Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 54 No.1 March 2023 ISSN 0046-5828

Hydraulic Conductivity Behavior of Soilcrete Specimens Created from Dredging Sand, Cement, and Bentonite

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ABSTRACT: Dredging sand is an inexpensive material utilized to rise elevations of highway embankments and earth levee bodies in the Southern Vietnam. However, the high permeability of the dredging sand can cause failures due to seepage flows during annual flood seasons. The dredging sand mixing cement with or without bentonite is expected to be suitable low permeability as an impermeable material. However, hydraulic conductivity of soilcrete and bentonite specimens created from dredging sand taken in the Mekong delta has limit research data. This study aims at better understanding of the hydraulic conductivity of the dredging sand samples taken in Dong Thap province mixed with cement and bentonite. The effects of the hydraulic conductivity of soilcrete and bentonite soilcrete specimens on time, cement contents, bentonite contents, cement types, and hydraulic gradients were investigated. The tests followed the ASTM D5084 standard using the both falling head-constant tailwater and falling head-rising tailwater methods. The results indicate that: (1) the hydraulic conductivity of the soilcrete and bentonite specimens decreased with increasing in testing duration and cement contents; (2) the hydraulic conductivity of the soilcrete specimens was lower 10^4 to 10^5 times than that of the compacted sand; (3) the hydraulic conductivity of the bentonite soilcrete specimens was lower 10 times than those of the soilcrete specimens; (4) the PCS cement can induce the long-term reduction of soilcrete permeability; (5) the effect of hydraulic gradients on soilcrete hydraulic conductivity was ignorable; (6) the soilcrete hydraulic conductivity varies from 10^{-9} to 10^{-10} m/s.

KEYWORDS: Hydraulic conductivity, Permeability, Soilcrete, Dredging sand, Hydraulic gradient.

1. INTRODUCTION

Dredging sand is a popular economical material used to rise elevations of the ground surface for almost all construction projects like roads and earth levees in the Southern Vietnam. The dredging sand has been often taken on riverbeds of rivers in the Southern Vietnam, such as the Mekong River and its branches. The dredging sand is usually a fill material inside earth levees covered by dredging clay in earth levees' slopes. However, washouts of sand inside earth levees due to seepage flows during annual flood seasons are the main factor to cause earth levees' failures in the Mekong delta. Clay cores inside earth levees are the current solutions, but suitable clays to create clay cores become rare in the Mekong delta. Soilcrete made from the dredging sand mixing cement with or without bentonite is promising to be an alternative fill material.

Several research on soil mixing cement with or without bentonite reported that the soilcrete hydraulic conductivity was significantly low (Helson et al., 2018; Ata et al., 2015; Iravanian, 2015; Alkaya and Esener, 2011; Bahar et al., 2004). The hydraulic conductivity of several specimens formed from sand, cement, and kaolinite was less than 10^{-8} m/s at the age of 28 days (Helson et al., 2018). Ata et al. (2015) published that the hydraulic conductivity of specimens mixed from sand, cement, and bentonite was close to 10^{-8} m/s at 28 days. The hydraulic conductivity of a soilcrete specimen created from 15% bentonite, 5% cement, and 80% sand was 10^{-9} m/s at 28 days of age (Iravanian, 2015). Alkaya and Esener (2011) found that a specimen made from 5% cement plus 10% bentonite mixed with sand achieves a hydraulic conductivity of 10^{-9} cm/s. A sandy soil sample mixed with cement contents of 5, 10, 15, and 20% provided hydraulic conductivity of 10^{-8} m/s or less (Bahar et al., 2004).

The hydraulic conductivity of sand mixing bentonite was lower 10^{-6} m/s and at least 10^4 times less than those of sand (Martirosyan and Yamukyan, 2018; Tong and Shackelford, 2016; Ameta and Wayal, 2015; Xu et al., 2011; Gueddouda et al., 2010; Castelbaum and Shackelford, 2009; Sällfors and Öberg-Högsta, 2002; Kenney et al., 1992; Cowland and Leung, 1991). The hydraulic conductivity of sandy soil mixing bentonite at 7.5, 10, and 12.5% was as low as 10^{-8} m/s (Martirosyan and Yamukyan, 2018). Xu et al. (2011) reported that k_s of sand mixing 5% bentonite reduced from 10^{-6} m/s to 10^{-10} m/s. Sällfors and Öberg Högsta (2002) recommended that bentonite contents of 4% to 13% mixed with sand can form impermeable materials for seepage cut-off. Cowland and Leung (1991) and Kenney et al. (1992) concluded that k_s was 10^{-9} m/s at a bentonite content of 7%.

This paper investigated hydraulic conductivity of soilcrete specimens molded from dredging sands taken in the Mekong delta mixing various cement types at several cement contents with or without bentonite. Hydraulic conductivity tests were conducted using designed flexible wall permeameters applying the both falling head–constant tailwater and falling head-rising tailwater methods. Test duration was up to 100 days. Variation of hydraulic conductivity with time, cement contents, bentonite contents, cement types, and hydraulic gradient was examined.

2. MATERIAL AND METHODOLOGY

2.1 Laboratory Testing Standards

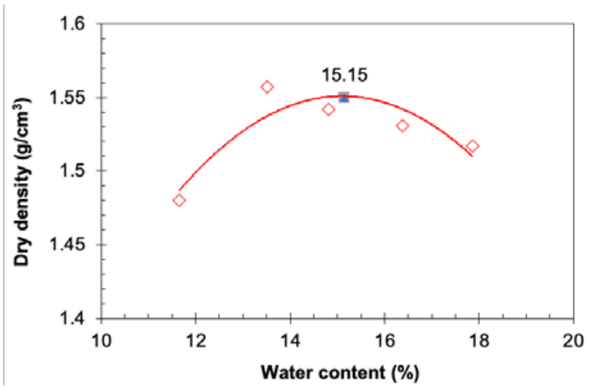
Specimens were created following the ASTM D698 for compacted sand specimens and the TCVN 9403:2012 (the Vietnam standard) for soilcrete specimens. The hydraulic conductivity of all specimens were conducted following the ASTM D5084 using the falling head-constant tailwater and falling head-rising tailwater methods.

2.2 Testing Materials

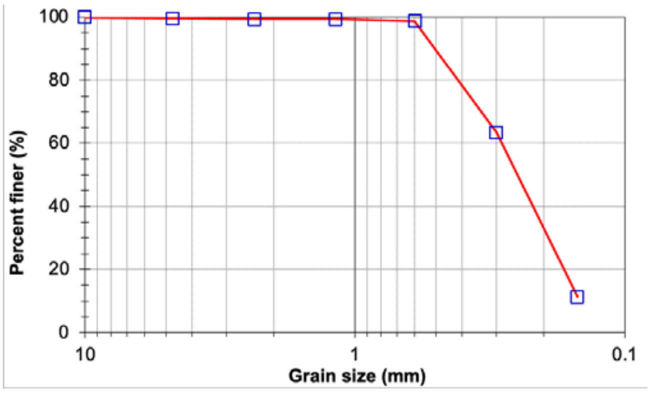
A dredging sand sample was taken in Dong Thap province in the Mekong delta. The sand sample was tested for the key properties such as compaction, grain size distribution, and so on. Table 1 provides the key properties of the sand sample, and Figure 1 shows the grain size distribution and compaction of the sand.

Table 1 The key properties of the sand sample

Optimal moisture content, w_{op} (%)	Wet density, γ_w (kN/m^3)	Dry density, γ_{dmax} (kN/m^3)	pH	Organic content, OC (%)
15.15	17.84	15.55	6.7	6.76



(a) Standard compaction curve



(b) Grain size distribution curve

Figure 1 The grain size distribution and compaction of the dredging sand

The three cement types used to mix with the sand sample to form soilcrete specimens were OPC40, PCB40, and Portland cement plus 50% slag (PCS). Table 2 displays the main characteristics of the cement types. The typical parameters of bentonite following the API SPEC 13A are given in Table 3. Tap water was used to mix with cement, and the key properties are presented in Table 4.

Table 2 Properties of the cement types

Properties	OPC40	PCB40	PCS
Compressive strength: At three days ± 45 min At 28 days ± 8 hours	 ≥ 21 ≥ 40	 ≥ 18 ≥ 40	 ≥ 22 ≥ 50
Setting time (minutes): Initial Final	 ≥ 45 ≤ 375	 ≥ 45 ≤ 420	 ≥ 45 ≤ 600
Specific surface area, cm^2/g	≥ 2800	≥ 2800	≥ 3300
Fine fraction (%): Percent fine remaining on the seize ≥ 0.09 mm	≤ 10	≤ 10	≤ 10
SO_3, %	≤ 3.5	≤ 3.5	≤ 3.5
MgO, %	≤ 5	-	≤ 6
Na_2O_{eq}, %	≤ 0.6	-	-

Table 3 Properties of bentonite

Specific gravity (g/cm^3)	Moisture (%)	Liquid limit (%)	Fine fraction ≤ 0.075 mm (%)
0.9	10	440	80

Table 4 The maximum allowable contents (mg/L) (TCVN 4506:2012)

Total dissolved salts	Sulfate $(SO_4)^{2-}$	Chloride $(Cl)^-$	Non-dissolvable solids
10000	2700	3500	300

2.3 Specimen Preparations

2.3.1 Compacted Sand Specimen, S0

Water was added in a dry dredging sand sample and uniformly mixed to rise a water content of 15.15%, the optimum water content. A plastic mold with dimensions of $D \times H = (62 \times 140)$ mm was used to create a compacted sand specimen at an equivalent compacted energy of 600 kN-m/m^3 (ASTM D698). The specimen was then saturated by submerging water under a vacuum pressure of -80 to -90 kPa for 1-2 days.

2.3.2 Sand Mixing Cement Specimens

A mount of dry cement with a specific cement content was mixed with a mount of dry sand before the amount of water was calculated following a w:c ratio of 0.7:1, and additional was added to reach the optimum water content of the dredging sand, then mixed for about 5 minutes (Table 5). The mixed material was placed into plastic molds with dimensions of (H = 65 mm; D = 62 mm) by three layers and compacted by a vibrating compactor to eliminate as much air bubbles as possible. Each set of mixed material was prepared for only 1-3 soilcrete specimens and within the total preparing duration of 30 minutes or less. All specimens were covered by plastic wrap and cured under water for two days. Then, the specimens were extruded out of the molds, measured for dimensions, and de-aired underwater and a vacuum pressure of -80 to -90 kPa for at least 24 hours before installing into the flexible wall permeameters. Cement contents of 200, 250, 300, 350, and 400 kg/m^3 were applied for the PCB, respectively. A cement content of 300 kg/m^3 was used for the OPC and PCS, respectively.

Table 4 The key components of materials to form soilcrete specimens

Specimen ID	Cement types	Cement content (kg/m^3)	Mass of soil sample (g)	Mass of dry cement (g)	Mass of water (g)
S0	-	0	754	-	-
S1	OPC	200	350	39.3	27.5
S2	OPC	250	350	49.1	34.4
S3	OPC	300	350	58.9	41.2
S3b	OPC	300	350	58.9	41.2
S4	OPC	350	350	68.7	48.1
S5	OPC	400	350	78.6	55
SB	PCB	300	350	58.9	41.2
SS	PCS	300	350	58.9	41.2

2.3.3 Sand-Cement-Bentonite Specimens

Similarly, additional mount of dry bentonite at bentonite contents of 25, 50, 75, and 100 kg/m^3 was added in the above proportion amount of dry sand and dry cement, and uniformly mixed by a mixing machine for 5 minutes. The rest steps were carried out the same as the above procedure. However, the PCB cement at a content of 300 kg/m^3 was only used to create the bentonite soilcrete specimens (Table 6).

Table 6 The key components of materials to form bentonite soilcrete specimens

Specimen ID	Bentonite Content (kg/m^3)	Mass of soil sample (g)	Mass of dry cement (g)	Mass of bentonite (g)	Mass of water (g)
B0	0	350	58.9	0	41.23
B1	25	350	58.9	4.9	44.7
B1b	25	350	58.9	4.9	44.7
B2	50	350	58.9	9.8	48.1
B3	75	350	58.9	14.7	51.5
B4	100	350	58.9	19.6	55

2.4 Testing Instrument and Implementation

A designed flexible wall permeameter model is shown in Figure 2. All exchange water channels were located in the bottom plate. The permeameter can perform at a cell water pressure of 400 kPa and a water head-in pressure of 200 kPa. The permeameter can carry out the falling head-constant tailwater and falling head-rising tailwater methods according to the ASTM D5084. The permeameter was performed for calibration to verify leakages before conducting hydraulic conductivity tests on soilcrete specimens.

Hydraulic conductivity of the compacted sand specimen was tested using a rigid wall permeameter with the falling head-constant tailwater method (ASTM D5856). Hydraulic gradients of 2-5 was applied to avoid leakage along the rigid wall. For soilcrete specimens, hydraulic conductivity was obtained using the designed flexible wall permeameter (Figure 2) with the falling head-constant tailwater method under hydraulic gradients of 30-45 and the falling head-rising tailwater method under hydraulic gradients of 100-150. Reading data was obtained every day to investigate the change of soilcrete hydraulic conductivity with time. All soilcrete specimens were carried out for at least 90 days.

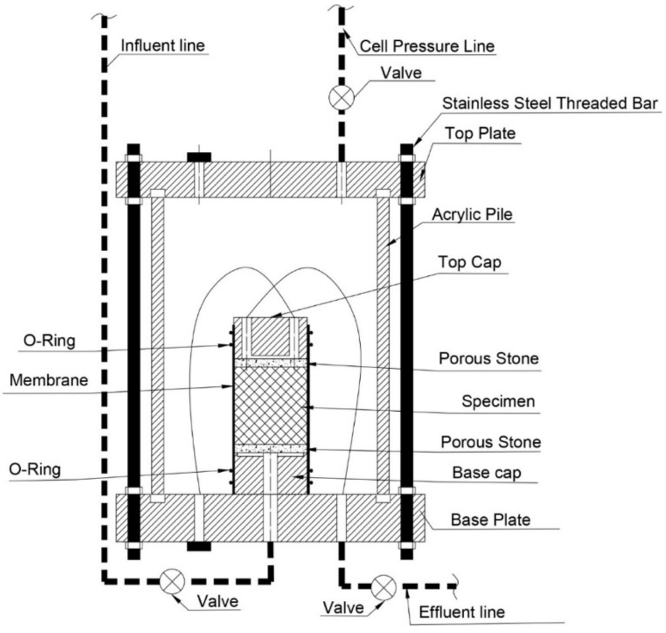


Figure 2 A designed flexible wall permeameter

Hydraulic conductivity was analyzed using Equations (1) and (2) at room temperature. Equations (1) and (2) were employed for the falling head-constant tailwater and the falling head-rising tailwater methods, respectively.

$$k = 2.303\frac{aL}{At}\log\frac{h_1}{h_2} \qquad (1)$$

$$k = 2.303\frac{aL}{2At}\log\frac{h_1}{h_2} \qquad (2)$$

where k – hydraulic conductivity (m/s); L – length of specimen (m); A – area of specimen (m^2); a – area of head-in pipe (m^2), ($a_{in} = a_{out} = a$); $t = t_1 - t_2$ – reading duration (seconds) at head-in of h_1 và h_2; h_1 – head in at reading time t_1 (m); h_2 – head in at reading time t_2 (m).

Hydraulic conductivity at the standard temperature of 20^{0}C, k_{20}, converted by Eq. (3).

$$k_{20} = R_T \times k \qquad (3)$$

where k – hydraulic conductivity at room temperature; R_T – converting ratio (ASTM D5084).

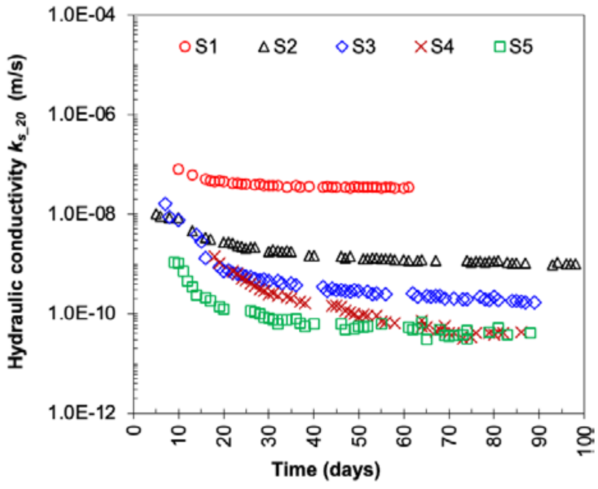
3. RESULTS AND DISCUSSIONS

About 15 specimens created from the dredging sand mixing cement with or without bentonite were conducted for hydraulic conductivity up to 100 days in the laboratory. The collected data was carefully analyzed for the following investigations.

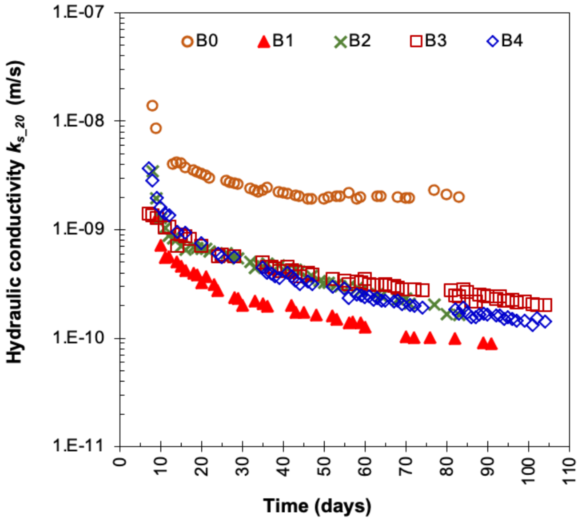
3.1 Soilcrete Hydraulic Conductivity Varying with Time

Hydraulic conductivity of all soilcrete specimens, k_s, decreases with testing duration (Figure 3a). It seems that k_s reduced slightly after the age of 28 days. A similar trend was also reported by Tran-Nguyen et al. (2020), Helson et al. (2018), Mollamahmutoglu and Avci (2018), Bellezza and Fratalocchi (2006), and Akbulut and Saglamer (2004). However, k_s from the soilcrete specimens at cement contents of 300, 350, and 400 kg/m^3 diminished more profoundly than those of 200 and 250 kg/m^3, respectively. At a higher cement content, the hydration and pozzolanic reactions may take time to complete inside soilcrete specimens (Bahar et al., 2004; Kamruzzaman, 2002). The higher cement content was (e.g., the S5 specimen), the much more CSH and CAH products were generated, filling pores in a soilcrete specimen to cause lower hydraulic conductivity. However, at high cement content with constant w/c ratio of 0.7, amount of water in specimen was not maybe enough to hydrate cement completely. Consequently, the k_s of the S5 specimen decreased sharply and became equal to the k_s of the S4 specimen after 60 days (Figure 3a).

Figure 3b exhibits the hydraulic conductivity of the all bentonite soilcrete specimens made from the sand, PCB cement, and bentonite contents of 0, 25, 50, 75, and 100 kg/m^3, respectively. k_s decreased remarkably up to 60% for the first two weeks and then reduced moderately. Tran-Nguyen et al. (2020), Helson et al. (2018) and Akbulut and Saglamer (2004) also found comparable behaviors. The ion exchanges between Ca^{2+} ion in cement, pozzolans in bentonite, and soil particles took time to complete (Wong et al., 2008; Kamruzzaman, 2002). As the result, the void spaces in the bentonite soilcrete specimens reduced gradually (Iravanian, 2015; Ahnberg, 2003).



(a) Soilcrete specimens



(b) Bentonite soilcrete specimens

Figure 3 Hydraulic conductivity of all specimens versus time

3.2 Effects of Cement Contents on Hydraulic Conductivity

Figure 4 displays the hydraulic conductivity of the soilcrete specimens at OPC cement contents of 0, 200, 250, 300, 350, and 400 kg/m^3 at the age of 28 days, respectively. k_s decreased markedly with increasing in cement contents. The hydraulic conductivity of the soilcrete specimens was appreciably lower than that of the compacted sand specimen up to 10^5 times and agreed well to Alkaya and Esener (2011), Bellezza and Fratalocchi (2006), and Bahar et al. (2004) (Table 7). The hydration reactions took place in soilcrete specimens creating gels or Calcium-silicate-hydrate (CSH) and Calcium-aluminate-hydrate (CAH) to fill the void spaces of a specimen and to bind soil particles. Consequently, the soilcrete specimen has less void spaces than the compacted sand specimen to lead a lower hydraulic conductivity (Abbey et al., 2018).

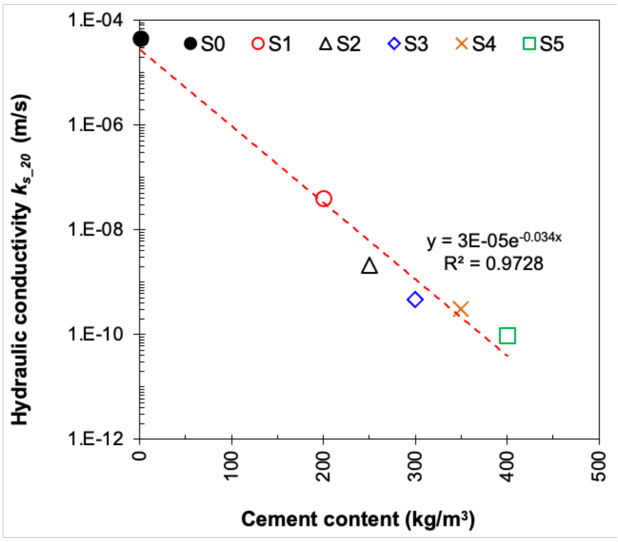


Figure 4 The hydraulic conductivity of the soilcrete specimens at 28 days of age versus cement contents

Table 7 List of hydraulic conductivity of soilcrete specimens

Reference	Description of soilcrete specimens	Hydraulic conductivity (m/s)
Bahar et al. (2004)	Clay sandy soil in Tiziouzou (Algiers), A_c = 5% to 20%	1.4 ×10^{-7} to 2.7×10^{-9}
Bellezza and Fratalocchi (2006)	75% Sand - 25% Clay mixture, A_c = 0 to 5%	8.4×10^{-8} to 1.7×10^{-11}
Alkaya and Esener (2011)	Sand in Yenicekent (Denizli), A_c = 0 to 10%	1.02×10^{-9} to 3.5 ×10^{-10}
Amhadi and Assaf (2020)	Desert sand in Libya, A_c = 3% to 7%	8.63×10^{-7} to 1.33×10^{-7}
This Study	Dredging sand in Southern Vietnam A_c = 0 to 400 kg/m^3 or 0 to 25.8%	4.37×10^{-5} to 9.7×10^{-11}

3.3 Effects of Bentonite Contents on Hydraulic Conductivity

Overall, the hydraulic conductivity of the bentonite soilcrete specimens at the age of 28 days was one order lower than that of the soilcrete specimens at the same cement content (Figure 5). k_s at a bentonite content of 25 kg/m^3 was lower than those at higher bentonite contents. Similar reports can be found from Abbey et al. (2018), Ata et al. (2015), Iravanian (2015), and Alkaya and Esener (2011). The negative charges in the surface of bentonite particles are believed to absorb water and to bind water elements strongly to minimize movement of water flow (Alkaya and Esener, 2011). The ion exchanges among Ca^{2+} ions, bentonite, and soil particles also lessened void volumes in a soilcrete specimen to cause a reduction of hydraulic conductivity (Nontananandh et al., 2005).

At greater bentonite contents, k_s increased fairly and was almost identical at the bentonite contents of 50, 75, and 100 kg/m^3, respectively (Figure 5). Ata et al. (2015) and Xu et al. (2011) published similar data. A higher bentonite content in bentonite soilcrete specimens is thought of occupying, replacing partial volume of soil particles. Free bentonite particles swell and generate more void space in bentonite soilcrete specimens (Taha and Taha, 2007). An appropriate amount of bentonite can create impermeable materials from dredging sands, but abused bentonite contents cause inverse effects.

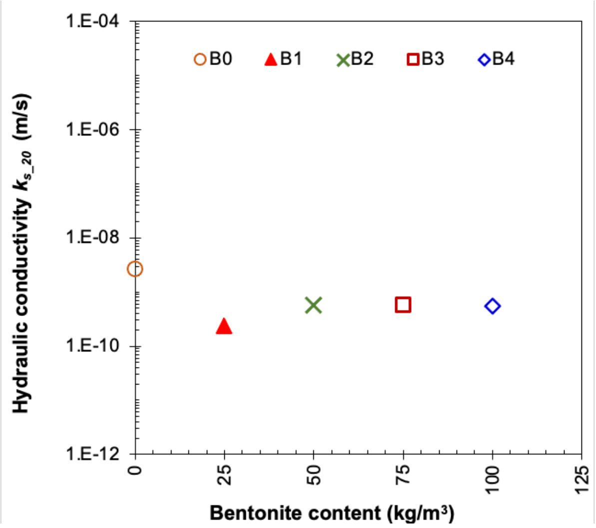


Figure 5 The hydraulic conductivity of the bentonite soilcrete specimens at the age of 28 days

3.4 Effects of Cement Types on Soilcrete Hydraulic Conductivity

The OPC, PCB, and PCS cement types were used to investigate variation of soilcrete hydraulic conductivity at a cement content of 300 kg/m^3 and time. k_s of all soilcrete specimens decreased with time at different rates (Figure 6). k_s of the soilcrete specimens made from the OPC and PCB cements had comparable rates, although the OPC cement produced the lower k_s. The PCS cement induced sharp reduction of k_s, especially after the age of 35 days. Mollamahmutoglu and Avci (2018) and Markou and Droudakis (2013) found the identical tendency. The OPC cement contents 95% pure clinkers and produces quickly more gels (C-S-H and C-A-H) by the hydration reactions. In short terms, the OPC generates profound decrease of k_s to compare with the PCB and PCS cements. On the contrary, the PCS cement contents more pozzolans and less clinkers than the OPC and PCB cements. In short terms, the hydration reactions of the PCS cement create less gels than that of the OPC and PCB cements. However, the hydration reactions of the PCS are still in progress and provide more gels to fill more void spaces in the soilcrete specimens to lead lower hydraulic conductivity (Markou and Droudakis, 2013; Lura et al., 2001). Additionally, the particles of the PCS cement are finer than those of the OPC and PCB cements and increase void filling capacity to cause lower hydraulic conductivity (Mollamahmutoglu and Avci, 2018; Markou and Droudakis, 2013).

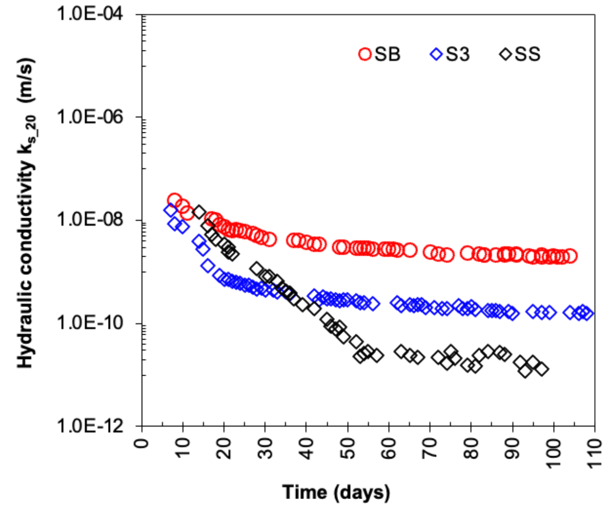


Figure 6 The hydraulic conductivity of the soilcrete specimens made from various the cement types

3.5 Effects of Hydraulic Gradients on Hydraulic Conductivity

The two bentonite soilcrete specimens were utilized to examine how hydraulic gradients effect on hydraulic conductivity. Figure 7 shows the hydraulic conductivity of the B1 and B1b specimens at the age of 28 days. Both specimens were made from dredging sand, a cement content of 300 kg/m^3, and a bentonite content of 25 kg/m^3. The B1 and B1b specimens were tested in two designed flexible wall permeameters under a hydraulic gradient of 40 and 132, respectively. The hydraulic conductivity was almost identical and agreed well to Assaad and Harb (2013), Gueddouda et al. (2010), and Picandet et al. (2010).

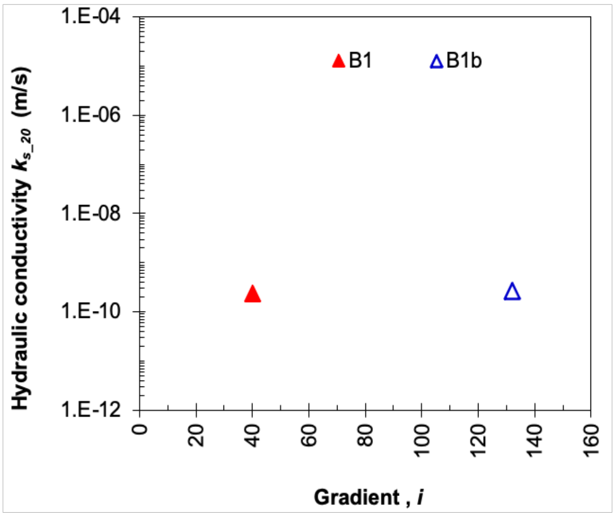


Figure 7 The hydraulic conductivity of the bentonite soilcrete specimens versus hydraulic gradients

3. CONCLUSIONS

A set of the several soilcrete and bentonite soilcrete specimens were made and tested for hydraulic conductivity using the designed flexible wall permeameters up to 100 days to compare with the hydraulic conductivity of the compacted sand specimen. The three cement types of OPC, PCB, and PCS were used to create soilcrete specimens at various cement contents. The bentonite contents of 25, 50, 75, and 100 kg/m^3 were employed to investigate effects of bentonite on hydraulic conductivity, respectively. The falling head-constant tailwater and the falling head-rising tailwater methods were applied to conduct hydraulic conductivity tests. The rigid wall permeameter was used to obtain the hydraulic conductivity of the compacted sand specimen implementing the falling head-constant tailwater method. The results indicate the following findings:

(1) Soilcrete and bentonite soilcrete hydraulic conductivity decreased with increasing in testing duration.
(2) Soilcrete hydraulic conductivity is reduced with increasing in cement contents.
(3) Soilcrete hydraulic conductivity was 10^4 to 10^5 times lower than that of the compacted dredging sand sample.
(4) A relevant amount of bentonite can induce lower hydraulic conductivity of soilcrete for 10 times, but higher amount of bentonite can cause the increase of soilcrete hydraulic conductivity.
(5) The OPC cement makes soilcrete hydraulic conductivity reduced quickly, and the PCS cement causes soilcrete hydraulic conductivity decreased significantly after 35 days.
(6) The effect of hydraulic gradients is apparently neglectable on k_s soilcrete hydraulic conductivity.

4. ACKNOWLEDGMENTS

This study is funded by Vietnam National University in Ho Chi Minh City (VNU-HCM) under the grand no. B2018-20-04. The authors acknowledge the support from the VNU-HCM and Ho Chi Minh City University of Technology.

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