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Materials Characteristics of Soil-cement Samples under Various Maintenance Conditions

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Abstract. Subsidence of embankment foundation at the approach roadway is quite common in South Vietnam because natural soil layers are high water content and low bearing capacity. Soil-cement columns could be a potential method to deal with foundation subsidence. A critical issue is to determine proper soil-cement mixtures, mainly depending on maintenance conditions. In this study, materials characteristics of soil-cement samples are experimentally tested under various maintenance conditions. To achieve the objective, first, we drill to get natural soil samples at various depths for different boreholes located in southern Vietnam. Second, soil samples are used to fabricate soil-cement cylinder samples. Third, a set of fabricated samples are maintained under various environmental conditions for 7, 14, and 28 days. Last, experimental tests are conducted to test axial compressive strength to evaluate the effects of environmental parameters on strength development. The result reveals that the proportion of soil cement should be properly designed for soil layers to maximize the performance of the soil-cement column.

1. Introduction

The Vietnamese Mekong Delta is formed from different sediments that have a thickness from 10 m to over 20 m. It is primarily made of clay mud, sandy clay mud, and silty clay mud, and some areas can be soiled with salt, alum, and organic. Because these sediments are mostly soft to identical soft, most infrastructure foundations have to reinforce to ensure structural safety. Recently, due to rapid population growth, the demand for urban development in Vietnam, especially in the Southern part, has significantly increased, thus increasing great attention to developing or improving treatment methods for poor soil foundations before building constructions [1-3].

Soil enhancement methods have been introduced for the last five decades, with improving soil geotechnical characteristics to meet the demand of technical specifications in construction projects (e.g., foundations, highways, and slopes). Various studies in laboratory and field tests have confirmed that cement soils can increase the strength of soil properties with respect to hydration, hardening, solidification, and ion exchange between soil-cement. Moreover, cement, typically consisting of alumina, silica, calcium, and iron compounds, is popularly utilized to stabilize slope protection and soil improvement for foundations [4, 5]. Soil-cement is a mix of soil, Portland cement, and water to compact to preferred density and strength. When cement is mixed with water, hydration occurs, thus resulting in the cementitious compounds, which is the increment of specimen strength. This method can be considered as a low-cost, simplified process and well-mechanical and physical properties.

In South Asia, cement deep mixing methods are commonly applied [6, 7]. Due to the complex characteristics and compositions of soft soil layers, soil with high organic or highly plastic clays could be stabilized with cement stabilization [8]. In addition, the composition of minerals and chemicals significantly influences the hydration and hardening of soil-cement specimens. Various research has been conducted on material characteristics of soil-cement samples for soil improvement, including soil-cement mix, unconfined compressive strength, shear modulus, and elastic modulus [9-12].

It is reported that the soil properties and mixing types have primary parameters that affect the mechanical characteristics (especially axial compressive strength) of soil-cement specimen [3, 9, 10, 13-16]. Specifically, Nguyen and Huynh [14] studied factors impacting the unconfined compressive strength of soil-cement specimens. The authors focused on analyzing of cement ratio on lateral compressive strength of soil-cement piles. Diego et al. [16] researched the physical-mechanical properties of soil-cement samples, which were reinforced with fiber and mineral wool. The result evidenced that bending strength resistance was increased with adding mineral wool and fiber. Moreover, Pham et al., [17] studied the compressive strength of fabricated soil-cement piles in the laboratory and in the field. The authors suggested that the amount of cement per soil should be larger than or equal to 300 kg/m^3 for weak geology for examined locations in southern Vietnam.

The groundwater level where soil-cement samples were constructed could have effects on the material characteristics of soil-cement columns. The soil layer above the groundwater level can be hydrated. When designing a soil-cement mixture, the selection of cement ratio should consider the effects of groundwater level on the strength development of the soil-cement column. The issues have not been reported so far. In Vietnam, TCVN 9403:2012 "stabilization of soft soil, the soil cement column method" has been currently applied for soil stabilization. Due to various conditions (e.g., construction technology of soil-cement column, construction cost, and varied geological conditions), the application of the technique is quite limited. Moreover, the subsidence of embankment foundations, especially at the approach roadway, is quite common, especially in South Vietnam, because natural soil layers are high water content and low bearing capacity [18]. It requires further studies on the effects of material characteristics of a soil-cement specimen, which is focused on the strength of the specimen under various maintained conditions.

In this study, materials characteristics of soil-cement samples are experimentally tested under various maintenance conditions. The following approaches are implemented to achieve the objective. Firstly, natural soil samples are obtained at various depths for different boreholes located in southern Vietnam. Secondly, soil samples are used to fabricate soil-cement cylinder samples. Third, a set of fabricated samples are maintained under various environmental conditions for 7, 14, and 28-day curing. Last, experimental tests are conducted to test axial compressive strength to evaluate the effects of environmental parameters on strength development.

2. Design and manufacture of soil cement samples

2.1. Experimental test of natural soil sample in Southern Vietnam

To analyze effects of maintenance conditions on material properties of soil-cement samples, three boreholes in Southern Vietnam were conducted to get natural soil samples, as shown in Figure 1. The first borehole, namely HK1, was located in Ward 3, Vinh-Long city, Vietnam, with a sampling depth from -24m to -32m (the depth from the natural elevation). The second borehole, namely HK2, was located in Long-Ho district, Vinh-Long province, Vietnam, with a sampling depth from -1.8m to -8.0m. The last borehole, namely HK3, was located in Tra-Noc industrial zone, Can-Tho city, Vietnam, with sampling depth from -18m to -26m.

Figure 2 shows onsite geological drilling for the collection of natural soil samples. The groundwater lines at HK1, HK2, and HK3 were respectively -1.71 m, -1.2 m, and -2.93 m compared to natural elevation, as seen in Figure 2a. Soil samples used to make the soil-cement specimen were all below the groundwater line. As shown in Figure 2b, a geological drilling machine was used to get soils at designed elevations via steel piles. In the drilling activities, for each of two meters depths of the borehole, the soil sample was obtained one time. Specifically, soil sampling times at HK1, HK2, and HK3 were 5, 6, and 5 times, respectively. After getting natural soil from boreholes, the soil was stored in plastic tubes to maintain soil properties, as seen in Figure 2c. All tests were conducted following the instruction in "TCVN 9437:2012, the process of boring engineering geology investigations".

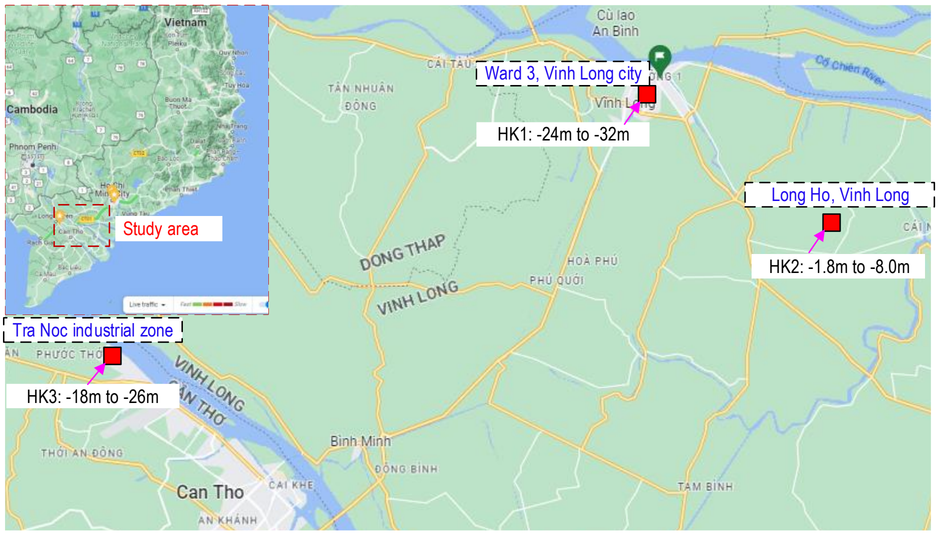


Figure 1. Location of the geological boreholes, Southern Vietnam.

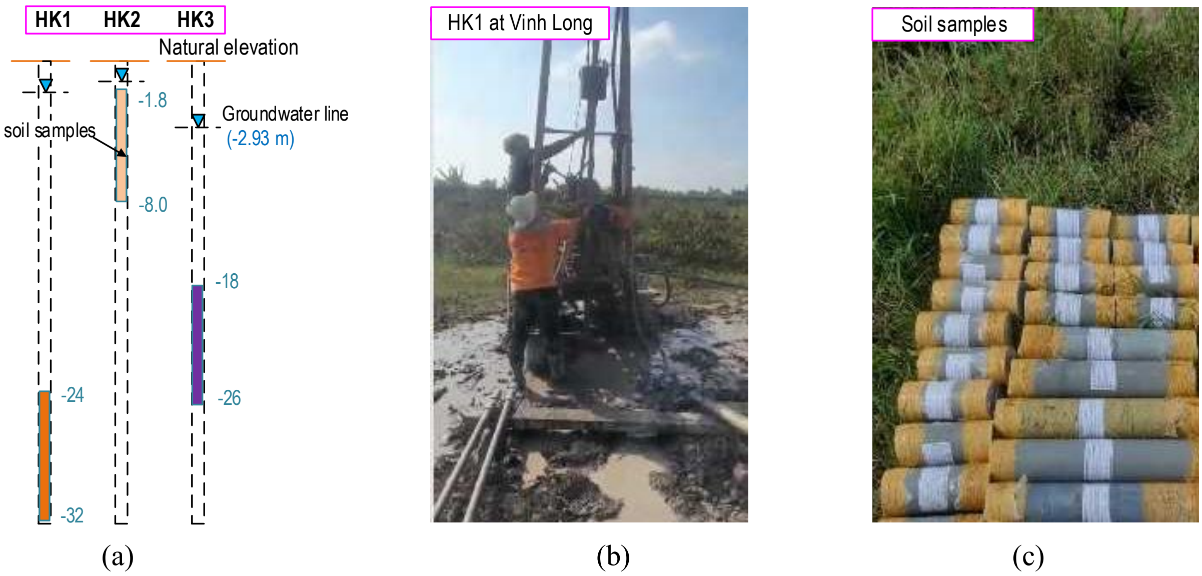


Figure 2. Onsite geological drilling for the collection of natural soil samples: (a) HK1-HK3 depth, (b) Sampling soil at HK1, (c) Natural soil samples.

From soil samples for various sampling depths of each borehole, natural soil was mixed together to get the mixed soil. Then, the mixed soil was used to test physical-mechanical properties, as shown in Table 1. In the table, the notations ρ_d, ρ, w, and q_u represent dry weight, natural weight, humidity, and axial compressive strength of soil samples. All tests were conducted based on guidelines in Vietnamese national standards for soil properties (e.g., "TCVN 4202-2012: Soils - Laboratory methods for determination of unit weight"). Moreover, Standard Deviation (SD) and Coefficient of

Variation (CV) were calculated based number of soil samplings (i.e., 5 times at HK1, 6 times at HK2, 5 times at HK3), as shown in Table 1. The CV values, measuring the distribution/dispersion of data around mean values for each tested soil parameter, were relatively small. It indicated that soil samples at each borehole can be classified in the separated soil layer. As observed in the table, the natural soil exhibits high water content and low bearing capacity, thus requiring treatment methods applied to increase soil strength capacity.

Table 1. Physical-mechanical properties of soil.

No	Description	ρ_d (g/cm^3)		ρ (g/cm^3)		w (%)		q_u (kPA)
		Mean	SD/CV	Mean	SD/CV	Mean	SD/CV	
HK1	Soft-malleable clay; semi-hard clay	1.20	0.059 0.050	1.69	0.049 0.029	41.13	3.495 0.085	115.50
HK2	Gray-brown clay (flowing stage)	0.98	0.023 0.023	1.60	0.040 0.025	62.67	2.194 0.035	42.56
HK3	Clay mud, clay mud with sand layers	1.28	0.050 0.039	1.66	0.052 0.032	50.10	2.764 0.055	55.60

2.2. Design of soil-cement mixture

In this study, the soil-cement sample was designed according to guidelines in the national standard TCVN 9403:2012 [1]. The cylindrical mold was made of a plastic tube with an inner diameter of 55mm and a height of 120mm. The rubber caps were used to keep moisture. Also, the inner surface of the molds was cleaned and greased to remove specimens easier from the molds.

Equations (1) and (2) show the volume of cement and the amount of mixing water for a specimen, as follows:

$$W_c = \frac{1+w}{1+w_0} a_w . W_0 \quad (1)$$

$$W_w = \left(\frac{w-w_0}{1+w} + \mu a_w\right) \frac{1+w}{1+w_0} W_0 \quad (2)$$

where W_0, W_c, W_w, and w are the weight of dried soil (kg), cement weight (kg), water weight (kg), and natural soil moisture (%) calculated for a specimen, respectively; a_w, μ are cement content, water/cement ratio and w_x = 200 (kg/m^3) is the amount of cement. As seen in the table, the natural soil moisture of soil samples at the fabrication times of soil-cement samples was relatively different from that of the intact sample (see Table 1) due to the different times between soil sampling at a construction site and fabrication of soil-cement samples. Also, SD and CV were also calculated for natural soil moisture, w, as presented in Table 2. Table 2 shows the components of the soil-cement mixture for a sample calculated from Equations (1) and (2).

Table 2. Cement-soil mixture for soil-cement samples.

No	w_x (kg/m^3)	a_w (%)	μ	$\rho(*)$ (g/cm^3)	w (%)		W_c (g)	W_o (g)	W_w (g)
					Mean	SD/CV			
HK1	220	13.0	0.8	1.56	30.2	2.77 0.09	62.8	382.3	87.7
HK2	220	13.7	0.8	1.42	45.3	2.87 0.06	62.5	343.3	98.5
HK3	220	13.3	0.8	1.76	37.3	2.21 0.06	72.6	428.2	104.8

Nghi-Son cement PC40 was used in the study. Table 3 shows the compressive strength of the cement sample for different testing days. Tested cement samples were fabricated by following guidelines from “cement – test methods – determination of strength TCVN 6016:2011”. For each case, 6 samples were tested to determine the average value of cement strength. As seen in the table, the variation between the strength of ith tested sample was lower than 10%, so the cement strength was calculated by averaging the strength of 6 samples. The compressive strength of the cement sample at 28 days is over 40 MPa.

Table 3. Compressive strength of cement sample.

Testing date	Strength at 3 days		Strength at 7 days		Strength at 14 days		Strength at 28 days	
	f_i (MPa)	$\frac{f_i - f_{tb}}{f_{tb}}$ (%)	f_i (MPa)	$\frac{f_i - f_{tb}}{f_{tb}}$ (%)	f_i (MPa)	$\frac{f_i - f_{tb}}{f_{tb}}$ (%)	f_i (MPa)	$\frac{f_i - f_{tb}}{f_{tb}}$ (%)
1st sample	20.86	-8.8	33.26	6.8	35.32	-7.4	44.62	7.89
2nd sample	21.92	-4.2	32.71	4.3	38.21	5.2	43.89	4.70
3rd sample	23.87	4.3	29.82	-8.3	38.89	8.2	41.25	-6.84
4th sample	24.7	8.0	30.2	-6.6	38.34	5.8	43.96	5.01
5th sample	22.7	-0.8	32.5	3.4	36.19	-3.6	41.32	-6.54
6th sample	23.2	1.4	31.8	0.4	35.11	-8.3	41.85	-4.22
Average f_{tb} (MPa)	22.88		31.72		37.01		42.82	

2.3. Manufacture of soil cement samples

To fabricate a soil-cement sample, each component of the designed mixture (see Table 2) was accurately weighed. The procedure for fabricating samples is as follows. At first, an intact soil sample from the borehole was torn into small crumbs, and it was carefully mixed with cement. Second, an amount of water was put into the mixed cement and soil, and it was mixed for about 10 minutes. Third, the mixture was put into the mold (55 mm in diameter and 120 mm in height), including three layers, and the height of each layer was about 40 mm. For each layer, a steel rod (10mm in diameter, 350mm long) was used to compact, and the depth of compaction was the same as the height of each layer (about 40 mm). Finally, after removing the excess mixture from the mold surface, the mold is covered by a cap, as shown in Figure 3.

(a) (b) (c)

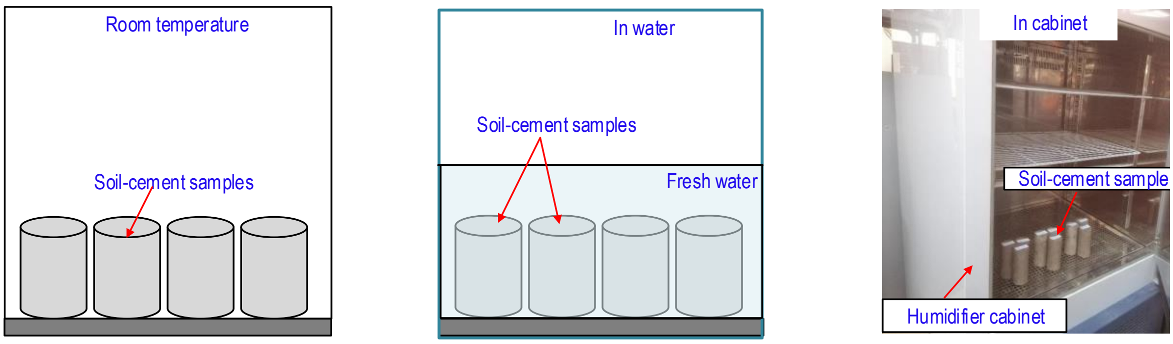
Figure 3. Three groups of soil-cement samples using different soil sources: (a) Using soil from HK1, (b) Using soil from HK2, (c) A soil-cement group, HK3.

There were three groups of soil-cement samples that were fabricated using different soil sources. The samples were numbered using the syntax *HKj.M.n.m.i*, in which *HKj* presents soil from the name of boreholes (i.e., HK1, HK2, and HK3); *n* is the ordinal number of different curing conditions (see Section 2.4); *m* is the date of tested samples, including 7, 14, and 28 days; *i* is the ordinal number of the sample in the same testing condition (*i* = 1-3) to calculate average stress/strain of the samples. As zoomed in Figure 3c, sample 3M2.14.2 was fabricated using soil from HK3, curing condition II, tested at 14^h and 2^{nd} sample among the three ones in the group. For each of HK1, HK2, or HK3, there were 27 samples fabricated. In other words, a total of 81 samples were cast and tested.

2.4. Three examined maintenance conditions for soil-cement samples

After casting for three days, the samples were demolded, and the samples were then weighed and measured the real size after the curing time, as shown in Table 4. As observed in the table, the height of the specimen was slightly reduced from 120 mm to 112 mm for 1M1.7.3 (at 7 days), 109 mm for 1M1.14.3 (at 17 days), and 110 mm (at 28 days). Moreover, the diameter of the specimen was insignificantly changed (55 mm for 1M1.7.3 or 54mm for 1M1.14.3). H, D and W_t are the real height, diameter, and weight of the soil-cement specimen, respectively.

According to guidelines from TCVN 9403:2012 (treatment method for weak soil foundation using soil-cement column), three curing conditions were tested to simulate the working conditions of soil-cement pillars, as shown in Figure 4a-c. For the first curing condition (see Figure 4a and Table 4), the 27 samples (each of HK1, HK2, and HK3 having 27 specimens) were kept at normal conditions (room temperature). For the second curing condition, the 27 specimens were completely submerged in water tanks using fresh water, as seen in Figure 4b. For the third curing condition, the 27 soil-cement specimens were maintained in the humidifier cabinet (see Figure 4c). The temperature was maintained at 20^{o}C with 90% of humidity.



(a) (b) (c)

Figure 4. Curing conditions for soil-cement samples: (a) Maintained condition, (b) Maintained condition II, (c) Maintained condition III.

Table 4. Names and height of soil cement samples.

HK	Samples for a 7-day test Name	H - D - W_t	Samples for a 14-day test Name	H - D - W_t	Samples for a 28-day test Name	H - D - W_t	Condition
HK1	1M1.7.1	112 - 55 - 424	1M1.14.1	109 - 54 - 333	1M1.28.1	110 - 55 - 326	I (air)
	1M1.7.2	112 - 55 - 425	1M1.14.2	110 - 55 - 335	1M1.28.2	109 - 55 - 320	
	1M1.7.3	112 - 55 - 423	1M1.14.3	113 - 54 - 345	1M1.28.3	110 - 54 - 320	
	1M2.7.1	112 - 55 - 429	1M2.14.1	110 - 55 - 438	1M2.28.1	111 - 55 - 437	II (water)
	1M2.7.2	111 - 54 - 437	1M2.14.2	112 - 56 - 427	1M2.28.2	110 - 56 - 436	
	1M2.7.3	112 - 55 - 440	1M2.14.3	113 - 56 - 446	1M2.28.3	116 - 56 - 467	
	1M3.7.1	112 - 54 - 416	1M3.14.1	113 - 55 - 438	1M3.28.1	109 - 56 - 425	III

HK	Samples for a 7-day test		Samples for a 14-day test		Samples for a 28-day test		Condition
	Name	H - D - W_t	Name	H - D - W_t	Name	H - D - W_t	
	1M3.7.2	110 - 55 - 409	1M3.14.2	112 - 55 - 424	1M3.28.2	109 - 55 - 422	(cabinet)
	1M3.7.3	112 - 55 - 421	1M3.14.3	110 - 55 - 420	1M3.28.3	112 - 55 - 437	
HK2	2M1.7.1	110 - 55 - 401	2M1.14.1	115 - 55 - 315	2M1.28.1	108 - 55 - 284	I (air)
	2M1.7.2	110 - 55 - 404	2M1.14.2	108 - 55 - 294	2M1.28.2	110 - 54 - 283	
	2M1.7.3	112 - 55 - 399	2M1.14.3	110 - 55 - 300	2M1.28.3	108 - 55 - 285	
	2M2.7.1	113 - 54 - 433	2M2.14.1	110 - 55 - 423	2M2.28.1	110 - 55 - 420	II (water)
	2M2.7.2	110 - 54 - 424	2M2.14.2	109 - 55 - 418	2M2.28.2	113 - 55 - 430	
	2M2.7.3	115 - 55 - 450	2M2.14.3	111 - 55 - 426	2M2.28.3	108 - 55 - 404	
	2M3.7.1	113 - 55 - 416	2M3.14.1	111 - 55 - 411	2M3.28.1	110 - 55 - 405	III (cabinet)
	2M3.7.2	112 - 55 - 404	2M3.14.2	110 - 55 - 407	2M3.28.2	110 - 55 - 414	
	2M3.7.3	113 - 55 - 405	2M3.14.3	106 - 55 - 400	2M3.28.3	109 - 55 - 410	
HK3	3M1.7.1	111 - 54 - 406	3M1.14.1	109 - 55 - 300	3M1.28.1	107 - 54 - 273	I (air)
	3M1.7.2	108 - 55 - 386	3M1.14.2	108 - 54 - 293	3M1.28.2	109 - 54 - 279	
	3M1.7.3	111 - 55 - 395	3M1.14.3	107 - 54 - 278	3M1.28.3	106 - 54 - 266	
	3M2.7.1	111 - 55 - 396	3M2.14.1	109 - 55 - 408	3M2.28.1	110 - 55 - 408	II (water)
	3M2.7.2	112 - 55 - 410	3M2.14.2	110 - 55 - 407	3M2.28.2	111 - 55 - 410	
	3M2.7.3	110 - 55 - 388	3M2.14.3	110 - 56 - 418	3M2.28.3	111 - 55 - 408	
	3M3.7.1	110 - 55 - 387	3M3.14.1	110 - 55 - 403	3M3.28.1	110 - 55 - 399	III (cabinet)
	3M3.7.2	110 - 55 - 382	3M3.14.2	109 - 55 - 400	3M3.28.2	111 - 47 - 400	
	3M3.7.3	112 - 55 - 427	3M3.14.3	110 - 56 - 409	3M3.28.3	110 - 55 - 404	

3. Experimental test on soil-cement specimen

3.1. Experimental setup

Figure 5 shows the experimental setup of the soil-cement sample on a compression machine (Triplex II, VJ Tech) to measure the stress-strain relationship under applied load. The specimen was placed in the middle of two supported plates, and a load cell was used to get the actual applied force to the specimen. By inputting geometric constants of the specimen, a small software installed on a laptop enabled to record the stress-strain behaviors of the tested specimens. The loading speed was set as 1 mm/min, and the test on each specimen was stopped if the specimen deformed rapidly or near failure.

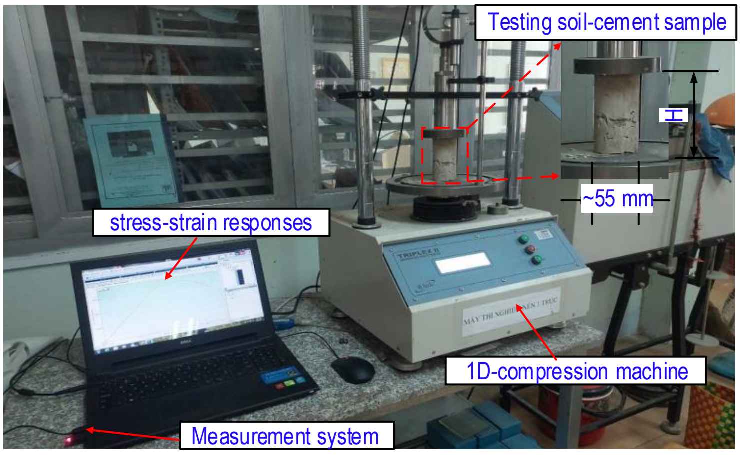
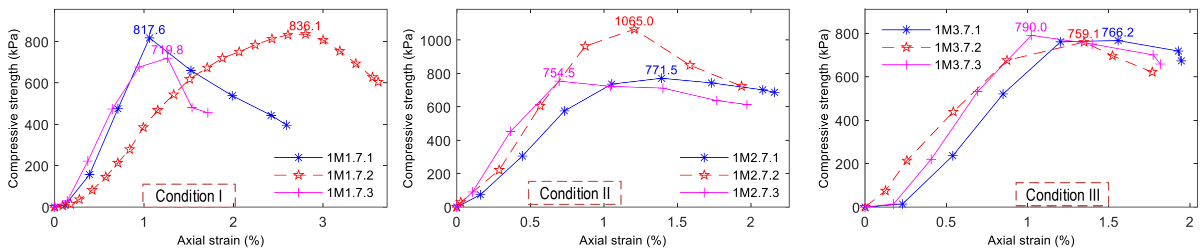


Figure 5. Experimental setup of soil-cement sample on compression machine.

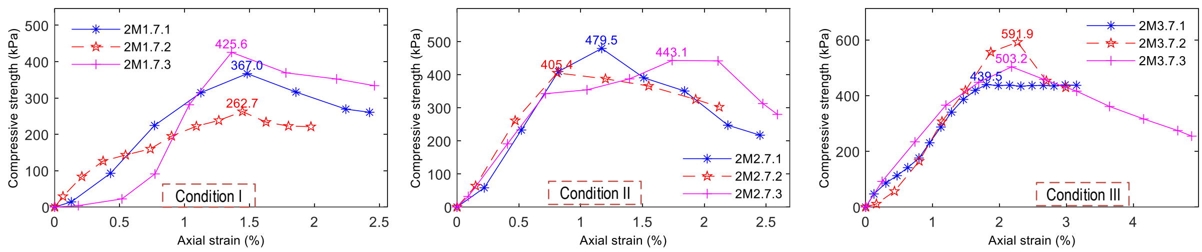
3.2. Stress-strain relationship of soil-cement specimen under compression force

Figure 6a-c shows the stress-strain relationship of soil-cement specimens, which were fabricated using soil from HK1, HK2, and HK3, at 7-day curing under three maintenance conditions, respectively. As previously described, each maintenance condition had three tested samples, so there were nine tested samples at 7-day curing from the same soil source. Specifically, 1M1.7.1, 1M1.7.2, was 1M1.7.3 were three tested samples fabricated using soil from HK1, under maintenance condition I, and tested at 7-day curing (see Figure 6a). Moreover, 1M2.7.1, 1M2.7.2, and 1M2.7.3 were three tested samples fabricated using soil from HK1, under maintenance condition II, and tested at 7-day curing (see Figure 6a). In addition, 1M3.7.1, 1M3.7.2, and 1M3.7.3 were three tested samples fabricated using soil from HK1, under maintenance condition III, and tested at 7-day curing (see Figure 6a).

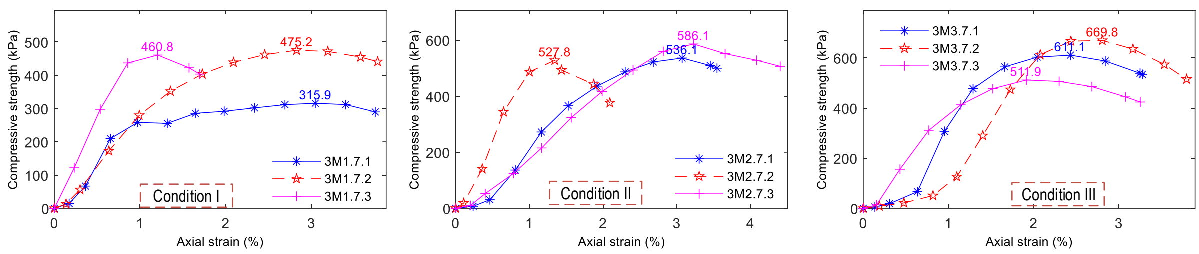
As observed in Figure 6, under increasing axial compressive stress, the axial strain increased, but the stress-strain relationship was slightly different from specimens in the same maintenance condition. Precisely, for soil-cement samples fabricated using soil from HK1, the average stress at 7-day curing, which was calculated from 817.6 kPa (1M1.7.1), 835.1 (1M1.7.2) and 719.8 (1M1.7.3), was 791.2 kPa for the maintenance condition I (in air, normal condition). Additionally, the average stress was 863.7 kPa and 771.7 kPa for maintenance conditions II (in water) and III (in the humidifier cabinet), respectively (see Figure 6a). For soil-cement samples fabricated using soil from HK2, the average stresses at 7-day curing were respectively 351.7 kPa, 442.7 kPa, and 511.5 kPa for the maintenance conditions I, II, and III (see Figure 6b). For soil-cement samples fabricated using soil from HK3, the average stresses at 7-day curing were respectively 417.3 kPa, 550.0 kPa, and 597.6 kPa for the maintenance conditions I, II, and III (see Figure 6c).



(a)



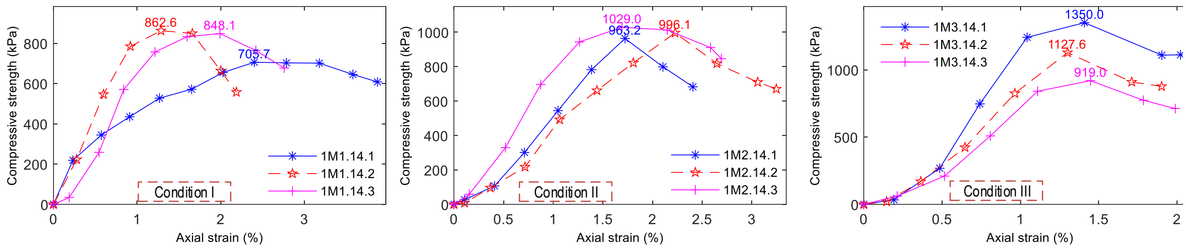
(b)



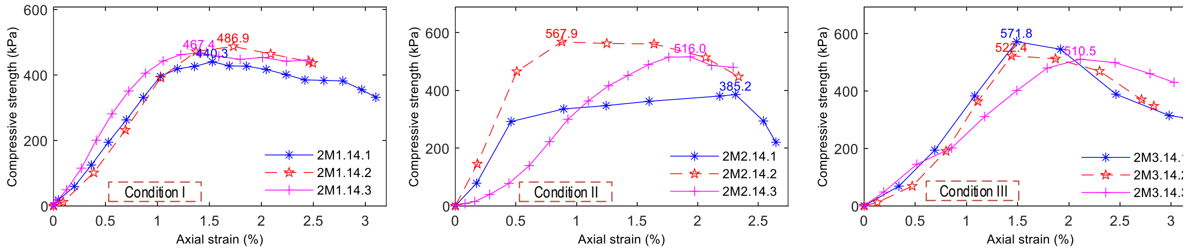
(c)

Figure 6. Stress-strain relationship of soil-cement specimen at 7-day curing under various conditions: (a) Soil-cement samples fabricated using soil from HK1, (b) Soil-cement samples fabricated using soil from HK2, (c) Soil-cement samples fabricated using soil from HK3.

Figure 7a-b shows the stress-strain relationship of soil-cement specimens, which were fabricated using soil from HK1 and HK2 at 14-day curing under three maintenance conditions, respectively. Each maintenance condition also had three tested samples. Under increasing axial compressive stress, the axial strain increased, and the stress-strain relationship was slightly different from specimens among specimens in the same maintenance condition.



(a)



(b)

Figure 7. Stress-strain relationship of soil-cement specimen at 14-day curing under various conditions: (a) Soil-cement samples fabricated using soil from HK1, (b) Soil-cement samples fabricated using soil from HK2.

For soil-cement samples fabricated using soil from HK1, the average stress at 14-day curing, which was calculated from 705.7 kPa (1M1.14.1), 862.6 (1M1.14.2) and 848.1 (1M1.14.3), was 805.5 kPa for the maintenance condition I (in the air). The average stress was 996.1 kPa and 1132.2 kPa for maintenance conditions II (in water) and III (in the humidifier cabinet), respectively (see Figure 7a). For soil-cement samples fabricated using soil from HK2, the average stresses at 14-day curing were respectively 464.9 kPa, 489.7 kPa, and 534.9 kPa for the maintenance conditions I, II, and III (see Figure 7b).

Figure 8a-b shows the stress-strain relationship of soil-cement specimens, which were fabricated using soil from HK2 and HK3 at 28-day curing under three maintenance conditions, respectively. Each maintenance condition also had three tested samples (e.g., 3M3.28.1, 3M3.28.2, and 3M3.28.3 samples fabricated from HK3, maintenance condition III, tested at 28-day curing). As observed the figure, when axial compressive stress increased, the axial strain increased. For soil-cement samples fabricated using soil from HK2, the average stress at 28-day curing, which was calculated from 494.8 kPa (2M1.28.1), 509.0 (2M1.28.2) and 497.4 (2M1.28.3), was 500.4 kPa for the maintenance condition I (in the air). The average stress was 634.4 kPa and 733.7 kPa for maintenance conditions II (in water) and III (in the humidifier cabinet), respectively (see Figure 8a). For soil-cement samples fabricated using soil from HK3, the average stresses at 28-day curing were respectively 792.1 kPa, 908.1 kPa, and 1094.4 kPa for the maintenance conditions I, II, and III (see Figure 8b).

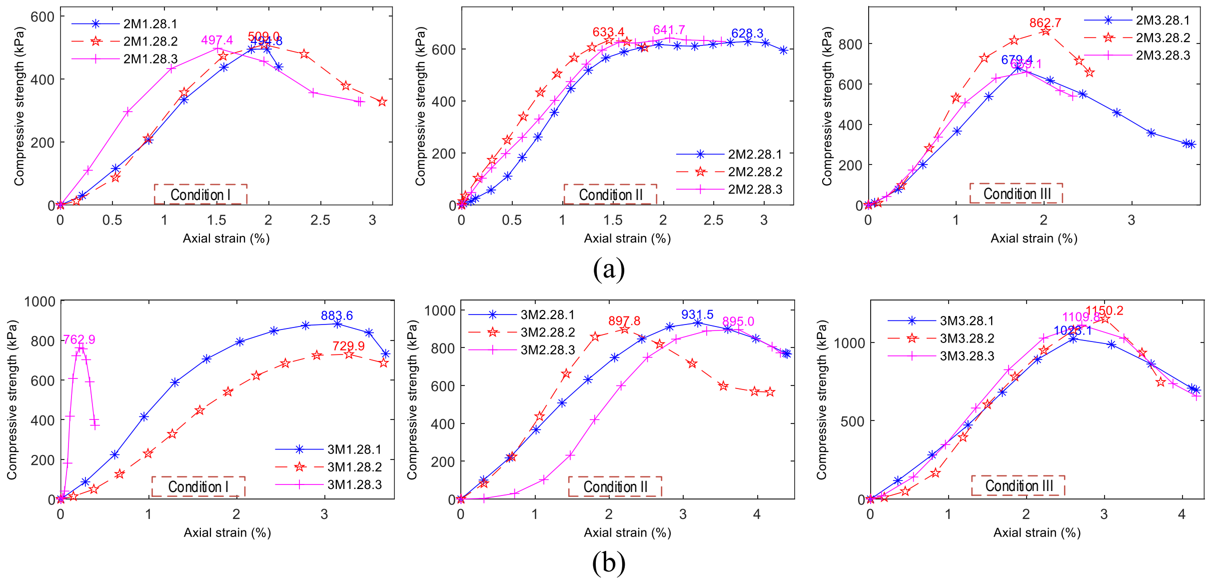


Figure 8. Stress-strain relationship of soil-cement specimen at 28-day curing under various conditions: (a) Soil-cement samples fabricated using soil from HK2, (b) Soil-cement samples fabricated using soil from HK3.

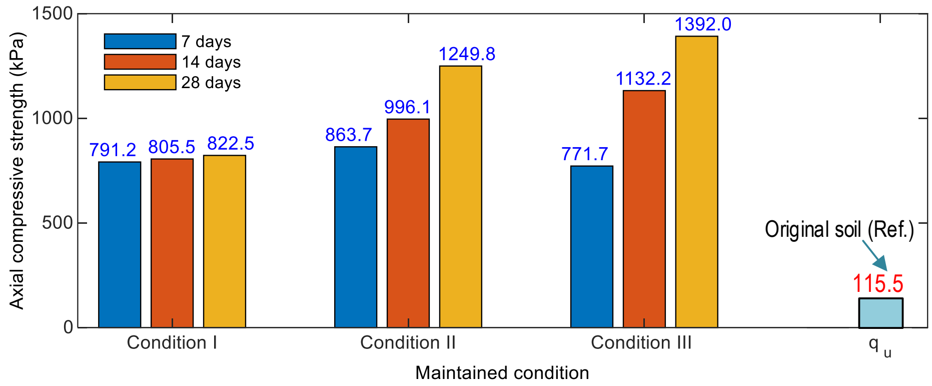
3.3. Evaluating compressive strength of soil-cement specimen under different maintenance conditions

Table 5 shows the average compressive strength and the standard deviation of soil-cement samples under different maintained conditions. It is noted that the value (e.g., 791.2 kPa at HK1, maintained condition I, at 7 days) was calculated using the experimental strength of three samples (see Figure 6a). The standard deviation values for each tested sample group were varied, and the minimum value was 5.51 kPa, and the maximum value was about 212.97 kPa. It confirmed that the strength development of soil-cement is dependent on the maintained condition.

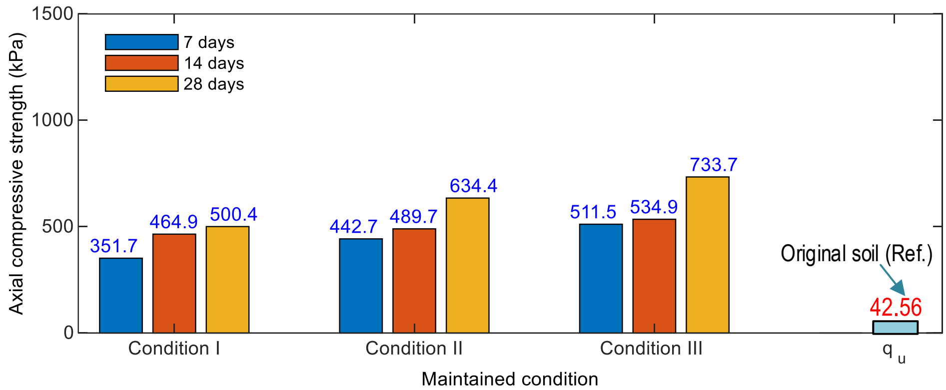
Table 5. Average compressive strength and its SD values of soil cement samples.

Soil samples	Maintained condition	Axial compressive strength (kPa)			Standard deviation (kPa)		
		7 days	14 days	28 days	7 days	14 days	28 days
	I (air)	791.2	805.5	822.5	51.01	70.78	20.49
1	II (water)	863.7	996.1	1249.8	142.51	26.84	212.97
	III (Cabinet)	771.7	1132.2	1392.0	13.23	176.02	94.28
	I (air)	351.7	464.9	500.4	67.38	19.09	6.17
2	II (water)	442.7	489.7	634.4	30.26	76.84	5.51
	III (Cabinet)	511.5	534.9	733.7	62.48	26.53	91.58
	I (air)	417.3	715.2	792.1	71.91	19.40	66.05
3	II (water)	550.0	772.9	908.1	25.77	10.03	16.61
	III (Cabinet)	597.6	856.0	1094.4	65.17	13.82	53.03

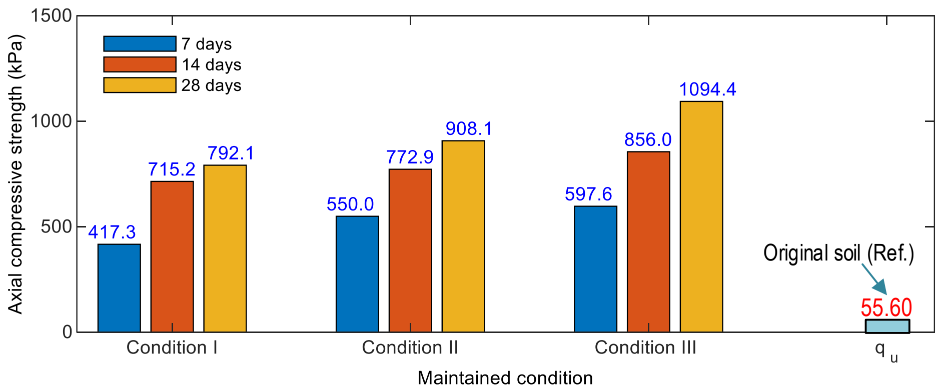
Figure 9a-c shows the average axial compressive stress of soil-cement samples at 7, 14, and 28-day curing under three maintenance conditions, which were fabricated using soil from HK1, HK2, and HK3, respectively. The average axial stresses were computed from three strength values of specimens in the same maintenance condition. The axial compressive stresses of natural soil for each borehole (namely original soil) were also plotted for comparison. Generally, the compressive stress increases with respect to the curing days of the specimen, and the strength depends on the maintenance conditions of specimens and soil sources used for specimen fabrication.



(a)



(b)



(c)

Figure 9. Average axial compressive stress of soil-cement samples at 7, 14, and 28-day curing under various maintenance conditions: (a) Soil-cement samples fabricated using soil from HK1, (b) Soil-cement samples fabricated using soil from HK2, (c) Soil-cement samples fabricated using soil from HK3.

As shown in Figure 9a, soil-cement samples were fabricated using soil from HK1 (soft-malleable clay; semi-hard clay with q_u = 115.50 kPa). The specimen strength was slightly increased from 791.2 kPa (at 7 days) to 822.5 kPa (at 28 days) for the curing condition I (in the air). Meanwhile, the specimen strength was significantly increased from 863.7 kPa (at 7 days) to 1249.7 kPa (at 28 days) for the curing condition II (in water). Furthermore, the specimen strength was expressively increased from 771.7 kPa (at 7 days) to 1392.0 kPa (at 28 days) for the curing condition III (in cabinet). Compared to the original soil (without treatment), the strength of the treated soil was significantly improved. Importantly, the compressive strength from the maintenance conditions II and III resulted in higher than that from the curing condition I.

As shown in Figure 9b, soil-cement samples were fabricated using soil from HK2 (Gray-brown clay-flowing stage with q_u = 42.56 kPa). The specimen strength was slightly increased from 351.7 kPa (at 7 days) to 500.4 kPa (at 28 days) for curing condition I. It was 442.7 kPa (at 7 days) to 634.4 kPa (at 28 days) for curing condition II, and the value was 511.5 kPa (at 7 days) to 733.7 kPa (at 28 days) for curing condition III. Similar to the development of compressive strength of soil-cement samples using soil from HK1, maintenance condition II and III also give better conditions for developing strength.

As shown in Figure 9c, soil-cement samples were fabricated using soil from HK3 (Clay mud, clay mud with sand layers with q_u = 55.60 kPa). The specimen strength was slightly increased from 417.3 kPa (at 7 days) to 792.1 kPa (at 28 days) for curing condition I. It was 550.0 kPa (at 7 days) to 908.1 kPa (at 28 days) for curing condition II, and the value was 597.6 kPa (at 7 days) to 1094.4 kPa (at 28 days) for curing condition III. Similar to the development of compressive strength of soil-cement samples using soil from HK1 or HK2, maintenance conditions II and III also yielded higher compressive strength.

As observed in Figure 9, different soil properties (see Table 1) yielded differences in the strength of the soil-cement specimen. The soil from HK2 with q_u = 42.56 kPa gave the lowest strength (733.7 kPa) under the same amount of cement and maintenance conditions (e.g., 1094 kPa for HK3). It is noted that in the southern Vietnam, the soil near the natural elevation has lower strength (i.e., see the value of q_u in Table 1), and the soil properties were also different from the locations.

4. Discussion on effects of maintained condition on strength development of soil-cement sample

As observed in Figures 6-8, the compressive strength of soil-cement samples was relatively different for the samples in a group of the same maintained condition or different maintained conditions. The maximum strain determined at maximum compressive strength was about 2.5%. This observation was well-matched to the previous study [15]. Moreover, in general, samples maintained in fresh water (i.e., maintained condition II) yielded higher axial strain compared to other conditions (see Figure 8b). This is because the soil-cement sample is dehydrated under the maintained condition I and III. Meanwhile, the maintained condition III yielded the highest compressive strength (see Figure 9) for different soil properties (HK1-HK3).

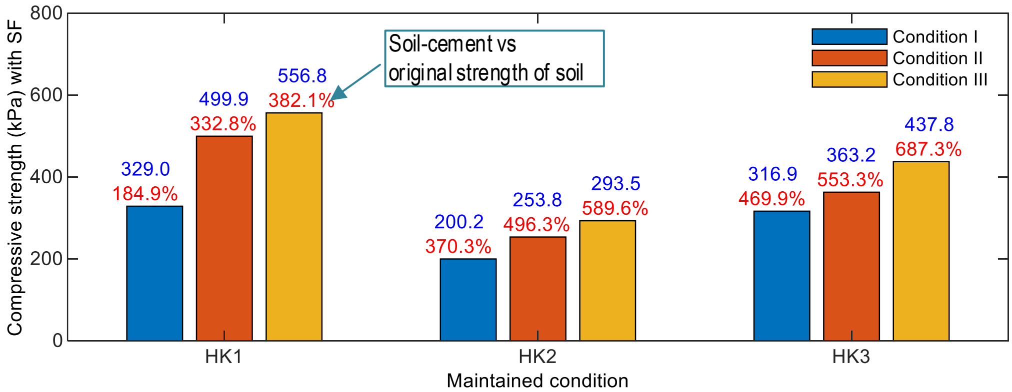


Figure 10. Strength increment (at 28 days) of soil-cement samples versus untreated soil.

As observed in Figure 1, the groundwater level was different for each construction site. When the soil cement technique is applied to enhance soil capacity, the strength development of soil-cement specimen above the groundwater line can be considered as maintained condition I. Also, the strength development of soil-cement specimens below the groundwater line can be considered as maintained condition II. Since the soil-cement specimen's strength depends on the maintained condition (as seen in Figure 9), it is necessary to consider the effect when designing a soil-cement mixture on the strength of soil-cement on a real construction site.

In order to evaluate the effectiveness of the treatment method, the strength of the specimen in the laboratory was compared with the natural soil specimens (without treatment). Moreover, the strength on the laboratory is usually larger than that measured from onsite construction due to influences on construction conditions. The safety factor is usually picked from SF = 2-3 to consider these effects. Figure 10 shows the strength increment (at 28 days) of soil-cement samples versus the untreated soils (from HK1, HK2, and HK3), in which the safety factor was set by 2.5. As observed in the figure, the treated soil increased from about 180% to 680% strength compared to the original soil. Especially, the treated soil from HK3 gave the highest effectiveness among three HK1, HK2, and HK3 for three maintenance conditions. Meanwhile, the treated soil from HK1 offered the lowest effectiveness in the group. The result could come from the soil properties. As shown in Table 1, the soil from HK1 was soft-malleable clay to semi-hard clay, and the soil, itself has relatively high strength (i.e., 115.6 kPa). Meanwhile, the soil from HK3 was clay-mud with sand layers with q_u = 55.6 kPa. The sand in soil combined with cement could increase the strength of the specimens. This observation was consistent with other previous studies [14, 16, 19].

5. Concluding remarks

This study presented the effects of various maintenance conditions on the strength of soil-cement samples. At first, natural soil samples were obtained at various depths for different boreholes in southern Vietnam. Second, the soil samples were used to fabricate the soil-cement cylinders. Third, a set of manufactured samples were maintained in the air, water, and humidifier cabinet for 7, 14, and 28 days. Last, the experimental tests were conducted to test compressive strength for evaluating the effects of environmental parameters on strength development.

From the experimental results, the following concluding remarks can be drawn. First, the maintenance conditions show significant effects on the strength of the specimen, and the soil-cement sample should be cured in the water of humidify cabinet. Second, the soil properties of the foundation have an essential effect on the specimen strength. The soil-cement method gave a higher effectiveness for soil containing sand layers. When designing a soil-cement mixture, the selection of cement ratio should consider the effects of groundwater level on the strength development of the soil-cement column. The cement ratio should be larger for the soil layer above the groundwater line compared with that below the groundwater line.

In the future, the effects of cement amount on the compressive strength of soil-cement columns should be investigated. Also, the onsite application of soil-cement columns for weak ground reinforcement is encouraged.

CRediT author statement

Ba-Huy Vo: Conceptualization, Methodology, Validation, Formal analysis. **Hoai-Luan Dinh:** Conceptualization, Visualization, Writing-Original draft manuscript. **Ngoc-Loi Dang:** Investigation, Validation, Writing-Reviewing and Editing.

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