Analysis of Factors Affecting Solidification Strength of Sludge in a Landfill Area of Shenzhen

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Abstract

Parallel and orthogonal tests are used to explore the influence law of the dosage and age of curing agent on the strength of solidified sludge. The test results show that: 1) The strength of solidified sludge is mainly related to the cement content and dry soil content, and presents a good linear relationship. The influence of gypsum content is not significant. As the age increases, the strength is greatly affected by the cement content. 2) At different ages, the unconfined compression strength of solidified sludge presents a linear relationship, and the change law of later strength can be predicted by early strength. 3) Degree of influence of curing agent dosage: cement dosage > gypsum dosage > dry soil dosage. The optimal mixture ratio is 8% of cement content, 30% of gypsum content (proportion of cement content), and 4 times of dry soil content (multiple of cement content).

Keywords

1. Introduction

Domestic treatment of sludge is mostly landfill methods. As a sludge product after sewage treatment, sludge has the characteristics of easy rancidity, high moisture content, low permeability coefficient and low strength. Therefore, nowadays, with insufficient urban development space, the sludge strength of sludge landfill site is difficult to meet the requirements of individual landfill or bear the

upper load as foundation. The solidification treatment of sludge by some on-site solidification methods can make it meet the requirements of foundation filling and has important significance for eco-city construction [1]. *In-situ* curing achieves the solidification effect of the sludge by adding a solidified material to the soft soil to cement the soil particles and dissipate the water. Domestic research on *in-situ* curing has focused on the choice and ratio of curing agents. Zhang Chunlei [2] solidified the dredged mud by adding a curing agent, which verified that the *in-situ* solidification method can improve the strength, deformation and permeability of the dredged mud. Lin Anzhen [3] studied the effect of *in-situ* solidification and found that the solidified dredged mud can be used as a filling material in practical engineering and its feasibility is analyzed. Foreign scholar Sezer [4] *et al.* used lime and fly ash as curing agents to obtain the variation of sludge strength with the amount of curing agent through laboratory tests. Filz G M [5] *et al.* studied the strength of solidified sludge by incorporating different amounts of curing agent to obtain the best ratio of cement and fly ash solidified sludge. Lin [6] and Ouhadi [7] used slaked lime and lime-fly ash as sludge solidifying agents respectively to determine the appropriate mix ratio and verify its feasibility. By studying the effect of organic matter on the *in-situ* solidification method, Helene Tremblay [8] found that the strength of the solidified sludge decreased with the increase of the organic matter content in the curing agent. In the research of *in-situ* solidification method by domestic and foreign scholars, cement, fly ash, lime, slag and other solidified materials are often used as curing agents. In this paper, the dry soil rarely used in the study is used as *in-situ* solidified material, and combined with cement and gypsum; the effect of research on sludge strength is in a sludge landfill in Shenzhen.

2. Test Materials and Methods

2.1. Test Materials

The test uses the original sludge, which was taken from a sludge landfill in Shenzhen (as shown in **Figure 1**). After the sludge and curing agent of the sewage treatment plant were directly mixed and treated, the landfill was centralized. After that, it covers about 0.5 m of loess. After excavation on site, the odor emission was more obvious (mainly ammonia, hydrogen sulfide, methane and other gases generated by organic matter spoilage). The sludge was black peat-like, and the average natural moisture content of the average sludge was 105.4%, the average specific gravity was 2.59, the average natural density was 1.61 g/cm^3, and the average permeability coefficient was 2.65×10^{-7} cm/s. The average content of particles of ≤0.075 mm in the sludge of the sludge landfill is about 40%.

The sludge landfill soil belongs to peat silt, and the micro-structure image of sludge soil is shown in **Figure 2**. It can be seen from the figure that the soil is mostly in the form of massive structure, and the surface of the soil particles is attached with fluffy materials. Only a small amount of soil is in the form of a

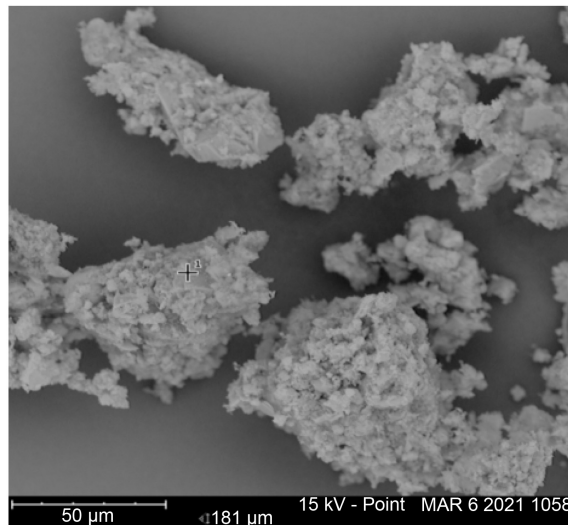Figure 1. Sludge landfill upper layer covering soil 0.5 m.

Figure 2. Undisturbed sludge microstructure image.

sheet, which is related to the addition of a large amount of flocculant to the sludge during the sewage treatment. Therefore, it has the characteristics of strong flocculation and high combined water content, which leads to the conventional curing method such as vacuum pre-pressing method and stacking pre-pressing method being too low in efficiency to achieve the curing effect. In this paper, cement is the main curing agent, and gypsum and dry soil are used as curing agent.

2.2. Test Methods

In this test, the YYW-1 manual lime soil unconfined pressure gauge (as shown in Figure 3) was used to measure the unconfined compressive strength. According to the steps in the specification, a cylindrical specimen with a diameter of 39.1 mm and a height of 80 mm was placed on the instrument. Then, by rocking the rocker, the platform below the sample is raised while applying vertical pressure to the soil sample until the sample is destroyed. The axial pressure

Figure 3. YYW-1 manual lime soil unconfined pressure gauge.

at which the sample is broken is called the unconfined compressive strength and is expressed by q_u.

According to the experience of the previous attempts in this study and the *in-situ* curing test [5], the gypsum content was selected as 0%, 20%, 30%, 40% of the cement content based on 8% of the cement content. 50%. The dry soil was selected as 1 times, 2 times, 3 times and 4 times of the cement content. To investigate the curing effect, parallel tests and orthogonal tests were set up.

Parallel test, by controlling the amount of two additives unchanged, changing the amount of another additive, to achieve the principle of controlling a single variable, such as Table 1.

Orthogonal test, uses orthogonal tables to find better influence conditions from a small number of trials to achieve the best experimental results [9]. The test measures the degree of influence of the corresponding factors on the test results by the magnitude of the R value, and the greater the R value, the greater the influence. The test was designed according to the three factors and three levels, see Table 2, and from Table 2, the L9 (3^3) orthogonal table was used to obtain the test plan, see Table 3.

3. Test Results Analysis

3.1. Influence of Cement Content on Solidified Sludge Strength

Table 4 shows the unconfined compression strength values of solidified soils with different formulations at different ages. Figure 4 shows the relationship between the unconfined compression strength of solidified soil and the amount of cement added. In the three stages of different ages, the unconfined compression strength of the solidified sludge is increasing during the process of increasing the cement content from 4% to 10%, and the growth rate is above 60%, up to 173.18%. When the cement content increased from 8% to 10%, the growth rate of each of the three curves was above 110%. It can be seen that the strength of

Table 1. Parallel test mix ratio (gypsum and dry soil are relative cement content).

Group	Cement content	Gypsum content	Dry soil content
1.1	4%	0%	0
1.2	6%	0%	0
1.3	8%	0%	0
1.4	10%	0%	0
2.1.1	8%	20%	0
2.1.2	8%	30%	0
2.1.3	8%	40%	0
2.1.4	8%	50%	0
2.2.1	8%	0%	1 Multiple
2.2.2	8%	0%	2 Multiple
2.2.3	8%	0%	3 Multiple
2.2.4	8%	0%	4 Multiple

Table 2. Orthogonal test factor level table (gypsum and dry soil are relative cement content).

Level	Cement	Plaster	Dry soil
1	4%	10%	2 Multiple
2	6%	20%	3 Multiple
3	8%	30%	4 Multiple

Table 3. Orthogonal test scheme (gypsum and dry soil are relative cement content).

Group	Cement content	Gypsum content	Dry soil content	Test results
3.1	4%	10%	2 Multiple	X1
3.2	4%	20%	3 Multiple	X2
3.3	4%	30%	4 Multiple	X3
3.4	6%	20%	2 Multiple	X4
3.5	6%	30%	3 Multiple	X5
3.6	6%	10%	4 Multiple	X6
3.7	8%	30%	2 Multiple	X7
3.8	8%	10%	3 Multiple	X8
3.9	8%	20%	4 Multiple	X9

the sludge increased linearly with the increase of cement content.

3.2. Effect of Gypsum Content on Solidified Sludge Strength

Figure 5 shows the relationship between the strength of solidified sludge and the amount of gypsum, of which the cement addition is 8%. The strength of solidified sludge increases first and then decreases with the increase of gypsum content, and when the gypsum content accounts for 30% of the cement content, the solidified sludge strength peaks, and the strength is about 30% higher than that

Table 4. Summary of unconfined compression strength of each group in parallel test.

|	Mixing ratio (gypsum and dry soil are relative cement content)			Unconfined compression strength (unit: kPa)		
Group	Cement content	Gypsum content	Dry soil content	7 d	14 d	28 d
1.1	4%	0%	0	21.55	25.20	31.92
1.2	6%	0%	0	58.87	68.47	82.17
1.3	8%	0%	0	106.12	111.55	131.96
1.4	10%	0%	0	171.17	212.97	281.44
2.1.1	8%	20%	0	108.45	120.59	140.26
2.1.2	8%	30%	0	123.54	143.99	160.35
2.1.3	8%	40%	0	110.05	126.26	149.41
2.1.4	8%	50%	0	108.70	124.23	147.73
2.2.1	8%	0%	1 Multiple	106.76	112.38	132.62
2.2.2	8%	0%	2 Multiple	109.33	114.25	133.38
2.2.3	8%	0%	3 Multiple	112.24	124.91	142.70
2.2.4	8%	0%	4 Multiple	123.54	133.62	157.32
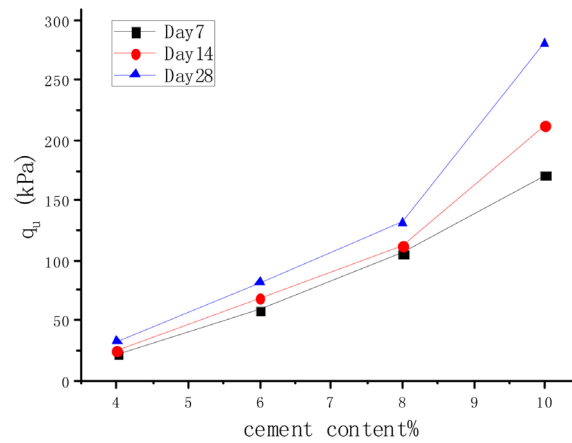
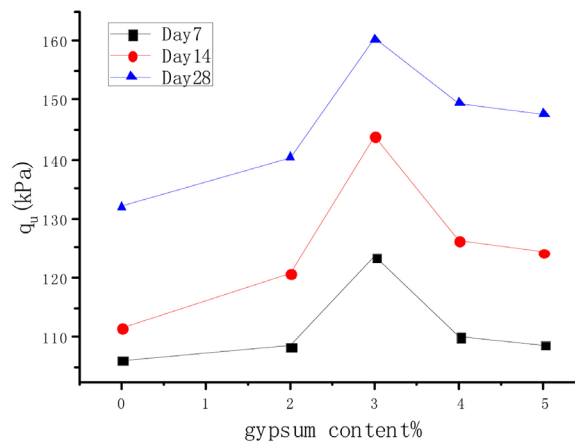**Figure 4.** Relationship between q_u and cement content.

Figure 5. Relationship between q_u and gypsum content.

without adding gypsum.

3.3. Influence of Gypsum Content on Solidified Sludge Strength

Figure 6 shows the relationship between the solidified sludge strength and the dry soil content. When the age was 7 d, the strength of the solidified sludge increased by 0.06%, 2.41%, 2.66%, 10.07% compared with the non-incorporated dry soil. The dry soil content was positively correlated with the solidified sludge strength. Under the dry soil content of 4 times the cement dosage, the unconfined compression strength at 7 d, 14 d and 28 d was increased by 16.42%, 19.79%, 19.22% compared with that when not mixed with dry soil.

Figure 7 and Figure 8 are the fitting curves of the cement and dry soil content and the unconfined compression strength, which all conform to the fitting function $y = Ax + B$ type, and when the cement acts alone, the coefficient A increases as the age increases. The fitting curve is shown in Table 5.
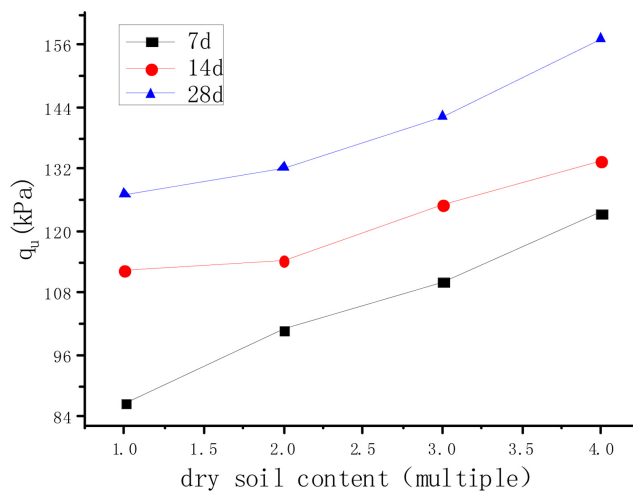

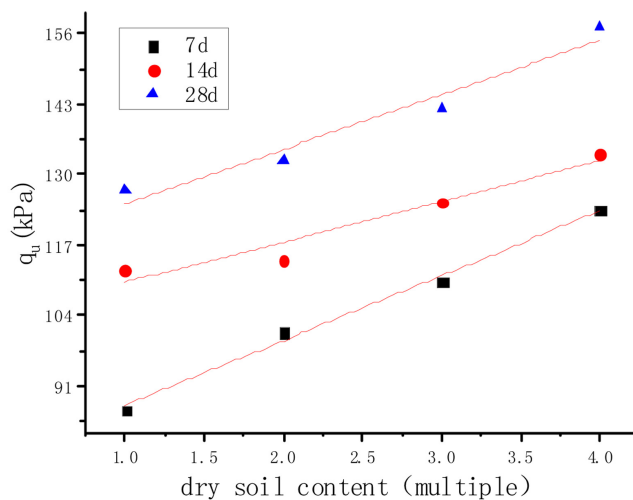**Figure 6.** Relationship between q_u and dry soil content.

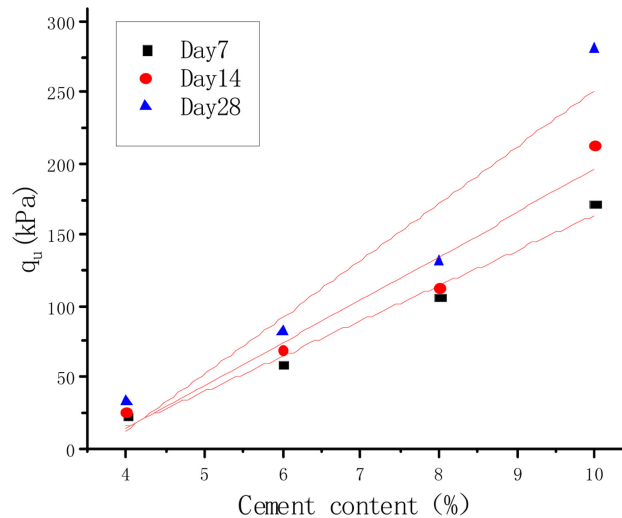**Figure 7.** Cement content and q_u fitting curve when cement is used alone.

Figure 8. Dry soil content and q_u fit curve when cement content is 8%.

Table 5. Fitting formula of unconfined compression strength of solidified sludge under different curing agent dosage conditions.

Age	Fitting of cement content and q_u when cement is used alone		Fitting of dry soil content with q_u when cement content is 8%	
	Fitting function	R^2	Fitting function	R^2
7 d	$y = 24.81x - 84.209$	0.97655	$y = 11.959x + 75.485$	0.96096
14 d	$y = 30.32x + 107.688$	0.92141	$y = 7.437x + 102.698$	0.91101
28 d	$y = 39.92x + 102.698$	0.90239	$y = 10.059x + 114.529$	0.92986

3.4. Effect of Age on the Strength of Solidified Sludge

As shown in **Figures 9-11**, the unconfined compression strength of the solidified sludge is enhanced with the increase of age under the three different curing agent dosages. From **Figure 12**, in the same set of tests, the strength of the solidified sludge at 28 days of age is about 1.34 times the intensity of 7 d in the age, *i.e.*: $q_{u28} = 1.34q_{u7}$, and the intensity at 14 d is about 1.12 times that at 7 d, that is, $q_{u14} = 1.12q_{u7}$.

3.5. Orthogonal Test Analysis

Tables 6-8 are the calculation results of R values of different ages, where K1, K2, and K3 represent the average values of unconfined compression strength at each level of each factor. At the same time, the difference R of the average intensity in each horizontal direction of the same factor (extreme difference = the maximum value of the average intensity − the minimum value of the average intensity) was used to reflect the magnitude of the impact of changes in the horizontal direction of each factor on the test results (intensity). A very large extreme difference means that the change in the level of the factor has a large impact on the test results [10].
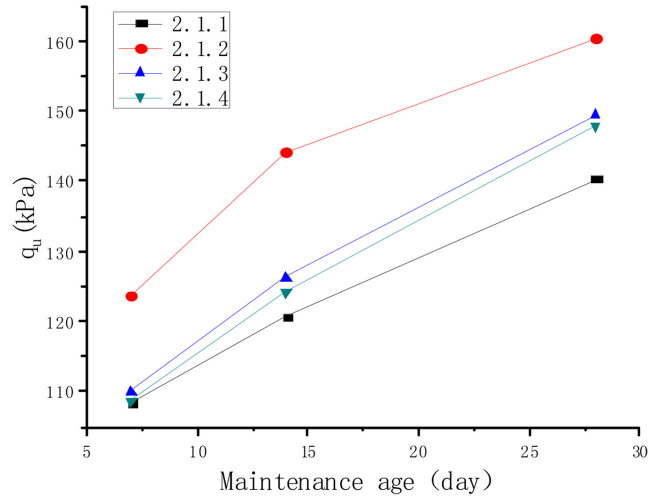
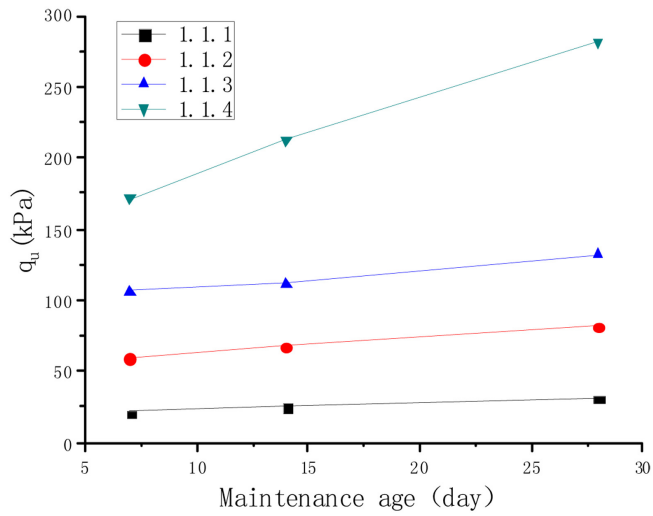**Figure 9.** Effect of age on q_u when cement content is different.

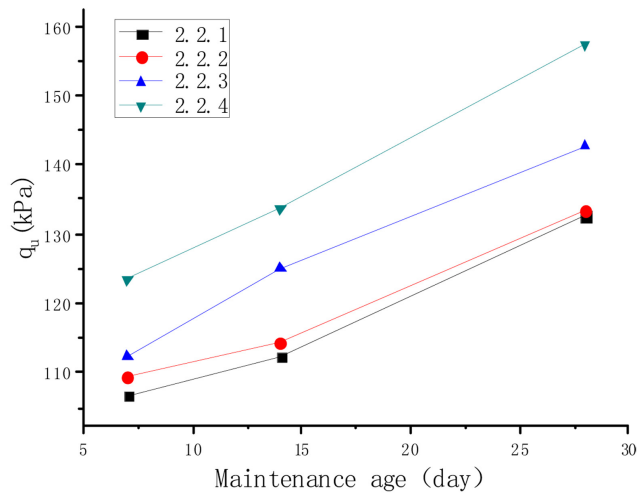**Figure 10.** Effect of age on q_u in the case of different gypsum content.

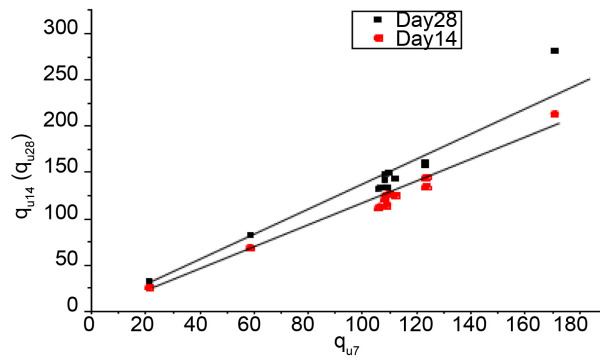**Figure 11.** Effect of age on q_u when dry soil content is different.

Figure 12. $q_{u14}(q_{u28})$-q_{u7} relationship fitting curve.

Table 6. Calculation of R value at age 7 d.

	Cement	Plaster	Dry soil
K1	35.26	84.48	90.20
K2	97.22	105.33	85.69
K3	138.96	81.63	95.54
max	138.96	105.33	95.54
min	35.26	81.63	85.69
R	103.70	23.70	9.85

Table 7. Calculation of R value at age 14 d.

	Cement	Plaster	Dry soil
K1	41.12	99.59	105.93
K2	115.10	119.50	102.91
K3	161.21	98.34	108.60
max	161.21	119.50	108.60
min	41.12	98.34	102.91
R	120.09	21.16	5.69

Table 8. Calculation of R value at age 28 d.

	Cement	Plaster	Dry soil
K1	47.09	116.46	120.03
K2	124.44	136.74	132.10
K3	209.21	127.53	128.61
max	209.21	136.74	132.10
min	47.09	116.46	120.03
R	162.12	20.28	12.08

In Tables 6-8, the R values of cement are 103.7, 120.09, and 162.12 at three different ages, which are the maximum influencing factors and are 5-8 times of the R value of gypsum. The soil R value is 10 - 24 times, the cement content is the main factor, and the dry soil and gypsum content are secondary factors.

4. Conclusions

1) The cement content and the dry soil content have a good linear relationship with the strength of the solidified sludge $y = Ax + B$ (A > 0), and the effect of cement content on the strength is higher than that of the dry soil. From the fitted function, the amount of curing agent can be estimated according to the strength requirements, and the actual engineering can be guided.

2) The age of the solidified sludge has a good linear relationship with the unconfined compression strength $q_{u28} = 1.34q_{u7}$, $q_{u14} = 1.12q_{u7}$. In this ratio, the strength of the late solidified sludge can be estimated from the strength value of 7 d in length.

3) It can be seen from the orthogonal test that the strength is affected by the three curing agents: cement content > gypsum content > dry soil content. Through experiments, it is determined that the optimal curing agent mix ratio was 8% of cement content, 30% of gypsum content (% of cement content), and 4 times of dry soil content (multiple of cement content).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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