal with manganese slag. Due to the high cost of treatment, China mainly chooses the damming method for storage. However, due to the occupation of valuable land, excessive ammonia nitrogen, sulfate and other heavy metal ions will be produced, causing serious pollution to the surrounding soil (Scattolin M et al. 2020). Some pollutants will flow into the river after being washed by the rain, seriously damaging the growth of crops and affecting human health. It has caused serious environmental pollution and security risks to aquatic ecosystem and agricultural ecosystem. Geoff et al. (2003) analyzed the accident of a tailings dam rupture in a copper mine site, and revealed that the marine environment near the accident was polluted by heavy metals in the tailings. He also found that an old waste dump would also cause potential heavy metal pollution to the ecosystem. Ran H et al. (2021) explored the sources, spatial distribution of metal(loid)s, and the risks to public health from these metal at an abandoned arsenic mine site. Falayi T (2019) used Ferrochrome as a precursor investigate for the synthesis of a geopolymer, and the unconfined compressive strength and metal leachability of the synthesized geopolymer was investigated. On the other hand, the rapid development of highway construction in various countries directly leads to the large consumption of soil, stone and cement lime in the road. Therefore, it has become a hot issue to explore the use of industrial

waste residue as pavement base and subgrade filling materials in recent years. Zhang Y et al. (2019) used electrolytic manganese residue, red mud and carbide slag as main raw materials to prepare the road base material, the mix was optimized and mechanical properties, durability, strength formation mechanism and environmental behavior were investigated. Using manganese slag as subgrade filling material can not only improve the utilization rate of manganese slag, but also solve the problems of manganese slag storage, land occupation and environmental pollution. Moreover, in a certain range of transportation distance, it can reduce the direct cost of highway engineering and produce huge social and ecological benefits.

In order to verify the feasibility of manganese slag as highway subgrade material, in this study, we compared the solidification effect of mixed solidified manganese slag with fly ash, cement and quicklime, and determined the best scheme to eliminate and solidify the soluble manganese and ammonia nitrogen in manganese slag. The permeability coefficient, cohesion and internal friction angle of manganese slag were obtained through the permeability test and triaxial test of manganese slag samples. On this basis, the finite element simulation was carried out for the stability of 50 schemes with different slope height or slope ratio, so as to provide reference for highway construction using manganese slag.

Methods And Theory

2.1 Saturated-unsaturated seepage theory

According to Darcy's law of unsaturated soil and the seepage continuity equation of porous media, the saturated-unsaturated differential equation expressed by pressure head can be obtained as follows (Su 2020):

$$\frac{\partial}{\partial x_i} \left[k_{ij}^s k_r(h_c) \frac{\partial h_c}{\partial x_j} + k_{i3} k_r(h_c) \right] + Q = [C(h_c) + \frac{\theta}{n} S_s] \frac{\partial h_c}{\partial t} \quad (1)$$

Where k_{ij}^s is the saturation permeability tensor; k_r is the relative permeability; h_c is the pressure head; Q^* is the source and sink term; $C(h_c)$ is the water capacity, n is the porosity; and S_s is the unit water storage.

2.2 Theory of strength and slope stability

Fredlund's double stress variable formula is used as the unsaturated shear strength theory:

$$s = c' + \sigma_n \tan \varphi' + (u_a - u_w) \tan \varphi^b \quad (2)$$

Where c, φ' are effective strength parameters; σ_n is the difference between normal normal stress and pore gas pressure; u_a is the pore gas pressure; u_w is the pore water pressure; φ^b is the strength increased by negative pore water pressure. The stability analysis of the earth-rock dam slope adopts the Morgenstern-Price method in the limit equilibrium method, and the Morgenstern-Price method can well reveal the interaction force between the soil strips without any simplification.

Model Test

3.1 Curing test

3.1.1 Solidification test of manganese slag mixed with fly ash

An appropriate amount of manganese slag samples were measured for the test to detect the leaching concentrations of Mn and NH_4^+ . Table 1 and Fig. 1 show that the leaching concentration of Mn and NH_4^+ decreases significantly with the increase of fly ash content. When the content of fly ash is 25%, the leaching concentration of Mn and NH_4^+ meet the design requirements of highway subgrade

Table 1
The test results of leaching toxicity of fly ash
with different dosage

Fly ash content	Mn (mg/L)	NH_4^+ (mg/L)
5%	1.044	249.32
10%	0.024	146.93
15%	0.012	139.02
20%	0.007	25.53
25%	0.002	1.64

3.1.2 Solidification test of manganese slag mixed with cement

Manganese slag and quicklime (Content of CaO is 87%) were selected as raw materials to test the leaching concentration of manganese and ammonia nitrogen. The test results are shown in Table 2 and Fig. 2. When the cement content is 4%, the leaching concentration of Mn is 1.204 mg/L, which meets the design requirement of 2mg/L; When the cement content is 15%, the NH_4^+ leaching concentration is 1.57mg/L, which meets the design requirements of highway subgrade with NH_4^+ leaching concentration of 25mg/L.

Table 2
The test results of leaching toxicity of cement
with different dosage

Cement content	Mn (mg/L)	NH ₄ ⁺ (mg/L)
4%	1.204	492.6
6%	0.922	290.63
8%	0.189	233.69
10%	0.035	154.3
12%	0.018	132.89
15%	0.001	1.57

3.1.3 Solidification test of manganese slag mixed with quicklime

The leaching concentrations of manganese and ammonia nitrogen are detected, and the test results are shown in Table 3 and Fig. 3. When the dosage of quicklime is 10%, the leaching concentrations of Mn and NH₄⁺ are 0.009mg/l and 11.67mg/l respectively, which meet the design requirements of highway subgrade.

Table 3
The test results of leaching toxicity of quicklime
with different dosage

Quicklime content	Mn (mg/L)	NH ₄ ⁺ (mg/L)
4%	0.569	412.89
6%	0.027	295.95
8%	0.012	91.29
10%	0.009	11.67
12%	0.003	1.00

It can be seen from the test results that the curing effect of the three curing materials on soluble manganese is remarkable. The results show that only when the cement content reaches 15% or the fly ash content reaches 25% or the quicklime content reaches 10%, the residual value of ammonia nitrogen can meet the design requirements.

Compared with cement, quicklime has lower cost and certain economic benefits; Compared with fly ash, the amount of quicklime to achieve the same treatment effect is only 40% of fly ash, which has certain technical advantages. Considering the solidification effect and technical advantages of the three materials, 10% quicklime is selected to eliminate and solidify the soluble manganese and ammonia nitrogen in manganese slag.

3.2 Variable head permeability test

In order to study the permeability characteristics of solidified manganese slag mixed with quicklime, a variable head permeability test was carried out for manganese slag with 10% quicklime, the permeability coefficient of variable head under standard temperature can be calculated as follows:

$$k_{20} = 2.3 \frac{\eta_t}{\eta_{20}} \frac{aL}{At} \lg \frac{H_1}{H_2} \quad (3)$$

Where: k_{20} is the permeability coefficient of the sample at standard water temperature (20°C), cm/s; η_t is the dynamic viscosity coefficient of water at the test water temperature, kPa·s; η_{20} is the dynamic viscosity coefficient of water at standard water temperature, kPa·s; a is cross-sectional area of the variable head pipe, cm²; L is sample height, cm; H_1 and H_2 are the starting and ending water heads, cm. A is water area of the sample, cm²; T is penetration time, s, $t = 600$ s in this test.

Table 4 shows the permeability test records of solidified manganese slag mixed with quicklime. It can be seen from Table 4 that the permeability coefficient of manganese slag mixed with 10% quicklime is between 1.24×10^{-5} cm/s and 1.52×10^{-5} cm/s, and the average permeability coefficient is 1.38×10^{-5} cm/s. The permeability coefficient of manganese slag mixed with quicklime is relatively large, which is equivalent to that of fine sand and has good drainage performance. This indicates that adding quicklime manganese slag can not only timely remove the groundwater from the seepage, reduce its erosion to the subgrade, but also effectively reduce the erosion and infiltration of the surface water to the subgrade, and prevent the instability of the subgrade, therefore it is a kind of subgrade filling material with great water permeability.

Table 4
Permeability test record of solidified manganese slag mixed with quicklime

Time(s)	Initial level H_1 (cm)	Terminal level H_2 (cm)	k_{15} (cm/s)	k_{20} (cm/s)	Average value(cm/s)
600	150.0	133.8	1.34×10^{-5}	1.52×10^{-5}	1.38×10^{-5}
600	133.0	121.0	1.10×10^{-5}	1.24×10^{-5}	
600	121.0	108.6	1.23×10^{-5}	1.39×10^{-5}	
600	150.0	134.9	1.20×10^{-5}	1.36×10^{-5}	
600	134.9	120.9	1.24×10^{-5}	1.41×10^{-5}	
Note: k_{15} is the permeability coefficient when the water temperature is 15°C; k_{20} is the permeability coefficient when the water temperature is 20°C.					

3.3 Triaxial test

Triaxial shear test (Fig. 4) is a method to measure the stress-strain relationship and shear strength of soil. The triaxial shear test needs to apply axial pressure to several cylindrical specimens under different confining pressures until the specimens are sheared. Then, several Mohr circles of ultimate stress are drawn by using the principal stress of specimen failure under different confining pressures. According to Mohr Coulomb strength theory, the shear strength index such as cohesion and internal friction angle of soil are obtained. In order to obtain the strength index of solidified manganese slag with quicklime, the consolidated undrained triaxial shear test was carried out by adding 10% quicklime into manganese slag.

The stress-strain curves of manganese slag mixed with quicklime under different confining pressures obtained from the triaxial test are shown in Fig. 5. It can be seen that under three confining pressures, with the gradual increase of axial strain, the difference of principal stress first increases to a peak value and then decreases, showing a strain-softening type. When the confining pressure is 100 kPa, the peak value of shear stress difference occurs at 1.75% of the axial deformation, which is 260.27 kPa. When the confining pressure is 200 kPa, the peak value of shear stress difference occurs at 2.07% of axial deformation, which is 328.27 kPa. When the confining pressure is 300kPa, the peak value of shear stress difference occurs at 2.07% of axial deformation, which is 422.15kpa.

Cohesion is an important indicator of the shear strength of soil. Through the particle analysis test of natural manganese slag, it is found that the manganese slag is mainly composed of powder and sand, and less clay, so it should be similar to non-cohesive soil, which means its cohesion is small. The results of consolidated undrained shear test of manganese slag mixed with 10% quicklime show that its cohesion is as high as 57.11kpa, indicating that the incorporation of quicklime increases the shear strength of manganese slag. According to the envelope diagram of the damage stress circle under different confining pressures (Fig. 6), the cohesion of the manganese slag mixed with 10% quicklime is 57.11kPa, and the internal friction angle is 19.82°.

Numerical Simulation

4.1 Finite element model

In order to study the influence of different section structure forms of manganese slag highway slope on slope stability, the section scheme of manganese slag highway under different slope height and slope ratio is optimized. The finite element model and material partition of slope are shown in Fig. 7. It is assumed that the failure of manganese slag highway slope obeys Mohr Coulomb criterion. Fig. 7 shows the finite element model of manganese slag slope with slope height of 16m and slope ratio of 1:1. The mesh is divided into 2325 nodes and 2225 elements

In the finite element model, the slope height of the manganese slag highway is 2m, 4m, 6m, 8m, 10m, 12m, 14m, 16m, 18m, 20m, and the slope ratio is 1:1, 1:1.25, 1:1.5, 1:1.75, 1:2, a total of 50 cross-section schemes, of which the slope top width is 12m, the distance from the slope toe to the edge of the foundation is 30m, and the foundation depth is 30m. The schematic diagram of the finite element model of some schemes is given, as shown in Fig. 8 and Fig. 9.

4.2 Geological parameters and working conditions

The calculation parameters of finite element model are measured by field test, and the physical and mechanical index parameters of manganese slag slope materials are shown in Table 5 and Table 6, in which Table 5 is the calculation material parameters of manganese slag slope seepage, and Table 6 is the calculation index parameters of stability and deformation. The soil water characteristic curve of manganese slag slope material is shown in Fig. 10, in which Fig. 10(a) is the volume water content function curve, and Fig. 10(b) is the permeability coefficient function curve.

Table 5 Parameters of seepage calculation

partition	volume-weight (kN/m ³)	Permeability coefficient (m/s)	Saturated volumetric moisture content (m ³ /m ³)
Manganese slag	18.8	1.38×10^{-7}	0.417
Soil foundation	21.6	5.21×10^{-8}	0.15

Table 6 Parameters of stability calculation

partition	Poisson's ratio	internal friction angle (°)	Cohesion (kPa)	Elastic modulus (MPa)
Manganese slag	0.25	19.82	57.11	174.6
Soil foundation	0.35	7.4	45	35

Result Analysis

5.1 Selection of optimal section

Fig. 11 shows the distribution diagram of safety factor of manganese slag slope under different slope height and slope ratio. It can be seen from the distribution trend diagram of safety factor in Fig. 11 that when the slope ratio is fixed, the higher the slope height is, the smaller the safety factor is, which means the more dangerous the slope is. When the slope height is fixed, the smaller the slope ratio is, the larger the safety factor is, which means the safer the slope is.

Figure 12 shows the distribution of sliding surface of manganese slag slope when the slope ratio is 1:1, 1:1.5, 1:2 and the slope height is 10m. Table 7 shows the corresponding safety factor of some section calculation schemes. It can be seen from Table 7 that when the slope height is 20m and the slope ratio is 1:1, the safety factor of the slope reaches the minimum value of 1.300, which means the slope is in the most dangerous state. Considering that the slope height in practical engineering is generally 8 m ~ 12 m, combined with the stability calculation results of numerical simulation, the section scheme of

manganese slag highway with slope height of 10 m and slope ratio of 1:1.5 is selected as the optimal scheme.

Table 7
Section calculation scheme and corresponding safety factor

Section scheme	Slope height	Slope ratio	Safety factor
C-1	6	1:1	3.009
C-2		1:1.25	3.160
C-3		1:1.5	3.228
C-4		1:1.75	3.305
C-5		1:2	3.383
D-1	8	1:1	2.420
D-2		1:1.25	2.550
D-3		1:1.5	2.601
D-4		1:1.75	2.653
D-5		1:2	2.717
E-1	10	1:1	2.122
E-2		1:1.25	2.145
E-3		1:1.5	2.192
E-4		1:1.75	2.250
E-5		1:2	2.289
F-1	12	1:1	1.839
F-2		1:1.25	1.889
F-3		1:1.5	1.927
F-4		1:1.75	1.967
F-5		1:2	2.021
G-1	14	1:1	1.611
G-2		1:1.25	1.672
G-3		1:1.5	1.741
G-4		1:1.75	1.781

5.3 Stability analysis of manganese slag slope under different rainfall intensity

The variation of the safety factor of manganese slag slope under different rainfall intensities is shown in Fig. 13. It can be seen that when the manganese slag slope encounters rainfall, the greater the rainfall intensity is, the smaller the safety factor of the slope is, which means the more dangerous the slope is.

The most dangerous sliding surface of manganese slag slope under different rainfall intensities in the process of rainfall is shown in Fig. 14. The safety factor is 2.227 when there is no rain, and the slope is in the safest state. The safety factor of manganese slag slope under the condition of rainfall intensity of 50 mm/d is 1.884, and the slope is in the most dangerous state. Therefore, in the actual manganese slag slope engineering management should focus on high-intensity rainfall conditions, do a good job in safety warning. Therefore, in the actual management of manganese slag slope engineering, more attention should be paid to the stability of manganese slag slope when high intensity rainfall occurs.

Conclusion

(a) The results show that fly ash, cement and quicklime have remarkable solidification effect on soluble manganese. Only when the content of cement reaches 15%, or the fly ash reaches 25%, or the lime reaches 10%, the residual value of ammonia nitrogen can meet the design requirements. Considering the solidification effect, economic benefits and technical advantages of the three materials, the optimal scheme is to eliminate and solidify the soluble manganese and ammonia nitrogen in manganese slag with 10% quicklime.

(b) When the slope ratio is fixed, the higher the slope height is, the smaller the safety factor is. When the slope height is fixed, the smaller the slope ratio is, the larger the safety factor is. Considering that the slope height in practical engineering is generally 8 m ~ 12 m, combined with the stability calculation results of numerical simulation, the section scheme of manganese slag highway with slope height of 10 m and slope ratio of 1:1.5 is selected as the optimal scheme.

(c) When the rainfall intensity is different, the greater the rainfall intensity is, the smaller the safety factor of manganese slag slope is. In the actual project operation management process, more attention should be paid to the stability of manganese slag slope when high intensity rainfall occurs.

Declarations

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Compliance with Ethical Standards

Conflict of interest The authors wish to confirm that there are no known conflicts of interest associated with this publication

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Figures

Figure 1

Relationship between leaching concentration of Mn and NH_4^+ after solidified manganese slag with different fly ash content

Figure 2

Relationship between leaching concentration of Mn and NH_4^+ after solidified manganese slag with different cement content

Figure 3

Relationship between leaching concentration of Mn and NH_4^+ after solidified manganese slag with different quicklime content

Figure 4

Instruments for triaxial experiment

Figure 5

Stress and strain curves under different confining pressures

Figure 6

Envelope of consolidated undrained shear strength

Figure 7

Finite element model and materials

(a)The slope ratio is 1:1 (b)The slope ratio is 1:1.5 (c)The slope ratio is 1:2

Figure 8

Slope model with 8 m slope height

(a)The slope ratio is 1:1 (b)The slope ratio is 1:1.5 (c)The slope ratio is 1:2

Figure 9

Slope model with 14 m slope height

(a) Volume water content function (b) permeability coefficient function

Figure 10

Soil water characteristic curve

Figure 11

overall distribution trend of safety coefficient of manganese slag slope under different slope height and slope ratio

Figure 12

location of the most dangerous sliding surface of manganese slag slope with the height of 10m

Figure 13

Change trend of safety factor of manganese slag slope under different rainfall intensity

(a) rainfall intensity is 0 mm / d

(b) rainfall intensity is 10 mm / d

(c) rainfall intensity is 30 mm / d

(d) rainfall intensity is 50 mm / d

Figure 14

Location of the most dangerous sliding surface under various working conditions