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Effect of Cement Content on Erosion Resistance of Solidified Soil

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Abstract: In this paper, sand and clay are selected as research objects for unit erosion test, and the effect of cement content on the erosion resistance of different soils was analyzed. The test results show that the erosion resistance of sand and clay gradually increases with the increase of cement content, but due to the different properties and strength growth mechanisms of clay and sand, the growth trend of strength with cement content is different. The increase in sand strength is continuous, and when the cement content reaches 12%, the soil can withstand the water flow with large shear stress; When the cement content is 10%, the erosion resistance of clay is much greater than 8%; The cement content of 10% can be used as the optimal cement content for curing soil.

1. Introduction

The erosion of soil by water is an important factor that causes the damage of underwater structures such as bridge foundation. Among the damage time of Bridges worldwide, flood erosion accounts for the largest proportion[1]. Xiong Wen[2] calculated a total of 1,682 bridge failure events from 1807 to 2021, 69% among which were caused by the erosion of bridge foundation. Therefore, the erosion of the soil around the foundation by water flow is the main cause of bridge damage[3]. Traditional protection methods of underwater structures mainly include riprap, sandbag, etc., but there are some problems such as inaccurate positioning and poor protection effect[4], which is not convenient for application in engineering. As a kind of environmental protection material, solidified soil can not only improve the erosion resistance strength of soil, but also realize environmental protection and utilization of waste resources. Theoretically, it can be used as the choice of foundation erosion protection.

At present, among commonly used solidified materials, inorganic materials have relatively good curing effect. As the most common inorganic additive material in solidified soil, the content of cement has an important influence on the strength growth of solidified soil. Predecessors also have some studies on the influence of cement content. Wang Rong[5] studied the strength performance of high moisture content peat after cement solidification, and found that with the increase of cement content, the failure mode of solidified soil changed from plastic failure to brittle failure. The higher the cement content, the higher the unconfined compressive strength of solidified soil, and the better the strength performance. Sun Haichao[6] studied solidified silt with different water content and cement content, and found that there was a critical point in the trend of cement content increasing soil strength, and the strength performance of solidified soil would be greatly improved at this point. Tan Peng[7] took the high liquid limit soil in Dongting Lake area of Hunan Province as the research object, in which cement, quick lime, fly ash, sulfonated oil(SO) and other curing agents were added in a certain proportion to improve the strength of soil. In terms of strength improvement, inorganic materials had a more obvious effect, and the strength was positively correlated with the content of inorganic materials. Wang Zishuai[8] studied the sulfate attack resistance of industrial waste slag-cement solidified soil and found that the addition of industrial waste slag could significantly delay the sulfate attack on solidified soil, and the order of the corrosion resistance of solidified soil was different with different dosage of industrial waste slag. It can be seen that the cement content does have a great impact on the strength of solidified soil, but the research on the erosion resistance strength of solidified soil is still blank, so it is necessary to use relevant theories and test methods for further study.

In this paper, EFA was used to carry out a unit erosion test on solidified sand and solidified clay, to explore the influence of cement content on the growth of erosion resistance strength of solidified soil with different soil properties, and to summarize the law of the change of erosion resistance strength of solidified soil with cement content, so as to provide reference for the subsequent engineering application of solidified soil in erosion protection.

2. Test protocol

2.1 Test Materials

Typical sand and clay were used as the research objects, and the sand particle gradation curve was shown in Figure 1, and the basic physical and mechanical parameters of clay were shown in Table 1. The cement used is ordinary Portland cement, strength grade 42.5, and the performance indicators of cement are shown in Table 2; In addition, a new type of liquid curing agent is added to the sample of this test, which can fully react with cement and better play the role of cement in cured soil, and its main components include water, sodium silicate, epoxy resin, silica, etc.

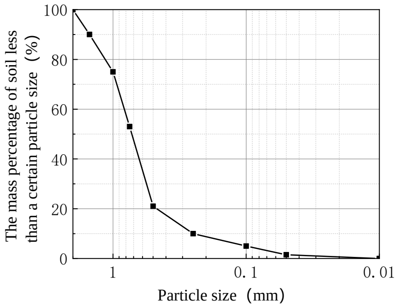

Figure 1: Sand particle grading curve

Table 1: Physical and mechanical parameters of clay

The type of soil	Density/(g cm^{-3}).	Liquid limit/%	Plastic limits/%	Plasticity index
clay	1.97	28.51	17.87	10.64

Table 2: Cement performance index

Loss on ignition/%	MgO/(%)	SO_3/(%)	Cl^-/(%)	Specific surface area//(m^2/kg)	Coagulation time/(min).	
					Initial coagulation	Final coagulation
4.50	2.01	2.29	0.010	395	169	252

2.2 Specimen making

Before preparing the sample, the soil is dried, crushed and screened, and the method of standing is used for curing and solidification to form the strength of the sample. The specific sample preparation process is as follows:(1) Mix the cement and soil samples in proportion, so that the two are fully mixed and uniform in the absence of water, and then pour into the cement mortar mixer;(2) Take a certain amount of water and curing agent in proportion, mix it evenly, pour it into the cement mortar mixer, and stir for 3-5 minutes to make it fully mixed evenly;(3) Pour the sample into the test container and place it on the shaker table to vibrate for 3-5 minutes;(4) After the vibration is completed, the sample is placed at room temperature for 2-6 hours to make the sample form strength, and the sample is taken for unit flushing test after several hours of curing.

In this experiment, the water content is the proportion of water to soil, the cement content is the proportion of cement to soil, and the liquid curing agent content is the same, which is 0.02%. In the process of sample preparation, water content take liquid limit moisture content is appropriate [9]. According to the initial coagulation time and final coagulation time of the cement, the curing time range is determined to be 6 hours. The test includes sand test and clay test, sand is represented by S, clay is represented by CL, the number represents the cement content, and the test mix ratio design is shown in Table 3.

Table 3: The mix ratio of the test

Specimen number	Sand quality/g	Water quality/g	Quality of cement/g	Hardener mass/g
S4	2000	320	80	0.4
S6	2000	320	120	0.4
S8	2000	320	160	0.4
S10	2000	320	200	0.4
S12	2000	320	240	0.4
S14	2000	320	280	0.4
CL4	2000	570	80	0.4
CL6	2000	570	120	0.4
CL8	2000	570	160	0.4
CL10	2000	570	200	0.4
CL12	2000	570	240	0.4
CL14	2000	570	280	0.4

2.3 Test equipment

The erosion test equipment used in this test is the erosion function apparatus (EFA), Figure 2 is the schematic diagram of the test equipment. The equipment is mainly composed of water storage tank, water pump, rectangular pipeline, electronically controlled top soil piston, electromagnetic flow meter, computer control system and other parts, which can continuously maintain the uniform and stable water flow rate. Among them, the rectangular pipe section size is 50.8mm×101.6mm; The pipe length is 1.22m; The maximum flow rate of the pump is 120m3/h, the electronic control valve is used to adjust the flow rate of the pump, and the test flow rate range is 0.1m/s~6m/s; The sampler is a standard Shelby tube with a cross-sectional diameter of 76.2 mm.

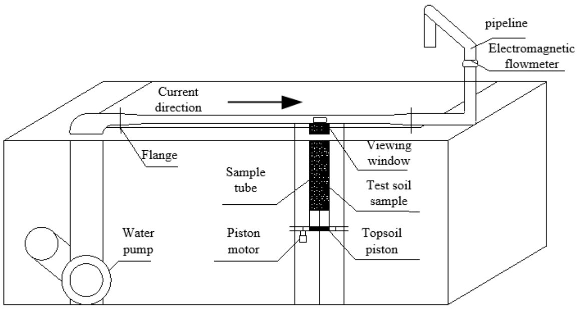

Figure 2: Erosion function apparatus

The test steps are as follows: (1) The prepared soil sample is loaded into the sample cylinder and fixed in the top soil piston groove; (2) Gently scrape the surface of the soil sample with steel wire, shake the rocker to embed the top of the sample cylinder into the lower opening of the rectangular pipe, and adjust the height to make the top of the cylinder flush with the bottom of the pipe; (3) Set the water flow rate from small to large, each group of erosion test is carried out under 3~7 different flow rates, observe the soil sample erosion during the test and keep the soil sample surface level with the bottom of the pipeline, each stage flow rate increment depends on the speed of scouring, the maximum is 6m/s. In order to ensure the accuracy of the test, the washing duration at each flow rate is 10~20min, and the test time is determined according to the erosion rate of the soil sample, the faster the erosion rate, the shorter the duration.

The water flow shear stress is calculated according to the equation[10]:

$$\tau = \frac{f}{8}\rho V^2$$

Among them: τ is the bed surface shear stress; ρ is the density of water; f is the friction coefficient; V is the average flow rate of the section. The friction coefficient f is a function of the ratio of the relative roughness ks to the hydraulic diameter D, which can be determined according to the Moody diagram， D=68mm, ks takes 0.5D50, D50is the median particle size.

3. Results and analysis

3.1 Determination of critical shear stress

Previous scholars can give quantitative criteria for critical shear stress through different erosion test results. McNeil[11] and Smith[12] defined the erosion rate corresponding to the critical shear stress by erosion test 10-4 cm/s~10-3cm/s and 10-4 cm/s. According to the research of the above scholars, the shear stress corresponding to the erosion rate of 10-4cm/s (3.6mm/hr) is the critical shear stress.

The value method on the erosion rate image is: if the erosion rate curve has an intersection point with a horizontal line with an ordinate of 3.6mm/hr, the shear stress corresponding to the intersection point is taken as the critical shear stress; If there is no intersection between the erosion rate curve and the horizontal line with an ordinate of 3.6mm/hr, the two smallest test data points on the erosion rate curve are connected into a straight line and extended in the direction of the small abscissa and ordinate, and the extension line has an intersection point with the horizontal line with an ordinate of 3.6mm/hr, and the abscissa corresponding to the intersection point is the critical shear stress, as shown in the Figure 3 is shown.

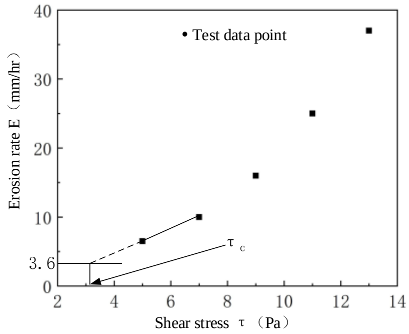

Figure 3: Determination of critical shear stress

3.2 Analysis of erosion rate

The erosion rate can reflect the erosion strength of the soil, under the same shear stress, the smaller the erosion rate, the greater the erosion strength, and its performance is more conducive to engineering applications.

Figure 4 shows the results of the sand erosion rate test. It can be seen in the figure that with the continuous increase of cement content, under the action of the same shear stress, the erosion rate is getting smaller and smaller, especially when the cement content is 6%, 10% and 12%, the erosion rate decreases greatly, and the cement content reaches 12%. At 14%, under the action of large shear stress, the erosion resistance rate of the soil can still be maintained at a low level, with good erosion resistance.

Due to the increase of cement content, the amount of tricalcium silicate, dicalcium silicate and other substances in the soil increases, and the reaction products of the hydration reaction are increased, and more hydrated calcium silicate, calcium alumina, etc. are generated, which improves the strength of the soil. At the same time, the increase of cement content will also produce more calcium hydroxide, react with SiO2 to generate hydrated calcium silicate, these products are mixed with water to form a fluid material, fill the pores of sand particles, and greatly improve the strength of sand after condensation and hardening; Cement hydration releases a certain amount of heat and consumes a large amount of water, so that the pore water between the sand particles is removed, which is more conducive to filling the pores between the particles of popular materials and improving the erosion resistance of the soil.

Figure 5 shows the results of the clay mix ratio scouring test. It can be clearly seen in the figure that with the gradual increase of cement content, the erosion resistance of the soil is gradually enhanced, especially when the cement content is 10%, the erosion strength of the soil is greatly increased compared with 8%, and when the shear stress in the figure is 12Pa, the soil whose cement content is 10% is twice as low as the 8% erosion rate, which shows the influence of the increase of cement content on the erosion resistance rate of the soil. The same as sand, when the cement content is large, even in the case of large shear stress, the erosion rate of the soil is still not high, due to the large cohesion of the clay itself, the cement content of 10% will produce a similar phenomenon.

In addition to the increase in hydration products and the amount of calcium hydroxide, the increase in the erosion resistance of clay is due to the production of more high-valent cations that can be exchanged for ion, which enhances the gravitational attraction between particles. In addition, the increase of cement content makes the hydration reaction consume more water, which greatly reduces the moisture content of the clay, which is conducive to the growth of the strength of the solidified soil.

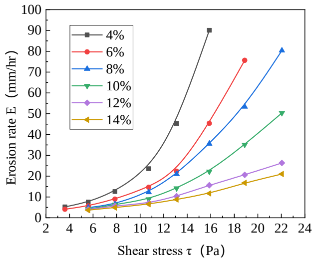

Figure 4: Sand erosion rate curve

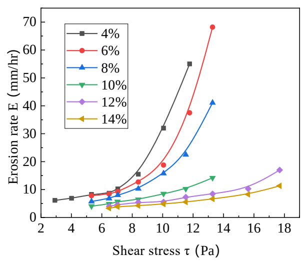

Figure 5: Clay erosion rate curve

The erosion resistance of sand and clay gradually increased with the increase of cement content, but due to the different properties and strength growth mechanisms of clay and sand, the strength growth trend of solidified soil with cement content was also different. As the strength of sand continues to increase, the erosion resistance of soil will be greatly improved with each increase of cement content. When the cement content reaches 12%, the soil can resist water flow. Although the clay strength also increases, it can be seen that when the cement content is 10%, the erosion resistance of the soil is greater than 8%, which may be due to the cation exchange in the soil or the water content reaches a certain threshold, making the erosion resistance of the clay qualitative change.

3.3 Analysis of critical shear stress

The critical shear stress refers to the water flow shear stress corresponding to the soil from static to moving critical state under the action of water flow. The critical shear stress can well characterize the erosion resistance of the soil in the critical stage, and it is also the critical value for the soil to begin to fail. Therefore, the change trend of critical shear stress on soil with the increase of cement content is of great significance to study the optimal mixing ratio of solidified soil.

Figure 6 shows the change of critical shear stress of sand with the increase of cement content. It can be clearly seen that when the cement content is less than 10%, the critical shear stress of the soil continues to increase, and each time the cement content increases, the critical shear stress of the soil will increase greatly. However, after the cement content reaches 10%, the growth trend of critical shear stress slows down, and it can be concluded that 10% cement content is the change node of the growth trend of sand critical shear stress. This is similar to the results of the erosion rate analysis.

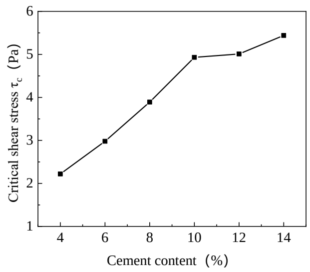

Figure 6: Change of critical shear stress in sand

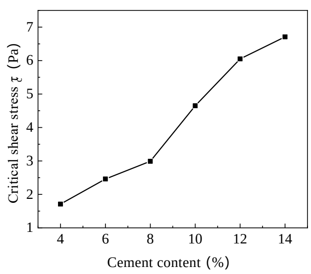

Figure 7: Change of critical shear stress in clay

Figure 7 shows the change of clay critical shear stress with the increase of cement content. The trend of clay critical shear stress with cement content is different from that of sand, and it is in a continuous growth process, but it can be clearly seen that the growth trend of critical shear stress becomes larger when the cement content is 10%, which indicates that when the cement content reaches 10%, the erosion resistance of the soil has increased significantly, which is more consistent with the results of the erosion rate curve analysis, indicating that the cement content is 10% is also an important node for the increase in erosion resistance of solidified clay.

Through the above analysis, it can be seen that compared with the cement content of 8%, the increase of sand and clay critical shear stress of 10% is 27% and 56%, respectively, which are the maximum values, combined with the results of the erosion rate analysis. The cement content of 10% can be used as the optimal cement content for solidified soil.

4. Conclusion

In this paper, unit tests were carried out on sand and clay, and the following conclusions were drawn according to the test results:

(1) The erosion resistance strength of sand and clay gradually increases with the increase of cement content, but due to the different properties and strength growth mechanisms of clay and sand, the strength growth trend of solidified soil with cement content is also different.

(2) The increase in sand strength is continuous, and when the cement content reaches 12%, the soil can resist the flow of water with large shear stress; Although the strength of clay also increases with the increase of cement content, it can be clearly seen that when the cement content is 10%, the erosion resistance of the soil is much greater than 8%.

(3) The critical shear stress-cement content relationship curve and the critical shear stress increment-cement content relationship curve- of the solidified soil-were analyzed, and the cement content was 10%. It is an important node for the growth of erosion resistance of solidified soil, so combined with the relevant mechanism of strength growth, the cement content of 10% can be used as the optimal cement content.

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