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Experimental study of the compressive strength of chemically reinforced organic-sandy soil

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Abstract. Organic-sandy soils that contain abundant organic matters are widely encountered in estuarine cities. Due to the existence of organic matters, the strength and stiffness of this type of soil are significantly low. As a result, various geotechnical engineering problems such as difficulties in piling and constructing embankments and a lack of strength in poured concrete may occur in many estuarine sites; ground improvement such as cement treatment to this type of soils is needed. In this study, laboratory tests were performed to investigate the compressive strength of organic-sandy soil reinforced with primarily cement, in which the influences of several factors, namely types of cement and additional stabilizing agent, cement content, and water-cement ratio, were investigated and the orthogonal experimental design scheme was adopted. Based on the test results, an optimal permutation of these influencing factors is suggested for the reinforcement of organic-sandy soils, which can provide a useful reference for the relevant engineering practice.

Keywords: organic-sandy soil; chemical reinforcement; cement; orthogonal experimental design; compressive strength

1. Introduction

In estuarine cities (e.g., Haikou and Sanya in Hainan Island, China), the implementation of construction projects is often difficult due to various geotechnical engineering problems such as difficulties in piling and constructing embankments and a lack of strength in the in-situ poured concrete (see Oh *et al*. 2007, Hu *et al*. 2015). Based on numerous site investigations, it is suggested that all these engineering problems are mainly caused by a peculiar type of sandy soil that is commonly encountered in these estuarine cities. This type of sandy soil shown in Fig. 1, hereafter termed organic-sandy soil, contains abundant organic matters with a mass fraction of about 7% (see Hu *et al*. 2017) and predominantly mineral component of SiO_2 (around 77% by mass); as a result, its strength and stiffness are significantly low. An electron image of the organic-sandy soil is shown in Fig. 2, the interval between every two dots shown at the bottom right representing a length of 100 μm. The organic matters present in this sandy soil are formed in a diverse environment that is affected by sea and land alternately; therefore, the organic matters contain significantly complex constituents. The organic-sandy soil is different from the conventional soft soil composed of grains and from the remnants of shells found in existing forms of organic matters in sand. The organic-sandy soil has a special structure because of the specific contact between organic matters and sand grains, which results in peculiar mechanical properties and the aforementioned engineering problems; reinforcement measure such as cement treatment is needed to the organic-sandy soil before the subsequent construction activities. The improving effect on the engineering performance of cement-admixed soft clay has been extensively examined (e.g., Chew *et al*. 2004, Voottipruex and Jamsawang 2014, Liu *et al*. 2015, Tsuchida *et al*. 2015, Park 2016, Yi *et al.* 2016, Kholdebarin *et al.* 2016, Kumar and Gupta 2016, Taghavi *et al.* 2017, Liu *et al.* 2017, Xiao *et al.* 2017, Chian *et al.* 2017, Gupta and Kumar 2017). The relevant studies performed on sandy soils are much fewer (e.g., Shooshpasha and Shirvani 2015, Karabash and Cabalar 2015, Ate 2016). Particularly, to date, very limited studies have been performed to examine the performance of reinforced organic-sandy soil and the relevant engineering practice is highly dependent on the experience obtained for other types of soils. Hence, further studies are needed to deepen the understanding of the mechanical behavior of the reinforced organic-sandy soil.

The choice of cement is especially important, because it can significantly affect the mechanical behavior of the soil-cement admixture. Besides, other stabilizing agents such as flyash and slaked lime are usually added into the cement to enhance the manifestation of various soil-cement admixture properties such as working performance, strength, volume stability, and durability (e.g., Kawasaki *et al*. 1981, Saitoh *et al*. 1990, Ahnberg *et al*. 1995). In the current study, laboratory tests were conducted to investigate the mechanical behavior of organic-sandy soil reinforced with

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(a) On-site photo

(b) Sifted soil in laboratory

Fig. 1 Organic-sandy soil

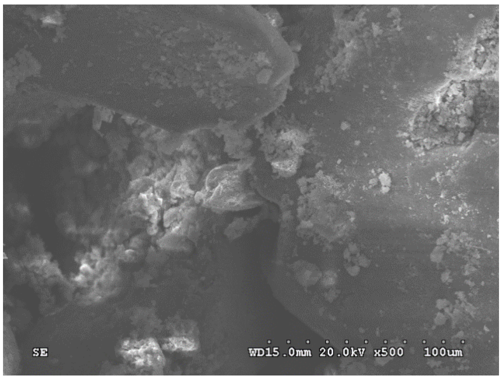


Fig. 2 Microstructure of the organic-sandy soil (magnification factor = 500)

cement; the influences of several factors, namely types of cement and additional stabilizing agent, cement content, and water-cement ratio, were detailedly investigated. Based on the test results of unconfined compressive strength of the organic-sandy soil reinforced with cement, an optimal permutation of the influencing factors is suggested, which provides a useful reference for the relevant engineering practice.

2. Cement reinforcement mechanism and experimental materials

In this study, the soil-cement samples were produced by evenly mixing the organic-sandy soil, cement, water, and one type of additional stabilizing agents in a certain proportion, where the additional stabilizing agents are

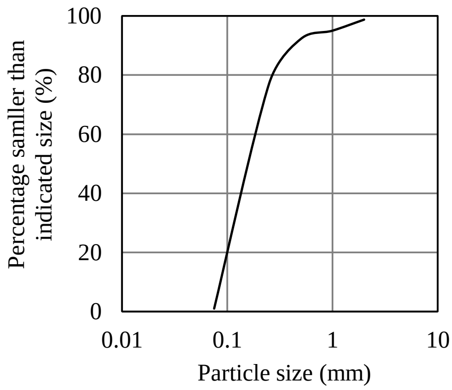


Fig. 3 Particle size distribution of the organic-sandy soil

slaked lime, flyash, and limestone powder. The cement-reinforced organic-sandy soil exhibits complex properties because of the existence of organic content, which is different from the concrete due to the absence of coarse aggregates and also different from the normal cement mortar due to its high content of organic matters. The mechanism of reinforcement was analyzed subsequently to theoretically support findings obtained from the laboratory experiments in this paper. In general, the interaction among the constituents in the admixture includes the following aspects (see Tremblay *et al.* 2002, Chen and Wang 2006): (i) hydrolyzation and hydration of cement, (ii) action between sand or soil particles and the products of hydrolyzation and hydration reactions, (iii) carbonation, and (iv) the adsorption of humus acid particles on sand or soil particles.

2.1 Hydrolyzation and hydration reactions

The ordinary Portland cement consists of the following minerals: $3CaO{\bullet}SiO_2$, $2CaO{\bullet}SiO_2$, $3CaO{\bullet}Al_2O_3$, $4CaO{\bullet}Al_2O_3{\bullet}\ Fe_2O_3$, and $CaSO_4$. Thus, the minerals in the cement consist of various oxides, such as CaO, SiO, Al_2O_3, Fe_2O_3, and SO_3. The $3CaO{\bullet}SiO_2$ accounts for 50% of the aforementioned Portland cement; thus, this compound largely determines the strength of the cement. The $2CaO{\bullet}SiO_2$ accounts for 25% in the cement, which governs the cement's long term strength. The $CaO{\bullet}Al_2O_3$ accounts for approximately 10% in the cement, and it accelerates the solidification of cement. Among the aforementioned products formed during the hydrolyzation and hydration reaction of cement, some will precipitate in the form of crystals and/or deposit on the surface of the soil-cement.

Moreover, some of the products can continue to further react with each other. All these phase transitions and reactions decrease voids between sand particles, thereby increasing the density and strength of the soil-cement mixture containing both organic matters and sandy particles.

2.2 Chemical actions between cement and particles of organic-sandy soil

Some of the products generated during the hydrolyzation and hydration reactions of cement would

Table 1 Relationships between adsorption types and acting forces

Adsorption Type	Acting Force	Acting Range *
Chemisorption	Covalent bond	Chemical bond acting range
	Hydrogen bond	Chemical bond acting range
Electrostatic Adsorption	Coulomb force	$1/r$
	Ion-dipole acting force	$1/r^2$
Physical Adsorption	Orientation force	$1/r^3$
	Induction force	$1/r^6$
	Dispersion force	$1/r^6$

*r: the distance between two ions

Table 2 Parameters of organic-sandy soil

Parameter	Value
Maximum dry density (g/cm³)	1.723
Cohesion (kPa)	4.2
Friction angle (degree)	30
Characteristic value of subgrade bearing capacity (kPa)	160
Constrained modulus (MPa)	20

Table 3 Main components of experimental cement (%)

Cement type	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
P•C32.5	22.50	6.18	3.31	64.33	1.08	1.89
P•O42.5	21.82	5.69	3.40	67.09	1.51	1.86

Table 4 Main mechanical indices of experimental cement

Cement type	Compressive strength (MPa)			Rupture strength (MPa)		
	3-day curing	7-day curing	28-day curing	3-day curing	7-day curing	28-day curing
P•C32.5	11.03	18.40	33.78	2.75	4.45	7.15
P•O42.5	25.43	36.55	45.45	5.55	7.40	8.50

continue to react with the organic matters and sandy soil particles typically through the forms of ion-exchange and aggregation, and coagulation reaction, the basic information of which is given below.

Ion-exchange and aggregation (see Ma *et al*. 2016): After the organic-sandy soil melts in water, the Na^+ or K^+ ions exchange with Ca^{2+} ions formed in the hydrolyzation and hydration product $Ca(OH)_2$. Tiny sand particles gradually become bigger in size, and they begin to aggregate and form larger particles in the mixture. As a result, the density of the cement-soil mixture increases following the aggregation; also, the cement-soil mixture's strength increases substantially.

Coagulation reaction: A lot of mixtures containing calcium would be generated as products of the hydrolyzation and hydration reactions of cement. Ca^{2+} ions precipitated from the solution in abundance following the reactions would react with mineral components of the sandy soil particles such as SiO and Al_2O_3, regardless of the organic content in the soil-cement mixture. Thus, more chemical compounds that are insoluble in water would be generated by the following chemical reactions:

$$SiO_2 + Ca(OH)_2 + nH_2O \rightarrow CaSiO_2 \cdot (n+1)H_2O$$

$$Al_2O_3 + Ca(OH)_2 + nH_2O \rightarrow CaAl_2O_3 \cdot (n+1)H_2O$$

In the above reactions, all the generated chemical compounds precipitate out in the form of crystals, which can efficiently fill the voids between sand particles. As a result, both the density and strength of the cement-soil mixture are substantially increased.

2.3 Carbonation

The redundant $Ca(OH)_2$ in water and the sandy soil solution containing organic matters chemically react with CO_2 gas both in water and air. The product of this reaction is $CaCO_3$, which is almost insoluble in water. This compound consequently deposits in the solution and increases the strength of the organic-sandy soil. The following carbonation reaction represents the synthesis of $CaCO_3$ compound:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 \downarrow + H_2O$$

2.4 Adsorption mechanism of humus acids and sand particles

Humic and fulvic acids, two main humus acids, can combine with minerals in sand, because sand particles adsorb and exchange ions with humus acids such as humic acid and fulvic acid; these acids contain various active functional groups. Humus acids can react with positive ions in the soil-cement slurry, and they can generate complex compounds, as the carboxyl and phenolic hydroxy groups in humus acids participate in various complexation reactions. The organic matters of humus acids interact with the sandy soil particles containing organic traces; the interaction between humus acids and sandy soil particles occurs due to various cohesive forces, such as covalent bond, hydrogen bond, and Van der Waals' force. The cementation associated with these chemical and physical interactions can aggregate more chemical compounds on the surfaces of sand particles, thereby enhancing the agglomerating forces of organic-sandy soil and leading to aggregations throughout the surfaces. As a result, the surface characteristics of sand particles can be significantly affected. Table 1 summarizes the adsorption types and the corresponding acting forces and ranges.

2.5 Experimental materials

The experimental organic-sandy soil was obtained from a foundation pit of an engineering site at Longlou town in Wenchang city, China, the engineering properties of which are listed in Table 2.

In the current study, two primarily popular types of cement in Hainan Island were used; that is, P•C32.5 and P•O42.5 types of cement. The former has a low strength at the initial phase, while the latter has a high strength at the initial phase. Laboratory experiments were performed on these two types of cement exhibiting different strengths. The main components of the experimental cements are listed in Table 3, and the unconfined compression and rupture strengths of them are presented in Table 4.

Additional stabilizing agents are slaked lime, flyash, and limestone powder. Slaked lime is the white solid powder sold in market, and its chemical formula is $Ca(OH)_2$. It should be noted that $Ca(OH)_2$ is slightly soluble in water as it is a binary alkali; it has general properties of an alkali. Although it corrodes skin and fabric, it has wide applications in various industries. For this experimental study, Grade II flyash was purchased from the Haikou Power Plant (Hainan Province, China). The flyash was dry in appearance and consisted of finely ground particles.

When the main solid waste is discharged from coal-fired power plants after coal combustion, flyash is the fine ash that gets collected from the generated smoke. It is indeed beneficial to use flyash as the admixture in engineering projects: it not only reduces garbage discharge issues and environment pollution, but it also retreats and recycles the waste of coal power plants. Limestone powder is an inorganic compound. It is commercially available as a white solid powder sold in the market, and its 99% content is $CaCO_3$. Because calcite mineral is the main component of limestone powder, it is neutral in nature. Moreover, it is almost insoluble in water but soluble in hydrochloric acid. China has abundant reserves of limestone powder; therefore, a study on limestone powder has lot of significance in terms of economic value. In this study, the weight ratio of each type of additional stabilizing agent to cement is fixed at 7.5% in each experiment. The slurry formed by cement, an additional stabilizing agent, and water can fill pores of organic-sandy soil, improving pore structures of the sand body. Consequently, the cement-soil strength increases with these chemical modifications. Besides, admixtures, which are easily obtainable at low cost, can reduce the adverse effects of acidic materials on cement hydration associated with the cement-reinforced organic-sandy soil. Consequently, the reinforced organic-sandy soil has greater strength.

3. Experimental procedure

3.1 Experimental apparatus

The experimental apparatuses used in this study are introduced below.

Sieve: The organic-sandy soil can contain some large plant roots, especially at a certain depth far below the surface. These large roots may influence the effect of cement reinforcement on the organic-sandy soil to some extent; however, for laboratory small sample tests, considering these large roots would likely increase the uncertainty in the test results and hence distract the main focus of the current study. In this study, before starting the testing procedure, the organic-sandy soil was smashed into pieces using a rubber hammer. Then, the crushed pieces were sifted using a sieve with a diameter of 2 mm. Thus, the effect of large plant roots was eliminated from the soils (see Fig. 1(b)). From the sieve analysis, the particle size distribution curve for the organic-sandy soil used in this study can be obtained, as shown in Fig. 3.

Oven: Because it usually takes a long time to dry the organic-sandy soil in air, the organic-sandy soil is dried more efficiently in an oven. By drying in an oven, the accurate water content of the soil sample can be established. As such, the accuracy of experiment results was enhanced.

Cement paste mixer: The soil-cement material was stirred with water for four minutes to achieve a uniform admixture, which was then poured carefully into a testing mould. The geometric size of the testing mould is $70.7 \times 70.7 \times 70.7$ mm^3 (see Fig. 4). Care should be exercised to avoid breakage or damage to moulded sample, which could be caused by air gun during demoulding.

Vibrating table: In the testing mould, the admixture is converted into a compact form using the vibrating table.

Electronic universal testing machine: In this study, we used the CMT-100 Electronic Universal Testing Machine having a maximum load of 100 kN (see Fig. 4(d)).

Other apparatuses: Electronic balance is used to weigh the sand sample before testing. Beaker and measuring cylinder are used to weigh water. After the cement-soil slurry is put into the testing mould, the surface of the sample is made flat using a scraper. Plastic wrap is used to cover the flat surfaces of the testing samples.

3.2 Preparing and curing of testing samples

Preparation process: First, calculate and accurately weigh the dosages of the experimental materials. Secondly, evenly mix and stir all the experimental materials. Thirdly, carry out manual mixing and then transfer the admixture to a mixing machine.

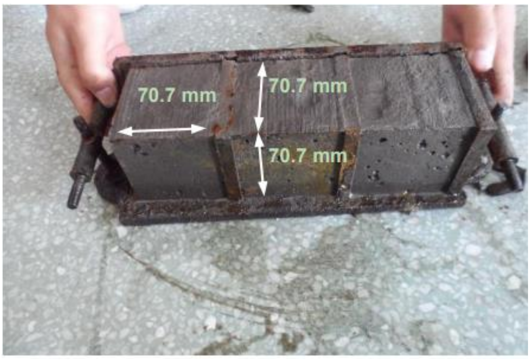
Forming process (see Fig. 4): First, evenly coat the standard iron mould with lubricating oil, which makes the demoulding process manageable. Secondly, put the soil-cement slurry that is evenly mixed and prepared into the mould thrice, and manually vibrate the mould initially, and then evenly vibrate the mould on the vibrating table. Thirdly, scrape off the extra cement soil outside the mould by a scraper manually, covering the mould with a plastic wrap, and then demould it after 48-hour curing.

After demoulding, the cement testing samples were cured in a standard curing room at a temperature of approximately 20°C and a relative humidity of no less than 95%. The curing process was carried out for certain days (e.g., 7, 14, and 28 days) before the unconfined compressive strength tests were performed.

3.3 Unconfined compressive strength test

The unconfined compressive strength of reinforced soil (e.g., Lee *et al*. 2015) is usually adopted to evaluate the reinforcement effect of the cement. In this study, the CMT-100 Electronic Universal Testing Machine having a maximum load of 100 kN was employed to carry out the unconfined compressive strength tests (see Fig. 4(d)). Before testing, lubricating oil was coated on the pressure-bearing surface where the testing machine would establish contact with the samples. The loading rate was maintained

(a) Moulded samples



(b) Demoulding samples after 48 hours curing

(c) Demoulded samples

(d) Unconfined compressive strength testing

Fig. 4 Procedure of sample preparation and test

at 1 mm/min during the testing process. The compressive strength of cement testing samples is calculated from the following expression

$$f_{cu} = P/A \tag{1}$$

Table 5 Orthogonal experimental table

Level	Factor		
	Additional stabilizing agent (A)	Cement content (B)	Water-cement ratio (C)
1	Slaked lime	10%	0.45
2	Flyash	15%	0.60
3	Limestone powder	20%	0.75

Table 6 Orthogonal experimental table

Test No.	Factor		
	Additional stabilizing agent (A)	Cement content (B)	Water-cement ratio (C)
1	Slaked lime	10%	0.45
2	Slaked lime	15%	0.60
3	Slaked lime	20%	0.75
4	Flyash	10%	0.60
5	Flyash	15%	0.75
6	Flyash	20%	0.45
7	Limestone powder	10%	0.75
8	Limestone powder	15%	0.45
9	Limestone powder	20%	0.60

Table 7 Definition of conceptions used in orthogonal experiment analysis

Index	Remarks of index	Extreme difference
A1	Average of the 3 test results with Factor A under Level 1 e.g., A1 = (Test 1 + Test 2 + Test 3) / 3	Extreme difference among Factor A: maximum difference among A1, A2 and A3
A2	Average of the 3 test results with Factor A under Level 2	
A3	Average of the 3 test results with Factor A under Level 3	
B1	Average of the 3 test results with Factor B under Level 1 e.g., B1 = (Test 1 + Test 4 + Test 7) / 3	Extreme difference among Factor B: maximum difference among B1, B2 and B3
B2	Average of the 3 test results with Factor B under Level 2	
B3	Average of the 3 test results with Factor B under Level 3	
C1	Average of the 3 test results with Factor C under Level 1 e.g., C1 = (Test 1 + Test 6 + Test 8) / 3	Extreme difference among Factor C: maximum difference among C1, C2 and C3
C2	Average of the 3 test results with Factor C under Level 2	
C3	Average of the 3 test results with Factor C under Level 3	

where f_{cu} is the compressive strength of sample at testing age, with unit of MPa; P is the load corresponding to the failure of sample, with unit of N; A is the pressure-bearing area of the sample, with unit of mm^2.

The representative value of the compressive strength should be determined as follows: (1) In one set of experiments, the arithmetic average of three repetitive experimental values shall be considered as the strength value; (2) If the difference between the maximum or minimum value of the three experimental values and the median value is more than 15%, then the median value will be considered as the strength value; (3) If the differences between the median value and both the maximum and minimum values of the three experimental values are greater than 15%, then all the three tests are considered as invalid.

3.4 Design of experimental scheme

The orthogonal experimental design has been widely applied in scientific experiments because it is a speedy process that also ensures high efficiency. With this design strategy, experiments can be designed systematically to achieve experimental goals with less elaborate experiments. In this method, an appropriate amount of typical points are chosen from several testing points to form an orthogonal table, which is then used to schedule and perform all experiments. Then, the experimental results will also be analyzed in accordance with the orthogonal table. The testing points are typical in the orthogonal table; therefore, the factors represented by those points are balanced (see Li *et al*. 2014). This implies that every set of an orthogonal experiment can evenly represent the full-scale test. Therefore, the requirements of a full-scale test are satisfied equivalently, and the experiment goals are also achieved to a satisfactory extent. Detailed information about the orthogonal experimental design can be found in literature (e.g., amongst others, Taguchi 1986, Ge *et al*. 2012). The types of additional stabilizing agents, cement content, and water-cement ratio were taken into account for the orthogonal experimental design in the current study. Each factor has three levels, as listed in Table 5. The ranges of cement content and water-cement ratio are based on the practical ranges adopted in real projects. The testing goals are the unconfined compressive strengths of cement-soil testing samples cured for 7 days, 14 days, and 28 days. The effects of all these three factors have been considered while developing the design of mix proportion of cement soil. Therefore, the orthogonal experiment will be carried out according to the standard three factors in three levels of orthogonal experiment table $L_9(3^4)$, as shown in Table 6. The relevant concepts to be used in the orthogonal experiment scheme are defined in Table 7.

4. Results and discussions

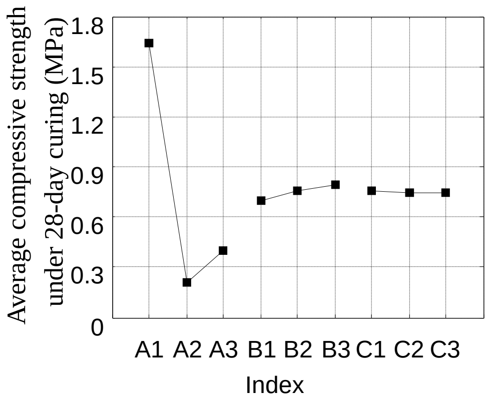
Table 8 summarizes the results of unconfined compressive strength tests in this study. Tables 9 and 10 present the extreme differences of the tests under 28-day curing period. The results indicate that the extreme difference is overwhelmingly caused by the selection of additional stabilizing agent, regardless of the cement type. This implies that the effect of additional stabilizing agent type (Factor A) on the unconfined compressive strength is the most significant influencing factor.

Fig. 5 shows the trends of unconfined compressive strength of the soil sample against different factors. As can be seen, the additional stabilizing agent type (Factor A) affects the experimental results significantly in both the sets of experiments. Among the additional stabilizing agents used, the use of slaked lime tends to have the most significant effect on increasing the unconfined compressive strength of the cement-soil sample.

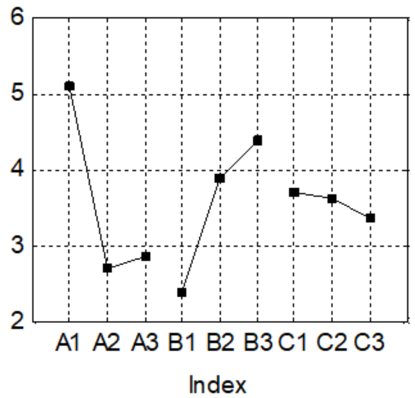
Besides, the unconfined compressive strength tends to increase with the increase of cement content (Factor B). However, by comparing Figs. 3(a) and 3(b), it can be inferred that the cement content has a much more significant influence on the samples reinforced using P•O42.5 cement than that using P•C32.5 cement. When the cement content ranges from 10% to 15%, the compressive strength of cement-soil increases from 2.4 MPa to 4.4 MPa associated with P•O42.5 cement and from 0.7 MPa to 0.8 MPa for P•O32.5 cement, respectively. The unconfined

Table 8 Results of unconfined compression tests

Test No.	Amount of materials (g)				Unconfined compressive strength (MPa)					
					P•C32.5 cement			P•O42.5 cement		
	Organic-sandy soil	Cement	Water	Additional stabilizing agent	7-day curing	14-day curing	28-day curing	7-day curing	14-day curing	28-day curing
1	1900	211.2	306.8	15.8	0.245	1.111	1.640	1.497	3.172	3.634
2	1900	316.8	401.9	23.8	0.594	1.063	1.612	2.237	4.067	5.076
3	1900	422.4	528.6	31.7	0.582	1.091	1.670	3.209	5.404	6.595
4	1900	211.2	338.5	15.8	0.061	0.077	0.146	1.691	2.178	2.478
5	1900	316.8	449.4	23.8	0.063	0.089	0.244	1.113	1.785	2.381
6	1900	422.4	401.9	31.7	0.074	0.096	0.236	1.461	2.676	3.228
7	1900	211.2	370.2	15.8	0.093	0.111	0.312	0.354	0.724	1.061
8	1900	316.8	354.4	23.8	0.115	0.172	0.411	2.447	3.484	4.194
9	1900	422.4	465.2	31.7	0.157	0.195	0.482	1.747	2.928	3.332

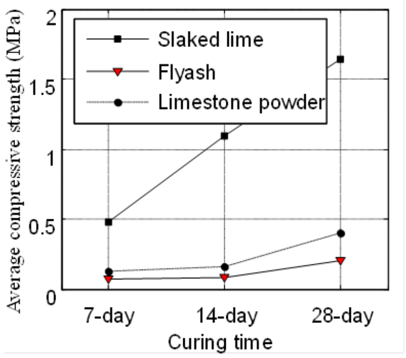


(a) Using P•C32.5 cement

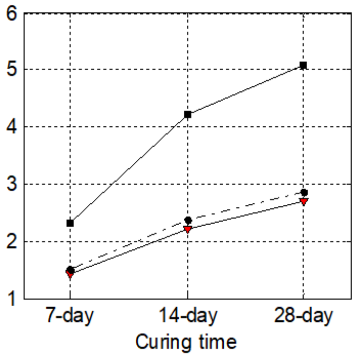


(b) Using P•O42.5 cement

Fig. 5 The trends of average compressive strength of cement-soil against different factors (Indices in the x-axis are defined in Table 7; curing time is 28 days)

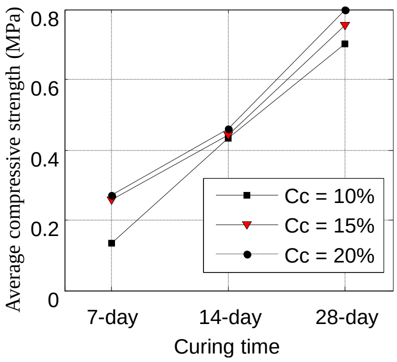


(a) Using P•C32.5 cement

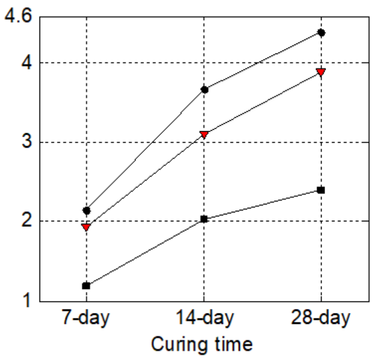


(b) Using P•O42.5 cement

Fig. 6 Trends of average compressive strength against the curing time, involving different additional stabilizing agents associated with both P•C32.5 and P•O42.5 cements



(a) Using P•C32.5 cement



(b) Using P•O42.5 cement

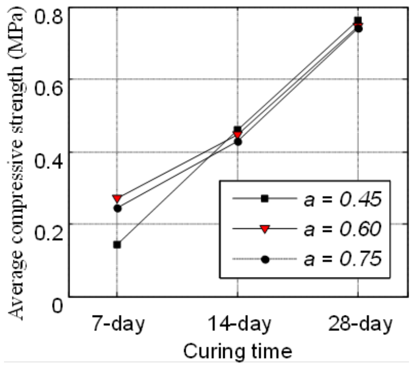
Fig. 7 The trends of average compressive strength against curing time, associated with varying cement contents of both P•C32.5 and P•O42.5 cements (Cc = cement content)

Table 9 Extreme difference analysis results for cement type of P•C32.5

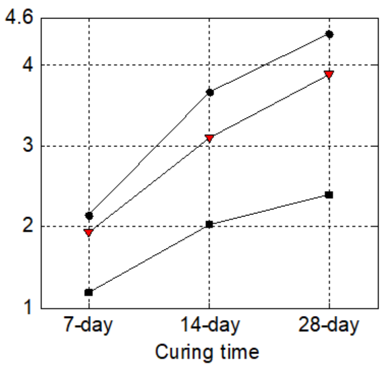
Factor	Extreme difference	Sum of the squared deviations	Degrees of freedom	Sum of squares
A	1.432	3.623	2	1.8115
B	0.097	0.014	2	0.0071
C	0.020	0.001	2	0.0003
Sum	-	3.638	6	1.8189

Table 10 Extreme difference analysis results for cement type of P•C42.5

Factor	Extreme difference	Sum of the squared deviations	Degrees of freedom	Sum of squares
A	2.406	10.831	2	5.4156
B	1.994	6.455	2	3.2277
C	0.340	0.199	2	0.0993
Sum	-	17.485	6	8.7436



(a) Using P•C32.5 cement



(b) Using P•O42.5 cement

Fig. 8 The trends of average compressive strength against curing time, involving different water-cement ratios with both P•C32.5 and P•O42.5 cements (Cc = cement content)

compressive strength gradually decreases with the increase in water-cement ratio (i.e., Factor C); however, the strength of cement-soil reinforced using P•C32.5 cement decreases at a slower rate and is more stable than that associated with P•O42.5 cement.

Fig. 6 shows the trends of average compressive strength against the curing time involving different additional stabilizing agents. As can be seen, the average compressive strength generally increases as the curing time increases, regardless of the types of additional stabilizing agent or cement. Furthermore, the strength of samples with slaked lime increases much more significantly than those with flyash and limestone powder.

Fig. 7 shows the trends of average compressive strength against the curing time, involving varying cement contents (Factor B). As Fig. 7(a) shows, the variation of cement content has a limited influence on the strength for cases involving P•C32.5 cement, especially when the curing time is greater than or equal to 14 days. In contrast, the cement content has a much more significant influence on cases with P•O42.5 cement, although the increasing trend of the average compressive strength decreases as the cement content increases from 15% to 20%. This finding is likely to serve as a guideline for the selection of cement type for the treatment of organic-sandy soil.

Fig. 8 shows that the average compressive strengths of soil-cement testing samples with different water-cement ratios gradually increase with the curing period; however, the average compressive strength can be significantly influenced by the water-cement ratio (Factor C), especially for a curing period of 7days. As shown in Fig. 8(a) of the cases with P•C32.5 cement, compared to the samples with a water-cement ratio of 0.45, the samples with water-cement ratios of 0.60 and 0.75 have greater strengths at the initial phases and slightly smaller strengths as curing period becomes longer. Similar trends can also be found in Fig. 8(b) for the cases associated with P•O42.5 cement.

In order to investigate the underlying reasons for the above findings shown in Figs. 5-8, a series of additional chemical experiments were performed. After soaking the sandy-soil sample with water, the distillation of the leaving solution was conducted. The measured pH value of the distilled solution was 6.21, which is weakly acidic in nature. This indicates that most H^+ ions were already consumed during the testing of the above solution. The phenolic group and the alkyl chains existed in humus acids of organic sand particles; these functional groups can be easily protonized, and a lot of H^+ ions can hence be ionized. These factors are responsible for the weak acidity of the distilled soaking solution.

Among the three types of additional stabilizing agents, the alkalinity of slaked lime is the greatest while that of flyash is the weakest. The OH^- ions of slaked lime can neutralize H^+ ions in the sand sample, reducing the effects of organic matters on cement hydration and increasing the strengths of cement-reinforced soils. Therefore, slaked lime increased the strengths of cement-reinforced soils in the most obvious manner. When the cement content was around 10–20%, a steady increase in the cement content ensured a gradual increase in strengths of cement-reinforced soils. Water content in sands increased with an increase in water-cement ratio ranging from 0.45 to 0.75 in this study. If the water content was too high, extra free hydrones in soil-cement that did not participate in cement hydration filled the extra voids inside the soil-cement admixture. Consequently, there was a loss in the compressive strength of soil-cement. The forgoing analysis shows that soil reinforced with P•O42.5 cement has greater compressive strength than that using P•C32.5 cement. The effects of introducing an additional stabilizing agent type on the soil-cement testing samples are more significant than those induced by varying the cement content, and the changes in the strengths of soil-cement samples with varying cement content are more pronounced than those arising from different water-cement ratios. The graphs shown in Fig. 5 illustrating the trends of compressive strengths with variations in factors and levels suggest that the optimal permutation of the influencing factors for cement-reinforced organic-sandy soil is A1B3C1, i.e., using slaked lime as the additional stabilizing agent type, a cement content of 20% and a water-cement ratio of 0.45.

5. Conclusions

In this study, the mechanical behavior of organic-sandy soil reinforced by cement was investigated. Two types of cements (i.e., P•C32.5 and P•O42.5) were adopted as the main stabilizing agent. The influences of three another factors, namely type of additional stabilizing agents, cement content, and water-cement ratio, on the unconfined compressive strength of cement-reinforced sandy soil were examined; three levels of each factor were selected according to the design orthogonal experiments. Test results suggest that the organic-sandy soil reinforced by P•O42.5 cement has much larger strength than that using P•C32.5 cement. For both types of cement, the effect of additional stabilizing agent on the soil-cement sample is more significant than those of two other factors, namely cement content and water-cement ratio; it seems that the factor of water-cement ratio has the least effect on the test results. Based on the test results, an optimal permutation of the influencing factors for the cement-reinforced sandy soil is obtained, i.e., using slaked lime as the additional stabilizing agent, a cement content of around 20%, and adopting the water-cement ratio as 0.45. The findings obtained from this study likely can serve as a useful reference for the practical engineering practice involving the cement treatment of organic-sandy soil deposits which are widely encountered in many estuarine cities. However, it should be noted that the cement-stabilized soils are often non-uniformity in strength in reality (see Liu *et al*. 2016, Liu *et al*. 2018). The non-uniformity in strength may be attributed to the variation in mix ratio. The effect of this kind of non-uniformity on the overall performance of a real project will be the future study of the current work.

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